Characteristics of Oil and Gas Accumulation in Yong'an-Meitai Area of the Fushan Depression, Beibuwan Basin, South China Sea

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Abstract: The Yong'an-Meitai area is the focus of the present exploration in the Fushan Depression, Beibuwan Basin, South China Sea. All oils from this area are geochemically characterized by higher Pr/Ph ratio, higher proportion of heavy molecular weight hydrocarbons, and higher proportion of C_{29} regular steranes, which indicate that the organic matter of source rocks might have been deposited in an oxidizing palaeoenvironment and be dominated by higher plant organic matter input. The oil from E_3w_2 (the second member of Weizhou Fm. of the Oligocene) has a much higher density, relatively higher Pr/nC$_{17}$ and Ph/nC$_{18}$ ratios, and a "UCM—unresolved complex mixture" on gas chromatograms, which indicate that it has been slightly biodegraded. CPI and other terpane and sterane isomer ratios suggest they are all mature oils. The timing of oil charging in E_3w_2 and E_2l_1 (the first member of the Liushagang Fm. of the Eocene) determined by the homogenization temperatures of fluid inclusions and thermal evolution history are from 9-3 Ma and 8-3 Ma, respectively. Thus, the interpretation of E_3w_2 as a secondary reservoir is unlikely. The timing of oil charging is later than that of hydrocarbon generating and expulsion of Liushagang Fm. source rocks and trap formation, which is favorable for oil accumulation in this area. All molecular parameters that are used for tracing oil filling direction decrease with shallower burial depth, which suggests vertical oil migration. The widely occurring faults that penetrate through the source rocks of the Liushagang Fm. may serve as a fine oil charging conduit.

Key words: Reservoir geochemistry, homogenization temperature, burial and thermal history, oil migration and accumulation, the Fushan Depression

1. Introduction

Located in the southeastern Beibuwan Basin, South China, the Fushan Depression is the focus of the present exploration. Hydrocarbon exploration in this depression began at the end of the 1950s, with approximately 50 wells being drilled in the subsequent three decades. Since the early 1990s, a number of commercial oil and gas fields have been discovered in this depression (Li, *et al.*, 2007a). Up to date, Huachang, Jinfeng, Meitai oil and gas fields and Yong'an and Bohou-Chaoyang oil-bearing structures have been discovered.

Meitai oil fields, Yong'an and Bohou-Chaoyang oil-bearing structures are located around the Huangtong hydrocarbon generation sag (Fig. 1). The dark mudstone of Eocene Liushagang Formation (E_2l) is thought to be the main source rocks for hydrocarbons in the Fushan Depression. Four sets of oil-bearing intervals have been observed in this area. They are the second member of the Weizhou Formation (E_3w_2), the first, second and third members of the Liushagang Formation (E_2l_1, E_2l_2 and E_2l_3, respectively). The density of these oils varies significantly, in a range of 0.8040 g/cm^3 in E_2l_1 to 0.9536 g/cm^3 in E_3w_2 (Table 1). As to the heavy oil in E_3w_2, it was previously thought be a secondary oil reservoir. Our research indicates that it is not the case. Furthermore, there is no systematic study of the hydrocarbon accumulation characteristics in this area. By using reservoir geochemical analysis techniques, homogenization temperature measurements of fluid inclusion, reconstruction of sedimentary burial and thermal history by basin modelling, this paper presents the oil organic geochemical characteristics, episodes, timing, direction and conduit of oil charging.

2. Geological setting

Situated in the north of the Hainan Island and the south of the Qiongzhou Strait, the Fushan Depression is one of the many Mesozoic-Cenozoic rifting half-grabens in the northern continental shelf of the South China Sea. This NE-E trending depression forms the southeastern part of the Beibuwan Basin (Fig. 1), filled with over 9,000 m of Cenozoic sediments in an area of approximately 3,000 km^2, one third of which is offshore.

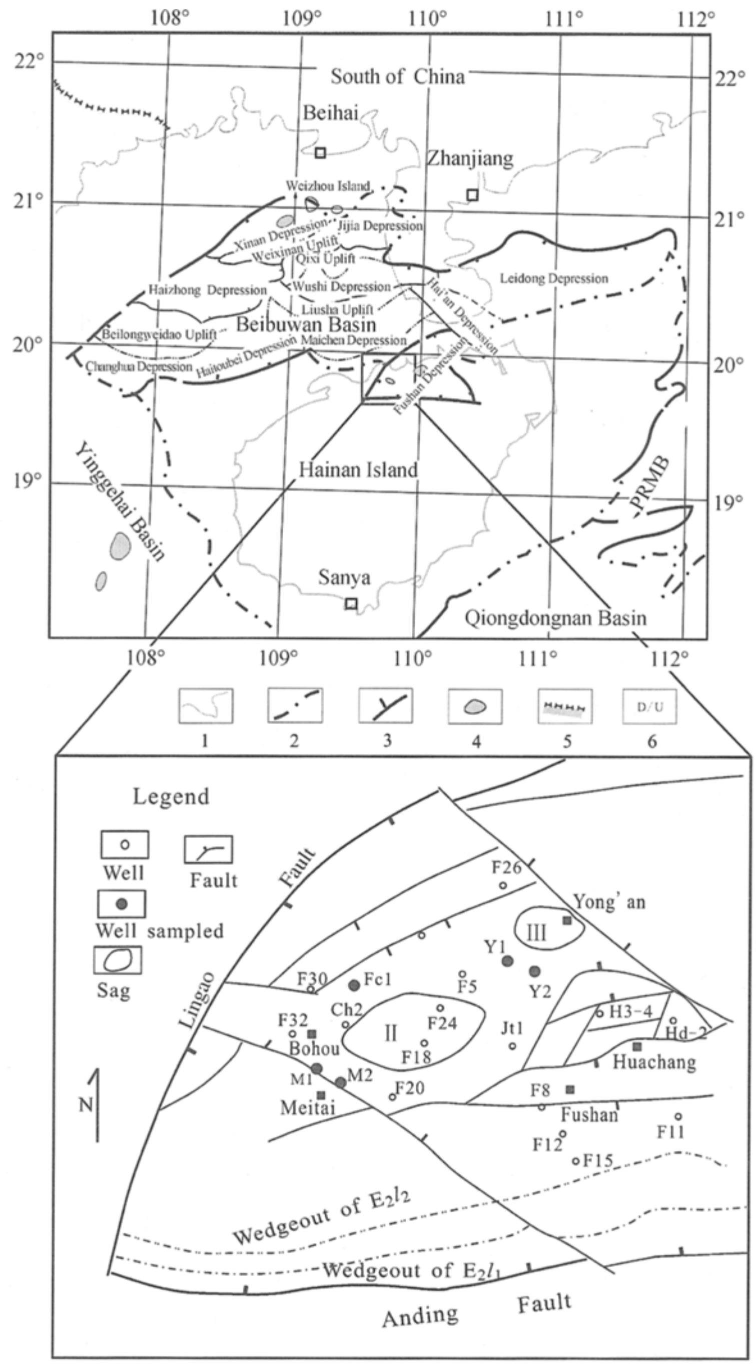
Table 1 Bulk properties of oils from Yong'an-Meitai area in the Fushan Depression

Fm.	Well No.	Interval m	Density [1)] g/cm^3	Sulfur %	Wax %	Viscosity mPa·s	Pour point °C	Well sampled
	F23	1363.2-1418.8	0.9536	0.19	2.07	203.00	-8.0	
E_3w_2	Y1	1945.4-1947.6	0.9428	Nd[2)]	Nd	Nd	Nd	*
	F29	1535.0-1570.4	0.9515	0.19	1.50	184.40	-16.0	
E_3w_3	F28	1710.2-1711.8	0.9103	Nd	Nd	Nd	Nd	
	F29	1621.6-1624.4	0.9470	0.23	2.87	155.32	-18.0	
	Y1	2952.0-2994.0	0.8186	0.04	Nd	2.05	19.0	*
	Y2	3148.4-3182.2	0.8040	0.06	6.98	1.27	9.0	*
	F5	3391.0-3435.8	0.8591	0.17	14.98	5.00	31.0	
E_2l_1	Fc1	2605.0-2698.2	0.8257	0.04	Nd	3.09	20.0	*
	F36	1763.6-1764.6	0.9297	0.21	6.83	81.95	22.0	
	F25	2351.4-2458.2	0.8441	0.07	Nd	5.65	27.0	
	Ch2	2498.2-2509.0	0.9080	Nd	22.29	2.16	29.7	
	Fc1	3523.5-3532.7	0.8276	0.04	Nd	3.43	27.0	*
E_2l_2	F29	1714.0-1742.0	0.8662	0.05	Nd	11.16	32.0	
	F30	1198.2-1201.0	0.8535	0.11	18.97	10.04	30.0	
	M1	3105.2-3108.0	0.8435	0.09	Nd	3.27	23.0	*
E_2l_3	M1	3084.0-3086.0	0.8294	0.32	13.49	3.32	26.0	*
	M2	3014.0-3047.6	0.8436	0.09	21.67	7.31	27.8	*

Notes: 1) Density at 20 °C; 2) Nd: No data

Four orogenic events during the late Mesozoic to Neogene (Fig. 2) controlled the tectonic evolution and sedimentary filling of the Beibuwan Basin (Gong, 1997; Qiu and Gong, 1999). The Shenhu orogeny that occurred during the late Cretaceous resulted in a number of grabens and half-grabens. From Paleocene to Eocene the Zhuqiong orogeny was the main period of rifting that led to the present Beibuwan Basin. In the early rifting stage, the basin was mainly filled with alluvial and fluvial red pebbled sandstones and mudstones of the Changliu Formation (E_1c). In the late rifting stage, organic-rich mudstones of the Liushagang Formation (E_2l) were deposited in a series of well-developed lakes, forming the most important hydrocarbon source rocks in this basin. The Liushagang Formation is the time equivalent of the Wenchang Formation in the Pearl River Mouth Basin (PRMB) (Qiu and Gong, 1999; Zhang, *et al.*, 2004). Major boundary faults occurring in this period controlled the framework of the Fushan Depression. During the late Oligocene Nanhai orogeny, the area was dominated by a shallow lake and swamps, leading to organic-rich mudstones with thin coal interbeds of the Weizhou Formation (E_3w), the second important source unit in the basin. At the late stage of the Nanhai orogeny, the Fushan Depression was filled with shallow marine deposits, intercalated with fluvial sediments in the second member of the Weizhou Formation. During the Neogene Dongsha orogeny, block faulting dominated the basin evolution. Tectonic movements were usually accompanied by extrusive volcanism, resulting in a series of uplifted and subsided blocks during the deposition of the Jiaowei (N_1j), Dengloujiao (N_1d) and Wanglougang (N_2w) formations (Fig. 2).

The study area was situated in the east part of the Fushan Depression (Fig. 1). It consists of Yong'an anticline, Bohou-Chaoyang fault nose-like structure and Meitai fault blocks.



Legends: 1-Coastline; 2-Boundary of basin; 3-Fault; 4-Oil/gas field; 5-National boundary; 6-Depression/Uplift

Fig. 1 Map (upper) showing the location of the Fushan Depression, Beibuwan Basin; the schematic structural map (lower) of Yong'an-Meitai area, and the sampling wells

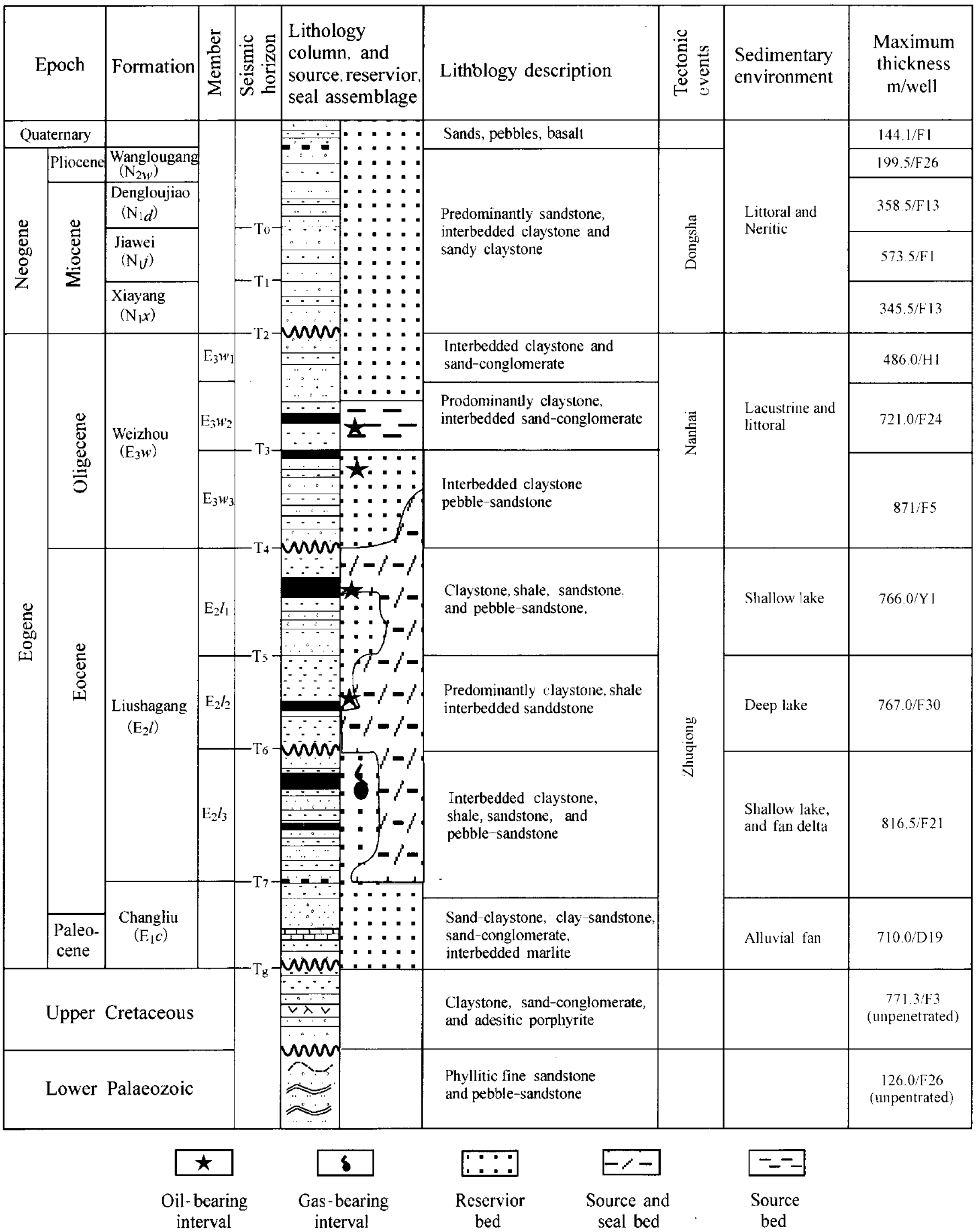


Fig. 2 Generalized stratigraphy and tectonic events of the Fushan Depression

3. Samples and methods

Nine oil samples covering all four oil-bearing intervals were collected from the study area. Oils were quantitatively separated into aliphatic, aromatic and NSO-compounds fractions by routine column chromatography on a silica gel plus alumina (9:1 v/v) column. GC-MS analysis was performed for the aliphatic and aromatic fractions.

Full scan GC-MS was performed on a Thermal Finnigan Trace-DSQ spectrometer interfaced to a gas chromatograph equipped with a 30 m fused silica capillary column (HP-5MS, 0.25 mm I.D., 0.25 μm film thickness). Helium was used as the carrier. The oven temperature was initially set at 50 °C, and programmed to 120 °C at 20 °C /min , to 250 °C at 4 °C /min, then to 310 °C at 3 °C/min with a final hold of 30 min. A scan speed 1.4 scan/s from 50 to 500 atomic mass unit (amu) was used in the mass spectrometer. Electron ionization at 70 eV was used.

The pyrrolic nitrogen fraction was separated by the "two-stage isolation method" (Li, *et al.*, 1999b). GC/MS of the pyrrolic nitrogen fractions was performed by using a Thermal Finnigan Trace-DSQ spectrometer combined with a gas chromatograph equipped with a 30 m fused silica capillary column (HP-5MS, 0.25 mm I.D., 0.25 μm film thickness). The analytical procedure refers Li, *et al.* (1995; 1998; 1999a). The GC oven was initially at 80 °C for 1 min, then ramped to 150 °C at 15 °C /min and to 270 °C at 3 °C/min with a final hold of 10 min. The mass spectrometer was operated in selective ion monitoring (SIM), electron impact modes with an electron energy of 70 eV.

A total of 21 cores or rock cuttings from Y1 and F5 wells were sampled for vitrinite reflectance measurement. Polished blocks were made for all these samples. Vitrinite reflectance R_o (%) was measured on each polished block by using a Leica Model MPV-SP microscopic photometer. The measured R_o (%) profile was used to constrain and calibrate the reconstructed thermal history by basin modelling. The BasinMod-1D software was used to reconstruct the burial and thermal history of Y1 well.

Twelve oil sand samples were also collected for oil-bearing fluid inclusion observation and homogenization temperature measuring. The FI Analytical Laboratory of Beijing Research Institute of Uranium Geology performed the polarized light and fluorescent light observation and homogenization temperature measurement with a Leica DMRXHC Transmission-Reflectance Polarized and Fluorescent Microscope and Linkam THMS-G600 heating-freezing stage. The analysis error of homogenization temperature was ±1 °C.

4. Organic geochemical characteristics of oils

All oils have a very low content of sulfur and a low to moderate content of wax, which are the typical characteristics of lacustrine oil. The oils in E_3w have higher density ranging from 0.9103 to 0.9536 g/cm^3. The oil density in E_2l_3 is the lowest (Table 1). These values tend to decrease with increasing depth. The saturated hydrocarbon is the dominant fraction in all samples with saturates to aromatics ratios of 2.84 to 7.94. The asphaltenes and non-hydrocarbons are generally lower in all oils (Table 2). All these oils have relatively high contents of pristane relative to phytane. The pristane to phytane ratios (Pr/Ph) range from 2.74 to 4.00, with an average of 3.56, which indicates that the oils were derived from the organic matter that deposited in similar oxidizing environment. The gammacerane/C_{30}-hopane (parameter *A* in Table 3) values are as low as 0.00 to 0.06, which also indicates fresh water and oxidizing environment. This is also supported by a high content of C_{27} βα-diasteranes (parameter *B* in Table 3).

Table 2 Fractional composition and acyclic terpenoids related parameters of oils from Yong'an-Meitai area in the Fushan Depression

Well	Fm.	Interval m	Saturates %	Aromatics %	Asphaltenes and non-hydrocarbons, %	S/A 1)	Pr/Ph	Pr/nC_{17}	Ph/nC_{18}	CPI 2)
Y1	E_3w_2	1945.4-1947.6	67.15	23.67	9.18	2.84	3.69	2.81	0.76	1.20
Y1	E_2l_1	2952.0-2994.0	82.16	12.03	5.81	6.83	3.46	0.56	0.18	1.20
Y2	E_2l_1	3081.2-3019.2	83.33	12.56	4.10	6.63	3.97	0.51	0.16	1.15
Y2	E_2l_1	3081.2-3019.2	86.95	10.96	2.10	7.94	4.00	0.57	0.18	1.17
Fc1	E_2l_1	2605.0-2698.2	76.76	16.22	7.03	4.73	3.45	0.78	0.26	1.24
Fc1	E_2l_2	3523.2-3532.7	82.99	10.88	6.12	7.63	2.74	0.42	0.16	1.13
M1	E_2l_3	3084.0-3086.0	72.39	19.02	8.59	3.81	3.63	0.67	0.19	1.23
M1	E_2l_3	3105.2-3108.0	73.30	15.34	11.36	4.78	3.45	0.68	0.21	1.22
M2	E_2l_3	3011.8-3047.6	67.72	12.17	20.11	5.57	3.68	0.60	0.19	1.22

Notes: 1) Saturates/aromatics ratio; 2) Carbon preference index

Table 3 Selected biomarker parameters of oils from Yong'an-Meitai area in the Fushan Depression

Well	Fm.	Interval m	*A*	*B*	C_{27} %	C_{28} %	C_{29} %	*C*	*D*	*E*
Y1	E_3w_2	1945.4-1947.6	0.02	0.63	41.95	10.19	47.85	0.58	0.34	0.54
Y1	E_2l_1	2952.0-2994.0	0.03	0.62	24.76	25.18	50.06	0.61	0.48	0.54
Y2	E_2l_1	3081.2-3119.2	0.06	0.55	25.02	17.82	57.15	0.64	0.48	0.42
Y2	E_2l_1	3081.2-3119.2	0.00	0.83	31.48	29.61	38.91	0.53	0.45	0.44
Fc1	E_2l_1	2605.0-2698.2	0.02	0.58	37.23	11.12	51.65	0.56	0.30	0.46
Fc1	E_2l_2	3523.2-3532.7	0.04	0.82	47.22	12.00	40.78	0.57	0.50	0.60
M1	E_2l_3	3084.0-3086.0	0.05	0.62	36.41	13.65	49.94	0.59	0.35	0.55
M1	E_2l_3	3105.2-3108.0	0.05	0.66	33.36	11.83	54.82	0.59	0.34	0.62
M2	E_2l_3	3011.8-3047.6	0.05	0.63	35.07	15.80	49.13	0.59	0.33	0.52

Notes: *A*=Gammacerane/C_{30}-hopane; *B*=C_{27}-βα-diasterane/C_{27}-sterane; *C*=C_{31}-hopane 22S/(22S+22R); *D*=C_{29}-sterane ββ/(ββ+αα); *E*= C_{29}-sterane 20S/(20S+20R)

The relative proportion of C_{27}-C_{28}-C_{29} regular steranes is a commonly used parameter to indicate the composition of organisms (Peters, *et al.*, 2005). The C_{27}-C_{28}-C_{29} steranes ternary diagram (Fig. 3 and Table 3) shows that all these oils are all characterized by high C_{29} and low C_{28} contents, which indicates the source input of terrigenous plant dominance. The chromatogram of normal alkanes (Fig. 4) exhibit a bimodal pattern with dominance of high molecular weight hydrocarbon (C_{27}), which also indicates their terrigenous-dominated source input.

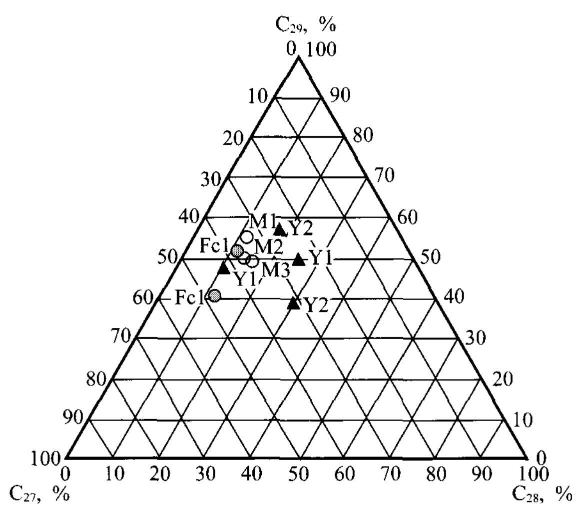


Fig. 3 Ternary diagram showing the relative composition of C_{27}, C_{28} and C_{29} regular steranes of oils from Yong'an-Meitai area in the Fushan Depression

The CPI values are from 1.17 to 1.24 (Table 2), which shows that all these oils are generated from mature organic matter. C_{31}-hopane 22S/(22S+22R) and C_{29}-sterane 20S/(20S+20R) (parameters *C* and *E* in Table 3) have got to the equilibrium point, which also indicates at least a mature oil.

It appears that the oil of E_3w_2 in Y1 well was slightly biodegraded. The light hydrocarbons were partly depleted (Fig. 4d). The concentrations of pristane and phytane are apparently higher than normal C_{17} and C_{18} alkanes with Pr/nC_{17} and Ph/nC_{18} ratios of 2.81 and 0.76, respectively. Those values are generally lower than 0.70 and 0.20 in other samples (Table 2 and Fig. 5). Moreover, there is a hump (UCM—unresolved complex mixture) on the gas chromatogram of oil in E_3w_2 (Fig. 4d). All evidence indicates that the oil of E_3w_2 in Y1 was slightly biodegraded.

5. Timing and episodes of oil charging

A total of 12 oil sands from E_3w_2 (1,945.4-1,947.6 m) and E_2l_1 (2,992.0-2,998.0 m) of Y1 well, and E_2l_1 (2,930.0-2,931.2 m) of Y2 well were sampled for oil-bearing fluid inclusion survey and homogenization temperature measurement of associated NaCl-H_2O fluid inclusions.

Samples of E_3w_2 are dominated by gas-fluid hydrocarbon inclusions, which exhibit fluorescence of brownish yellow or light yellow. The homogenization temperatures mainly range from 85 to 95 °C with an average of 87 °C (Fig. 6a).

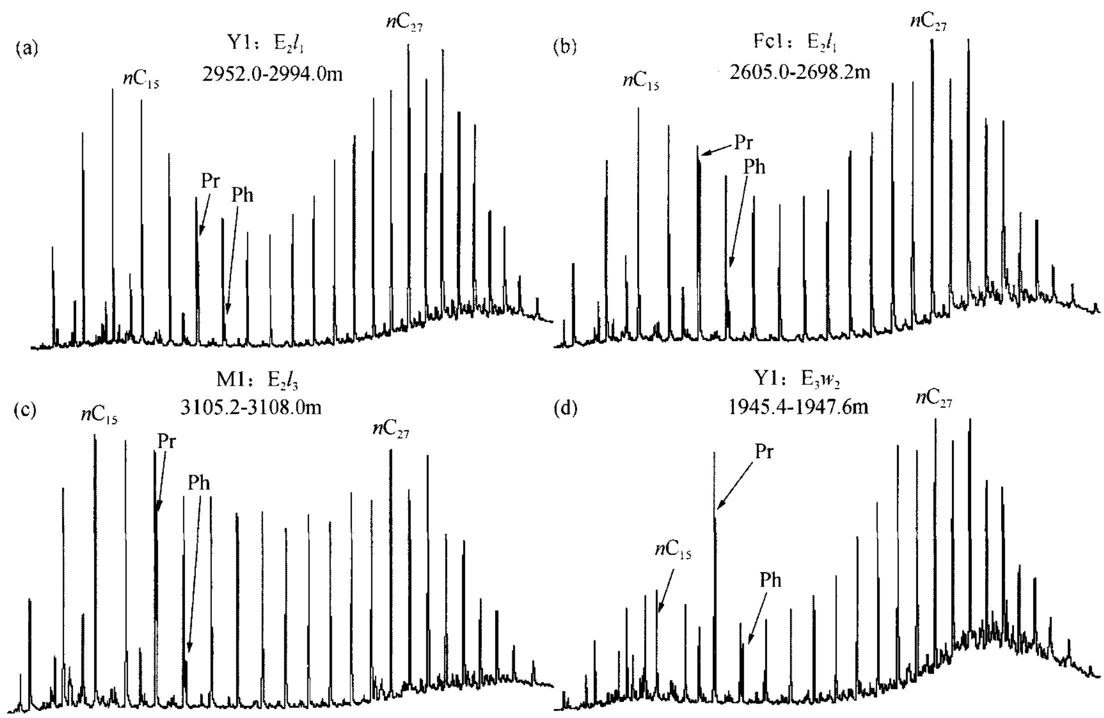


Fig. 4 Gas chromatograms of saturated hydrocarbon fraction in oils from Yong'an-Meitai area

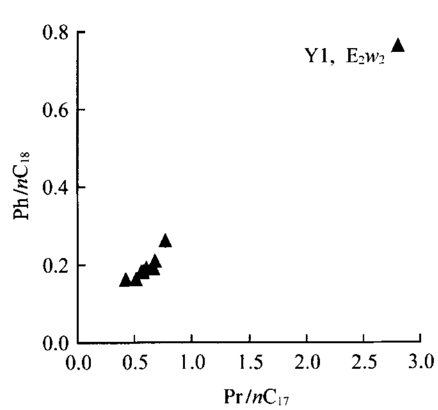


Fig. 5 Pr/nC_{17}—Ph/nC_{18} plot of oils from Yong'an-Meitai area in the Fushan Depression

(The sample of E_3w_2 in Y1 well has much higher Pr/nC_{17} and Ph/nC_{18} values)

Oil sands from E_2l_1 are also dominated by gas-fluid hydrocarbon inclusions. The color of fluorescence is yellowish-white or bluish-white, which indicates their relatively higher maturity. The homogenization temperatures mainly range from 115 to 125 °C, with an average of 117 °C (Fig. 6b)

The characteristics of hydrocarbon-bearing fluid inclusions from E_2l_1 of Y2 well are similar to those from E_2l_1 of Y1 well. The homogenization temperatures also range from 115 to 125 °C, with an average of 117 °C (Fig. 6c). Generally speaking, it seams that the homogenization temperature of E_2l_1 is higher than that of E_3w_2.

The depositional burial and thermal history of Y1 well was reconstructed by BasinMod-1D software. A total of 21 measured R_o data were used to establish the thermal evolution profile to constrain and calibrate the burial and thermal history obtained by modelling (Li, *et al.*, 2007b). Only if the thermal history obtained by modelling is consistent with the measured one, can the geological parameters used in modelling be considered reasonable and the reconstructed burial and thermal history reliable. Fig. 7 shows the burial and thermal history of Y1 well. Fig. 8 shows that the thermal evolution profile by modelling is well consistent with that of measured one. Combined with the reconstructed burial and thermal history, the episode and timing of oil charging can be determined (Fig. 7) The main oil charging timing in E_2l_1 reservoirs is from the end of mid-Miocene to early Pliocene (9-3 Ma) with only one episode. Although the homogenization temperatures of fluid inclusion from E_3w_2 are approximately 30 °C lower than those of E_2l_1, the timing of oil charging is identical, which indicates that the hydrocarbon of E_3w_2 reservoirs was entrapped at the same time. Thus, the interpretation of E_3w_2 reservoirs as secondary reservoirs is unlikely to be correct. According to basin modelling and geological survey, it was thought that the principle hydrocarbon generation and expulsion time of Liushagang source rocks is from 16 to 10 Ma. The timing of latest trap formation is also earlier than Miocene[①]. So the timing of oil charging is later than that of hydrocarbon generation and expulsion and trap formation, which is favourable for oil entrapment in this area.

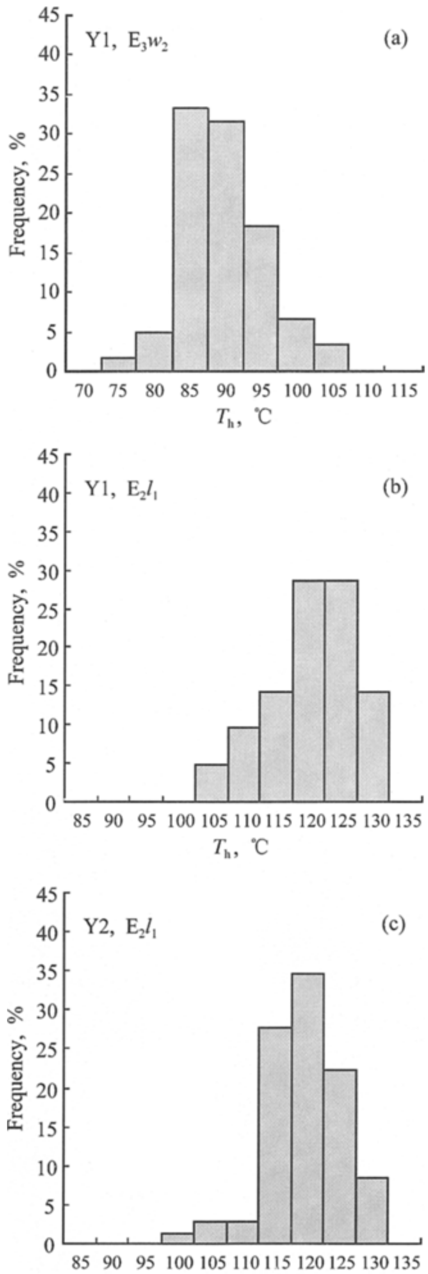


Fig. 6 Histograms showing the distribution of homogenization temperatures (T_h, °C) of fluid inclusions in Yong'an area of the Fushan Depression

(a) Y1 well, E_3w_2, 1909.0-1948.7 m, number of T_h data 60; (b) Y1 well, E_2l_1, 2992.0-2998 m, number of T_h data 21; (c) Y2 well, E_2l_1, 2930.0-2931 m, number of T_h data 72

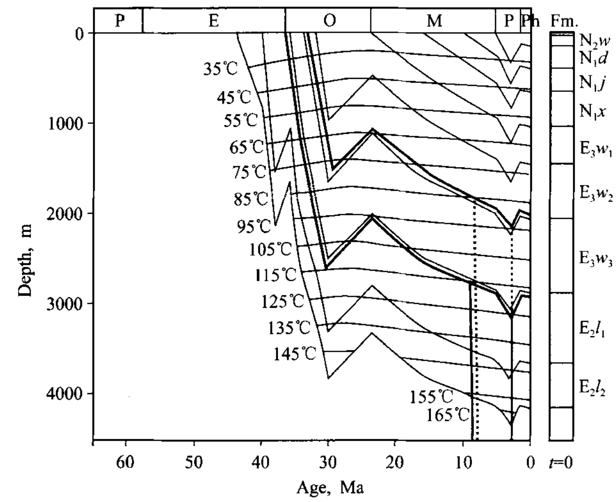


Fig. 7 Episode and timing of oil charging in Yong'an-Meitai area by using homogenization temperature of fluid inclusion and the reconstructed burial and thermal history

(The timing of oil charging in E_2l_1 is approximately 9-3 Ma, and that of E_3w_2 is approximately 8-3 Ma)

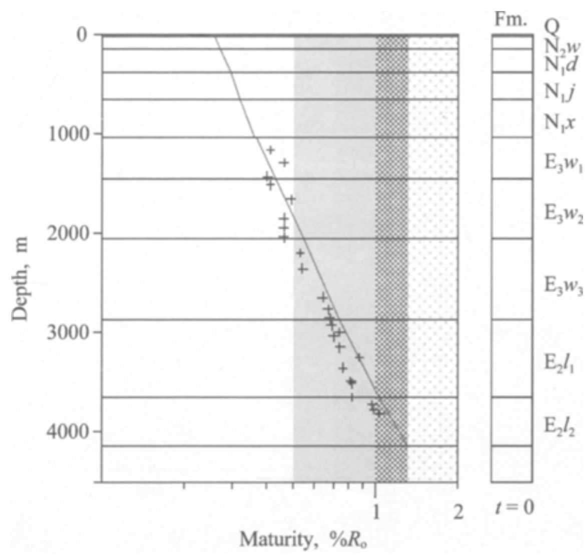


Fig. 8 A comparison between measured Ro data and those obtained by modelling

(Symbol "+" representing measured R_o values, while the line by modelling)

6. Oil charging direction and conduit

England, *et al.* (1987) first established an oil charging model in sandstone reservoirs, providing a scientific theoretical basis for the reconstruction of oil charging direction and pathway, the determination of filling point and source kitchen as well as the predication of "satellite reservoir" based on oil maturity, oil/gas ratio and oil physical properties (Larter and Aplin, 1995).

① Chen D. X. and Shi Y. M. (2004) Petroleum Systems of Fushan Depression, Hainan

According to simulation experiments and/or geological case studies, Stoddart, *et al.* (1995), Li, *et al.* (1995; 1998), and Wang, *et al.* (2004a) reported the tracing results of oil migration and filling pathway in reservoirs by using pyrrolic nitrogen compounds, i.e., carbazole, alkylcarbazoles and benzocarbazoles as tracers. [a]/([a]+[c]) benzocarbazole ratio was selected in this study.

Dibenzothiophenes (DBTs), as heterocyclic compounds, are commonly regarded as aromatic sulfur compounds (ASC), and mainly consist of DBT and its C_1-C_3 alkyl derivatives, which are usually detected in the aromatic fraction of crude oil and sediment bitumen. From the middle 1980s, Hughes (1984) and Connan, *et al.* (1986) detected DBTs in crude oils by means of gas chromatography-flame photometry detector (GC-FPD) and gas chromatography-mass spectrometry (GC-MS), when only two methyldibenzothiophene isomers (MDBTs), i.e. 1- and 4-MDBTs, were identified. Up to the 1990s, Chakhmakhchev, *et al.* (1997) used GC-MS with selected ion monitoring mode (SIM) to confirm 3 dimethyldibenzothiophene isomers (DMDBTs), i.e. 1,4-, 2,4- and 4,6-DMDBTs. Wang, *et al.* (2004b) thought that alkyldibezo- thiophene molecular ratios, 4-/1-MDBT, 2,4-/1,4- and 4,6-/1,4-DMDBT can act as molecular tracers for the charging direction and pathway in oil reservoirs. In this paper, 2,4-/1,4-DMDBT ratio was selected for direction and pathway tracing.

Geochemical parameters related to methylated naphthalenes can be used to indicate the difference of maturity, biodegradation, and source input between oil and sedimentary organic matter samples, even though some saturated hydrocarbon compositions such as steranes and terpanes isomer ratios get to equilibrium end (Alexander, *et al.*, 1985; Radke, *et al.*, 1990; 1994). Poor signal-to-noise ratios of most of the oil samples from the Fushan Depression were observed in the mass chromatograms of biomarkers, especially in the Huachang light oils and condensates. Contrast tests can exclude the effect of experimental conditions. Poor signal-to-noise ratios may result from low concentration of biomarkers. Low biomarker concentrations are typical of highly mature rock extracts, light oils and condensates, where most biomarkers were destroyed. Some crude oils from lacustrine or terrigenous-dominated marine source rocks are low in steranes (Peters, *et al.*, 2005). Most part of the oils in the Fushan Depression are light oils and condensates, except a number of samples from this study area. In this study, we chose methylnaphthalene related geochemical parameters TMNr (defined by van Aarssen, *et al.*, (1999)) as tracers.

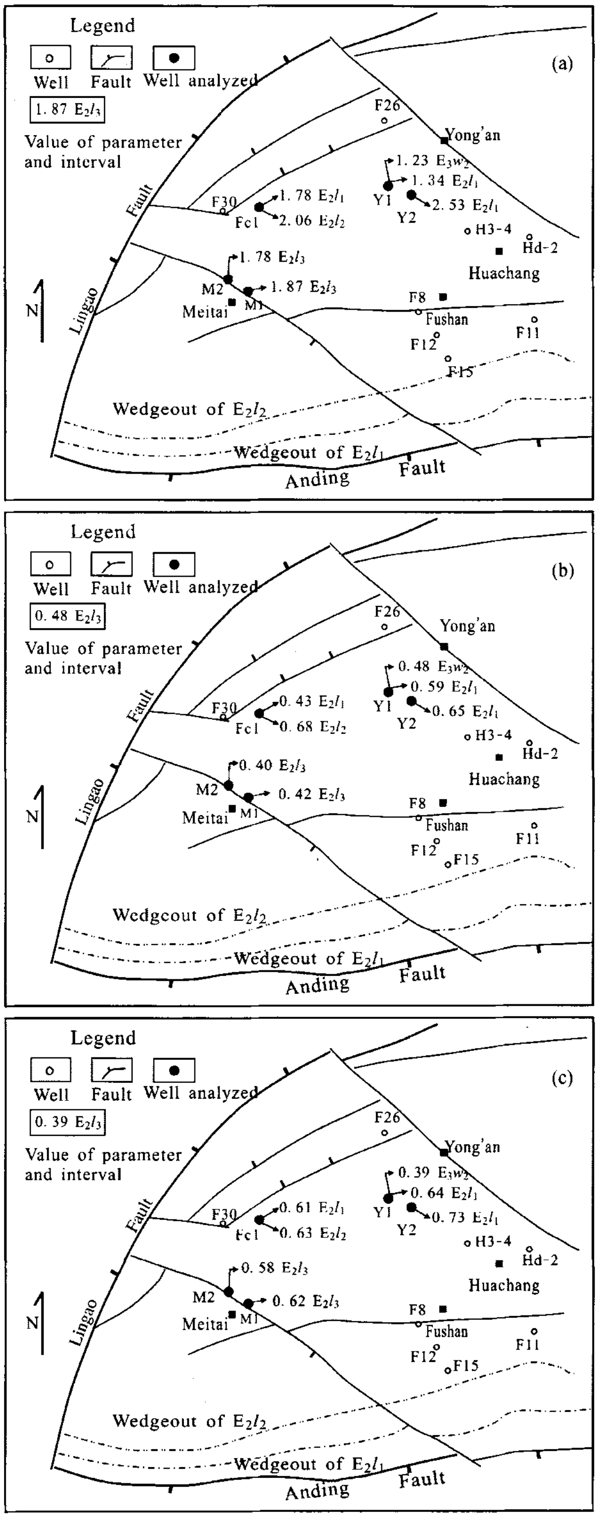


Fig. 9 Map of geochemical parameters tracing oil charging direction in oil reservoirs of Yong'an Meitai area, the Fushan Depression

(a) 2,4-/1,4-DMDBT ratios, (b) [a]/([a]+[c]) Benzocarbazole ratios, and (c) TMNr ratios

Fig. 9a shows the 2,4-/1,4-DMBT values of oils from Yong'an-Meitai area. This ratio of M2 well (1.87) is slightly higher than that of M1 well (1.78). In Fc1 well, this value of E_2l_2 (2.06) is apparently higher than that of E_2l_1 (1.78). The oil from E_3w_2 in Y1 well has the lowest 2,4-/1,4-DMBT ratio. This value gradually increases with increasing depth in the Yong'an structure. They are 1.23, 1.34 and 2.53 at the depth of 1,945.4-1,947.6 m (E_3w_2 of Y1 well), 2,952.0-2,994.0 m (E_2l_1 of Y1 well) and 3,081.0-3,119.0 m (E_2l_1 of Y2 well). This trend suggests vertical oil migration from E_2l_2 to E_2l_1 and then to E_3w_2. Maturity difference and gradient indicate the process of oil filling.

[a]/([a]+[c]) benzocarbazole ratios and TMNr values are shown in Fig. 9b and Fig. 9c. Both of these two geochemical tracing parameters have similar characteristics and changing trends. All selected geochemical tracers show vertical oil migration in Yong'an-Meitai area. During vertical migration, the oils might be oxidized and biodegraded, causing the loss of part of the light hydrocarbon and normal alkanes in E_3w_2 oils, and subsequently resulting in higher density and higher Pr/nC_{17} and Pr/nC_{18} ratios.

The widely occurring faults that penetrate through the source rocks of the Liushagang Formation may serve as a fine oil charging pathway.

7. Conclusions

1) All oils have similar geochemical characteristics and are derived from the same or similar source kitchens dominated by land plant organic matter input and deposited in an oxidizing palaeoenvironment. The oil from E_3w_2 has a higher density, relatively higher Pr/nC_{17} and Ph/nC_{18} ratios, and a bump on its gas chromatogram, which indicates that it has undergone biodegradation. CPI and other biomarker maturity parameters show that they are all mature oils.

2) The homogenization temperatures of fluid inclusions in E_3w_2 of Y1 well and E_2l_1 of Y1 and Y2 wells range from 85-95 °C and 115-125 °C, respectively. The timing of oil charging in E_2l_1 reservoirs obtained by burial and thermal evolution history is 9-3 Ma with one episode. That of E_3w_2 is 8-3 Ma, which indicates oil charged in E_3w_2 traps at the same period. The interpretation of secondary reservoir of E_3w_2 is not likely. The timing of oil charging is consistent with that of hydrocarbon generation and expulsion and trap formation, which is favourable for oil entrapment.

3) Some geochemical parameters, such as aromatic sulfur compounds related 2,4/1,4-DMDBT ratio, pyrrolic nitrogen compounds related benzocarbazole [a]/([a]+[c]) ratio and aromatics related trimethylnaphthalene TMNr are used for oil charging direction and pathway tracing. The values of all these three parameters decrease with the shallower reservoir burial, which suggests vertical oil migration. The widely occurring faults that penetrate through the source rock of the Liushagang Formation can serve as conduit for oil migration.

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