

## 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 4<sup>th</sup> Member of the Shahejie Formation ( $Es_4^l$ ) and 1<sup>st</sup> 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 3<sup>rd</sup> 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 4<sup>th</sup> 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

*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 4<sup>th</sup> Member of the Shahejie Formation (Es<sub>4</sub><sup>1</sup>) and 1<sup>st</sup> Member of the Kongdian Formation (Ek<sub>1</sub>). 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 3<sup>rd</sup> and the upper 4<sup>th</sup> Members of the Eocene Shahejie Formation (Es<sub>3</sub><sup>1</sup> and Es<sub>4</sub><sup>4</sup>), 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,

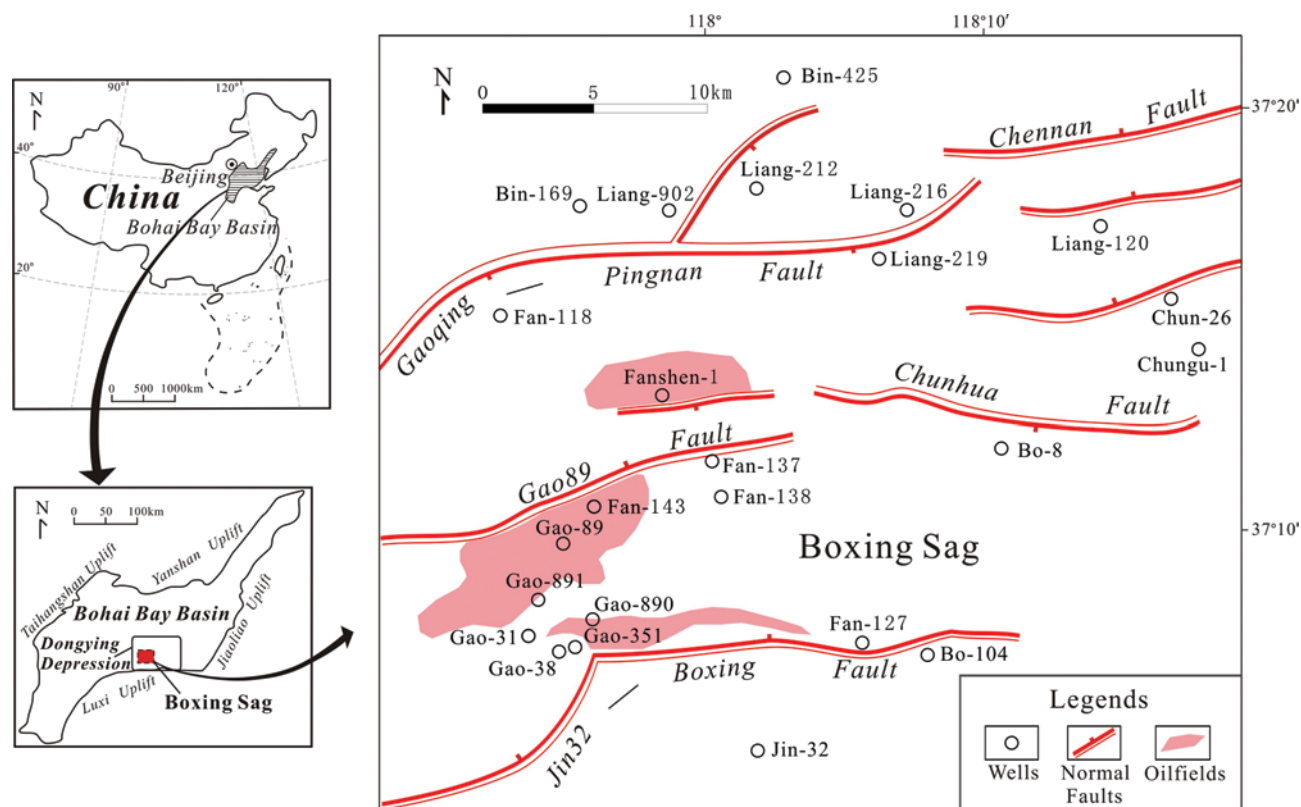


Figure 1. Geological location, and sample distribution, of the Boxing sag in the Dongying depression, eastern China.

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<sub>1</sub> (1<sup>st</sup> Member of the Shahejie Formation), Es<sub>3</sub><sup>m</sup> (middle 3<sup>rd</sup> Member of the Shahejie Formation), Es<sub>3</sub><sup>l</sup> and Es<sub>4</sub><sup>u</sup>. The two main source rocks are Es<sub>3</sub><sup>l</sup> and Es<sub>4</sub><sup>u</sup> 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<sub>4</sub><sup>l</sup> and Ek<sub>1</sub>) are the favorable as well as the potential reservoir bed. Two regionally extensive units represent the cap rock: the thick Ed<sub>3</sub>-Es<sub>1</sub> (3<sup>rd</sup> Member of the Dongying Formation and 1<sup>st</sup> Member of the Shahejie Formation) and the Es<sub>3</sub><sup>l</sup>-Es<sub>4</sub><sup>u</sup> dark mudstone. The study on the source of Paleogene red-bed oil in the Boxing sag has

System	Series	Formation	Member	Symbol	Lithologic profile	Depositional environment	Source rocks	Reservoir beds	Cap rocks	
Paleogene	Oligocene	Dongying	1 <sup>st</sup>	Ed <sub>1</sub>		Fluvial delta				
			2 <sup>nd</sup>	Ed <sub>2</sub>						
			3 <sup>rd</sup>	Ed <sub>3</sub>						
		Shahejie	1 <sup>st</sup>	Es <sub>1</sub>		Lake				
			2 <sup>nd</sup>	Es <sub>2</sub>		Semi-deep to deep lake, delta, shallow lake				
			3 <sup>rd</sup>	Upper	Es <sub>3</sub> <sup>u</sup>		Semi-deep to deep lake, delta			
				Middle	Es <sub>3</sub> <sup>m</sup>		Semi-deep to deep lake, delta, turbidite fan			
				Lower	Es <sub>3</sub> <sup>l</sup>		Semi-deep to deep lake, delta			
			4 <sup>th</sup>	Upper	Es <sub>4</sub> <sup>u</sup>		Semi-deep to deep lake, shallow lake			
	Lower	Es <sub>4</sub> <sup>l</sup>			Beach bar, shore, shallow lake					
	Eocene	Kongdian	1 <sup>st</sup>	Ek <sub>1</sub>		Fluvial plain, shallow lake				
			2 <sup>nd</sup>	Ek <sub>2</sub>		Shallow lake				
			3 <sup>rd</sup>	Ek <sub>3</sub>						

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<sub>3</sub><sup>l</sup>, Es<sub>4</sub><sup>u</sup>, Es<sub>4</sub><sup>l</sup> and Ek<sub>1</sub> 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<sub>3</sub>) 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<sup>-1</sup>. 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<sup>-1</sup> 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<sup>-1</sup>. 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<sup>-1</sup> and continued to rise to 310 °C at a rate of 3 °C·min<sup>-1</sup>, 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<sub>3</sub><sup>l</sup> and Es<sub>4</sub><sup>u</sup> source rocks are summarized in Table 1 and Figure 3 and are described in the following section.

Table 1. Biomarker parameters of Es<sub>3</sub><sup>l</sup> and Es<sub>4</sub><sup>u</sup> 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 <sub>3</sub> <sup>l</sup> 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 <sub>4</sub> <sup>u</sup> 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 <sub>4</sub> <sup>u</sup> 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<sub>17</sub>; 4. Ph/*n*-C<sub>18</sub>; 5. CPI = [(*n*-C<sub>25</sub> + *n*-C<sub>27</sub> + *n*-C<sub>29</sub> + *n*-C<sub>31</sub> + *n*-C<sub>33</sub>) / (*n*-C<sub>24</sub> + *n*-C<sub>26</sub> + *n*-C<sub>28</sub> + *n*-C<sub>30</sub> + *n*-C<sub>32</sub>) + (*n*-C<sub>25</sub> + *n*-C<sub>27</sub> + *n*-C<sub>29</sub> + *n*-C<sub>31</sub> + *n*-C<sub>33</sub>) / (*n*-C<sub>26</sub> + *n*-C<sub>28</sub> + *n*-C<sub>30</sub> + *n*-C<sub>32</sub> + *n*-C<sub>34</sub>)] / 2; 6. tricyclic terpanes/17 $\alpha$ -hopanes; 7. gammacerane/C<sub>31</sub> homohopane = gammacerane / (22S 17 $\alpha$ , 21 $\beta$ -homohopane + 22R 17 $\alpha$ , 21 $\beta$ -homohopane); 8. C<sub>35</sub> homohopane index = 100 × 17 $\alpha$ , 21 $\beta$ -pentashomohopane (22S+22R) / [17 $\alpha$ , 21 $\beta$ -homohopane (22S+22R) + 17 $\alpha$ , 21 $\beta$ -bishomohopane (22S+22R) + 17 $\alpha$ , 21 $\beta$ -trishomohopane (22S+22R) + 17 $\alpha$ , 21 $\beta$ -tetrashomohopane (22S+22R) + 17 $\alpha$ , 21 $\beta$ -pentashomohopane (22S+22R)]; 9. C<sub>27</sub>/C<sub>29</sub> sterane = 20R 5 $\alpha$ , 14 $\alpha$ , 17 $\alpha$ -cholestane / 20R 24-ethyl-5 $\alpha$ , 14 $\alpha$ , 17 $\alpha$ -cholestane; 10.  $\alpha\alpha\alpha$ -C<sub>29</sub> sterane 20S/(20S+20R) = 20S 24-ethyl-5 $\alpha$ , 14 $\alpha$ , 17 $\alpha$ -cholestane / (20S 24-ethyl-5 $\alpha$ , 14 $\alpha$ , 17 $\alpha$ -cholestane + 20R 24-ethyl-5 $\alpha$ , 14 $\alpha$ , 17 $\alpha$ -cholestane)  $\alpha\alpha\alpha$ -20R; 11 diasteranes/regular steranes.

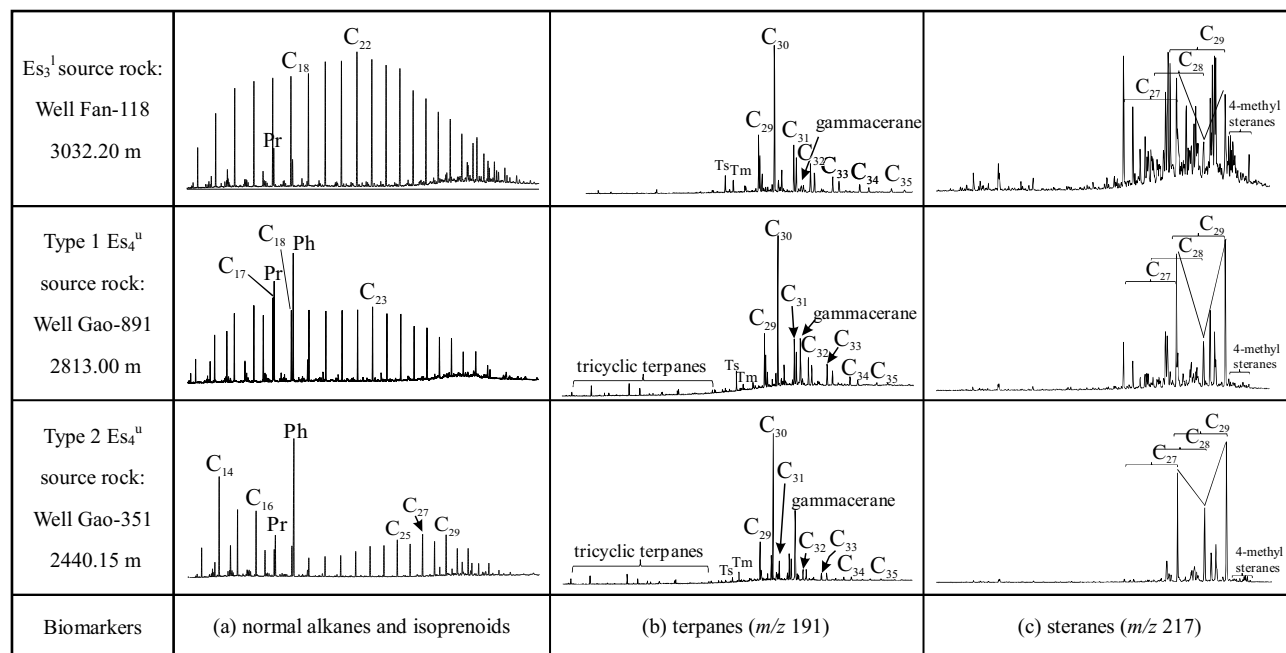


Figure 3. Gas chromatograms of saturated hydrocarbons (a) and mass chromatograms of terpanes ( $m/z$  191) (b) and steranes ( $m/z$  217) (c) of the source rocks in the Boxing sag of the Dongying depression, eastern China.

### Es<sub>3</sub><sup>1</sup> source rock

The *n*-alkanes show Gaussian distribution or weak double peak pattern and the peak is between *n*-C<sub>22</sub>–*n*-C<sub>25</sub>, 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<sub>22</sub> 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/17 $\alpha$ -hopanes lower than 0.07 and gammacerane/C<sub>31</sub> homohopane lower than 0.20 (Table 1, Figure 3b). The C<sub>35</sub> homohopane index is between 5.42% and 7.15% (Table 1).

The  $\alpha\alpha\alpha$ -20R C<sub>27</sub>/C<sub>29</sub> sterane is 0.72–1.41,  $\alpha\alpha\alpha$ -20R C<sub>28</sub> sterane shows lower concentration than that of  $\alpha\alpha\alpha$ -20R C<sub>27</sub> and C<sub>29</sub> steranes, and the concentration 4-methyl steranes is very high (Table 1, Figure 3c).

### Es<sub>4</sub><sup>u</sup> source rock

The Es<sub>4</sub><sup>u</sup> source rock can be subdivided into two types according to the relative distribution of *n*-alkanes (Table 1, Figure 3a): Type 1 Es<sub>4</sub><sup>u</sup> source rock extracts show Gaussian distribution centered between *n*-C<sub>23</sub>–*n*-C<sub>25</sub> (e.g., well Gao-891, peak of *n*-alkanes is *n*-C<sub>23</sub>); Type 2 Es<sub>4</sub><sup>u</sup> source rock extracts show double peak pattern, namely *n*-C<sub>14</sub>–*n*-C<sub>18</sub> or *n*-C<sub>20</sub>–*n*-C<sub>25</sub> (e.g., well Gao-351, peak of *n*-alkanes is *n*-C<sub>14</sub>).

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<sub>3</sub><sup>1</sup> source rock samples (tricyclic terpanes/17 $\alpha$ -hopanes = 0.05–0.79, gammacerane/C<sub>31</sub> homohopane = 0.37–8.1). The C<sub>35</sub> homohopane index is between 3.50% and 21.41%, half of which is bigger than that of the Es<sub>3</sub><sup>1</sup> source rock samples (Table 1, Figure 3b).

Like the Es<sub>3</sub><sup>1</sup> source rock samples,  $\alpha\alpha\alpha$ -20R C<sub>28</sub> sterane of Es<sub>4</sub><sup>u</sup> source rock samples also shows obviously lower concentration compared to that of  $\alpha\alpha\alpha$ -20R C<sub>27</sub> and C<sub>29</sub> steranes, and the ratio of  $\alpha\alpha\alpha$ -20R C<sub>27</sub>/C<sub>29</sub> sterane is lower than 1 except for two samples (0.29–1.41). Unlike to the Es<sub>3</sub><sup>1</sup> source rock samples, the concentration of 4-methyl steranes of Es<sub>4</sub><sup>u</sup> source rock samples is very low (Table 1, Figure 3c).

### Depositional environments of Es<sub>3</sub><sup>1</sup> and Es<sub>4</sub><sup>u</sup> source rocks

Previous studies indicated that the main source rocks of the Boxing sag are Es<sub>3</sub><sup>1</sup> (fresh-brackish or brackish lake) and Es<sub>4</sub><sup>u</sup> (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  $Es_3^1$  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-methyl 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/17 $\alpha$ -hopanes ratio, moderately higher  $C_{35}$  homohopane index, and very low concentration of 4-methyl 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  $Es_3^1$  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  $Es_3^1$  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  $Es_3^1$  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 syn-sedimentary 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/17 $\alpha$ -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  $\alpha\alpha$ -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	$Es_4^1$	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	$Es_4^1$	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	$Es_4^1$	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	$Es_4^1$	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) = 17 $\alpha$ , 21 $\beta$ -homohopane 22S/(22S+22R).

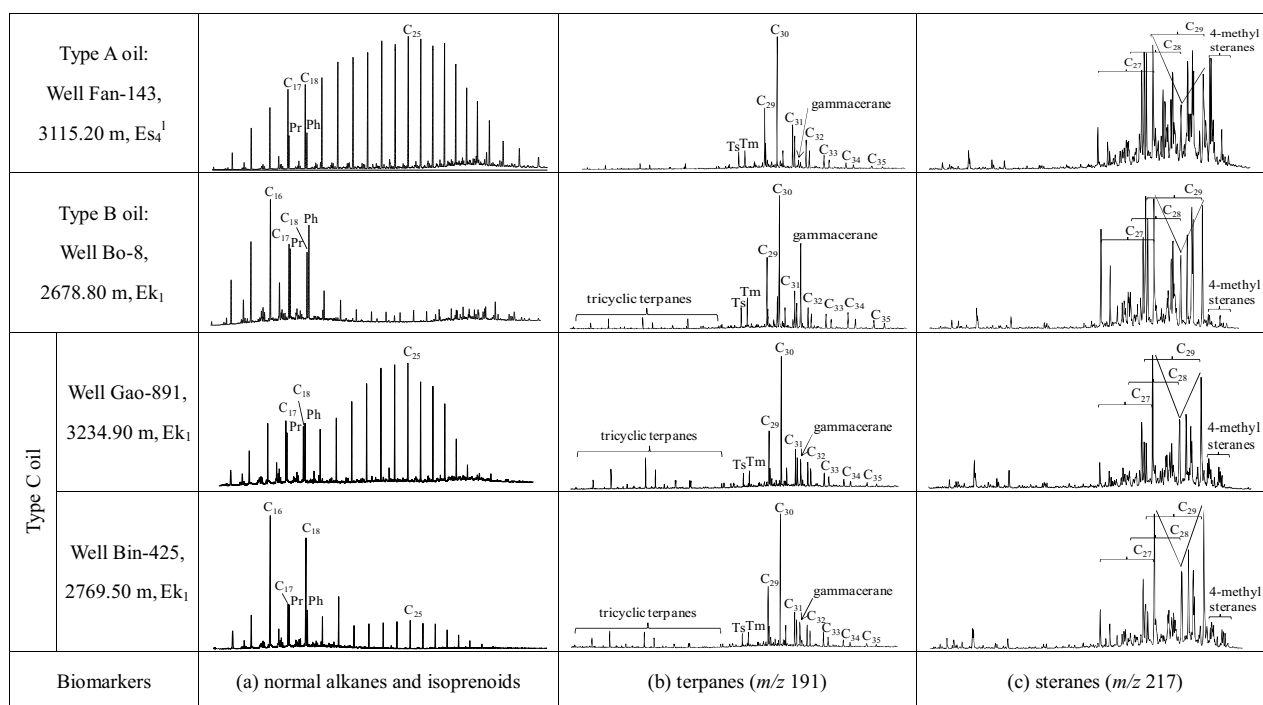


Figure 4. Gas chromatograms of saturated hydrocarbons (a) and mass chromatograms of terpanes (*m/z* 191) (b) and steranes (*m/z* 217) (c) of the Paleogene red-bed oil in the Boxing sag of the Dongying depression, eastern China.

is 0.79–0.94,  $\alpha\alpha\alpha$ -20R C<sub>28</sub> sterane shows notable lower concentration than that of  $\alpha\alpha\alpha$ -20R C<sub>27</sub> and C<sub>29</sub> steranes, and diasteranes and 4-methyl 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<sub>16</sub> as the main peak, CPI is 1.17; Pr/Ph is 0.71, Pr/*n*-C<sub>17</sub> is 0.98 and Ph/*n*-C<sub>18</sub> is 1.55 (Table 2, Figure 4a). The concentration of gammacerane and the C<sub>35</sub> homohopane index are very high (gammacerane/C<sub>31</sub> homohopane = 1.66, C<sub>35</sub> homohopane

index is 12.42%), tricyclic terpanes/17 $\alpha$ -hopanes is 0.12 (Table 2, Figure 4b). The  $\alpha\alpha\alpha$ -20R C<sub>27</sub>/C<sub>29</sub> sterane is 1.22,  $\alpha\alpha\alpha$ -20R C<sub>28</sub> sterane shows a significant lower concentration than that of  $\alpha\alpha\alpha$ -20R C<sub>27</sub> and C<sub>29</sub> steranes (Table 2, Figure 4c). Diasteranes show less concentration than that of Type A oil, and 4-methyl 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<sub>25</sub> as the main peak (Figure 4a), whereas

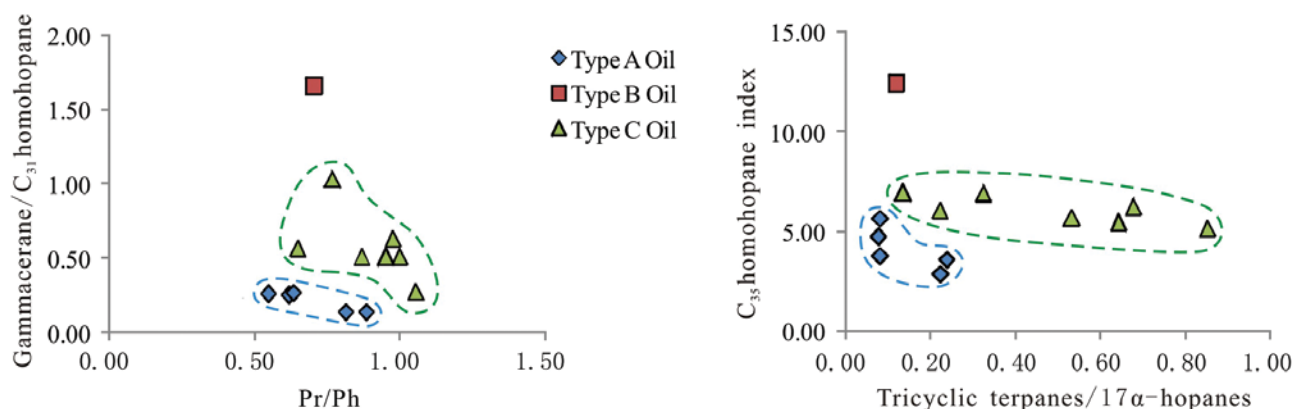


Figure 5. Biomarker scatter plots showing the classification of the Paleogene red-bed oil in the Boxing sag of the Dongying depression, eastern China.



the sample from well Bin-425 plot mostly in the left part with  $n\text{-C}_{16}$  as the main peak (Table 2, Figure 4a). CPI is 0.93–1.45, Pr/Ph is 0.93–1.45, Pr/ $n\text{-C}_{17}$  is 0.52–1.54 and Ph/ $n\text{-C}_{18}$  is 0.69–1.01 (Table 2). Tricyclic terpanes/ $17\alpha$ -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  $\alpha\alpha\alpha\text{-20R}$   $C_{27}/C_{29}$  sterane is 0.68–1.04 (Table 2),  $\alpha\alpha\alpha\text{-20R}$   $C_{28}$  sterane shows a lower concentration than that of  $\alpha\alpha\alpha\text{-20R}$   $C_{27}$  and  $C_{29}$  steranes, and a medium concentration of diasteranes and 4-methyl 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/ $17\alpha$ -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.

## 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-methyl steranes, we consider that Type A oil (e.g., sample from well Fan-143, 3115.20 m) is derived from  $Es_3^1$  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/ $n\text{-C}_{18}$  > 1) and gammacerane predominance, relatively higher tricyclic terpanes/ $17\alpha$ -hopanes ratio and  $C_{35}$  homohopane index, and very low concentrations of diasteranes and 4-methyl 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  $Es_3^1$  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  $Es_3^1$  (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  $Es_3^1$  (e.g.,

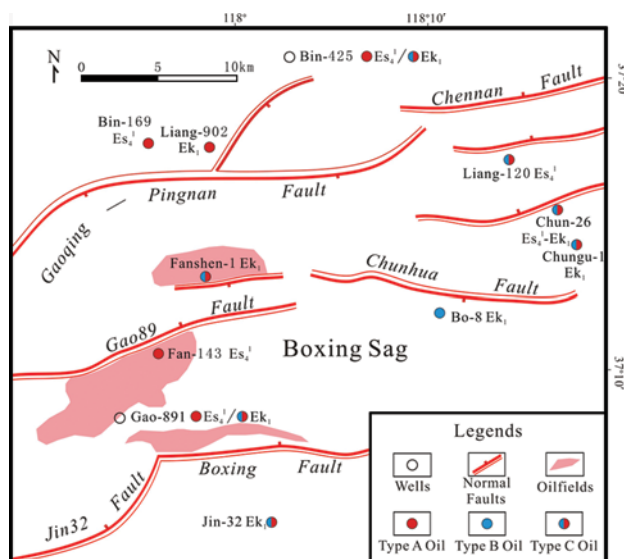


Figure 6. Distribution of the different oil types of the Paleogene red beds in the Boxing sag of the Dongying depression, eastern China.

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  $Es_4^u$  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:  $Es_3^1$  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<sub>4</sub><sup>1</sup> in the western part of the basin is classified as Type A oil, the oil in Ek<sub>1</sub> in the eastern part of the basin (well Bo-8) is classified as Type B oil, and the oil in Ek<sub>1</sub> 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<sub>3</sub><sup>1</sup> source rock, Type B oil is originated from the Es<sub>4</sub><sup>u</sup> source rock, and Type C oil is a kind of mixed oil generated from both Es<sub>3</sub><sup>1</sup> and Es<sub>4</sub><sup>u</sup> 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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