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Research article

Natural gas geological characteristics and great discovery of large gas fields in deep-water area of the western South China Sea

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Abstract

To accelerate the petroleum exploration in deep sea of China, since the period of "the 11th Five-Year Plan", the sedimentary process, source rock formation and hydrocarbon generation and expulsion process in deep-water area of the Qiongdongnan Basin in the western South China Sea have been studied systematically using the data like large-area 3D seismic survey, logging, drill core (cuttings) and geochemical analysis, providing three innovative understandings, i.e. excellent hydrocarbon source conditions, good accumulation conditions, and grouping and zonal distribution of large exploration targets. From the study, the following conclusions are drawn. First, the deep-water area located in the southern and central parts of the Qiongdongnan Basin was formed under the control of such tectonic events as Indosinian–Eurasian Plate collision, Himalayan uplifting and South China Sea expansion, and experienced Paleogene lift and Neogene depression stages. Second, accompanied by lacustrine deposition, faulting activity was violent in Eocene; whereas in Early Oligocene, rift continued to develop under a sedimentary environment of marine–terrestrial transitional facies and littoral-neritic facies. Third, oil generation predominated Eocene lacustrine mudstone and gas generation predominated Lower Oligocene marine–terrestrial transitional facies coal-measure strata compose two sets of major source rocks. Fourth, analysis in respect of thermal evolution level, hydrocarbon generation volume and hydrocarbon generation intensity shows that Ledong, Lingshui, Baodao and Changchang sags belong to potential hydrocarbon-rich kitchens, among which Ledong and Lingshui sags have been proved to have great hydrocarbon generation potential by drilling. Fifth, researches of deep-water sedimentology and hydrocarbon accumulation dynamics reveal that Paleogene and Neogene plays are developed vertically, and favorable hydrocarbon accumulation zones like the Central Canyon lithologic trap zone (group), Changchang circum-sag trap zone (group) and southern Baodao fault terrace zone are developed horizontally in the area. Sixth, with its excellent petroleum accumulation conditions and great exploration potential, the Central Canyon lithologic trap zone should be taken as the preferred drilling target, which has been verified correct by the discovery of the Central Canyon Gas Field — the largest gas field in the northern South China Sea.

Keywords: Western South China Sea; Qiongdongnan Basin; Deep-water; Natural gas; Large gas field; Submarine canyon; Play; Exploration area

The global deep sea basins have plentiful hydrocarbon resources, with huge discovered oil and gas reserves. The major hydrocarbon enrichment regions in deep seas are the passive continental margin basins on the two coasts of the Atlantic Ocean (such as the Gulf of Mexico, West Africa, and Brazil), and coasts of Southeast Asia, Australia and East Africa [1–5].

The South China Sea is a tectonic region controlled by several tectonic factors (such as plate collision, and ocean expansion), and is always a hot spot of ocean geological study and hydrocarbon exploration. In northern South China Sea, there are several petroliferous basins, such as the Pearl River Mouth Basin, the Yinggehai Basin and the Qiongdongnan Basin. Its shallow water regions have undergone more than 30 years of exploration, and abundant oil and gas was discovered there [6–11]. However, exploration in its deep-water regions (water depth > 300 m) started later, with

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lower exploration degree. During the past ten years, deep-water exploration in the Qiongdongnan Basin in northwestern South China Sea has been gradually deployed, with 13000 km^2 3D seismic data acquired, several exploratory wells drilled, and gas discoveries obtained. Previous studies indicate that the Qiongdongnan Basin has bigger differences with other oil-rich deep-water basins in the world, with its special geological characteristics [12]. Since the 1990s, oil companies in China and abroad have finished several rounds of studies, but there is still no clear cognition on the basic conditions for oil and gas accumulation. There are several critical problems restricting evaluation and exploration in this basin. First, its source rock types and abundances are not clear. It also has great burial depth (up to 10000 m), unknown evolution degree and unconfirmed resource potential. Second, its shelf region has no large-scale river and delta, thus it is suspected that there is no large reservoir body and fine reservoir bed in its deep-water areas, but there are possibly carbonate reservoir beds. Third, its hydrocarbon migration and accumulation patterns, plays and exploration directions are not clear. Hence, studies were made by using large-area 3D seismic and well data, structural dynamics, seismic sedimentology, sequence stratigraphy, and hydrocarbon-rock geochemical correlation to analyze the petroleum system, accumulation factors and association. Through these studies, it is confirmed that the coal-measure mudstones are fine source rocks, with well-developed turbidite channels sand reservoirs, and confirmed structural-lithological trap groups. These results have resolved the critical problems of hydrocarbon accumulation, directed drillings, made large gas field discovery and exploration breakthroughs possible, and indicated huge hydrocarbon exploration potentials in deep-water regions.

1. Geologic setting

1.1. Tectonic division

The Qiongdongnan Basin is a Cenozoic epicontinental extension basin, located in a NE striking extensional rifting belt at the northwestern epicontinental margin of the South China Sea. This basin has a tectonic feature of “SN zoning in belts & EW zoning in blocks”. It mainly includes the following three primary tectonic units: the Northern Depression Belt, the Middle Depression Belt and the Southern Uplift Belt.

The deep-water regions are mainly located in the Middle Depression Belt and the South Uplift Belt, with water depth of 300–3000 m, covering an area of about 53000 km^2 in the deep-water basin. From west to east, they mainly consist of the Ledong, Lingshui, Beijiao, Songnan, Baodao and Changchang Sags, and two low bulges (Fig. 1). Except for the Beijiao and Songnan Sags, the other four sags have areas of 4000–8000 km^2, with a total area of around 30000 km^2. The maximum deposit thickness of the Cenozoic era is more than 12000 m, with two-layer structures (lower fault and upper depression).

1.2. Formation and deposit

According to biostratigraphic and petrologic data in dozens of wells in shallow water regions and several wells in deep-water regions in the Qiongdongnan Basin, combined with seismic data interpretation and well correlation, the complete formation distribution in Eocene–Quaternary in deep-water regions can be revealed (Fig. 1).

There are no wells with oil/gas drilled in Eocene series. However, by use of seismic data correlation, it is supposed that there is medium–deep lacustrine sedimentation in several separated individual fault sags.

There are transitional facies – neritic facies in the Yacheng Fm in lower Oligocene, basically in continuous distribution. In local regions, there are semi-closed lagoons, with coast plains or fan deltas in sag edges or low bulges.

The upper Oligocene Lingshui Fm is mainly neritic deposit, with deeper water body (mostly outer neritic setting) and fan deltas developed in some regions.

The Neogene Miocene consists of lower Miocene (Sanya Fm), middle Miocene (Meishan Fm) and upper Miocene (Huangliu Fm). During this period, marine transgressive scope gradually expanded to the whole basin, mainly in a neritic-bathyal setting. Typical shelf–slope system developed in the northern region of this basin, with deep-water slope deposit. The Central Canyon that was approximately parallel to the slope break belt in the Middle Depression Belt was at its peak development, with widely distributed turbidite channel sandstone and mass flow.

During Pliocene–Quaternary (Yinggehai Fm – Quaternary), the slope in the northern basin continued to advance to sea direction. The setting then was bathyal, with large-scale submarine fans developed in the middle basin.

1.3. Tectonic evolution

1.3.1. Plate tectonic environment and deep structure

During the Mesozoic Era, the Qiongdongnan Basin was in the South China continental margin. During the early Tertiary, initial rifting of this basin occurred in Eocene, with intracontinental rifts developed. During the early Oligocene, the Indosinian–Eurasian plates collided violently, and the Qinghai–Tibetan Plateau and the Himalayas were uplifted. Influenced by extrusion effect, the Qiongdongnan Basin subsided intensively, forming several rifts [13]. Physical modeling experiments show that the Honghe Fault rifting enhanced the extension and subsidence of the western region of this basin, which influenced the southward extension of the Ledong Sag. Until the end of the Oligocene, the rifting activity diminished, with no large faults developed, then it entered post-rift sag stage, and successively subsided. The north continental slope was formed, becoming deep-water basin in the Middle Depression Belt.

In the Qiongdongnan Basin, the Moho reflection is basically continuous, and the burial depths of the Moho surface are generally between 15 and 20 km, with a feature of being deeper in the west and shallower in the east, roughly being a

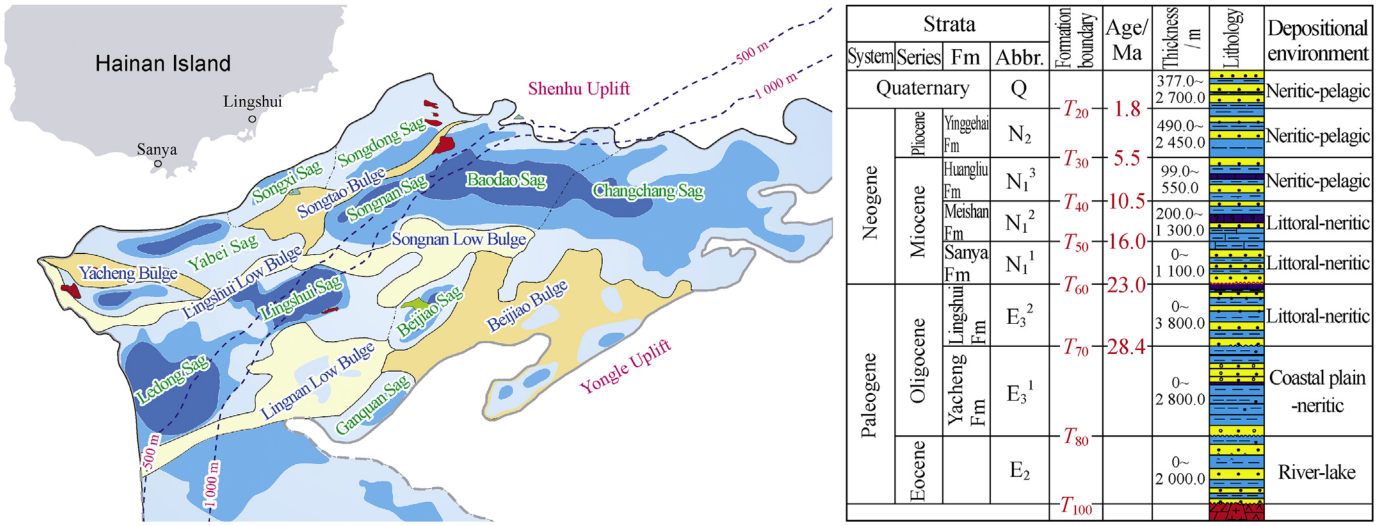

Fig. 1. Tectonic units and chronostratigraphic graph of the Qiongdongnan Basin (Modified from Ref. [12]).

mirror image of the water depth. The burial depths of the Moho surface became deeper quickly from the Middle Depression to the two sides. Thus, it can be seen that, during the Cenozoic era, violent thinning occurred in the Middle Depression within a narrower scope. The eastern Moho surface is much close to the basement (the min thickness at the thinnest region is about 1.2 km), the Xisha ocean trough in the Changchang Sag is supposed to be much thinning, and the basement might have started to become ocean crust. This area and the Xisha ocean trough development have a vertical overlapping relationship with the expansion of the South China Sea basins [14] (Fig. 2).

1.3.2. Faulting activity and the formation of the deep-water basins

The northern depression belt of the Qiongdongnan Basin in the shallow water region extended and cracked in a relatively cooler lithospheric environment, forming a single faulted rifting belt mainly with a half-graben style, and a smaller individual sag. Whereas, the Middle Depression Belt extended

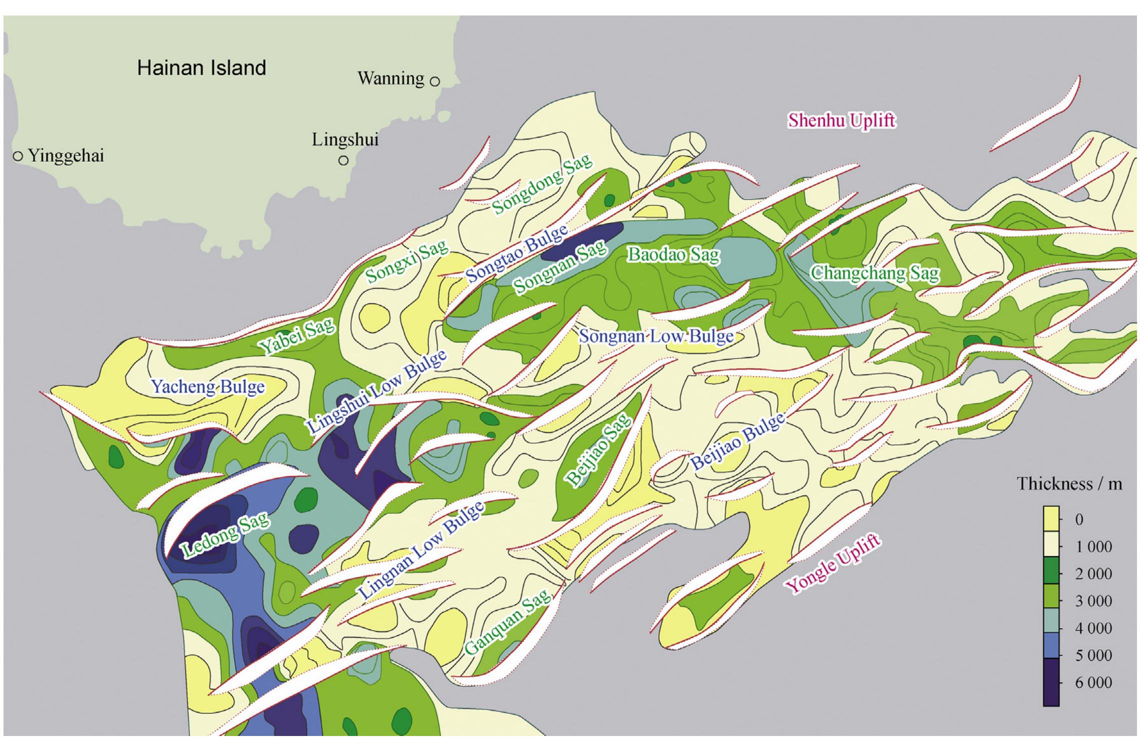

Fig. 2. Tectonic framework of the Qiongdongnan Basin during the Eocene−Oligocene transition.

and rifted in a relatively hotter lithospheric environment, forming a composite rifting belt composed of half-grabens and grabens (Fig. 3), with a bigger individual sag.

This area mainly has four sets of faults (NNE, NE, near EW, and NW−NWW). The sag shapes and spatial distribution of the faults in this basin have certain regularities: changing from mainly NE striking to nearly EW striking from its west to east. The major stress direction of this basin underwent three stages: the major stress direction of T_{100}−T_{80} (45−36 Ma) was SSE striking; that of T_{70} (30 Ma) changed to be nearly N−S striking in clockwise; the extensional stress direction of T_{60} (21 Ma) was SE striking.

During the early rifting stage, the faults (intracontinental rifts) were mainly in NNE and NE striking directions, such as the faults in southern Lingshui Sag and southern Beijiao Sag etc (Fig. 2). During early Oligocene, the faults were mainly in EW striking, such as the southern Baodao Sag. During the late Oligocene, the faults were mainly in NWW striking, such as the western Changchang Sag. In the western region, the NE striking direction of the early rift continued to present. But in the eastern region, most of the sags show strong overlapping and reworked feature of the early NE striking rift by later near EW striking rift.

The No.2 Fault is an important controlling boundary in the northern deep-water region below present shelf slope break belt (Fig. 3). Its activity rate during T_{100}−T_{80} was smaller; it was bigger and stable during the rifting stage T_{80}−T_{70} (generally 150−250 m/Ma); and it was the biggest during T_{70}−T_{60}. During T_{62}−T_{61}, the activity rate was bigger in middle of this fault, and gradually decreased to its two sides. After the end of Oligocene, its activity rate became weaker.

According to paleontologic stratigraphy analysis of drilled wells, the deposit of the deep-water continental slope occurred after middle Miocene (10 Ma), then there were deposit slope break, while previous structures were controlled by the hidden No. 2 Fault or flexural slope break. From west to east, the continental slope forms are progradation, accretion and gentle slope respectively, and these forms were controlled by tectonic basement, faulting activity and provenance supply, leading to different types and diversities.

The development of the shelf slope break has a feature of being "earlier in the east and later in the west, sectionalized development, and finally unified". The diversity of the faulting activity controlled the types and deadline of the tectonic slope break belt during the rifting stage in Paleogene. Tectonic subsidence controlled the location and time where and when the prograding shelf slope break began to develop during the accelerated subsiding stage in Neogene. Deposit deliverability controlled the overlapping types of the sedimentary sequences in shelf slope break. The formation of the eastern deep-water region had close relationship with the formation of the Xisha ocean trough. Following the expansion of the western and northern ocean basins in South China Sea, and the violent extending and thinning of the Earth crust, the region with the biggest water depth was formed.

2. Natural gas accumulation conditions and petroleum system

2.1. Source rocks and hydrocarbon-rich sags

2.1.1. Three sets of source rocks

There are three types of source rocks in Paleogene in the Qiongdongnan Basin, i.e. lacustrine mudstone in Eocene, coal-measure strata in marine−terrestrial transitional facies in lower Oligocene, and marine mudstone in Oligocene. Specifically, the lacustrine mudstone in Eocene has not been drilled. According to shallow water hydrocarbon analysis and seismic data, it is supposed to be potential source rock. Another two sets of source rocks have been drilled, and the coal-measure source rock has been proved by gas−source correlation [15,16].

The coal-measure source rock in the Oligocene Yacheng Fm is the major source rock in the deep-water region, mainly filled with near-shore higher plants. The regions at the sag edge platform near provenances and the areas above slope break in the gentle slope belt are favorable for coal forming, being favorable regions for sedimentary. The source rock in the Yacheng Fm is widely distributed, with big deposit thickness difference, mainly in coast plain facies in low bulges. The coal-measure strata in the first member of the Yacheng Fm are chiefly distributed in coast plain facies and some littoral areas in southern Lingshui Sag near the Lingnan Low Bulge, with deposit thickness of 60−120 m. Some thicker coal-measure strata are also developed in the lagoon area in southern Lingnan Low Bulge (120−150 m). In

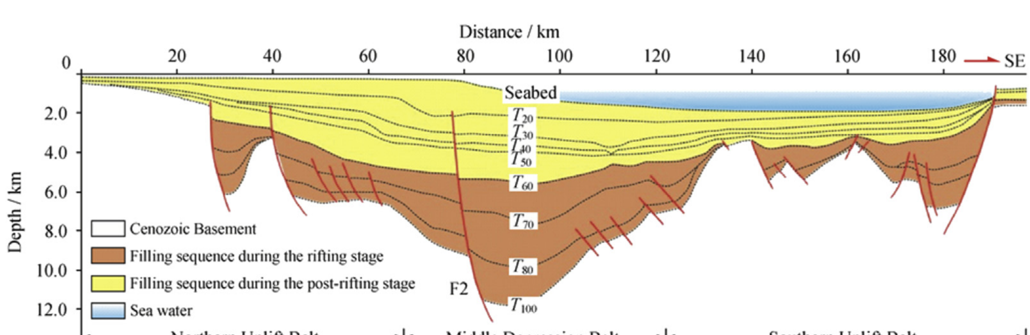

Fig. 3. Geologic profile of the deep-water area in the Qiongdongnan Basin.

Songnan−Baodao sags, these coal-measure strata are principally distributed in the region in coast plain facies near the Songnan Low Bulge, and the transition zone between the Songnan Low Bulge and the Beijiao Sag. In the Lingnan Low Bulge, the Songnan Low Bulge and the Beijiao Sag, drilled wells prove the wide development of the Yacheng Fm (Fig. 4).

The coal-measure strata drilled in Well YL-1 prove the existence of the Yacheng Fm source rocks in deep-water regions. In Well YL-1, three sets of thin coal layers were found in the first member of the Yacheng Fm whose setting was mainly coast plain facies. *TOC* values in coal layers in the first member of the Yacheng Fm are 15%−20%, and average *TOC* values in mudstone are more than 1%, being fine source rocks. Coal-bearing mudstone is 96 m thick. They show a feature of medium−strong amplitudes, relatively continuous − continuous reflections.

The muddy source rock in the Lingshui Fm is mainly filled with mudstone in neritic facies. Most of the samples have *TOC* values of less than 1.0%, only a few >1.5%, and most of the samples have hydrocarbon generation potential ($S_1 + S_2$) between 0.5 and 5.0 mg/g, belonging to ordinary source rocks. However, they are bigger and wider, which could compensate the disadvantage of low organic matter content, thus they still have some hydrocarbon generation potentials.

2.1.2. Source-rock maturity and gas potential

The thermal maturity (R_o) values of the Paleogene source rocks are all up to or over high mature stage, mainly generating gas. The maturity values of the Yacheng Fm are generally higher, more than 4.0% in the sag centers in the second and third members of the Yacheng Fm, thus their hydrocarbon generation potentials have been exhausted. The maturity values of the Oligocene Lingshui Fm in the western Qiongdongnan Basin are more than 1.5%, mainly generating gas.

The maturity of source rocks has tight relationship with the "high thermal" feature of the deep-water basin. Analysis of the thermal gradient values of five wells show that the thermal gradient values in deep-water regions have a feature of continuous increasing from west to east within 4.35−5.05 °C/100 m.

By recovering stratigraphic burial history and geothermal history in sags, we found that the source rocks entered oil generation threshold and gas generation threshold during earlier periods, starting from the first member of the Yacheng Fm and the second member of the Lingshui Fm, respectively, and sequentially lagging from the Ledong Sag to the Changchang Sag. The Beijiao Sag was the latest one (to generate oil during the Sanya Fm, and to generate gas during the Meishan Fm). The hydrocarbon generation thresholds in the middle Lingshui, Songnan and Baodao sags are similar.

Based on the basin modeling results by the IES PetroMod software, plentiful natural gas resources were discovered in deep-water regions, with a total natural gas resource potential of 3.5×10^{12} m^3. According to an analysis of hydrocarbon supply direction, except for the hydrocarbons migrating to shallow water regions, the natural gas resources in deep-water regions are about 2.5×10^{12} m^3.

On the basis of source rock distribution scope (e.g. area and volume), thermal evolution degree and hydrocarbon generation scale, by comparing various hydrocarbon generation sags in deep-water regions, we preferred the Lingshui Sag as the richest hydrocarbon generation sag, the secondary ones are Ledong, Baodao and Changchang sags. The Lingshui Sag should be the optimum target for drilling and discovering oil and gas.

2.2. Reservoir beds

As the deep-water regions in the Qiongdongnan Basin are far away from the northern shelf provenance, and the southern

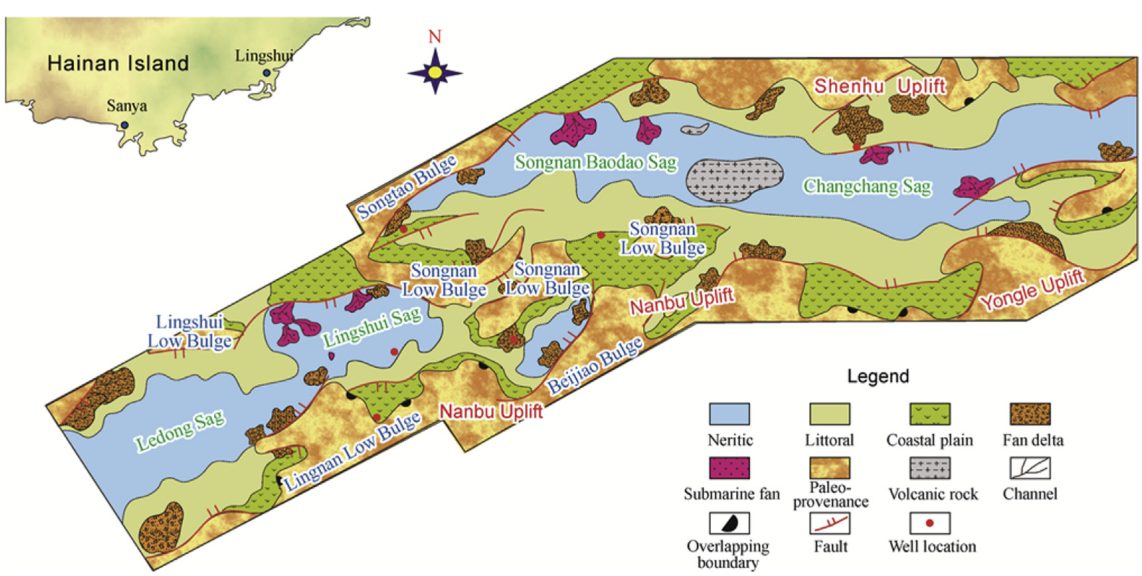

Fig. 4. Plane distribution map of the deposit system of Yacheng Fm in the Qiongdongnan Basin.

uplifting region fundamentally submerged below sea level, lack of large-scale provenance input, the major reservoir beds are distal turbidite sandstones formed by gravity current. Turbidite channel sandstones and submarine fans are the major reservoir beds [17].

Combined with the analysis of sedimentary facies and drilling results, we found that reservoir beds in deep-water regions include (from upper to lower): (1) turbidite sandstone reservoir bed in the Central Canyon in the Miocene Huangliu Fm; (2) basin floor fan in the Miocene Sanya Fm; (3) turbidite channel and low-level fan in the Lingshui Fm (Fig. 5).

2.2.1. Turbidite sandstone reservoir bed in the Central Canyon in the Huangliu Fm

The Central Canyon underwent three development stages (down-cutting in the early stage, stable filling in the middle stage, and mass flow cutting in the late stage), with hydrodynamic variation from stronger to weaker [18]. In the west−middle section of this canyon, sandstone deposits in gravity flow channel are widely developed: there are six vertical overlapped sand groups in the Huangliu Fm in the Central Canyon in Ledong, Lingshui and Songnan sags. During later stages, they were all eroded by muddy channels, distributed on the two sides of the Central Canyon in podiform (Fig. 6), forming a fine reservoir−caprock assemblage.

The small burial depth (2000−2500 m below seabed) is favorable for pore and permeability preservation. The turbidite channel sandstones are separated by several sand bodies, continuously distributed on the two sides of the canyon. The area of single sand body is between 15 and 40 km^2, and their thickness is between 10 and 35 m. The turbidite channel sandstones in the Huangliu Fm in the Central Canyon have been confirmed to be the best reservoir beds.

2.2.2. Submarine fans in late Oligocene and Miocene

By applying some reservoir prediction methods (such as 3D seismic data interpretation and attribute analysis, wave impedance inversion, time-frequency analysis), we predicted that submarine fan reservoir beds are developed in all the sags in deep-water regions [19]. Many submarine fans can be identified in the Neogene system (taking the Changchang Sag and the Songnan Sag as examples), and some of them have been revealed by drilling. Drilling in Well CC-1 proved that sandstones are well developed in the second member of the Lingshui Fm, with sand/layer ratio of 45% and better developed reservoir beds. It is one type of good reservoir beds drilled at present: the turbidite channel sandstones in neritic deposit environment.

The submarine fan in the second member of the Sanya Fm in the Songnan Sag is developed on the Songnan Low Bulge. It is composed of three lobate bodies in high amplitude and mounded reflection, retrograding southwards sequentially. The submarine fan reservoir bed was encountered in the first member of the Sanya Fm in the depth of 3499−3631.5 m of Well YL-2, with the total sand thickness of 77 m, the ratio between sandstone and stratum thickness of 58%, and the maximum single sand layer thickness of 4.5 m.

2.3. Migration features

The analysis of success and failure of several exploratory wells in the deep-water regions indicates that the main reason for the failed wells is the lack of fine sandstone reservoir bed and the difficulty in long lateral migration (>30 km). For instance, the upper Yacheng Fm/Lingshui Fm to Quaternary in the Lingnan Low Bulge are thick mudstones, lack of reservoir beds, thus hydrocarbons in the Lingshui Sag could not migrate to the south in lateral direction in the low bulge area.

The advantage lies in that the overall faulting activity in middle-frank areas of the sag in deep-water regions were stronger, then faults and fractured belts could act as the major pathways for lateral hydrocarbon migration. During the Lingshui period in deep-water regions, the faults were universally active, but gradually ceased until the end of T_{40}. In particular, the eastern Baodao−Changchang sags have dense faults developed, and most of these faults reach the Yacheng Fm (even the Eocene source rocks), thus they can connect the effective source rocks, then hydrocarbons could migrate in the vertical direction.

By combining the sandstone conducting conditions and vertical conducting conditions in deep-water regions, we think that hydrocarbons mainly migrated directly in a vertical direction, or migrated within a short distance and in vertical and lateral directions, and hydrocarbon accumulation areas are also distributed inside sags and the bulge edges near sags.

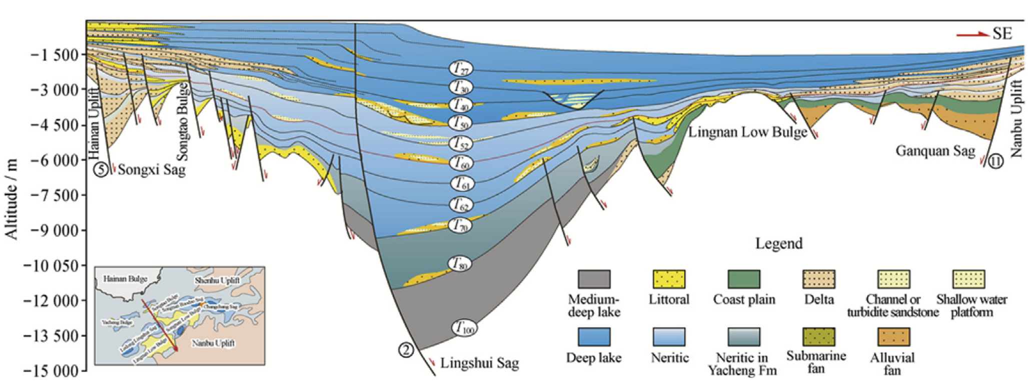

Fig. 5. Favorable reservoir−caprock assemblage in deep-water regions in the Qiongdongnan Basin.

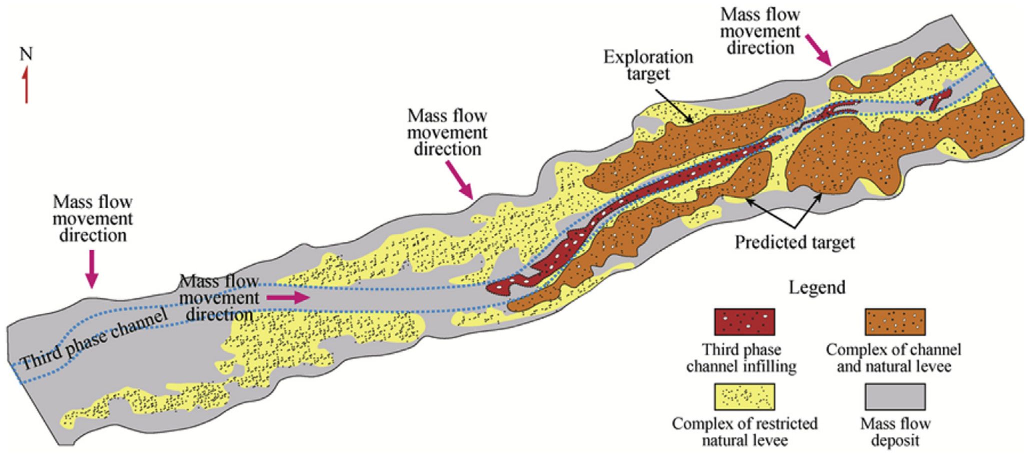

Fig. 6. Infilling scheme map of the Lingshui Sag in the Central Canyon of the Qiongdongnan Basin.

2.4. Trap conditions

During the rifting stage, because of the strong normal faulting activity, in the low bulge background or in the fault terrace development belts of boundary faults, several faults are generally distributed in nearly parallel or en echelon style, forming a series of bulge drape anticlines complicated by anticline, faulted anticline, faulted block and fault (mainly in faulted anticline), such as the fault terrace belt around the Changchang Sag, southern fault terrace belt in the Baodao Sag, and faulted anticline belt in the Songnan low bulge. Their trap scales are commonly moderate, with area between 20 and 100 km^2 (few are between 150 and 200 km^2). Moreover, poly-phase traps in the Lingshui Fm, or the traps in the Lingshui Fm and the Yacheng Fm are developed congruently. The Lingshui Fm (T_{62}) has the most traps, and the Yacheng Fm takes the second place. Most of the traps are several faulted anticlines or faulted blocks complicated or separated by faults, forming a large trap.

During the post rift stage in early Miocene, the faulting activity gradually diminished, with small fault displacements and few fault-related structures. However, the development of submarine fans and turbidite channel sandstones formed lithological and structural-lithological composite traps. Such traps mainly include the structural-lithological trap belt in the Huangliu Fm in the western–middle section of the Central Canyon, the submarine fan trap belt in the Meishan Fm at northern Lingshui slope, and the submarine fan trap belt in the Sanya Fm in the middle Changchang Sag.

2.5. Two sets of plays

By integrating major reservoir–caprock assemblage measures, trap types and favorable hydrocarbon migration and accumulation areas, we divide the plays in this basin into two sets (Paleogene and Neogene). The Paleogene plays mainly refer to the Lingshui (Yacheng is the next) reservoir beds and traps and their reservoir beds are principally submarine fans, and channel sandstones or littoral sand bar in some local regions (Fig. 7). The Neogene plays mainly refer to the Miocene (Pliocene Yacheng is the next) reservoir beds and traps and their reservoir beds are mainly turbidite channel sandstones and submarine fans.

The Neogene play is predominantly lithological traps whose scales have big differences depending upon sand bodies or fan sizes; the secondary traps are structural-lithological composite ones. The major hydrocarbon migration pathways are small faults and microfractures. Generally, there is less fault reconstruction, thus a unified hydrocarbon reservoir could be formed. Though certain single turbidite channel sandstone was smaller (20–30 km^2), multilayer overlapping hydrocarbon accumulation increased hydrocarbon enrichment.

The Paleogene play is fundamentally structural traps (such as faulted anticline and faulted block), usually with bigger scales. Because this play is separated by faults, several independent hydrocarbon reservoirs might be formed. The major hydrocarbon migration pathways are big faults. Various layers have various burial depths. The predicted physical properties of the Neogene reservoir beds are better.

Favorable hydrocarbon accumulation regions were predicted according to the above results, and three major exploration belts in the deep-water regions were confirmed: the Central Canyon trap belt (group) (mainly the Huangliu Fm), the faulted terrace belt in southern Baodao Sag (the Lingshui Fm), trap belt around the Changchang Sag (Lingshui Fm and Sanya Fm). Their total natural gas resources are more than 1 tcm. Hereinto, the Ledong–Lingshui section in the Central Canyon trap belt is located in a hydrocarbon-rich sag, with sufficient hydrocarbon sources and well-developed turbidite channel sandstones. There are many structural-lithological composite traps, with good vertical migration and accumulation conditions and large exploration potential, thus they were evaluated to be the optimum favorable drilling regions.

3. Discovery of large gas fields and gas reservoir characteristics in the Central Canyon

In 2010, the first exploratory well of more than 1000 m deep was drilled in the western area of the Central Canyon in

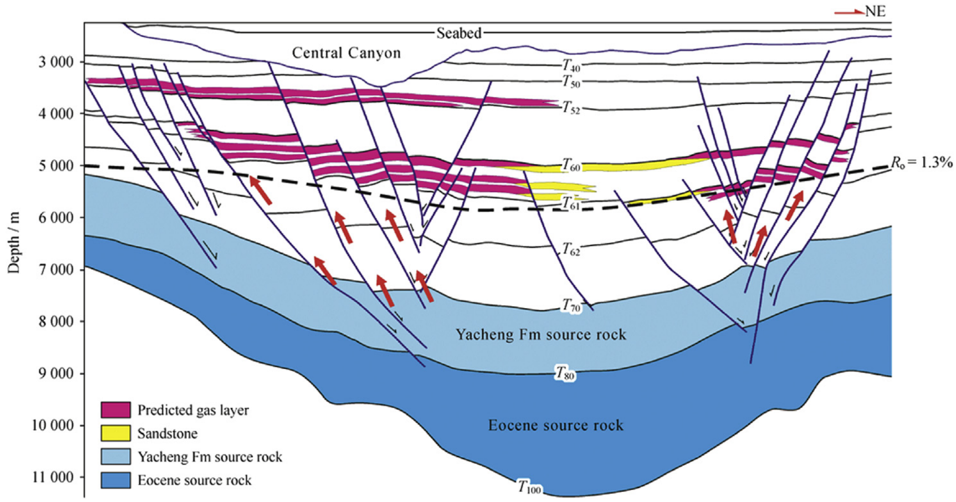

Fig. 7. The Paleogene play in the Changchang Sag in the Qiongdongnan Basin.

the Qiongdongnan Basin, with the first small natural gas discovery obtained, initially proving the petroleum system in the Lingshui Sag in the deep-water region. During 2011–2012, 3D seismic data acquisition area was expanded, the whole Central Canyon was evaluated, and an exploration deployment plan was made. In 2014, CNOOC adopted the self-developed "Offshore Oil 981" deep-water drilling rig to continuously drill seven wells in the western area of the Central Canyon, and all these wells succeeded, discovering the Lingshui A large gas field [20]. This is the first commercial large gas field discovered in the deep-water region of the western South China Sea, with proved geologic gas reserves up to 2000×10^8 m^3. This also proved that the Lingshui Sag is an effective petroleum system. This is a gas pool group consisting of several adjacent and independent gas pools.

3.1. Trap features

Lingshui A structure is located in the Central Canyon in the northern Lingshui Low Bulge in the Qiongdongnan Basin. It is a structural-lithological trap composed of the Yinggehai Fm in this canyon, mainly developing two sets (I and II) of turbidite channel sandstones. The sand layers show low frequency, continuous and strong refection feature on seismic sections (Fig. 8). Among them, sand layer I was separated to seven blocks by later muddy channels, and several sand bodies individually form lithological traps, with anticline trap shape in local zones.

3.2. Natural gas source

Gas mud logging in Well LS-AW-1 shows high methane content, very low heavy hydrocarbon content, very dry components, and $C_1/(C_1-C_5)$ of 0.97–0.98. According to natural gas isotope analysis, its $\delta^{13}C_1$ is −39.4‰ to −38.8‰, belonging to high maturity humic gas, similar to the YC13-1 gas field, sourced from the deep Yacheng Fm with high maturity.

3.3. Reservoir beds

The reservoir beds in the canyon can be subdivided into five sets, separated by mudstones in bathyal-abysmal facies, and forming fine reservoir–caprock assemblage. They can be classified into two stages: Huangliu Fm and Yinggehai Fm. There are 3–4 layers of turbidite channel sandstones in the middle–lower Huangliu Fm. The Yinggehai Fm is a set of submarine fan reservoir beds developed during the later period of the canyon infilling. The sand bodies are overlapped in vertical direction. The thicknesses of the reservoir beds are generally between 15 and 30 m, and the maximum thickness of a single layer is up to 70 m. The channel sandstones in the Huangliu Fm are mainly fine sandstones. The submarine fans in the Yinggehai Fm are mainly siltstones, interbedded with thin fine sandstones.

The burial depths of sandstones are between 2900 and 3600 m (2000–2300 m after subtracting water depth). The physical properties are generally fine, with porosity >25%, permeability between dozens to hundreds of millidarcy. In contrast to the upper and lower surrounding mudstones, these sandstones have apparent different features of low velocity and low density. Several sets of reservoir–caprock assemblages provided conditions for forming several oil and gas layers.

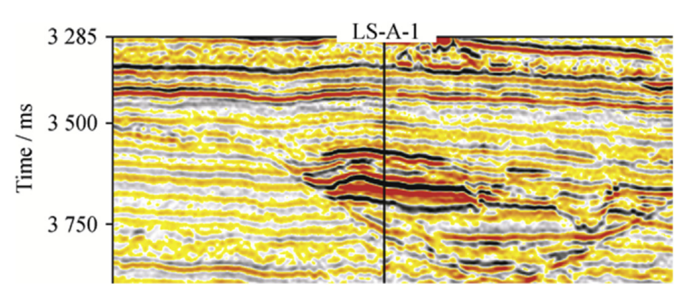

Fig. 8. Seismic section through Well LS-A-1 in the Central Canyon.

3.4. Migration, accumulation and gas–water system

There are no apparent faults in the Lingshui A gas field and its surrounding areas. Most of the layers around the southern Lingshui in the Central Canyon are Miocene thick mudstone formations in neritic facies. Several fuzzy regions in banded shape in vertical direction were found in southern Lingshui in T_{30} sand body, with a feature of low velocity. The lower formations have obvious pull-down characteristics. They connect the deep source rocks and shallow traps in vertical direction.

The source rock of the Yacheng Fm in the Lingshui Sag entered gas generation and expulsion peaks from the Yinggehai Fm period to present, and this structure was finalized during the early period of the first member of the Yinggehai Fm. Therefore, there was better collocation between trap formation time and hydrocarbon migration time. Natural gas was accumulated by vertical migration. During the later period, its preservation condition was fine, and gas pools were not destroyed. In lateral direction, several sand bodies accumulated hydrocarbons individually, with various gas-water systems (Fig. 9). In vertical direction, one gas pool may contain several gas-bearing sand layers, with various gas-water contacts, and forming overlapped multi-layer gas pools.

4. Conclusions

1) Himalayan uplifting and South China Sea expansion commonly controlled the formation and evolution of the Qiongdongnan Basin. The overlapping of the rifting period during the Eocene Epoch and later faulted depression period during the Oligocene Epoch led to the feature of "zoning in SN direction, blocking in EW direction" and its distribution feature in its east and west regions of this basin. During Neogene Epoch, it was mainly post-rift depression, with no more faults developed, but with strong subsidence (especially in the eastern basin).
2) Since 10 Ma, the deep-water basin was developed along with the Earth crust extension and violent subsidence. The northern continental slope was formed above the Paleogene hidden faults. Bathyal formations were deposited widely in the central basin. From west to east, the continental slope forms are progradation, accretion and gentle slope, respectively, which are controlled by tectonic basement, faulting activity and provenance supply etc., leading to different types and diversities.
3) In respect of source rock types and features, there are three sets of source rocks (lacustrine mudstones, coal-measure strata and marine mudstones) in the deep-water

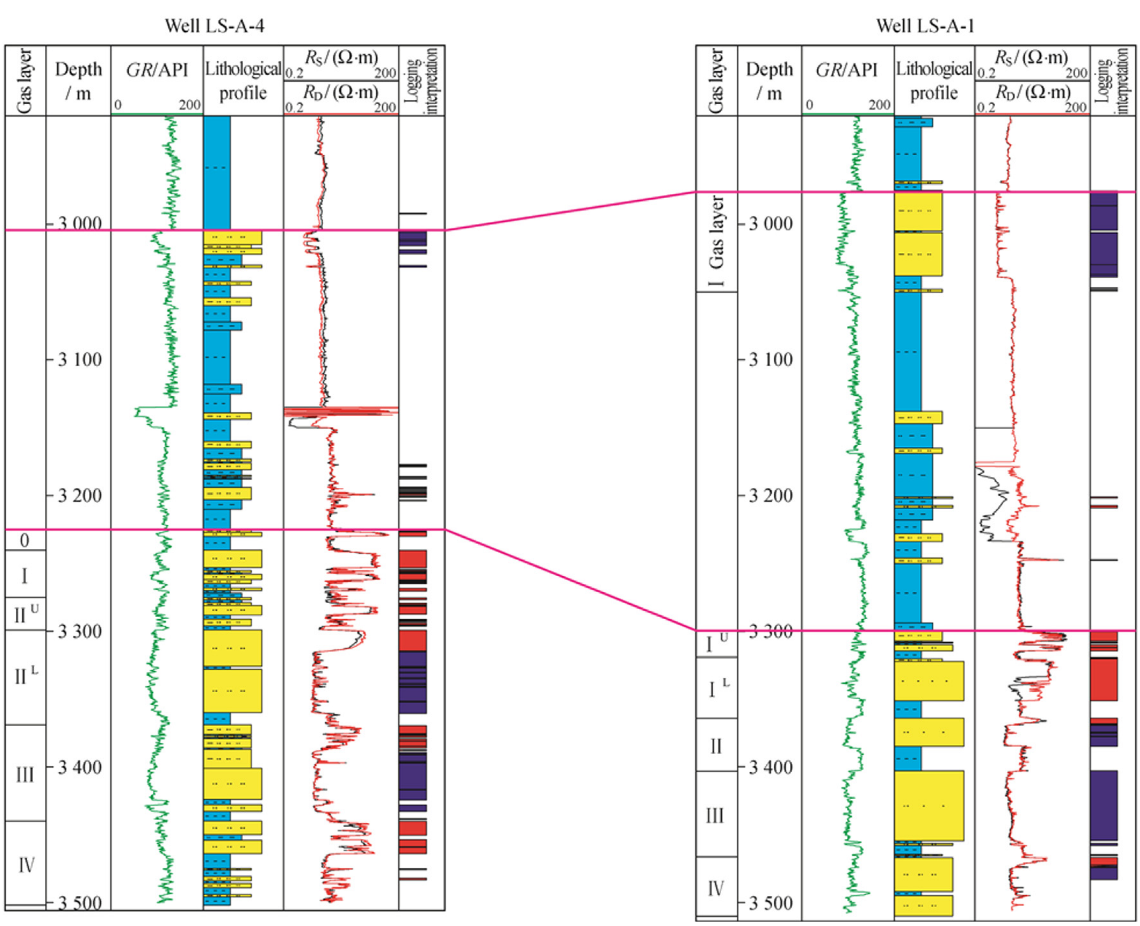

Fig. 9. Correlation graph of gas layers between Well LS-A-1 and Well LS-A-4 in the Central Canyon.

regions. The hydrocarbon-rich sags include Lingshui, Baodao and Changchang. The source rocks are at high mature–over mature stage, mainly generating gas.

4) The major reservoir beds include turbidite channel sandstones in the Central Canyon in Miocene–Pliocene, submarine fans in the Sanya Fm, turbidite channel sandstones and submarine fans in the Lingshui Fm.
5) In vertical direction, there are two sets of plays (Paleogene and Neogene). The major advantageous exploration areas include the trap zone in turbidite channel sandstone in the Central Canyon, the trap zone around the Changchang Sag, the faulted terrace zone in southern Baodao Sag, etc. They have plentiful oil and gas resources.
6) The large gas fields in the Central Canyon have the features of "lower generation and upper storage or paleo-generation and neo-storage". During later periods, natural gas was accumulated by vertical migration and infilling. Gas pools were controlled by both structure and lithology. Hydrocarbon accumulation occurred in several sand bodies independently.

Fund project

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