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Quantitative prediction of palaeo-uplift reservoir control and favorable reservoir formation zones in Lufeng Depression

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Abstract:
In this paper, taking the Lufeng Depression as the study object, the distribution characteristics and reservoir-controlling conditions of palaeo-uplift are analyzed from both qualitative and quantitative perspectives. The distribution characteristics of the three-level palaeo-uplift structural pattern are elucidated, which show that the palaeo-uplifts went through three structural evolutionary stages: Eocene, Early-Middle Miocene, and Late Miocene, with long-term inherited development characteristics. Palaeo-uplift controls the distribution of hydrocarbon planes, the direction of dominant hydrocarbon transport, the development of various traps, and the types of hydrocarbon reservoirs. Applying the principle and method of "multi-element matching reservoir formation model", the corresponding geological and mathematical models are established, which indicate that 86.29% of the number of reservoirs are distributed on the top and slope of the palaeo-uplift, and the reserves and number decrease with the distance to the top of the palaeo-uplift. Based on the palaeo-uplift control model, four high-probability areas for palaeo-uplift control in the Wenchang and Enping Fms are predicted, which are mainly located in the Lufeng middle-low uplift, the Dongsha uplift, and uplifts within the depression.

1. Introduction

Palaeo-uplift refers to any positive structural unit that existed during the accumulation period in geological history. There are several explanations for the genesis of palaeo-uplift: (1) It is thought to be related to a divergent plate or regional extension, in which the sharp subsidence of the side depression or rift valleys causes balanced uplift in the area where the uplift is located (Xie et al., 2004); (2) It could be attributed to plate convergence or regional extrusion, in which the compression of regional stresses cause the overall uplift, leading to missing or the stripping of more strata (Flemings and Jordan, 1989); (3) It may have developed by inheriting the basement paleotectonic pattern (Dickinson, 1974; Cloetingh, 1988). The palaeo-uplift and its associated structures have been consistently one of the most favorable areas for exploration in petroliferous basins. Since the discovery of oil fields in the central anticline of Illinois Basin, scientists have been exploring oil and gas around the "uplift" (Levorsen, 2001). The exploration practice in recent decades shows that the palaeo-uplift is one of the geological factors controlling oil and gas enrichment in the basin, which not only affects the internal structural and sedimentary environment of the basin, but also points to long-term oil and gas transportation. Research on the role of palaeo-uplifts controlling oil and gas has long been the focus of many scholars and exploration scientists. Various studies have made a lot of progress in the study of reservoir control by the multi-stage superposition of palaeo-uplifts (Davis, 1987), the structural evolution of palaeo-uplift and its hydrocarbon-bearing properties (Bethke et al., 1990), and the pattern of oil and gas accumulation in

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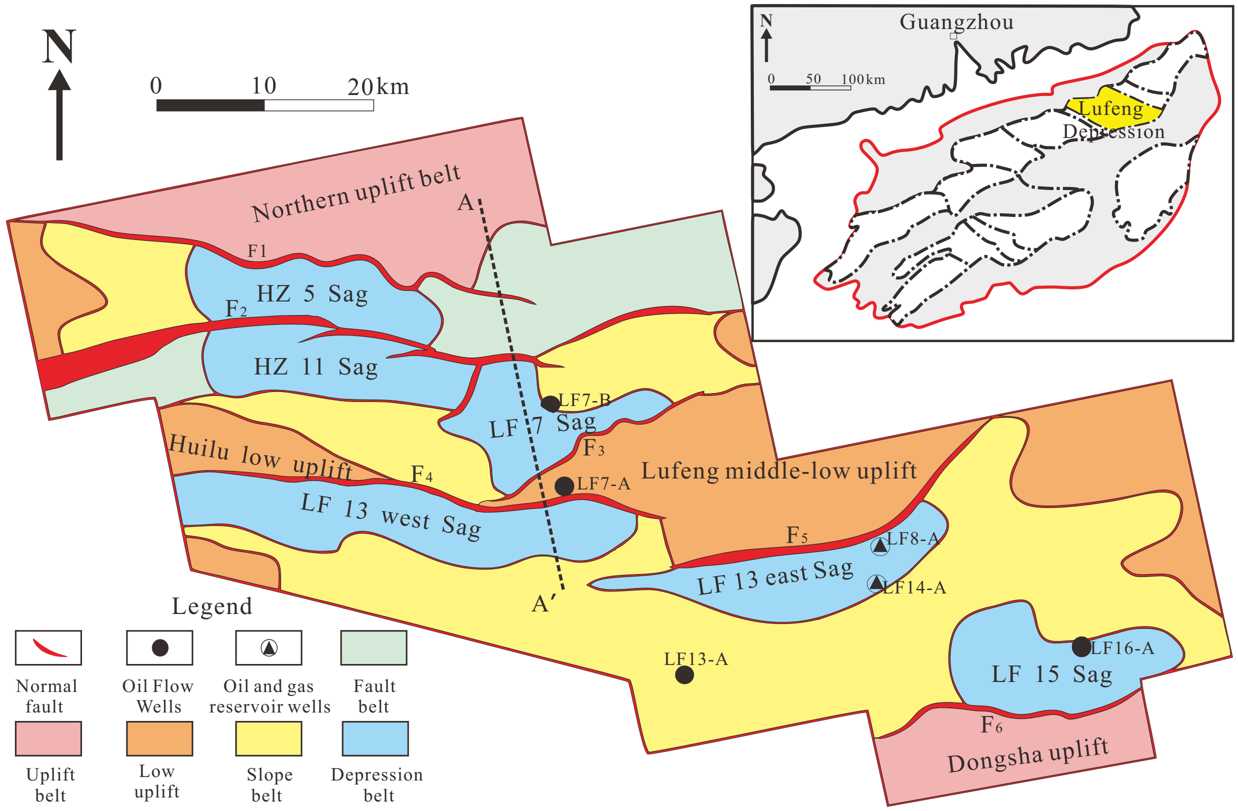


Fig. 1. Geographical location, structural unit division of the Lufeng Depression (modified after Yu et al. (2016); Yu and Koyi (2017)).

palaeo-uplifts and slope zones (Catalan et al., 1992), which are of great significance to the exploration in the Tarim Basin, Sichuan Basin, Ordos Basin, and other areas. The formation and development of large oil and gas fields in the world are mostly related to the background of paleo-uplifts, such as the North Sea Oil Field (United Kingdom), the Red Water Oil and Gas Field in Alberta Basin (Canada), the Oakola Gas Field in Permian Basin (United States), the East Texas Oil Field, the East Sichuan (China), the Kaijiang Gas Field, the Daqing Oilfield in Songliao Basin, etc. (Lorant et al., 2000; Fox et al., 2014; Pang et al., 2019; Bai, 2021; Yan et al., 2021).

Scholars have carried out a multitude of research on the Lufeng Depression and analyzed its structure, deposition, accumulation, and other properties. It is considered that its structural development mainly experienced the superposition of two rifting periods; the sedimentary characteristics migrated from south to north from early to late, the reservoir formation conditions are complex, and the reservoir-controlling elements are diverse (Yu et al., 2016; Yu and Koyi, 2017; Zheng et al., 2018). However, the intensity of research on the reservoir-controlling characteristics, oil-gas-controlling mechanism, and modeling of different parts of the palaeo-uplift has been relatively weak. Scholars such as Pang et al. (2010) put forward a "multi-functional element matching accumulation model" in the study of hydrocarbon accumulation characteristics, which provides a new research idea for the quantitative evaluation of palaeo-uplift controlling accumulation, and has certain guiding significance. The application of "multi-functional element matching accumulation model" to execute the methodological process for predicting favorable reservoir formation areas is divided into four steps: (1) Carrying out the analysis of oil and gas bearing basins to find out the basic geological conditions for the formation and distribution, development history and spatial spreading characteristics of oil and gas reservoirs. (2) The determination of the main formation periods of hydrocarbon-bearing basins during the course of geological history by simulating the mass production and discharge of hydrocarbons from hydrocarbon source rocks. (3) Establishing a geological model of four major elements controlling oil and gas reservoirs by studying the distribution characteristics and statistics of discovered oil and gas reservoirs. (4) Carrying out the prediction of favorable reservoir formation areas in different reservoir formation periods for a certain target layer, developing a geological model of the reservoir formation period by superimposing and compounding the favorable reservoir formation zones of each element of the same target formation, and determining the favorable development zones of the uplift-controlled reservoirs. Accordingly, this study investigates the favorable accumulation areas of the palaeo-uplifts in the Lufeng Depression from the qualitative aspect, to summarize the palaeo-uplift's structural characteristics and evolution model, and to quantitatively evaluate the relationship between the palaeo-uplift and the accumulation control probability and range. Therefore, an effective mathematical model is established to predict the probability of hydrocarbon accumulation and favorable areas in this region, and the

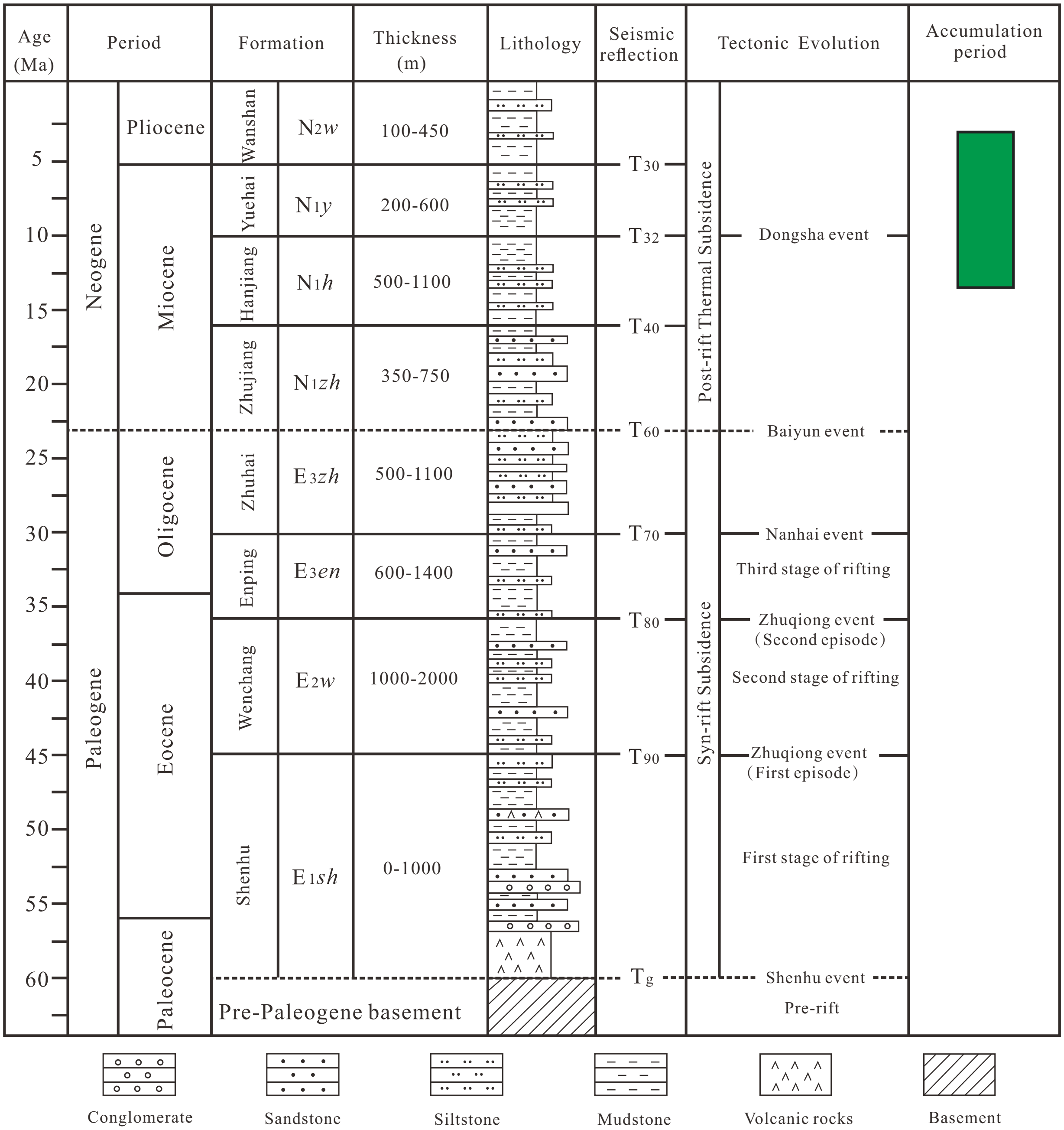


Fig. 2. Stratigraphic histogram of the Lufeng Depression (modified after Yan (2016)).

reliability of the prediction results is validated.

2. Geological setting

The Pearl River Mouth Basin (PRMB) was formed at the junction of the Indian Plate, Pacific Plate and Eurasian Plate, which has a double-layered structure of first rifting and then thermal subsidence (Patriat and Achache, 1984; Lee and Lawver, 1995; Yu and Koyi, 2017; Zheng et al., 2018; Li et al., 2021). There are significant differences in structural evolution among the depressions, sags and sub-sags. The formation, migration and accumulation conditions of oil and gas are different, and the types of oil and gas reservoirs formed, the rules of accumulation, and the controlling factors also vary (Robinson et al., 1998; Franke et al., 2014; Jiang et al., 2015).

The Lufeng Depression is located in the northeastern part of PRMB. It has a NE-SW orientation and covers an area of approximately 7,760 km^2, with the Dongsha uplift to its south, the Haifeng uplift to its east, the Northern uplift belt to its north, and the Huilu low uplift to its west (Fig. 1). Explorations have identified several sets of oil-bearing layers in this depression. It is one of the oil-rich and hydrocarbon-generating subunits in the PRMB with the greatest potential, whose structural evolutionary history can be divided into rift, depression and structural activation periods, which respectively correspond to the periods of deposition of Wenchang Formation (E_2w)-Enping Formation (E_2en), Zhuhai Formation (E_3zh)-Zhujiang

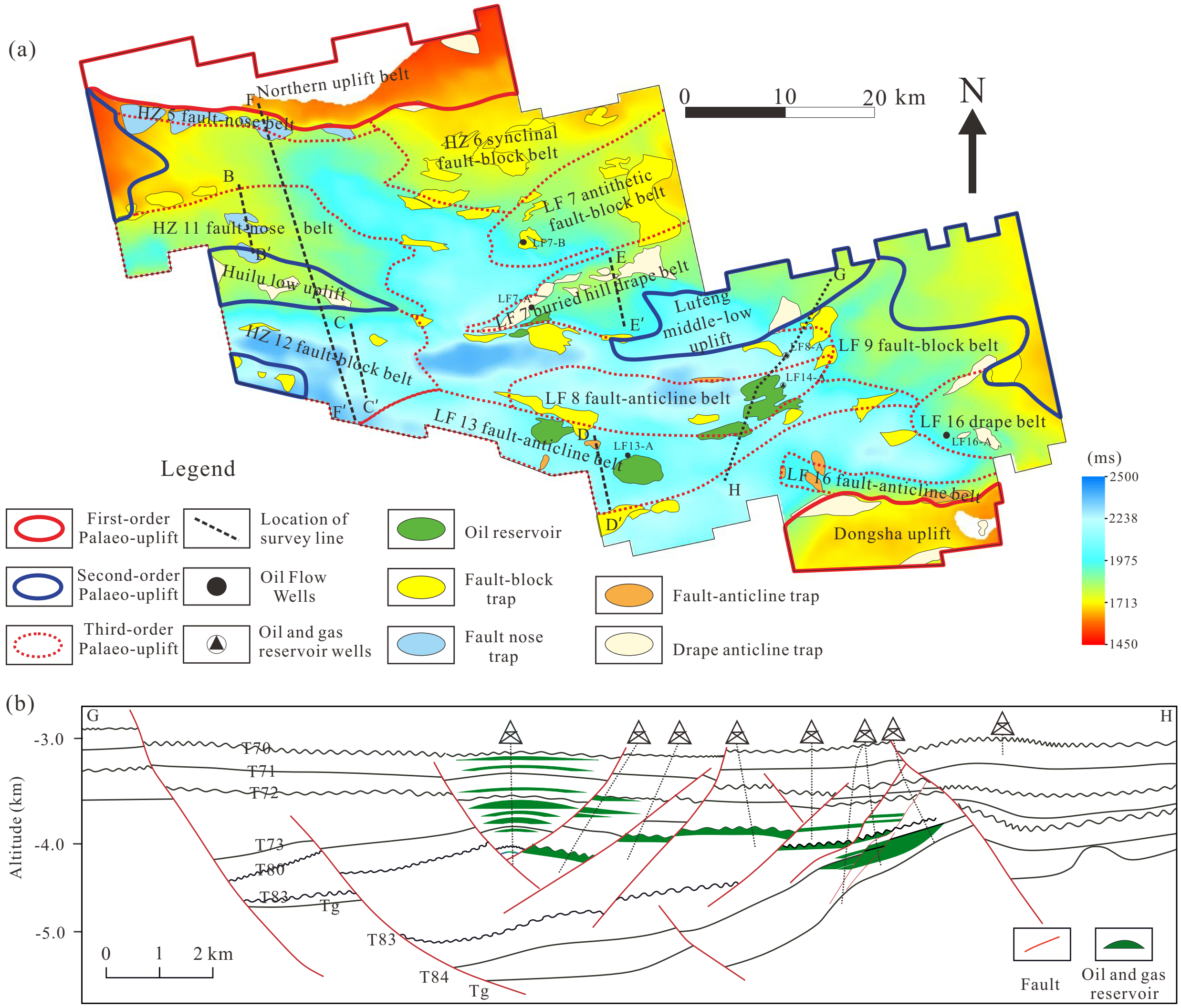


Fig. 3. Distribution map of palaeo-uplifts, traps and reservoirs in the Lufeng Depression.

Formation (N_1zh)-Hanjiang Formation (N_1h), and Yuehai Formation (N_1y)-Wanshan Formation (N_2w)-Quaternary (Q) (Fig. 2, Yu et al., 2016; Ge et al., 2018).

Affected by the early NW-trending stress field and the late approximate NS-trending stress field, the tectonic traces are mainly NEE and approximate EW trending. Influenced by the division of the Lufeng middle-low uplift, the Lufeng Depression can be divided into the Lufeng South sub-depression and the Lufeng North sub-depression, forming a structural pattern of “two depressions and one uplift” as a whole. The internal sub-depression can be further divided into different sags. From south to north, the position of sags are LF 15, LF 13 East, LF 13 West, LF 7, HZ 11, and HZ 5 (Fig. 1). The faults developed at the edge of each sag can be divided into depression-controlling, sag-controlling, and belt-controlling faults. The trend can be classified into NNE, NNE, NWW, etc.

According to the residual thickness of Wenchang and Enping Fms, the morphological characteristics of the main seismic reflection layers, and the boundary faults or isopach lines of specific strata, the paleo-uplift in the Lufeng Depression can be divided into three levels (Figs. 1 and 3(a)).

1) The first-order uplift corresponding to the depression level is mainly distributed in the Northern uplift belt and the Dongsha uplift. These palaeo-uplifts are relatively large-scale, mainly formed due to the extrusion of pre-Cenozoic folds and affected by the early NW-trending and late N-S-trending stress fields, so the internal structural traces are mainly in the NEE and nearly E-W directions.
2) Relatively second-level uplifts such as the Lufeng middle-low uplift and the Huilu low uplift are called second-order palaeo-uplifts. This type is also a paleo-geomorphic uplift formed by early pre-existing structures, but it remained fairly stable in the later development process, and its activity rate was relatively lower than that of the first-order uplift. The second-order uplifts have an important impact on the pattern and structural evolution of internal depression.
3) The third-order palaeo-uplift mainly refers to the structural belt formed by the combination of a series of uplift structures (buried hills, anticlines, faulted anticlines,

etc.). It is similar to the so-called third-order structural belt, which is a complex composed of adjacent third-order structures with the same genetic connection and common development history (including other types of traps associated with the third-order structures).

3. Distribution and evolution of palaeo-uplifts

3.1 Classification and distribution

Secondary structural belts are defined as positive structural units composed of tertiary structures with the same origin. The present study follows the following principles when dividing and naming secondary structural belts in the Lufeng Depression: (1) Under the existing framework of the division of secondary structural units (uplift and depression), the scope of the divided secondary structural belts should follow the guidelines of being small and short, and try not to cut the boundaries of secondary structural units. However, the traps controlled by the boundary faults of some secondary structural units, whether on the uplift (hanging wall) or in the depression (footwall), have the same origin and are controlled by the fault, so they are classified as a structural belt. At this time, the extent of secondary structural belts crosses the boundaries of secondary structural units. Some slope belts also cross the boundaries of secondary structural units. (2) The boundary of the secondary structural belt is subject to the distribution range of existing traps. If faults are the controlling factor, the extension range of faults is considered. (3) The division of secondary structural belts shall comprehensively consider the structural location, the main controlling factors of traps, and the main controlling faults. The naming of secondary structural belts should reflect both the structural location and the type (Figs. 3(a) and 4(e)).

The third-order palaeo-uplifts are mainly distributed in the marginal areas of sags and uplifts, are small in scale and mainly distributed in bands (Fig. 3). This type of palaeo-uplift is often a compound hydrocarbon accumulation zone, which has a controlling effect on oil and gas. At the same time, not only there are structural traps but also different stratigraphic and lithological traps. The third-order palaeo-uplifts can be divided into four types according to the structural location, main controlling factors of traps, main controlling faults, etc., as follows:

1) Fault-nose structural belt (Fig. 4(a)): This formation type is related to fault activity and basement uplift. Most of the nose-shaped structures are formed on the hanging wall, or the palaeogeomorphology of the basement structural layer is inclined to the depression, forming a deflection or uplift, on which the Paleogene is overlaid to form a nose-shaped uplift belt. The typical Huizhou 11 fault-nose belt is located on the north side of the Huilu low uplift, with the Enping Fm draping over it to form a nose-shaped uplift belt.
2) Fault-block structural belts (Fig. 4(b)): The formation of fault-block belts is related to the activity of contemporaneous faults. Because the strata between the faults rotate with the same or opposite tendency to the faults, a stepped structure is formed. It has a combination of block construction. A typical one is the Huizhou 12 fault-block belt, which presents a step-shape with north-faulting and south-overlapping, and is divided into two by a large-scale fault, forming two large-scale fault block structures.
3) Fault-anticline structural belt (Fig. 4(c)): This is caused by reverse normal fault activity during the rifting period, cutting the basement into several tilting fault blocks, and the fault ceases activity with the end of rifting, forming a faulted anticline in the lower structural layer. The typical LF 8 fault-anticline belt is located between the LF 15 Sag and the LF 13 East Sag.
4) Buried hill drape structural belt (Fig. 4(d)): The development of drape structural belts is closely related to the development of basement buried hills. Before the rifting process, weathering and denudation resulted in the formation of residual hill-shaped landforms or rifts. During the rifting process, the basement flexed and uplifted to form a fault block mountain, on which the Paleogene sedimentary caprock was deposited in the form of overlay or drape, thus forming a buried hill drape structure. A typical such structure is the LF 7 buried hill drape structural belt. The basement forms a fault-block mountain, and the Wenchang Fm stratum is missing. The Enping Fm is thin and directly overlaid on the basement, and a buried hill drape structure is developed.

On the whole, the grades and types of different uplifts have an important relationship with the distribution and structural characteristics of the Lufeng Depression. They not only restrict the structural characteristics of the sag or internal depression but also have a significant impact on sedimentation.

3.2 Structural evolution characteristics

The structural evolution process of the profile was recovered using the balanced profile technique (Fig. 5) and was based on the stratigraphic development history. The structural evolution of the palaeo-uplift in the Lufeng Depression is divided into three main stages.

The first stage is the rifting period. During the depositional period of Wenchang and Enping Fms, an uplift pattern was formed in the depression. The distribution range of the first-order and second-order uplifts is fixed, and the large faults at the joint boundary of these two types of uplifts control their structure and distribution in the depression. With the continuous intensification of subsequent multi-episode rifting, the faulting activities became intense, forming large-scale fault block tilting, uplifting and other structures, which provided the conditions for the development of buried hills. In general, early rifting controlled the basic conditions and structural framework for the formation of the basement palaeo-uplift in the depression.

The second stage is the thermal subsidence period. During the depositional period of Zhuhai to Zhujiang Fms, the palaeo-uplift continued to develop. During the late deposition of the Zhuhai Fm, the rifting gradually weakened, and the Lufeng Depression entered a stable thermal subsidence stage as a whole. Later, the transgression began, and marine sedimentary

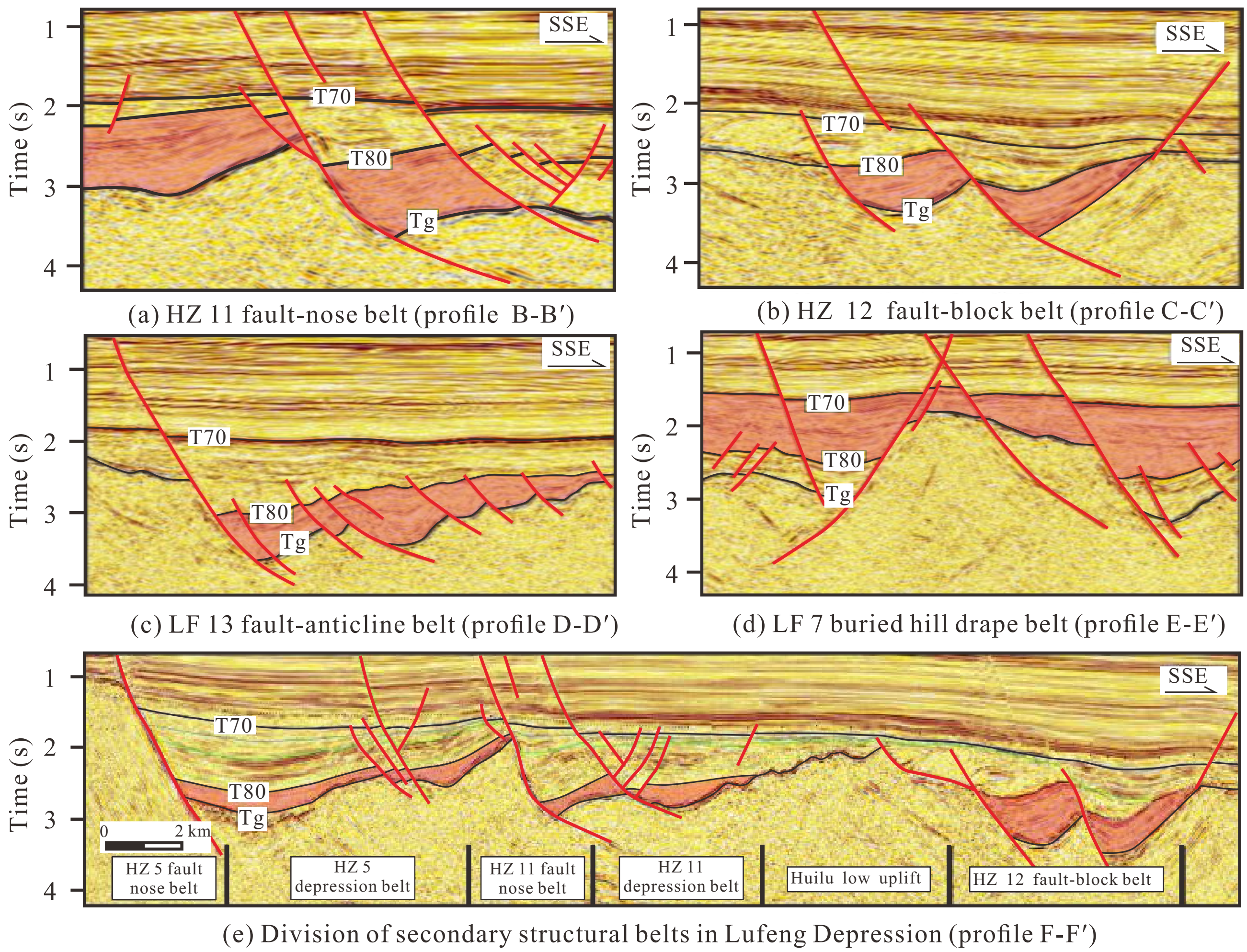


Fig. 4. Types of the main palaeo-uplift structural belts in the Lufeng Depression (for section locations, see Fig. 3).

caps were formed in the Lufeng Depression, which were overlaid on the early paleo-structure background. The structural shape and scale of the palaeo-uplift changed to a certain extent, but it generally inherited the characteristics of the earlier palaeo-uplift.

The last stage is the late structure activation period. During the deposition of the Hanjiang Fm, the palaeo-uplift underwent a certain scale transformation. Under the action of the later Dongsha event, large-scale faults were activated and some new faults developed, leading to the formation of the tilting anticline. At the same time, with the rotation and flexural uplift of the fault block, the scale of the early buried hill structural belt and the arch-tensional anticline also transformed to a certain extent. However, it had little effect on the first-order palaeo-uplift, and the overall morphological changes were small, basically inheriting the developmental characteristics of pre-existing structures.

Judged by the above structural evolution characteristics, the structural evolution of different levels of palaeo-uplifts in the Lufeng Depression has experienced three stages. The embryonic development in the rifting period, inheritance in the thermal subsidence period, and adjustment and transformation in the activation period generally correspond to the developmental characteristics of “inheritance as the main, transformation as the auxiliary”.

4. Characteristics of paleo-uplift controlled hydrocarbon reservoirs

4.1 Plane distribution of hydrocarbon reservoirs

Palaeo-uplift is the point of oil and gas transport and the place of accumulation, which controls the distribution range of oil and gas. It should be pointed out that this process is the uplift during the accumulation period rather than the current uplift that controls the distribution range of oil and gas. The oil and gas distribution of certain current reservoirs may have a less obvious relationship with the present-day uplift, possibly due to the migration or disappearance of the original uplift as a result of tectonic evolution. In this case, it is necessary to study the history of oil and gas formation and recover the characteristics of palaeo-uplift during the accumulation period, to better understand the relationship between oil and gas reservoirs and the palaeo-uplift. Therefore, the formation and development characteristics of palaeo-uplift need to be clarified to predict the possible distribution range of oil and gas reservoirs.

Under the condition of sufficient oil resources, the larger the distribution range of the palaeo-uplift, the greater the range and quantity of oil and gas distribution may be (Li et al., 2017). The Lufeng Depression presents the feature of a "full belt with oil" on the plane, and both deep and shallow oil reservoirs exhibit the feature of "ring distribution". Among them, Neogene oil reservoirs are distributed far away from the hydrocarbon-generating sag. Meanwhile, the Paleogene oil reservoirs are mainly distributed in the LF 7 buried hill drape belt, the LF 8 fault-anticline belt, the LF 14 fault-block belt, and the LF 13 fault-anticline belt. The LF 13 structural belt is the most abundant one in oil and gas, followed by the sub-sag uplift area, which is located in the inner ring accumulation area, showing the characteristics of near-source accumulation. On the whole, the palaeo-uplift controlled the main direction of oil and gas migration and the apex of convergence in the Lufeng Depression. The discovered oil and gas reservoirs were arranged in the NW trend and accumulated in the top traps of the palaeo-uplift (Fig. 3).

4.2 Types of traps

After experiencing multiple stages of tectonic events and sedimentary cycles, the Lufeng Depression formed several types of fault noses (Fig. 4(a)), fault blocks (Fig. 4(b)), faulted anticlines (Fig. 4(c)), and drape anticlines (Fig. 4(d)). At the same time, the formation and evolution of palaeo-uplifts controlled the formation of structural belts and further governed the formation and evolution of traps (Fig. 3). Since the structural evolution of the palaeo-uplift exhibits the characteristics of inheritance as a whole, this determines the particularity of trap development conditions. During the Shenhu event in the early stage of rifting, buried hill structures related to the basement uplift pre-existing structures were mainly formed in the Lufeng Depression. During the first and second episodes of the Zhuqiong event, the fault activity was strong. The lacustrine sediments (Wenchang and Enping Fms) directly overlaid on the basement buried hills, forming syngenetic structures with thin roofs and thick wings, and complex traps formed by overlying and annihilating the sand bodies of the Wenchang and Enping Fms developed around the structural traps. The structural activity was weak during the subsequent thermal period, and bio-lithological traps were easily formed. In the late faulting period, the NWW-trending faulting activity that occurred in the early stage gradually increased, which not only transformed the old overlying anticlines but also affected the early formation of the anticline. Since then, the traps have been strengthened and promoted, forming a variety of traps with the characteristics of horizontal connection and vertical overlap.

4.3 Hydrocarbon migration and accumulation

The uplift is located in the low potential area of hydrocarbon fluid migration in the hydrocarbon accumulation unit, which is one of the favorable places for hydrocarbon accumulation (Schowalter, 1994). At the same time, the early structure of the Lufeng Depression was mostly half-graben or duplex half-graben. Steep or gentle slope belts are developed around palaeo-uplifts and buried hills, and the strata containing source rocks are overlaid in the direction of palaeo-uplifts, which is favorable for oil and gas to climb and migrate along slopes or faults. Finally, the structural ridges, source faults and unconformities controlled by the palaeo-uplift will all serve as dominant migration paths for oil and gas to the palaeo-uplift (Fig. 6). When restoring the plan of the structural ridge distribution range of the Enping Fm in the T32 depositional period of the Lufeng Depression by software, it can be seen that the existing oil and gas reservoirs are distributed on the structural high where the structural ridge is the dominant hydrocarbon migration path.

5. Quantitative characterization and favorable area prediction

The method to describe quantitatively the reservoir-controlling effect of palaeo-uplift is mainly based on the theory of "multi-functional elements matching the reservoir-forming model" proposed by scholars such as Pang et al. (2010). This method, which is mainly based on the comprehensive analysis of regional geology according to the top structural map of the target layer, determines the distribution range of the palaeo-uplift. At the same time, the paleo-uplift units are normalized and segmented. Then, the number of discovered oil reservoirs or reserves in different segments of the palaeo-uplift are counted to establish a mathematical model. In this way, the probability and probability plane distribution of palaeo-uplift controlling reservoirs can be calculated, and the range of favorable reservoir-forming areas controlled by palaeo-uplifts can be determined.

5.1 Quantitative characterization

1) Compilation of the structural map of the target layer during the accumulation period. By investigating and summarizing the previous research results, it is established that the main hydrocarbon-generating depressions in the Lufeng Depression and the hydrocarbon-generating and expelling periods of source rocks have been determined (Fig. 2, Peng et al., 2015; Yan, 2016; Li et al., 2017; Zheng et.al., 2018). The source rocks in the Lufeng Depression are mainly in the third and fourth members of the Wenchang Fm of Paleogene. Large-scale hydrocarbon expulsion occurred in the Lufeng Depression around 8-6 Ma. Therefore, the contour map of the top structure during the accumulation period should be firstly restored, and the main target layers can be predicted as five strata, including the upper and lower members of the Wenchang and Enping Fms, and the Zhuhai Fm.
2) Determination of the distribution range of regional palaeo-uplifts during the accumulation period. According to the comprehensive analysis of the palaeo-uplift and its related structures in the Lufeng Depression, the distribution range, evolution process, and reservoir-controlling role of the third-order palaeo-uplift are clarified. Combined with the structural contour map of the target layer,

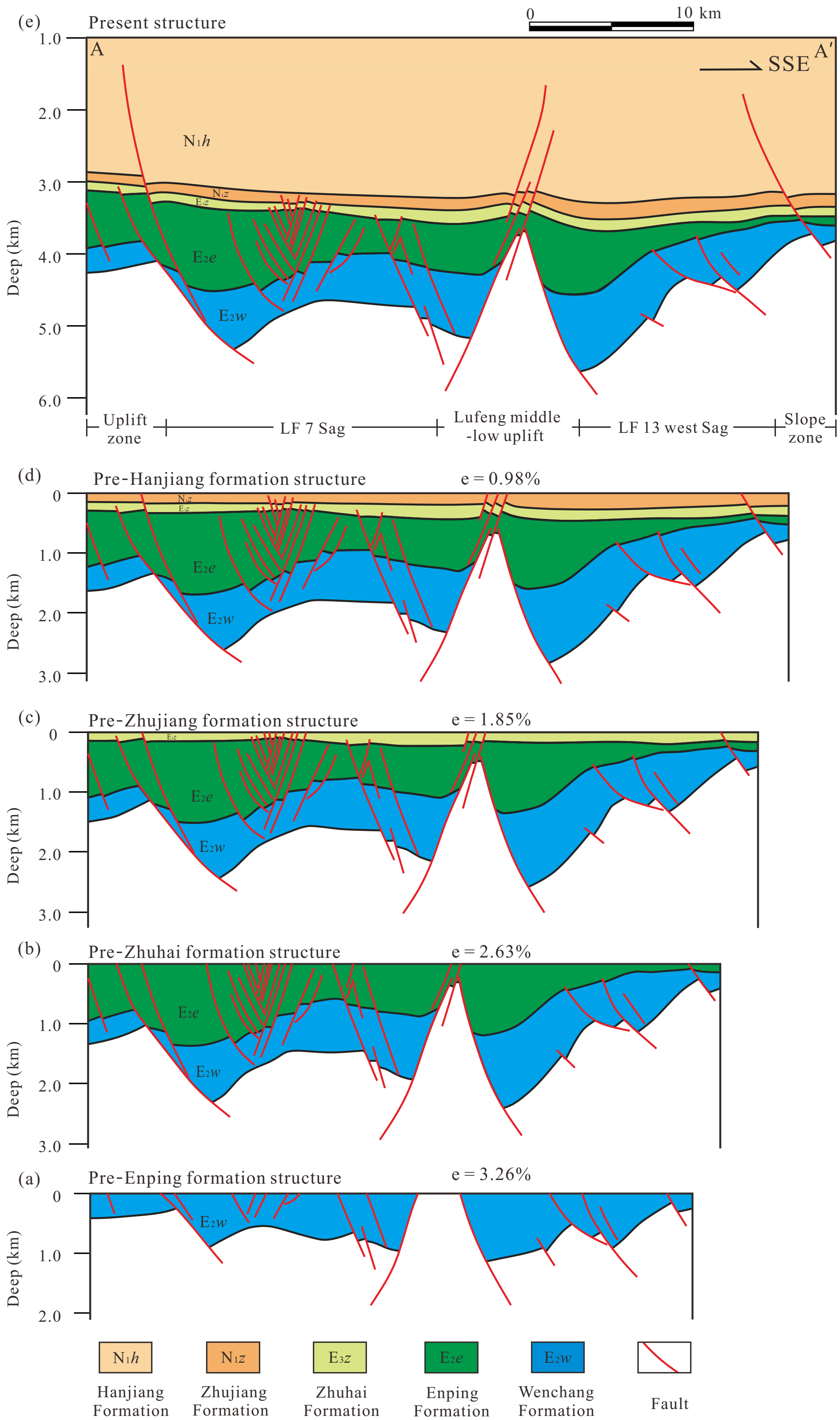


Fig. 5. Structural evolution profile (for section locations, see Fig. 1).

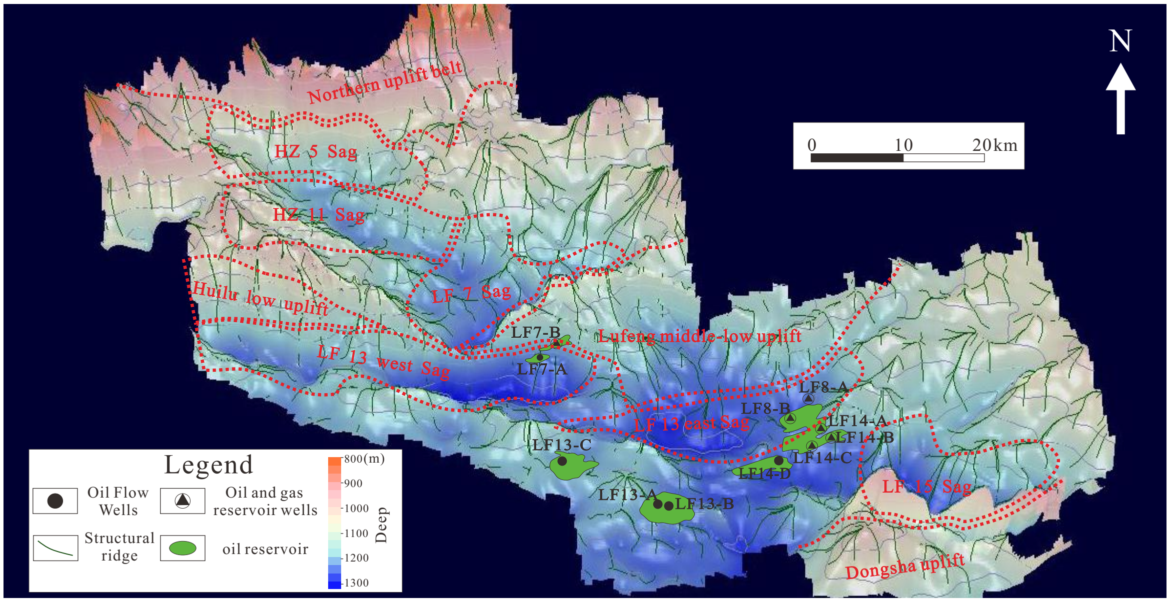


Fig. 6. Distribution map of structural ridges in the Enping Fm during the depositional period of T32 in the Lufeng Depression.

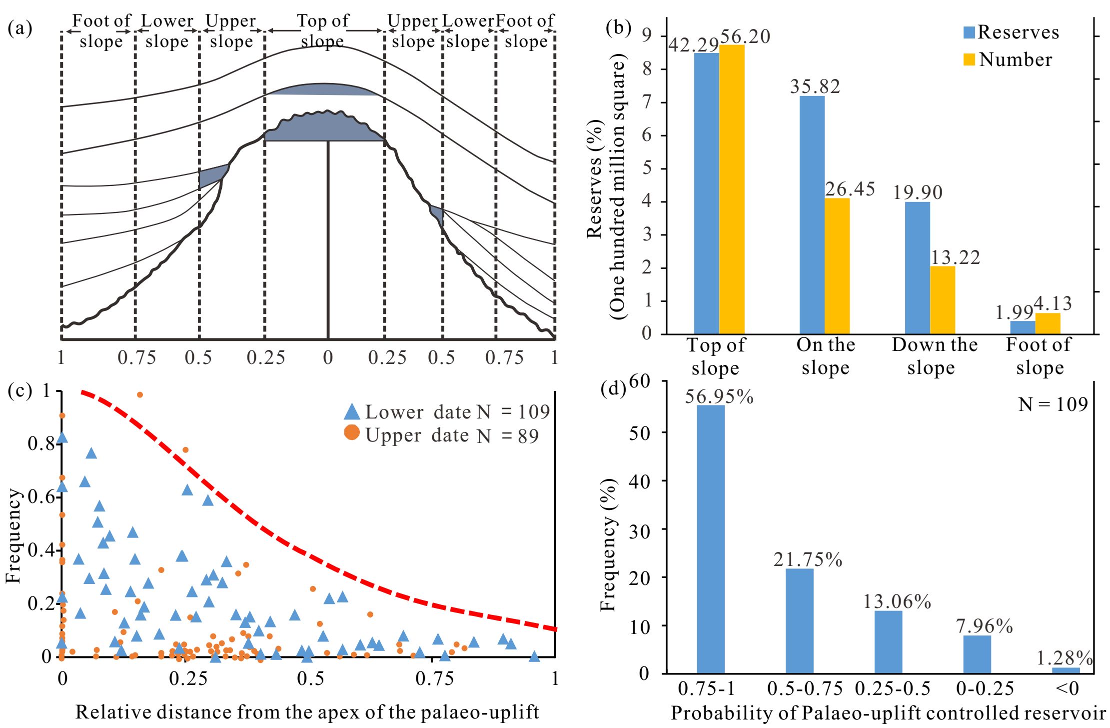
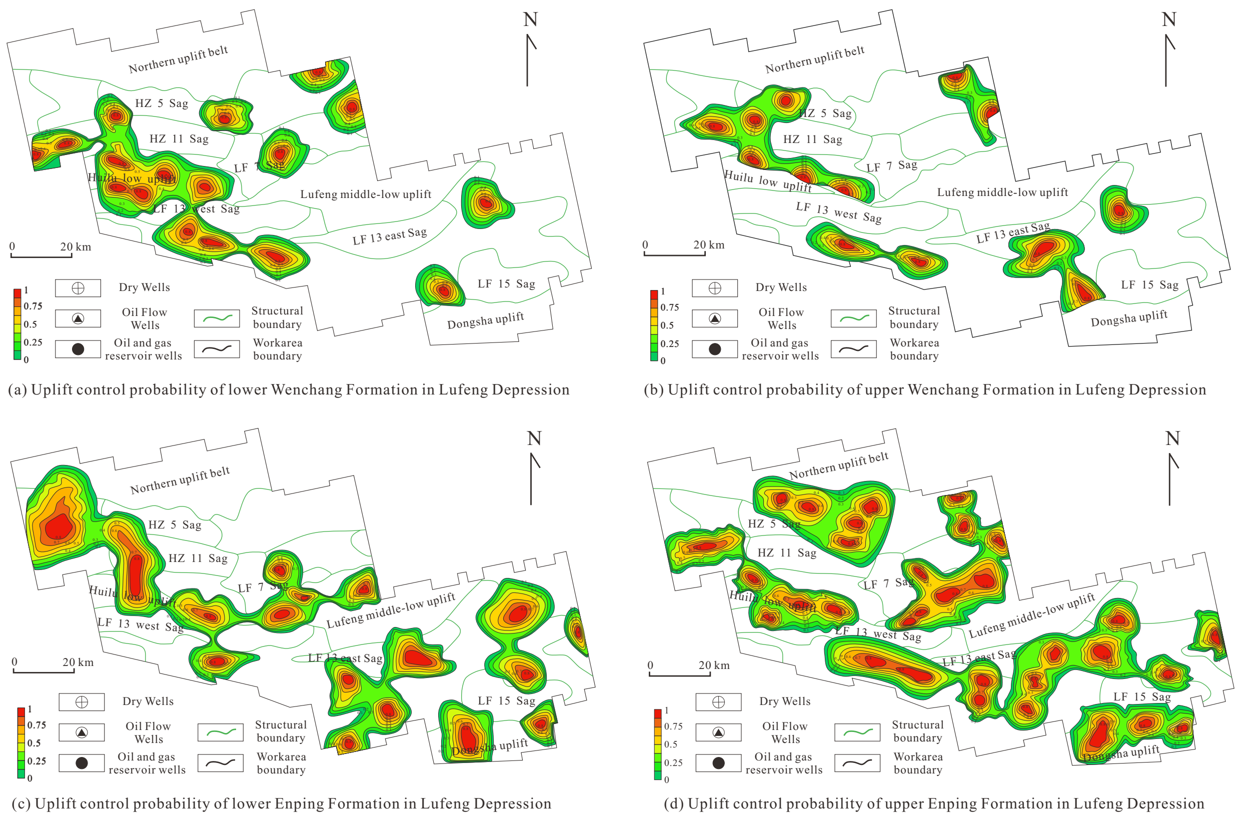


Fig. 7. Characteristics map of palaeo-uplift controlled reservoirs.

the distribution range of the palaeo-uplift of each target layer is determined.

3) Normalized segmentation processing of palaeo-uplifts. Due to the different sizes of the palaeo-uplifts encountered in practical work, to facilitate the statistical analysis and processing of palaeo-uplifts of different scales, this study normalizes the palaeo-uplifts according to the methods described below. The vertex of the palaeo-uplift is set as the origin, and the value is 0. We define the base of the palaeo-uplift extending from the apex into the depression as 1. Therefore, the oil and gas reservoirs under the control of the palaeo-uplift are distributed in the area between 0 and 1. For the convenience of later discussion, the palaeo-uplift can be divided into different units. The foot of the slope, lower slope, upper slope, and top of the slope were defined as $0 \sim 0.25$, $0.25 \sim 0.50$, $0.50 \sim 0.75$, and $0.75 \sim 1.00$, respectively (Fig. 7(a)).

4) Statistics of the number of reservoirs. Two principles should be adhered to in the statistical analysis of palaeo-uplifts (Pang et al., 2010): Trying to select relatively



(a) Uplift control probability of lower Wenchang Formation in Lufeng Depression

(b) Uplift control probability of upper Wenchang Formation in Lufeng Depression

(c) Uplift control probability of lower Enping Formation in Lufeng Depression

(d) Uplift control probability of upper Enping Formation in Lufeng Depression

Fig. 8. Probability map of the palaeo-uplift controlled reservoirs during the depositional period of T32, the main target layer in the Lufeng Depression.

stable and inherited paleo-uplifts, and attempting to select large and medium-sized oil and gas reservoirs formed in the late stage, which have experienced few structural changes, and the adjustment, reformation and destruction are relatively weak. According to the above two criteria, 109 oil and gas fields and oil-bearing structures (several oil reservoir samples) have been discovered. These are superimposed with the normalized palaeo-uplift plan to calculate the percentage distribution of the number of oil reservoirs in different layers. After statistical analysis, it is found that 86.29% of these reservoirs are distributed on the top and upper part of the palaeo-uplift (Figs. 7(b) and 7(c)), and the number of oil fields decreases with the distance to the top of the palaeo-uplift. This shows that the slope area from the top of the palaeo-uplift and its vicinity is the most enriched part, and it is the key area for future exploration and deployment (Figs. 7(a) and 3(b)).

5.2 Mathematical model for probability

According to the quantitative statistical relationship of palaeo-uplift controlled reservoirs, the normalized number distribution is converted into reservoir-forming probability (Fig. 7(c)). Through data fitting, a mathematical model of the accumulation probability of different parts of the palaeo-uplift in the Lufeng Depression is established:

$$y = 190.51e^{-0.906x} \tag{1}$$

where y denotes the probability of palaeo-uplift controlling the reservoir, which is dimensionless; x is the relative distance from the oil and gas reservoir to the vertex of the positive structural unit, which is also dimensionless.

Therefore, according to the distribution range of the palaeo-uplift and the location of its high point, the probability of the palaeo-uplift controlling the reservoir can be calculated.

5.3 Prediction and evaluation of distribution zones

According to fitting formula Eq. (1), combined with the paleo structural map of the accumulation period, the uplift control probability distribution map of four main target layers was drawn (Fig. 8). On the whole, the probability distribution of uplift control based on the structural map of the target layer matches the distribution characteristics of regional palaeo-uplifts. In addition, the probability distributions of uplift control of the four sets of target formations have certain similarities. From the lower Wenchang Fm to the upper Enping Fm, the favorable zones for uplift control and accumulation are developed in the southwest of HZ 5 Sag, HZ 11 Sag, west of LF 13 Sag, LF 7 Sag, east of LF 13 Sag, and LF 15 Sag (Fig. 8), reflecting the inherited control of the evolution of palaeo-uplift in the Lufeng Depression. According to the probability map of palaeo-uplift controlled reservoirs in the main target layers of the Lufeng Depression, the most favorable areas for palaeo-uplift controlled reservoirs are located in the Lufeng middle-low uplift, the Dongsha uplift, and the inner steep slope area of sags. At the same time, inside the sags, such as the LF 13 East Sag, the uplift within sags is also an area with a high probability of palaeo-uplift controlled reservoirs.

5.4 Reliability test

The reliability inspection of palaeo-uplift reservoir control passed the back-generation inspection of discovered oil and gas reservoirs, failed well inspection, and high-yield good inspection.

1) According to the current distribution of oilfields in the Lufeng Depression, except for a few small-scale oil-bearing structures, all reservoirs are within the probability distribution of uplift control, and most of them are high-probability reservoirs. The back-substitution analysis of the number of oil and gas reservoirs shows that 78% of the oil and gas reservoirs are distributed in the range of uplift control probability that is greater than 0.5, and 91.06% of the oil and gas reservoirs are distributed in the range of uplift control probability that is greater than 0.25 (Fig. 7(d)). Therefore, it is proved that palaeo-uplift is one of factors controlling accumulation.
2) In this study, 27 failed wells were selected for statistical analysis according to different target layers. A total of 26% of the wells were outside the accumulation probability or within the range of less than 25% of the accumulation probability. These failed wells were mainly controlled by a single element of the palaeo-uplift. However, at the same time, there are also some failed wells in favorable accumulation areas, which are mainly related to accumulation factors such as source rocks, traps, reservoirs, caps, or oil and gas migration (Peng et al., 2015).

On the whole, the test results show that the quantitative prediction of palaeo-uplift controlled reservoirs has certain feasibility and reliability.

6. Conclusions

1) There are three orders of paleo-uplifts in the Lufeng Depression, which are divided into first-order uplifts, second-order uplifts, and third-order uplifts. They have experienced three structural evolution stages. Embryonic development in the rifting period, inheritance in the thermal subsidence period, and adjustment and transformation in the activation period generally correspond the developmental characteristics of “inheritance as the main, transformation as the auxiliary”.
2) The range of palaeo-uplift in the Lufeng Depression controls the distribution range of plane oil and gas, and its reservoir-controlling effect is reflected not only in controlling various types of traps (fault block, fault nose, fault anticline, draped anticline, etc.) but also governing the dominant path of hydrocarbon migration and accumulation. Hydrocarbon tend to follow the gentle slope or steep slope belt, and the uplift to the high part accumulates.
3) Geological and mathematical models of the distribution range and probability of oil and gas reservoirs under the control of palaeo-uplifts are established. The critical condition for the palaeo-uplift to control the reservoir in the Lufeng Depression is determined, that is, 86.29% of reservoirs are distributed on the top and upper part of the palaeo-uplift, and the number of oil and gas fields increases with the decreases of the distance from the top of palaeo-uplift. The areas with a high probability of palaeo-uplift controlled reservoirs are the Lufeng middle-low uplift, the Dongsha uplift, and uplifts within sags.

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Conflict of interest

The authors declare no competing interest.

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