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Sedimentary Features and Distribution of High-Quality Reservoirs in the Ledong Area, Yinggehai Basin

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Abstract

The Ledong-30 area is located in the southern part of the central depression of the Yinggehai basin, where the exploration activity aims to gas in the middle and deep strata is started lately. The previous studies on the sedimentary system and main controlling factors of reservoir formation are mainly focused on the middle and shallow strata above the Huangliu Formation. Based on a fine interpretation of seismic data, the sedimentary characteristics, internal structures, and distribution rules of submarine fans and gravity flow channels in the Ledong-30 area are analyzed in this paper. In addition, the dynamic migration processes of their planar distribution and the vertical evolution law (vertical sequence combinations and superposition features of turbidity events) are also addressed. At last, the internal structural characteristics of the gravity flow system and comprehensive formation mechanisms of the large-scale gravity flow sediments (turbidities fans) are also been analyzed, which is helpful for the prediction of favorable reservoir distribution. The results can be used directly to guide oil and gas exploration in the Ledong area of the Yinggehai basin.

Keywords

Ledong-30 Area, Sequence Stratigraphy, Depositional System, Submarine Fan, Reservoir Characteristics

1. Introduction

The Ledong area is located in the southern part of the central depression of the Yinggehai basin, where the Meishan and Huangliu formations are the important hydrocarbon-bearing reservoirs in the middle and deep strata. Within the Meishan and Huangliu formations, the temperature is about 200˚C, and the pressure coefficient is more than 2.0, which shows the formations are typical high-temperature and overpressure reservoirs. The axial gravity flow channels and submarine fans controlled mainly by the source-sink system from the Hainan uplift are developed well in these reservoirs, which has good exploration potential. Due to the considerable burial depth of the middle-deep reservoir, however, the compaction is controlled strongly. At the same time, the high content of plastic minerals leads to the weak compaction resistance of the rock. The high content of local carbonate cement makes the sandstone in this area become a low-porosity and low-permeability reservoir, and the super-pressure system developed in the late stage cannot improve the densified low-permeability reservoir. However, it has compaction resistance [1]. With the deepening of exploration, it has been gradually recognized that reservoir hypotonicity has become a bottleneck to obtaining industrial gas flow in the Ledong area, and how to find the "sweet spot" reservoir in the context of hypotonicity is the critical problem that needs to be solved.

Therefore, this paper carries out a study on the prediction of high-quality reservoirs in the critical exploration targets in the study area using the spatial and temporal evolution of shelf-slope breaking, high-precision sequence stratigraphic mapping, the development mechanism of submarine fan-waterway sedimentary system in the Ledong area and the exemplary description of large reservoir groups, to characterize their spatial spreading patterns and infer their high-quality reservoir development areas, to guide the subsequent oil and gas exploration in the area.

2. Research Background

After nearly 60 years of exploration in the Yinggehai basin, proven gas reserves of over 100 billion cubic meters have been obtained. Several large- and medium-sized gas fields and gas-bearing structures have been discovered in the Dongfang and Ledong areas. With the deepening of exploration in shallow areas with normal temperature and pressure, several gas fields such as Dongfang 1-1, Ledong 22-1, and Ledong 15-1 have been discovered in the shallow strata, and the focus of exploration has now shifted to the mid-deep lithological traps of the Miocene gravity flow, and the discovery of Dongfang 13-1/2 gas field with high temperature and high-pressure in the mid-deep exploration in the Dongfang area, which has obtained over 100 billion cubic meters of proven gas reserves, showing the excellent prospect of oil and gas exploration in the mid-deep basin [2]. The study area of this paper is located in the southeast corner of the Yinggehai basin, separated from the Yacheng area of the southeast Qiongdong basin by the No.1 fault. The area is adjacent to the Yacheng bulge and Yanan depression of the southeast Qiongdong basin in the north-east direction. It is connected to the Ledong-10 area of the Yinggehai basin in the northwest and the Zhongjian bulge in the south (**Figure 1**).

Several gas fields, such as Ledong 15-1, 22-1, 10-1, Yacheng 13-1, and Lingshui 25-1, have been discovered around the study area, which shows that the

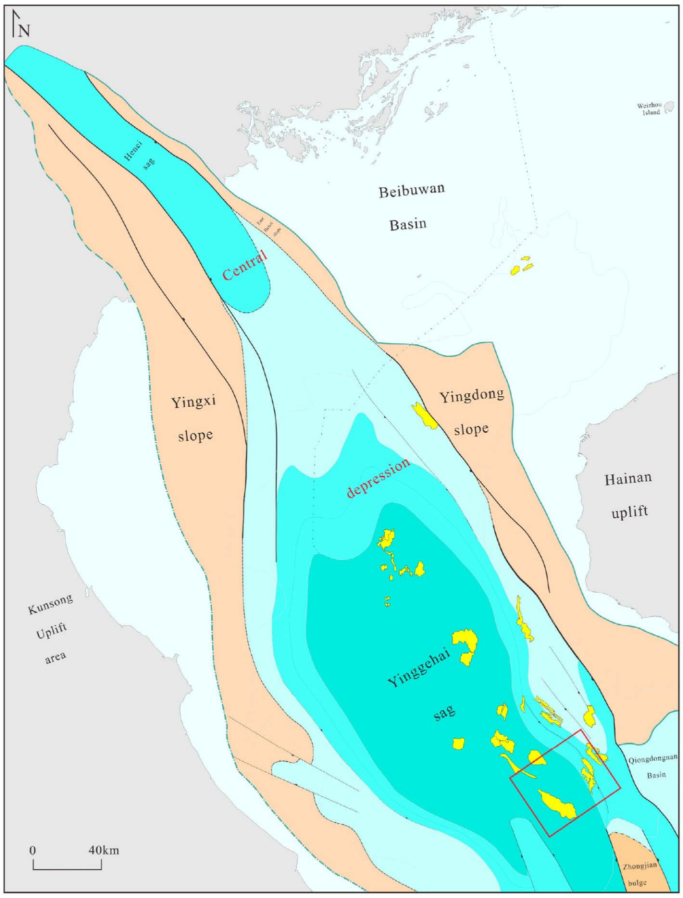


Figure 1. Location map of Ledong-30, Yingqiong Combined Area.

necessary oil and gas geological conditions in the area are very excellent [3]. Due to the considerable burial depth of the Miocene in the study area is more than 4000 m, combined with the high-temperature and overpressure, geological conditions are more complex, and the exploration degree is relatively low. Only Ledong 1A well was drilled in the Ledong-30 area, located in the downcomer of the No.1 fault. During the 13th Five-Year Plan period, commercial breakthroughs had been achieved in the exploration of the Miocene lithologic traps in the Ledong-10 area, southern segment of sag slope belt, Yinggehai basin, which greatly enhanced the exploration value of the Miocene lithologic traps in this area [4].

3. Type and Evolution of Structural Slope Break in Ledong Area

Large-scale, long-term active syndepositional faults form a sedimentary geomorphic mutation zone that becomes the fault slope break zone. The activity of syndepositional faults makes the fault slope-break zone have an important influence on the filling space and sedimentation of the basin. The slope-break zone constitutes the boundary of tectonic palaeogeomorphic unit and sedimentary facies domain in the basin [5]. Structural slope break types control the overall distribution of sequence development. In areas with well-developed fault systems, main faults and regulatory faults are combined in various ways to control the changes of stratigraphic thickness and sedimentary facies. Large slope break zones are usually important sites for accumulating slip turbidities at the front or front edge of deltas in the lower domain submarine fans and higher domains and have an essential control on the source system from the gentle slope direction and the distribution of sand bodies. In contrast, the local variations in the accommodable space formed by minor faults combination directly influence sedimentation [6].

Except for the No. 1 boundary fault developed in the Yingdong slope zone, there is no large fault system in the Ledong-30 area. The evolution of the boundary fault mainly controls the formation and evolution of the basin. According to the characteristics of boundary faults, internal structure, planar spreading, tectonic location, and developmental and evolutionary stage, the types of the tectonic slope break in the study area can be divided into four types: denudation multi-stage fault step, multi-stage fault step, flexure-fault step combination, and flexure slope break. The faults that form these tectonic slope breaks are combined into different types in profiles and planes, controlling the formation of specific paleo-morphologies, controlling the variation of accommodating space, and influencing the direction of advancement of the local clastic system and the spreading pattern of the sandbodies [7].

In the study area, during the deposition periods of the Lingshui, Sanya, Meishan, and Huangliu formations, the stages of tectonic evolution were the fault-depression transition period, thermal subsidence period and accelerated thermal subsidence period (**Figure 2**), when different types of tectonic slope break were formed. During the deposition period of the Lingshui Formation, it is in the fault-depression transition period, characterized by the development of stripping-type multi-stage fault-order slope break; during the deposition period of the Sanya and Meishan formations, it is in the thermal subsidence period, developing multi-stage fault-order slope break in the early stage and flexural-fault-order combination slope break in the later stage; during the deposition period of the Huangliu Formation, it is in the accelerated thermal subsidence period, characterized by the development of flexural slope break type. Therefore, the overall structural evolution of the study area controlled the characteristics of structural slope break types in the depression, from the denudative multi-step slope break developed in the early stage to the multi-step slope break developed in the middle stage and the flexural-step combination slope break, and then mainly to the development of flexural slope break types [8].

4. Source-Sink System and Paleogeomorphology in Ledong-30 Area

Previous studies on the provenance system of the Yinggehai basin were mainly based on the provenance analysis of the Honghe and Hainan Island, which severely limited the vision of researchers and the process of hydrocarbon exploration due to the lack of seismic and drilling data in the western part of the basin

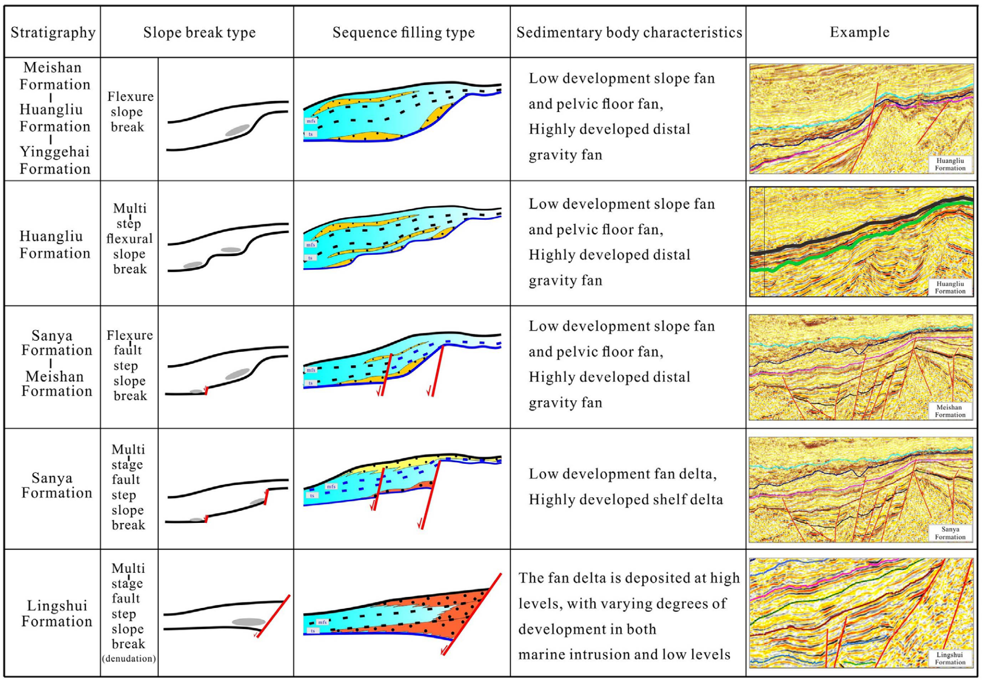


Figure 2. Typical tectonic slope fold type and its evolution in the Ledong-30 area.

(Yingxi slope zone). Based on a large number of previous research results, this study makes full use of the latest drilling data and new seismic data in the Yingqiong basin, focusing on the provenance analysis of heavy minerals and seismic reflection characteristics in the Yingqiong basin to explore the provenance background of the depositional period of the Huangliu and Yinggehai formations in the Ledong-30 area. These four aspects corroborate and complement each other.

The study shows that the Ledong-30 area has general characteristics of the Yanan bulge, the Yingdong slope, and Vietnam, where three different provenances together supply the filling sediments (Figure 3). The total sedimentation rate in the study area from the Lingshui Formation to the Huangliu Formation continues to decrease, with a significant influence of tectonics on sedimentation, and a sudden increase in the sedimentation rate when the second section of the Yinggehai Formation begins to be deposited, with a significant influence of loaded sedimentation. During the sedimentary period of the Huangliu Formation, the paleogeomorphic continental shelf was larger in the northeast and began to shrink when entering the Yinggehai Formation. The sedimentary center of the Huangliu Formation was located in the western region, and the sedimentary center of the Yinggehai Formation expanded southward and gradually parallel to the continental shelf line in the axial direction [9].

5. Analysis of the Sedimentary System in the Ledong-30 Area

The cores of several critical wells in the region were described by observation and analyzed for facies determination. The sedimentary facies in the study area

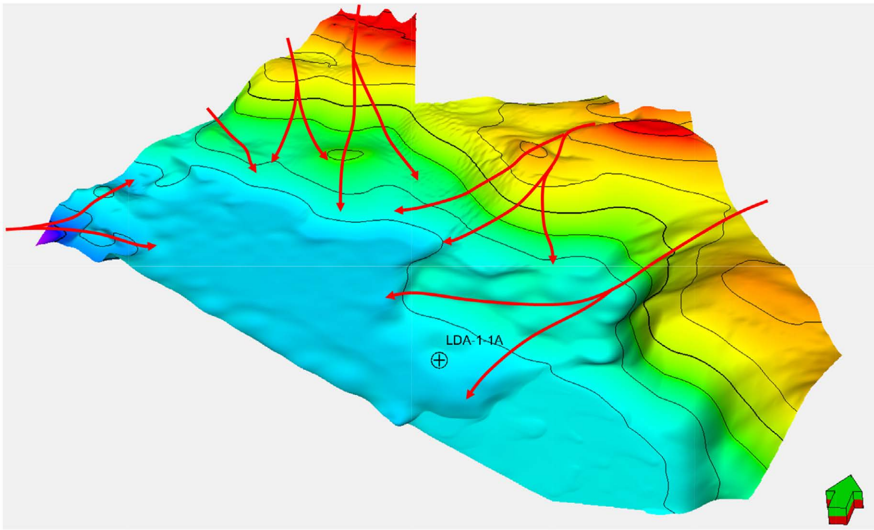


Figure 3. Paleolandscape map of SQHL2 in Ledong-30 area (Three major source systems supply the basic source-sink pattern of the study area).

involve fan delta, barrier-type coastal, and gravity flow channel facies, etc. The fan delta sedimentary facies in the study area can be divided into fan delta plain subfacies, fan delta front subfacies, and subdivided into distributary channel, interchannel, underwater distributary channel, underwater distributary bay, mouth bar and other sedimentary microfacies. The barrier coastal sedimentary facies involve four sedimentary microfacies, which are sand ping, mud ping, mixed ping, and tidal channel, the gravity flow channel facies have two sedimentary micro-facies, including main channel and diffuse sedimentation [10].

Comprehensive analysis of geological data such as cores, logs, rms properties, and paleo-morphology shows that the study area entered the accelerated subsidence period during the deposition of the Huangliu Formation. At the same time, in the deposition period of Huangliu Formation, the No.1 fault was mainly active in the southern section in the early stage and the whole section in the late stage, but the range of activity was very small. In the deposition period of the lowstand tract, the water body was generally shallow, and the denudation of the lower strata caused by forced regressions led to the development of the lower fan body. In the southwest part of the study area, large-scale channel gravity flow was developed, and the channel distribution range was wide. Below the No.1 fault, there were all shallow marine sediments in this period, which can be divided into the low fan and pelvic floor fan-developed areas by using the sequence model [11]. Although turbidite fan deposits are developed as a whole, the slope fan deposits developed on the slope and the pelvic floor fan deposits developed on the bottom of the slope can be recognized on seismic profiles.

They are combined with the analysis of the depositional filling pattern and genesis of gravity flow channels during the deposition of the Huangliu formation in the Yinggehai basin. In the context of a significant drop in relative sea level, the large-scale delta developed during the Meishan formation sedimentary period provides sufficient material sources for the channels, and the inherited down-cut valley developed at the front of the delta directly connects the delta material sources and gravity flow channels, providing sand transport channels for channel filling. The abundant deltaic sources are transported to the confluence area by the East branch channel nearby and develop multi-phase thick channel sands; the bottom shape of the channel formed by the weak zone of axial fracture underneath the channel controls the development and direction of the channel, which is an important tectonic cause for the formation of gravity flow in this area (**Figure 4**). Therefore, the gravity flow channel during the sedimentary period of Huangliu formation in Yinggehai basin was formed under the coupling effect of the drastic drop in relative sea level, the near-distance supply of large-scale provenance, the straight-developed sand transport channel and the underlying fault fracture zone [12].

6. Characteristics and Distribution of High-Quality Reservoirs in the Ledong-30 Area

6.1. Main Controlling Factors of High-Quality Reservoir

Favorable sedimentary phase zones provide good innate conditions for the formation and distribution of high-quality reservoirs, but later diagenesis can also have significant impacts on the storage properties of sandbodies. Through a comprehensive study of cast thin sections, scanning electron microscopy, cathodoluminescence, and X diffraction data from several core wells in the study area, it is concluded that the diagenetic effects controlling the reservoir properties in the study area mainly involve compaction, cementation, and dissolution, while compaction and cementation reduce the reservoir porosity and make the properties worse, and dissolution increases the reservoir porosity and improves their properties [13].

Overpressure protection of a large number of primary pores. Jon Gluyas *et al.* showed that the formation is under an anomalous pressure gradient where the pore fluid pressure is higher than the hydrostatic pressure, and the overpressure supports part of the buried load. It thus reduces the effect of compaction, and the anomalously high pore space can be preserved. The theoretical derivation by Jon Gluyas *et al.* suggests that a 1 MPa overpressure is equivalent to an 80 m reduction in effective burial depth. Liubo *et al.* also concluded that anomalous overpressure preserves more pore space to a certain extent.

Abnormal high pressure is generally developed in the central diapiric zone of Yinggehai basin [14]. The Yinggehai basin possesses high sedimentation and deposition rates, and the uneven compaction is caused by rapid deposition. At the same time, hydrocarbon generation and high temperature cause fluid expansion. About 4.0 to 5.0 Ma ago, overpressure was formed in the Meishan and Huangliu formations. At this time, the overlying Yinggehai formation has just begun to deposit. The diagenesis of the first section of the Huangliu formation is weak. Protected by overpressure, the evolution of porosity and permeability has slowed down, and a large number of primary pores have been retained [15].

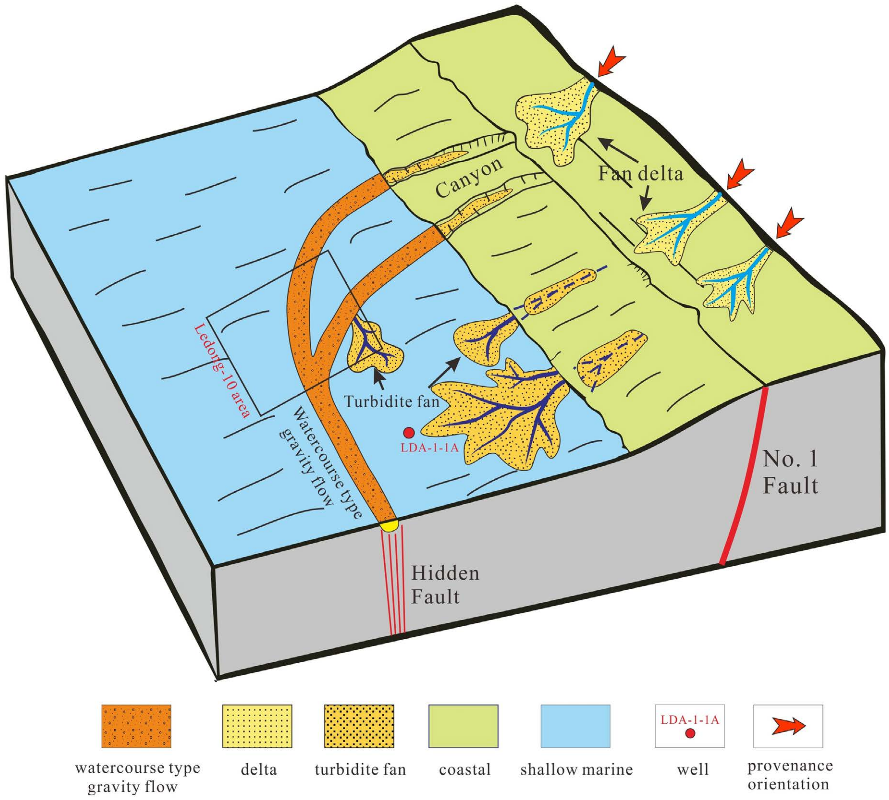


Figure 4. Map of gravity flow deposition pattern in the Ledong area.

6.2. Fine Characterization of Large Reservoirs

The second member of the Huangliu Formation is the key reservoir in the Ledong-30 area, which has relatively smooth and continuous seismic reflection wave group characteristics (Figure 5), vital homophase axis energy, and the provenance direction mainly come from the Yacheng direction. The high part of Yacheng is the coastal area and the shallow sea area westward. A series of provenance recharge channels can be identified on the eastern shelf edge of the study area, which exhibits high dip property values in plan and is mainly "U" shaped or disk-shaped in profile, with different sizes of channels, among which FP4 is the main source input channel in the Ledong-30 area, and its large size provides the necessary guarantee for the development of the fan (Figure 6). According to the seismic reflection structure and sedimentary characteristics, the gravity flow submarine fan in the second section of the Huangliu formation is divided into three parts: early-stage fan, middle-stage fan, and late-stage fan. The early and mid-stage fans are located below the maximum sea-flood surface, and the mid-stage is developed on a larger scale.

From Figures 7-9, it can be seen that the critical reservoirs in the second section of the Huangliu formation in the study area develops three stages of fan bodies: the overall internal fan range is larger, the middle stage fan scale is the largest, the late stage fan scale is slightly smaller than the middle stage fan, and the early stage fan scale is smaller. The early sandbodies is concentrated in the

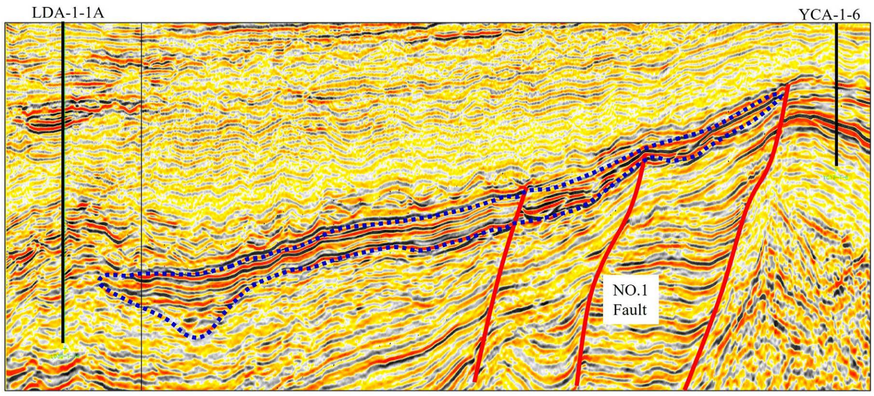


Figure 5. Seismic profile characteristics of the submarine fan in the second section of the Huangliu Formation in the Ledong-30 area.

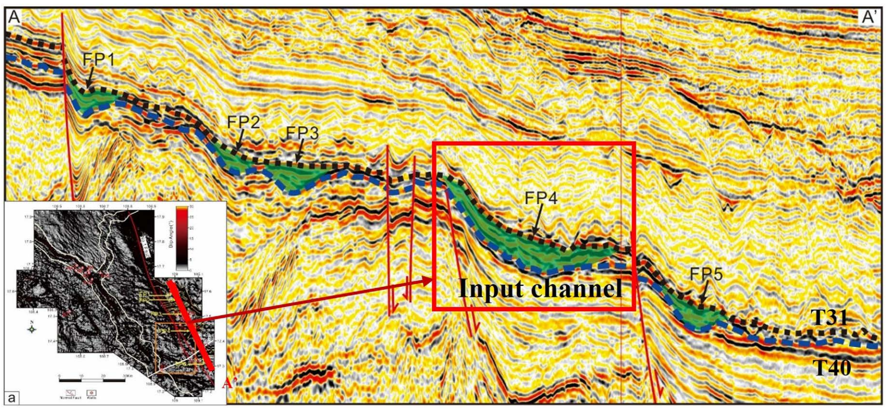


Figure 6. Schematic diagram of the source channel of the submarine fan in the second section of the Huangliu Group in the Ledong-30 area.

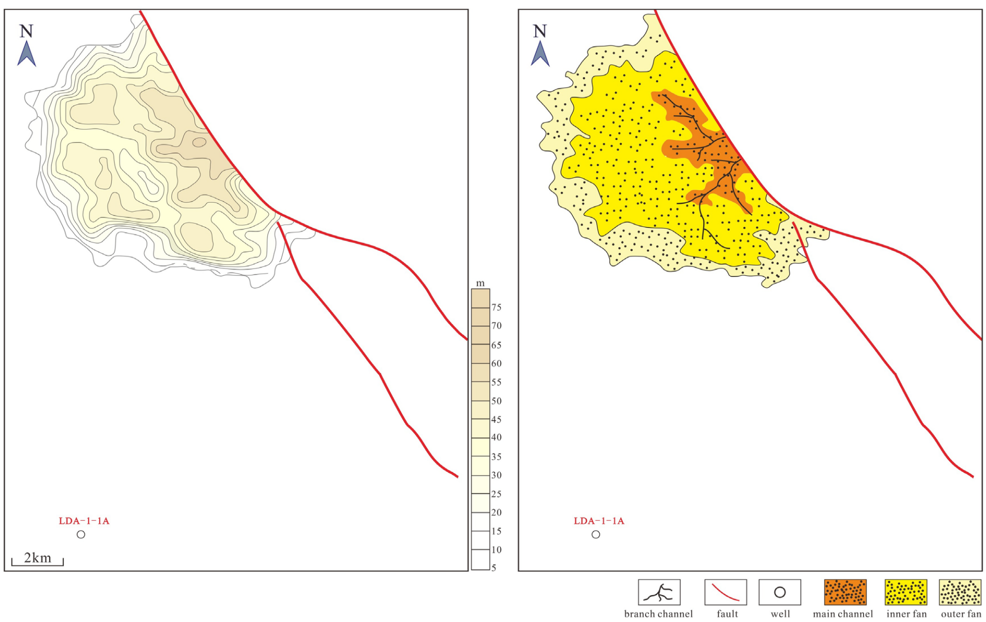


Figure 7. Thickness map and sedimentary facies plan of the early gravity flow fan in the second section of the Huangliu Formation.

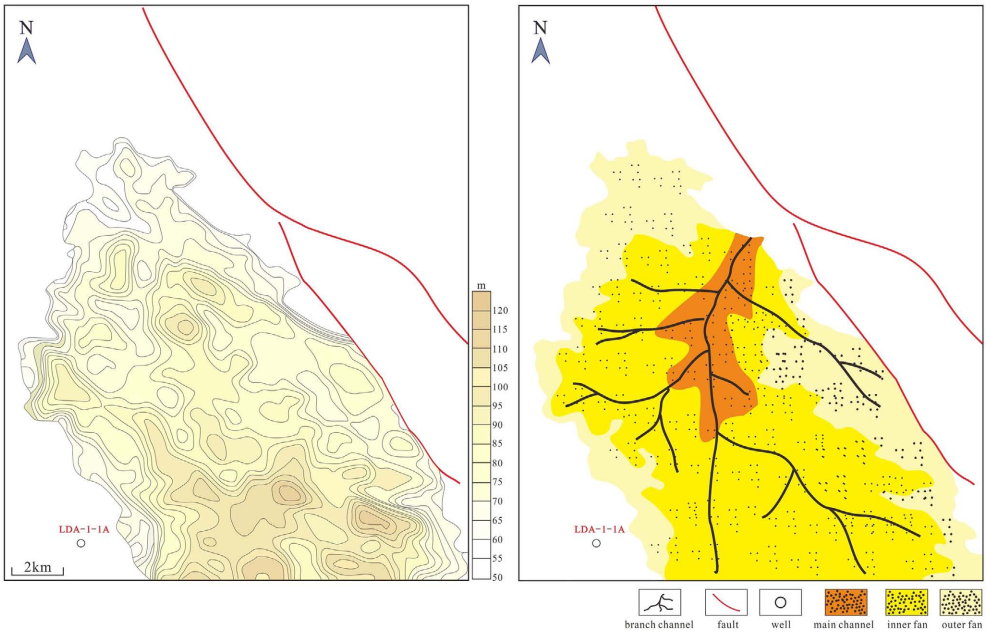


Figure 8. Thickness map and sedimentary facies plan of the middle gravity flow fan in the second section of the Huangliu Formation.

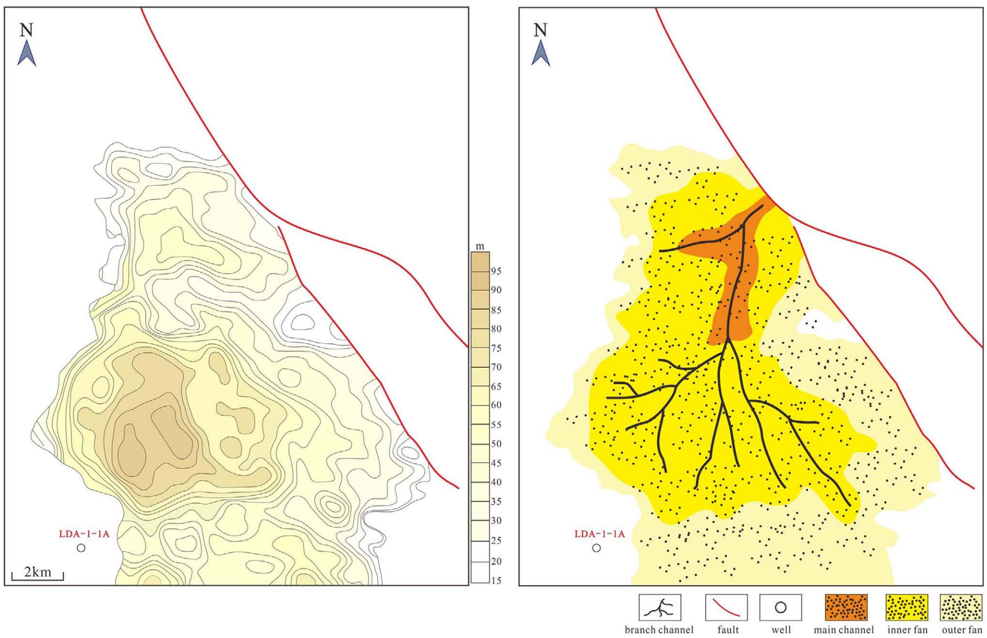


Figure 9. Thickness map and sedimentary phase plan of the late gravity flow fan in the second section of the Huangliu Formation.

root of the No.1 fault, the thickness center of the middle and late sandbodies is in the middle section of the fan body, the thickness of the middle sandbodies can reach 120 m, the thickness of the late sandbodies can reach 95 m at the thickest, and the thickest place of the early sandbodies is 75 m.

The sandstone in the study area has low longitudinal and transverse wave velocity ratio characteristics and low Poisson's ratio anomalies. Based on the longitudinal wave impedance, transverse wave impedance, and longitudinal and transverse wave velocity ratio seismic inversion data body intersection map (**Figure 10**), the relatively favorable development area of the sandbodies can be predicted. The sandstone is relatively developed in the southern part of the early fan body, and the sandstone is relatively developed in the middle part of the middle and late fan bodies. The area is affected by high-velocity mudstones as well as lateral, inhomogeneous variations in lithology properties [16].

A comprehensive study of the relatively favorable development area of sandbodies, based on the sedimentary facies of the third stage fan body superimposed the palaeogeomorphological characteristics of the second member of the Huangliu Formation, the predicted distribution of planar porosity and permeability in the study area was drawn (**Figures 11-13**). The middle stage of the second member of the Huangliu Formation in the study layer has the best pore permeability, with the highest porosity of 17%, followed by the late and early stage fans, with the highest porosity of 15%, and the permeability of the third stage fans is generally less than 10 md.

7. Conclusions

1) Combined with the analysis of drilling rock and electricity, seismic phase difference and hyperbolic event superposition relationship in the Ledong-30 area, the stratigraphic framework was established. The evolution rules from fault-step/multistage fault-step to flexural slope break of the Lingshui-Yinggehai formations were also addressed, and the development rules of the slope fan and basin floor fan under the control of the second member of the Huangliu Formation stratigraphic low-level flexion slope break was clarified. There are three provenance directions in the Ledong-30 area, namely, Yanan Bulge, Yingdong

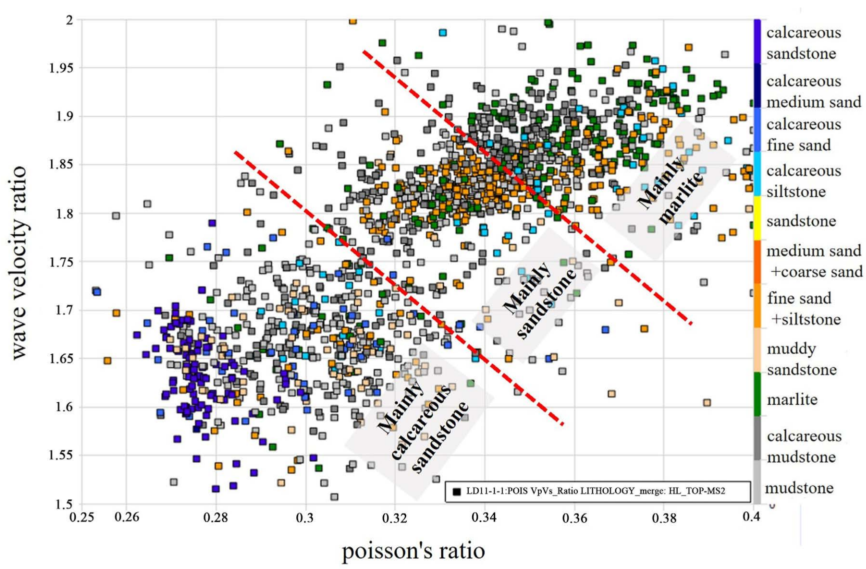
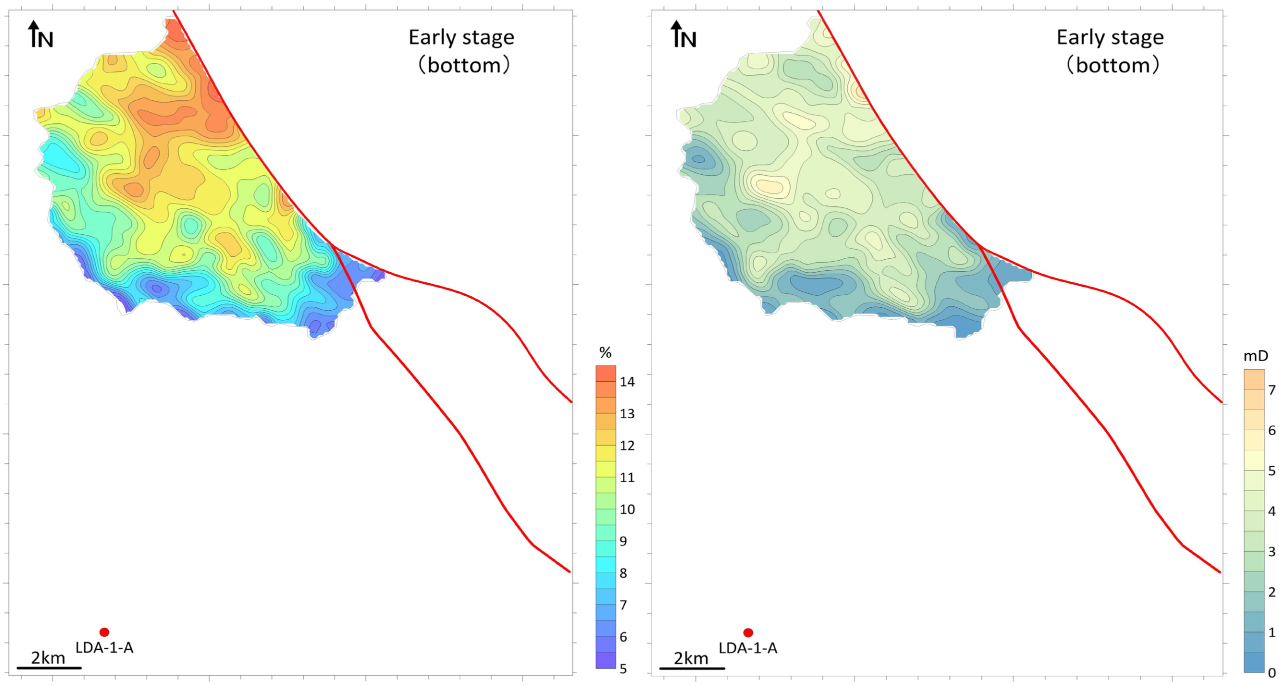
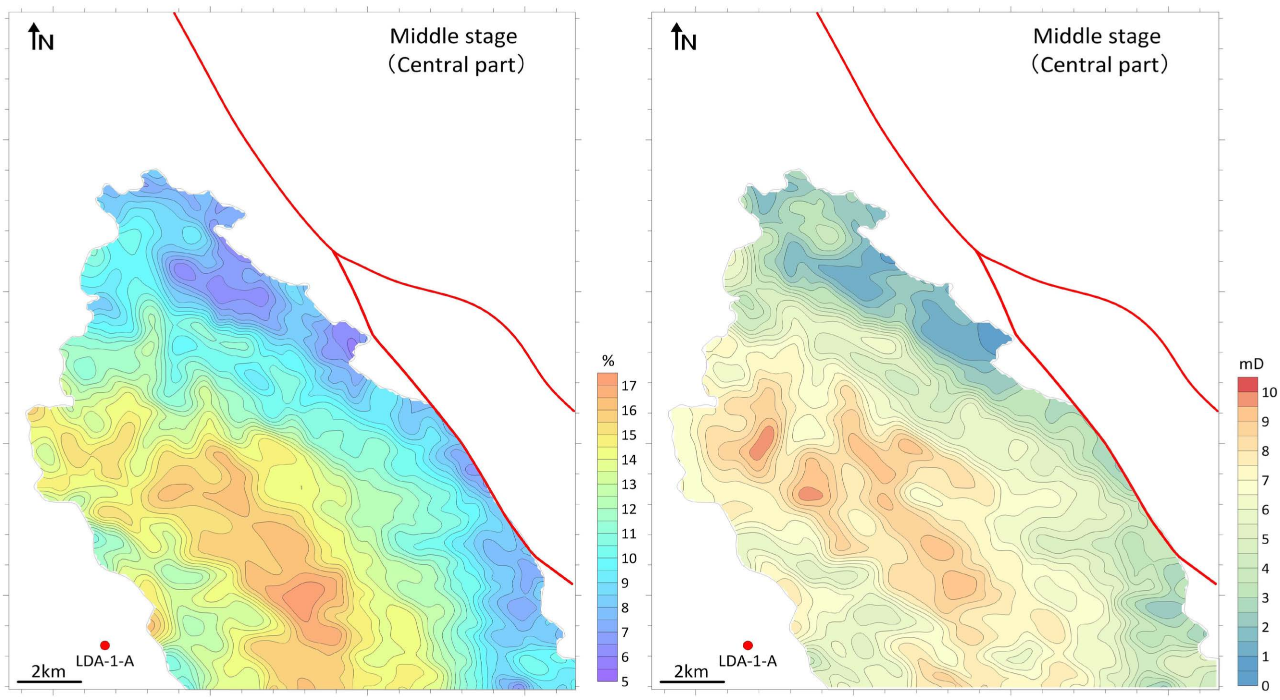


Figure 10. Analysis of lithologically sensitive elastic parameters of the Huangliu-Meishan Formation.



(a) Average porosity (b) Average penetration rate

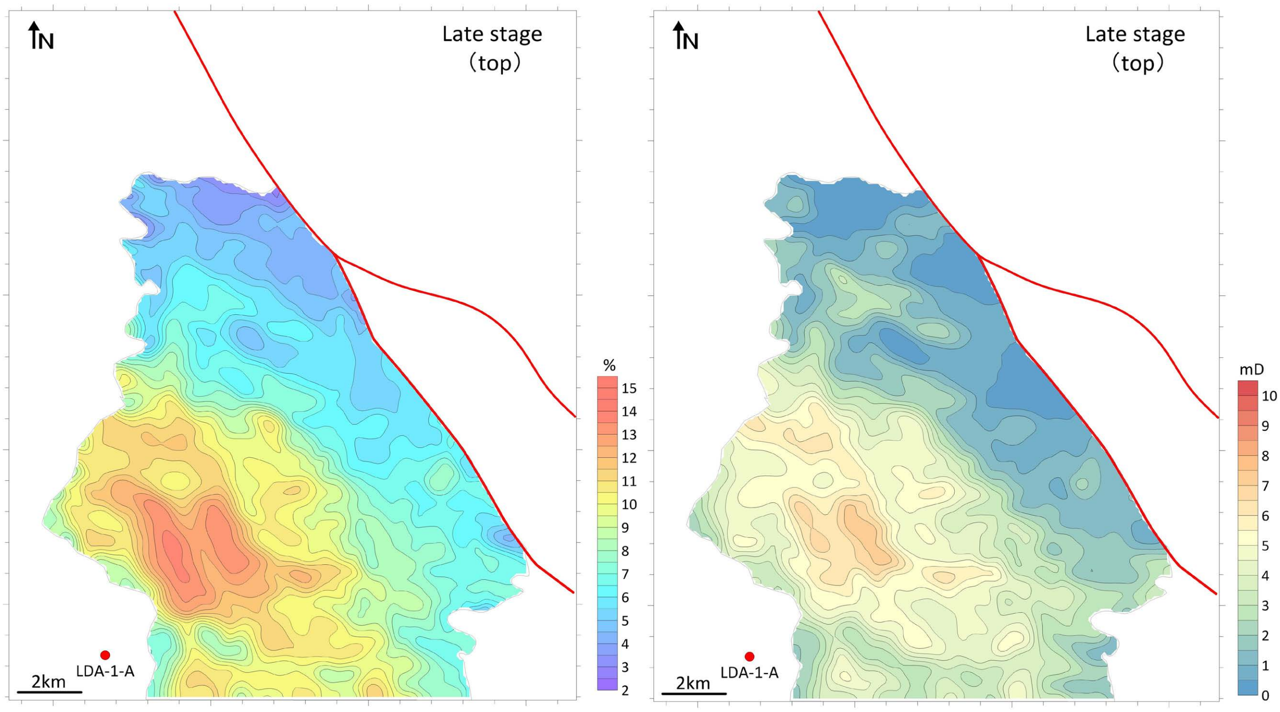
Figure 11. Average pore permeability plan of the early sandbodies in the second section of the Huangliu Formation.



(a) Average porosity (b) Average penetration rate

Figure 12. Average pore permeability plan of the sandbodies in the middle of the second section of the Huangliu Formation.

Lope and Vietnam, but Hainan Island is the main provenance direction. The subsiding rate of the basement during the deposition period of the Lingshui-Huangliu Formation continued to be low, and the rate began to increase



(a) Average porosity (b) Average penetration rate

Figure 13. Average pore permeability plan of the late-stage sandbodies in the second section of the Huangliu Formation.

sharply during the deposition of the Yinggehai Formation. In terms of paleo-morphology, the Huangliu and Yinggehai formations have a shelf-slope pattern, with the shelf of the Huangliu formation being more extensive and the shelf of the Yinggehai formation gradually shrinking. The study area is mainly a shallow and semi-deep sea depositional environment.

2) The types of sedimentary micro-facies in the study area were classified. The evolution rules of the spatial and temporal distribution of the third-level sequence sedimentary systems of the Huangliu-Yinggehai formations are clear: large-scale canyon channels and gravity flow fans were frequently developed during the deposition period of the Huangliu Formation, and the upward gravity flow deposition gradually shrank.

3) The middle deposition area of the fan bodies in the Ledong-30 area is the front end of the gravity flow branch channel, and the thickness of sandbodies is predicted to be large in the middle period. The sandstone probability body profile shows independent sand units with upward-tilted cusp extinction and a nose-like tectonic background, together with the upward-tilted cusp extinction sandbodies, which can form structural-lithological traps.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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