



Sedimentary System Evolution and Petroleum Geological Significance of the Quaternary Ledong Formation in Qiongdongnan Basin

Li Wenlong^{1,*}, Mao Xueliang¹, Song Peng², Wu Bin², Yang Zhenjian¹

¹Zhanjian Branch of CNOOC (China) Co., LTD, Zhanjian, China

²Hainan Branch of CNOOC (China) Co., LTD, Haikou, China

Email address:

liwl6@cnooc.com.cn (Li Wenlong)

*Corresponding author

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Abstract: Quaternary Ledong formation in Qiongdongnan Basin is rich in hydrate, it is import to clarify the evolution and distribution rule of the sedimentary system of Ledong formation in this area. Based on 3D seismic data and drilling data, combined with the characteristics of regional sea level change, and guided by the principle of sequence stratigraphy, this paper established a high-precision sequence stratigraphic framework of Ledong Formation, identified five third-order sequences, and pointed out that the S14 interface was the conversion surface of progradational continental slope to accretive continental slope. The Ledong Formation was divided into the upper member of Ledong Formation and the lower member of Ledong Formation, which controls the development of submarine fans. The results show that the lower member of Ledong Formation has developed a large channelized submarine fan of the western provenance central canyon system, and the upper member of Ledong Formation has developed a small scale submarine fan, mass flow and sheet sand complex sedimentary body outside the northern provenance canyon system. The sedimentary type and temporal and spatial evolution characteristics are defined, which provides geological basis for the prediction of favorable reservoir distribution of hydrate and shallow gas in this area.

Keywords: Qiongdongnan Basin, Ledong Formation, Sequence Stratigraphic Framework, Submarine Fan, Geological Significance

1. Introduction

Qiongdongnan Basin is one of the main petroleum-bearing basins in the northern South China Sea. At present, many large and medium-sized gas fields have been found which proves that the basin is rich in natural gas resources [1-3]. In Qiongdongnan Basin, especially in the deep water area, oil and gas exploration is mainly aimed at the Tertiary strata, and there is little research on the Quaternary Ledong Formation. With the continuous advancement of oil and gas exploration, the Quaternary Ledong Formation contains natural gas hydrate [4]. In recent years, domestic and foreign studies have found that shallow oil and gas and high saturation hydrates are often found in relatively high-quality coarse-grained sediments [5-7], and the implementation of

high-quality reservoirs is the key to the study of shallow oil and gas and large-scale hydrates in the Qiongdongnan Basin [8-10]. At present, the study of Quaternary Ledong Formation in Qiongdongnan Basin is still in its infancy. The establishment of sequence stratigraphic framework, provenance system, sedimentary characteristics, and the prediction of favorable reservoirs are still unclear, which restricts the understanding of shallow oil and gas and hydrate exploration in Qiongdongnan Basin. Based on the understanding of tectonic sedimentary evolution and high-resolution three-dimensional seismic data in Qiongdongnan Basin, this paper studies the fine sequence framework of Quaternary Ledong Formation and the identification and characterization of sedimentary system, which provides geological support for the evaluation and

optimization of favorable targets in the study area.

2. Regional Geological Conditions

The Qiongdongnan Basin is a Cenozoic intracontinental rift basin developed on the Mesozoic basement [11, 12]. It is adjacent to the Pearl River Mouth Basin in the east, Yinggehai Basin in the west, Yongle Uplift in the south, and Hainan Island in the north. According to the regional tectonic characteristics, the Qiongdongnan Basin can be divided into four first-order tectonic units, including the northern depression zone, the central uplift zone, the central depression zone and the southern uplift zone. The formation of Qiongdongnan Basin has experienced four evolutionary stages: Eocene fault depression stage, Oligocene depression stage, Early Miocene fault depression stage and Middle Miocene – Quaternary passive continental margin stage [13-15]. Correspondingly, Eocene Lingtou Formation, Oligocene Yacheng Formation and Lingshui Formation, Neogene Miocene Sanya Formation, Meishan Formation and Huangliu Formation, Pliocene Yinggehai Formation and Quaternary Ledong Formation were developed from bottom to top [16]. The study area is located in the Lingnan slope zone and Songnan low uplift area. Due to the accumulation of shallow oil and gas and the occurrence of hydrates in the range of hundreds of meters below the seabed, it is mainly Quaternary sediments.

3. Sequence Stratigraphic Framework

Through the comprehensive analysis of the high-precision sequence stratigraphic framework section of the well Xike 1, the Qiongdongnan Basin experienced five stages of sea level changes in the Quaternary Ledong Formation [17-20], which laid an effective basis for the analysis of sequence stratigraphic framework based on sea level changes. On this basis, through the combination of well seismic data, using the termination relationship of typical seismic profiles (onlap, toplap, downlap, truncation, etc.), six third-order sequence interfaces (S20, S18, S16, S14, S12, S0 and other seismic interfaces, S0 is the current

seabed interface) are identified in the Quaternary Ledong Formation of Qiongdongnan Basin. Among them, the S20 (1.9Ma) seismic interface corresponds to the regional unconformity interface between the Ledong Formation and the Yinggehai Formation. The study area shows the seismic reflection characteristics of medium-strong amplitude and medium-good continuity. According to the logging data of LSX-1-1 well, the lithology is mudstone with thin fine sandstone. The S14 (0.8Ma) seismic interface is the interface with the largest sea level change since the Quaternary. It is the conversion surface from the progradational slope to the aggradational slope in the region. The seismic reflection in the study area is characterized by medium-good continuity, medium-strong amplitude, and locally visible truncation (channel incision). Therefore, the Ledong group was divided into Ledong group (S20 ~ S14) and Ledong group (S14 ~ S0) from bottom to top. The S18 and S16 seismic interfaces correspond to the two third-order sequence interfaces under the Ledong Formation. S18 shows medium-good continuity and weak-medium amplitude reflection characteristics. Above the Ledong sag-south slope interface, there is obvious channel incision characteristics and below the interface, there is weak amplitude reflection. The S16 interface shows medium-better continuity and medium-strong amplitude reflection characteristics. There are also many incised features above the interface, and the incised degree is significantly stronger than that of the S18 interface. The interface of S12 is characterized by medium-good continuity and medium-intensity amplitude reflection on the earthquake. Above the interface, it is mainly characterized by medium-amplitude and medium-good continuity sheet reflection, and there is obvious slump erosion above the interface.

According to the above sequence boundary characteristics, combined with high-precision three-dimensional seismic data, the Ledong Formation is divided into the lower section of the Ledong Formation and the upper section of the Ledong Formation from bottom to top. The lower section of the Ledong Formation is further divided into SQ1 (S20-S18), SQ2 (S18-S16), SQ3 (S16-S14), and the upper section of the Ledong Formation is divided into SQ4 (S14-S12), SQ5 (S12-S0), a total of 5 third-order sequences (Figure 1).

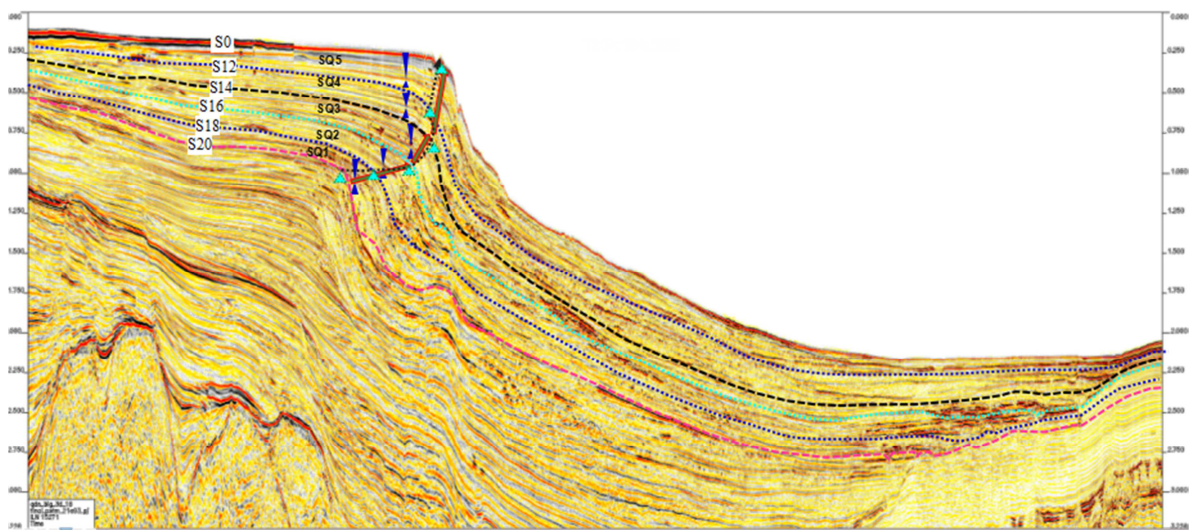


Figure 1. The sequence stratigraphic framework of the Quaternary Ledong Formation in Qiongdongnan Basin.

4. Sedimentary Characteristics and Evolution of Ledong Formation

The Qiongdongnan Basin entered the stage of regional thermal subsidence in the Quaternary period, and the tectonic activity was weakened. Under the influence of sea level rise and fall, paleogeomorphology limitation and provenance supply, the scale, distribution characteristics and spatial and temporal migration of the sedimentary system have obvious differences. Under the constraint of constructing the sequence stratigraphic framework of the Ledong Formation, the Quaternary Ledong Formation in the Qiongdongnan Basin has experienced five major sea-level cycles. Multi-stage regression is conducive to the development of gravity flow deposits in the low-stand system tract. The Ledong Formation mainly develops channelized submarine fans, mass flows, turbidite sands, and deep-sea mud. Combined with 3D seismic data, multi-stage sandy gravity flow deposits and multi-stage mass flow deposits are traced and interpreted in the study area. Through the fine description of the sedimentary bodies in the study area, the source direction, distribution characteristics and evolution of the sedimentary bodies in each period are clarified.

4.1. Analysis of Sedimentary Facies

During the sedimentary period of the lower Ledong Formation, a relatively rapid sea level fluctuation cycle occurred, and the sea level continued to decline significantly, which was conducive to the development of the gravity flow submarine fan sedimentary system. In the Lingnan slope area-low uplift area in the western part of the study area, a set of large submarine fans are identified by 2D and 3D seismic data, and the fans are widely distributed. During the late Miocene-Pleistocene period, the shelf slope of the Qiongdongnan Basin continued to move southeastward. The Ledong Formation inherited the restricted canyon landform characteristics of the Miocene Huangliu Formation-Pliocene Yinggehai Formation. Affected by the western provenance, a large amount of clastic material accumulated rapidly in the center of the sag through the submarine canyon to form a large submarine fan. According to the seismic attributes, the

submarine fan area is more than 3000 km². Under the background of high in the west and low in the east, the west side of the fan body is fully supplied by the western provenance and has obvious characteristics of incised channelization. The southeast side is limited by the canyon wall of the early Yinghuang Formation, which shows an elongated flower shape with southeast convergence in the plane. The submarine fans in the lower part of the Ledong Formation are vertically subdivided into one, two and three stages, which are vertically superimposed and developed in SQ1, SQ2 and SQ3 sequences (Figure 2). In the early stage of the lower section of the Ledong Formation (SQ1), the sea level decreased slightly, and the sea level was close to that of the late Yinggehai Formation. The paleogeomorphology of the Ledong Formation was generally high in the west and low in the east. The western source was transported along the central canyon along the low-lying terrain in the center of the basin to the farther central depression plain area. The characteristics of the debris from the west to the east are obvious on the seismic profile. With the continuous decline of sea level in the middle and late stage of the lower Ledong Formation (SQ2-SQ3), the slope break from T20 to T14 also continues to migrate to the southeast, and the western provenance continues to advance to the southeast. It is vertically superimposed with the first-stage submarine fan developed in the SQ1 sequence, and the three-stage submarine fan on the plane has the characteristics of successive migration and swing to the southeast. On the north-south seismic profile perpendicular to the submarine fan, the two-way underlap characteristics are obvious. The incised channel can be seen locally, and the progradation characteristics along the source direction are clear. Under the influence of sea level decline, the source supply is enhanced. Under the limitation of inherited canyons, the third-stage submarine fan pushes farther southeast than the previous two submarine fans, and the hydrodynamic conditions are significantly enhanced. The 'V' or 'U' type erosion incised channels are strongly characterized, and the later stage is mainly filled with mud with weak amplitude and disorderly reflection, which cuts the submarine fan into multiple blocks.

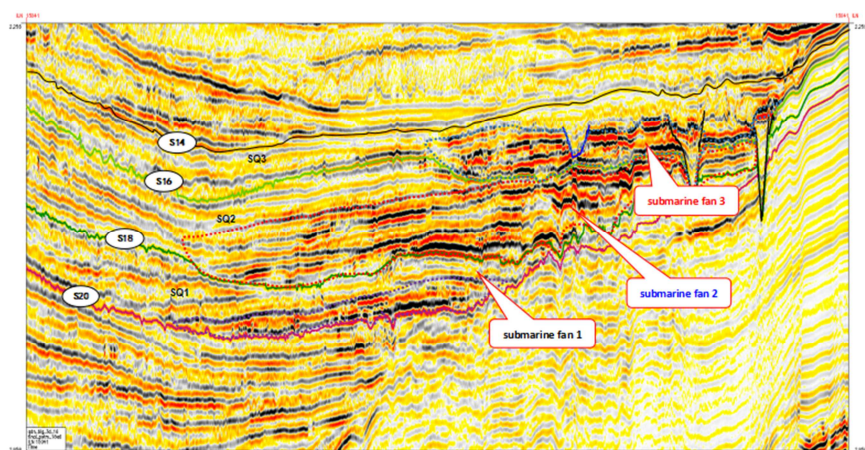


Figure 2. Seismic characteristics of submarine fan in lower Ledong Formation of Qiongdongnan Basin.

During the sedimentary period of the upper section of the Luoledong Formation, the progradational slope was transformed into the aggradational slope, and the sedimentary style was greatly changed from the lower section [21, 22]. A set of small-scale submarine fan reservoirs were identified in the Lingshui X area of the Songnan low uplift in the eastern part of the study area, which provided the source for the northern continental shelf area. The early high-level delta denudation formed by the rivers such as the Lingshui River in the north entered the slope through the waterway, and formed sandy sedimentary bodies such as submarine fans in the shallow layer of the deep sea plain area. Due to the limited supply capacity of the source, the scale of fan development is small. On the seismic profile, the submarine fan sedimentary body shows obvious progradation characteristics from north to south, and the east-west direction is characterized by two-way underlap. Combined with seismic attributes and hydrate drilling analysis, the submarine fan is distributed in the northeast direction as a whole, with two stages in the vertical direction and three lobes in the horizontal direction (Figure 3b, 3c). Its scale, thickness and shape are obviously different from the

characteristics of large submarine fans inherited from the central canyon system in the lower section of the western Ledong Formation. In addition, due to the continuous decline of sea level, the degree of slump in the slope area increases which is easy to cause the instability of the slope. Under the induction of tectonic movement, block slump (mainly argillaceous) is formed [23, 24], and MTDS is generally developed in the deep water plain area. The earthquake is mainly characterized by clutter, blank, weak amplitude reflection structure, and lateral mutation pinchout. In addition, a special set of seismic reflection units is developed in the study area, which is developed in the X area of Lingshui, showing a sheet sand structure of sub-parallel, medium intensity and good continuity seismic reflection structure. It is vertically mixed with block flow deposits in a 'flat' way, and there is no erosion or erosion interface inside. The overall performance is a 'sandwich biscuit'-like MDT-sheet sand complex (Figure 3a). Affected by the southern uplift, the MDT-sheet sand composite sedimentary body is mainly developed in the central plain area, and it is speculated that the hydrodynamic conditions in this period are relatively limited.

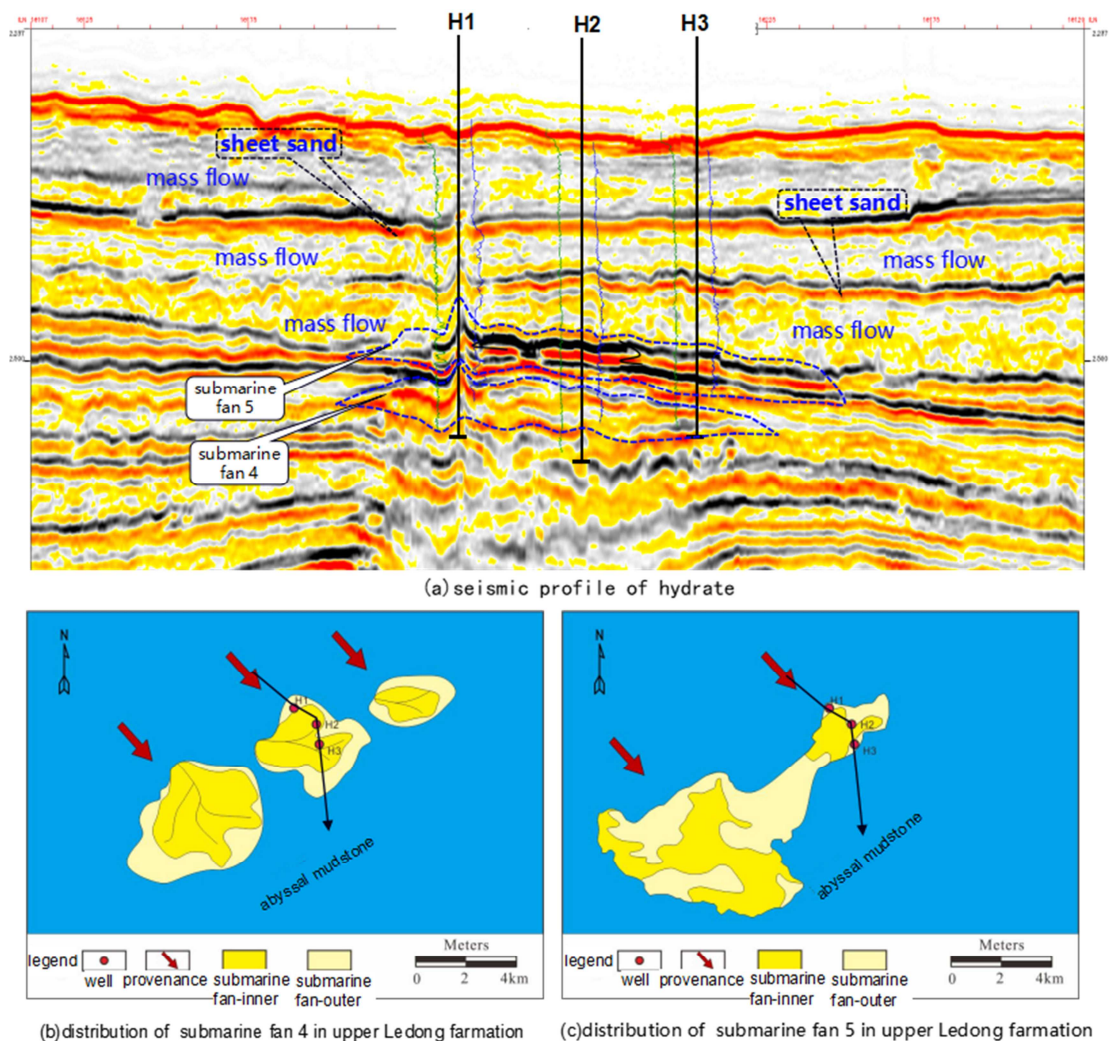


Figure 3. Sedimentary filling characteristics of upper Ledong Formation in Qiongdongnan Basin.

From the perspective of sedimentary characteristics, there are two types of sand-rich reservoirs in the shallow Ledong Formation, one is the northern provenance submarine fan deposit, and the other is the central canyon channelized submarine fan deposit. During the upper part of the Ledong Formation, as the sea level continued to decline, the northern shelf edge delta collapsed, and a large amount of debris accumulated in the deep sea plain area to form the northern provenance submarine fan deposit. This type of reservoir is developed in Lingshui X area of Songnan low uplift in the study area. However, due to the unstable source supply, the distribution range of single submarine fan is limited and the thickness is thin. Well H1 / 2 / 3, a hydrate exploration well, has obtained fine sandstone samples in the north source submarine fan. The sandstone reservoir is thin and the grain size is fine. In the Lingnan slope zone-uplift area, the canyon system of the Ledong Formation is inherited and developed, and the sufficient western provenance is high in the west and low in the east. Under the topographic background, many sets of channelized submarine fan sand bodies are superimposed in the NE-SW direction, and the predicted reservoir size and thickness are better than the Lingshui X area.

4.2. Sedimentary Distribution and Evolution

During the sedimentary period of the Ledong Formation,

the sedimentary bodies such as submarine fan, mass flow and sheet sand are obviously different in lateral distribution and vertical evolution. The sedimentary filling stage of Ledong Formation (S20-S0) can be divided into three evolution stages, that is, the stage of central canyon system channelized submarine fan filling dominated by western provenance in S20-S14. In the early Pleistocene, the sea level dropped and the delta advanced the farthest, forming a channelized submarine fan sedimentary body with the source and sink characteristics of 'continental shelf delta source-large slope valley group sand transport-slope toe confluence fan-three-stage superposition'. It does not have a typical lobe shape, which is characterized by northeast strip and vertical superposition. S14-S12 sequence is the main stage of submarine fan and mass flow sedimentary filling supplied by the northern source. S12-the stage dominated by mass flow-sheet sand composite sedimentary filling. On the whole, the Ledong Formation formed a vertical evolution sequence of three-stage channelized submarine fans and deep-sea mud from bottom to top. In the late stage, with the influence of sea level, continental slope style and provenance supply, the upper part of the Ledong Formation mainly developed small-scale northern provenance submarine fans, mass flow-sheet sand complexes and deep-sea mud deposits (Figure 4).

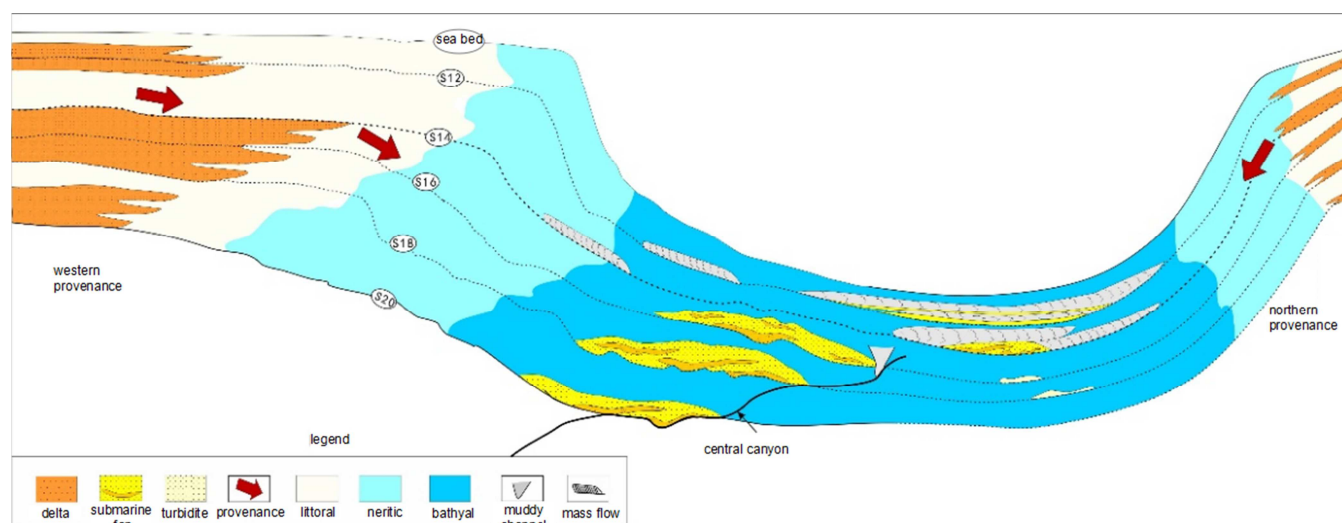


Figure 4. Sedimentary evolution model of the Quaternary Ledong Formation in Qiongdongnan Basin.

4.3. Significance of Oil and Gas Exploration in Quaternary Ledong Formation

The research shows that the fluid migration channels, such as shallow faults, gas chimneys, and fissures in the study area, are developed and communicated to the Quaternary and are located in the deep pyrolysis gas convergence center. The deep pyrolysis gas can enter the multi-stage channelized submarine fan reservoir developed in the shallow Ledong Formation along the migration channel, and the natural gas accumulates under the stable domain, and the hydrate is

enriched and accumulated within the stable domain. The extensive development of the late mass flow in the Ledong Formation can be used as a high-quality caprock for natural gas hydrates, and the exploration of hydrates in the Lingshui X area has been fully confirmed. On the whole, it has a multi-factor coupling accumulation mode of sufficient gas source-fault / gas chimney and other dominant migration channels-late block flow sealing-large axial canyon system submarine fan gas accumulation under the stability domain / submarine fan reservoir hydrate enrichment accumulation on the stability domain. The oil and gas potential is huge. It is an

important target stratum for oil and gas exploration in the Qiongdongnan Basin. It is a favorable area for the central canyon gas field to enter the deep sea and realize the breakthrough of the trillion atmospheric zones in the western South China Sea.

5. Conclusion

- (1) Combined with high-precision 3D seismic data, the Quaternary Ledong Formation in Qiongdongnan Basin can be divided into lower and upper sections. The lower section of Ledong Formation is further divided into three third-order sequences of SQ1, SQ2 and SQ3, and the upper section of Ledong Formation is divided into two third-order sequences of SQ4 and SQ5.
- (2) Ledong Formation mainly develops two types of sand-rich reservoirs: northern provenance submarine fan and central canyon channelized submarine fan. The sedimentary reservoir type of the northern provenance submarine fan is developed in the Lingshui X area of the Songnan low uplift in the study area, but the distribution range of the submarine fan is limited and the thickness is thin. The central canyon channelized submarine fan of Ledong Formation is developed in the Lingnan slope belt-convex area, and many sets of channelized submarine fan sand bodies are superimposed in NE-SW direction. It is predicted that the reservoir size and thickness are better than those in Lingshui X area.
- (3) The submarine fan field of the large axial canyon system of the Ledong Formation in the Lingnan slope zone-uplift area has a multi-factor coupling accumulation model of natural gas accumulation under the stability domain / natural gas hydrate accumulation within the stability domain. It has great oil and gas potential and is a favorable area for shallow gas and hydrate exploration.

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Biography

Li Wenlong (1987-), petroleum exploration engineer.