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Controlling effect of tectonic-paleogeomorphology on deposition in the south of Lufeng sag, Pearl River Mouth Basin

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Abstract:
Paleogene depositional systems in the south of Lufeng sag have complex spatial distribution, which are influenced by pre-depositional paleogeomorphology and multi-period tectonic activities. In this paper, to clarify the controlling effect of tectonic-paleogeomorphology on sedimentary facies distribution and effectively guide oil and gas exploration, the Paleogene paleogeomorphic pattern in the south of Lufeng sag is reconstructed by the impression method, and the temporal and spatial evolution laws of the main faults are clarified. The results show that braided river deltas developed stably in the long-axis gentle slope belt of the lake basin, while the short-axis sedimentary system changed from fan deltas to braided river deltas in response to the change of active strength of dominant faults from strong to weak. It is found that the scale of the sedimentary fan is closely related to the activity of the main fault, the area of the catchment, and the vertical elevation difference. The steep cliff is controlled by the boundary fault with large fault throw and steep section, and there are wedge-shaped sand bodies near the steep cliff. The multi-level fault-step zone provides the driving force for the advancement of the sedimentary system, and the sand body extends for a long distance. It is established that the supply capacity of the source area and the accommodated space of the lake basin are coupled to control the deposition scale. Moreover, the slope controlled by the combination of paleogeomorphic assemblage and the activity of the main fault determines the sedimentary type, and the structural slope-break zone defines the spreading pattern of the sands.

1. Introduction

The source-to-sink system has gradually become a research hotspot in the interdisciplinary fields of basin dynamics, sedimentary dynamics, and tectonic geomorphology in the past decade (Allen, 2008; Martinsen et al., 2010). Its core theoretical idea is that factors such as tectonics, climate and sea-level changes affect the entire process of the production, transformation and accumulation of sediments and dissolved substances from source to sink. Basin tectonic movement, climate change and source erosion have important impacts on sediment transport and depositional processes, as well as sand body distribution and development (Allen and Hovius, 1998; Sϕmme and Jackson, 2013). In continental rifted lake basins, tectonic activity and paleogeomorphology are the fundamental factors controlling the origin of sequence boundaries, the migration of depositional centers, sequence architecture, the diversity of sedimentary systems, and sand body development (Henstra et al., 2017). Therefore, studies on the controlling effect of tectonic-paleogeomorphology on sediments and sand bodies has intensified regarding the research of continental faulted basins in recent years (Gawthorpe and Leeder, 2000; Xin et al., 2013; Chen et al., 2020).

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Paleogeomorphic reconstruction can not only clarify the spatial matching relationship between the source and depositional areas or sedimentary center, but also reveal the controlling effect of different tectonic-paleomorphological units on the types of sedimentary systems (Liu et al., 2019). At the same time, the description of the gully system in paleogeomorphology is of great significance for the reconstruction of the paleowater system, as it enables the clarification of transport path of sediments, and thus the prediction of distribution location of sedimentary sand bodies. The total amount of sedimentary detrital material in the sag is closely related to the vertical elevation difference of the source area and the area of catchment, which is of great significance for the prediction of the scale of sedimentary fan (Li et al., 2021). Long-term active synsedimentary faults and their assemblages restrict the change of accommodating space in the basin during the rifting period, thus influencing the sediment dispersion system and the distribution pattern of sand bodies in the basin (Feng et al., 2016).

The Pearl River Mouth Basin is a typical Cenozoic passive continental margin rift basin with a complex tectonic evolution process. Its rifting period experienced multiple episodes of rifting cycles. Controlled by the structure of the basin and the topographical features of the surrounding area, there are many tectonic-sedimentary patterns of "alternating reliefs and sub-sags" (Zhao et al., 2021). Moreover, there are multiple provenance areas for the supply of detrital materials, the types of transport channels and the tectonic-sedimentary slope break styles are abundant, and the fault combination styles and levels are diverse, resulting in various types of sedimentary systems and the complex development of sand bodies (Li et al., 2021). The south of Lufeng sag is the area with the highest exploration potential in the Pearl River Mouth Basin. Previous studies have established that this area responds to different fault activities and tectonic subsidence processes, resulting in the formation and evolution of the Huilu low-relief (HLR), Dongsha uplift (DU), Lufeng central horst (LCH) and Lufeng eastern relief (LER); the sedimentary filling style and sand body distribution of each interval of the Paleogene Wenchang Formation and Enping Formation are obviously different (Xia et al., 2019; Ge et al., 2020). Most studies on the controlling factors of sedimentary systems in the south of Lufeng sag have been based on the single dimension of paleogeomorphic pattern and tectonic activity, ignoring the synergistic control of tectonic activity and paleogeomorphology on sedimentary systems. Therefore, the development mechanism, evolution law and distribution range of sedimentary systems and sand bodies under the control of tectonic-paleogeomorphology need to be further investigated. In this paper, the seismic and logging data in the study area are comprehensively used to quantitatively reconstruct the paleo-fault characteristics and paleo-geomorphic characteristics in the south of Lufeng sag during the Paleogene Wenchang and Enping depositional periods. Combined with the detailed sedimentary system map in the study area, the controlling effect of tectonic-paleogeomorphology on deposition in the south of Lufeng sag during the Paleogene depositional period is further revealed, which is of considerable importance for predicting the development of favorable reservoirs.

2. Geological setting

The Pearl River Mouth Basin is located on the edge of a vast continental shelf and continental slope in the northern South China Sea. It is a Cenozoic hydrocarbon-bearing basin formed on the complex folded Paleozoic and Mesozoic basements. The Lufeng sag is located in the northeast of Zhu I Depression in the Pearl River Mouth Basin, with a northeast direction and an area of about 7760 km^2. Its interior is divided into two by the HLR and the nose-shaped LER extending from east to west, forming two sags in the north and south. The study area extends from the south of Lufeng sag to the south of the nose structure, and its interior can be divided into several sub-sags, namely, in order from south to north, the Lufeng 15 sub-sag, the Lufeng 13 eastern sub-sag and the Lufeng 13 western sub-sag (Fig. 1).

Under the influences of the collision between the Pacific plate, Indian plate and Eurasian plate, and the expansion of the South China Sea, the Pearl River Mouth Basin experienced five large-scale tectonic movements. From early to late, these were the Zhuqiong I movement, Zhuqiong II movement, Nanhai movement, Baiyun movement, and Dongsha movement. Its tectonic evolution can be divided into three different development stages, namely the rifting stage, the depression stage and the block fault lifting stage (Zhang et al., 2017). The basin mainly deposited the Paleogene Shenhu Formation, Wenchang Formation, Enping Formation and Zhuhai Formation, Neogene Zhujiang Formation, Hanjiang Formation, Yuehai Formation, Wanshan Formation, and Quaternary Deposits. Among them, the Shenhu Formation, Wenchang Formation and Enping Formation are continental fault-depression deposits, with are obviously controlled by synsedimentary faults, and present many wedge-shaped and near-parallel formations; the Zhuhai Formation, Zhujiang Formation and Hanjiang Formation are marine depression deposits, in which the thickness of the stratum gradually decreases from the central part to the two sides; The Yuehai Formation, Wanshan Formation and Quaternary were deposited in the late neotectonic movement stage (Li et al., 2021). The target layers of this study are the Paleogene Wenchang Formation and the Enping Formation, which correspond to the rifting stage and are generally continental lake basin deposits. These were braided river delta, fan delta and deep lacustrine facies during the depositional period of the Wenchang Formation, while during the deposition of the Enping Formation, the water body became shallow, and there were large areas of braided river delta facies and shallow lake swamp deposits. The lacustrine mudstone in the Wenchang Formation is the main source rock, with oil and gas accumulation in its sand bodies and the braided river delta sand bodies in the Enping Formation (Lin et al., 2022) (Fig. 2).

3. Methods

The present study is carried out using 3D contiguous seismic data in the work area of 2100 km^2 and the logging data of 20 exploratory wells that have been drilled. The research methods involve: (1) reconstruction of paleogeomorphology; (2) statistics on fault activity.

At present, the commonly used methods for paleogeomor-

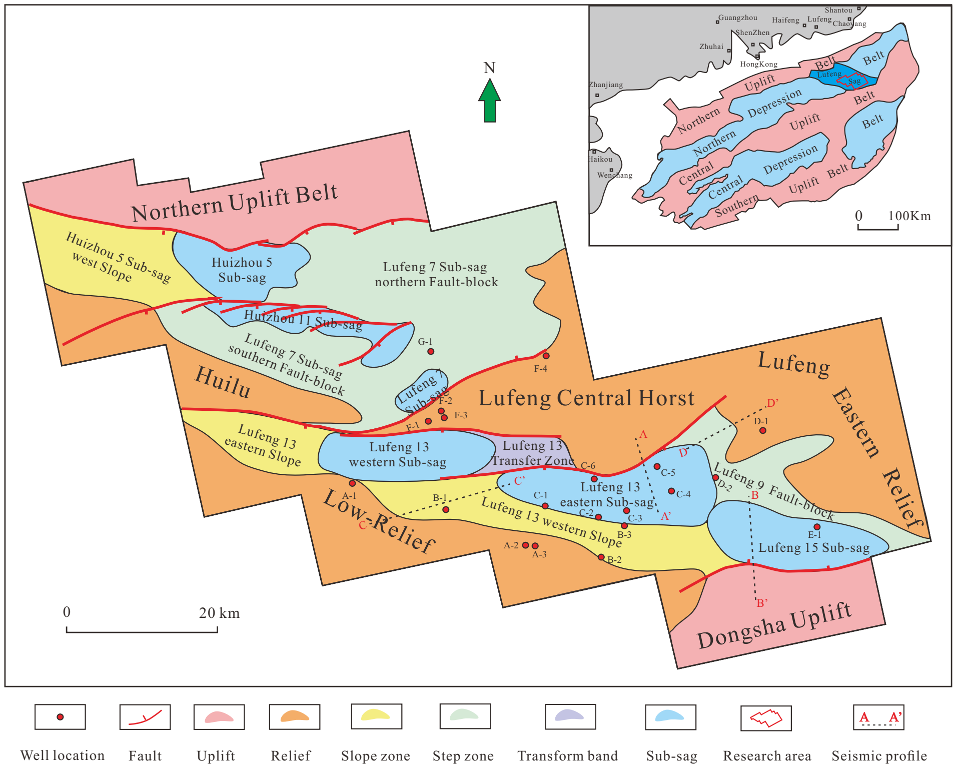

Fig. 1. Tectonic location and structural unit characteristics of the Lufeng sag, Pearl River Mouth Basin.

phological reconstruction mainly include the sedimentological analysis method, sequence stratigraphic analysis method, formation thickness method, impression method, and the back stripping and filling method (Zhao et al., 2021). Among them, the residual stratum thickness method and the seismic layer flattening method can only complete the restoration of the ancient landform in the sedimentary area. To systematically understand the composition of the source-sink system in the south of Lufeng sag, determine the catchment area, transportation distance, and topographic background of different sedimentary systems, and the distribution and scale of the sedimentary system in the basin, it is necessary to carry out integrated paleogeomorphical reconstruction for the sedimentary area and the denudation area. The impression method can break through the limitations of the depositional area and the denudation area. Therefore, this paper uses the impression method for the paleogeomorphical reconstruction of the south of Lufeng sag during the depositional period of the Paleogene Wenchang Formation and the Enping Formation.

The impression method is one of the most widely used ancient landform restoration methods. Cao et al. (2021) applied this method to restore the karst paleogeomorphology in the southeastern Ordos Basin, and studied the control effect of the paleogeomorphology on the physical properties of the reservoir. Jin et al. (2017) restored the morphological characteristics of the paleogeomorphology of Dengying Formation in the Moxi-Gaoshiti area of the Sichuan Basin by the impression method and distinguished different paleogeomorphic units according to the geomorphological characteristics. Yu et al. (2022) also adopted this method for the restoration of the karst paleogeomorphology at the top of the Middle Triassic Leikoupo Formation in the northwestern Sichuan Basin. When using the impression method to reconstruct the paleotopography, the selection of the overlying base level in the overlying sedimentary layer is of primary importance, and the first sedimentary sequence boundary or the largest flooding plane in the primary overlying and denuded area is generally preferred (Xian et al., 2017). The depositional range of the Wenchang Formation in the south of Lufeng sag was limited, and it gradually expanded with the passage of time until the depositional range of the Upper Enping depositional period covered the entire area for the first time. Therefore, in this study, the T70 interface at the top of Enping Formation was selected as the isochronous datum for paleogeomorphic reconstruction.

Taking the top interface T70 of Enping Formation as the top, and the bottom interfaces Tg and T80 of Wenchang Formation and Enping Formation of the target layer as the bottom, we establish the original formation thickness between top and bottom. According to the principle of filling, the original stratum thickness between the overlying stratigraphic interface and the target interface can mirror the paleogeomorphic shape. The original stratum thickness consists of two parts: residual stratum thickness and denudation thickness. The residual stratum thickness uses the seismic data in the study area, the current stratum thickness is calculated separately on the basis of the identification of each stratum interface, and the non-deposition area is recorded as zero. The thickness of the denuded formation is extrapolated from the seismic data by the formation trend extension method.

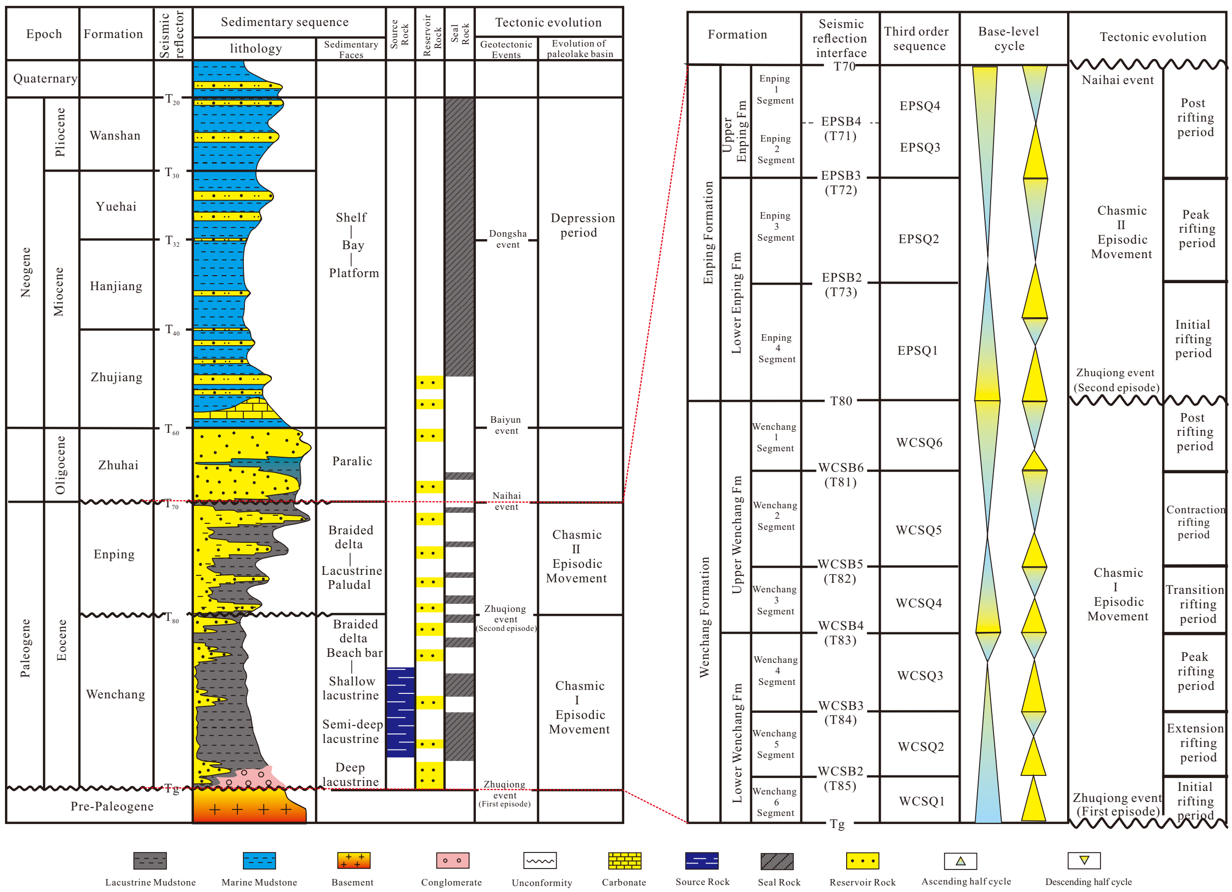

Fig. 2. Stratigraphic column of the Lufeng sag, Pearl River Mouth Basin (modified from Niu et al., 2019). Fm, Formation.

Given that different lithologies are subject to compaction, the formation thickness generally increases after compaction correction, but the geomorphological pattern shown by its planar distribution usually does not fundamentally change. Therefore, no compaction correction is carried out in the reconstruction of the ancient landform. In addition, the time span of the third-order sequence reaches the level of one million years (Ma), and the influence of paleo-water depth on the formation thickness will inevitably be weakened by long-term and inherited sedimentation. Therefore, this study does not carry out paleobathymetric correction.

On the basis of the reconstruction of ancient landforms, the scope of the provenance area is divided, the catchment area of each provenance area is selected, and the seismic profile of each relief (uplift) is intercepted along the provenance direction, to obtain the vertical elevation and slope angle corresponding to each provenance. At the same time, the fault drop method is employed to study the activity of the main fault. The vertical distance between the upper and lower walls is calculated on the seismic profile perpendicular to the fault strike, and the temporal and spatial evolution law of the main fault is clarified. Combined with the detailed sedimentary system map of the study area, the controlling effect of the tectonic-paleogeomorphology on the type and scale of the sedimentary system in the south of Lufeng sag during the Paleogene depositional period is revealed. In addition, according to the development positions and inclinations of boundary faults and small faults in the sub-sag, the corresponding slope-break belt types are divided, and the controlling effect of structural slope-break belts on sedimentary filling is discussed. Finally, the Paleogene tectonic-paleogeomorphic coupling-controlled sedimentary model is constructed for the south of Lufeng sag, which has a definite guiding significance for predicting the development of favorable reservoirs.

4. Results

4.1 Tectonic evolution

The tectonic evolution of the Pearl River Mouth Basin can be divided into three stages: the rifting stage (rifting episode I and rifting episode II), the thermal subsidence stage, and the fault activation stage. Among them, the rifting episode I and II correspond to the depositional period of the Wenchang Formation and Enping Formation, respectively. During the depositional period of the Wenchang Formation, under the influence of episode I of the Zhuqiong Movement, the Pearl River Mouth Basin as a whole was in a northwest-southeast (NW-SE) trending extensional environment, and the northeast-east northeast (NE-ENE) trending fault activity was intense. During the deposition of the Enping Formation, under the influence of the extrusion of Indosinian block, the direction of tensile stress in the Pearl River Mouth Basin changed from

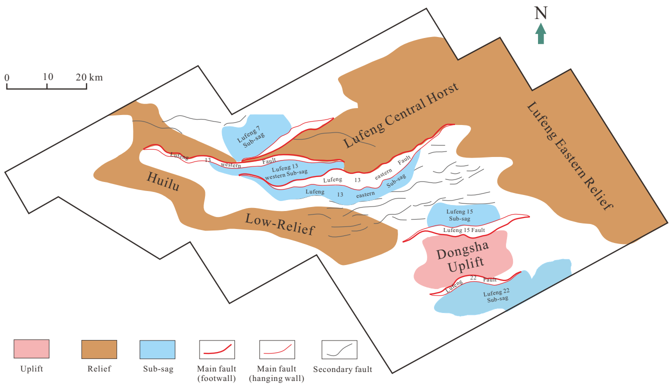

Fig. 3. Distribution of the top basement (Tg) fault system in the south of Lufeng sag (modified from Yu et al., 2016).

NW-SE to north south (NS), the NE-ENE direction of fault activity gradually weakened, and the west northwest-east west (WNW-EW) direction became the dominant fault trend in the Enping Formation (Wang et al., 2019).

There are two sets of fault systems in the south of Lufeng sag, namely NE-ENE and WNW-EW trending, both of which are normal faults (Fig. 3). The NE-ENE trending fault formed later, cutting and reforming the WNW-EW trending fault. Among them, NE-ENE trending faults are extensional or extensional-torsional faults formed under the action of NW-SE tensile stress, which began to develop during the depositional period of the Wenchang Formation and have a strong sag-controlling effect. During the deposition of the Enping Formation, the fault throw was greatly reduced, and the sag control effect was significantly weakened; WNW-EW trending faults formed under the action of near north-south tensile stress. During the deposition of the Wenchang formation, the fault activity was weaker, and the Enping Formation was less active. The deposition period was significantly enhanced, and the depression control effect was obvious. There are 3 main faults in the study area, their overall scale is large, and the extension distance exceeds 20 km. From south to north, these faults are the Lufeng 15 fault, Lufeng 13 eastern fault, and Lufeng 13 western fault, all of which are depression-controlling faults. Under the control of boundary faults, the south of Lufeng sag has a semi-graben structure as a whole (Yu et al., 2016).

4.2 Tectonic-paleogeomorphic response

The depositional period of the Wenchang Formation corresponds to the first episode of the rift, which was influenced by the strong boundary faulting activities, forming a structure-sedimentary filling pattern of "deep lake and narrow sub-sag" (Fig. 4). Due to the control of various boundary faults, the structure of each sag appears as a half-graben structure as a whole. The Lufeng 13 eastern sub-sag and Lufeng 13 western sub-sag are both pan-like half-graben structures with northern faults and southern overhangs.

The south of Lufeng sag shows a paleogeographical pattern of alternating reliefs and sub-sags. During the depositional period of the Wenchang Formation, only near-source sediments were developed. The four surrounding uplifts (reliefs) are the stable sources of the south of Lufeng sag, including the DU in the southeast, the LER in the east, the LCH in the north, and the HLR in the southwest (Zhang et al., 2012). The DU is a secondary structural unit in the Central Uplift Belt of the basin, with an area of about 29×10^3 km^2. During the deposition of the Wenchang Formation, it was first in the stage of uplift and denudation, and no deposition occurred. The HLR is distributed in an NW-SE trending strip, dipping from southeast to northwest with an area of about 1270 km^2, with a large number of overlying anticlines and extrusion anticlines developed on it. The LCH is located in the middle of the Lufeng sag with an area of about 905 km^2, which gradually decreased in width from east to west, and finally recombined into a fault zone. The area of the LER extends to about 1660 km^2, and it continued to provide sedimentary debris to the Lufeng sag during the Wenchang Period.

The sedimentary strata of the Enping Formation developed in the rifting episode II. Due to the change of regional tensile stress, the activity of dominant stress trend WNW-EW to Lufeng 13 western fault continued to rise, and the NE-ENE to Lufeng 13 eastern fault and Lufeng 15 fault were weak. The area of the lake basin continued to expand, and the water depth gradually decreased, showing the structure-sedimentary filling pattern of a "wide basin and shallow lake" (Fig. 5). The reliefs in the Lufeng sag were gradually submerged, the supply capacity was significantly weakened, which led to the domination of far-source South China Fold Belt outside the basin (Zhang et al., 2012). The DU is still in the stage of uplift and denudation, and continues to provide sedimentary debris to the Lufeng sag.

5. Discussion

As an important background for the development of sedimentary strata, the paleogeomorphology not only affects the original tectonic pattern, but also controls the supply system of ancient provenance, including provenance area, sedimentary area, and transportation direction and method (Evans and Rea, 1999; Lu et al., 2020). The configurational relationship between landform and provenance supply will form sedimentary systems with different sedimentary structures. In this paper, starting from the restoration of paleogeomorphology, the paleogeomorphic units and their spatial coupling characteristics in different periods are analyzed, their role in the provenance supply system and their matching relationship with sedimentary systems are studied, and different paleogeomorphic assemblages and their controlling effects on sedimentary systems and sandstone bodies are clarified. In addition, the control of the spatial distribution and activity intensity of the main faults on the deposition distribution and filling are eludicated, so that the type of sedimentary system and the distribution of sand bodies can be determined in terms of genesis.

5.1 Controlling effect of tectonic-paleogeomorph ology on sedimentary systems

5.1.1 Types of sedimentary facies

The sediment supply of continental rifted lake basins presents the characteristics of multi-source, near-source and

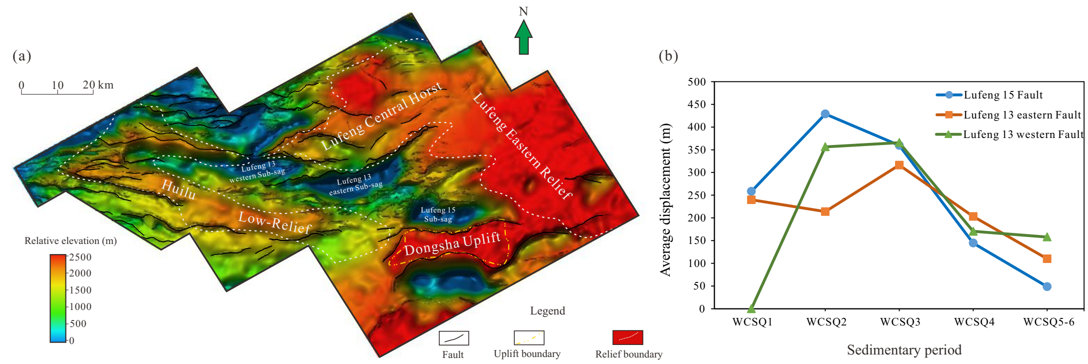

Fig. 4. Tectonic-paleogeomorphology features of the south of Lufeng sag during the depositional period of the Wenchang Formation: (a) paleogeomorphology of Tg interface, (b) fault activity.

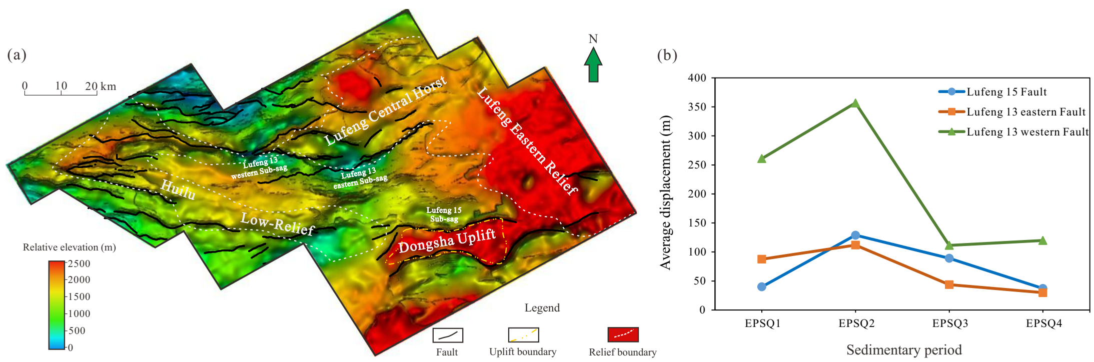

Fig. 5. Tectonic-paleogeomorphology features in the south of Lufeng sag during the depositional period of Enping Formation: (a) paleogeomorphology of T80 interface, (b) fault activity.

high-speed. In the near-source sediments, the topographic slope has a more significant control effect on the types of sedimentary facies. The slope of the terrain determines the dynamics of paleocurrents and the deposition rate of sediments. The greater the change of the terrain slope, the greater the hydrodynamic force, the larger the particle size of the sedimentary material that can be carried, and the faster the accumulation rate.

During the depositional period of the Wenchang Formation, the reliefs (uplifts) around the sub-sag in the south of Lufeng sag acted as the source, and the types of sedimentary facies under the controlling effect of different paleogeomorphic assemblages were significantly different (Fig. 6(a)). There is a relief – slope zone – sub-sag paleogeomorphic assemblage in the long axis direction of the lake basin, and the slope of the gentle slope belt controls the type of the sedimentary system; meanwhile, there is an uplift (horst) – fault zone – sub-sag paleogeomorphic assemblage in the short axis direction of the lake basin, with fault activity having an obvious controlling effect on the sedimentary facies type.

The Lufeng 15 sub-sag is adjacent to the DU in the uplift area, and is connected to the provenance area through the steep slope belt of the Lufeng 15 fault. The latter was highly active during the Wenchang period, with large undulations and steep slopes. The sedimentary debris quickly slipped from the high and steep DU, and was further accelerated into the Lufeng 15 sub-sag through the steep slope of the fault. The water body of the lake basin was deep, and the sediments quickly entered the lake to form fan deltas and nearshore underwater fans. The paleogeomorphic combination pattern of high and steep uplift – fault steep slope belt – sub-sag determined the extensive development of fan deltas in the Lufeng 15 sub-sag in the Wenchang period. The LCH was divided by faults, and the sedimentary debris carried by the ancient water flow was transported along the fault trough and finally converged in one place. Under the control of the Lufeng 13 eastern fault zone, the sediments quickly entered the lake. Due to the low degree of denudation in the LCH, only small floret-shaped fan deltas developed around its periphery.

The LER is connected with the gentle slope belt in the east of Lufeng, and is developing a broad and gentle low uplift – multi-level fault step gentle slope belt – sub-sag ancient landform combination pattern. It provides a good material basis for the long-distance transportation of sedimentary debris, and the continuous supply of the uplift forms a large-area braided river delta with a propulsion distance of more than 15 km. The HLR is strip-shaped and relatively low. It is close to the sub-sag, the sedimentary debris slipped from the HLR directly into the sub-sag, and the transportation distance is short, so a small-scale floret braided river delta developed along with the uplift. During the depositional period of the Enping Formation, the activity of the Lufeng 15 fault was greatly weakened, the paleogeomorphic undulations became significantly smaller, the water body of the lake basin became shallower, and a skirtlike shallow braided river delta developed around the DU in the south (Fig. 6(b)). The HLR and the LCH were gradually submerged under water and evolved into sedimentary areas. The Northern Uplift Belt has a strong supply capacity and features the development of a large-scale braided river delta, which has advanced to the south of Lufeng sag, and the extension distance can reach 40 km.

5.1.2 Scale of sedimentary system

The scale of the sedimentary system is controlled by the coupling between the supply capacity of the provenance area and the lake basin capacity space in the sag area. The area of catchment and the vertical elevation difference together determine the supply capacity of the provenance area. Catchment area refers to the area through which surface runoff converges to the same outlet location. The area of part of the DU that supplies the Lufeng sag is the catchment area of the DU in this study, and so on. The catchment area determines the amount of ancient water flow, which is an effective carrier for transporting detrital sediments. The change in the base level affects the size of the catchment area in the provenance area. During the low water stage, the sedimentary area is relatively limited, and the catchment area of the provenance area is large. During the high water stage, the lake level rises, the sedimentary area increases, the sedimentary body retreats to the provenance area, and the catchment area shrinks . At the same time, the vertical elevation difference provides potential energy for the transport of detrital sediments (Fu et al., 2020). The larger the vertical elevation difference, the greater the amount of sediment that the paleocurrent can transport.

During the depositional period of the Wenchang Formation, the main provenances were the LER and HLR along the long axis of the lake basin, and the secondary provenances were the DU and LCH along the short axis. The HLR and the LER have strong supply capacity, and a large area of braided river delta deposits have developed on the gentle slope belts on both sides of the lake basin in the south of Lufeng sag. Among them, the LER has a large catchment area of up to 1400 km^2, and a large-scale contiguous braided river delta is formed on the east side, with a spread area of about 200 km^2 and a propulsion distance of up to 20 km. The HLR has a large catchment area of more than 500 km^2, and the transition zone water system that has developed on it transports a large number of sedimentary debris to the Lufeng 13 eastern sub-sag. The largest distribution area of the river delta can reach 29 km^2, the extension distance is 15-18 km, and the scale is slightly smaller than that of the eastern delta. The catchment area and vertical elevation difference of the LER are larger than those of the HLR, that is, the scale of the braided river delta on the east side of the lake basin is much larger than that on the west side (Figs. 7(c) and 7(d)).

Fan deltas have developed on the periphery of LCH and DU on the north and south sides. Among them, the catchment area of the LCH is 288 km^2, while the DU has a smaller catchment area of only 76.8 km^2, with limited distribution. However, the DU, as an extra-basin provenance, has a large vertical elevation difference of up to 1976 m. The LCH, as a small provenance in the basin, has a vertical elevation difference of only 975 m. The higher vertical elevation difference of the DU compensates for its limited catchment area, so the scale of the fan body controlled by the DU is slightly larger than that of the LCH. The catchment area of the source area and the vertical elevation difference together determine the supply flux of sediments in the provenance area. The larger the catchment area, the larger the vertical elevation difference, the larger the supply flux in the provenance area, and the larger the scale of the sedimentary body in the sedimentary area (Figs. 7(a) and 7(b)). During the deposition of the Enping Formation, the HLR, LCH and LER in the basin were gradually submerged by water and evolved into sedimentary areas. The catchment area of the DU remained unchanged, and the scale of the depositional fan did not alter significantly compared with the depositional period of the Wenchang Formation. The extent of the lake basin on the east side became larger, and the provenance area of the sedimentary facies retreated and evolved into the Haifeng relief on the east side of the Lufeng sag.

The lake basin capacity space in the sag is closely related to the activity of the main faults. The Wenchang 6 segment corresponds to the early stage of the initial fault depression, the Lufeng 13 western fault is basically inactive, and the Lufeng 15 fault and the Lufeng 13 eastern fault has begun to move, but their activity is weak. Under the control of fault activity, the lake basin has only developed in the descending wall of the Lufeng 15 fault and the Lufeng 13 fault, which are separated from each other and their scope is relatively limited. The provenance around the lake basin continued to supply, and the lake basin was rapidly filled by fan delta glutenite and braided river delta medium-coarse sandstone (Fig. 8(a)).

The depositional period of the fifth member of Wenchang was the late stage of the initial rifting, when the activity of the main faults was strong, the scope of the lake basin was further expanded, and the sub-sags were connected. Small-scale crony-like fan deltas developed in the descending wall of each main fault. The two isolated faults, the Lufeng 13 western fault and the Lufeng 13 eastern fault, overlap to form a transition slope. Paleo-water systems carry sedimentary clastic materials through the transition zone to form the braids river delta. On both sides of the long axis of the lake basin, the provenances of the LER and the HLR are strong, and the gentle slope belts on the east and west sides are developing a large-scale braided river delta sedimentary system with a long advancing distance (Fig. 8(b)).

During the depositional period of the fourth member of Wenchang, it was in the stage of strong rifting, the activity of main faults basically reached the maximum, the development of the lake basin entered the peak period, and the water body was the deepest. The provenance development features good inheritance, as there are fan deltas with thick layers and a short extension distance in the hanging wall of the fault. At the same time, the rapid activity of boundary faults led to extensive lake transgression. With the continuous rise of the water level, the braided river deltas, developed in the gentle slope belts on the east and west sides of the lake basin, regressed significantly toward the provenance area, and the sedimentary scale was greatly reduced (Fig. 8(c)). The Wenchang 3 segment and the

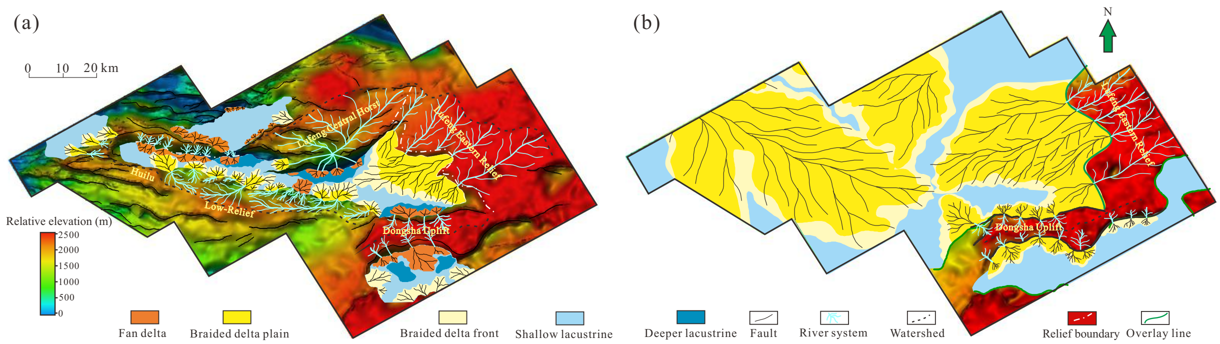

Fig. 6. Distribution map of the source-sink system in the Wenchang and Enping periods in the south of Lufeng sag: (a) Wenchang period, (b) Enping period.

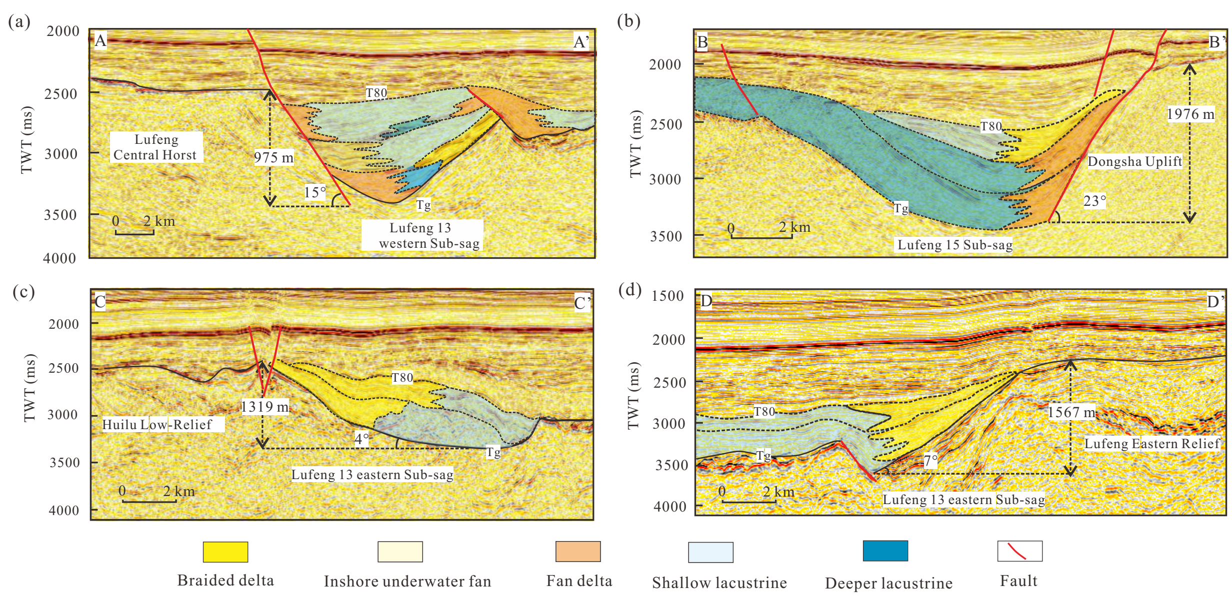

Fig. 7. Relationship between slope angle, vertical elevation difference and sedimentary system distribution of the provenance area in the south of Lufeng sag: (a) Lufeng Central Horst, (b) Dongsha Uplift, (c) Huilu Low-Relief, (d) Lufeng Eastern Relief.

Wenchang 1-2 segment correspond to the rift shrinking period when the activity of the main faults gradually weakened, the sag range decreased, and the water body became shallow. The scale of the braided river delta in the gentle slope belt on the east and west sides has recovered to some extent, and a fan delta has developed successively in the hanging wall of the fault. Under strong supply from the provenance area, the sag was gradually filled up (Figs. 8(d) and 8(e)).

In the early stage of the deposition of the Enping Formation, the activity intensity of the Lufeng 13 eastern fault and the Lufeng 15 fault was relatively weak, and only the Lufeng 13 western fault was highly active. Therefore, in addition to the development of a certain scale of fan delta in the hanging wall of the Lufeng 13 western fault, the south of Lufeng sag was an extensively developed braided river delta. With the advancement of filling, the lake level is gradually rising. Only the top of the HLR is exposed to the water surface, and the range of the east uplift is retreating and shrinking. The periphery of the lake basin is dominated by braided river deltas, which are rapidly advancing toward the center of the sag (Figs. 8(f) and 8(g)).

In the late Enping period, the transition from fault depression period to depression period occurred, the activity of main faults was greatly reduced, and the accommodation space of the lake basin was limited. The lake level continued to rise, and the water body became even shallower, showing the characteristics of an extremely shallow lake. The extent of LCH and LER was greatly reduced, and the HLR was submerged under water and was gradually accepting sediments. The blocking effect of the reliefs in the basin weakened, and the abundant supply in the Northern Uplift Belt outside the basin formed a large-scale shallow-water braided river delta, which rapidly advanced to the center of the lake basin and completely covered the HLR. At the end of the deposition of Enping Formation, the rifting gradually decreased and disappeared, and the size of the braided river delta gradually decreased with the shrinking of the lake basin (Figs. 8(h) and 8(i)).

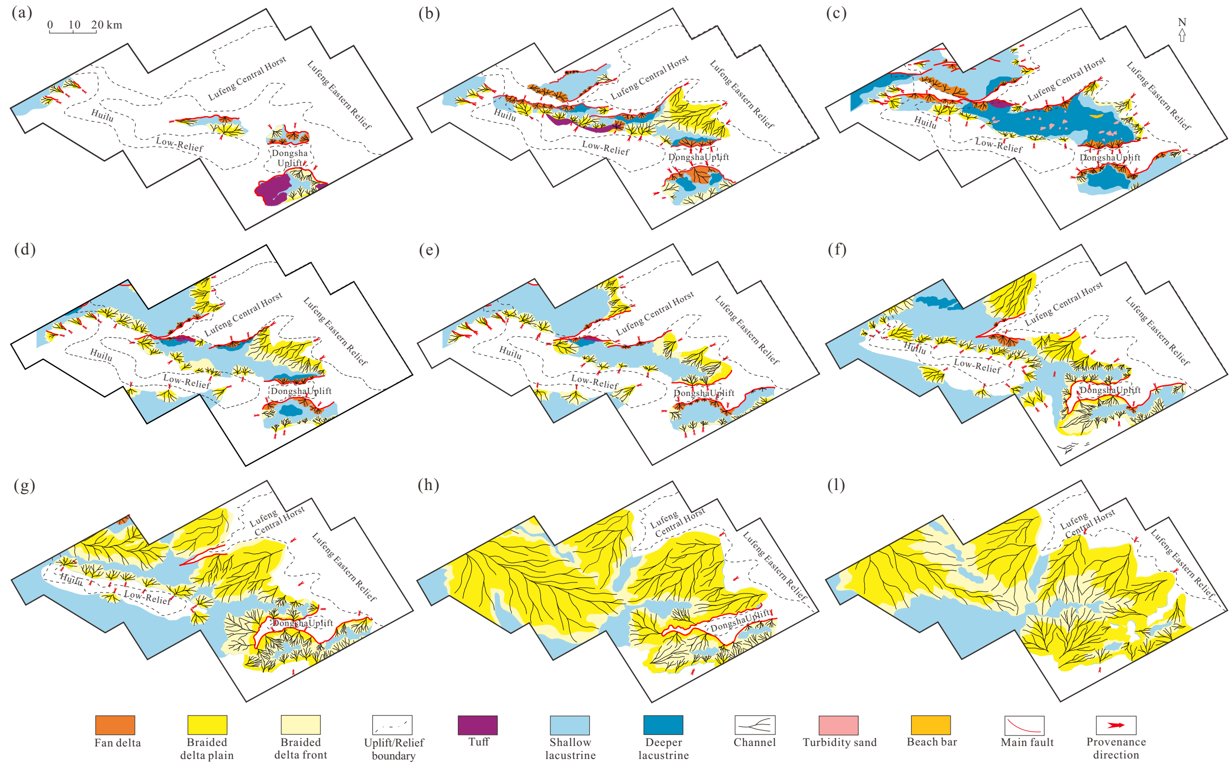

Fig. 8. Sedimentary facies evolution map of the Wenchang Formation and the Enping Formation in the south of Lufeng sag: (a) Wenchang 6 Segment, (b) Wenchang 5 Segment, (c) Wenchang 4 Segment, (d) Wenchang 3 Segment, (e) Wenchang 1,2 Segment, (f) Enping 4 Segment, (g) Enping 3 Segment, (h) Enping 2 Segment, (i) Enping 1 Segment.

5.1.3 Sedimentary filling

The boundary faults that control the evolution of the sag and the tectonic slope-break zone formed by the synsedimentary faults inside the sag determine the size of the accommodated space in the sag, restrict the type and development location of the sedimentary system, playing an important role in controlling the spatial distribution of sand bodies (Cohen, 1991). According to the development location and tectonic style of the tectonic slope-break belt, it can be divided into three types: steep cliff, steep slope fault-step type and gentle slope fault-step type (Fig. 9).

The first is the steep cliff deposition model, for which the Lufeng 15 fault is a typical case. The DU outside the fault directly provides sedimentary debris, and a vertically superimposed coarse clastic system continues to develop along the hanging wall of the fault. The occurrence of the hanging wall strata is horizontal or is in the dipping fault direction. The second type is the steep slope fault step, which is formed by the combination of the Lufeng 13 eastern fault and several secondary faults in the same direction. The LCH is the source, the fault steps in the same direction of the steep slope can accommodate little space, and many fan-delta sedimentary systems are developed. At the same time, under the driving force provided by the faults distributed in the same direction, the sediments are transported over a long distance. The third type is gentle slope fault step, which is mainly developed in the gentle slope belt in the south of Lufeng sag, and is controlled by multiple parallel normal faults arranged in steps. The LER has strong supply capacity, and the sediment transport distance is relatively long. Large-scale braided river deltas are developing there, and the sediment particle size is relatively small. Due to the slump and turbidity currents of gravity flow, sublacustrine fan sedimentary systems or turbidite sand bodies are likely to be formed in the hanging wall of the fault.

5.2 Sedimentary model based on tectonic-paleogeomorphology control

The fifth and sixth members of the Wenchang Formation correspond to the initial rifting stage of the Wenchang Formation. The main faults in the early stage have weak activity, the lake basin is small in scope, and the segmentation is strong. In the later stage of the initial rifting, with the increasing intensity of the main fault activity, the scope of the lake basin continued to expand, and it was distributed in contiguous pieces. The strong supply and sufficient accommodating space provided favorable conditions for the extensive development of the sedimentary system. At this time, the scale of the sedimentary fan body reached the maximum. The LER and the HLR along the long axis of the lake basin developed a geomorphic combination of relief – slope belt – sub-sag. The DU in the short-axis direction and the LCH is a combination of uplift (relief) – fault zone – sub-sag. The sub-sag developed next to the fault, and the type of sedimentary facies formed

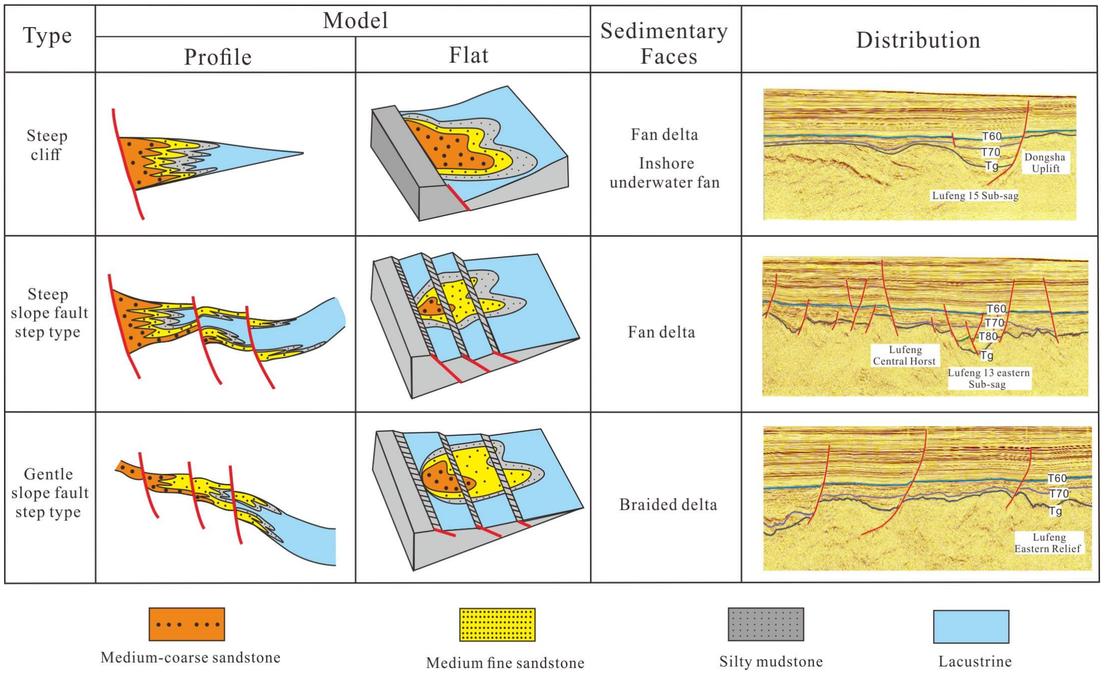

Fig. 9. Types of tectonic slope-break belts and distribution of sedimentary systems in the south of Lufeng sag (modified from Li et al., 2018).

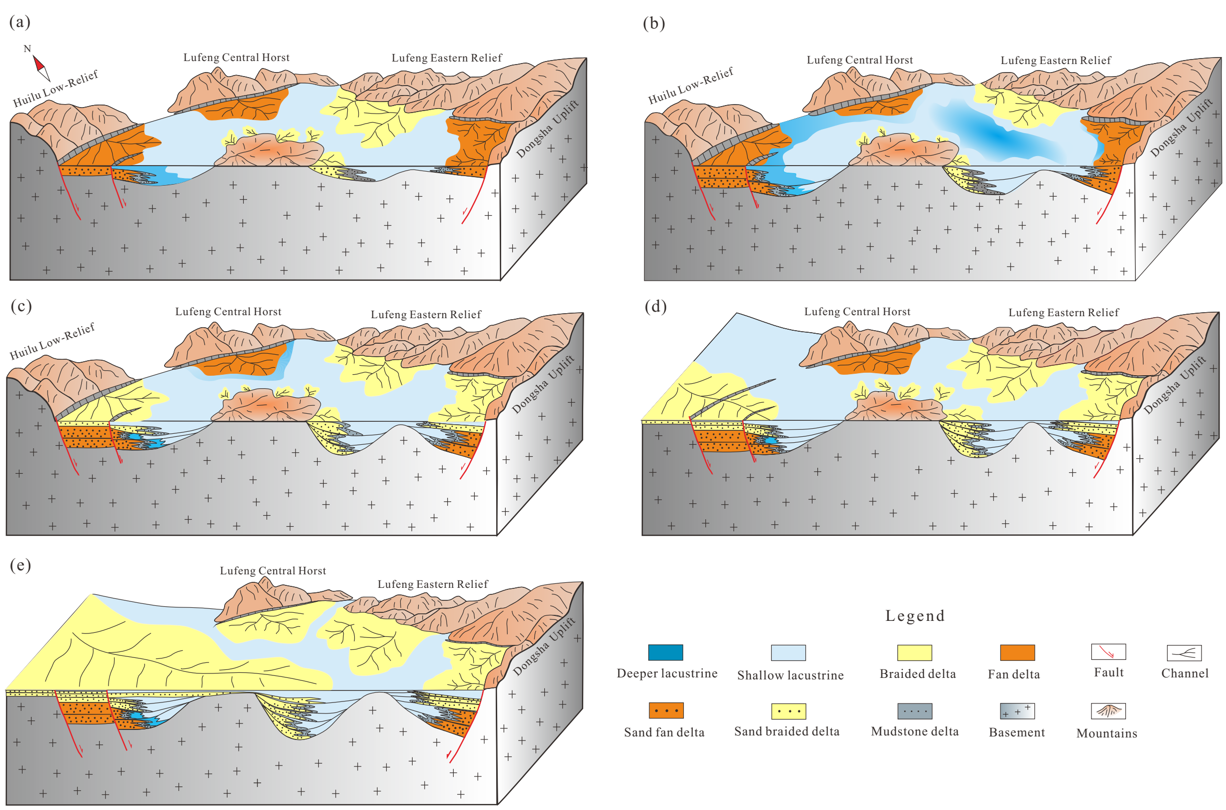

Fig. 10. Sedimentary model based on paleogene tectonics-paleomorphology control in the south of Lufeng sag: (a) late stage of initial rifting of Wenchang Fm, (b) peak rifting period of Wenchang Fm, (c) post rifting period of Wenchang Fm, (d) initial rifting period of Enping Fm, (e) post rifting period of Enping Fm.

is closely related to the activity of the fault. In the late stage of the initial rifting, the strong activity of the dominant faults produced fault cliffs, and fan delta sand bodies developed near the hanging wall of the faults (Fig. 10(a)).

The fourth member of the Wenchang Formation developed during the period of strong rifting. At this time, the intensity of boundary fault activity reached the maximum, and the water body became deeper. At the same time, the rapid activity of the fault led to the occurrence of lake transgression. The scope of the lake basin was further expanded, the raised areas on the east and west sides of the lake basin were partially submerged by water, the area of the catchment was reduced, and the supply capacity was significantly weakened. Eventually, the size of the braided river delta in the long axis of the lake basin has been greatly reduced (Fig. 10(b)).

The depositional period of the first and second members of Wenchang was a weak rift period, and the activity of the faults gradually weakened. The sedimentary system of the hanging wall of the main fault has changed from fan delta to braided river delta. Only the small-scale fan delta developed near the LCH. At the same time, the scope of the lake basin shrank and the area of the catchment recovered, but this limited by the accommodated space of the lake basin; the scale of the sedimentary system recovered, but it was significantly smaller than that in the later stage of the initial rift (Fig. 10(c)).

In the early stage of the rifting of Enping Formation, that is, the depositional period of the Wenchang 3 and Wenchang 4 segments, the periphery of the HLR was gradually submerged under water, only the top of the rift was exposed to the water surface, and the rest of the provenance developed in succession. The Northern Uplift Belt has strong supply capacity, and the HLR has an obvious blocking effect, so the northern braided river delta extends to the HLR. Except for the fan delta near the hanging wall of the fault in the LCH, large-scale braided river deltas have developed in the entire Lufeng sag (Fig. 10(d)).

In the late rift stage of Enping Formation (the Wenchang 1st member and the Wenchang 2nd member deposition period), the fault activity in the whole area was greatly weakened, the fault throw was small, and the sedimentary material formed a braided river delta sedimentary system along the fault slope. The HLR was completely submerged under water, and the barrier effect was weakened. The braided river delta under the control of the Northern Uplift Belt rapidly advanced to the center of the lake basin, completely covering the HLR. At the same time, under the action of high water level, parts of LCH turned into sedimentary areas. The south of Lufeng sag has been filled with large-scale braided river delta fans (Fig. 10(e)).

6. Conclusions

1) The catchment area and vertical elevation difference of the source area determine the source supply capacity, and the activity of boundary faults define the accommodation space of the lake basin. The coupling of the supply capacity of the uplift area and the accommodation space of the lake basin controls the scale of the sedimentary system.
2) There are two paleogeomorphic assemblage styles in the south of Lufeng sag: uplift – fault zone – sub-sag and relief – slope zone – sub-sag. The slope controlled by the combination of paleomorphology and the activity of the main fault determines the sedimentary type.
3) In the south of Lufeng sag, there are three types of structural slope-break belts that control sand: steep cliff, steep slope fault-step type, and gentle slope fault-step type. The structural slope-break zone influences the distribution of sedimentary sand bodies.

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Conflict of interest

The authors declare no competing interest.

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