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Research article

Physical simulation of gas reservoir formation in the Liwan 3-1 deep-water gas field in the Baiyun sag, Pearl River Mouth Basin

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Abstract

To figure out the process and controlling factors of gas reservoir formation in deep-waters, based on an analysis of geological features, source of natural gas and process of reservoir formation in the Liwan 3-1 gas field, physical simulation experiment of the gas reservoir formation process has been performed, consequently, pattern and features of gas reservoir formation in the Baiyun sag has been found out. The results of the experiment show that: ① the formation of the Liwan 3-1 faulted anticline gas field is closely related to the longstanding active large faults, where natural gas is composed of a high proportion of hydrocarbons, a small amount of non-hydrocarbons, and the wet gas generated during highly mature stage shows obvious vertical migration signs; ② liquid hydrocarbons associated with natural gas there are derived from source rock of the Enping & Zhuhai Formation, whereas natural gas comes mainly from source rock of the Enping Formation, and source rock of the Wenchang Formation made a little contribution during the early Eocene period as well; ③ although there was gas migration and accumulation, yet most of the natural gas mainly scattered and dispersed due to the stronger activity of faults in the early period; later as fault activity gradually weakened, gas started to accumulate into reservoirs in the Baiyun sag; ④ there is stronger vertical migration of oil and gas than lateral migration, and the places where fault links effective source rocks with reservoirs are most likely for gas accumulation; ⑤ effective temporal-spatial coupling of source-fault-reservoir in late stage is the key to gas reservoir formation in the Baiyun sag; ⑥ the nearer the distance from a trap to a large-scale fault and hydrocarbon source kitchen, the more likely gas may accumulate in the trap in late stage, therefore gas accumulation efficiency is much lower for the traps which are far away from large-scale faults and hydrocarbon source kitchens.

Keywords: Pearl River Mouth Basin; Baiyun sag; Liwan 3-1 gas field; Deepwater area; Gas reservoir formation; Simulation experiment; Source-fault-reservoir coupling gas accumulation pattern

The Liwan 3-1 gas field is located on the southeastern edge of the Baiyun sag in the central part of southern depression of the Pearl River Mouth Basin [1] (Fig. 1). With a total area of about 2×10^4 km^2, the Baiyun sag is adjacent to Panyu low uplift to its north, Dongsha uplift to its northeast-east, Southern uplift to its south and Yunkai low uplift to its west [2–4]. The Baiyun sag, with a basement of pre-tertiary, experienced early rifting and late depression, chronologically, there developed Shenhu Formation of Palaeocene, Wenchang Formation of pre-Eocene, Enping Formation of late-Eocene to pre-Oligocene in the early rifting period and Zhuhai Formation of late-Oligocene, Zhujiang Formation, Hanjiang Formation and Yuehai Formation of Miocene, Wanshan Formation of Pliocene and Quaternary in the late depression period [5]. Few wells encounter the Shenhu Formation and Wenchang Formation, only Wells LW4-1-1 and LW9-1-2 intersect a small part of the Wenchang Formation. The Shenhu Formation is composed of brown and gray massive sandstone

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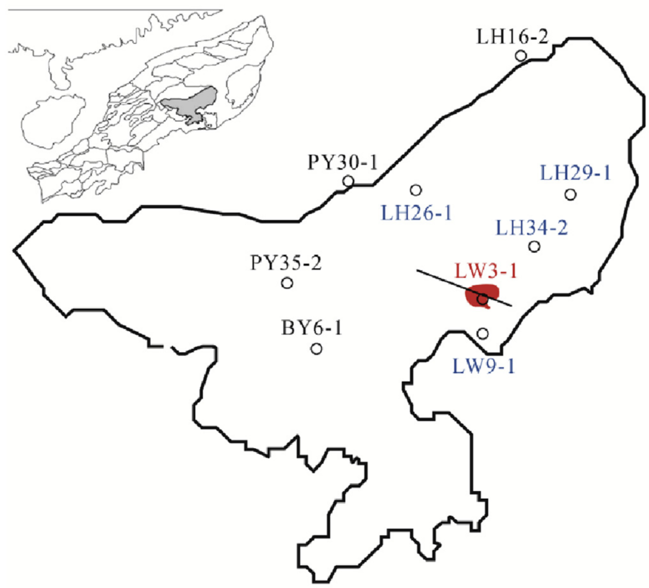

Fig. 1. Location of the Liwan 3-1 gas field and Baiyun sag in the Pearl River Mouth Basin.

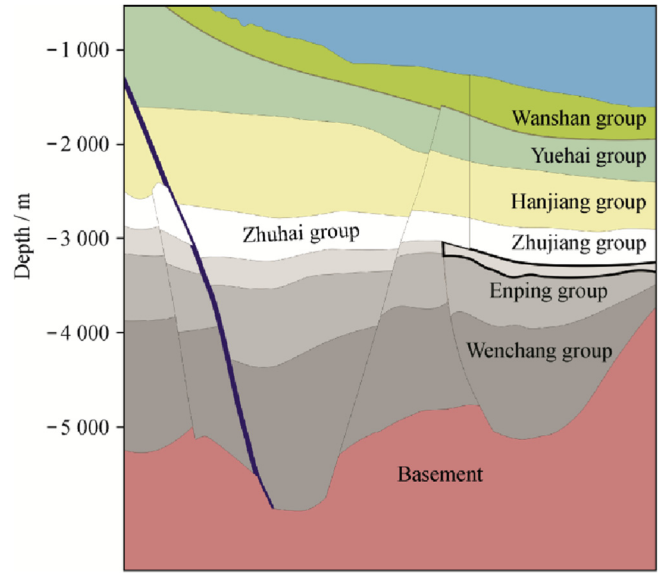

Fig. 2. Structure section of the Liwan 3-1 gas field.

and pyroclastic [6]; The Wenchang Formation mainly consists of deep lacustrine sandy shale; The Enping Formation of Lower Oligocene is mainly lacustrine coal seam bearing strata. The Zhuhai Formation, Hanjiang Formation and Yuehai Formation are respectively composed of littoral sandy mudstone, littoral mudstone and marine mudstone. The Wanshan Formation of Pliocene is made up of neritic sandstone and mudstone. Quaternary is composed of consolidated sand and clay [7]. There developed three types of vertical overlapping sandstone and mudstone reservoir-cap assemblage. They are: deep-water fan sedimentary system of the Zhujiang-Hanjiang Formation, shallow continental shelf delta system of the Zhuhai Formation, and continental lacustrine delta system of the Wenchang-Enping Formation with limited distribution [8]. Oil and gas discovered by far are mainly in the upper two reservoir-cap assemblages. Well LW3-1-1 leading to the discovery of the Liwan 3-1 gas field is the first deep-water well in China [9]. This field is representative in the deep-waters of the Pearl River Mouth Basin. Through the analysis of gas accumulation features and simulation of gas accumulation, the authors tried to figure out the accumulation process and the controlling factors of gas reservoirs in deep-waters, in the hope to provide basis and reference for the exploration and development of similar deepwater gas fields in China in the future.

1. Geological features

The Liwan 3-1 gas field is a faulted anticline trap in the background of regional incline (Fig. 2), which has a close connection with long-term fault activities [10]. Among those long-term active faults, F-LW1 cut through all the upper layers from the basement to the Wanshan Formation, but its fault throw decreases gradually from deep to shallow, reflecting the features of being long-term active, but less active in the late period, so it belongs to synsedimentary faults. The fault most closely related to the Liwan 3-1 structure is also a synsedimentary fault, the movement of which stopped in the middle Zhujiang period (Fig. 2), so Liwan 3-1 anticline is a synsedimentary anticline which has the basic conditions for long-term hydrocarbon supply from source rocks in the sag.

Well LW3-1-1 in the Liwan 3-1 gas field encountered Yuehai Formation, Hanjiang Formation, Zhujiang Formation and Zhuhai Formation, and a total of four gas layers has been discovered (Fig. 3). A gas-bearing sand layer found in the deep-water turbidite fan clastic rock at 3060.2–3077.2 m depth in the Zhujiang Formation, has a shale content of 19.4%, porosity of 24% and water saturation of 23.8%. Three gas-bearing sandstone layers have been found in the Zhujiang Formation delta front facies clastic rocks, at the depth of 3128.1–3148.2 m, 3168.6–3198.7 m and 3496–3513.4 m. These reservoirs have a shale content of 17.1–34.8%, porosity of 16.3–18% and water saturation of 30–39%. They show decrease of porosity and increase of water saturation with the increase of depth, representing medium porosity - permeability reservoirs. In general, the better the physical property of the reservoir, the more favorable it is for gas accumulation. It can be seen from Fig. 3 that the favorable reservoirs and cap rocks are mainly in the lower section of the Zhujiang Formation and the upper section of the Zhuhai Formation (Fig. 3). Bathyal-neritic shales in the middle-upper part of the Zhujiang Formation and the upper part of the Zhuhai Formation are regional caps.

2. Characteristics and origin of natural gas

The results of natural gas composition analysis show that the natural gas of this field has a hydrocarbon gas content of

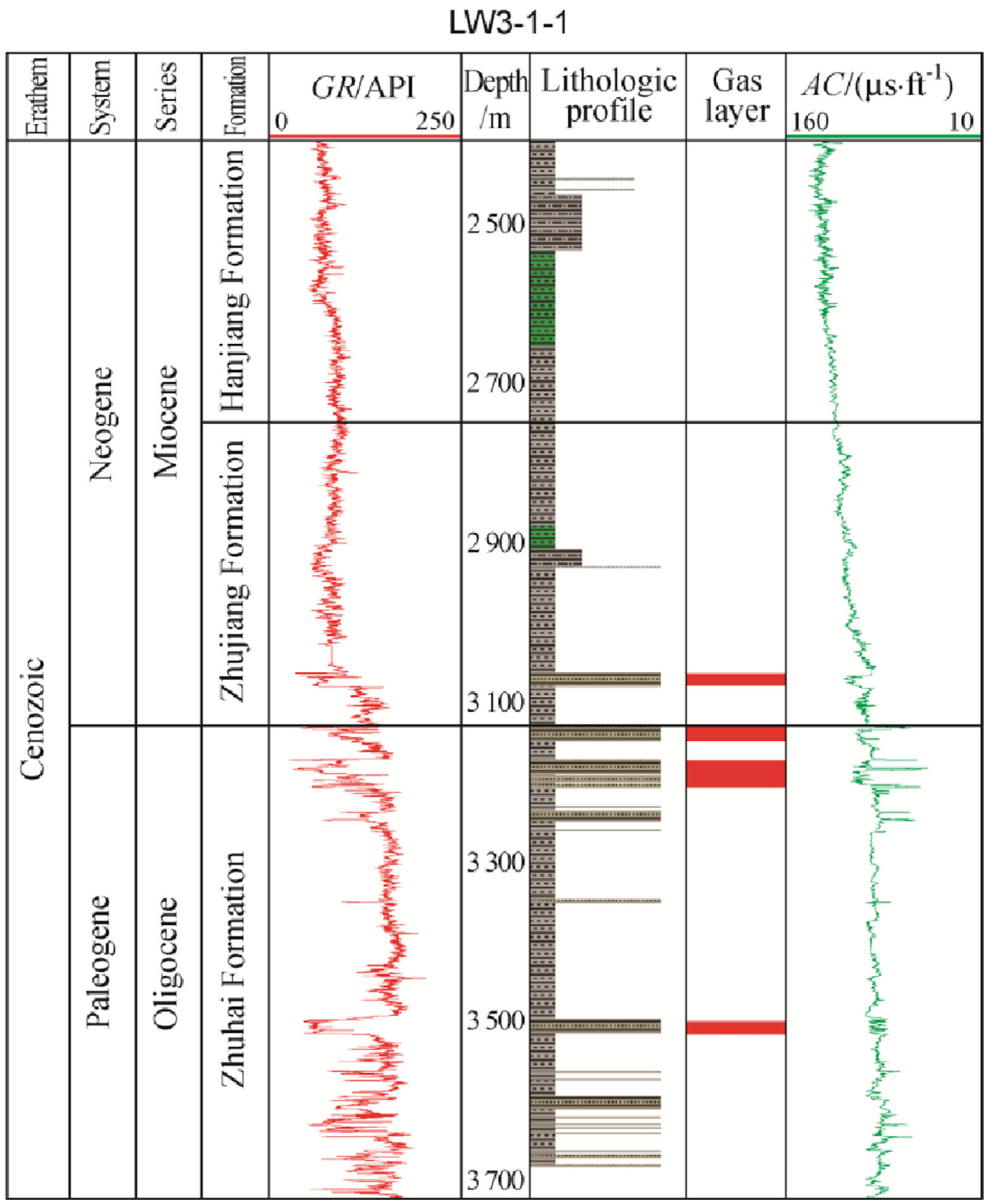

Fig. 3. Strata histogram of Well LW3-1-1 (1 ft = 0.3048 m).

more than 96%, N_2 content of 0.04–0.15%, CO_2 content of 2.37–3.21%, and dryness coefficient of 88.26–91.52%. So it is clear that the gas in the Liwan 3-1 gas field has low content of inorganic gas, and the characteristics of wet gas, which indicates that the maturity of parent material mainly is in the wet gas high maturity stage. With the increase of carbon number, weight of carbon isotope of natural gas increases, the carbon isotopic value of methane, ethane, propane and butane ranges from −36.6‰ to −37.1‰, from −28.9‰ to −29.6‰, from −27.2‰ to −29.1‰ and from −27.0‰ to −28.2‰ respectively (Table 1), low and relatively concentrated, indicating that the gas should be the product of transitional-sapropel type kerogen [11,12], and the type of parent material is relatively good. Carbon isotope value of CO_2 in the natural gas ranges between −5.7‰ and −7.8‰, greater than −8‰, indicating that the CO_2 should be of inorganic genesis. Hydrogen isotope in the natural gas (δD) also becomes heavier with the increase of carbon number; hydrogen isotope value of methane, ethane, propane and butane ranges from-158.1‰ to −175.6‰, from −135.6‰ to −164.5‰, from −120.3‰ to −160.1‰, and from −112.8‰ to −139.5‰ (Table 1). It can be seen that the hydrogen isotopic composition is heavier in general, reflecting that the source rocks are mainly formed in lacustrine environment with certain salinity.

Carbon and hydrogen isotopes in the natural gas and the light hydrocarbon composition show a good correlation with depth (Figs. 4 and 5). Hydrogen isotopic composition becomes heavier with the decrease of depth; the hydrogen isotopic composition of the gas-bearing zone in the lower Zhuhai Formation is obviously lighter. As the depth increases, carbon isotope composition in methane becomes heavier, composition in propane and butane becomes lighter, but composition in

Table 1
Carbon ($\delta^{13}C$) and hydrogen (δD) isotopic compositions (‰) of natural gas in the Liwan 3-1 gas field.

Depth (m)	δD_1	δD_2	δD_3	δD_4	$\delta^{13}C_1$	$\delta^{13}C_2$	$\delta^{13}C_3$	$\delta^{13}C_4$	$\delta^{13}C_{CO2}$
3070.0	−158.1	−135.6	−120.3	−112.8	−37.1	−29	−27.2	−27.1	−5.7
3144.5	−158.4	−137.5	−123.5	−114.4	−36.6	−29.1	−27.4	−27	−6.1
3189.5	−155.8	−138.2	−122.8	−115.05	−36.8	−28.9	−27.5	−27.4	−5.7
3499.5	−175.6	−164.5	−160.1	−139.45	−36.6	−29.6	−29.1	−28.2	−7.8

ethane has no obvious change. These changes of characteristics of carbon hydrogen isotopic composition have a certain relationship with different types of parent material and their maturity.

Comparison of the benzene/nC_6 and toluene/nC_7 of gas from Well LW3-1-1 with that of adsorbed gas of source rock in the Enping Formation and Zhuhai Formation (Fig. 5) shows that natural gas in the well has a closer relationship with the source rock in the Enping Formation. Comparison of light hydrocarbon parameters further confirmed that the associated oil in natural gas mainly comes from the source rock in the Enping Formation (Fig. 6). Therefore, according to the resemblance degree, natural gas in Well LW3-1-1 mainly comes from the source rock in the Enping Formation [13].

Sandstone extracts from the Zhujiang Formation and the Zhuhai Formation of Well LW3-1-1 are divided into two types: A and B. According to the difference of biomarker features, type A extract is from the two layers of sandstone in the Upper Zhujiang Formation and Zhuhai Formation, which is rich in oleanane and bicadinane series, lack of 4-methyl-C_{30} sterane series, and the abundance of pentacyclic triterpenoid is higher than that of steroid. There is high resemblance of distribution pattern of bicadinane W and T between mudstone of Enping Formation shale and type A asphalt and of oleanane and C_{30} hopane between Zhuhai Formation shale and type A asphalt, but there are big differences between biomarker distribution pattern of shale in Zhujiang Formation and Wenchang Formation and that of type A asphalte (Fig. 7). As a result, type A sandstone extract mainly comes from source rock in Enping Formation rich in bicadinane and source rock in Zhuhai Formation rich in oleanane (Fig. 7).

The characteristics of condensate oil in the second gas layer of Zhuhai Formation have a high resemblance with the characteristics of sterane and terpane in the source rock just below it, indicating that source rocks in Zhuhai Formation make some contribution to condensate oil in the gas pool. Type B asphalt comes from sandstone in the Zhuhai Formation (the fourth gas-bearing zone), which has abundant oleanane and a little bicadinane, abundance of pentacyclic triterpenoid higher than that of steroid and no 4-methyl-C_{30} sterane series. Careful comparison shows that composition of biomarkers of the Zhuhai Formation shale has the best correlation with type B asphalt, but those of other source rocks are quite different. Therefore, type B asphalt mainly comes from Zhuhai Formation source rocks (Fig. 7), showing features of in-situ generation and storage.

According to the comparison results of asphalt and condensate oil in natural gas, it is confirmed that the heavy hydrocarbon components and associated oil of natural gas in the Liwan 3-1 gas field mainly comes from the Enping Formation. But parameters of gas in the Liwan 3-1 gas field are not completely consistent with those of source rocks in the

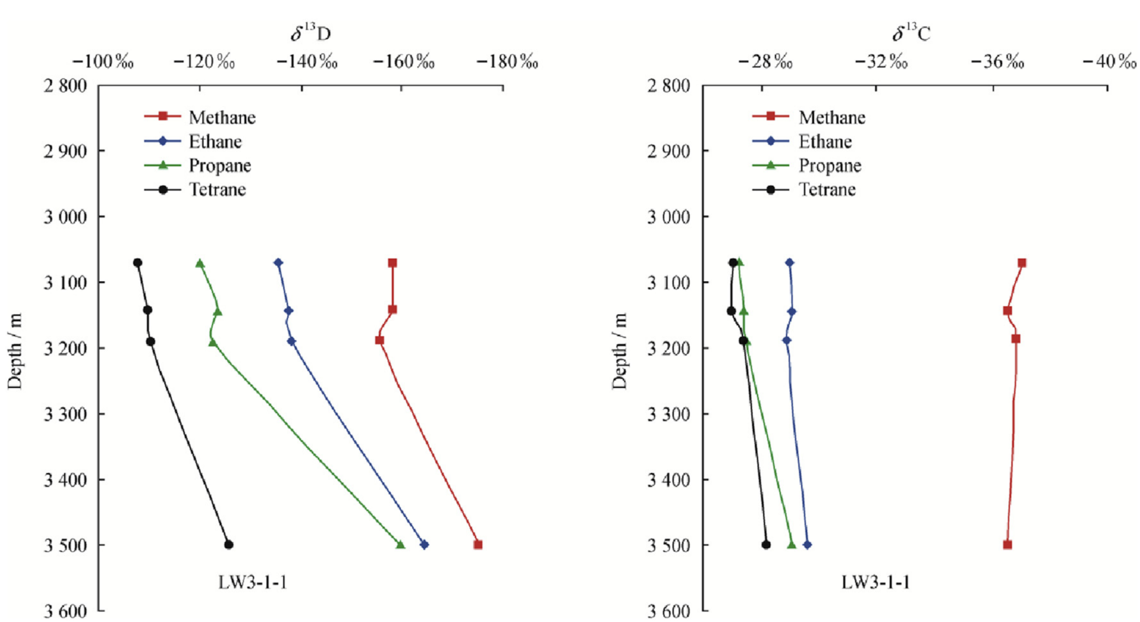

Fig. 4. Relationship between depth and the composition of light hydrocarbon in natural gas in Well LW3-1-1.

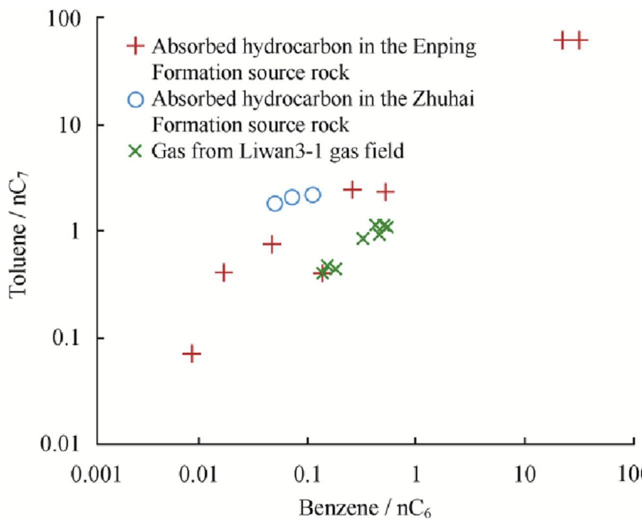

Fig. 5. Comparison of toluene/nC_7-benzene/nC_6 between natural gas and source rock.

Enping Formation in Figs. 5 and 6, and have some overlap with natural gas in the Panyu low uplift, and the type of natural gas parent material is more inclined to be sapropel kerogen. Source rocks in the Wenchang Formation makes certain contribution to natural gas in the Panyu low uplift, source rocks in the Enping Formation were formed in the transitional environment, so the type of parent material is mainly mixed - humic type which is difficult to form partial sapropel type of gas. Although source rocks in the Wenchang Formation drilled in Well LW4-1-1 of the Baiyun sag are medium source rocks, considering that the centers of subsidence and deposition of the Wenchang Formation, Enping Formation and Zhuhai Formation have high inheritance, this set of lacustrine source rock must exit in the Baiyun sag. Its parent material is mainly sapropel, which can form sapropel type of gas. In summary, natural gas and associated oil in Liwan 3-1 gas field mainly come from the Enping Formation and some from the Wenchang Formation, source rock in Zhuhai Formation have different contributions to the upper and lower gas pools, contribution of Enping Formation is universal.

3. Gas accumulation process

The formation of Liwan 3-1 gas field is closely related to the temporal-spatial coupling of effective source rocks, faults and reservoirs. Large-scale faults activity have been long lasting since the depositional stage of late Hanjiang - early Yuehai Formation, in the depositional stage of Enping Formation, deep source rocks in the sag had already matured and generated gas and oil, but faults during this period cut through all the formations, so without proper preservation conditions, gas generated almost all scattered and dispersed. Until the late depositional stage of Zhujiang Formation, the deep part of Wenchang and Enping Formations had already entered gas generation window, but large faults were still active, most oil and gas scattered and dispersed still, only after the early depositional stage of Yuehai Formation, the movement of large faults stopped or weakened gradually and the thickness of overlying marine mudstone increased gradually, and the sealing conditions became better. Since this period corresponds to 5-6 Ma, Liwan 3-1 gas field was formed in late Neogene- Quaternary period [14]. The homogenization temperature of the fluid inclusion in the four gas layers in Well LW3-1-1 shows a certain pattern, the homogenization temperature of I, II, III and IV gas layer ranges respectively 80–115 °C, 90–120 °C, 90–125 °C and 105–135 °C, the main temperature range increases with the increase of depth (Fig. 8). Fluid inclusions in different depth are different in homogenization temperature, but fluid inclusions in different measuring point shows continuity in homogenization temperature, which suggests that oil and gas migrated and accumulated into different layers in different horizons continuously, consistent with the constant subsidence after the deposition of the main targets.

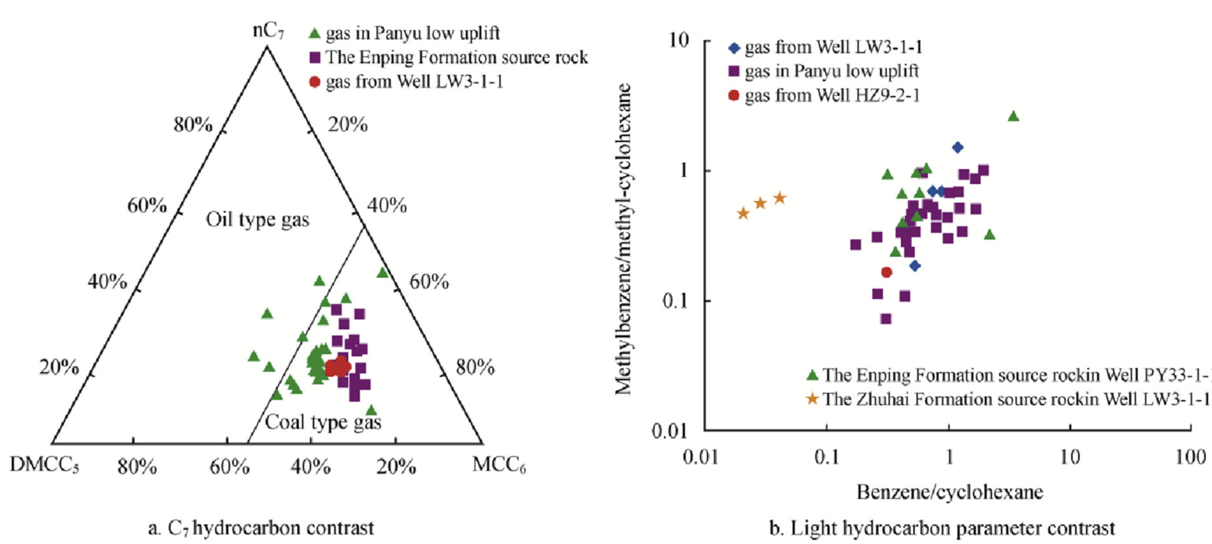

Fig. 6. Comparison of light hydrocarbon in natural gas and source rock in the Baiyun sag.

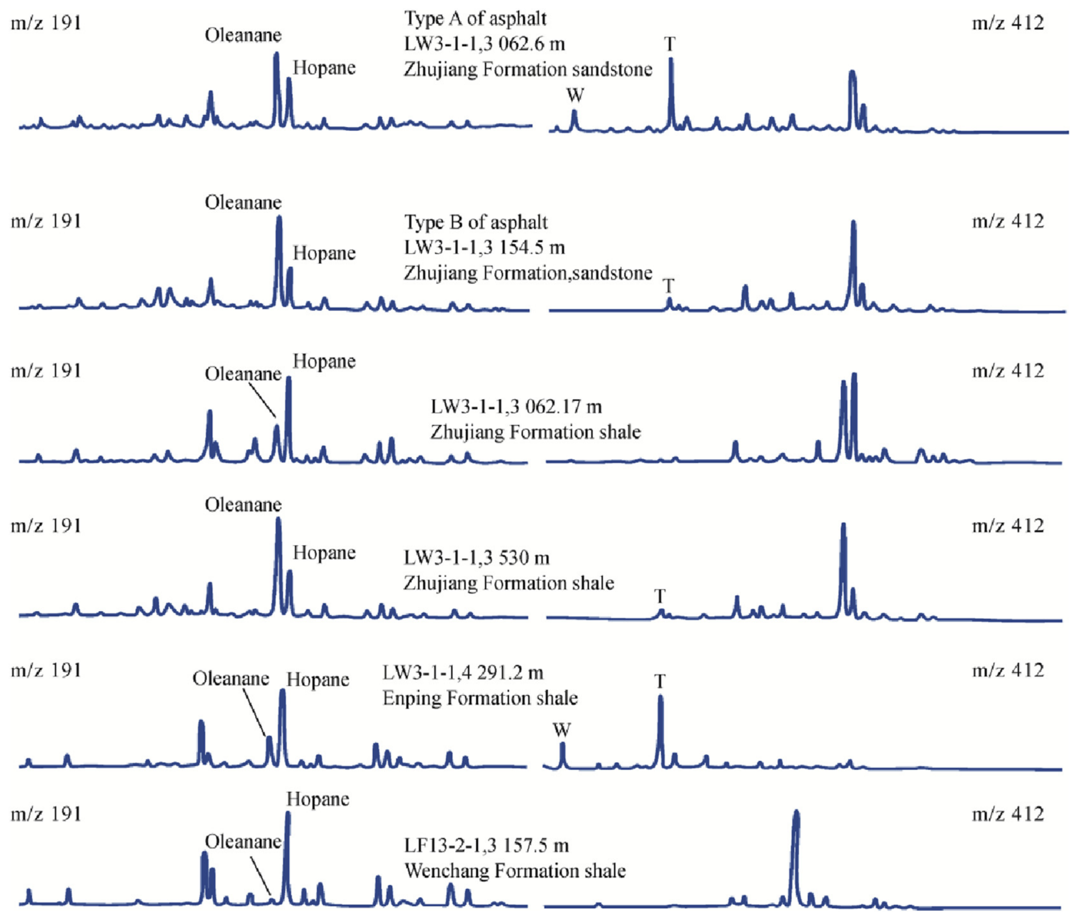

Fig. 7. Spectrum comparison chart of *m*/*z* 191 and *m*/*z* 412 between sandstone extract and saturated hydrocarbon of source rock in Well LW**3-1-1**.

It is inferred that all the four gas reservoirs were charged by oil and gas about 3.5 Ma, according to the burial history, thermal evolution history (Fig. 9) and the homogenization temperature of fluid inclusions of Well LW3-1-1. In summary, these reservoirs have late and continuous accumulation characteristics. This period corresponding to the new tectonic movement, witnessed the accelerated sedimentary rate, thickening of regional cap rocks and improving of preservation conditions.

The fault throw of T_1, T_2, T_4, T_6, T_7, T_8, and T_g interface in Liwan 3-1 structure increases gradually from shallow to deep, the faults acted long (Fig. 10). The activity of the faults fluctuated, relatively weak in Wenchang stage (T_g-T_8), strongest in Enping-Zhuhai stage (T_8-T_5), weakening in Zhujiang

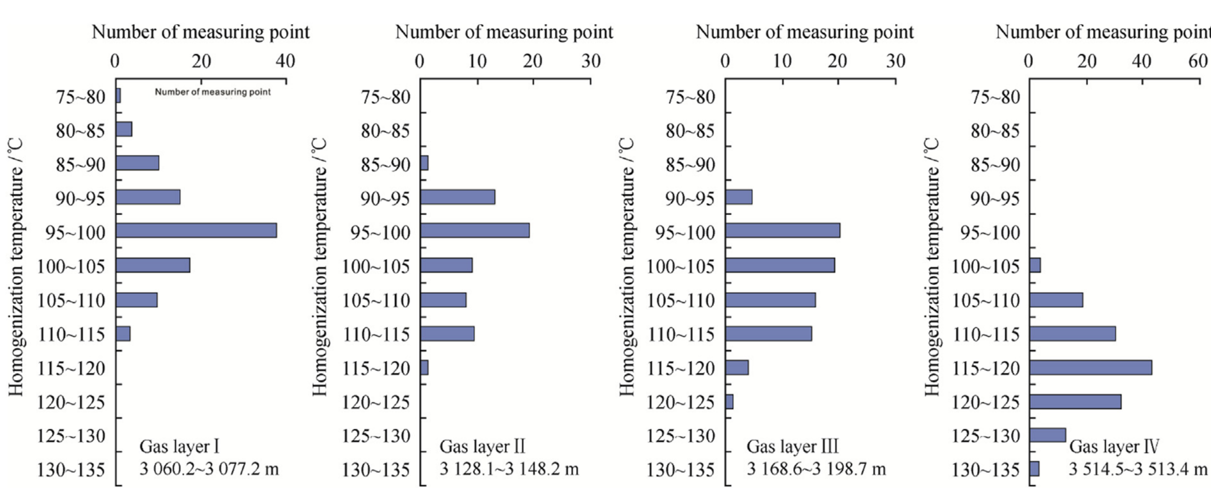

Fig. 8. Frequency distribution of fluid inclusion homogenization temperature of I−IV gas layers in Zhujiang−Zhuhai Formations in Well LW**3-1-1**.

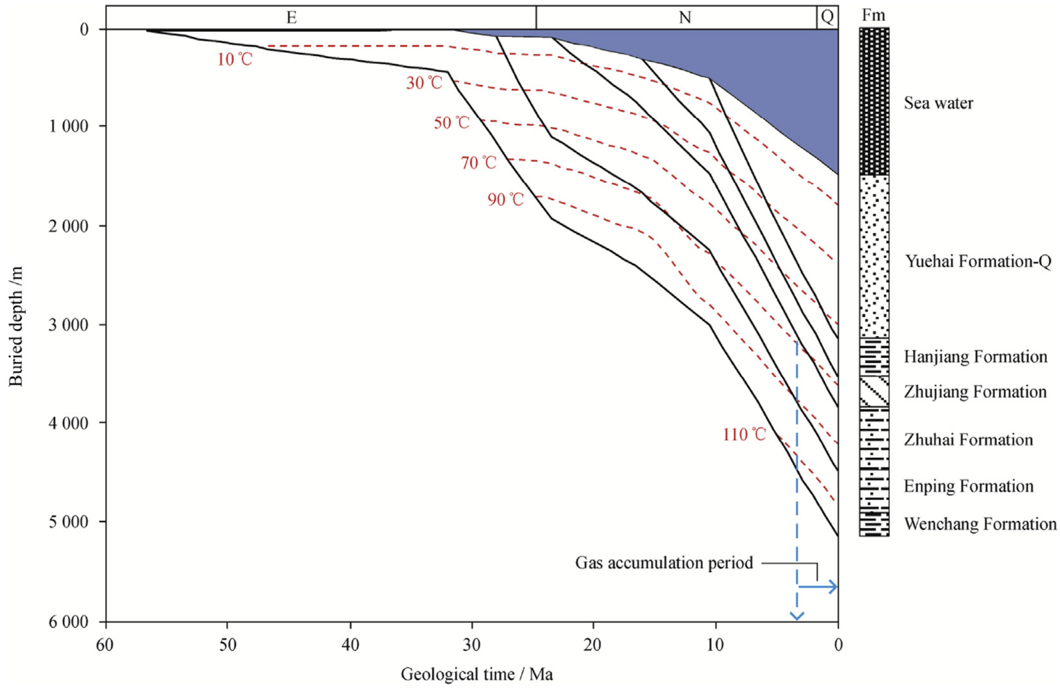

Fig. 9. Analysis chart of burial thermal evolution history and hydrocarbon charging time of Well LW**3-1-1**.

stage (T_5-T_4), getting stronger in Hanjiang stage (T_4-T_2) and significantly weakening since Yuehai stage. Since the long active growth faults communicated source rocks, oil and gas mainly scattered and dispersed during the strong-activity period; only after the weakening of the fault activities in the late period, when the fault throw was less than the thickness of overlying mudstone, oil and gas began to accumulate along the faults to the regional cap rocks due to the sealing of huge thick mudstone, which is in agreement with accumulation in the late period determined by homogenization temperature of inclusions. Weakened activity in the late period makes the faults conduits for oil and gas migration, and the direct contact of thick mudstone with fault surface prevents vertical dissipation of oil and gas effectively, at the same time, the source rocks in the late period have entered the oil and gas generation peak, and the reservoirs above have good physical conditions, the late effective temporal-spatial coupling of all these elements is the necessary condition for oil and gas accumulation, enabling effective oil and gas accumulation (Fig. 11).

4. Gas accumulation pattern

4.1. Physical simulation experiment of gas accumulation

In order to analyze the temporal-spatial coupling features of source rocks, faults and reservoirs in the deep-waters of the northern South China Sea, the authors established a physical model of gas migration and accumulation based on fine

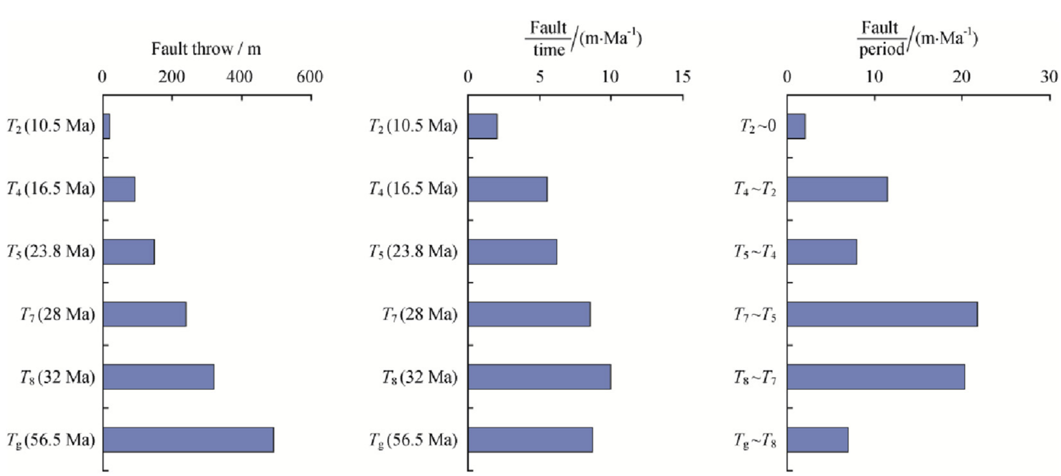

Fig. 10. Activity rate distribution of faults in the LW3-1 gas field in different periods of time.

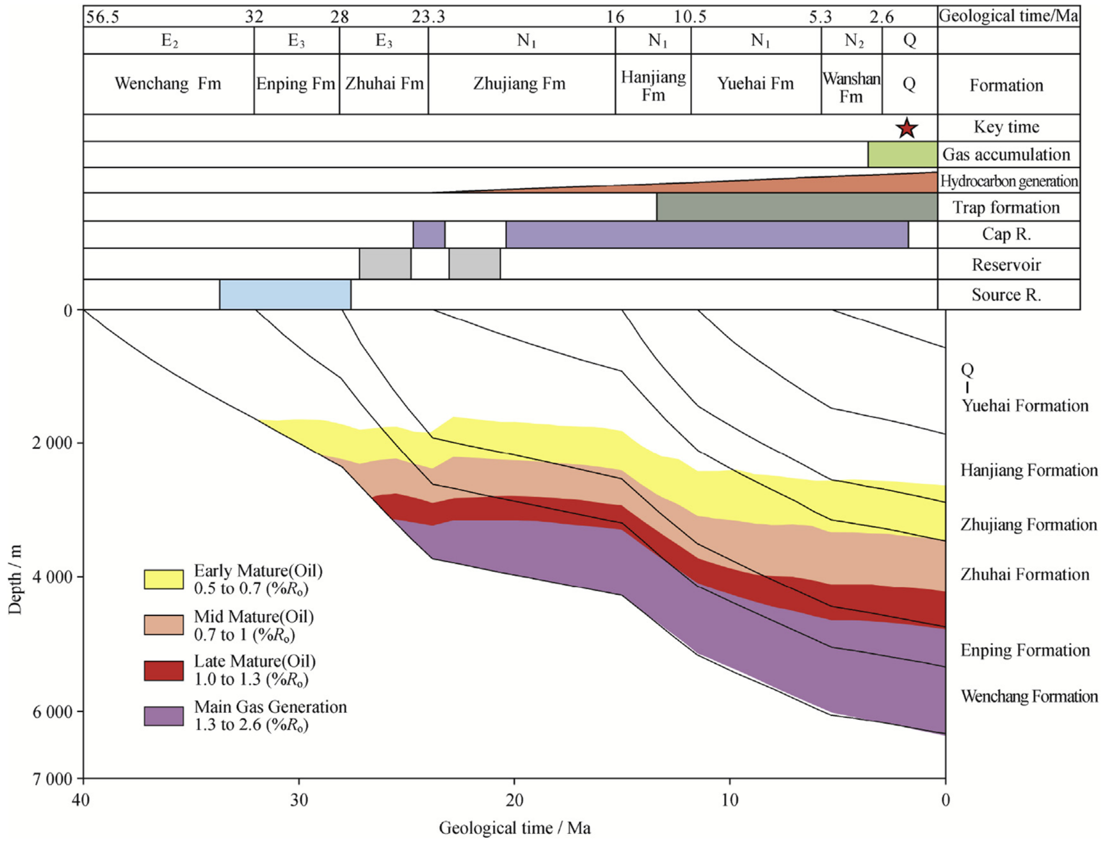

Fig. 11. Reservoir-forming events of Liwan 3-1 gas field, Baiyun sag (geological time in the graph is according to Mi Lijun et al., 2011 [15]).

description of Liwan 3-1 gas field to simulate the gas migration and accumulation. The size of the model is 50 cm × 30 cm × 2.2 cm, each sand bed and fault is filled with glass beads, and other parts are poor permeability mud as barrier layers and isolated layers, the injection port is at the bottom, and two outlets are at the top of two faults (Fig. 12). After the establishment of the experimental physical model, faults and sand beds were saturated with stained salty water to displace the residual air in the model. After the permeable faults and sands of the whole model were infilled with stained and saturated salty water, N_2 was injected from the injection port through pressure bottle and pressure regulator to displace the stained salt water, the changes of saturated salt water in faults and sand beds were observed at a certain time interval, and pictures of the process were taken.

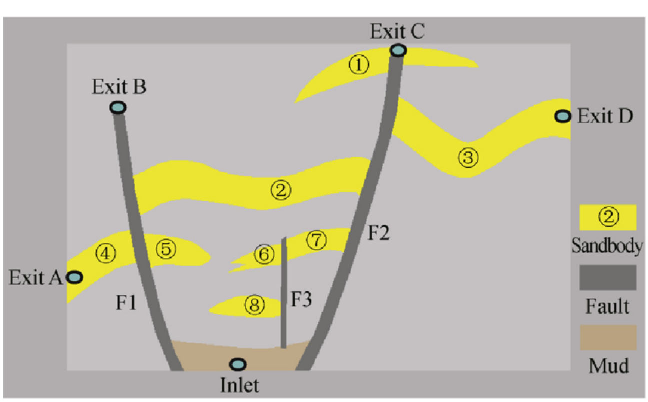

Fig. 12. The experiment model of gas migration and accumulation.

Gas injection pressure was 0.05 MPa at the beginning of the experiment, and dropped to 0.03 MPa after it became stable. 15 min after the beginning of gas injection, liquid came out of exit B, but exit C had no response yet; some gas could be noticed at the bottom of the three faults, and the color became lighter. The color of the fifth to tenth sand beds became lighter, and the first to fourth sand beds had no change (Fig. 13b). 30 min after the experiment began, liquid flew out of exit B, still exit C had no response, color of F1 fault became lighter further, changes in the lower part of F2 and F3 were stronger, but the upper part was weaker. The fifth to tenth sand beds were saturated with gas further, the second and third sand beds began to change, but the first and fourth sand beds only had slight gas response (Fig. 13c). 45 min after the beginning of the experiment, mixed liquid and gas came out of exit B, liquid flew out of exit C, color of F1 fault got even lighter, color of the fault below the fourth sand bed had greater change, gas in F2 displaced fluid further, F3 is gas saturated, the first and fourth sand beds had no obvious change, massive liquid in the third sand bed flew out through exit B, the fourth sand bed had no obvious change, the fifth to tenth sand beds were gas saturated (Fig. 13d). 60 min later, only gas came out of exit B, liquid still discharged from exit C, color of F1

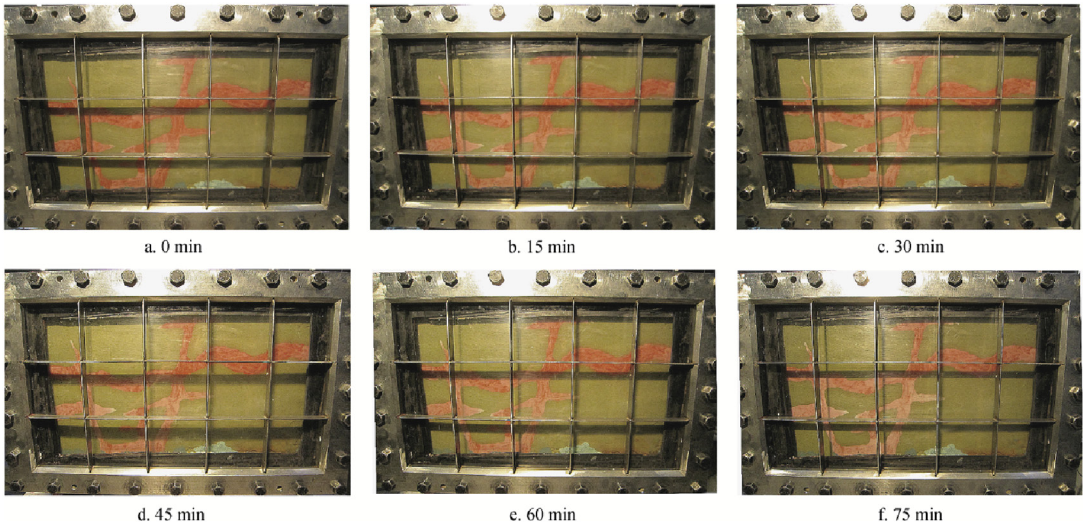

Fig. 13. Photographs of the experimental simulation process.

became stable, gas in F2 continued to displace fluid, color of the upper part of the third sand bed became lighter, its lower part became stable, F3 was gas saturated, the first sand bed began to have gas, anticline color close to the fault in the fourth sand bed was slightly lighter but had little change in the part far from the fault, other sand beds received injected gas continuously and was nearly saturated (Fig. 13e). 75 min later, the model became stable, with no liquid but only gas getting out of exits B and C, F1, F3 and the lower part of F2 were gas saturated, the upper part fault of the fourth sand bed was not gas saturated, a boundary line of exchange migration of oil and gas could be clearly seen, the part of first sand bed far away from the export was not gas saturated still, a large amount of fluid was detained in the fourth sand bed in which gas filling coefficient of the anticline part close to the fault was higher than that of the anticline part far away from the fault, and the rest sand beds were all saturated (Fig. 13f).

Features and attitude of faults and sand beds have major effects on the characteristics of migration and accumulation of natural gas according to this experiment (Fig. 14). The main characteristics of gas migration in the fracture zone are as follows:

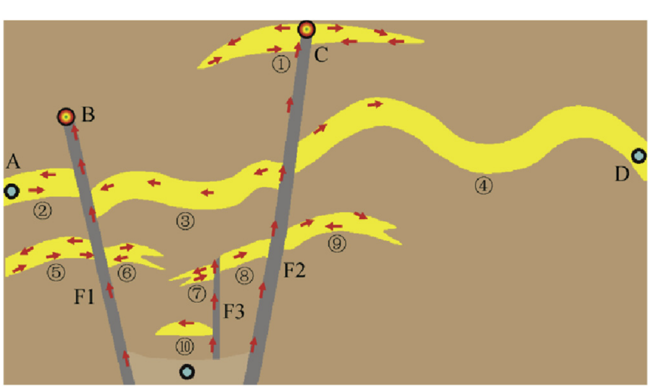

Fig. 14. Physical simulation of gas migration and accumulation process.

① The steeper the fracture zone, the faster the rate of gas vertical migration, conversely, the gentler the fracture zone, the slower the rate of gas vertical migration;
② Buoyancy plays an important role in the natural gas migration along fracture zones, the place near the hanging wall of a fault zone is the main migration channel of natural gas, the migration efficiency is low in the place close to the footwall;
③ Natural gas first migrates along the top of a sand body;
④ Sand body close to the air source is filled by gas first, but the sand body far away from the source is filled by gas later;
⑤ The sand body close to the fracture is saturated first;
⑥ With the same physical properties, the sand body located on the migration path is more conducive to gas migration and accumulation.
⑦ In the conditions of sufficient source and migration time, the sand body far away from the source rock is less likely to have gas accumulation.
⑧ Natural gas has stronger vertical migration than lateral migration.

4.2. *Gas accumulation pattern in the Baiyun sag*

The Liwan 3-1 gas field is the result of time-space coupling communication of effective traps and source rocks through faults. Large faults have long developed in the Baiyun sag, connecting source rocks with the overlying high porosity and permeability reservoirs and effective traps all the time. During the active period of these faults, oil and gas scattered and dispersed because the faults extend to surface or sea floor. Later as fault activities gradually weakened, and the effectiveness of traps enhanced, natural gas migrated upward through faults gradually accumulated in the trap near faults first, while traps far from faults had lower capacity to capture gas. In late stage, as overlying cap rocks get thicker, and

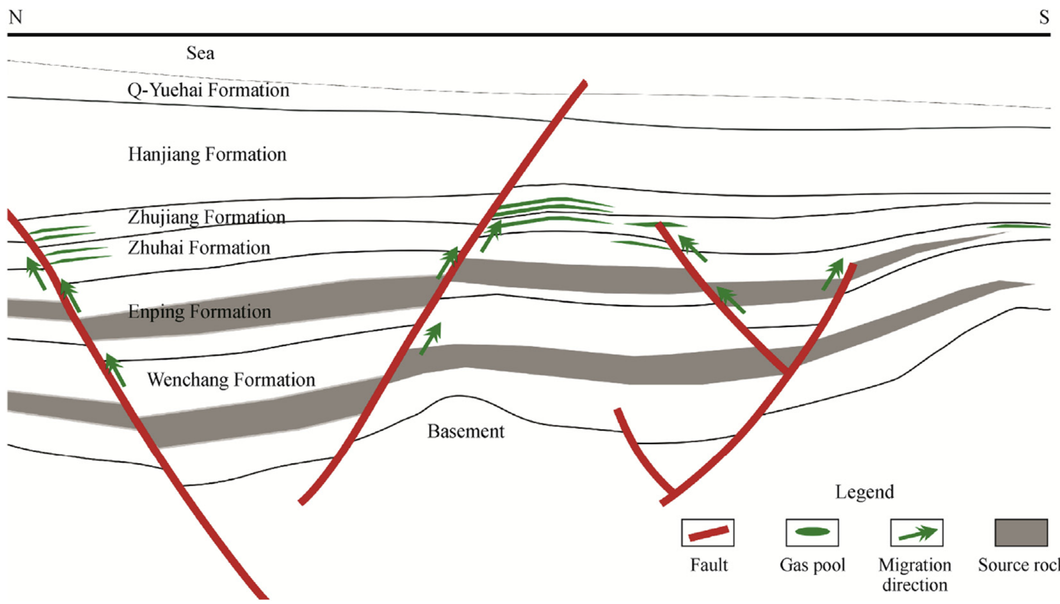

Fig. 15. Natural gas accumulation model of the Baiyun sag.

preservation condition becomes better, gas accumulated in the traps adjacent to the faults increases constantly, currently source rocks are still supplying gas to the reservoirs. It can be seen that the coupling of favorable reservoirs near the hydrocarbon generation sag and trap formation with hydrocarbon generation and expulsion period is one of the necessary conditions for the formation of oil reservoirs, the sealing by large area marine mudstone cap rocks is the basic condition for natural gas preservation (Fig. 15).

5. Conclusions

1) As a typical gas field in the deep-water area of the Baiyun sag, the Liwan 3-1 gas field is a faulted anticline trap in the background of regional tilt, closely related to long-term fault activities. Its forming process has important indicative function to the formation of gas reservoirs in the Baiyun sag.
2) The natural gas there is wet gas at high mature stage, with a low content of non-hydrocarbon gases. Carbon and hydrogen isotope and light hydrocarbon composition show obvious vertical migration signs. Associated liquid hydrocarbon in natural gas in the Zhuhai Formation and Zhujiang Formation comes mainly from the Enping and Zhuhai Formation source rocks; natural gas comes mainly from the Enping Formation source rocks, and a small amount of gas from the Wenchang Formation.
3) The gas has stronger vertical migration than lateral migration, and it is most likely to accumulate in the places where faults link the effective source rocks and reservoirs.
4) Late effective time-space coupling of source-fault-reservoir is one of the essential conditions for gas reservoir formation in the Baiyun sag. Traps near large faults are favorable places for late gas accumulation, conversely, traps far from large faults and hydrocarbon source kitchens are less likely to capture gas and form accumulation.

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References

[1] Zhu Junzhang, Shi Hesheng, Pang Xiongqi, Zhang Zhilin, Liu Baojun, Pang Xiong. Origins and accumulation characteristics of hydrocarbons in eastern Baiyun deep-water area. China Pet Explor 2012;17(2):20–9.
[2] Cui Shasha, He Jiaxiong, Chen Shenhong, Zou Heping, Cui Jie. Development characteristics of the Pearl River Mouth Basin and its geological conditions for oil and gas accumulation. Nat Gas Geosci 2009;20(3):384–91.
[3] Shao Lei, Meng Xiaojie, Zhang Gongcheng, Liang Jianshe. Feature of faults system and its influence on tectonic and sedimentary history of the Baiyun Sag. J Tongji Univ (Natural Science) 2013;41(9):1435–41.
[4] Wu Baozhen, Shi Xiaobin, Yang Xiaoqiu, Shi Hongcai, Jiang Haiyan, Yang Jun. Analysis on lithospheric strength of the Baiyun Sag and its surrounding area in the northern margin of the South China Sea. J Trop Oceanogr 2014;33(1):62–8.
[5] Pang Xiong, Chen Changmin, Chen Honghan, He Min, Shen Jun, Liu Baojun, et al. A study on hydrocarbon accumulation dynamics in Baiyun deep_water Area, Pearl River Mouth Basin. China Offshore Oil Gas 2008;20(1):9–14.
[6] He Jiaxiong, Chen Shenghong, Liu Shilin, Liu Hailing. Potential petroleum resources and favorable prospecting directions in the Pearl River Mouth Basin in northern margin of the South China Sea. Xinjiang Pet Geol 2008;29(4):457–61.

[7] Chen Changmin, Shi Hesheng, Xu Shiche. Forming conditions of tertiary oil and gas pools in the (eastern) Pearl River Mouth Basin. Beijing: Science Press; 2003.
[8] Pang Xiong, Chen Changmin, Peng Dajun. Petroleum and deep water fan system of the Pearl River Mouth Basin in South China sea. Beijing: Science Press; 2007.
[9] Mi Lijun, Zhang Gongcheng. Evaluation and strategic investigation of oil and gas resource in deep_water area of slope in South China Sea. Beijing: Geology Press; 2011.
[10] Zhu Junzhang, Jiang Aizhu, Shi Hesheng, Sun Yongge, Pang Xiong, Zhang Zhilin. The effective gas-source area and gas migration-accumulation model in the LW3-1 Gas Field, Baiyun Sag deep_water area, Pearl River Mouth Basin. China Offshore Oil Gas 2012;24(4):25–31.
[11] Dai Jinxing. Carbon and hydrogen isotopic compositions and original identification of various natural gases. Nat Gas Geosci 1993;2(3):1–40.
[12] Zhu Zhangjun, Shi Nansheng, He Ming, Pang Xiong, Yang Shaokun, Li Zhaowei. Origins and geochemical characteristics of gas in the LW3-1-1 well in the deep sea region of Baiyun Sag, Pearl River Mouth Basin. Nat Gas Geosci 2008;19(2):229–33.
[13] Fu Ning, Mi Lijun, Zhang Gongcheng. Source rocks and origin of oil and gas in the northern Baiyun depression of Pearl River Mouth Basin. Acta Pet Sin 2007;28(3):32–8.
[14] Shi Hesheng, Qin Chenggang, Gao Peng, Zhang Zhongtao, Zhu Junzhang, Zhao Renyong. Late gas accumulation characteristics in Panyu low-uplift and the north slope of Baiyun Sag, Pearl River Mouth Basin. China Offshore Oil Gas 2008;20(2):73–6.
[15] Mi Lijun, Zhang Gongcheng. Strategic investigation and evaluation of oil and gas resources in the deep northern slope sea of the South China Sea. Beijing: Petroleum Industry Press; 2012.