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Geochemistry of borehole cutting shale and natural gas accumulation in the deepwater area of the Zhujiang River Mouth-Qiongdongnan Basin in the northern South China Sea

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Abstract

The Qiongdongnan Basin and Zhujiang River (Pearl River) Mouth Basin, important petroliferous basins in the northern South China Sea, contain abundant oil and gas resource. In this study, on basis of discussing impact of oil-base mud on TOC content and Rock-Eval parameters of cutting shale samples, the authors did comprehensive analysis of source rock quality, thermal evolution and control effect of source rock in gas accumulation of the Qiongdongnan and the Zhujiang River Mouth Basins. The contrast analysis of TOC contents and Rock-Eval parameters before and after extraction for cutting shale samples indicates that except for a weaker impact on Rock-Eval parameter S_2, oil-base mud has certain impact on Rock-Eval S_1, Tmax and TOC contents. When concerning oil-base mud influence on source rock geochemistry parameters, the shales in the Yacheng/Enping, Lingshui/Zhuhai and Sanya/Zhuhai Formations have mainly Type II and III organic matter with better gas potential and oil potential. The thermal evolution analysis suggests that the depth interval of the oil window is between 3 000 m and 5 000 m. Source rocks in the deepwater area have generated abundant gas mainly due to the late stage of the oil window and the high-supper mature stage. Gas reservoir formation condition analysis made clear that the source rock is the primary factor and fault is a necessary condition for gas accumulation. Spatial coupling of source, fault and reservoir is essential for gas accumulation and the inside of hydrocarbon-generating sag is future potential gas exploration area.

Key words: cutting shale, organic geochemistry, gas accumulation, deepwater area, Qiongdongnan Basin, Zhujiang River Mouth Basin

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1 Introduction

The Zhujiang River (Pearl River) Mouth and the Qiongdongnan Basins are important gas-bearing basins in the northern South China Sea, with a great deal of oil and gas having been discovered (Zhu et al., 2008; He et al., 2008; Zhang et al., 2009, 2010). A great number of existing research achievements for the structure, sedimentology, reservoir, drilling, well logging and reservoir, geochemistry of source rock and crude oil, etc. have been finished (Li et al., 2006; Yu et al., 2009; Huang et al., 2012; Zhang et al., 2015a). In various geological conditions, the source rock is always an important geologic factor for which petroleum explorationists must conside (Tissot and Welte, 1984; Magoon and Dow, 1994). The first-hand information of source rock research in petroliferous basins comes from underground rock core in boreholes. Because there is too much cost for coring operation in boreholes offshore, particularly in the deepwater area of ocean, core samples are few in the study area. The deepwater area in the northern South China Sea refers to the area whose water depth is more than 300 m (Wang et al., 2016). Generally, coring operation in boreholes is performed mainly for reservoir, and even if rock core samples are acquired in offshore boreholes, shale samples are still few. Fortunately, rock cutting samples in boreholes may be obtained easily, but in the course of drilling, especially drilling on the sea, oil-base mud is usually used (Hunt, 1996; Mashhadi and Rabbani, 2015). This leads to cutting samples to be contaminated by artificial oil so that organic geochemistry evaluation of source rock is influenced obviously. Therefore, when source rock is researched using rock cutting samples, the impact of oil-base mud should be an important concerned factor. This research focuses on discussing geochemistry of source rock samples from cuttings in the boreholes and the control of source rock on natural gas distribution in the Qiongdongnan Basin and the Zhujiang River Mouth Basin.

2 Geologic setting

The Qiongdongnan Basin and the Zhujiang River Mouth

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Basin, covering an area of 6×10^4 km^2 and an area 17.5×10^4 km^2 in the northern South China Sea, respectively, are located at latitudes 17°00′–18°50′N and longitudes 108°51′–114°41′E, and latitudes 18°30′–20°30′N and longitudes 110°30′–118°E, respectively (Wang et al., 2002; Cai, 2005; Nie et al., 2005; Wang et al., 2010). The Qiongdongnan Basin, located to the southeast of the Hainan Island and to the southwest of the Zhujiang River Mouth Basin, is divided into five sags (Ledong-Lingshui, Songnan-Baodao, Changchang, Beijiao, and Ganquan Sags) and nine uplifts in the deepwater area (Zhang et al., 2015b; Liang et al., 2015). The Zhujiang River Mouth Basin, located to the east of the Hainan Island and to the northeast of the Qiongdongnan Basin, is divided into fourteen sags (Baiyun, Liwan, Shunde, and Chaoshan Sags) and eleven uplifts in the deepwater area (Liu et al., 2016; Wang et al., 2016) (Fig. 1).

The two basins are Cenozoic rift basins in the passive continental margin above the Pre-Tertiary rock basement, containing the Paleogene, the Neogene, and the Quaternary sedimentary formations (Gong et al., 1997; Qiu and Gong, 1999). The division and names of different formations are different in the two basins (Fig. 2). The sedimentary strata include the Eocene, the Oligocene Yacheng and Lingshui Formations, the Miocene Sanya, Meishan and Huangliu Formations, the Pliolcene Yinggehai Formation, and the Quaternary Ledong Formation from the oldest to the youngest in the Qiongdongnan Basin and the Paleocene Shenhu Formation, the Eocene Wenchang Formation, the Oligocene Enping and Zhuhai Formations, the Miocene Zhujiang, Hanjiang and Yuehai Formations, the Pliocene Wanshan Formation, and Quaternary from the oldest to the youngest in the Zhujiang River Mouth Basin (Zhu et al., 2008). In the Qiongdongnan Basin, the Eocene and the Yacheng Formations were formed during rifting period in continent, the Lingshui Formation was formed during transitional period from land to sea and sediments in shore and shallow marine environment, and the Neogene and the Quaternary were formed during depression period and deposited in empiric sea and shelf-slope environments (Zhang et al., 2015b; Wang et al., 2016). In the Zhujiang River Mouth Basin, the Shenhu, Wenchang and Enping Formations were deposited during rifting in continent, the Zhuhai Formation was sediments during transition period from land to sea, and the Cenozoic and the Quaternary were deposited in marine environment during depression (Qiu and Gong, 1999; Liu et al., 2016). The source rocks in the deepwater areas are chiefly the Yacheng, Lingshui and the Sanya Formations in the Qiongdongnan Basin and the Zhuhai and the Zhujiang Formations in the Zhujiang River Mouth Basin (Fu et al., 2007; Cui et al., 2009; Shi et al., 2014).

3 Samples and methods

The total of 104 cutting shale samples was obtained from Wells CC26-1-1, LS33-1-1, YL19-1-1, and CC26-1-1 in the Qiongdongnan Basin and Wells LH29-1-1, LW13-1-1, and LW9-1-2 in the Zhujiang River Mouth Basin. There are 57 and 47 samples in the Zhujiang River Mouth Basin and the Qiongdongnan Basin, respectively. Because there are dry mud and possible mud oil on the surface of obtained sample particles, the samples were rinsed with fresh water and 80-mesh sieve before testing so that mud and oil outside of sample particles were removed, but this method cannot remove mud oil inside of particles. Testing such as TOC, Rock-Eval pyrolysis, extraction, fraction separation and gas chromatography-mass spectrometry of saturated fraction were performed after the rinsed samples were dried by air.

All of the shale samples were crushed and sieved using an 80-mesh sieve. The powdered rock samples were mixed with 10%

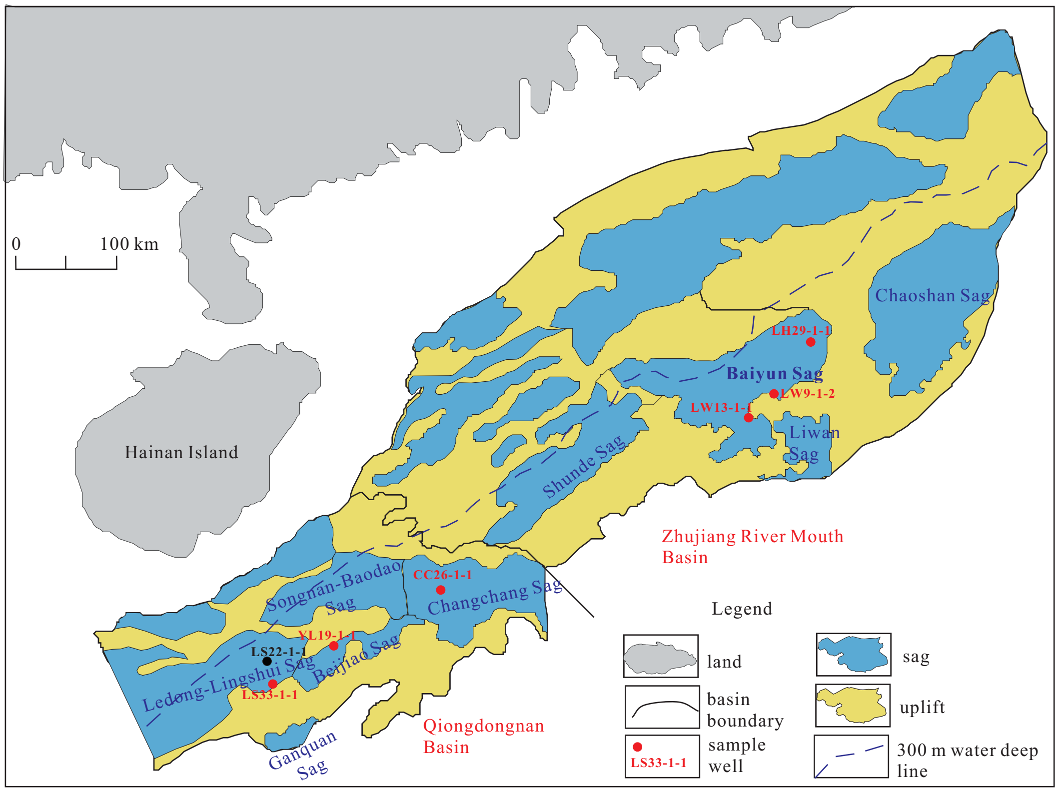

Fig. 1. Map showing the location and geological elements of the Qiongdongnan and the Zhujiang River Mouth Basins.

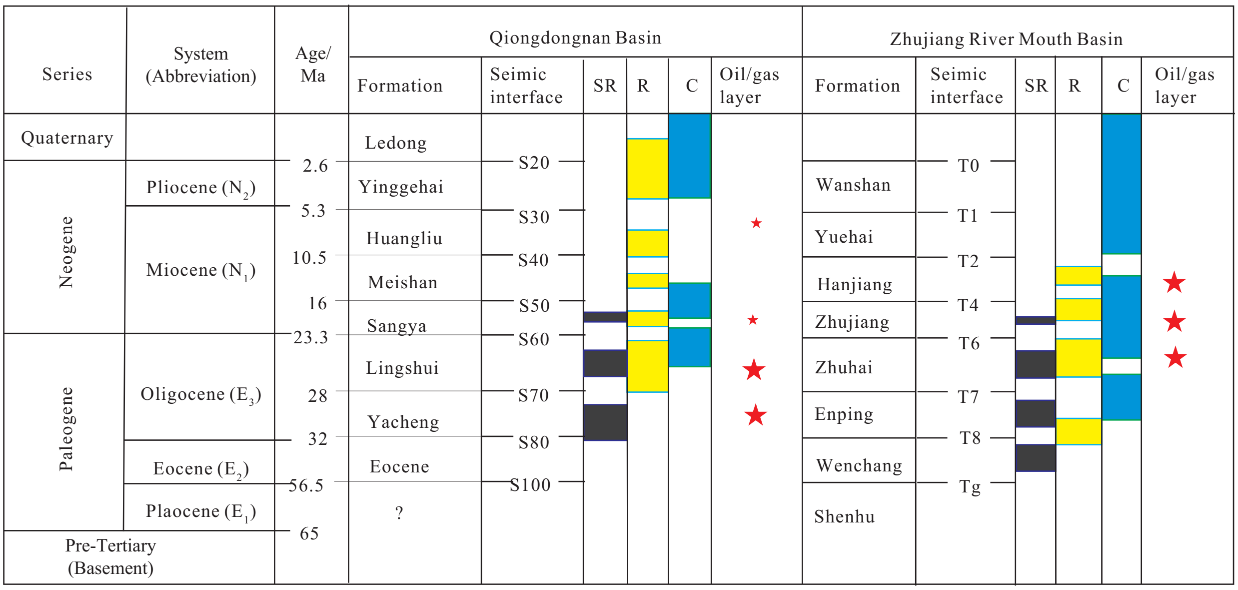

Fig. 2. The sedimentary formation contrast plot in the Qiongdongnan Basin and the Zhujiang River Mouth Basin. SR represents source rock, R reservoir and C cap.

(v/v) HCl for more than 1 h to dissolved the inorganic carbon, then samples must be washed using distilled water to obliterate the HCl, finally the TOC testing of samples were finished on Leco CS-230 carbon analyzer. The Rock-Eval analysis were performed on OGE-II rock pyrolyzer which was developed by Experimental Center of Petroleum Geology belonging to China Petroleum Exploration and Development Research Institute, and it could obtain mainly the data of S_1 ((mg HC)/(g Rock)), S_2 ((mg HC)/(g Rock)) and Tmax (°C). About 80–100 g of 25 powdered samples were extracted for 72 h with Soxhlet apparatus and chloroform to obtain soluble bitumen (extract). Fraction separation of extracts was performed using the apparatus of conventional column chromatography. The extracts were blended with petroleum ether to precipitate the asphaltene and the soluble fraction was separated into saturated, aromatic and resin by column chromatography using a silicagel-alumina column eluting with petroleum ether, dichloromethane and methanol. GC–MS analysis of saturated fraction was performed using a Thermo-Finnigan Trace-DSQ instrument equipped with a HP-5MS fused silica capillary column of 60 m long, 0.25 mm in diameters and 0.25 μm film thickness. The GC oven temperature was initially held at 50°C for 1 min and then programmed to 120°C at 20°C/min, 250°C at 4°C/min, and 310°C at 3°C/min, and was finally held at 310°C for 30 min. Residues of 25 samples after extraction were performed for testing of the TOC and Rock-Eval pyrolysis. Except for the tested data, the vitrinite reflectance (Ro) data were collected from the Research Institute of CNOOC, Beijing.

4 Results and discussion

4.1 *Geochemistry parameter contrast of shale samples before and after extraction*

The cross plot of S_1 versus TOC may be used to discriminate the nonindigenous and indigenous hydrocarbons embedded in the source rock, and a S_1/TOC ratio greater than 1.5 may indicate impact of migrated hydrocarbons on the source rock samples (Hunt, 1996; Mashhadi and Rabbani, 2015). In S_1 versus TOC diagram (Figs 3a and b), in the Zhujiang River Mouth Basin, except for one sample with a S_1/TOC value above 1.5, the other samples exhibit the S_1/TOC values less than 1.5 (Fig. 3a), while in the Qiongdongnan Basin, except two samples with S_1/TOC values less than 1.5, the other samples show the S_1/TOC values more

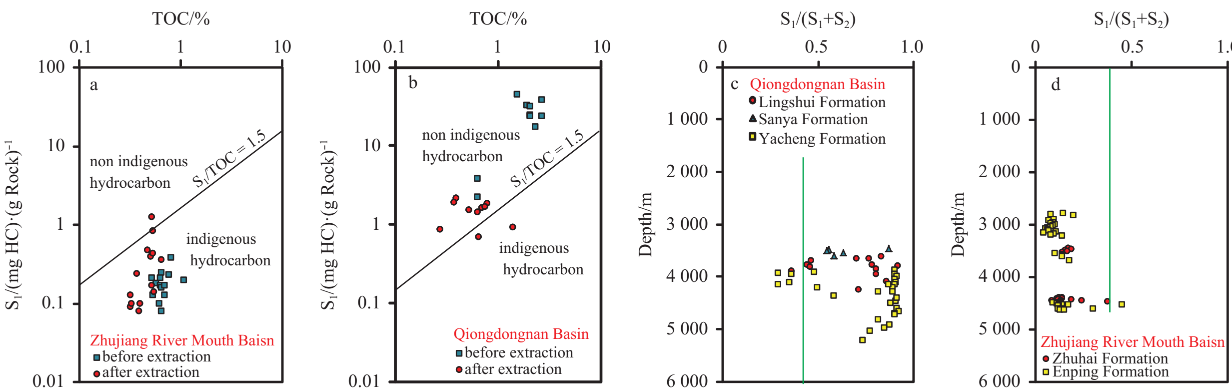

Fig. 3. The cross diagrams of TOC vs S_1 (a and b) and depth vs $S_1/(S_1+S_2)$ (c and d) of the cutting shales in the Zhujiang River Mouth Basin and the Qiongdongnan Basin of the northern China South Sea (according to Mashhadi and Rabbani, 2015).

than 1.5 (Fig. 3b). This seems to indicate that oil-base mud produces a stronger impact on the samples in the Qiongdongnan Basin than that in the Zhujiang River Mouth Basin. Because the oil-base mud was used in the course of drilling, the S_1 value would rise so that the production index [PI=$S_1/(S_1+S_2)$] value increases, therefore, the higher PI values may imply the shale samples were contaminated by the oil-base mud. PI values above 0.4 were thought to have contamination of mud additives (Mashhadi and Rabbani, 2015). Figures 3c and d show that most samples have the PI values more than 0.4 in the Qiongdongnan Basin and the less samples have the PI values lower than 0.4 in the Zhujiang River Mouth Basin. This also shows mud influence on Rock-Eval pyrolysis parameters of shale samples.

Figure 4 is the total ion current fragmentograms of saturated fraction in shale extracts from Well LW13-1-1. It can be seen that the saturated fractions of two shale samples have the same compound composition in which there are a great number of low molecules. This kind of compound distribution is obviously different from that of normal source rocks and discovered crude oil. They are comparable to that of the oil in mud. This once again indicates that oil-base mud has impacted on cutting shale samples.

The contrast diagram of TOC contents and Rock-Eval parameters of the shale samples before and after extraction were plotted in Fig. 5. After extraction, the TOC contents of shales mainly decrease (Fig. 5a). There are bigger variation in the samples whose TOC content before extraction are between 1% and 3%, while there are a small change in the samples whose TOC content before extraction are lower than 1% and higher than 3% (Fig. 5a). S_2 values have the best similarity before and after extraction, and all of samples are situated nearby the line of slope=1 (Fig. 5b). The S_1, S_1+S_2 and $S_1/(S_1+S_2)$ values have positive or negative variation before and after extraction. Some shale samples have higher S_1, S_1+S_2 and $S_1/(S_1+S_2)$ values before extraction, but they distinctly decrease after extraction (Figs 5c, d and e). In the rela-

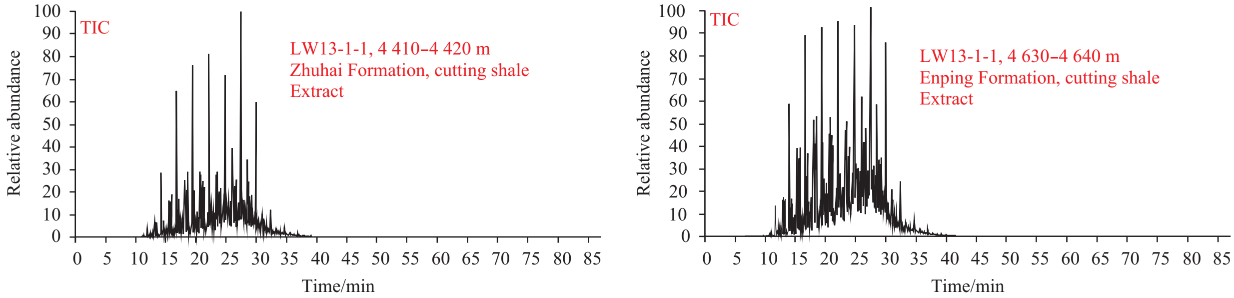

Fig. 4. The total ion current fragmentogram of two shale samples' saturated fraction in the Zhuhai and Enping Formations of Well LW13-1-1 in the Zhujiang River Mouth Basin.

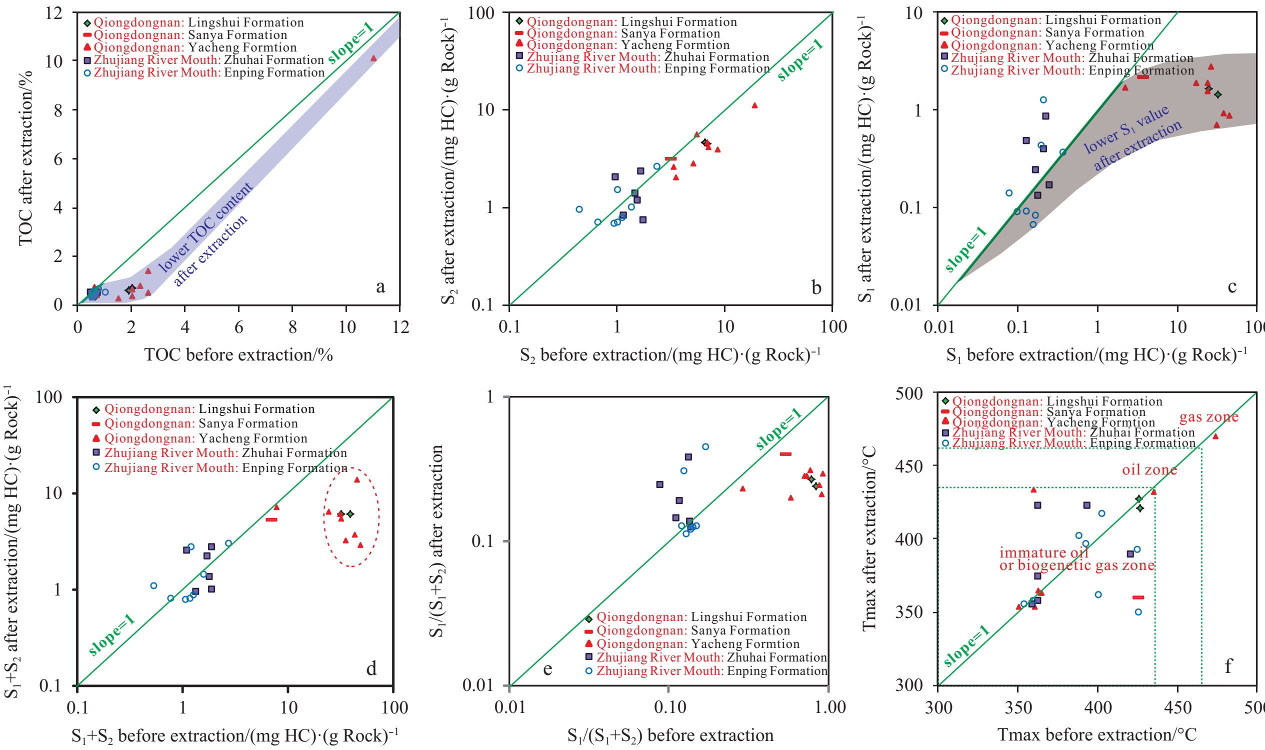

Fig. 5. The contrast plot of TOC content, Rock-Eval parameter values of the cutting shales in the Zhujiang River Mouth Basin and the Qiongdongnan Basin of the northern South China Sea. These figures indicate that almost all of the parameters derived from TOC and Rock-Eval analysis are influenced by the oil-base mud except the S_2.

tionship diagram of Tmax before and after extraction, most samples are nearby the line of slope=1, and a few samples deviate the line positively or negatively (Fig. 5f). This indicates that when being used to evaluate source rock, the S_2 may be the principal evaluation parameter, while the other parameters are used, impact of oil-base mud should be taken into account (Hunt, 1996).

4.2 *Quality of source rock*

Because there are only a small number of shale samples were extracted, the source rock quality evaluation is performed mainly using testing data before extraction, but the oil-base mud influence should be taken into account. In the Zhujiang River Mouth Basin, the TOC contents of the Zhuhai and Enping Formations' shales vary from 0.21% to 1.63% (average: 0.53%) and from 0.32% to 1.14% (average: 0.57%), respectively, and their S_1+S_2 values change from 0.53 (mg HC)/(g Rock) to 6.17 (mg HC)/(g Rock) (average: 2.69 (mg HC)/(g Rock)) and from 0.96 (mg HC)/(g Rock) to 3.92 (mg HC)/(g Rock) (average: 2.22 (mg HC)/(g Rock)), respectively (Fig. 6a). There are higher organic matter abundance in the shales of the Qiongdongnan Basin, the TOC contents of the Lingshui, Sanya and Yacheng Formations' shales change from 0.62% to 2.32% (average: 1.39%), 0.59% to 1.33% (average: 0.80%) and 0.46% to 10.99% (average: 1.87%), respectively, and their S_1+S_2 values vary from 6.35 (mg HC)/(g Rock) to 38.80 (mg HC)/(g Rock) (average: 21.36 (mg HC)/(g Rock)), 7.00 (mg HC)/(g Rock) to 22.77 (mg HC)/(g Rock) (average: 11.34 (mg HC)/(g Rock)) and 7.03 (mg HC)/(g Rock) to 48.55 (mg HC)/(g Rock) (average: 29.08 (mg HC)/(g Rock)), respectively. The cross plot of the TOC versus the S_1+S_2 (Fig. 6b) indicates that the source rocks in the Qiongdongnan Basin are better than that in the Zhujiang River Mouth Basin, even if oil-base mud influence is taken into account. On the basis of the above-menttioned analyses, the source rock evaluation grade in the study area should be decreased, but it can still be thought that the organic matter abundance of shales in the Qingdongnan Basin is higher than that in the Zhujiang River Mouth Basin.

S_2 is a parameter related to source rock hydrocarbon potential (Tissot and Welte, 1984; Wu et al., 1986). In the Zhujiang River Mouth Basin, the S_2 values of the Zhuhai and Enping Formations' shales vary from 0.45 (mg HC)/(g Rock) to 5.82 (mg HC)/(g Rock) (average: 2.38 (mg HC)/(g Rock)) and 0.75 (mg HC)/(g Rock) to 3.27 (mg HC)/(g Rock) (average: 1.85 (mg HC)/(g Rock)), respectively, and their hydrogen index (HI=S_2/TOC, (mg HC)/(g TOC)) values change from 81 (mg HC)/(g TOC) to 1 015 (mg HC)/(g TOC) (average:470 (mg HC)/(g TOC)) and from 204 (mg HC)/(g TOC) to 474 (mg HC)/(g TOC) (average: 315 (mg HC)/(g TOC)), respectively (Fig. 7a). In the Qiongdongnan Basin, the S_2 values of the Lingshui, Sanya and Yacheng Formations' shales change from 2.71 (mg HC)/(g Rock) to 6.86 (mg HC)/(g Rock) (average: 4.98 (mg HC)/(g Rock)), from 2.64 (mg HC)/(g Rock) to 3.51 (mg HC)/(g Rock) (average: 3.06 (mg HC)/(g Rock)) and 2.53 (mg HC)/(g Rock) to 18.83 (mg HC)/(g Rock) (average: 4.86 (mg HC)/(g Rock)), respectively, and their HI values range from 157 (mg HC)/(g TOC) to 751 (mg HC)/(g TOC) (average: 424 (mg HC)/(g TOC)), from 219 (mg HC)/(g TOC) to 542 (mg HC)/(g TOC) (average: 428 (mg HC)/(g TOC)) and from 157 (mg HC)/(g TOC) to 902 (mg HC)/(g TOC) (average: 337 (mg HC)/(g TOC)), respectively (Fig. 7b). In the cross diagrams of TOC versus S_2 for shales (Figs 7a and b), the shales in the Zhujiang River Mouth Basin contain mainly fair and poor source rocks, with a small number of good source rocks, while in the Qiongdongnan Basin, the Yacheng and Lingshui Formations contain more good and excellent source rocks and a small number fair source rocks, and Sanya Formation contains mainly fair source rocks and a small number of good source rocks (Fig. 7b).

In the cross diagram of TOC versus HI (Fig. 8), the Zhuhai and Enping Formations' shales in the Zhujiang River Mouth Basin fall in the zone of fair to excellent oil source rocks, and in the Qiongdongnan Basin, the shales of the Lingshui and Yacheng Formations fall in the zone of fair source rock to gas/oil source rock and the shales of the Sanya Formation fall mainly in the zone of good oil source rock (Korkmaz et al., 2013).

In the Zhujiang River Mouth Basin, the Tmax values of the Zhuhai and Enping Formations' shales vary from 350.0°C to 446.0°C (average: 411.8°C) and 355.0°C to 438.0°C (average: 397.7°C), respectively (Fig. 9a), and in the Qiongdongnan Basin, the Tmax values of the Lingshui, Sanya and Yacheng Formations' shales change from 354.0°C to 435°C (average: 412.6°C), 362°C to 427°C (average: 410.3°C) and 351°C to 474°C (average: 374.9°C), respectively (Fig. 9b). In the cross diagram of Tmax versus HI (Figs 9a and b), the shales exhibit lower Tmax values, more Type II organic matter and some Type I organic matter (Espitalié et al.,

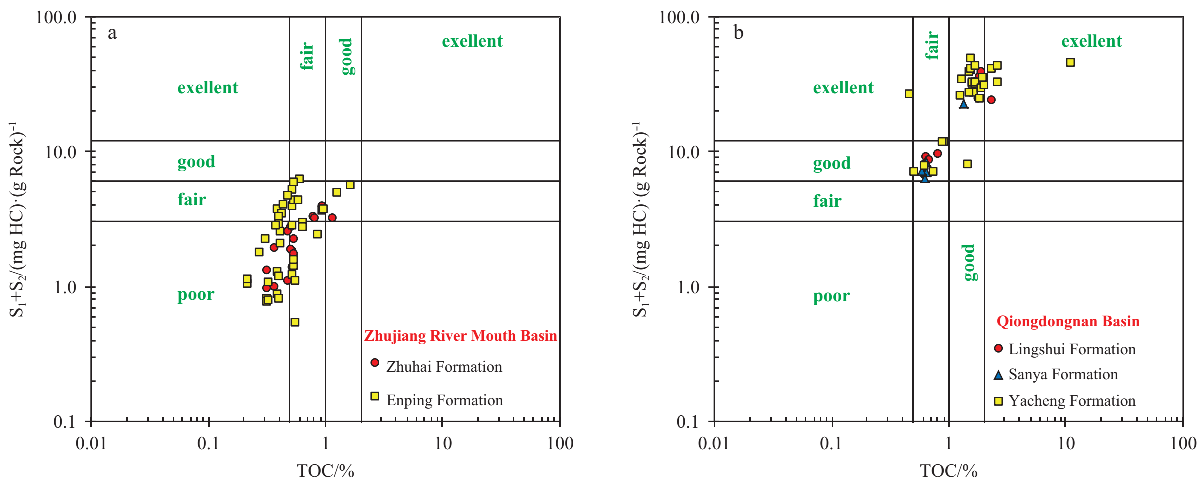

Fig. 6. The cross diagram of TOC contents vs S_1+S_2 values of the cutting shale in the Zhujiang River Mouth Basin and the Qiongdongnan Basin of the northern South China Sea

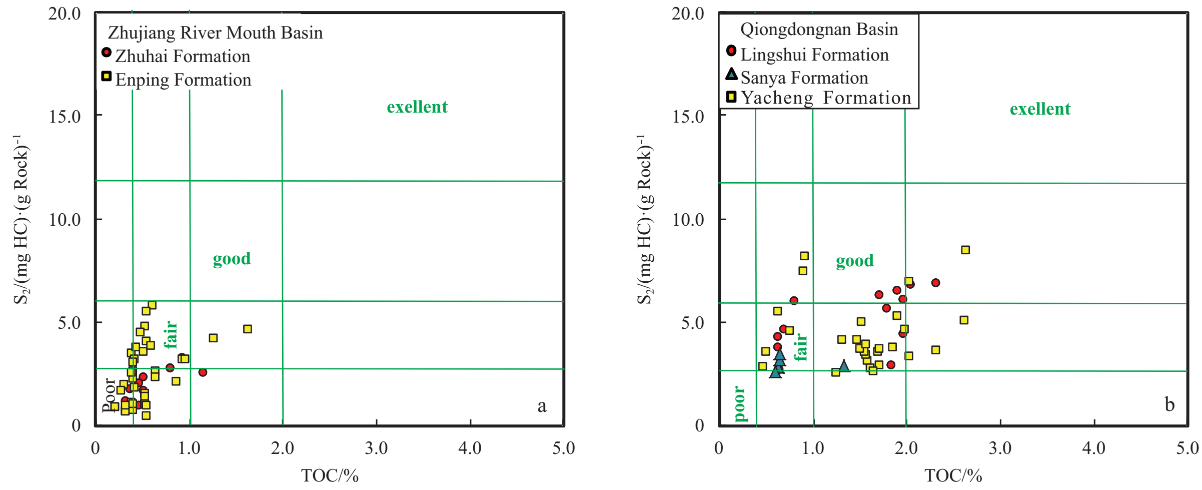

Fig. 7. The cross diagram S_2 vs TOC for the cutting shales of the Qiongdongnan Basin and the Zhujiang River Mouth Basin.

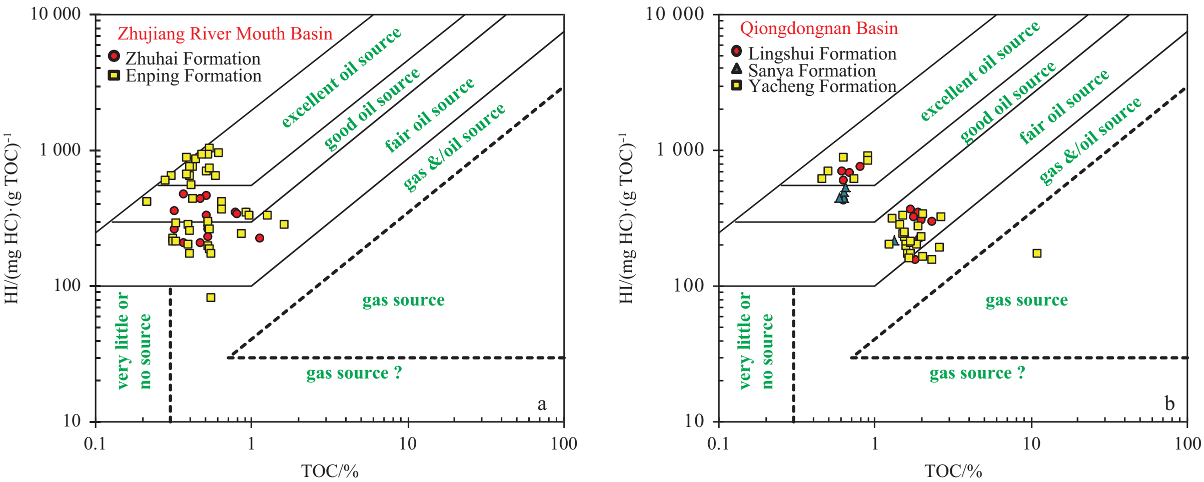

Fig. 8. The cross plot of TOC vs HI for the cutting shale samples in the study area.

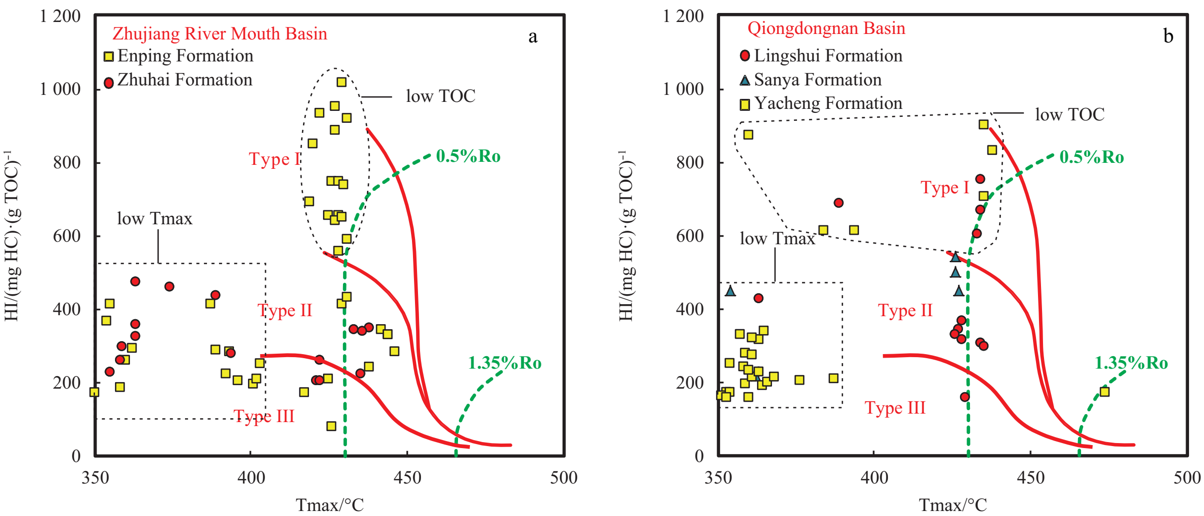

Fig. 9. The cross plot of Tmax values vs HI values of the cutting shale in the study area.

1984). This similarly also indicates that the shales in the research areas have oil and gas potential, but in the minor cross diagrams of TOC versus HI in Figs 10a and e, the higher HI values correspond to lower TOC values. According to this, it is referred that the shales in the study areas have more gas potential and weaker oil potential (Figs 8 and 9).

4.3 *Thermal evolution of source rock*

Although many parameters may be used to assess thermal maturity of source rock (Tissot and Welte, 1984; Killops and Killops, 2005; Peters et al., 2005), the vitrinite reflectance (Ro) is still an important maturity index (Tissot and Welte, 1984). The hydrocarbon index (HCI = S_1/TOC, (mg HC)/(g TOC)) is an important parameter for evaluating generated hydrocarbon amount of source rock relative to unit mass TOC (Espitalié et al., 1984; Wu et al., 1986). In the Zhujiang River Mouth Basin, the HCI values of the Zhuhai and Enping Formations' shales vary from 14.5 (mg HC)/(g TOC) to 239.9 (mg HC)/(g TOC) (average: 58.57 (mg HC)/(g TOC)) and 27.53 (mg HC)/(g TOC) to 157.95 (mg HC)/(g TOC) (average: 61.04 (mg HC)/(g TOC)), respectively; and in the Qiongdongnan Basin, the HCI values of the Lingshui, Sanya and Yacheng Formations' shales change from 425.1 (mg HC)/(g TOC) to 1 808.2 (mg HC)/(g TOC) (average: 1 027.5 (mg HC)/(g TOC)), 602.7 (mg HC)/(g TOC) to 1 488.0 (mg HC)/(g TOC) (average: 905.9 (mg HC)/(g TOC)) and from 240.9 (mg HC)/(g TOC) to 5 041.2 (average: 1 531.4 (mg HC)/(g TOC)), respectively. In Figs 10a, b, c, e, f, and g, there are a complex relation between depth and Rock-Eval pyrolysis parameters, particularly, some samples with obviously high HI, HCI, and low Tmax values inside dot line shape should be influenced by oil-base mud (Mashhadi and Rabbani, 2015). If despite of oil-base mud influence, the Rock-Eval parameters will difficultly reflect thermal evolution feature. If removing the samples influenced by oil-base mud, the Rock-Eval parameters of the other samples may approximately reflect the thermal evolution degree (see the red line in Fig. 10). Therefore, only using Rock-Eval parameters of the cutting samples, thermal evolution maturity of source rock is difficultly determined reasonably. In Figs 10d and h, there is a better relation of depth to Ro than Rock-Eval parameters in the Qiongdongnan Basin and the Zhujiang River Mouth Basin, and the top and bottom depths of oil window are 3 000 m and 5 000 m, respectively. The thermal maturity is an important factor affecting hydrocarbon generation of source rocks in the study area: before oil window, immature oil and biogenetic gas are generated; in the early stage of the oil window, a great deal of normal crude oil and a small quantity of gas is generated; in the late stage of oil window, more normal crude oil and wet gas are generated; and after oil window, a great deal of gas was generated (Tissot and Welte, 1984; Cheng et al., 1995).

4.4 *Control of effective source rock for gas reservoir*

At present, in the deepwater area, except that the LH16-2 structure contains liquid crude oil in the Zhuhai Formation, the other structures or traps accumulate mainly natural gas in the formations such as the Zhuhai/Lingshui, Zhujiang/Sanya, Hanjiang/Meishan of the Qiongdongnan Basin and the Zhujiang River Mouth Basin. Figure 11 exhibits horizontal distribution relationship of Ro contour, oil/gas area, and oil shows of the Lingshui/Zhuhai Formations. It can be observed that the discovered hydrocarbon is distributed mainly around the maturity center of source rock. This demonstrates that accumulated hydrocarbon has a horizontal migration. Because of deeper burial than the

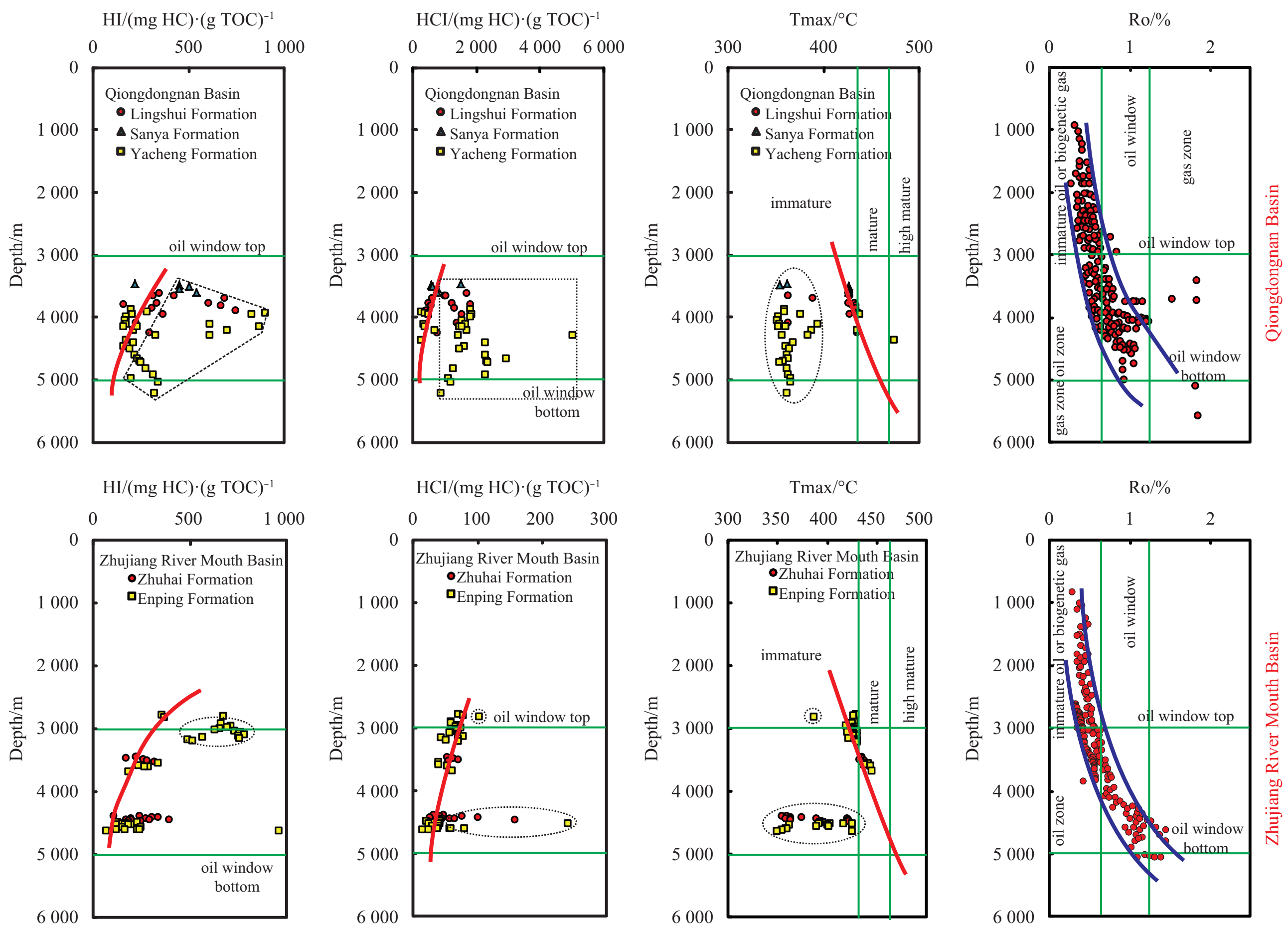

Fig. 10. The plot of Ro and Rock-Eval parameter values vs burial depth of cutting shales in the study area.

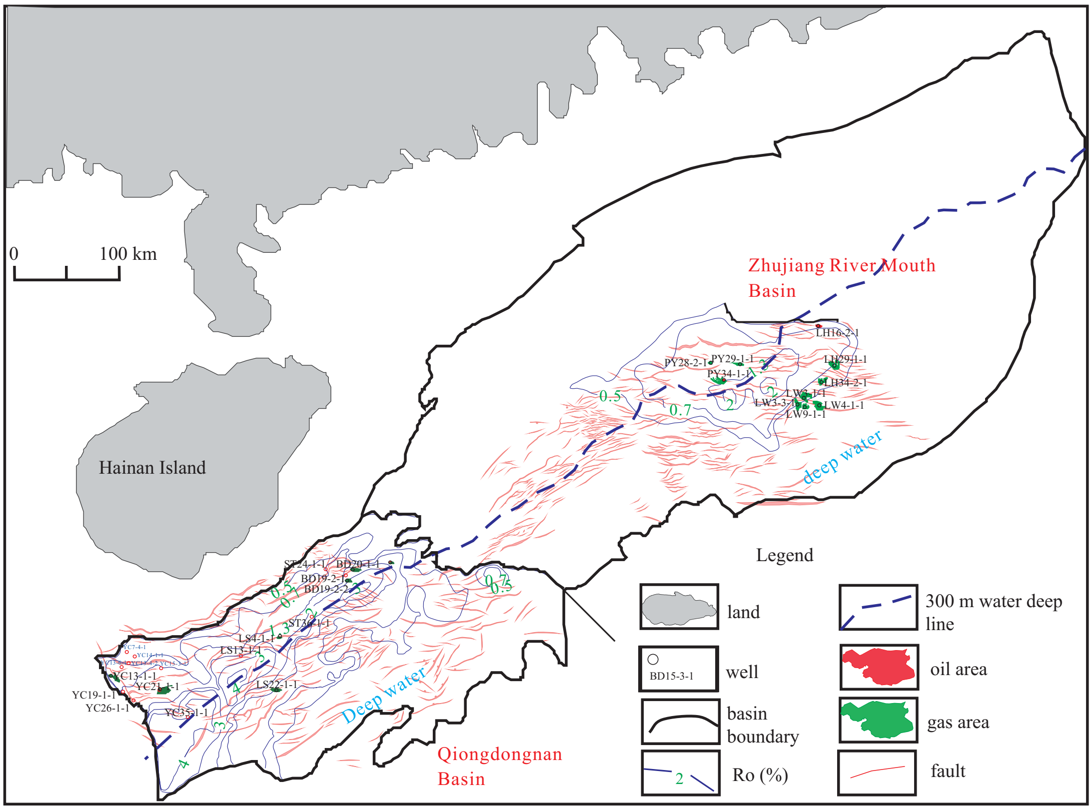

Fig. 11. The superposition map of the Ro contour and the oil/gas area and oil shows of the Lingshui/Zhuhai Formations in the study area.

Lingshui/Zhuhai Formation, the Yacheng/Enping Formation source rocks have a higher thermal maturity and generated more gas. According to the statistic result of the horizontal migration distance between discovered gas layers and the maturity center of source rock in or nearby the deepwater area of the Qiongdongnan Basin and the Zhujiang River Mouth Basin, the migration distance of gas is mainly in the interval of 15 000 m and 35 000 m, with some shallower than 15 000 m and a few between 35 000 m and 55 000 m (Fig. 12). This indicates that relatively short migration distance is the main of the gas accumulation in the deepwater area in the study area.

In the rift basins, fault is essential for vertical hydrocarbon migration (Anderson et al., 1994; Dholakia et al., 1998). In the deep formations such as the Yacheng/Enping, Lingshui/Zhuhai deposited during rifting in the study area, a great number of great faults are distributed, and in the upper formations such as the Yinggehai and Huangliu Formations formed during the late tectonic movement after rifting, some hidden small faults were produced (Fig. 13). These different scales of faults are main oil/gas migration pathway to communicate deep source rock with upper reservoir (Fig. 13). In the Ledong-Lingshui Sag of the Qiongdongnan Basin, the Huangliu Formation gas reservoir of the LS22-1 structure has a typical accumulation model for gas generation below, reservoir above and fault conducting (Fig. 13). Therefore, the gas reservoir above the source rock has an important connection with faults linking source rock and reservoir.

In Fig. 11, all of the discovered gas layers are distributed in the area in which faults are developed in the Qiongdongnan Basin and the Zhujiang River Basin. This indicates that fault is a key of gas accumulation. A great deal of shale in different formations is mainly the seals of gas reservoirs. From the abovementioned analyses, it can be seen that source rock is the primary factor and

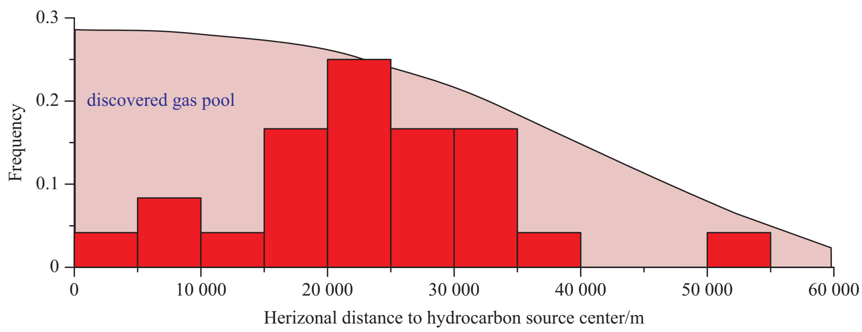

Fig. 12. The distribution of horizontal distance between hydrocarbon source kitchen center and gas pools in the study area.

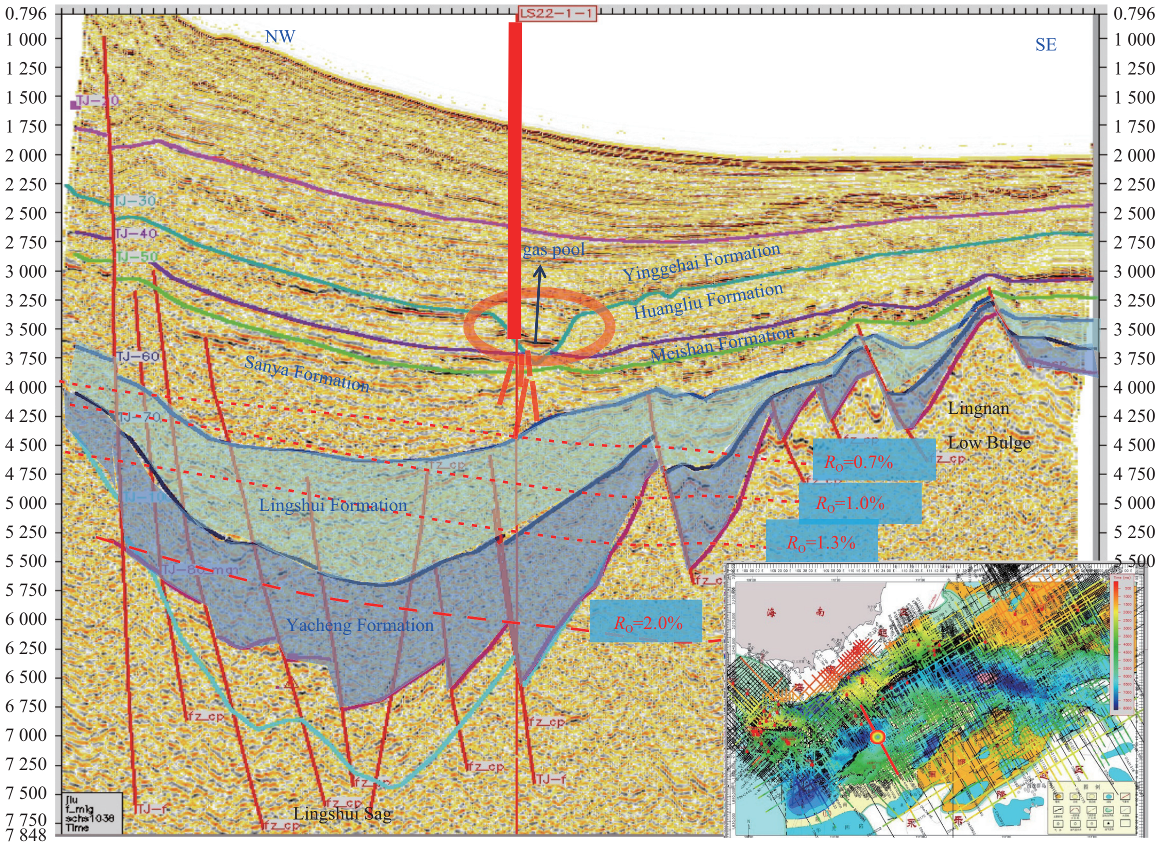

Fig. 13. Gas accumulation model map of the Huangliu Formation gas reservoir in Well LS22-1-1 of the deepwater area in the Ledong-Lingshui Sag of the Qiongdongnan Basin (in the LS22-1 structure, the source rock is in the deep Yacheng and Lingshui Formations and possible Sanya Formation, and faults links deep source rocks and upper reservoirs)

fault is a necessary condition for gas reservoir formation. Spatial coupling of source, fault and reservoir is the key of a gas reservoir formation in the study area. Except for discovered gas reservoirs around source rock center, there will be some potential gas accumulation discovered in the source rock kitchen in the future.

5 Conclusions

(1) In the deep sea area, there are few cores, but abundant rock cutting samples may be obtained from borehole. Therefore, the cuttings become an important foundation of source rock research. Except for weaker impact for Rock-Eval S_2 values, oil-base mud has more influences on S_1, S_1+S_2, S_1/(S_1+S_2), Tmax value, and TOC content, etc. When source rock is evaluated using cutting samples, influence of oil-base mud should be taken into account.

(2) In the study area, source rocks in the Yacheng/Enping, Lingshui/Zhuhai and Sanya/Zhuhai Formations contain mainly Type II and III organic matter, exhibiting better gas potential and weaker oil potential.

(3) Oil window depth range of source rock is between 3 000 m and 5 000 m, the source rocks in the deepwater area are mainly in the late stage of the oil window and the high-supper maturity stage, so they had generated abundant gas.

(4) Source rock and fault are the primary factor and the necessary condition for gas accumulation respectively. The excellent spatial coupling of source, fault and reservoir is the key of gas accumulation in the deepwater area. The inside of source rock kitchen is a potential gas exploration area in the future.

References

Anderson R N, Flemings P, Losh S, et al. 1994. Gulf-of-Mexico growth fault drilled, seen as oil, gas migration pathway. Oil & Gas Journal, 92(23): 97–103

Cai Qianzhong. 2005. Oil & Gas Geology in China Seas (in Chinese). Beijing: China Ocean Press, 161–167

Cheng Keming, Wang Tieguan, Zhong Ningning. 1995. Geochemistry of Source Rock (in Chinese). Beijing: Science Press, 17–40

Cui Shasha, He Jiaxiong, Chen Shenghong, et al. 2009. Development characteristics of Pearl River Mouth Basin and its geological conditions for oil and gas accumulation. Natural Gas Geoscience (in Chinese), 20(3): 384–391

Dholakia S K, Aydin A, Pollard D D, et al. 1998. Fault-controlled hydrocarbon pathways in the Monterey Formation. California. AAPG Bulletin, 82(8): 1551–1574

Espitalié J, Marquis F, Barsony L. 1984. Geochemical logging. Analytical Pyrolysis, 184: 276–304

Fu Ning, Mi Lijun, Zhang Gongcheng. 2007. Source rocks and origin of oil and gas in the northern Baiyun Depression of Pearl River Mouth Basin. Acta Petrolei Sinica (in Chinese), 28(3): 32–38

Gong Zaisheng, Li Sitian, Xie Taijun, et al. 1997. Continental Margin Basin Analysis and Hydrocarbon Accumulation of the Northern South China Sea (in Chinese). Beijing: Science Press, : 1–178

He Jiaxiong, Liu Hailing, Yao Yongjian, et al. 2008. The Petroleum Geology and the Resource Potential of the Marginal Basins in the Northern South China Sea (in Chinese). Beijing: Petroleum Industry Press

Huang Baojia, Li Xushen, Wang Zhenfeng, et al. 2012. Source rock geochemistry and gas potential in the deep water area, Qiongdongnan Basin. China Offshore Oil and Gas (in Chinese), 24(4): 1–7

Hunt J M. 1996. Petroleum Geochemistry and Geology. 2nd ed. New York: W H Freeman

Killops S, Killops V. 2005. Introduction to Organic Geochemistry. 2nd ed. Malden, MA: Blackwell

Korkmaz S, Kara-Gülbay R, İztan Y H. 2013. Organic geochemistry of the Lower Cretaceous black shales and oil seep in the Sinop Basin, Northern Turkey: An oil-source rock correlation study. Marine and Petroleum Geology, 43: 272–283

Li Xuxuan, Zhong Zhihong, Dong Weiliang, et al. 2006. Paleogene rift structure and its dynamics of Qiongdongnan Basin. Petroleum Exploration and Development (in Chinese), 33(6): 713–721

Liang Gang, Gan Jun, Li Xing. 2015. Genetic types and origin of natural gas in Lingshui sag, Qiongdongnan Basin. China Offshore Oil and Gas (in Chinese), 27(4): 47–53

Liu Zhifeng, Wang Shenglan, Ding Liang, et al. 2016. Structural features of the northern depression belt in the Pearl River Mouth Basin. Journal of Geology (in Chinese), 40(1): 135–141

Magoon L B, Dow W G. 1994. The Petroleum System-From Source to Trap (AAPG Memoir No. 60). Washington DC: AAPG

Mashhadi Z S, Rabbani A R. 2015. Organic geochemistry of crude oils and Cretaceous source rocks in the Iranian sector of the Persian Gulf: An oil-oil and oil-source rock correlation study. International Journal of Coal Geology, 146: 118–144

Nie Fengjun, Jiang Meizhu, Wu Leqiang, et al. 2005. Tectono-magmatism and hot fluid flow in the Pearl River Mouth Basin, South China Sea. Journal of East China Institute of Technology (in Chinese), 28(2): 107–111

Peters K E, Walters C C, Moldowan J M. 2005. The Biomarker Guide Volume 2, Biomarkers and Isotopes in Petroleum Systems and Earth History. 2nd ed. Cambridge: Cambridge University Press

Qiu Zhongjian, Gong Zaisheng. 1999. Petroleum Exploration in China: Volume 4. Offshore Oil and Gas Area (in Chinese). Beijing: Geological Publishing House

Shi Hesheng, He Min, Zhang Lili, et al. 2014. Hydrocarbon geology, accumulation pattern and the next exploration strategy in the eastern Pearl River Mouth Basin. China Offshore Oil and Gas (in Chinese), 26(3): 11–22

Tissot B P, Welte D H. 1984. Petroleum Formation and Occurrence. 2nd ed. New York: Springer-Verlag

Wang Qi, Du Lewei, Chen Gguojun, et al. 2010. Formation mechanism of carbonate cement in the Zhuhai Formation sandstone of Baiyun Sag. Acta Petrolei Sinica (in Chinese), 31(4): 553–558

Wang Zhenfeng, Sun Zhipeng, Zhang Yingzhao, et al. 2016. Distribution and hydrocarbon accumulation mechanism of the giant deepwater Central Canyon gas field in Qiongdongnan Basin, northern South China Sea. China Petroleum Exploration (in Chinese), 21(4): 54–64

Wang Jianglin, Zhang Xinbing, Wu Jiangsheng, et al. 2002. Comprehensive geophysical research of basement structure in Zhujiangkou Basin. Journal of Tropical Oceanography (in Chinese), 21(2): 13–22

Wu Liyan, Gu Xinzhang, Shen Zhiwei, et al. 1986. Quantitative Evaluation of Rapid Pyrolysis for Source Rock. Beijing: Science Press

Yu Junfeng, Pei Jianxiang, Xu Jing. 2009. New insight into oil and gas exploration in miocene and late Oligocene strata in Qiongdongnan Basin. Journal of Earth Science, 20(5): 811–823

Zhang Yingzhao, Fan Caiwei, Xu Xinde, et al. 2015a. Genesis and sources of natural gas in eastern Qiongdongnan Basin, South China Sea. Petroleum Geology & Experiment (in Chinese), 37(4): 466–472, 478

Zhang Wei, He Jiaxiong, Li Xiaotang, et al. 2015b. Petroleum system in Qiongdongnan Basin of the continental margin, the Northern South China Sea. Journal of Earth Sciences and Environment (in Chinese), 37(5): 80–92

Zhang Gongcheng, Liu Zhen, Mi Lijun, et al. 2009. Sedimentary evolution of Paleogene series in deep water area of Zhujiangkou and Qiongdongnan Basin. Acta of Sedimentogica Sinica (in Chinese), 27(4): 632–641

Zhang Gongcheng, Mi Lijun, Wu Jingfu, et al. 2010. Rises and their plunges: favorable exploration directions for major fields in the deepwater area, Qiongdongnan Basin. China Offshore Oil and Gas (in Chinese), 22(6): 360–368

Zhu Weilin, Zhang Gongcheng, Gao Le. 2008. Geological characteristics and exploration objectives of hydrocarbons in the northern continental margin basin of South China Sea. Acta Petrolei Sinica (in Chinese), 29(1): 1–9