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Hydrocarbon accumulation model based on threshold combination control and favorable zone prediction for the lower Enping Formation, Southern Lufeng sag

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Abstract:
Deep complex oil and gas reservoirs are the future directions of oil and gas exploration. The exploration potential of Paleocene deposits in the Lufeng sag is enormous. However, due to the greater burial depth and complex oil and gas accumulation conditions of the Paleocene, few large-scale reservoirs have been discovered and the next exploration strategy is unclear. In this study, based on the Paleocene geological data of the Southern Lufeng sag, a model of hydrocarbon accumulation based on functional element control is constructed using geostatistical and numerical simulation techniques. The hydrocarbon accumulation elements, thresholds, boundaries and scopes are clarified, and the favorable zones of hydrocarbon accumulation of the lower Enping Formation are predicted using the model of hydrocarbon accumulation based on threshold combination control. The results indicate that the source rock, reservoir, caprock, and low-potential area are the four functional elements controlling hydrocarbon accumulation. Since there are three types of low-potential zones, a total of six accumulation elements are considered to control hydrocarbon accumulation, and the corresponding hydrocarbon accumulation control thresholds are determined by the model of hydrocarbon accumulation according to the controlling effects of these accumulation elements. The predicted Type I favorable zones are located in the eastern part of Lufeng 13 east sub-sag and the northern and southern parts of Lufeng 7 sub-sag; Type II favorable zones are located in the western part and around the Lufeng 13 east sub-sag; Type III favorable zones are adjacent to Type II favorable zones. The hydrocarbon shows are all located in the overlapping zone of five or more accumulation elements.

1. Introduction

With the advancement of technology and the rising energy demand in China, deep oil and gas exploration has received increasing attention. The shift of oil and gas exploration from shallow to deep has become the trend in the development of the petroleum industry (Wang et al., 2019c). In recent years, many important breakthroughs have been achieved in oil and gas exploration and development in deep reservoirs (Xu et al., 2018). However, the geological characteristics of such reservoirs are complex and often characterized by the superposition of multi-phase diagenesis, complex reservoir evolution history and strong reservoir heterogeneity, which are limitations of deep oil and gas exploration (Zhong and Zhu, 2008; Xu et al., 2018).

The prediction of favorable zone has been the main focus of oil and gas exploration (Masson and Miles, 1986; Magoon and Dow, 1994; Jia et al., 2012; Wang et al., 2019a). In particular, in offshore oil fields, due to the high cost and technical difficulty of well drilling, the improved reliability of favorable zone prediction can help improve the success rate of drilling and reduce exploration costs, which has long been

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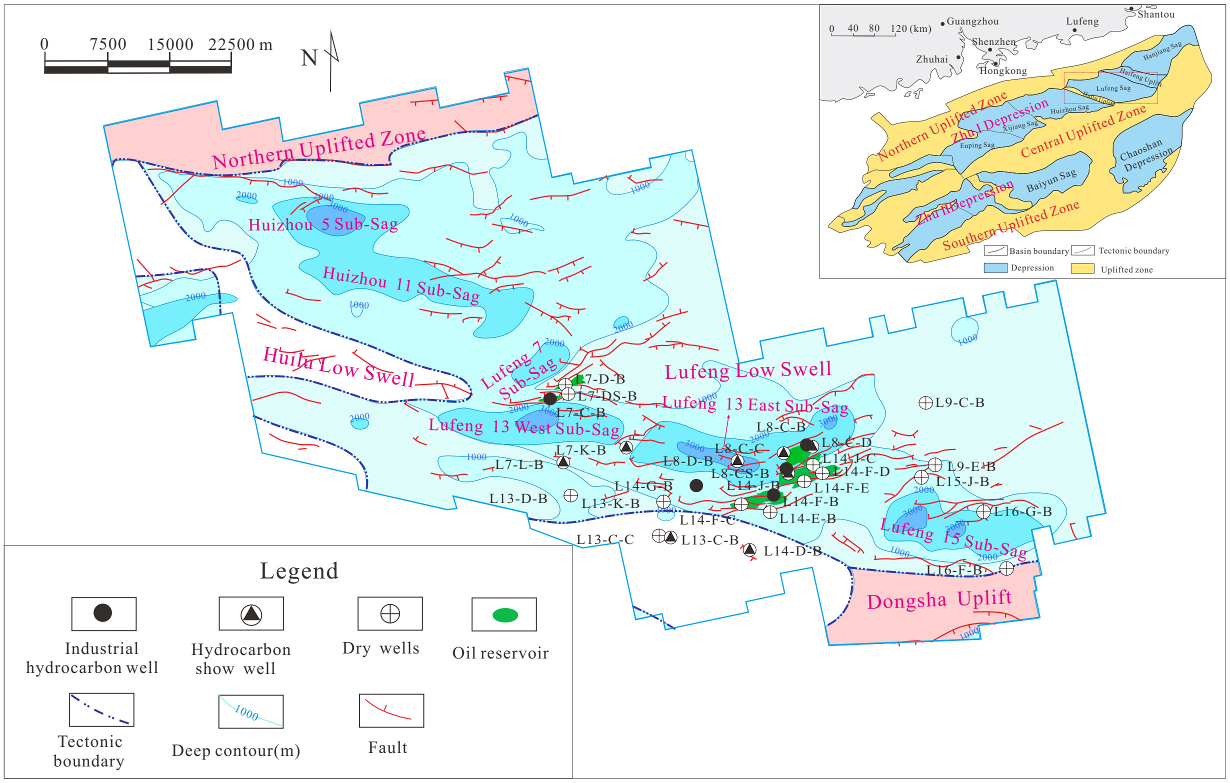

Fig. 1. Geographic location and plane distribution of Paleogene hydrocarbon reservoirs in Lufeng sag.

the goal of petroleum explorers and petroleum companies (Wu, 1985; Magoon and Dow, 1994; Wang et al., 2019b). In the early period of geological theory development, the prediction of favorable zones mainly relied on the anticline-controlled hydrocarbon accumulation theory (White, 1885), the trap-controlled hydrocarbon accumulation theory (McCollough, 1934), and the source-controlled hydrocarbon accumulation theory. Nowadays, the principal methods used to predict the formation and distribution of hydrocarbon reservoirs are the basin simulation method and the common risk segment (CRS) mapping method (Demaison and Huizinga, 1991; Perrodon, 1992; Magoon and Dow, 1994; Surdam, 1997; Wang et al., 2019b). However, these petroleum geological theories and exploration techniques successfully applied to shallow formations are unsuitable for the exploration and development of deep hydrocarbon resources.

The Lufeng sag is a significant petroleum-rich sag in the Pearl River Mouth Basin (Wang et al., 2019c), which is a major petroliferous basin in the South China Sea (Dong et al., 2009). Almost all of the discovered hydrocarbon reservoirs come from the source rocks of the Wenchang and Enping Formations (Zhu et al., 2009; Raji et al., 2015). However, oil and gas exploration in the Paleocene system has been restricted due to many factors, such as the high cost of offshore exploration, difficulty of data acquisition, relatively large burial depth, relatively worse reservoir properties, complex hydrocarbon formation conditions characterized by diverse hydrocarbon reservoir types, multiple sets of source rocks, multiple hydrocarbon generation centers, and multiple phases of hydrocarbon accumulation.

In this study, an improved method is utilized to predict the favorable zones in the lower Enping reservoir of the Lufeng sag. First, the features of functional elements controlling hydrocarbon enrichment, including source rock, reservoir, caprock, and low-potential zones, are analyzed in the lower Enping Formation. Second, a numerical model for hydrocarbon enrichment control for each functional element is established. Then, the thresholds for each functional element are recognized. Finally, a favorable hydrocarbon accumulation zone is predicted by the model of hydrocarbon accumulation based on threshold combination control. The research results have an important guiding significance for oil and gas exploration in the Lufeng sag, while the research methods can assist with the exploration of deep offshore petroleum reserves.

2. Geological setting

The Lufeng sag is located in the northeast of Zhu I Depression in the Pearl River Mouth Basin, with an area of about 7760 km^2 (Ma et al., 2022). It is northeast oriented, with the Lufeng low swell in the east, the Huilu low swell in the west, the northern uplift zone in the north, and the Dongsha uplift in the south. It contains six sub-sags. Since most of the currently drilled hydrocarbon shows are concentrated in the southern part of the sag, the study area is mainly in the Southern Lufeng sag, including Lufeng 13 west sub-sag, Lufeng 13 east sub-sag and Lufeng 15 sub-sag, among which the Lufeng 13 east sub-sag and Lufeng 15 sub-sag are the main hydrocarbon-rich sub-sags. The discovered hydrocarbon reservoirs are mainly located around the Lufeng 13 east sub-sag and the southern part of the Lufeng 15 sub-sag (Fig. 1). The conventional hydrocarbon reservoir types discovered in the Southern Lufeng sag mainly include the L7-C-B anticline hydrocarbon reservoir, the L8-C-B anticline hydrocarbon reservoir, the L14-G-B fault hydrocarbon reservoir, and the L14-F-B hydrocarbon reservoir (Ma et al., 2022).

The Lufeng sag was subject to sedimentary processes from terrestrial to marine facies during the Cenozoic (Shi et al., 2014; Chen et al., 2020), and is mainly a set of terrestrial-marine clastic rocks sediments. The Shenhu Formation is missing in the Lufeng sag, and the Wenchang Formation shows disconformity or unconformity on top of the pre-Paleocene basement (Zhu et al., 2009). The Lufeng sag Paleocene was mainly developed, from bottom to top, from the Wenchang Formation, Enping Formation and Zhuhai Formation. Among them, the Enping Formation is mainly a marsh, fluvial and lacustrine sedimentary facies, and the gray and dark gray mudstones of the shallow-lacustrine facies are included in the source rocks in the study area (Peng et al., 2016). The strata above the Enping Formation mainly consist of marine to littoral facies sediments. The reservoir-caprock assemblages in the upper Wenchang and Enping Formations are mainly composed of the sandstone reservoirs sedimented in the meandering river channel, braided delta and shallow lacustrine facies, as well as the partial mudstone caprocks sedimented in semi-deep to deep lacustrine, floodplain or shallow lacustrine facies. In this paper, the Paleocene Wenchang and Enping Formation are the main target Formations, and the lower Enping Formation is used as an example to predict the favorable hydrocarbon exploration zone.

3. Methods

The formation and distribution of hydrocarbon reservoirs are controlled by many factors (Magoon, 1987; Lerche and Thomsen, 1994; Magoon and Dow, 1994). During the mechanism of hydrocarbon accumulation, the hydrocarbon distribution threshold concerns the critical geological conditions that control the formation, evolution and distribution of hydrocarbon reservoirs. Using geological analysis, statistical analysis and numerical simulation for discovered hydrocarbon reservoirs in mature exploration areas, Pang et al. (2015) identified four key elements that are independent of each other and indispensable for reservoir formation and distribution, and revealed their critical hydrocarbon control thresholds, which are called functional elements. These are the conditions of source rock (S), reservoir (D), caprock (C), and low-potential zone (P). The latter is subdivided into palaeohigh zone (M) with low potential energy, fault zone (F) with low-pressure energy, and sandstone reservoir (L) with a large capillary force difference due to low interface potential energy. Hydrocarbons are controlled by the three potential energies to form anticline hydrocarbon reservoirs in the palaeohigh zone, fault hydrocarbon reservoirs near the fault zone, and lithologic hydrocarbon reservoirs in the sandstone reservoir with large capillary pressure difference (Pang et al., 2021). That is, four major functional elements and six accumulation elements control oil and gas accumulation. Each functional element has a certain controlling effect on hydrocarbon accumulation, with a threshold, boundary and range of control. Hydrocarbons can only accumulate under the functional element threshold control, and hydrocarbon reservoirs can only be found within the hydrocarbon accumulation range controlled by each functional element. At the same time, functional elements are related to each other, and the prediction and evaluation of favorable zones for hydrocarbon accumulation can only be realized only through the composite superposition of the corresponding functional elements in space and time (Wang et al., 2019b).

The superimposed composite of the controlled hydrocarbon accumulation range of each functional element in the plane can predict the favorable zone. The oil and gas accumulation model based on the controlling effect of multiple functional elements, namely the hydrocarbon accumulation control ranges of source rock, reservoir and caprock, are superimposed on the control ranges of the three low-potential zones (P) on the plane to predict the favorable hydrocarbon accumulation zones of the fault hydrocarbon reservoirs (CDFS), anticline hydrocarbon reservoirs (CDMS), and lithologic hydrocarbon reservoirs (CDLS). The final favorable hydrocarbon accumulation zone is expressed as the CDPS favorable zone by the superposition of the three types of favorable hydrocarbon accumulation zones. This paper analyzes the basic geological data of 28 wells, including logging interpretation data, lithology data, and sedimentation and tectonic-related data to establish a model of hydrocarbon accumulation based on threshold combination control for the lower Enping Formation and predicts the favorable hydrocarbon accumulation zone.

4. Results

4.1 Main controlling factors of reservoirs

4.1.1 Source rock

The thickness of Paleozoic source rocks in the center of the sub-sag is generally greater than that around the sub-sag in the Southern Lufeng sag. The discovered hydrocarbon reservoirs are mainly located within and around the source rocks.

The location with the greatest hydrocarbon expulsion intensity (HEI) of source rock is taken as the hydrocarbon expulsion center (HEC), and the ratio of the actual distance from the hydrocarbon reservoir to the HEC and the hydrocarbon expulsion radius of the source rock is taken as the relative distance from the hydrocarbon reservoir to the HEC (Larter and Aplin, 1995). By statistically analyzing the relationship between the relative distance from 32 data points to the HEC and the percentage of hydrocarbon reservoir reserves, a hydrocarbon accumulation model for source rock control can be established and the controlling effect of source rocks on hydrocarbon reservoir formation can be clarified. The results indicate that almost 90% of oil reserves are found in the range of 0.5-1.5 relative distance to the HEC. The further the distance from the HEC, the lower the percentage of reserves found. Moreover, hardly any oil reservoirs can be found when their relative distance to the HEC is greater than 2 (Fig. 2(a)). The hydrocarbon accumulation control threshold for the source

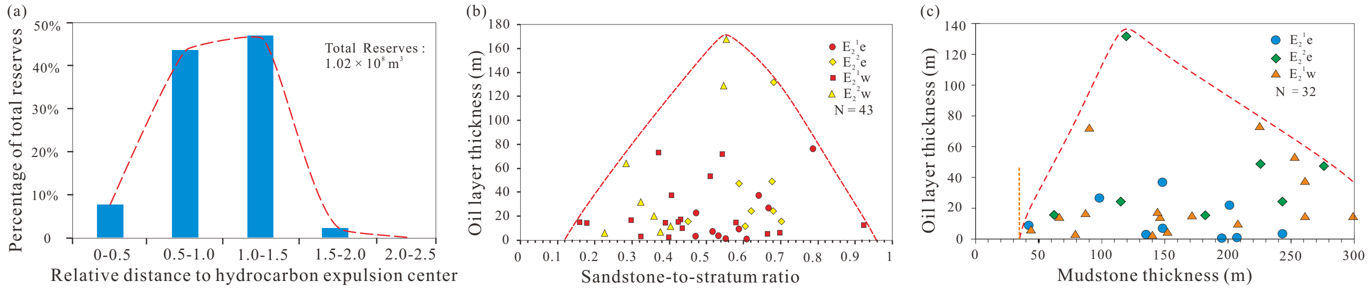

Fig. 2. (a) Reservoir model based on Paleocene source rock control for the Southern Lufeng sag, (b) Relationship between Paleocene sandstone-to-stratum ratio and oil layer thickness in the Southern Lufeng sag (E_2^1e, upper Enping Formation; E_2^2e, lower Enping Formation; E_2^1w, upper Wenchang Formation; E_2^2w, lower Wenchang Formation), (c) Relationship between the thickness of Paleozoic mudstone and the thickness of oil layer in the Southern Lufeng sag.

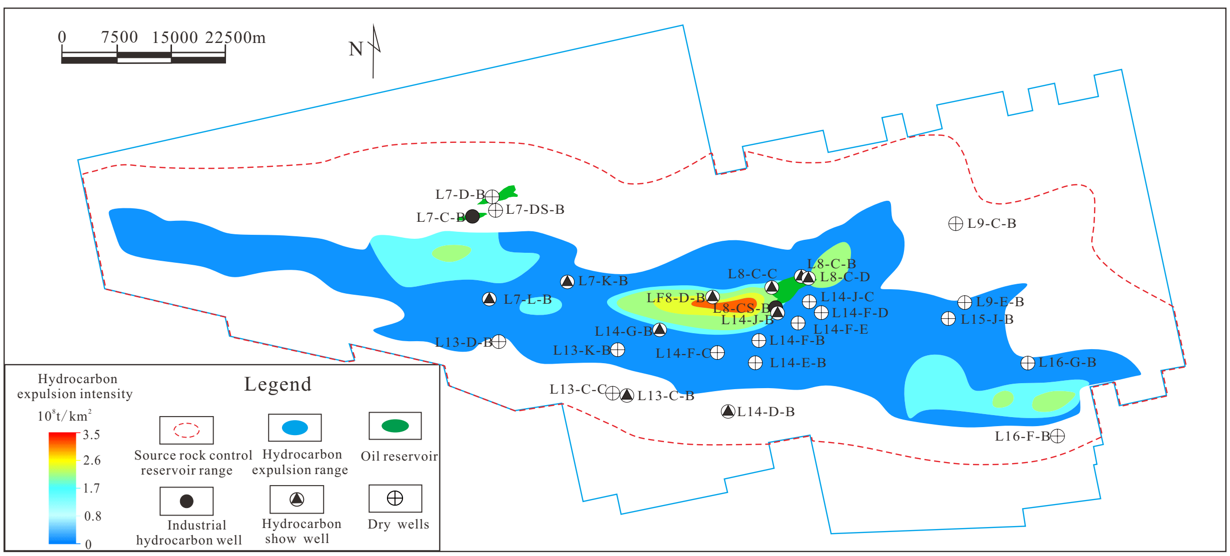

Fig. 3. Cumulative HEI distribution and source rock control range in the Southern Lufeng sag.

rock is twice the relative distance to the HEC, and it is difficult for hydrocarbons to accumulate over this threshold.

The largest HEI in the study area is located in the southwestern part of Lufeng 13 east sub-sag, and its HEI is 3.4×10^8 t/km^2. Most of the discovered oil reservoirs have the characteristic of being distributed around the HEC (Larter and Aplin, 1995). The range of source rock control on hydrocarbon accumulation is divided according to the source rock control threshold. Most of the discovered wells are located adjacent to the HEC (Fig. 3). Meanwhile, the HEC has the best hydrocarbon potential, but the percentage of reserves is low. This may be because fewer wells were deployed in the previous period, therefore, it can be used as a potential resource area.

4.1.2 Reservoir

Mainly braided delta and deep-shallow lacustrine facies developed in the lower Enping Formation of the Southern Lufeng sag, and sand bodies mostly formed in the braided river delta facies. The lacustrine facies sedimentary system is mainly developed in the Lufeng 13 east sub-sag, Lufeng 15 sub-sag and its western part. In addition, there are also scattered lacustrine facies in the southwestern and northeastern parts of Lufeng 13 west sub-sag, and the northern part of Lufeng 7 sub-sag. The braided river delta facies are mainly distributed in the northern part of the study area and around each sub-sag, and most of the wells with hydrocarbon shows are also distributed in the braided river delta facies.

As an important indicator of advantageous lithological facies in a hydrocarbon reservoir, the sandstone-to-stratum ratio shows a strong correlation with the hydrocarbon reservoir. Herein, the hydrocarbon accumulation model based on reservoir control was established by statistically correlating the sandstone-to-stratum ratio with the oil layer thickness for 43 data points of the Paleocene system. There is an obvious trend that the oil layer thickness and sandstone-to-stratum ratio first increases and then decreases (Fig. 2(b)), 66% of the oil layers are concentrated in the sandstone-to-stratum ratio range of 0.45-0.75, and the total oil layer thickness exceeds 850 m. According to the oil layer thickness distribution trend, few oil layers are found when the sandstone-to-stratum ratio is less

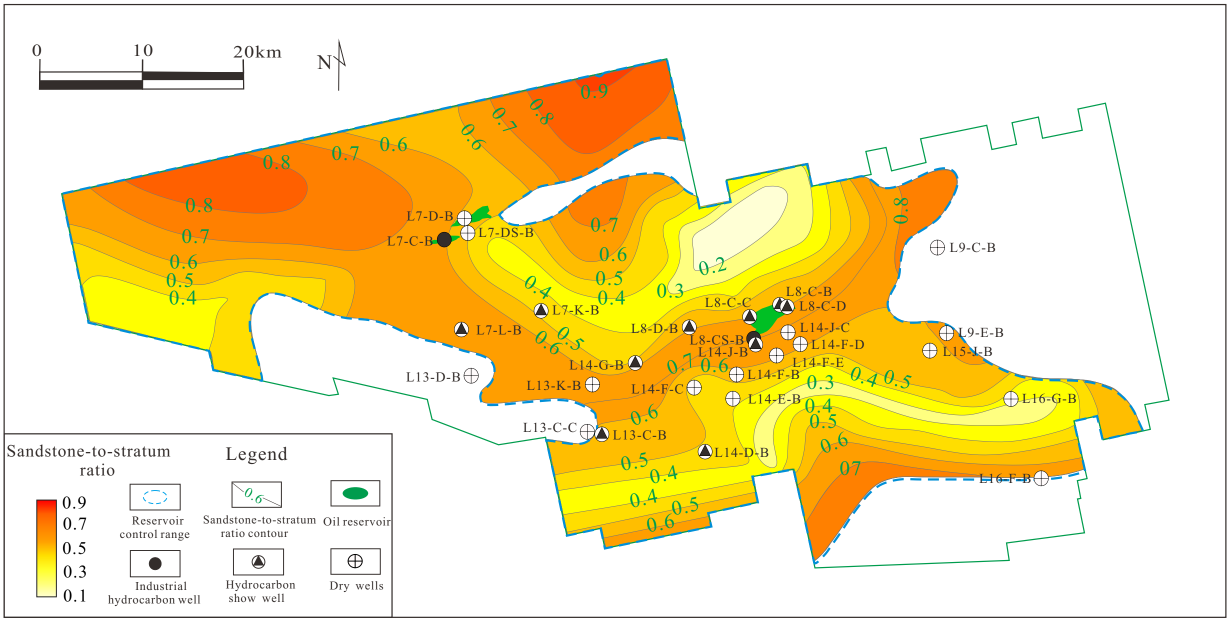

Fig. 4. Sandstone-to-stratum ratio and reservoir control range for hydrocarbon accumulation in the lower Enping Formation of the Southern Lufeng sag.

than 0.12 or more than 0.96 (Fig. 2(b)), and thus the reservoir control threshold for hydrocarbon accumulation is determined to be a sandstone-to-stratum ratio of 0.12 and 0.96.

The sand body in the northern part of the study area is widely distributed, mainly in Lufeng 13 west sub-sag and Lufeng 7 sub-sag, and the sand body is developed around the Lufeng 15 sub-sag and Lufeng 13 east sub-sag (Fig. 4). The hydrocarbon accumulation boundary and range of the lower Enping Formation under reservoir control were delineated according to the reservoir control threshold. The reservoir control range is widely distributed, indicating that the reservoir conditions in the lower Enping Formation are superior.

4.1.3 Caprock

Thickness is an important parameter for evaluating the caprock. The Wenchang Formation of the study area develops a large set of mudstones, which is a regional caprock. The Enping Formation is mainly partial caprock with a small distribution area, and the reservoir-caprock assemblages are characterized by thin mudstone and thin sandstone. Generally, the greater the thickness of the caprock, the more beneficial to the preservation of hydrocarbons (Nederlof and Mohler, 1981; Schlömer and Krooss, 1997; Ma et al., 2020). The thickness and distribution of mudstone can be used to determine the sealing capacity of the caprock.

In this paper, the relationship between the mudstone thickness and oil layer thickness of the partial caprock was statistically calculated from 32 data points in the Paleocene, and a hydrocarbon accumulation model based on caprock control was established. The results indicate that the oil layer thickness tends to increase and then decrease with increasing mudstone thickness, and the oil layer thickness is maximum in the range of 115-180 m mudstone thickness. At the same time, the oil layer is developed only when the mudstone thickness is greater than 35 m (Fig. 2(c)). If the mudstone thickness is too small, the caprock is easily destroyed by faults, which is not conducive to hydrocarbon protection, and its lateral sealing range will be limited. Therefore, the caprock control threshold for hydrocarbon accumulation is a mudstone thickness of 35 m.

The mudstone thickness of the lower Enping Formation does not exceed 300 m, and it shows the characteristics of large distribution inside the sub-sag and small in the surroundings. The area with the largest caprock thickness is mainly located in the northern part of the Lufeng 13 east sub-sag (Fig. 5). The boundary of caprock control for hydrocarbon accumulation and scope in the lower Enping Formation were delineated according to the caprock control threshold for hydrocarbon accumulation, and hydrocarbons are mainly distributed in the zone where the mudstone thickness is greater than 35 m (Fig. 5).

4.1.4 Hydrocarbon migration and accumulation dynamics

(1) Low-pressure energy

As the main pathway for the vertical migration of hydrocarbons, faults often play a vital role in the hydrocarbon accumulation and formation of hydrocarbon reservoirs. Generally, low-pressure energy zones are distributed where the faults are more developed.

In this paper, the hydrocarbon accumulation model based on low-pressure energy fault zone control was established by calculating the relationship between the distance from the fault and the number of Paleozoic reservoirs (Fig. 6(a)). The results indicate that the number of hydrocarbon reservoirs show a decreasing trend with the increasing distance from the fault. According to the change trend, few reservoirs are distributed in the region where the distance is more than 3.2 km from the fault. Therefore, the predicted hydrocarbon accumulation

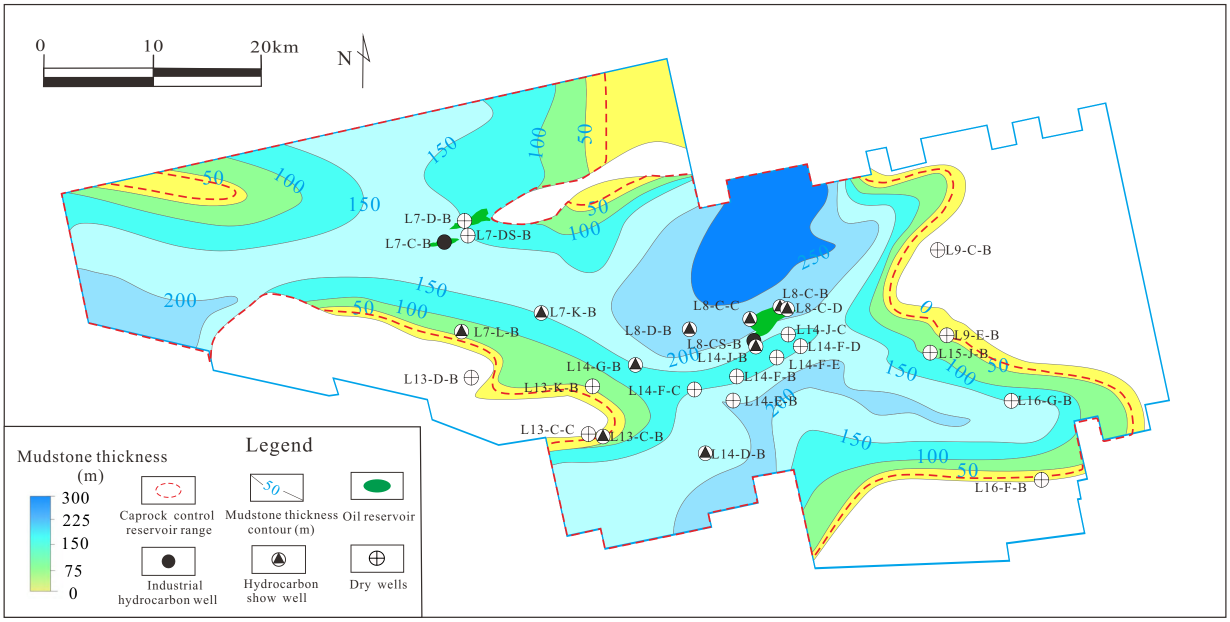

Fig. 5. Hydrocarbon accumulation range controlled by mudstone thickness and caprock in the lower Enping Formation of the Southern Lufeng sag.

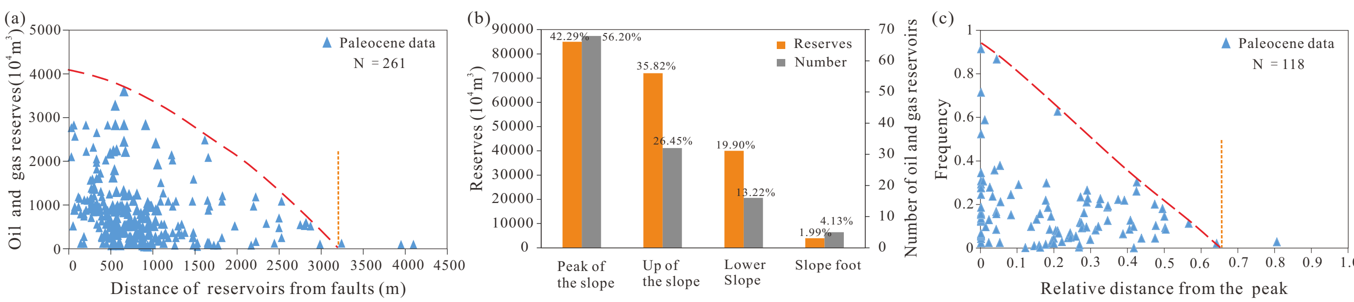

Fig. 6. (a) Relationship between distance to fault and oil and gas reserves of Paleozoic reservoirs in the Southern Lufeng sag, (b) Histogram of different parts of palaeohigh zone and reservoir distribution in the Southern Lufeng sag, (c) Scatter diagram of relative distance from the peak of the palaeohigh zone and frequency of hydrocarbon reservoirs in the Southern Lufeng sag.

threshold under low-pressure energy fault zone control is determined as a distance from the fault that is equal to 3.2 km.

The lower Enping Formation of the Southern Lufeng sag mainly develops east-west trending faults, and the areas with more developed faults are located in the northwestern part of the Lufeng 7 sub-sag and around the Lufeng 13 sub-sag. Among them, the faults inside the Lufeng 13 east sub-sag are more densely developed and have the most oil and gas discoveries, while the faults inside the Lufeng 15 sub-sag and Lufeng 13 west sub-sag are relatively sparse and have few oil and gas discoveries. The controlling effect of low-pressure energy on hydrocarbon accumulation features is obvious (Fig. 7).

(2) Low potential energy

In this paper, palaeohigh is defined as a positive tectonic unit that existed during the geological history of hydrocarbon reservoir formation. Hydrocarbons will accumulate in effective traps in the upper part of the palaeohigh zone under the impact of buoyancy along the dominant migration pathway, as most of the palaeohigh is a low potential energy zone (England et al., 1987; Robison et al., 1998; Xu et al., 2012).

According to the morphology of the palaeohigh zone, it can be divided into four parts: peak, upper part, lower part, and foot. From the statistical analysis of the reserves and number of hydrocarbon reservoirs in different parts of the palaeohigh zone, the effect of palaeohigh zone on hydrocarbon accumulation control is obvious. 95% or more of the hydrocarbon reservoirs are distributed in the upper part of the palaeohigh above the foot, and the closer to the peak of the palaeohigh, the more reserves and the higher the number of hydrocarbon reservoirs are found (Fig. 6(b)). The distance of the hydrocarbon reservoirs from the peak of the palaeohigh is transformed into the relative distance of oil and gas reservoirs from the peak of the palaeohigh (i.e., the ratio of the distance of hydrocarbon reservoir from the peak of the

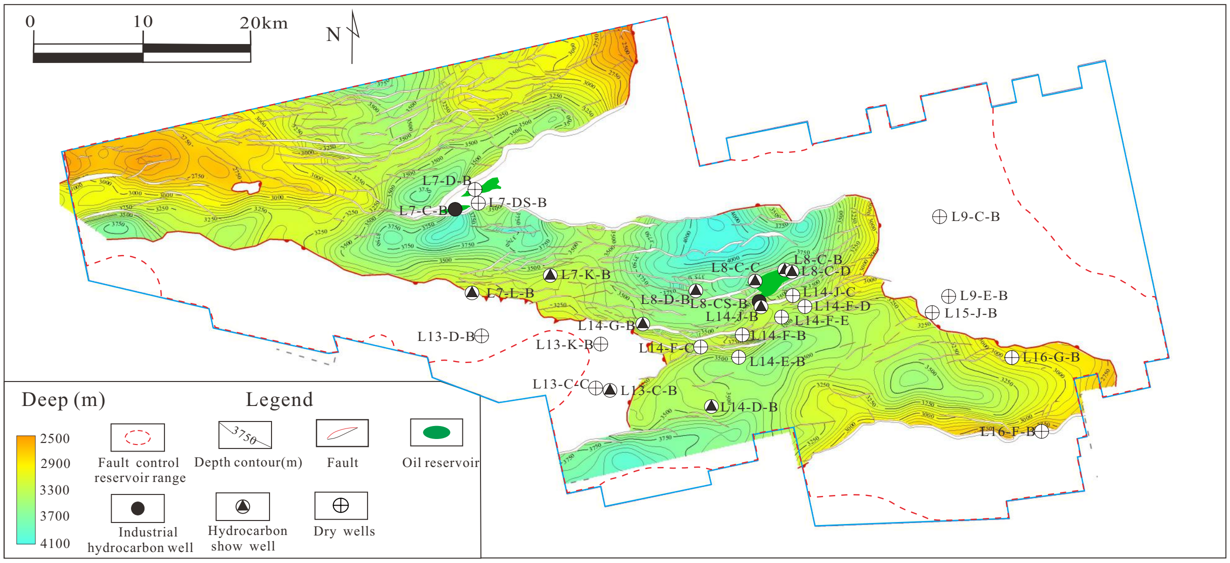

Fig. 7. Fault zone control range for hydrocarbon accumulation in the lower Enping Formation of the Southern Lufeng sag.

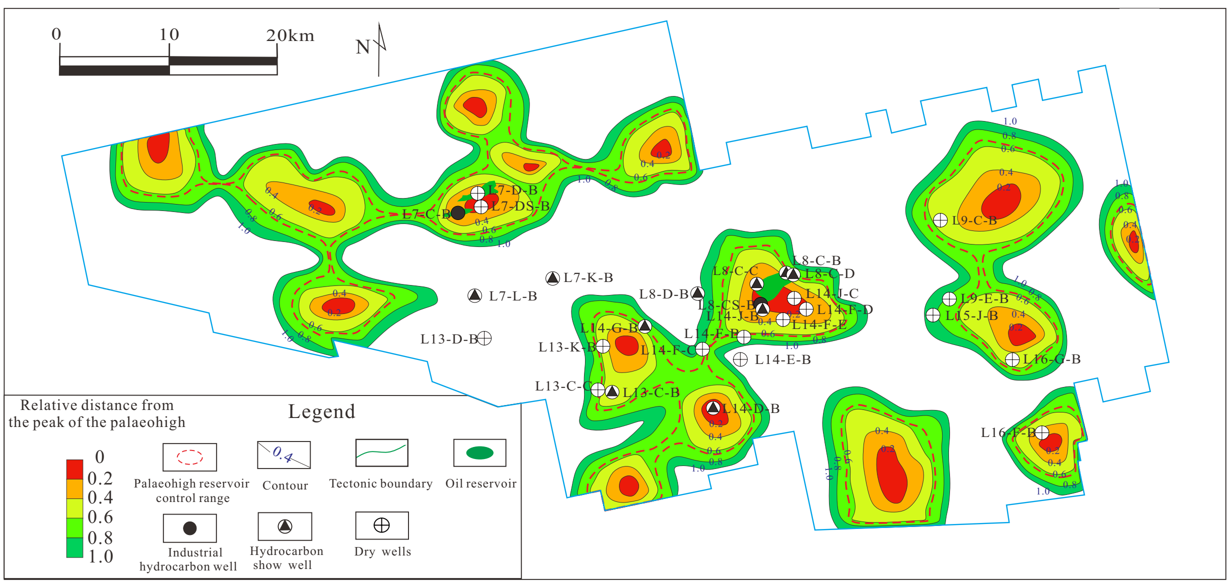

Fig. 8. Palaeohigh zone control range in the lower Enping Formation of the Southern Lufeng sag.

palaeohigh to the distance from the boundary to the peak of the palaeohigh), and the relationship between the relative distance of hydrocarbon reservoir from the peak of the palaeohigh and the frequency of hydrocarbon reservoir development is calculated. Subsequently, the hydrocarbon accumulation model based on palaeohigh control for the low potential energy zone is established. The results indicate that the development frequency of Paleocene reservoirs is inversely proportional to their relative distance from the peak of the palaeohigh, and the reservoirs are distributed within a relative distance of less than 0.65 (Fig. 6(c)).

The palaeohigh zone in the lower Enping Formation is distributed in continuous strips and independent blocks, which are mainly around the sub-sags. It occurs more frequently in the southern part of Lufeng 7 sub-sag and the southeastern part of Lufeng 13 east sub-sag, and all the discovered hydrocarbon reservoirs in the Enping Formation are located in the high part of the palaeohigh zone. The boundary and range of hydrocarbon accumulation in the lower Enping Formation under palaeohigh control were delineated according to the palaeohigh control threshold for hydrocarbon accumulation. The hydrocarbon accumulation range under palaeohigh control is relatively scattered, and most of the drilled wells with hydrocarbon shows are located in the positive tectonic zone within the controlled hydrocarbon accumulation range (Fig. 8).

(3) Low interface potential energy

The interfacial potential difference between the outside and inside of the sandstone reservoir, which plays a crucial role in hydrocarbon reservoir formation, is generated by the capillary

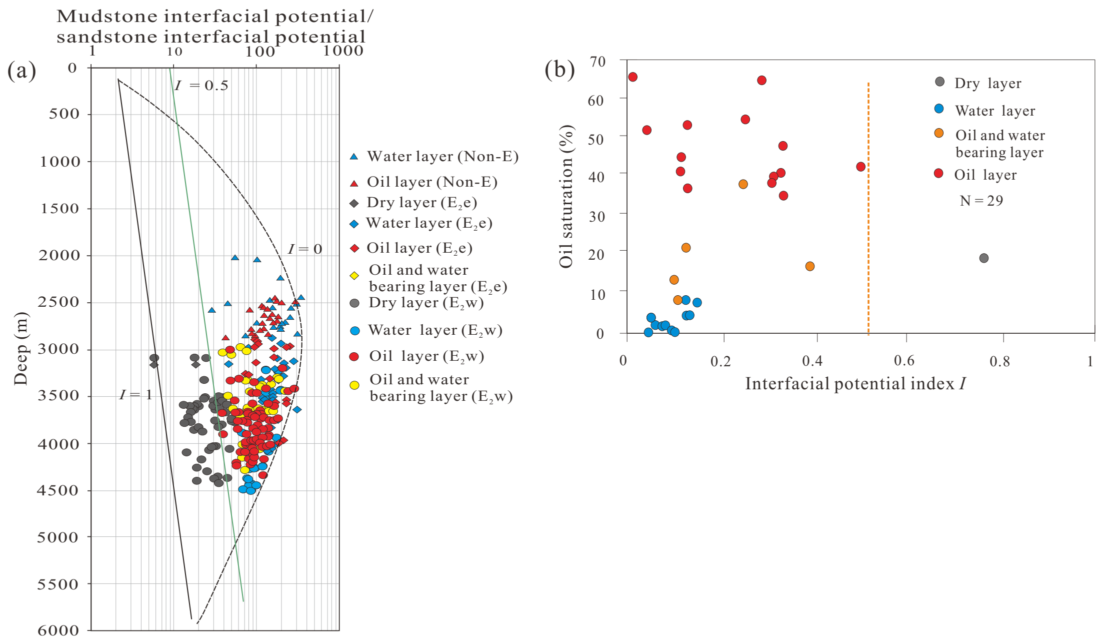

Fig. 9. (a) Relationship between interfacial potential and depth at the sandstone and mudstone interface (where Non-E is Non-Paleocene, E_2e is Enping Formation, E_2w is Wenchang Formation), (b) Relationship between interfacial potential energy and oil-bearing saturation in the Enping Formation of the Southern Lufeng sag.

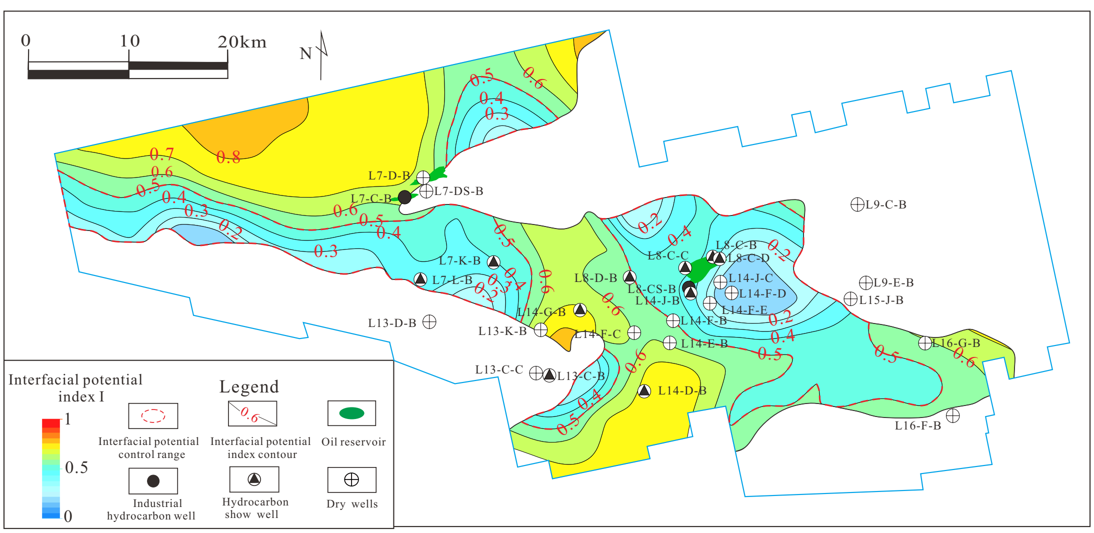

Fig. 10. Interfacial potential index distribution and lithologic sandstone body control range of oil and gas accumulation in the lower Enping Formation of the Southern Lufeng sag.

pressure difference between the inside and outside of the sandstone reservoir (Pang et al., 2021). Usually, the pore throat radius of sandstone is larger, and that of mudstone is smaller. At the interface of sandstone and mudstone, the pore throat radius of sandstone is larger than that of mudstone, which generates a capillary pressure difference between sandstone and mudstone. Oil and gas exhibit the characteristics of migrating from mudstone to sandstone reservoirs under the action of capillary pressure difference, and sandstone tends to be in a low interfacial potential energy zone, resulting in oil and gas easily forming lithologic hydrocarbon reservoirs in sandstone (Robison et al, 1998).

In the Southern Lufeng sag, the sand-mudstone interface potential difference controls the formation and distribution of hydrocarbon reservoirs. The interfacial potential index is used to characterize the controlling effect of sand-mudstone interface potential on hydrocarbon reservoirs, which is calculated by the following equation:

$$I = \frac{P_i - P_{\min}}{P_{\max} - P_{\min}} \tag{1}$$

where I represents the interfacial potential index; P_i represents the interfacial potential energy of sandstone, J; $P_{\max}$ denotes the maximum interfacial potential energy of mudstone at the same burial depth, J; $P_{\min}$ represents the minimum interfacial potential energy of sandstone at the same burial depth, J.

According to the relationship between the interfacial potential energy and the depth of sandstone and mudstone in the Southern Lufeng sag, the ratio of the interfacial potential energy of sandstone and mudstone tends to increase and then decrease with depth. The oil layers are developed in the area with $I < 0.5$ (Fig. 9(a)). Based on the relationship between the oil saturation and interfacial potential index of the Enping Formation, the model for hydrocarbon accumulation control in lithologic sandstone bodies in low-interface potential energy zones was established (Fig. 9(b)). The results show that the oil layer is mainly distributed in the area with $I < 0.5$, and the dry layer is mainly developed in the area with $I > 0.5$.

The hydrocarbon accumulation control boundary and scope of the lower Enping Formation were determined based on the hydrocarbon accumulation control threshold of low interface potential energy. The control range is mainly divided into four areas: two of them are located in the northeastern part of Lufeng 7 sub-sag and the southwestern part of Lufeng 13 east sub-sag, with fan-shaped distribution and a small area; the other two areas located in the southern part of Lufeng 13 west sub-sag and from Lufeng 13 east sub-sag to Lufeng 5 sub-sag are distributed along a long strip with a larger area (Fig. 10).

4.2 Hydrocarbon accumulation prediction based on threshold combination control by multi-functional elements

4.2.1 Prediction of favorable hydrocarbon accumulation zones of different types of reservoirs

Different types of hydrocarbon reservoirs have different formation dynamics and mechanisms. In this paper, the favorable zones of different types of reservoirs are predicted by the hydrocarbon accumulation method based on the threshold combination control of the aforementioned multi-functional elements.

The favorable zone of the fault hydrocarbon reservoir is mainly located in the central part of the study area, which has a large distribution area, and there is a possibility of fault formation under the hydrocarbon reservoir within its distribution area (Fig. 11(a)).

The distribution of favorable zones of anticline hydrocarbon reservoirs is more scattered, and the distribution area is relatively limited in the form of string beads and small blocks. They are mainly distributed in the southern part of Lufeng 13 sub-sag, the northern part of Lufeng 13 west sub-sag and around the Lufeng 15 sub-sag, and the discovered hydrocarbon reservoirs are also within the favorable zones (Fig. 11(b)).

The favorable zone of lithologic hydrocarbon reservoirs is divided into two large areas and two small areas. One large area is mainly located in the eastern part of Lufeng 13 east sub-sag and the southern part of Lufeng 13 west sub-sag, which are distributed in a strip; the other large area is mainly located in the northeastern part of Lufeng 7 sub-sag and the southwestern part of Lufeng 13 east sub-sag, which are in a block shape. Among them, more hydrocarbon reservoirs have been discovered in the favorable zone in the eastern part of the Lufeng 13 east sub-sag (Fig. 11(c)).

4.2.2 Prediction of composite favorable areas for multi-category reservoirs

By combining the control ranges of the four functional elements, we can establish the control model of integrated oil and gas reservoirs for the effective prediction of the integrated favorable hydrocarbon accumulation zone in the target section (Fig. 12). The favorable hydrocarbon accumulation zones are classified by different combination methods. The Type I favorable hydrocarbon accumulation zone is the superposition of three types of favorable, indicating that this area is anticline and lithologic hydrocarbon reservoirs with possible fault development. It also is the superposition of low-pressure energy zone, low potential energy zone and low interface potential energy zone in the study area. The Type II favorable hydrocarbon accumulation zone is the superposition of the two types of reservoir favorable zones, indicating that only two of the three types of reservoirs, namely, fault, anticline and lithologic hydrocarbon reservoirs, can be found in this area, and it is also the superposition of two of the potential energy zones, namely, low-pressure energy zone, low potential energy zone and low interface potential energy zone. The Type III favorable hydrocarbon accumulation zone is the favorable zone of only one of the three types of oil and gas reservoirs, and the area is controlled by only one type of potential energy. It should be noted that the ranges of Type I, II and III favorable zones are all candidates to find hydrocarbon reservoirs, which only represent the number of types of hydrocarbon reservoirs that may be found in their distribution range, but not the probability of finding such reservoirs.

Among them, Type I favorable zones are mainly distributed in the eastern part of 13 east sub-sag, and the northern and southern parts of Lufeng 7 sub-sag; Type II favorable zones are mainly distributed in the southern part of Lufeng 7 sub-sag, the southern part of Lufeng 13 west sub-sag and the northeastern and southwestern parts of Lufeng 13 east sub-sag, which are distributed in a string of pearls and strips; Type III favorable zones are mainly distributed around Type II favorable zones with a wider area (Fig. 12). The discovered hydrocarbon reservoirs and wells with existing hydrocarbon discoveries are located in Type I and Type II favorable zones.

4.3 Reliability analysis

The efficiency of the predicted favorable hydrocarbon accumulation areas is tested by analyzing the oil and gas discoveries of deployed exploratory wells in the lower Enping Formation and statistically calculating the proportions of different types of oil and gas drilling encounter wells in the overlapping area with different numbers of functional elements. The statistical results indicate that both industrial hydrocarbon wells and hydrocarbon show wells are located within the overlap of the three functional elements of source rock, reservoir, and caprock. The proportion of industrial hydrocarbon wells and hydrocarbon show wells increases with

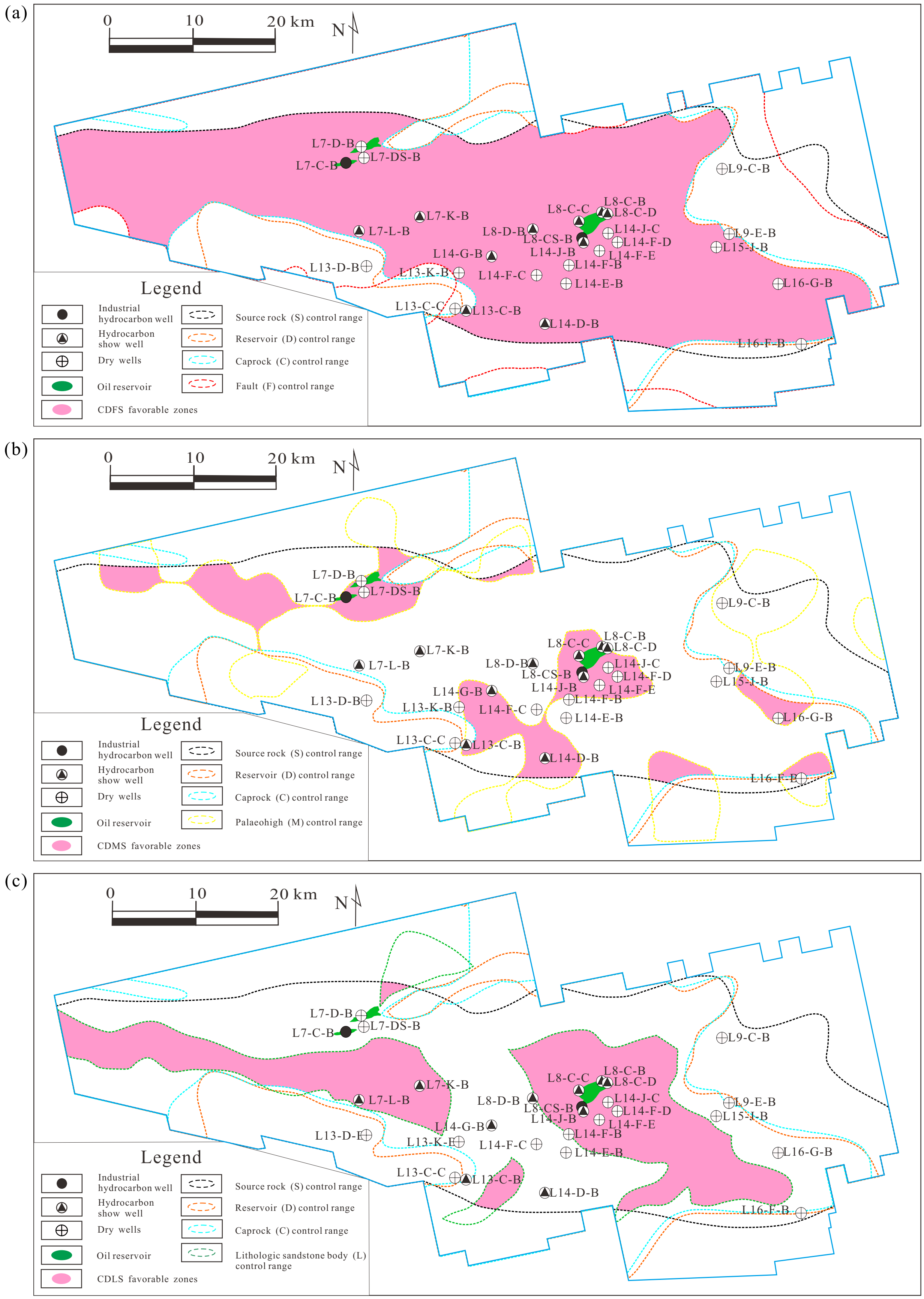

Fig. 11. Predicted favorable hydrocarbon accumulation zones for different types of reservoirs in the lower Enping Formation of the Southern Lufeng sag: (a) Fault hydrocarbon reservoir, (b) anticline hydrocarbon reservoir, and (c) lithologic hydrocarbon reservoir.

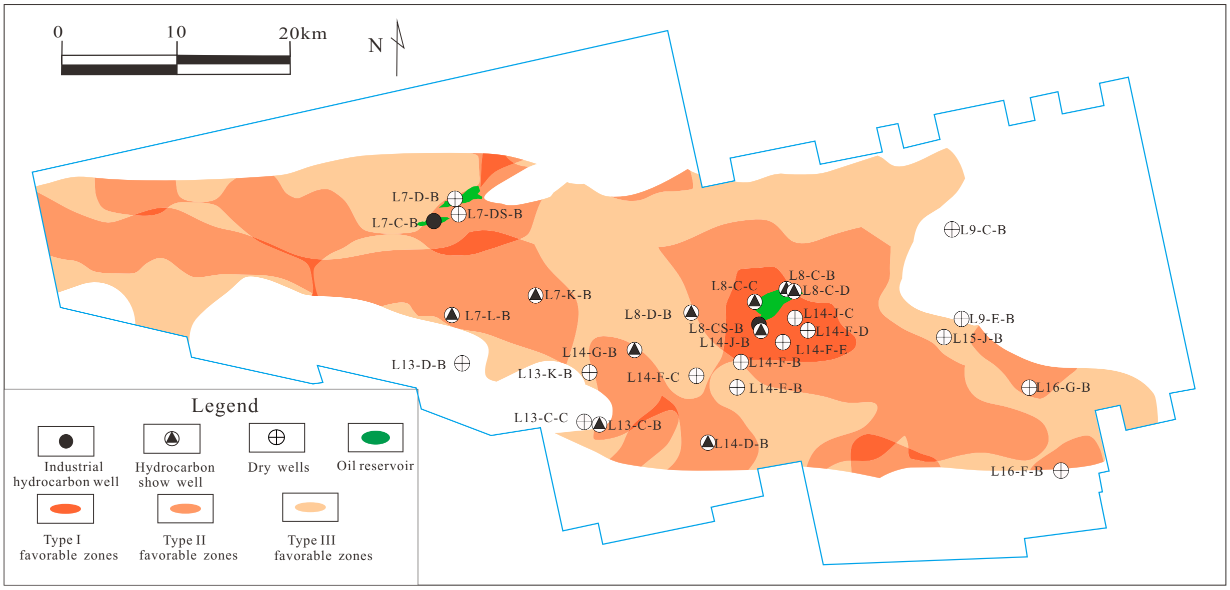

Fig. 12. Predicted potentially favorable reservoir hydrocarbon accumulation in the lower Enping Formation of the Southern Lufeng sag.

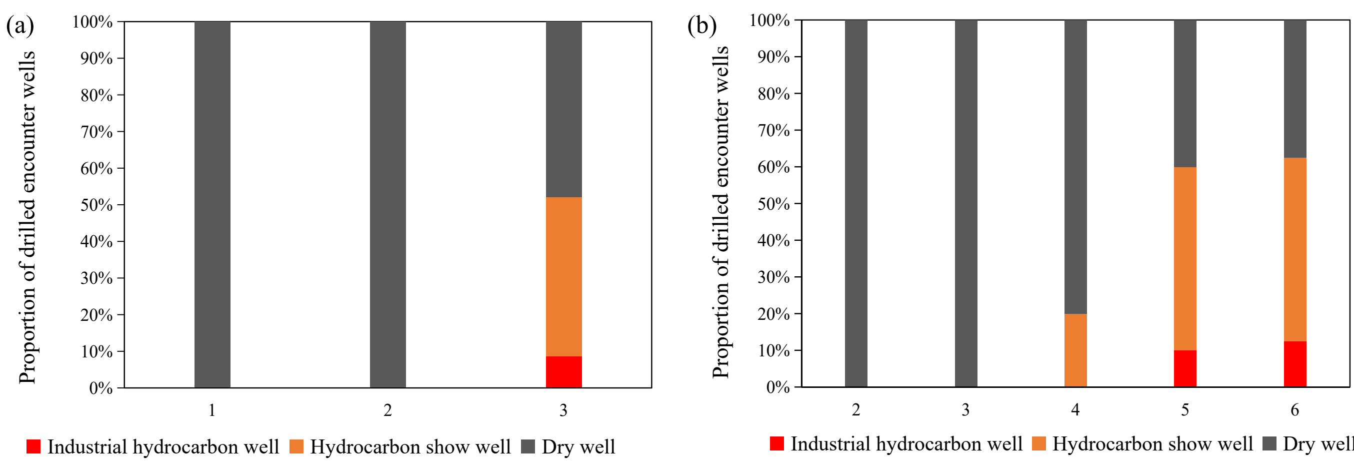

Fig. 13. Statistics of the number of overlapping control elements and drilling results for the lower Enping Formation: (a) Number of functional elements of source rock, reservoir and caprock, (b) number of accumulation elements.

the rising number of accumulation element overlays. The industrial hydrocarbon wells are located in only five and six accumulation element overlays (Fig. 13).

Next, the failed wells in the study area were analyzed. The results showed that there are 16 dry wells in the lower Enping Formation, and the 5 wells located outside the predicted favorable hydrocarbon accumulation zone by the CDPS multi-functional element overlay are all dry wells. In addition, there are 9 dry wells with less than 5 reservoir-forming elements, accounting for 56% of the total dry wells. Most failed wells have poor hydrocarbon-bearing properties mainly because one or more of the reservoir-forming elements are missing (Table 1). Both the oil and gas discoveries and the failed well tests show that the predictions are highly reliable and can be used to guide petroleum exploration.

5. Discussion

Limited by the sampling location and the number of samples, the current study has certain limitations. In this paper, only the threshold, boundary and range of hydrocarbon reservoir distribution are studied, and the study of the probability of hydrocarbon formation in the favorable hydrocarbon accumulation zone is missing. The current prediction of favorable hydrocarbon accumulation zone is only the threshold range of oil and gas reservoir formation, which means that oil and gas reservoirs can only be formed in the favorable zone, and it is more likely to find oil and gas reservoirs in this range, and it is difficult to find oil and gas reservoirs outside the favorable zone. However, it does not mean that oil and gas reservoirs can be formed in the favorable zone. For example, the results of oil and gas drilling encounters in the lower Enping Formation for some of the wells located within the predicted favorable

Table 1. Summary of the analysis of failed wells in the E_2^2e Formation of the Southern Lufeng sag.

Failed well	Functional elements				Failed well	Functional elements			
	D	C	M	L		D	C	M	L
L13-C-C	×	×	×	×	L14-F-C	✓	✓	×	×
L13-D-B	×	×	×	×	L7-D-B	✓	✓	✓	×
L9-C-B	×	×	✓	×	L14-F-E	✓	✓	✓	✓
L16-F-B	×	×	✓	×	L14-F-D	✓	✓	✓	✓
L9-E-B	✓	×	×	×	L13-K-B	✓	✓	✓	×
L14-E-B	✓	✓	×	×	L7-DS-B	✓	✓	✓	×
L14-F-B	✓	✓	×	×	L16-G-B	✓	✓	✓	×
L15-J-B	✓	✓	×	×	L14-J-C	✓	✓	✓	✓

zone of the CDPS are also unsatisfactory. The probability of reservoir formation also varies in different parts of the predicted favorable zones, and the grade of hydrocarbons found will be different. Further quantitative studies are needed to determine the probability of hydrocarbon accumulation in each part of the predicted favorable zones.

6. Conclusions

1) As the four major functional elements, the source rock, reservoir, caprock, and low-potential zones control oil and gas accumulation in the Enping Formation of the Southern Lufeng sag, and according to the established hydrocarbon accumulation control model, the boundary and range of each of these elements determine the control threshold of hydrocarbon accumulation. The source rock-controlled hydrocarbon accumulation threshold is twice the relative distance to the HEC, the threshold of reservoir control on hydrocarbon accumulation is a sandstone-stratum ratio of 0.12 and 0.96, the caprock-controlled hydrocarbon accumulation threshold is a mudstone thickness of 35 m, the threshold of hydrocarbon accumulation controlled by the three low-potential zones is 3.2 km distance from the fault, relative distance of 0.65 from the peak of the palaeohigh zone, and interfacial potential index of 0.5.
2) In this paper, the favorable hydrocarbon accumulation zones and CDPS of different types of reservoirs are predicted based on the hydrocarbon accumulation model based on threshold combination control. Type I favorable zones are distributed in the eastern part of the Lufeng 13 east sub-sag and northern and southern parts of the Lufeng 7 sub-sag; Type II favorable zones are distributed in the western area and around the Lufeng 13 east sub-sag; Type III favorable zones are located around the Type II favorable areas with a wide distribution. It is verified that the predicted favorable hydrocarbon accumulation zones are highly reliable and can be used to guide the next step of oil and gas exploration.

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Conflict of interest

The authors declare no competing interest.

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