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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