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PETROLEUM GEOLOGY

Segmented fault activity as a driving mechanism for multiphase fan delta lateral migration: A case study from the Paleogene Strata of Block G, Wenchang Sag, South China Sea

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ABSTRACT

The fan delta in the steep slope zone of a rift lake basin is an important oil and gas reservoir unit. The development of vertical multi-stage fan deltas has certain inheritance and vertical non-overlapping characteristics. The driving mechanism of the overall lateral migration of such multi-stage fan deltas is currently not completely clear. Taking the fan delta in the Paleogene steep slope zone of Block G in the Wenchang Sag in the northern South China Sea as the research object, based on core, logging, drilling data and high-precision 3D seismic data, using seismic facies analysis and fault displacement-rate analysis techniques to analyze the driving effect of fault segmentation activities on the lateral migration of the fan delta. The results show that: (1) The vertical multi-stage fan deltas show inherited development characteristics, and the plane shows lateral migration characteristics, with a migration rate of 0.1-0.5 km/Ma; (2) The center position of the fan delta is highly correlated with the low-velocity zone of fault activity, and 80% of the research samples are distributed in the low-velocity zone of fault activity; (3) The migration of the fan delta shows a two-stage driving characteristic of "fault-dominated positioning - geomorphic dynamic regulation". In the early stage, the segmented activity of the fault controls the injection position of the detritus in the uplift area into the lake basin. After the detritus enters the lake, it locally transforms the accommodation space in the basin, dynamically adjusts the sedimentary geomorphology, and then reshapes the sedimentary path and drives the lateral migration of the fan body.

Keywords: Rift Lake Basin; Fan Delta; Lateral Migration; Fault Segmentation Activity; Wenchang Sag

Actividad de fallas segmentadas como mecanismo impulsor de la migración lateral multifásica de deltas de abanico: Un estudio de caso en los estratos del Paleógeno del Bloque G, depresión Wenchang, Mar de China Meridional

RESUMEN

Un delta de abanico en la zona de pendiente pronunciada de una cuenca lacustre de rift constituye una unidad de reservorio de petróleo y gas de gran importancia. El desarrollo de deltas de abanico verticales y multietapa presenta características de herencia y ausencia de superposición vertical. Actualmente, el mecanismo que impulsa la migración lateral de estos deltas de abanico multietapa no está completamente claro. El objeto de estudio de este trabajo es el delta de abanico de la zona de pendiente pronunciada del Paleógeno en el Bloque G de la depresión Wenchang, en el norte del Mar de China Meridional, y permitió analizar los efectos de la segmentación de fallas sobre la migración lateral del delta utilizando datos de núcleos, registros, perforaciones y sísmica 3D de alta precisión, con técnicas de análisis de facies sísmicas y de tasas de desplazamiento de fallas. Los resultados indican lo siguiente: (1) Los deltas de abanico multietapa muestran características de desarrollo heredado en sentido vertical, y en planta presentan migración lateral, con una tasa de migración de 0,1-0,5 km/Ma; (2) La posición central del delta de abanico está altamente correlacionada con la zona de baja velocidad de actividad de fallas, y el 80% de las muestras analizadas se ubican en esta zona; (3) La migración del delta de abanico muestra una característica de doble etapa impulsada por el "posicionamiento dominado por fallas – regulación dinámica geomorfológica". En la etapa inicial, la actividad segmentada de la falla controla la posición de inyección de los detritos desde la zona de realce hacia la cuenca lacustre. Tras su ingreso, los detritos transforman localmente el espacio de acomodación de la cuenca, ajustan dinámicamente la geomorfología sedimentaria y, posteriormente, redefinen la ruta de sedimentación e impulsan la migración lateral del cuerpo del abanico.

Palabras clave: Cuenca lacustre de rift; delta de abanico; migración lateral; actividad de segmentación de fallas; depresión Wenchang

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Introduction

Fan delta is a coarse clastic fan-shaped sedimentary body formed by alluvial fans directly entering lakes or oceans as sources (Nemec and Steel, 1988), which has the characteristics of near-source, rapid accumulation, and large sedimentary thickness (Jin et al., 2006; Winsemann et al., 2007). In petroliferous basins, fan deltas can form good oil and gas reservoirs and are an important target area for oil and gas exploration (Ji et al., 2012). In recent years, the discovery of several large-scale sandy-conglomerate-rich oil and gas fields (Fu et al., 2020; Xu et al., 2024) has made fan deltas one of the hot issues in sedimentology research (Zhu et al., 2021). Previous studies have shown that the sedimentary process of fan deltas is controlled by multiple factors such as structure, climate, and source supply (Xian et al., 2007; Yan et al., 2020; Chen et al., 2024). Dong Daotao studied and believed that fault activities affect the development location of fan deltas. Fault types, fault combinations, and slope types control the development location of fan deltas (Dong et al., 2018; He et al., 2023). Ji Youliang studied and believed that climate is an important condition affecting the development of fan deltas. The alternation of flood periods and dry periods makes fan deltas have different sedimentary characteristics in the vertical direction (Ji et al., 2013); Zhang Wenmiao studied and believed that the scale of fan deltas is mainly affected by flood types and flow rates, and believed that the greater the peak flood flow, the easier it is to cause lateral migration of the river channel (Zhang et al., 2024). Although previous studies have revealed the control process of the formation of fan deltas from different angles, most of them focus on the formation process, geometric characteristics or development location within a single fan body, and lack research on the driving mechanism of the lateral migration or swing characteristics of vertical multi-stage fan deltas. This paper selects the Paleogene steep slope zone of Block G in the Wenchang Sag in the northern South China Sea as the research object. Based on drilling data and 3D seismic data, the well-seismic combined sedimentary facies boundary characterization technology and the fault displacement-activity rate quantitative analysis technology are used to determine the distribution location of fan deltas in different periods and the characteristics of fault activity. By coupling and analyzing the correlation between the two, the driving effect of fault segmentation activities on the overall lateral migration of multi-stage fan deltas is clarified. The research is conducive to a better understanding of the sedimentary evolution process of fan deltas and guiding oil and gas exploration.

1. Geological background

The Wenchang sag is located in the west of the Zhu III depression in the Pearl River Mouth Basin. It is a dustpan-shaped extensional petroliferous basin with an area of about 6000 km². The sag is adjacent to the Shenhu uplift in the south, the Yangjiang uplift in the north, the Enping sag in the east, and the Qionghai uplift in the northwest (Jiang et al., 2009; Yi et al., 2019). The Wenchang G area is located at the junction of the Wenchang A and B sags and covers the western regions of the Wenchang 14 and Wenchang 9 sags (Fig. 1). The main sedimentary period is from the end of the Eocene to the early Oligocene, showing typical sedimentary characteristics of a faulted lacustrine basin (Zheng et al., 2023). The Cenozoic developed Paleogene strata: Shenhu Formation, Wenchang Formation, Enping Formation, and Zhuhai Formation; Neogene strata: Zhujiang Formation, Hanjiang Formation, Yuehai Formation, and Wanshan Formation; Quaternary strata: Qionghai Formation (Fig. 2). The Zhu III south fault is the most important sedimentary-controlling fault in the study area, and its strong activity in the Paleogene controls the sequence structural style of the study area (He et al., 2017; Lei et al., 2017). The Zhu III south fault mainly has three major tectonic movements in the Paleogene, namely the Shenhu movement, the first stage of the Zhuqiong movement, and the second stage of the Zhuqiong movement. Affected by tectonic movements, the early Oligocene (Wenchang Formation and Enping Formation) is the rift lake filling period. The segmented activity of the Zhu III south fault has an important influence on the distribution of glutenite bodies in the sedimentary area. The southern Shenhu uplift is the main source area of the study area. A large amount of clastic material from the Shenhu uplift enters the lake from the steep cliff, forming a fan delta sedimentary system (Li et al., 2015).

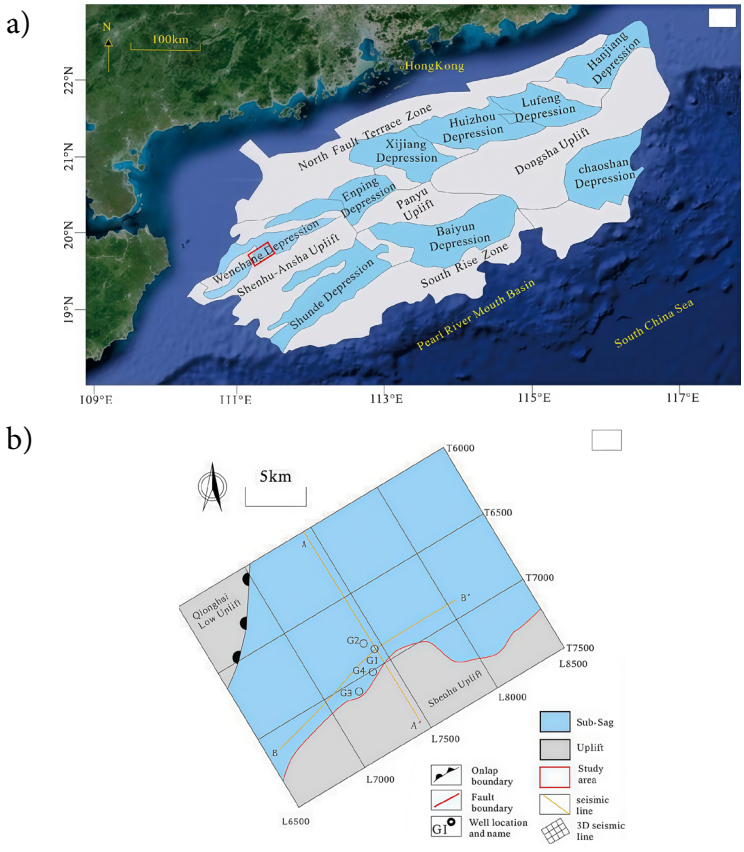

Figure 1. Structural map of Wenchang A depression

(a) Regional tectonic characteristics of the Pearl River Mouth Basin(modified from Zhu et al., 2016).
(b) Structural features of the Wenchang A Sag (modified from Zheng et al., 2018).

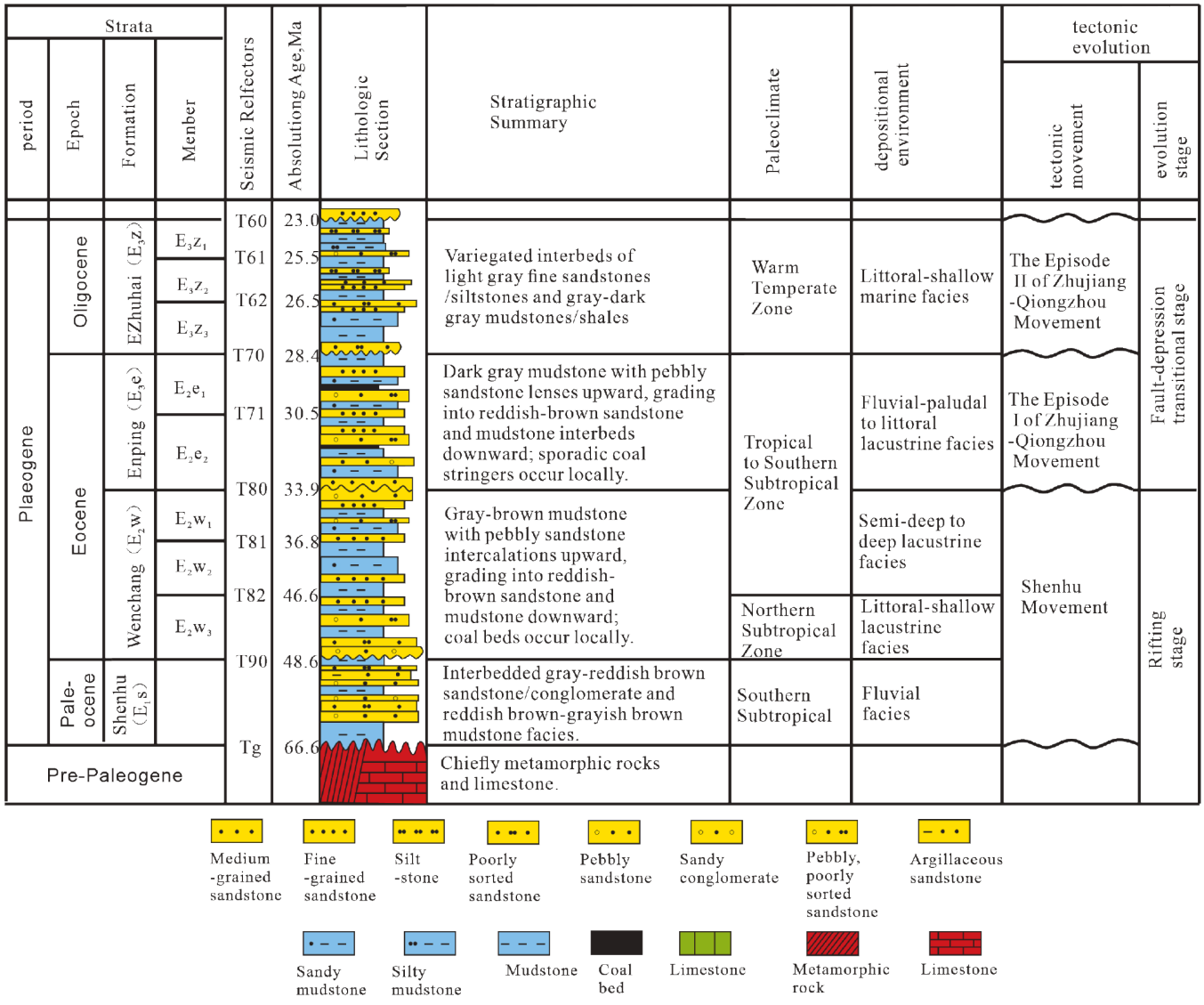

Figure 2. Comprehensive column chart of Paleogene in Wenchang A depression (modified fromWang et al., 2018)

2. Sedimentary characteristics

2.1 Typical core, logging, and seismic facies characteristics

This time, the sedimentary characteristics of the study area are comprehensively understood based on core, logging, and 3D seismic data. There are 4 drilling wells in the study area, with relatively high-resolution natural gamma curves and resistivity curves. A total of 16.62m of core data was obtained, including 7.9m of the cored section of the Enping Formation and 8.72m of the cored section of the Wenchang Formation. Combined with the relatively high-resolution 3D seismic data, the sedimentary environment is identified through the reflection characteristics of seismic profiles and the seismic attribute slices. The study area is a steep slope zone of a faulted lacustrine basin, and the source area clastic materials enter the lake along the steep slope fault, forming a fan delta-lacustrine sedimentary system. The inside of the fan is a sandy-conglomerate mixed body, and the outside of the fan is a lacustrine mudstone sedimentary body. Due to the difference in lithologic bodies inside and outside the fan, the logging curve characteristics and seismic reflection characteristics are significantly different. And then identify the boundary of the fan delta.

The fan delta includes two sedimentary subfacies: plain and front. The fan delta plain is formed by the rapid deposition of sandy conglomerate into the lake, mainly including sedimentary microfacies such as distributary channels and debris flows. The core is grayish-white sandy conglomerate and pebbly coarse sandstone. Vertically, it presents multi-stage superposition of normal rhythms, and the scouring surface can be seen at the bottom of the cycle. The gravel composition is complex, the sorting is poor, the rounding is poor, and the gravel is disordered. It gradually transitions upward to coarse-medium sandstone, and develops graded bedding and cross-bedding. On the logging, the natural gamma (GR) curve is generally low in value, and the resistivity (RT) curve is high in value. The logging facies morphology is “abrupt at the bottom, abrupt at the top, and serrated box-shaped” (Fig. 3); the fan delta front

includes sedimentary microfacies such as underwater distributary channels and estuary dams. The core of the underwater distributary channel is a large set of sandy-pebbly medium sandstone with scouring-filling structures at the bottom and normal grain order. The overall natural gamma (GR) curve is medium-low in value, and the resistivity (RT) curve is medium-high in value. The logging facies morphology is "abrupt at the bottom, gradual at the top, and serrated bell-shaped"; the estuary dam microfacies is pebbly coarse sandstone, coarse sandstone, and medium sandstone with medium sorting, massive structure or inclined bedding, and reverse grain order characteristics. The overall natural gamma (GR) curve is medium-low in value, and the resistivity (RT) curve is medium-high in value. The logging curve morphology is "abrupt contact at the top, gradual at the bottom, and serrated funnel-shaped" (Fig. 4). The fan delta appears as a wedge-shaped geological body with obvious geometric shape on the seismic profile, with poor internal continuity and medium-weak reflection intensity. Near the fault zone, it is characterized by short-axis and disordered weak reflections, and near the fan end, it is characterized by medium continuity, medium-strong amplitude, and obvious downlap reflection characteristics (Fig. 5b). On the vertical source profile, the boundary contour is generally lenticular, and the top mostly coincides with the sequence interface, and there is an obvious truncation phenomenon (Fig. 6b). The distribution trend of the fan delta can be displayed on the plane through the seismic RMS amplitude attribute. The fan delta shows red-yellow low amplitude value characteristics (Fig. 5d).

The lacustrine sedimentation is mainly deep lake-semi-deep lake sedimentary subfacies. The core is black and dark black mudstone, and locally there are interbeds of black mudstone and grayish-white sandstone. On the logging, the natural gamma (GR) curve is high in value, and the resistivity (RT) curve is low in value. The logging facies morphology is characterized by "flat linear or serrated linear", and locally it is a "fingered" thin sandstone layer. Its reflection characteristics on the seismic profile are significantly different from those of the fan delta. The seismic reflection event is extremely continuous, showing high continuity characteristics. The reflection energy is strong, and the event is parallel-subparallel (Fig. 5b). On the seismic RMS amplitude attribute, the lacustrine sedimentation shows blue-black high amplitude values, which is greatly different from the fan delta amplitude (Fig. 5d).

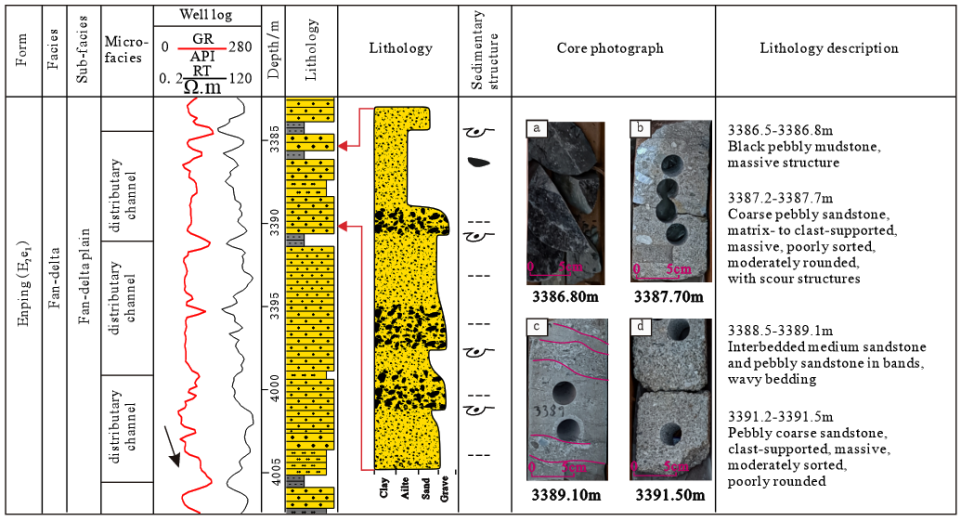

Figure 3. Integrated Core and Wireline Log Characteristics of the Enping Formation in Well G1, Block G, Wenchang Sag.

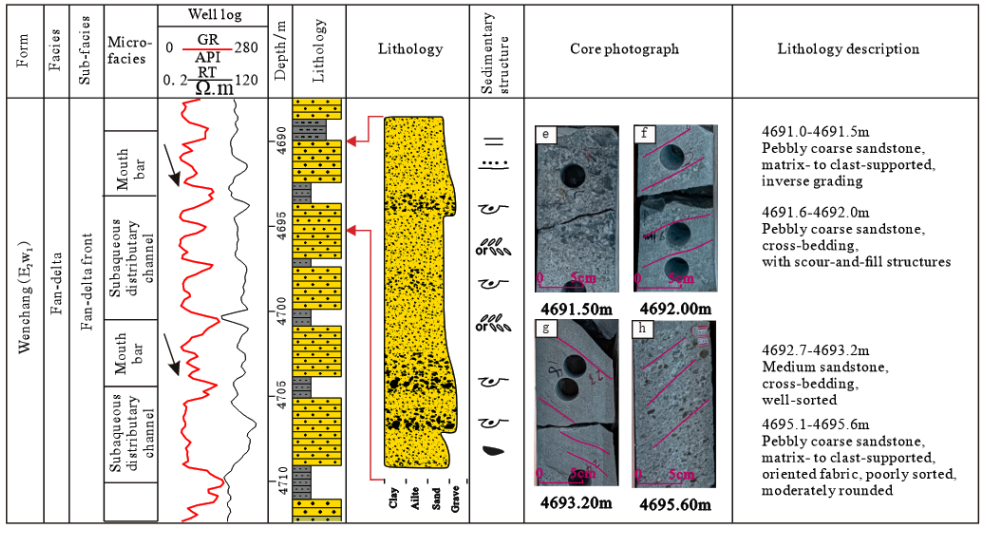

Figure 4. Integrated Core and Wireline Log Characteristics of the Wenchang Formation in Well G1, Block G, Wenchang Sag

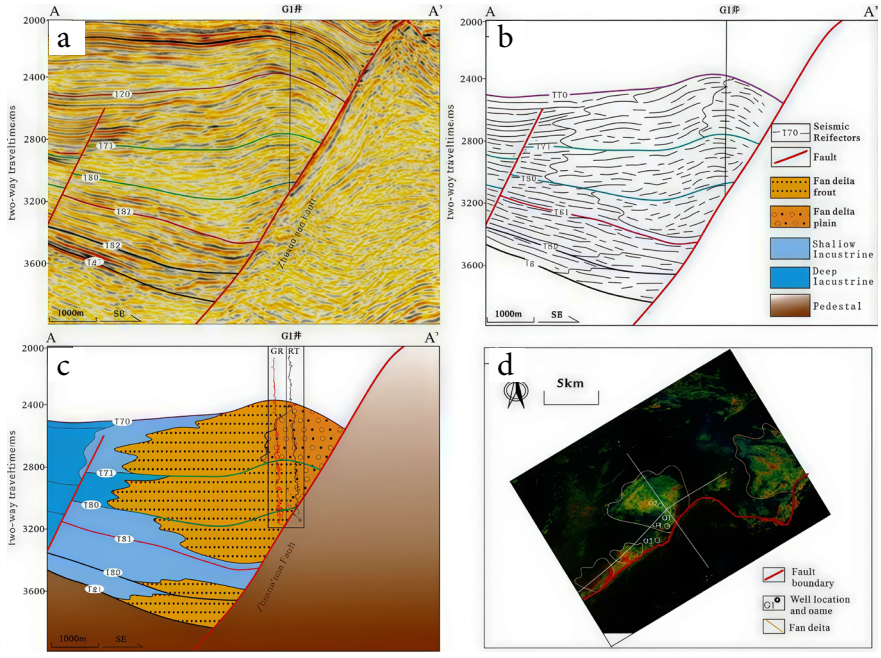

Figure 5. Seismic Facies Architecture of Fan Delta Systems and RMS Amplitude Attribute Analysis in the E_3e_2 Stratigraphic Horizon

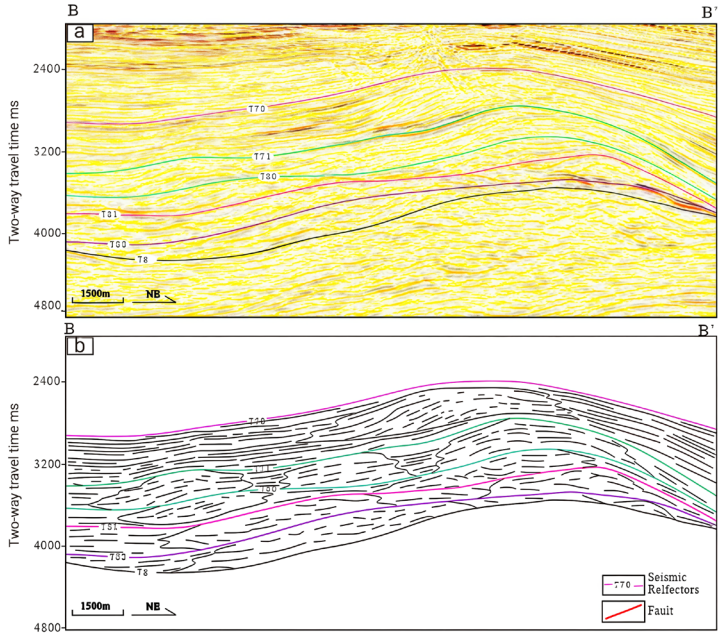

Figure 6. Seismic Facies Architecture in the Transverse Provenance Direction: Diagnostic Geometries and Reflection Patterns

2.2 Sedimentary facies characteristics

Based on the above research methods, the sedimentary boundary of the fan delta can be well identified. Through the sedimentary facies maps of each period, it can be seen that a total of 10 fan delta sedimentary bodies are identified in the 5 third-order sequences from the E_2w_3 stage to the E_2e_1 stage in the study area. The plane distribution location is shown in Figure 7. From bottom to top, there are mostly two fan deltas developing in the five periods, and only one fan delta on the right side in the sedimentary final stage E_2e_1. Taking the seismic line number of the long axis centerline of each fan delta as a reference, the development location of the fan delta is counted, and the parameters are shown in Table 1. This study details the development location of different fan deltas, and uses the line number of the long axis of the fan delta as a reference to calibrate the development location of each fan delta.

Table 1. Inline numbers of the centerlines of fan deltas in different periods

	Fan Delta1	Fan Delta2	Fan Delta3
Formation	**Inline**	**Inline**	**Inline**
E_2w_3	7140	7911	/
E_2w_2	7082	7742	/
E_2w_1	6830	7620	/
E_2e_2	6705	7202	7555
E_2e_1	/	7509	/

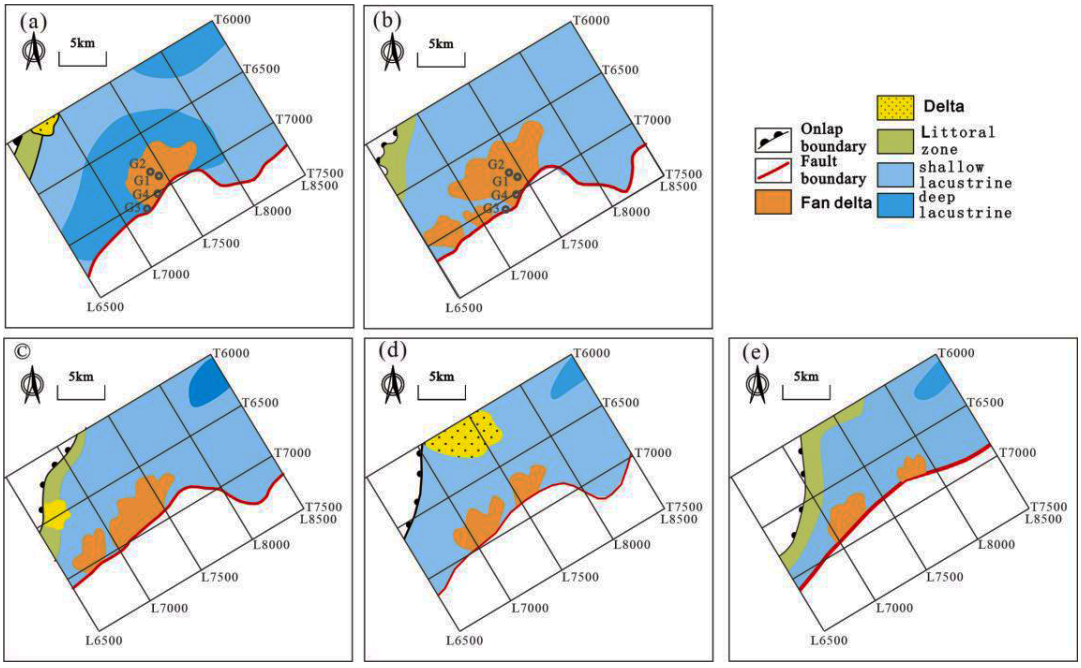

Figure 7. Stratigraphic Evolution of Sedimentary Facies in Block G, Wenchang Sag: A Comparative Analysis of Depositional Systems Through Key Horizons a-E_2e_1 Formation; b-E_2e_2 Formation; c-E_2w_2 Formation; d-E_2w_2 Formation; e-E_2w_3 Formation.

2.3 Lateral migration characteristics of the fan body

Combined with the seismic profile (Fig. 6b), during the sedimentary process, from the E_2w_3 stage to the E_2e_1 stage, the fan delta has obvious inheritance and migration development characteristics. The sedimentary centers of the fan deltas in different vertical periods do not coincide, showing obvious lateral migration characteristics. The fan bodies are divided into two groups, namely fan body group 1 and fan body group 2. Based on the inline number of the fan body centerline, the lateral offset of the fan body is counted. The acquisition bin of the 3D seismic data in this study is 12.5*12.5m, that is, the spacing between adjacent survey lines is 12.5 meters. The survey line range of the 3D seismic work area is: inline6500-inline8500. It is concluded that the migration amount of fan body group 1 is 2000-587m (Table 2), showing a trend of gradually decreasing migration amount (Fig. 8), and the migration amount of fan body group 2 is 700-1500m, showing a trend of gradually increasing migration amount. Combined with the regional geological age data (Fig. 2), the migration rate of the fan delta is calculated, and the migration rate of fan body group 1 is 155-275m·Ma^{-1}. The migration speed remains within a certain range of fluctuations without drastic changes, and the migration rate of fan body group 2 is 74-525m·Ma^{-1}. The migration speed also gradually increases.

Table 2. Fan body migration rate table

	Group1		Group2	
Formation	**Migration Distance/m**	**Migration Rate/m·Ma^{-1}**	**Migration Distance/m**	**Migration Rate/m·-Ma^{-1}**
E_2w_2	2112.5	215.6	725.0	74.0
E_2w_1	1525.2	155.6	1087.5	111.0
E_2e_2	800.5	275.9	1525.0	525.9
E_2e_1	587.5	172.8	/	/

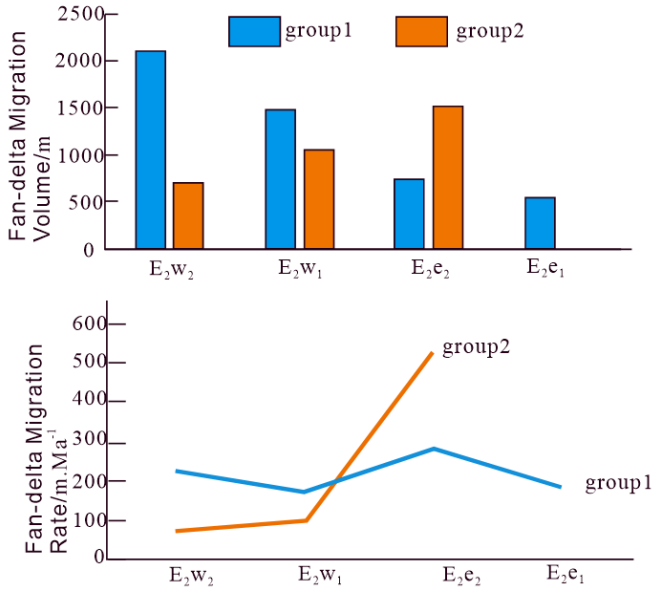

Figure 8. Fan Delta Progradation Metrics: Migration Distance (Left) vs. Migration Rate (Right)

3. Corresponding relationship between fault segmented growth and fan delta

During the connection of multiple faults, the fault activity characteristics show a sawtooth shape on the fault activity rate-strike length relationship

diagram, and the minimum value generally corresponds to the position where the faults connect wells (Hu et al., 2019). Using the fault displacement-rate curve, the activity of the boundary fault -the Zhu III south fault- is studied. Taking every 80 traces as an interval, the fault throw parameters between a total of six seismic reflection interfaces of T_g, T_{82}, T_{81}, T_{80}, T_{71}, and T_{70} are counted, and the fault activity rate in different periods is reflected through the line graph, and the strong fault activity area and the weak fault activity area are marked (Fig. 9). In the E_2w_3 period, the fault activity rate is 0-300, and there are local low-value points at inline7305 and inline7945, where the fault activity rate is low, corresponding to the connection positions of two relatively high-rate active faults, and two independent fan deltas are developed respectively. In the E_2w_2 period, there are two obvious low-speed fault activity areas, and the fault activity breakpoints are near inline7305 and inline7865, corresponding to the development of two independent fan deltas respectively. In the E_2w_1 period, the fault activity is strong, and the activity rate is on average 100-200. The relatively inactive points are at inline7030 and inline7625, among which the corresponding relationship between inline7030 and the fan delta is better, and the fan delta developed at inline7625 is obviously offset to the right, with a distance of 1535m from the centerline of the long axis of the fan delta. In the E_2e_2 period, there are two obvious low-speed fault activity areas, and the fault activity breakpoints are near inline6985 and inline7625, corresponding to the development of two fan delta sedimentary bodies, and a small fan delta is also developed at inline7305, while the fault is in a period of high-speed activity. In the E_2e_1 period, the fault activity breakpoints are near inline7100 and inline7400. Corresponding to the development of a fan delta at inline7400, and no fan delta is developed at inline7100. By comparing and analyzing the corresponding relationship between the fan delta and the fault activity, 80% of the centerlines of the long axes of the fan deltas in the study area are developed within the low-velocity zone of the fault activity or within 2km near the zone, and the two have a highly correlated relationship.

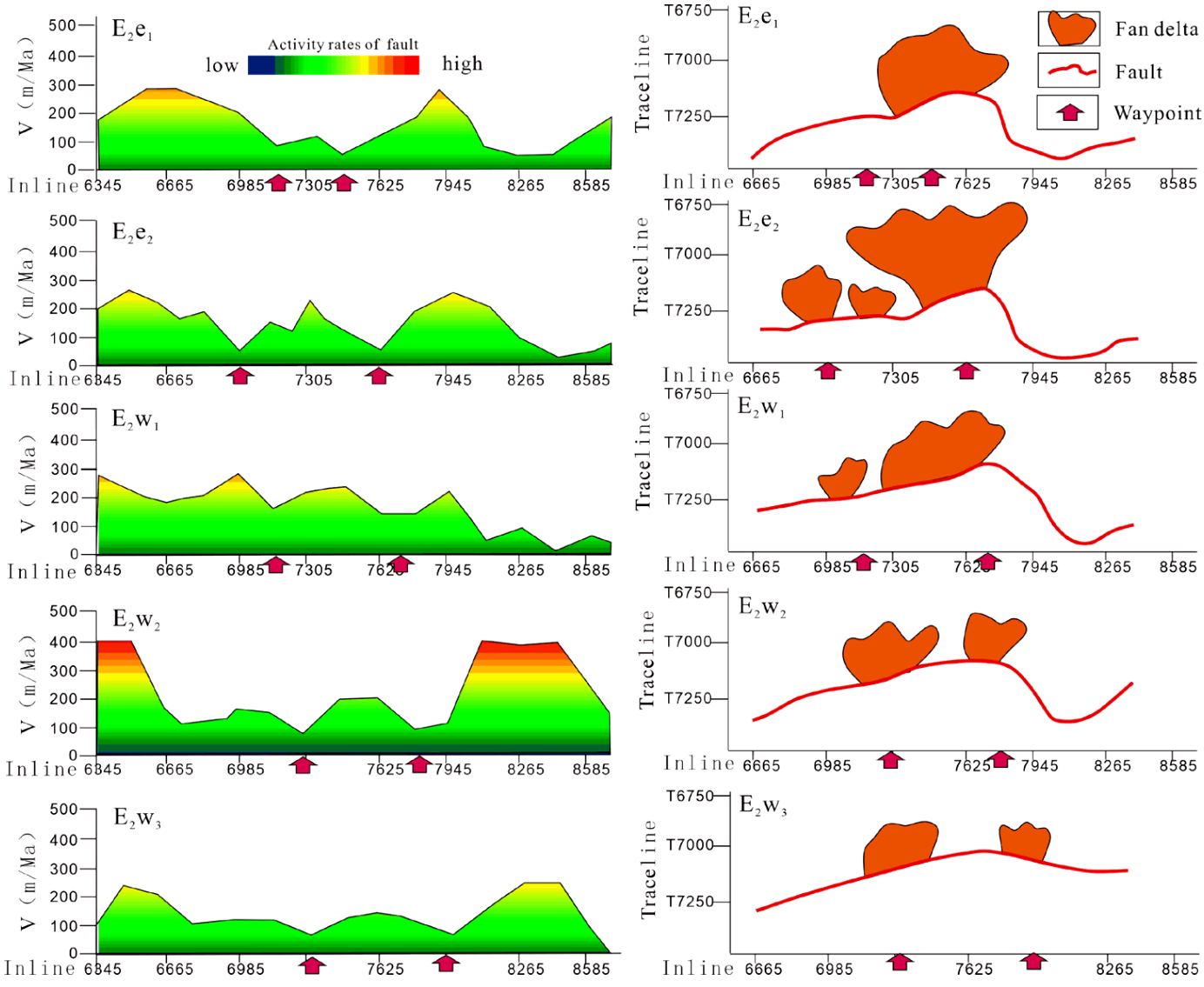

Figure 9. The Relationship between the Activity Rate of the Zhu III south Fault and the Corresponding Fan Delta

4. Discussion

4.1 Driving effect of faults on fan body migration

The study area is located in the steep slope zone of a faulted lacustrine basin, and the developed fan delta is adjacent to the basin-margin fault. Fault activity has a major controlling effect on sedimentary bodies. The Wenchang Formation and Enping Formation of the Paleogene in the Wenchang Sag are in the initial rifting stage and intense rifting stage of the faulted lacustrine basin. The boundary fault activity is intense. Under the control of regional stress, the lake basin subsides and the uplift area is uplifted. Different activity rates of faults cause different amounts of tectonic activity in different parts, and then change the geomorphological features. In the area with a high fault activity rate, the tectonic deformation is large. On the contrary, in the area with a low fault activity rate, the tectonic deformation is small. Then a relatively low-lying adjustment zone is formed at the connection of the segmented fault activities. This adjustment zone on the one hand forces the paleo-water system to adjust and converge to the low-potential area, and on the other hand becomes an important channel for the transportation of detritus into the lake basin. A large amount of detritus is transported into the lake basin through this channel to form fan delta deposits (Fig. 10). With the continuous activity of the basin-margin fault, the segmented activity points of the fault are different in different periods. The new fault segmentation points form new source injection channels, and the sedimentary position of the fan delta changes accordingly. Driving the fan delta deposit to migrate with the change of the fault activity segmentation point.

In the E_3e_1 period, there are two fault-segmented active zones, one develops a fan delta, and the other does not develop a fan delta; in the E_2e_2 period, the middle fan delta is deposited at the position of high fault activity (Fig. 10). This phenomenon shows that although the fault-segmented active zone provides a good channel for the transportation of detritus, if there is no supply of detritus, no fan delta deposit will be formed. On the contrary, under the condition of sufficient supply of detritus, the detritus will enter the lake basin along the steep slope in the non-fault-segmented active zone to form a fan delta deposit.

4.2 Influence of early fan body deposition on the migration of late fan bodies

Longitudinally comparing the cross-sectional characteristics of the fan delta in different periods (Fig. 6), the stratum thickness near the center line of the fan delta increases significantly. Combined with the truncated reflection characteristics of the top surface, it shows that after the early fan body is deposited, an uplift area is formed locally and is eroded. Due to the local geomorphological changes caused by the early deposition, which affects the accommodation space of the sedimentary area, under the condition of continuous source supply in the uplift area, the fan delta deposited in the late stage is redistributed along the low-potential channel in the low-potential area on the flank of the uplift area, which will also cause the lateral migration of the fan delta. This sedimentary self-feedback characteristic is also one of the driving factors for the lateral migration of the fan delta.

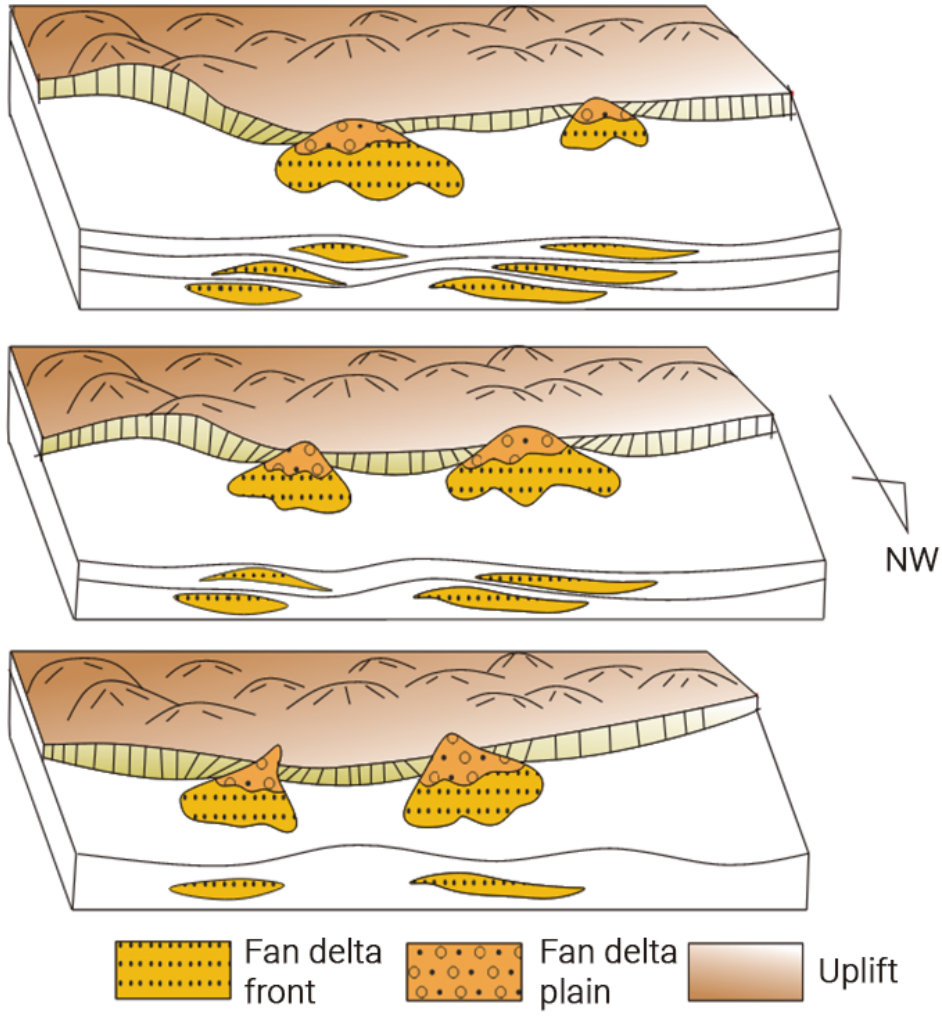

Figure 10. Diagram of sedimentary driving mode of fan delta caused by segmented fault activity

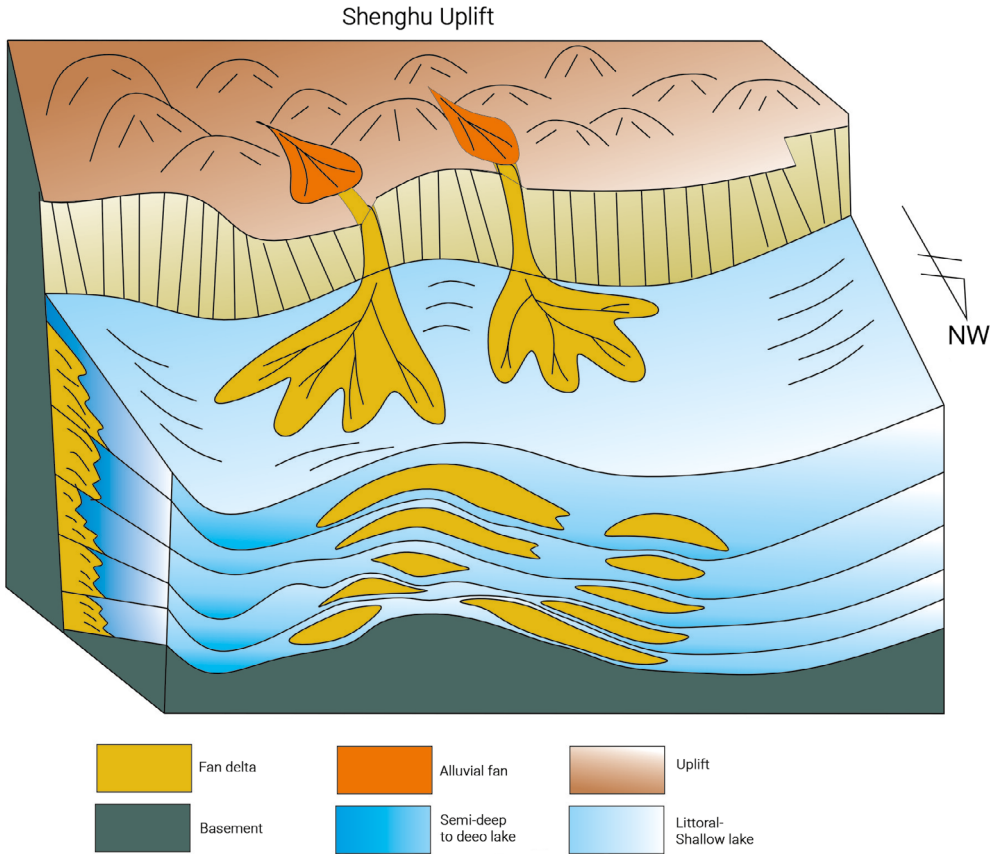

Figure 11. Sedimentary Evolution Model of Wenchang G Area

4.3 Implications of lateral migration of fan deltas

Based on the previous analysis, the lateral migration and evolution process of the fan delta in the study area presents a two-stage driving characteristic of "fault-dominated positioning - dynamic regulation of landform". Stage I is the fault-dominated period. The low-activity rate area at the connection of the fault segments forms a source supply channel, which directly controls the location of the source injection point and controls the development location of the fan body; Stage II is the geomorphic adjustment period. The accumulation of the early fan body leads to local uplift and reshapes the sedimentary landform, forcing the later sediments to be redistributed along the low-potential area, forming a composite superimposed pattern of lateral migration, and controlling the spatial migration and development relationship of the fan body (Fig. 11).

The glutenite body in the steep slope zone of the faulted lacustrine basin is a key area for exploration in the middle and deep layers in the Bohai Bay, Pearl River Mouth and other basins. It is currently in the early exploration stage, with few drilling data and relatively rich seismic data. For the prediction of the distribution position of the glutenite body, in different exploration areas, the method of "fault segmentation identification - migration path simulation" can be used. Based on the fault activity in different periods, the connection zone with relatively small fault activity rate is preferentially locked, and then combined with the local geomorphological characteristics, the development location of the fan delta is predicted, and then the prediction of the reservoir development area is guided.

5. Conclusions

The lateral migration of the fan delta in the steep slope zone of the faulted lacustrine basin is driven by the segmented fault activity. The evolution of the Paleogene fan delta in Block G of the Wenchang Sag reveals the following laws:

The basin-margin fault activity dominates the initial sedimentary position of the fan delta. The migration and position change of the fault-segmented active zone in different periods directly control the initial sedimentary position of the detritus and drive the lateral migration of the fan delta (migration rate 0.1-0.5 km/Ma). The development position of the fan delta is highly correlated with the low-velocity zone of the fault activity.

The rapid accumulation of the early fan delta leads to the attenuation of the local accommodation space, forcing the later sediments to be redistributed along the low-potential area on the flank of the fan body, forming a composite superimposed pattern of "vertical inheritance - lateral migration in the plane".

The fan delta evolution follows a two-stage driving model of "fault-dominated positioning - dynamic regulation of landform", guiding the "fault segmentation identification - migration path simulation" method of fan delta for oil and gas exploration, and then guiding the prediction of reservoir development areas.

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