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Research article

An analysis of natural gas exploration potential in the Qiongdongnan Basin by use of the theory of "joint control of source rocks and geothermal heat"

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Abstract

The Oligocene Yacheng Fm contains the most important source rocks that have been confirmed by exploratory wells in the Qiongdongnan Basin. The efficiency of these source rocks is the key to the breakthrough in natural gas exploration in the study area. This paper analyzes the hydrocarbon potential of each sag in this basin from the perspective of control of both source rocks and geothermal heat. Two types of source rocks occur in the Yacheng Fm, namely mudstone of transitional facies and mudstone of neritic facies. Both of them are dominated by a kerogen of type-III, followed by type-II. Their organic matter abundances are controlled by the amount of continental clastic input. The mudstone of transitional facies is commonly higher in organic matter abundance, while that of neritic facies is lower. The coal-measure source rocks of transitional facies were mainly formed in such environments as delta plains, coastal plains and barrier tidal flat-marshes. Due to the control of Cenozoic lithosphere extension and influence of neotectonism, the geothermal gradient, terrestrial heat flow value (HFV) and level of thermal evolution are generally high in deep water. The hot setting not only determines the predominance of gas generation in the deep-water sags, but can promote the shallow-buried source rocks in shallow water into oil window to generate oil. In addition to promoting the hydrocarbon generation of source rocks, the high geothermal and high heat flow value can also speed up the cracking of residual hydrocarbons, thus enhancing hydrocarbon generation efficiency and capacity. According to the theory of joint control of source quality and geothermal heat on hydrocarbon generation, we comprehensively evaluate and rank the exploration potentials of major sags in the Qiongdongnan Basin. These sags are divided into 3 types, of which type-I sags including Yanan, Lingshui, Baodao, Ledong and Huaguang are the highest in hydrocarbon exploration potential.

Keywords: Joint control of source rock and geothermal heat; Source rocks; Sedimentary environment; Geochemical behavior; Terrestrial heat flow; Exploration potential; Geothermal field; Yacheng stage; Qiongdongnan Basin

1. Introduction

The Qiongdongnan Basin is located in the northwest of the continental margin of northern South China Sea. It is a NE-NEE striking basin formed during the Cenozoic era. Hainan Uplift is to its north, Yongle Uplift is to its south, the Yinggehai Basin is to its west, and Shenhu Uplift and the Pearl River Mouth Basin are to its northeast [1–3]. This basin underwent three tectonic evolution phases: rifting during Paleogene, depression during the Early-Middle Miocene, and neotectonism since the Late Miocene. In the Paleogene rifting stage, this basin was filled with Eocene continental deposits, the Lower Oligocene Yacheng Fm transitional deposits, the Upper Oligocene Lingshui Fm marine deposits from bottom to top; in the Neogene stage, this basin received deposits of Miocene Sanya Fm, Meishan Fm and Huangliu Fm, Pliocene Yinggehai Fm and Quaternary strata in littoral-neritic marine and bathyal marine respectively [1,4–6]. The plane structure of the Qiongdongnan Basin is featured by zoning in SN direction and blocking in EW direction [7], including North Depression, Central Uplift, Central Depression, South Uplift and South Depression from north to south (Fig. 1). Among

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them, North Depression includes Yabei Sag, Songxi Sag and Songdong Sag from west to east; Central Depression includes Yanan Sag, Ledong Sag, Lingshui Sag, Beijiao Sag, Songnan Sag, Baodao Sag and Changchang Sag; and South Depression mainly includes Ganquan Sag and Huaguang Sag, etc.

Exploration in the Qiongdongnan Basin began in 1979, discovering Yacheng 13-1 and 13-4 gas fields in the periphery of Yanan Sag, proving that this sag is a hydrocarbon-rich sag, and it is also the sole sag confirmed by exploration and studies in the Qiongdongnan Basin. Moreover, several hydrocarbon-bearing structures were found in the shallow water area, showing favorable exploration prospect [8]. At the end of 2010, the shallow formations in the deep-water area of the Qiongdongnan Basin were firstly drilled, discovering natural gas in Lingshui 22-1 structure, which was the breakthrough in Lingshui Sag in the deep-water area. However, some target drillings failed in deep-water area afterwards, showing the complexity of hydrocarbon accumulation in deep-water area in the Qiongdongnan Basin [9,10]. This also puzzled the direction of hydrocarbon exploration in the deep-water area of this basin. Particularly, through an analysis of drillings in the deep-water area in the past few years, we found that efficient source rocks are key to the breakthrough in hydrocarbon exploration, and the source rocks in the Yacheng Fm of Oligocene is the most important source rocks that have been proved by drilling in the Qiongdongnan Basin up to now.

Therefore, we tried to, based on the theory of "joint control of source rocks and geothermal heat" [11–13], discuss the development features of the Yacheng Fm source rocks and the geothermal field features of each sag in the Qiongdongnan Basin. And combined with the discovered oil and gas status, we conducted preliminary prediction and classification of the hydrocarbon potential of each sag in the entire basin.

2. Development features of the Yacheng Fm source rocks

The Yacheng Fm has been proven to have the major source rocks of the Qiongdongnan Basin. The Yacheng Fm belongs to a transitional facies and semi-closed neritic environment on the whole, where coal-measure strata and grey thick mudstone are developed.

2.1. Depositional settings

The Yacheng Fm in the Qiongdongnan Basin was formed at the end of the rift stage. At that time, the paleo-lake was dying out, while large-scale transgression would begin, with a major depositional setting of transitional facies. Pollens in the Yacheng Fm are featured by predominant marsh phyllous vines and mangrove Zonocostatites ramonae; but the synchronous Enping Fm in the Pearl River Mouth Basin usually has quercus, dicolpopollis and polypodiidites. Both of them indicate the tropic-subtropic damp and hot climate at that time [14], which was favorable for developing palustrine, and this period was just the large-scale genetic stage of source rocks in sags. Controlled by NE and EW striking faults and the successive development of paleohigh, these sags were partly connected and partly separated during the Yacheng Fm. Owing to the barriers formed by the Yacheng Salient, Lingshui Low Salient, Songtao Salient, Lingnan Low Salient and Songnan Low Salient, the regions between North Depression, South Depression and Central Depression were relatively stable and confined environments, which was favorable for the enrichment and preservation of organic matters in the source rocks.

Unlike the Pearl River Mouth Basin which located to the northern South China Sea, the Qiongdongnan Basin lacks such a great river as the paleo-Pearl River to provide massive

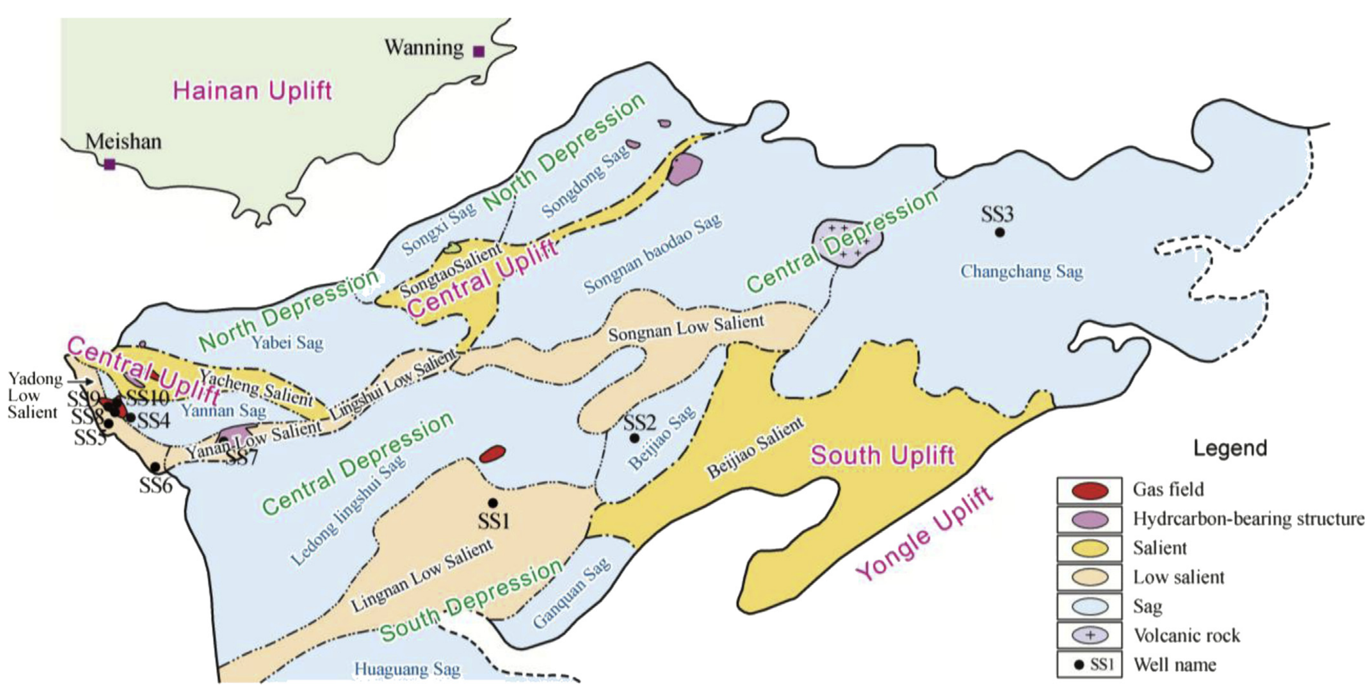

Fig. 1. Regional location and tectonic units of the Qiongdongnan Basin.

deposits. Therefore, the provenance in this basin was relatively insufficient, except the Sanya and Wanquan rivers. The Sanya River in the northwest and the Wanquan River in the northeast of the basin, which brought much supply, which formed thicker delta deposits. A case in point is Well SS4 drilled in the Sanya River Delta (Figs. 2,3-a,b).

Its major lithology is offwhite and light-grey gravels, glutenites, gritstones and medium sandstones, interbedded with thin grey carbargilites; gravels are subangularity-subrounded shape, with poor-moderate gradation. Gravel diameters can be up to 4 cm, scour surfaces and retention deposits are seen for many times, with positive rhythm and plentiful deposition phenomena (such as festoon cross-bedding, parallel beddings, wavy beddings, deformed beddings, bioturbated structures and carbonized plants stems). It is generally deposits from braided river delta plains to delta front facies. The probability curves of sandstone grain grades include two types (three sections and two sections), representing the deposits of a braided river channel and a underwater distributary channel respectively. Under a microscope, the major lithology types include medium grained arkosites, coarse grained feldspar lithic sandstones, feldspar greywackes, etc., with plenty of unstable minerals (such as mica and feldspar, etc.), and with lower maturity, indicating a relatively proximal depositional setting. GR curves were characterized by a toothed bell shape in the lower section and big micro-toothed box shape, bell shape and funnel shape (and box shape predominates) in the upper section, reflecting frequent hydrodynamic activities in the lower section and relatively stable activities in the upper section. Eight coal beds were interpreted by well logging data, with a total thickness of 3.56 m. The major coal generation environment is the braided river delta plain. In the third member of the Yacheng Fm in this well, early sections had big abundance of plant cutins, which was indicative of continental environment; but late sections had discontinuously distributed foram and marine dinophyceae, which had high concentrations, indicating that this region was affected by transgression.

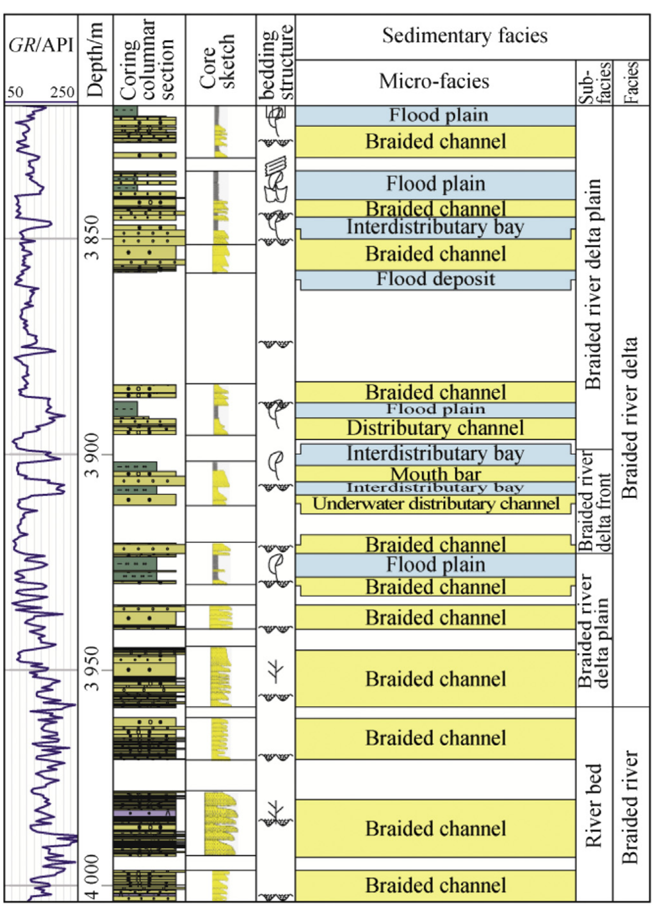

Fig. 2. Composite columnar graph of coring interval of the third member of the Yacheng Fm in Well SS4.

Other wells in Yacheng 13-1 have the same depositional features (Fig. 3-c–e), and the third member of the Yacheng Fm in Well SS5 near Well SS4 has the similar features (Fig. 3-c). The lithology of the lower third member of the Yacheng Fm in Well SS6 (it is to the south of Well SS5) is offwhite sandstones interbedded with grey and dark grey mudstones; then becomes interbedded offwhite sandstones and grey mudstones upward, with clear linsen beddings, vein beddings and wave beddings reflecting tidal action (Fig. 3-g), and worm holes developed very well. All these indicate the deepening of water and the strong affection of tide. Strongly affected by tides, the main coal generation environment in this area is the supratidal zone of tidal flats. The lithology of Lower Yacheng Fm in Well SS7 (it is at the Yanan Low Salient in southern Yanan Sag) is mainly light grey gritstones, interbedded with grey dark thin mudstones; and that of the Upper Yacheng Fm is grey mudstones interbedded with light grey thin packsand, or interbedded layers of them, with various abundance of foram and calcareous nannofossils; the foram is mainly nearshore benthic population, with a major particle diameter of more than 0.125 mm; the early planktonic foram also has higher concentration (30–400 pieces/50 g), with few associated neritic ostracodas and some pollen fossils such as *Granodiscus granulatus*, *Verrucosphaera verrucosa* and Campania, reflecting offshore or confined neritic environments during their depositional period. The source rocks is in the neritic as the main formation environment.

These wells at the periphery of Yanan Sag reflect that the braided river delta deposits in Yacheng 13-1 gas field, which became the tidal flat deposits screened by the barriers in Well SS6, and they were offshore-neritic deposit environments connecting with southern shallow sea in Well SS7. In the Yacheng Fm of Yanan Sag, a set of delta-barrier shore transitional coal-bearing sequence was developed [15], and the source rocks belong to nearshore deposits [16]; Yabei Sag, Songxi Sag and Songdong Sag located in the same secondary tectonic unit have similar features, but the quality of source rocks is related to the existence and scale of deltas in the sags.

Well SS1 is located in the Lingnan Low Salient of southern Central Depression in the deep-water area of the Qiongdongnan Basin. The Yacheng Fm in this well is composed of thick mudstones interbedded with thin limestones, siltstones and packsands as a whole; the lower section has grey mudstones interbedded with reddish brown mudstones, and the upper section has dark grey mudstones, reflecting continuously

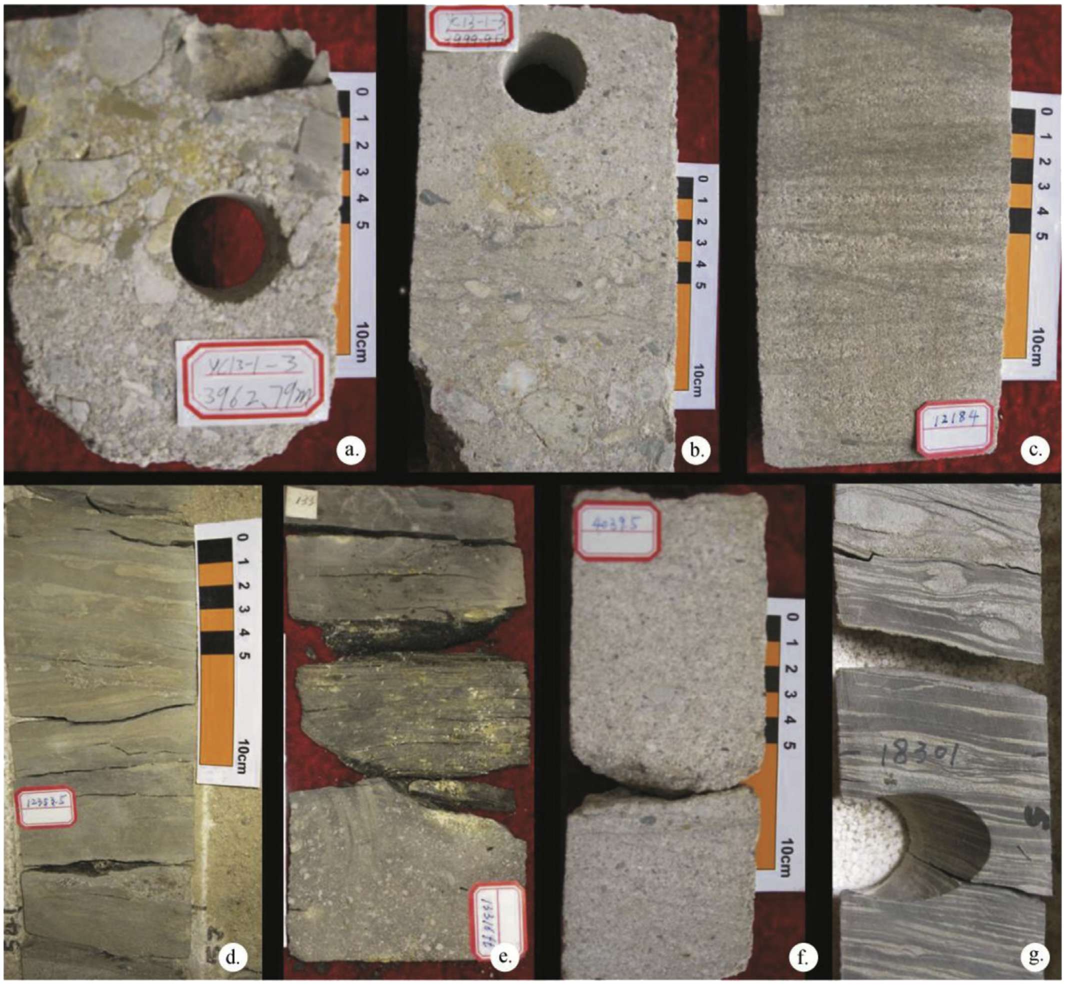

Fig. 3. Typical core photos of peripheral wells of the Yanan Sag. Note: a. scour surface and retention gravel deposits in Well SS4; b. gravel medium-coarse sandstone in Well SS4, positive size grading; c. wedge cross bedding in Well SS8; d. dark grey siltstone in Well SS8, bioturbated structure; e. coal seam in Well SS9; f. festoon cross bedding in Well SS5; g. vein, wave and linsen beddings in Well SS6, worm holes.

deepened water. There are glauconites, pyrites and chlorite grains, with carbonaceous fragments and coal seams in mud loggings. Palaeontologic analysis results are as follows: foram, calcareous nannoplankton and marine dinoflagellate are relatively and continuously distributed. But early abundance and diversity are lower in the early stage, but later they are higher. The major forams are pelagic ones, and their marine dinoflagellate distribution is similar to that in Lingshui Fm-Yinggehai Fm, indicating that early depositional environment is coast plains, and the late one is neritic facies. Well SS3 is located in the central Changchang Sag of the Central Depression. The Yacheng Fm in this well is thick grey−grey dark mudstones, locally interbedded with thin siltstones. Analysis of planktonic algae shows that the content of green algae and globular algae are lower (<10%); but the concentration of marine dinoflagellates that can reflect marine environment is up to 65%, and they are continually distributed, indicating that the Yacheng Fm in this well is typical open marine environment. Hence, we can see from the two typical wells that the Yacheng Fm in the Central Depression of the Qiongdongnan Basin is marine environment, the east part of this depression connected with an ocean and is open marine environment; the source rocks are the neritic mudstones in the central sag and the coal formations in the slope coastal plain and delta.

Horizontally (Fig. 4), during the depositional period of the third member of the Yacheng Fm (Ya-III member), the sea level was lower, and the water was shallower. The major deposits were coarse debris in braided river delta facies at sag borders, and lagoon and shore neritic areas were smaller. At that time, The braided river delta plains are dominated by coal-measure source rocks, and followed by tidal flat coal-measure source rocks, lagoon mudstones and neritic mudstones. However, because of a strong hydrodynamic force, turbulent environment, big slope degree, and coarse grain grade, the coal beds were thinner and were easily branched. During the depositional period of Ya-II member, transgression occurred for the first time, with the water body expanded, and the sedimentary scope enlarged. Braided river deltas were only developed in Yacheng 13-1 gas field area, northeastern Songdong Sag and Baodao Salient, the major deposits at sag periphery were widespread tidal flats and small coastal plains; the main coal generation environments were braided river

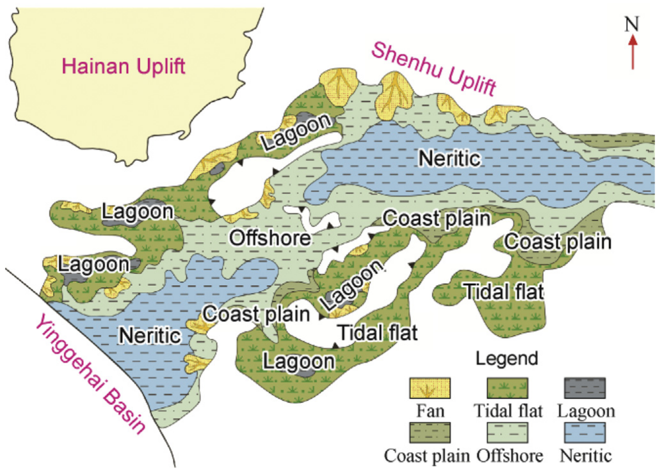

Fig. 4. Planar sedimentary facies of the Yacheng Fm in the Qiongdongnan Basin.

delta plains, tidal flats and coastal plains; the major environments for mudstone source rocks were lagoons and neritics. During the middle period of Ya-I member, transgression occurred for the second time, and regression occurred during the late stage, but the water depth was greater than that of Ya-II member [14]. The environment was relatively stable, with finer lithology and the coal beds mostly interbedded with mudstones, which were favorable for the development of good source rocks. The major developing environments and modes of source rocks are similar to that of Ya-II member.

2.2. The geochemical features of source rocks

There are many indices for evaluating source rock quality like scale, organic matter type, abundance, maturity and hydrocarbon generation and expulsion quantity of sags [17−19]. The evaluation on the Yacheng Fm source rocks of sags in the Qiongdongnan Basin should be conducted in combination with the sedimentary facies belts.

Previous studies have proven that the major source rocks in the Qiongdongnan Basin include two types: transitional facies and marine facies source rocks. The source rocks in transitional facies mainly refer to the coal-measures composed of coal, carbonaceous mudstones and mudstones. Their development is related to delta plain swamps, fluvio-lacustrine swamps and coast plain swamps [13,20−22]. Therefore, the study on the source rocks of such basins should not only consider the scope of the central sag area (just as in the study on source rocks in the deep lake area of a continental lake basin), but also consider more about the effectiveness of marginal facies.

It can be easily seen from the Yacheng Fm thickness map of the Qiongdongnan Basin that the whole Central Depression is wide and thick, indicating that the scale of marine mudstones at that time was wider. A good example is Lingshui Sag which can be divided into Lingshui-20 Subsag and Lingshui-15 Subsag. During the depositional period of the Yacheng Fm, the areas of the two subsags were 2500 and 2260 km^2, and their max thicknesses were 2750 and 3200 m respectively. But the scale of coal-measures should be analyzed in combination with marginal facies of this sag. The scales of Beijiao Sag in South Depression and Yanan Sag in Central Depression are equivalent, with an area of 1400 and 800 km^2, and max thickness of 2150 m and 2300 m respectively during the Yacheng Fm period. But affected by the sufficiency of depositional matter, the scale of good source rocks in Beijiao Sag is smaller than that in Yanan Sag. The source rock of the Yacheng Fm in Huaguang Sag is about 200−1000 m thick, but it has larger area (5000 km^2). The source rock of the Yacheng Fm in Yabei Sag has a wider area, but it is thinner. Songxi Sag and Songdong Sag located in the same structural belt are smaller in area and thickness. However, affected by the organic matter provided by the provenance in the NE direction, the area of coal-measure source rocks is larger in Songdong Sag, which greatly increased the hydrocarbon generation potential.

Based on an analysis of source rocks in the areas surrounding Yanan Sag and adjacent regions, the source rocks in the transitional facies generally have higher organic matter abundance, dominated by humic kerogen (few are humic-prone mixed type), being source rocks with high abundance. Mudstone source rocks in marine facies have lower organic matter abundance, only higher in some local intervals of local areas. Their hydrocarbon generation materials are also humic kerogen that reflects terrestrial input. Organic matter in these two types of source rocks mainly came from terrestrial higher plants, with very little contribution from hydrobiontic algaes [20,23].

In the Yacheng 13-1 gas field province on Yaxi Low Salient to the northwest of Yanan Sag, several sets of braided river delta plain deposits were drilled, with higher organic matter abundance ($TOC > 10\%$) (Fig. 5). No coal beds were found in the Yacheng Fm in Well SS7, with organic matter abundance decreased successively; the max *TOC* in shore-neritic mudstones in Well SS7 is 1.2% (Fig. 5), and rock pyrolysis hydrocarbon generation potential 1.0−5.0 mg/g, which shows that the organic matter abundance is apparently affected by the supply of terrestrial higher plants in fluvial and delta facies. Well SS2 is located in the central Beijiao Sag in the deep-water area. Three thin coal beds (about 6 m thick) were drilled in the Yacheng Fm, and they are transitional tidal flat deposits. As this well is located in the tidal channel, the water was turbulent. It belonged to an oxidization-prone environment with lower organic matter abundance; no coal sample was taken from this well; the *TOC* of mudstones is 0.4%−0.9% (Fig. 5), and the rock pyrolysis hydrocarbon generation potential is mostly 1.0−2.0 mg/g (a few are 2.0−3.0 mg/g). The organic matter abundance of source rocks in marine mudstones revealed by drilling in the deep-water area of this basin is lower. For example, in Well SS3 located in the Changchang Sag of the Central Depression, the *TOC* of the Yacheng Fm source rocks is 0.4%−0.8% (Fig. 5), and the rock pyrolysis hydrocarbon generation potential is about 2.0 mg/g. The *TOC* of neritic mudstones in Well SS1 in the Lingnan Low Salient is 0.33%−1.17% (averagely 0.79%) [8], and the

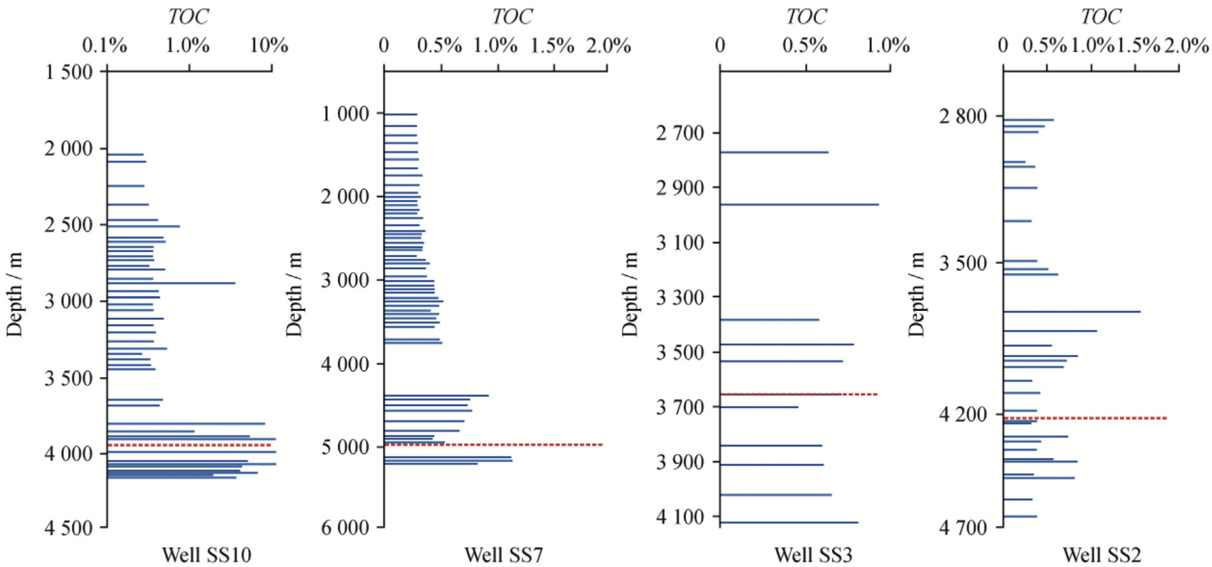

Fig. 5. Contrast of organic matter abundances of source rocks in several wells in the Qiongdongnan Basin (formation below red dash line is the Yacheng Fm).

rock pyrolysis hydrocarbon generation potential is 2.0−4.0 mg/g. The controlling factors and changing regularity of organic matter abundance of such source rocks are similar to those of other basins at outer regions in China offshore areas. For instance, the total max thickness of coal beds in the delta plain in the Eocene Pinghu Fm in Xihu Sag of the Donghai Basin is up to 75.8 m, and the average *TOC* of coal beds is more than 50%; whereas the *TOC* of marine mudstones in the Palaeocene Lingfeng Fm in Lishui Sag is 1.6% [20]. Thin coal beds and carbonaceous mudstones were encountered in Enping Fm on the north slope of Baiyun Sag in the Pearl River Mouth Basin, so it belongs to delta plain deposits, with high organic matter abundance in coal (*TOC* is up to 58.76%) [20]; the neritic mudstone source rocks were encountered in the Enping Fm in the eastern Baiyun Sag, with *TOC* between 1% and 2%. Both the above two groups of data indicate that the coal-measure source rocks in deltas with plentiful depositional matter supply are better than neritic mudstones.

3. Geothermal features of the Qiongdongnan Basin

3.1. Features of present geothermal field and heat flow value

The distribution of present geothermal gradient and heat flow anomaly in this Basin is mainly controlled by the redistribution of shallow heat flow caused by lateral thermal conductivity difference between uplift areas and depression areas and groundwater activities [24]. Actual data and study results show that controlled by extending degree of Cenozoic lithosphere and affected by neotectonism, the crust at continental slopes becomes thinner, usually with higher geothermal gradient, present temperature and terrestrial heat flow value in deep-water areas of the Basin. The average geothermal gradient in wells in the north shallow-water areas is 3.66 ± 0.6 °C/100 m, and that in deep-water areas is 3.91 ± 0.74 °C/100 m, higher than the average geothermal gradient (3.0 °C/100 m) of global sedimentary basins [25]. The maximum present temperature of the Yacheng Fm in Central Depression in deep-water areas is 350 °C, and that in Beijiao Sag and Yanan Sag in shallow-water areas is about 200 °C. The average terrestrial heat flow value in the north shallow-water areas is 66 ± 9.8 mW/m^2, and that in the deep-water areas of continental slopes is 77.5 ± 14.8 mW/m^2 (Fig. 6), 10 mW/m^2 higher than that of the average terrestrial heat flow value (63 ± 24.2 mW/m^2) [26] in the land areas of China.

There are three major reasons for forming "hot basin" in deep-water areas [27]: a. there are different extending degrees of Cenozoic lithosphere, being stronger in the south deep-water areas than in the north shallow water areas; thermal anomaly caused by the extending and thinning of lithosphere led to higher basement heat flow values in the south deep-

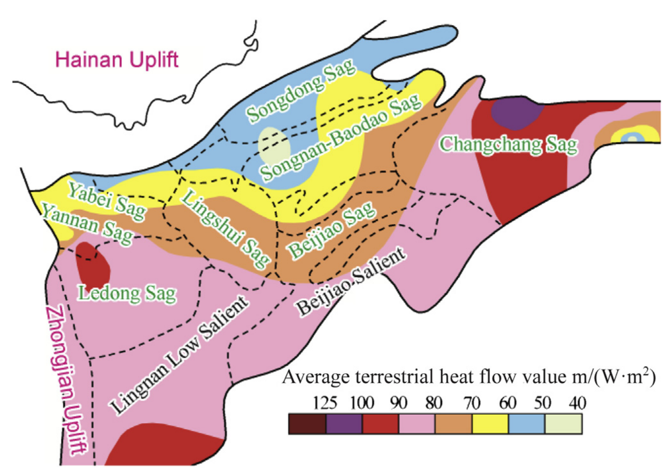

Fig. 6. Distribution of terrestrial heat flow values of the Qiongdongnan Basin.

water areas than that in the north shallow-water areas; b. Neotectonism since the end of Late Miocene - Pliocene led to quickened subsidence of the basin, and deep strong extension generated additional heat flow value and caused thermal anomaly; and c. magmatic activities and fault activities led to high heat flow anomaly in some local areas.

3.2. Influence of heat on source rock maturity

Some factors like geologic time, temperature and thermal action related to source rocks affect the thermal evolution, maturity and hydrocarbon generation of organic matters [28,29]. Apart from promoting the hydrocarbon generation of source rocks, the high geothermal temperature can also speed up the cracking of residual hydrocarbons, making the maximum creacking of the hydrogen-rich organic matters in source rocks to generate natural gas, thus enhancing the hydrocarbon generation efficiency and capacity [20]. Simultaneously, the hot setting not only determines the predominance of gas generation in the deep-water sags, but also can let the shallow-buried source rocks in shallow water be in oil window to generate oil. It can be seen from the fitting results of geothermal modeling of a single well in the Bonaparte Basin in Australian and the maturity of Jurassic source rocks in this well [30] that the maturity has the tendency of becoming higher with the increase of temperature, and that the position with high present heat flow corresponds to the position with high maturity of source rocks, which is also coincident with the major gas generation position of the Basin. Various depressions in the Qiongdongnan Basin have different organic matter thermal evolution degrees of source rocks: the closer to the central depression, the higher the organic matter thermal evolution degree of source rocks is [31]. The R_o values of source rocks in the North Depression are mainly between 0.6% and 2.1%, generating both oil and gas. The R_o values of source rocks in the Central Depression are mainly more than 2.0%, predominantly generating gas. The R_o values of source rocks in the South Depression are mainly between 0.6% and 2.5%, which is similar to that in the North Depression, generating both oil and gas [31,32]. Hence, the thermal evolution history of source rocks has important meanings for the effectiveness of source rocks and hydrocarbon exploration potentials in the Qiongdongnan Basin.

Different tectonic subsidence and buried histories of basins can also lead to different maturity evolution paths. Quick subsidence and burial usually correspond to quick maturity increase and increasing of thermal evolution degree of source rocks. Fig. 7 shows the overlapping graphs of formation coupling burial history with maturity history of source rocks of Line 94216 in the Qiongdongnan Basin. Two artificial well positions are located at the edge and center of the sag respectively. It can be seen that there were two stages of quick subsidence and one stage of slow subsidence in the Yacheng Fm, corresponding to two stages of quick maturity increase and one stage of slow maturity increase processes. Early quick subsidence occurred during 32.0–23.3 Ma, belonging to a quick extension stage of the rift period of this Basin. Though quick maturity increase of source rocks occurred during this stage, thermal evolution degree of source rocks at the sag edge was still very low (just or not entering oil generation window); thermal evolution degree of source rocks in the central sag was lower, but these source rocks could enter gas generation windows during a later period. The second quick subsidence occurred in 5.4 Ma. Affected by tectonic regime transformation of Honghe Faulted Zone, this Basin quickly subsided and received a very thick Yinggehai Fm deposit, leading to quick increasing of thermal evolution degree of source rocks in the Yacheng Fm, and reaching a high-mature-over-mature stage.

4. "Joint control of source rocks and geothermal heat"–exploration potential of the sags in the Qiongdongnan Basin

Oil and gas were formed by joint control of source rocks and geothermal heat. Potential source rocks are the internal cause of oil and gas generation, and heat is the external cause. Both are necessary. The coupling action of them controlled the

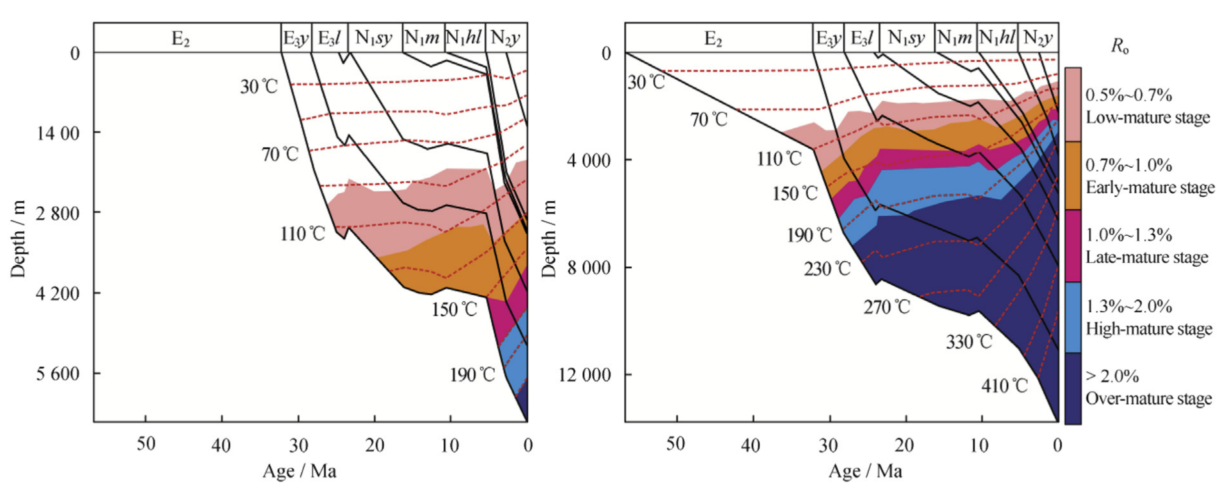

Fig. 7. Overlapping graph of formation burial history and maturity history of source rocks of Line 94216 in the Qiongdongnan Basin.

hydrocarbon generation, generation scale, phase (oil or natural gas) and regional distribution modes of oil and gas in petroleum areas [12].

4.1. Oil and gas discovered

At present, there are three commercial oil and gas discoveries and a series of hydrocarbon-bearing structures in the Qiongdongnan Basin (Fig. 1). The three commercial discoveries are Yacheng 13-1 and Yacheng 13-4 gas fields in the periphery of Yanan Sag, and Lingshui 22-1 gas field in the shallow layer of Lingshui Sag. Yacheng 13-1 gas field has reserves of near 100 billion m^3 [33,34], and its source rocks are the transitional facies coal-measures and mudstones in the Yacheng Fm in Yanan Sag. More than 50 m gas layers were interpreted in the waterways of Yinggehai Fm in Well LS22-1-1, and such gas is high-mature coal-related gas whose source rocks are coal-measures in coast plains and neritic facies mudstones in the Yacheng Fm in Lingshui Sag. Based on a geochemical analysis of natural gas on the north slope of Baodao Sag [35], shallow natural gas in Block 13 of Baodao Sag may be mainly biogas/low-mature gas, with some mature gas. Among them, biogas/low-mature gas came from immature and low-mature Miocene-Oligocene source rocks in the Songdong Sag nearby, and mature gas came from the Baodao Sag. High-mature natural gas was obtained in the 2nd member of Lingshui Fm in Baodao 19-2 structure. Analysis indicates that such gas came from the north slope of Baodao Sag. Furthermore, the discoveries of some small hydrocarbon-bearing structures also directly or indirectly confirmed the hydrocarbon generation capacity of some sags.

4.2. Analysis of exploration potential of each sag

The Yacheng Fm (the major source rock in the Qiongdongnan Basin) has been analyzed in detail from two aspects (“source” and “heat”) in former sections. Based on the theory that hydrocarbon generation is controlled by the coupling of the two factors, we comprehensively evaluate and rank the exploration potentials of 11 major sags in the Qiongdongnan Basin (Table 1 and Fig. 8), so as to provide some guidance and helps for future exploration.

Type-I sags includes Yanan, Lingshui, Baodao, Ledong and Huaguang sags. Yanan Sag has been proven to be a hydrocarbon-rich sag in the Qiongdongnan Basin, with Yacheng 13-1 giant gas field around it. The development of the Yacheng Fm delta provided sufficient organic matters for source rocks; moreover, this sag is deeper and has higher maturity, thus it has the biggest exploration potential. Natural gas generated by high-mature humic source rocks was obtained in the central waterway of shallow Lingshui Sag formation. It is presumed that such natural gas was generated by source rocks of coast plain coal-measures and neritic mudstones, then became mature by high heat flow in this area and migrated to shallow formations. The Lingnan Low Salient in southern Lingshui Sag has huge exploration potential, but near-source accumulation and high-quality reservoirs should be preferentially considered. Baodao Sag has been proven to have the capacity to generate high-quality mature natural gas, which has migrated to and accumulated in the shallow formations of the north slope; however, the Songnan Low Salient south to it has less hydrocarbon accumulation possibility due to the underdevelopment of connecting-source faults between this uplift and the Baodao Sag, thus the exploration highlights in south area of Baodao Sag should be near the source rocks. Ledong Sag only has Yacheng 35-1 gas-bearing structure. Though there is no big exploration breakthrough in this sag, it has big scale, high heat flow value and high maturity, and there are some marine mudstone source rocks in it, so its exploration potential should not be neglected. As the exploration in Huaguang Sag is only conducted recently, there are few seismic and well drilling data, which restricts the geologic understanding of and hydrocarbon exploration in this sag [36]. However, based on a basic research, it is considered to have favorable exploration prospect.

Table 1
Classification of major sags in the Qiongdongnan Basin.

Sag type	Sag name	Sag structure	Source rock feature	HFV/($mW \cdot m^{-2}$)	Hydrocarbon discoveries
I	Yanan	Half graben	Delta coal-measure, Neritic mudstone, Lagoon mudstone	60−80	Yacheng 13-1 and 13-4 gas fields, Yacheng 13-6, Yacheng 19-1, Yacheng 21-1 gas-bearing structures
	Lingshui	Graben	Coast plain coal-measure, Neritic mudstone	60−80	Lingshui 21-1gas field
	Baodao	Graben	Delta coal-measure, Neritic mudstone	60−80	Baodao 19-2, Baodao 13-1, Baodao13-3, Baodao 13-3s, Songtao 24-1 gas-bearing structures
	Ledong	Graben	Neritic mudstone	80−90	Ledong 35-1 gas-bearing structure
	Huaguang	Composite	coal-measure	80−90	No
II	Beijiao	Half graben	Tidal flat-lagoon	70−80	Yongle 19-1 hydrocarbon-bearing structure
	Yabei	Half graben	Tidal flat-lagoon	50−60	Yacheng 7-4 oil-bearing structure
	Songnan	Half graben	Neritic mudstone	50−70	No
	Changchang	Graben	Neritic mudstone	70−100	No
III	Songdong	Half graben	Tidal flat-lagoon	50−60	Forming few biogas and low-mature gas
	Songxi	Half graben	Tidal flat-lagoon	50−60	Songtao 32-2 oil-bearing structure

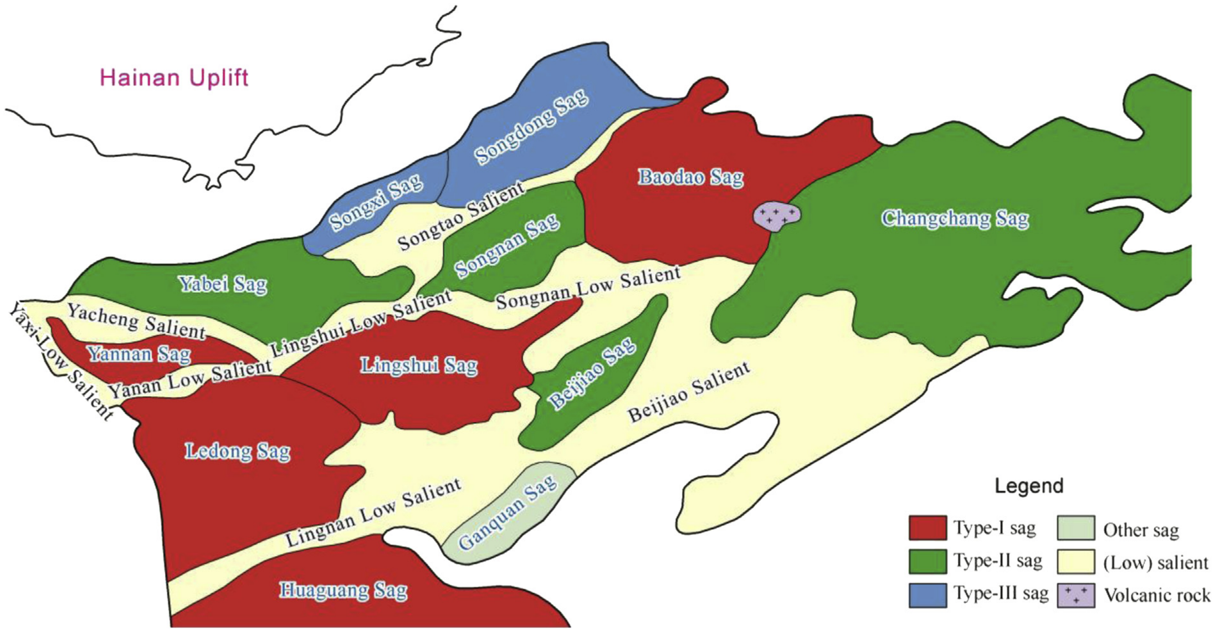

Fig. 8. Classification of major sags in the Qiongdongnan Basin.

Type-II sags include Beijiao, Yabei, Songnan and Changchang sags. Beijiao Sag has similar structures, scales and maturity to Yanan Sag, but lack large-scale deposit source input. Their major source rocks are only coal-measures in tidal-flats with lower organic matter abundance. Their exploration targets should be the areas with good source rocks, near-source accumulation and well-developed reservoirs. There are more wells drilled around Yabei Sag, but there is no commercial discovery. Based on an analysis, the southeast slope may be the most developed area of coal-measure source rocks in tidal flats, with greater potential. At present, no oil and gas show has ever been found in Songnan Sag and Changchang Sag, but these two sags are bigger and buried deeply, especially the near-source drilling on the uplifts in Changchang Sag may possibly obtain breakthrough.

Type-III sags include Songdong and Songxi sags. These two sags are smaller and buried shallowly, with lower heat flow value, hard to form high-mature commercial natural gas, but may form oil accumulation. Moreover, Songdong Sag has sufficient deposit matter supply in the northeast, and better coal-measure source rocks might be formed.

5. Conclusions

1) Two types of source rocks occur in the Yacheng Fm of the Qiongdongnan Basin, namely transitional facies mudstones and neritic facies mudstones. They are both dominated by humic kerogen (few are humic-prone mixed type). Their organic matter abundances are controlled by the amount of continental clastic input. The transitional facies mudstones are commonly higher in organic matter abundance, while the neritic facies mudstones are lower. The transitional facies coal-measure source rocks were mainly formed in such environments as delta plains, coastal plains and barrier tidal flat-marshes.
2) Due to the control of Cenozoic lithosphere extension and the influence of neotectonism, the geothermal gradient, terrestrial heat flow value (HFV) and level of thermal evolution are generally high in deep water. The hot setting not only determines the predominance of gas generation in the deep-water sags, but also can let the shallow-buried source rocks in shallow water be in oil window to generate oil. Apart from promoting the hydrocarbon generation of source rocks, the high geothermal and high heat flow can also speed up the cracking of residual hydrocarbons in the source rocks, and thus enhancing the hydrocarbon generation efficiency and capacity.
3) Based on the theory of joint control of source rocks and geothermal heat on hydrocarbon generation, we evaluate and preliminarily rank the exploration potentials of the 11 major sags in the Qiongdongnan Basin. We believe that the Yanan, Lingshui, Baodao, Ledong and Huaguang sags belong to Type I sag so they have the maximum hydrocarbon exploration potential.

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References

[1] Gong Zaisheng. The major oil and gas fields of China offshore. Beijing: Petroleum Industry Press; 1997. p. 167–72.
[2] Zhang Gongcheng, Mi Lijun, Wu Jingfu, et al. Rises and their plunges: favorable exploration direction for major fields in the deepwater area, Qiongdongnan Basin. China Offshore Oil Gas 2010;22(6):360–8.
[3] Li Ying, Zhang Gongcheng, Lü Dawei, et al. Depositional characteristics and coal forming environment of Yacheng Formation, Qiongdongnan Basin. Coal Geol Explor 2011;39(1):1–5.
[4] Zhu Weilin. Some key geological issues on oil and gas exploration in the northern deepwater area of the South China Sea. Acta Geol Sin 2009;83(8):1059–64.
[5] Tao Weixiang, Zhao Zhigang, He Shibin, et al. Petroleum geological conditions and exploration prospects in deepwater area of Northwestern South China Sea. Geosicientia Sin 2005;26(4):359–64.
[6] Li Xuxuan, Liu Baoming, Zhao Junqing. Paleogene sequence configuration, depositional filling pattern and hydrocarbon- generation potential in Qiongdongnan Basin. China Offshore Oil Gas 2007;19(4):217–23.
[7] Zhang Gongcheng, Mi Lijun, Wu Shiguo, et al. Deepwater area–The new prospecting targets of northern continental margin of South China Sea. Acta Pet Sin 2007;28(2):15–21.
[8] Huang Baojia, Li Xushen, Wang Zhenfeng, et al. Source rock geochemistry and gas potential in the deep-water area, Qiongdongnan Basin. China Offshore Oil Gas 2012;24(4):1–7.
[9] Zhu Weilin, Zhong Kai, Li Youchuan, et al. Characteristics of hydrocarbon accumulation and exploration of the northern South China sea deepwater basins. China Sci Bull 2012;57(20):1833–41.
[10] Zhang Yina, Zhang Gongcheng, Liang Jianshe, et al. Sediment filling and source rock characteristics of oligocene yacheng formation in changchang depression of Qiongdongnan Basin. Mar Geol Front 2012;28(5):8–16.
[11] Zhang Gongcheng, Zhu Weilin, Mi Lijun, et al. The theory of hydrocarbon generation controlled by source rock and heat from circle distribution of outside-oil fields and inside-gas fields in South China Sea. Acta Sedimentol Sin 2010;28(5):987–1005.
[12] Zhang Gongcheng. Co-control of source and heat: the generation and distribution of hydrocarbons controlled by source rocks and heat. Acta Pet Sin 2012;33(5):723–38.
[13] Zhang Gongcheng, Chen Guojun, Zhang Houhe, et al. Regular distribution of inside-oil fields and outside gas fields controlled by source rocks and heat in China offshore basins. Acta Sedimentol Sin 2012;30(1):1–19.
[14] Xie Jinyou, Zhu Youhua, Li Xushen, et al. The cenozoic sea-level changes in Yinggehai-Qiongdongnan Basin, northern South China sea. Mar Orig Pet Geol 2012;17(1):49–58.
[15] Lu Jun, Liu Zhen, Zhang Gongcheng, et al. Seismic facies analysis and filling history reconstruction of small faulted depressions in Northern South China Sea-A historical case on Yacheng formation in yanan depression of the Qiongdongnan Basin. Mar Geol Front 2011;27(7):13–22.
[16] Wang Minfang. A compassion of petroleum accumulation between Ya 13-1structure and Ya 21-1structure in Yanan Depression within Qiongdongnan Basin. Acta Geosci Sin 2002;23(6):559–62.
[17] Chen Jianping, Zhao Changyi, He Zhonghua. Criteria for evaluating the hydrocarbon generating potential of organic matter in coal measures. Petroleum Explor Dev 1997;24(1):1–5.
[18] Lu Shuangfang, Ma Yanling, Cao Ruicheng, et al. Evaluation criteria of high-quality source rocks and its applications: Taking the Wuerxun Sag in Hailaer Basin as an example. Earth Sci–J China Univ Geosciences 2012;37(3):535–42.
[19] Tan Junying, Wang Wenlong, Wang Yanbin, et al. Marine source rock assessment for lower cambrian niutitang formation in middle and upper Yangtze region. Mar Geol Front 2011;27(3):23–7.
[20] Li Youchuan, Deng Yunhua, Zhang Gongcheng. Zoned distribution of source rocks and hydrocarbon offshore China. China Offshore Oil Gas 2012;24(1):6–12.
[21] Li Youchuan, Mi Lijun, Zhang Gongcheng, et al. The formation and distribution of source rocks for deep-water area in the northern of South China Sea. Acta Sedimentol Sin 2011;29(5):970–9.
[22] Deng Yunhua. Analysis on differences of petroleum type and geological conditions between two depression belts in China offshore. Acta Pet Sin 2009;30(1):1–8.
[23] Zhu Weilin, Zhang Gongcheng, Yang Shaokun, et al. Gas geology of continental margin in Northern South China Sea. Beijing: Petroleum Industry Press; 2007. p. 101.
[24] Hu Shengbiao, Zhang Rongyan, Luo Yuhui, et al. Basin thermal history and petroleum potential in Bohai sea. China Offshore Oil Gas (Geology) 2000;14(5):306–13.
[25] Zhu Fangbing. Distinctive characteristics of fluid dynamical field and oil generation in Ying-Qiong Basin. Geol Sci Technol Inf 2003;22(1):76–8.
[26] Hu Shengbiao, He Lijuan, Wang Jiyang. Compilation of heat flow data in the China continental area. Chin J Geophys 2001;44(5):611–26.
[27] Mi Lijun, Yuan Yusong, Zhang Gongcheng, et al. Characteristics and genesis of geothermal field in deep-water area of the Northern South China Sea. Acta Pet Sin 2009;30(1):27–32.
[28] Yang Shuchun, Cai Dongsheng, Feng Xiaojie, et al. Thermal maturation and hydrocarbon generation stages of the pre-tertiary source rocks in south basin, the Southern Yellow Sea. China Offshore Gas Geol 2003;17(6):370–5.
[29] Yang Shuchun, Lu Qingzhi, Song Chuanzhen, et al. Evolution of Mesozoic source rock's organic maturation in Kuqa Foreland Basin and its influence factors. Oil Gas Geol 2005;26(6):770–7.
[30] Duan Wei, Hou Yuguang, He Sheng, et al. Jurassic source rock thermal and maturity history modeling in the Bonaparte Basin of Australia. Geol Sci Technol Inf 2011;30(3):65–71.
[31] Zhang Gongcheng, Miao Shunde, Chen Ying, et al. Distribution of gas enrichment regions controlled by source rocks and geothermal heat in China offshore basins. Nat Gas Ind 2013;33(4):1–17.
[32] Li Wenhao, Zhang Zhihuan, Li Youchuan, et al. Geochemical characteristics and hydrocarbon generation of Paleogene Oligocene source rocks in Qiongdongnan Basin. Nat Gas Geosci 2011;22(4):700–8.
[33] The Writing Group of Petroleum Geology of Continental Shelf and Adjacent Sea Area. Petroleum geology of continental shelf and adjacent sea area (Part 1). In: Petroleum Geology of China, vol. 16. Beijing: Petroleum Industry Press; 1990.
[34] The Writing Group of Petroleum Geology of Continental Shelf and Adjacent Sea Area. Petroleum geology of continental shelf and adjacent sea area (Part 2). In: Petroleum Geology of China, vol. 16. Beijing: Petroleum Industry Press; 1990.
[35] Huang Baojia, Li Li, Huang Heting. Origin and accumulation mechanism of shallow gas in the north Baodao Slope, Qiongdongnan Basin, South China Sea. Petroleum Explor Dev 2012;39(5):530–6.
[36] Yang Taotao, Wu Jingwu, Wang Bin, et al. Structural pattern and sediment filling in Huaguang Sag of Southern Qiongdongnan Basin. Mar Geol Quaternary Geol 2012;32(5):13–8.