

# Control effects of the synsedimentary faults on the basin-marginal fans in the central part of the deep-water area of early Oligocene Qiongdongnan Basin, South China Sea

Guangzeng Song<sup>1,2\*</sup>, Zengxue Li<sup>2</sup>, Haizhang Yang<sup>3</sup>, Dongdong Wang<sup>2</sup>, Ying Chen<sup>3</sup>, Rui Sun<sup>3</sup>

<sup>1</sup>School of Water Conservancy and Environment, University of Jinan, Ji'nan 250022, China

<sup>2</sup>Key Laboratory of Sedimentary Mineralization and Sedimentary Minerals in Shandong Province, Shandong University of Science and Technology, Qingdao 266590, China

<sup>3</sup>Beijing Research Center, CNOOC (China) Co., Ltd., Beijing 100010, China

Received 26 August 2019; accepted 30 March 2020

© Chinese Society for Oceanography and Springer-Verlag GmbH Germany, part of Springer Nature 2021

## Abstract

The synsedimentary faults and basin-marginal fans located in the central part of the deep-water area of the early Oligocene Qiongdongnan Basin have been investigated using seismic profiles, boreholes, and well-log data. Through the formations of the characterized paleogeomorphology, such as transverse anticlines, fault ditches, and step-fault belts, the synsedimentary faults are known to have controlled the development position, distribution direction, and extension scales of the basin-marginal fans. For example, at the pitching ends of two adjacent faults, transverse anticlines developed, which controlled the development positions and distributions of the fans. During the early Oligocene, the faults controlled the subsidence center, and fault ditches were formed at the roots of the faults. In the surrounding salient or low salient areas, which were exposed as provenance areas during early Oligocene, the fault ditches acted as the source channels and determined the flow paths of the clastics, where incised valley fills were obviously developed. The fault ditches which developed in the sedimentary basins were able to capture the drainage systems and influenced the distributions of the fans. The large boundary faults and the secondary faults generated two fault terraces and formed step-fault belts. The first fault terrace caused the clastics to be unloaded. As a result, fans were formed at the entrance to the basin. Then, the second fault terrace caused the fans to move forward, with the fans developing in a larger extension scale. The results obtained in this study will potentially be beneficial in the future prospecting activities for reservoirs and coal-measure source rocks in the basins located in the deep-water areas of the South China Sea.

**Key words:** deep-water area, synsedimentary fault, basin-marginal fan, transverse anticline, fault ditch, step-fault belt

**Citation:** Song Guangzeng, Li Zengxue, Yang Haizhang, Wang Dongdong, Chen Ying, Sun Rui. 2021. Control effects of the synsedimentary faults on the basin-marginal fans in the central part of the deep-water area of early Oligocene Qiongdongnan Basin, South China Sea. *Acta Oceanologica Sinica*, 40(2): 54–64, doi: 10.1007/s13131-021-1749-7

## 1 Introduction

In the past twenty years (1999–2019), research has been conducted regarding the control effects of synsedimentary structures (in particular, synsedimentary faults) on the sequence architecture or sedimentation in rift basins. These have become international hot topics for the petroleum basin analysis, and have drawn attention from the researchers both at home and abroad (Ravnås and Steel, 1998; Lin et al., 2004; Athmer and Luthi, 2011; Liu et al., 2015; Yang et al., 2017). Howell and Flint (1996) considered that the synsedimentary faults and fault conversion zones in rift basins were similar to the shelf slopes in passive continental margins. When researching marine rift basins, Ravnås and Steel (1998) concluded that the activations of synsedimentary faults could have control effects on the formations of accommodation spaces and transfer zones, and also further influence the source channels and unloading of source clastics in a basin.

Lin et al. (2004) suggested that the synsedimentary faults in the Dongying Sag and Zhanhua Sag had potentially influenced the development and distributions of the sedimentary systems, and presented the concept of a slope break belt. In the studies conducted by Athmer and Luthi (2011), it was suggested that the synsedimentary faults and their combination patterns had led to the formation of relay ramps, and discussed the effects of relay ramps on the routes and deposition of sediment. Although Song et al. (2014) and Liao et al. (2016) have conducted similar research, the majority of the previous researchers seldom focused on the rift basins located in deep-water sea areas which lack borehole information data. In such cases, recognizing the control effects of synsedimentary faults on basin sedimentation could be very beneficial.

With the success of the explorations conducted in the Gulf of Mexico, Columbus Basin, and the coast of Africa, basin-marginal

Foundation item: The National Natural Science Foundation of China under contract Nos 41872172, 41672096 and 41702114; the Major National Science and Technology Projects under contract No. 2016ZX05026007-004; the Natural Science Foundation of Shandong Province under contract No. ZR2019QD008; the Natural Science Foundation of Guizhou Province under contract No. 20191148.

\*Corresponding author, E-mail: [songguangzeng2006@163.com](mailto:songguangzeng2006@163.com)

fans have gradually received increasing attention from petroleum geologists. Significant economic interest has been paid not only for the fact that basin-marginal fans can serve as important reservoirs, but also for their acknowledged significance for coal-bearing successions, which can potentially act as critical hydrocarbon source rocks (Lv and Chen, 2014; Wang et al., 2016; Lv et al., 2019). With the increasing demands for hydrocarbon resources and the excessive prospecting of onshore areas, the deep-water areas have become increasingly more significant for hydrocarbon exploration (Loucks and Ruppel, 2007). The deep-water areas of the South China Sea, and in particular, the Qiongdongnan Basin, have drawn increased attention in recent years (Zhang et al., 2007; Li et al., 2010). However, unlike onshore basins, there is a lack of borehole data revealing the buried strata and potential basin-marginal fans. This has resulted in high risk factors for petroleum explorations in deep-water areas. Moreover, fundamental geological research on effective methods for predicting basin-marginal fans with scientific approaches are astonishingly rare.

With that being said, the study selected the central part of the deep-water area of the early Oligocene Qiongdongnan Basin as an example, in order to discuss the control effects of the synsedimentary faults on basin-marginal fans. It was considered that the results of this study would not only assist in improving the accuracy of the predictions of the locations, distributions, and scales of the basin-marginal fans, but also address the lack of drill borehole data information in deep-water areas and contribute to reducing the high risks related to future explorations of the basins similar to the Qiongdongnan Basin.

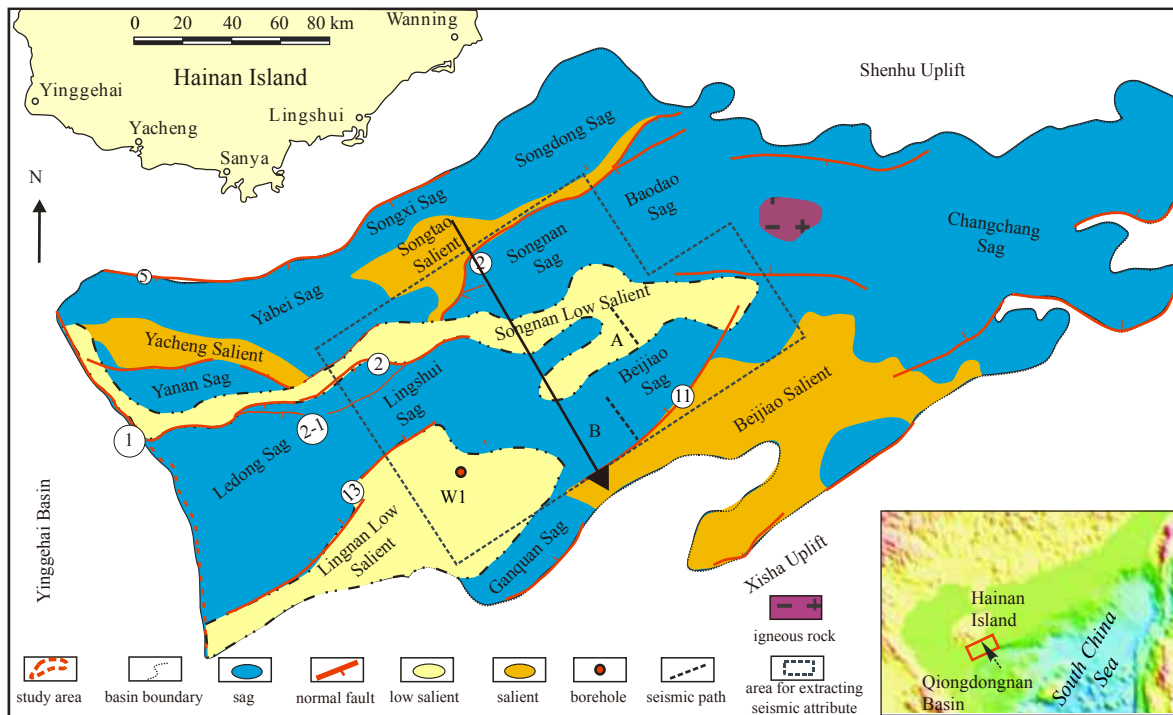
**2 Geological background**

Located at the northwestern section of the South China Sea, the Qiongdongnan Basin is a rift basin which was formed by

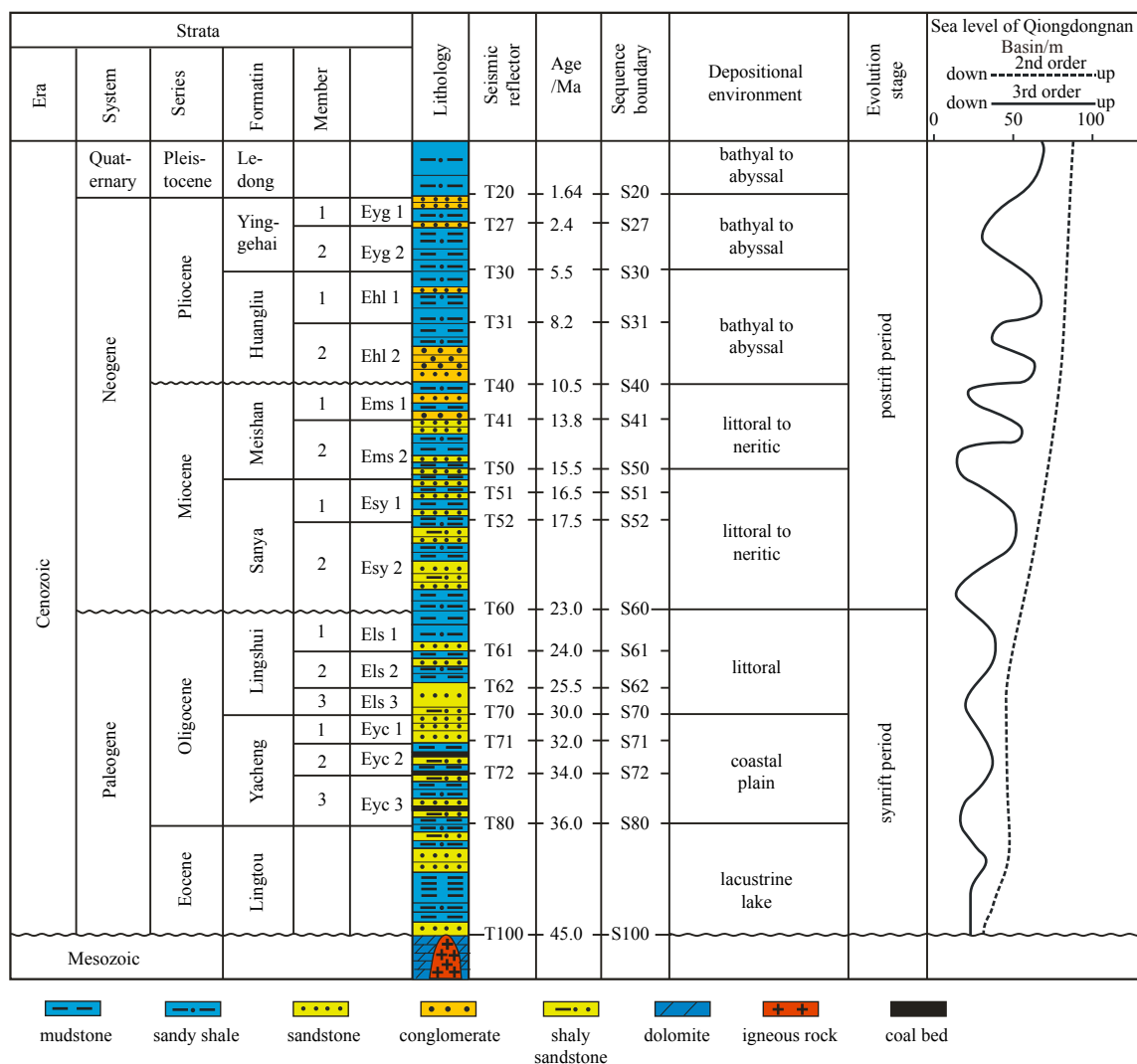
Cenozoic extensions and distributed over a Mesozoic basement (Zhang, 2010; Lei et al., 2018). At the present time, the basin has received significant attention, not only because of its becoming one of the most economically promising hydrocarbon-exploration basins in the South China Sea, but also for its important geographic location (Lei et al., 2019). The basin is bounded by the Zhujiang River Mouth Basin to the east, the Xisha Uplift to the south, the Yinggehai Basin to the west, and the Hainan Island to the north. The basin trends in a NE direction with extensions to the SSE, and measures approximately 290 km in length and 181 km in width, as detailed in Fig. 1.

There are two patterns of structures in the basin: graben and half-graben. These are developed with segmentation from east to west and zonation from north to south (Zhao et al., 2015a). Similar to other rift basins, the lower half-grabens or grabens and horsts, along with the late Neogene depressions, constitute a typical “two-layered” structural pattern in the Cenozoic Qiongdongnan Basin, which is separated by the unconformity surface-T60 (Zhao et al., 2018). The Paleogene was the synrift period of the Qiongdongnan Basin, during which the faults were strongly activated and even controlled the subsidence center. This was particularly true during the early Oligocene (Song et al., 2014). It has been determined that the sedimentary environment of the Paleogene Qiongdongnan Basin had changed from an Eocene lacustrine basin to an Oligocene littoral environment. The sedimentary facies mainly included fans and littoral facies along the basin margins, and turbidite fans and neritic facies in the center area of the basin (Zhang et al., 2017; Song et al., 2020). The Yacheng Formation was deposited during the early Oligocene. This has drawn a lot of attention from researchers since it is believed to have played an important role in hydrocarbon generation and preservation within the Qiongdongnan Basin (Fig. 2).

In the Qiongdongnan Basin, the Changchang Sag, Baodao



**Fig. 1.** Geological map of the Qiongdongnan Basin and the tectonic units in the central part of deep-water area. A and B are the locations of the seismic profiles used in Fig. 4. W1 is the well name used in Fig. 4. ①: No.1 Fault; ②: No.2 Fault; ②-1: No. 2-1 Fault; ⑤: No. 5 Fault; ⑪: No. 11 Fault; ⑬: No. 13 Fault.



**Fig. 2.** The sketch of the stratigraphic sequence, lithology character, depositional environment and the tectonic stage of Cenozoic Qiongdongnan Basin. The age of the sequence boundaries was provided by the China National Offshore Oil Corporation, the tectonic stage was modified from Song et al. (2014) and Zhao et al. (2015a), and the sea level of Qiongdongnan Basin was adopted from Sun et al. (2010).

Sag, Songnan Sag, Beijiao Sag, Lingshui Sag, Ledong Sag, Songnan Low Salient, Lingnan Low Salient and so on, are considered to be in the deep-water area, as detailed in Fig. 1. In this study, the central deep-water area of the basin, including the Songnan Sag, Lingshui Sag, Beijiao Sag, and Songnan Low Salient, were investigated as typical developed phenomena of synsedimentary faults controlling basin-marginal fans. During the early Oligocene, the majority of the surrounding salient or low salient areas were exposed as provenance areas, and had supplied the sediment clastics (Zhao et al., 2015b). It was observed that large NNE-trending boundary faults had been activated in the research area, including the No. 2 Fault, No. 13 Fault, and No. 11 Fault. In addition, secondary faults were evident, such as the No. 2-1 Fault (see Fig. 1 for the location).

### 3 Data and methods

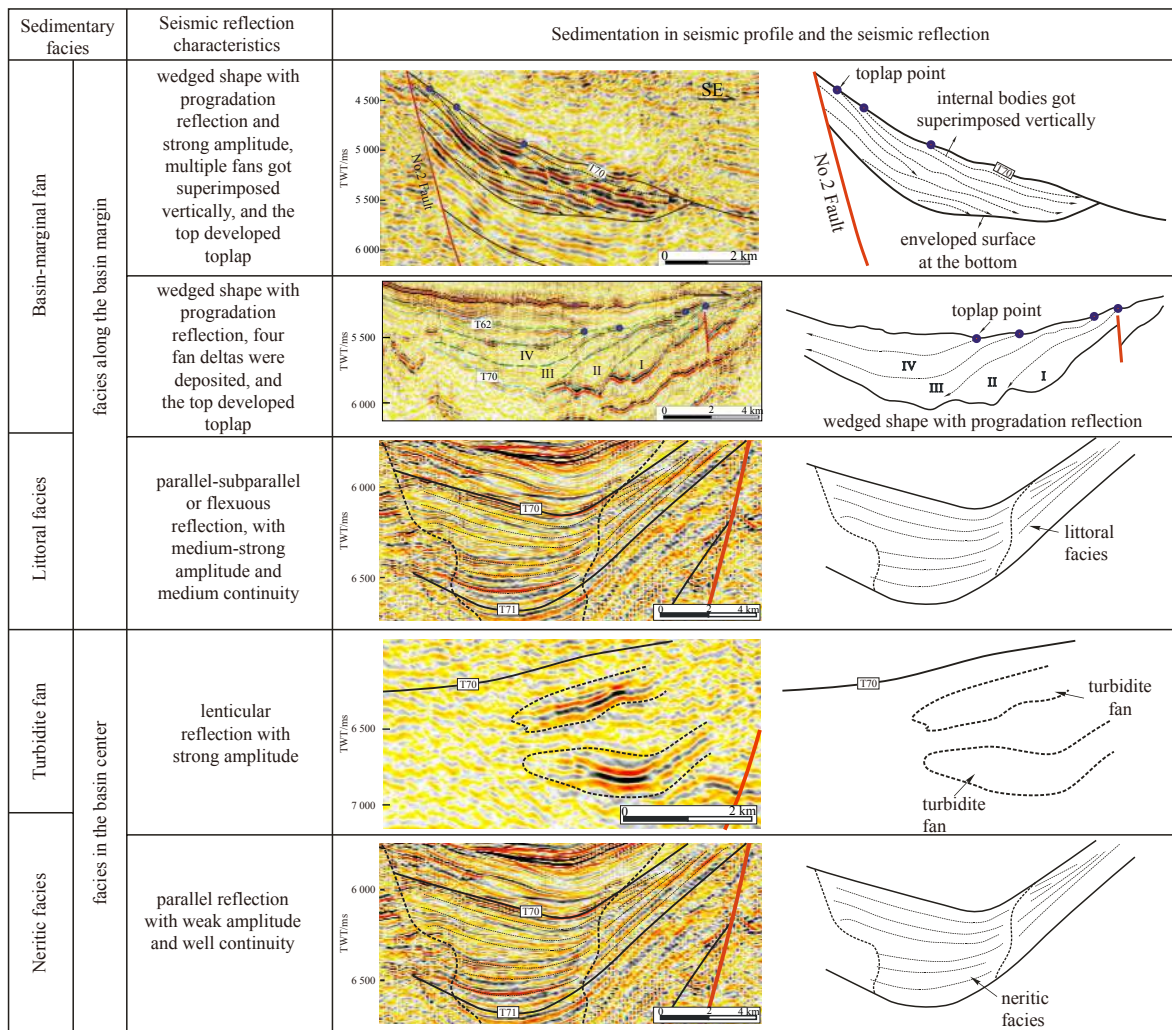
In this study, the previous research results in the study area, as well as the well-log, borehole, and seismic profile data provided by the China National Offshore Oil Corporation (CNOOC), comprised the basic reference documents. The seis-

mic reflections presented by the different sedimentary facies of the Paleogene Qiongdongnan Basin were found to be distinct and characterized, as shown in Fig. 3. These data provided the foundation for further research and allowed the current study to focus on the following goals: (1) analyzing the combination and activation of the synsedimentary faults; (2) recognizing the basin-marginal fans.

First of all, through the recognition of the sequence boundaries, the latest geological data and high-quality seismic profiles were used to establish the Paleogene sequence stratigraphic architecture of the study area. These interpretations served as the foundation framework for the subsequent investigations of the synsedimentary faults and basin-marginal fans.

Then, the characteristics of the synsedimentary faults were delineated, including the combination patterns and the spatial evolution of the faulting activities.

A comprehensive recognition process of the basin-marginal fans was carried out, which was mainly based on analyzing the perfect seismic facies and seismic plane attributes. Furthermore, the characteristics of the fans were quantitatively delineated,



**Fig. 3.** The main sedimentary facies and relevant seismic reflection characteristics of Oligocene Qiongdongnan Basin. TWT: two-way-travel time.

which mainly described the locations, distributions and horizontal extension scales of the fans.

Finally, the observed coupling relationship in the study area was interpreted for the purpose of discussing the interactions between the synsedimentary faults and the basin-marginal fans.

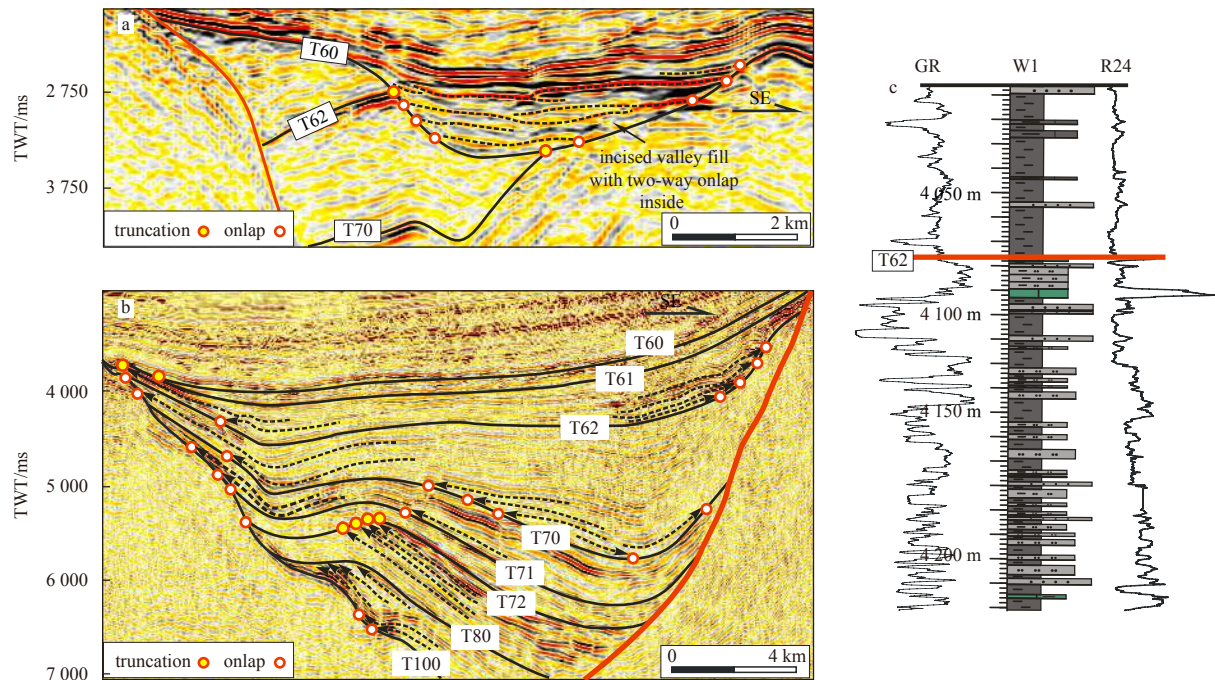
#### 4 Results

##### 4.1 Sequence framework

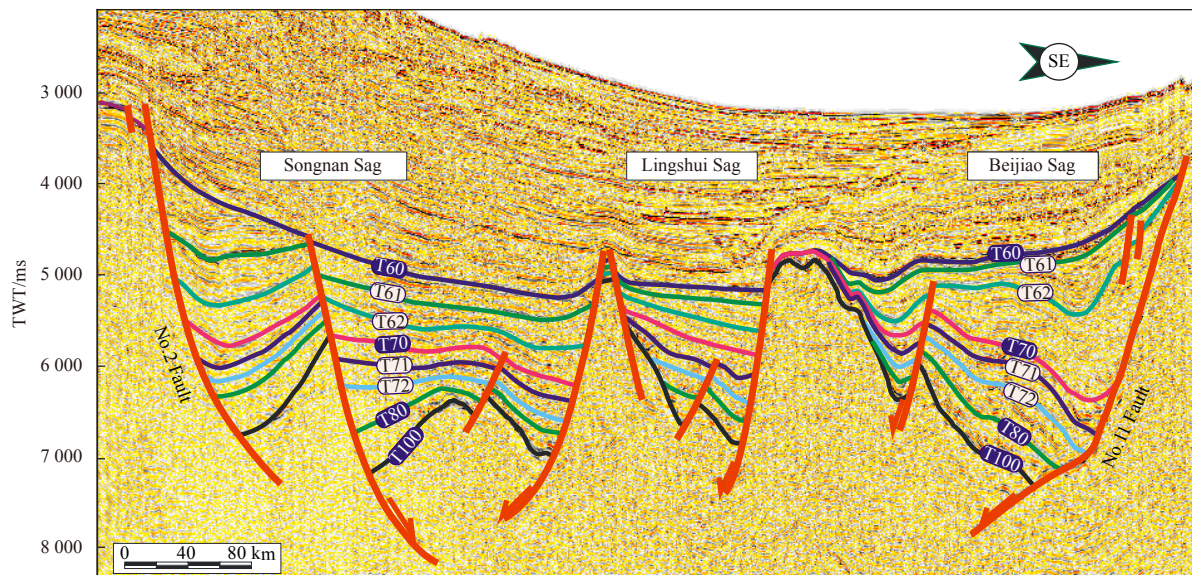
In the present study, the sequence identification used for the Paleogene Qiongdongnan Basin was similar to that used by Posamentier et al. (1988) and Vail et al. (1977). Through comprehensively analyzing the seismic profiles, the available data was complemented by the data obtained from boreholes and well logs. As a result, a total of seven sequence boundaries were identified. These were recognized as the incised valley, onlap, and truncation surfaces in the seismic profiles, or abrupt changes in the log profile data (Zhang et al., 2015; Lei and Ren, 2016), as illustrated in Fig. 4. It was found that the seven sequence boundaries presented distinct characteristics in continuity, amplitude, conformity, and so on. For example, T60 was an angular unconformity surface largely developed along the basin, which truncated the underlying strata, and toplap

points or the incised valley developed above. T61 was observed to be an angular unconformity surface which changed into correlative conformity surface towards the central basin. It had displayed a medium-strong amplitude with medium-strong continuity. In the case of T62, characteristics similar to T61 were presented. T70 was observed to be an angular unconformity surface which was largely developed, with a medium amplitude and medium continuity. T71 was found to present an angular unconformity surface, which then changed into a correlative conformity surface toward the central basin area. It was characterized by medium-weak amplitude and medium-weak continuity. T72 and T80 presented characteristics similar to T71. However, T80 was observed to display limited development. T100 was an unconformity surface and acted as the basement boundary, in which medium-strong continuity with medium-weak amplitude were evident. T100 was found to be largely developed along the entire basin.

It was found that by identifying the sequence boundaries, the Paleogene sequence stratigraphic architecture of the study area could be accurately established, as shown in Fig. 5. As can be seen in the figure, the “two-layered” structural pattern was separated by the unconformity surface T60, as previously introduced in this study’s geological background section. In addition, Fig. 5



**Fig. 4.** The recognition of sequence boundaries of the deep-water area of Qiongdongnan Basin. a. Seismic profile A, see location in Fig. 1. The incised valley indicated that T60 acted as a sequence boundary, which truncated the underlying strata. b. Seismic profile B, see location in Fig. 1. The onlap and truncation represented the unconformable contacts on the sequence boundaries. c. Well 1 (W1), see location in Fig. 1. The abrupt changes in the lithology and well log profile data.



**Fig. 5.** Paleogene sequence stratigraphic framework of the deep-water area of Qiongdongnan Basin. The location is shown in Fig. 1.

details the large boundary faults, in which the No. 2 Fault and No. 11 Fault are clearly recognizable. These faults displayed large displacements and had controlled the subsidence center of the basin.

#### 4.2 Control effects of the syndepositional faults on the formation of the transverse anticlines

The activities of the syndepositional faults, particularly the major boundary faults, may change along the fault trend (Li et al., 2013a, 2013b). Where the faults experienced decreased activities,

a type of characterized paleogeomorphology formation referred to as a transverse anticline would result (Wang et al., 2010). These anticlines could essentially control the entrance of clastics from the provenance areas to the basin. Moreover, at the locations where the pitching ends of the two syndepositional faults contacted, transverse anticlines could also develop, since the faulting activities tended to decline rapidly at the pitching ends (Qi, 2007). According to the previous research results, the activities of the No. 2 Fault had decreased in the transitional zone between the Lingshui Sag and the Songnan Sag (Fig. 6), which led

to a major transverse anticline being formed (Fig. 7). As the No. 2 Fault was strongly active, the No. 2-1 and No. 9 faults had developed as adjusting faults, with one secondary transverse anticline developed at the location where these two adjusting faults

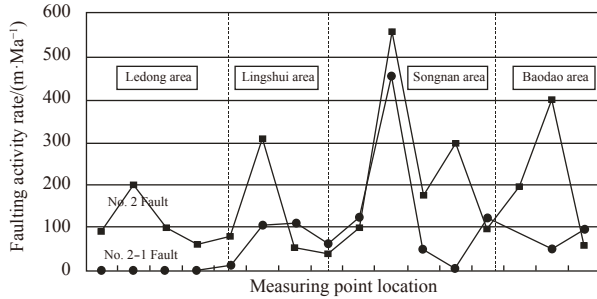


Fig. 6. The spatial changes of the faulting activity rate of No. 2 Fault and No.2-1 Fault (modified from Lin et al. (2010)).

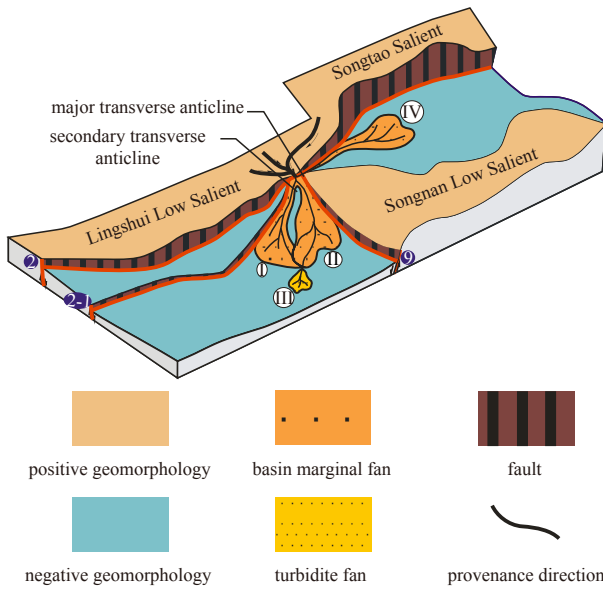


Fig. 7. The overlapped transverse anticlines controlled by the synsedimentary faults and the influence on basin-marginal fans.

contacted (Fig. 7). These major transverse anticlines not only controlled the entrance locations of the clastics to the basin, but also acted as the barriers to separate the clastics in two directions. One group entered the Songnan Sag to form the No. IV basin-marginal fan. The other entered the Lingshui Sag and was further controlled by the secondary transverse anticline, dispersing in two directions to form the No. I fan along the No. 2-1 Fault and the No. II fan along the No. 9 Fault, as detailed in Fig. 7. The recognition and spatial distributions of the above-mentioned numbered fans had conformed perfectly with the seismic attributes and seismic profiles (Figs 8 and 9).

4.3 Control effects of the synsedimentary faults on the formation of the fault ditches

During the early synrift period, the faults had controlled the formation of the local subsidence center, which was then distributed along the down-thrown wall of the faults forming fault ditches (Ravnås and Steel, 1998). The early Oligocene was the early synrift period of the Qiongdongnan Basin (Song et al., 2014; Zhao et al., 2018), during which fault ditches were largely developed in both the surrounding salient or low salient areas and the sedimentary basins.

During the early Oligocene, the surrounding salient or low salient areas were exposed as the source areas, where the fault ditches could act as the source channels. These channels could develop inside incised valley fills and further control the basin-marginal fans. Figure 10a details the RMS (root-mean-square) amplitude seismic attributes of the Songnan Low Salient. In the figure, the incised valley fills presented strong amplitude and showed the lateral shapes of long belts. These belts were parallel to the NE–SW trended faults and were located at the roots of the faults, which indicated the control effects of the faults on the source channels. In Fig. 10b, valleys can be easily recognized in the paleogeomorphology of the Songnan Low Salient, which were controlled by the synsedimentary faults and acted as source channels.

It is well known that the directions of delta progradation are the forward directions of the source materials, which also represent the directions of the clastic-carrying drainage flows after flowing into a basin. Meanwhile, the directions of the drainage flows are controlled by the source channels. Therefore, the progradation directions of the fans could potentially reflect the source channels (Liu et al., 2015). It was observed in the present

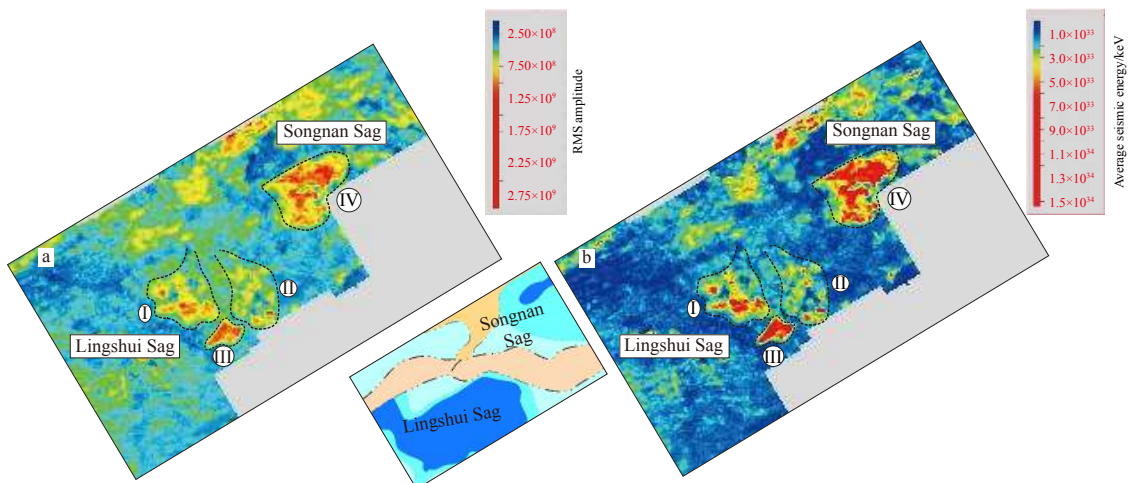
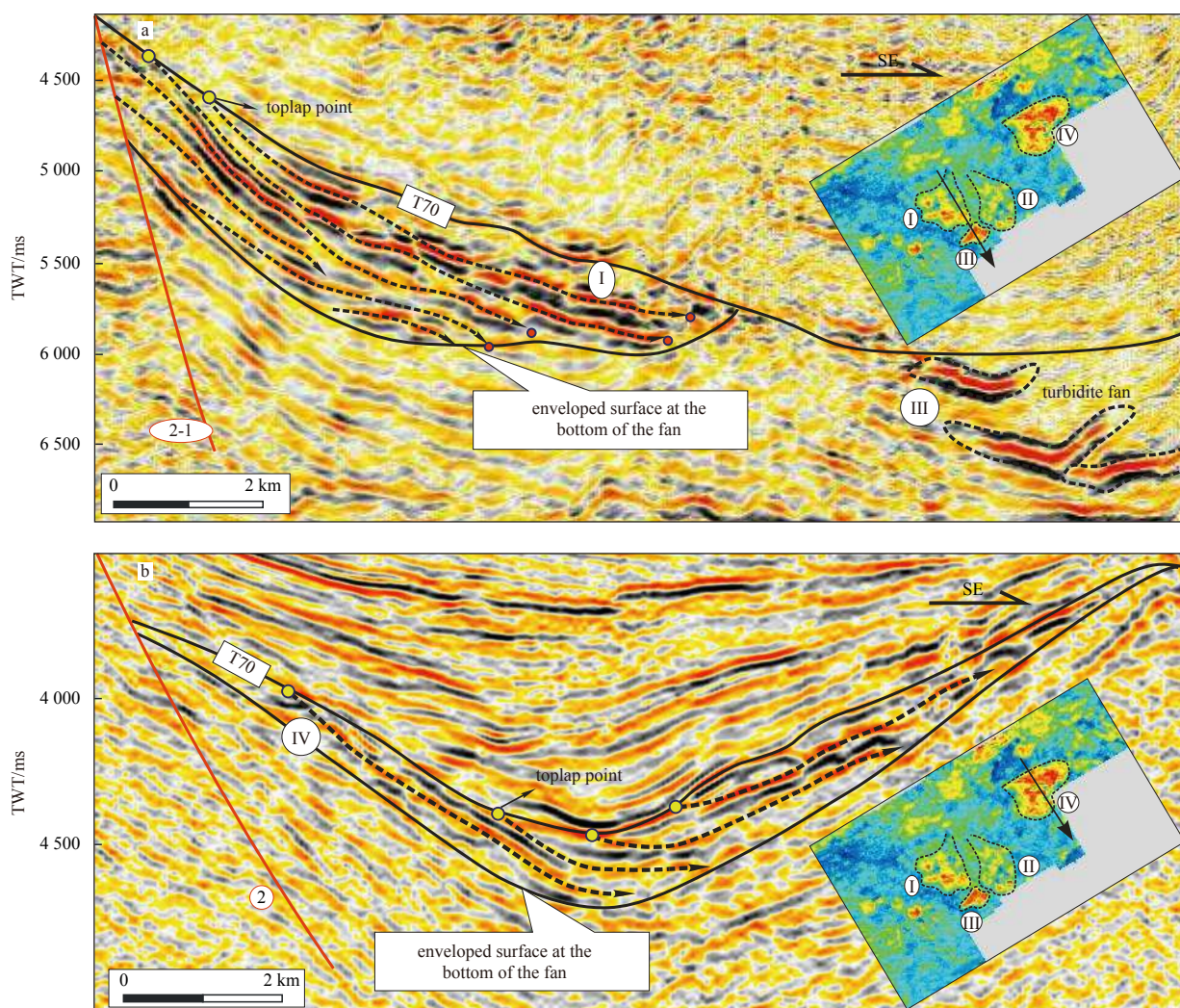


Fig. 8. Horizontal seismic attribute of the early Oligocene Yacheng Formation, which indicated the spatial distribution of the basin-marginal fans. a. The RMS (root-mean-square) amplitude seismic attribute; b. the average energy seismic attribute.



**Fig. 9.** The seismic facies characteristics of the fans controlled by the transverse anticlines. a. No. I fan presented wedged shape with progradation reflection and strong amplitude inside, No. III fan showed lenticular shape with strong amplitude inside; b. No. IV fan showed lenticular shape with progradation inside. The accommodation space was so limited that the toplap points developed along the basin margin, because the sediment input amount was relatively rich and could fill up the accommodation space easily.

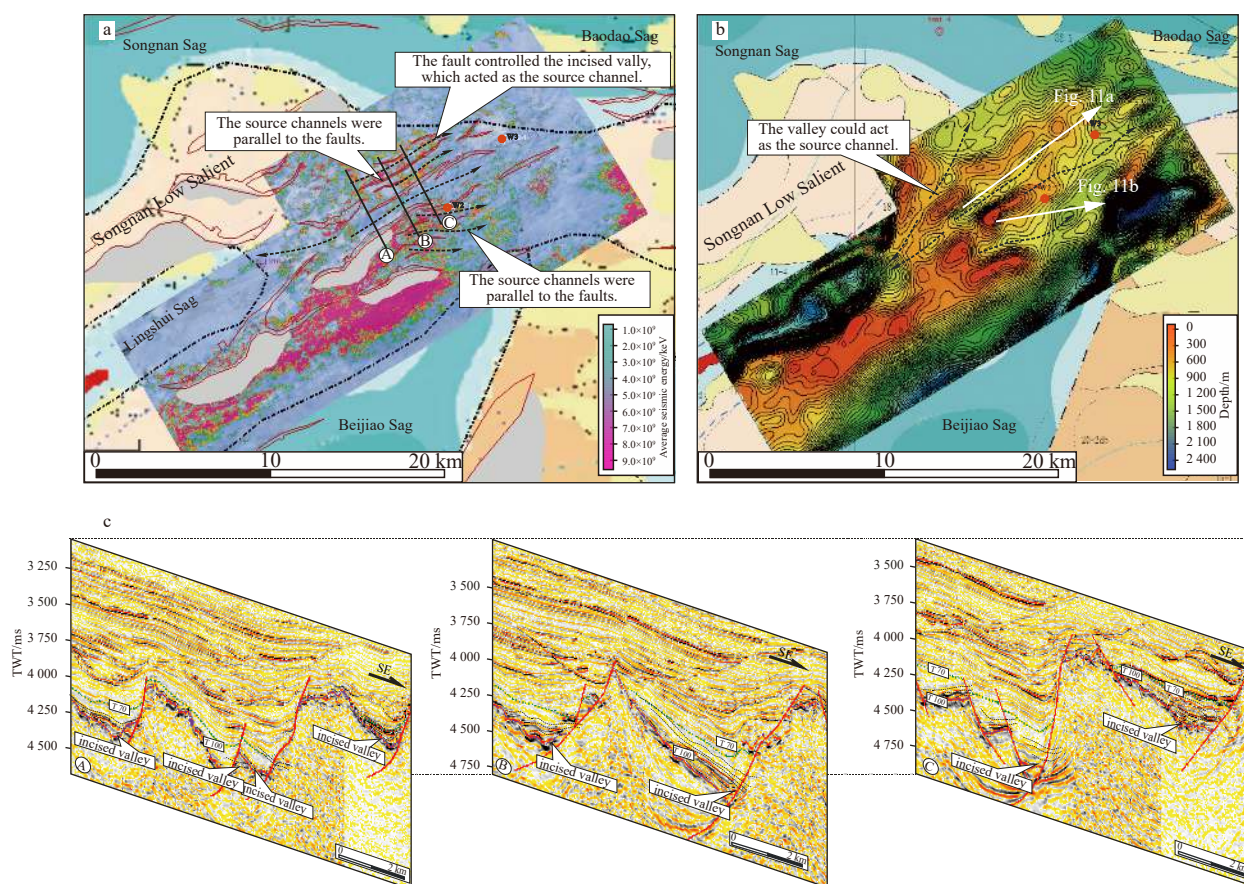
study that, along the directions of the valleys moving toward the basin, the fans showing progradation reflections were obviously recognized in the seismic profiles (Fig. 11). This had perfectly proven that the valleys essentially acted as the source channels. In seismic profile shown in Fig. 10c, it can be observed that incised valley fills with strong amplitude reflections were perfectly developed at the down-thrown walls of the faults. In addition, the incised valleys had evolved with the lateral evolution of the faults, which corresponded well with the data shown in Fig. 10a.

In study area, the fault ditches not only acted as source channels, but also controlled the distribution directions of the fans when the fault ditches were located in the sedimentary basins (Fig. 12). The No. 11 Fault was the boundary fault of the Beijiao Sag and had been strongly activated during the early Oligocene, during which fault ditches had formed. In Beijiao Sag, the drainage system had carried the clastics to the basin and then had flowed along the trend of the fault ditches since the fault ditches had low topography. Then, once the clastics were unloaded, basin-marginal fans had formed. As a result, the distributions of the basin-marginal fans were parallel with the trends of the faults (Fig. 13).

#### 4.4 Control effects of the synsedimentary faults on the formation of the step-fault belts

Step-fault belts are a type of complex geomorphology, which are characterized by a multi-level fault-terraces and controlled by a number of parallel and frequently active synsedimentary faults (Song et al., 2014; Li et al., 2015).

In the Oligocene Qiongdongnan Basin, the tectonic activities were known to be intense, and the faults were strongly activated. The major boundary faults in the study area developed as large displacements in which secondary faults were formed. The majority of those faults were parallel with the boundary faults and displayed ladder-like profiles, subsequently forming step-fault belts. For example, the No. 13 Fault was developed between the south Lingnan Low Salient and the north Lingshui Sag, with a secondary fault also formed. As a result, a step-fault belt had been generated, as shown in Fig. 14. It was believed that the Lingnan Low Salient may have acted as the provenance area to supply clastics, and the Lingshui Sag was essentially the sedimentary area. During the process of flowing forward, the drainage system carrying debris from the Lingnan Low Salient would have encountered the first fault-terrace caused by the boundary fault.



**Fig. 10.** The fault ditches controlled by the small synsedimentary faults in Songnan Low Salient. They acted as the source channels and developed inside incised valley fills. a. The RMS (root-mean-square) amplitude seismic attribute of Songnan Low Salient; b. the paleogeomorphology of Songnan Low Salient; c. the incised valley fill showed strong amplitude reflection, which was located at the down-thrown wall of the small synsedimentary faults.

Then, as the hydrodynamic conditions weakened due to the sudden increase in the accommodation space at the first fault-terrace, the debris was unloaded, and a sedimentary fan body was formed. This fan body had continued to extend as the second fault-terrace lowered the topography. Therefore, the fans had developed larger extension scales. This phenomenon was observed and perfectly delineated in the seismic profile (Fig. 15).

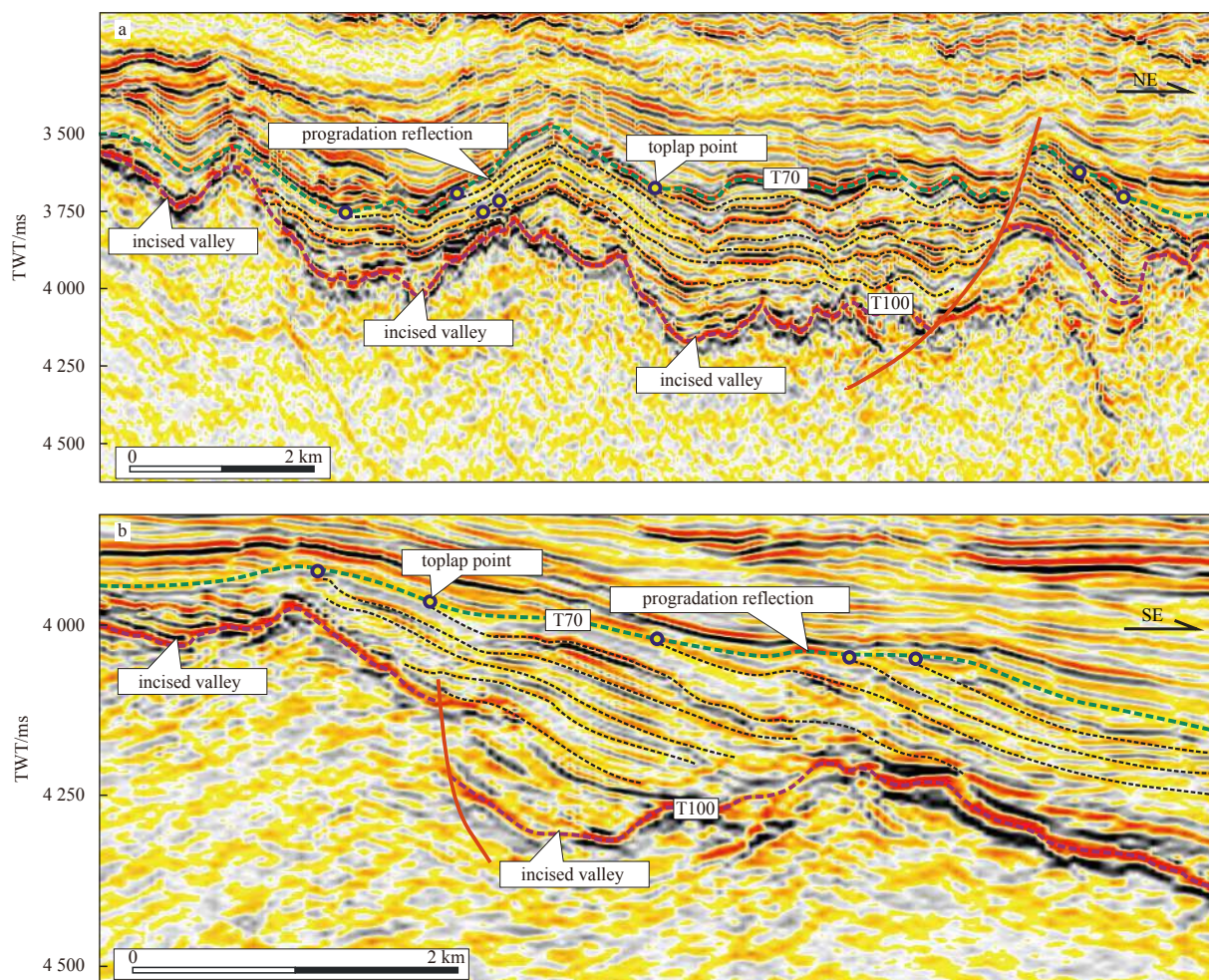
## 5 Discussion

In actuality, it was determined that the paleogeomorphology had acted as the direct factor in controlling the spatial evolution of the basin-marginal fans. The synsedimentary faults had controlled the fans through influencing the paleogeomorphology, such as the transverse anticlines, fault ditches and step-fault belts which are considered to be important types of paleogeomorphology.

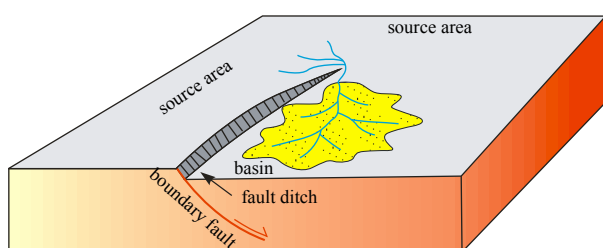
The transverse anticlines introduced in this study had acted as the barriers to separate the flow paths of the clastics in two different directions when entering the basin, resulting in the fans being distributed along both sides of the anticline hinges. However, the control effects on the fans of the transverse anticlines remained to be defined, since there were considerable divergences in the opinions expressed in the literature (Jolley and Morton, 2007; Athmer and Luthi, 2011). For example, Hou et al. (2012) indicated that the main drainage systems controlled by the transverse anticlines were the positions of the delta fans,

which was in conflict with the results achieved in this study, as well as the results from Jolley and Morton (2007) who suggested that the Clair transverse anticline had acted as an effective barrier to sediment transport through most of the late Palaeocene. In addition, Athmer and Luthi (2011) suggested these controlling effects would have been different during the various rifting stages, due to its observed relationship with the ratio between the tectonic uplifts and the incision rates.

It has been confirmed that fault activities could not only influence the altitude levels of the provenance areas and the amount of the clastics (sediment supply), but also have control effects on the subsidence to increase accommodation space. If the sediment supplies were relatively abundant when compared with the increases in the accommodation space, the sediment clastics from the provenance areas could potentially easily fill up the accommodation space along the basin margins when entering the basin, and then continue to move forward. These actions would result in the fans extended further and development of toplap points due to the overcompensated deposition. In another scenario, if the amount of sediment supply became relatively small when compared with the accommodation space, there would not be enough clastics to fill up the accommodation space along the basins. In such cases, only a few toplap points would form and the fans would have difficulty moving forward. In this study, it was found that the majority of the fans in the seismic profiles displayed developed toplap points (Figs 9, 11 and 13). Therefore, it



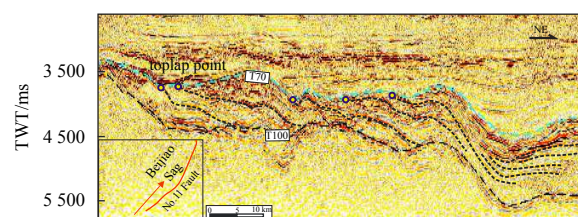
**Fig. 11.** The progradation reflection in the seismic profiles along the source channels toward the basin. At the base, incised valleys developed, which implied that the source channels developed at the early period, then the channels were filled up, and the fans developed when the base-level rose. Toplap points also formed along the basin margin, with the same reason as introduced in Fig. 10.



**Fig. 12.** The boundary fault controlled to form fault ditches in the basin, and further influenced the distribution direction of the fans.

was concluded that the early Oligocene subsidence of the deep-water area was relatively limited and the sediment input had been abundant (Zhao et al., 2015a, 2018). This may have been due to the fact that the early Oligocene was an early synrift period, when the basin subsidence rate and the sedimentary base level were low. Therefore, the surrounding provenance areas may have been extensively exposed, thereby providing sufficient clastics.

It has been speculated that basin-marginal fans could potentially serve as reservoirs for hydrocarbon deposits since they are

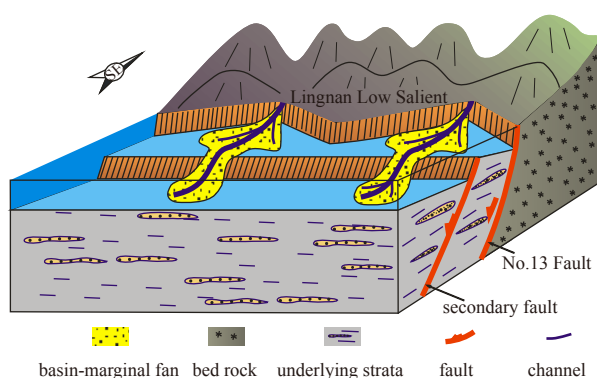


**Fig. 13.** The basin-marginal fan presented progradation reflection in this seismic profile, revealing NW-SE was the distribution direction of the fan, and the direction was parallel with the trend of No. 11 Fault. The Location of No. 11 Fault is shown in Fig. 1.

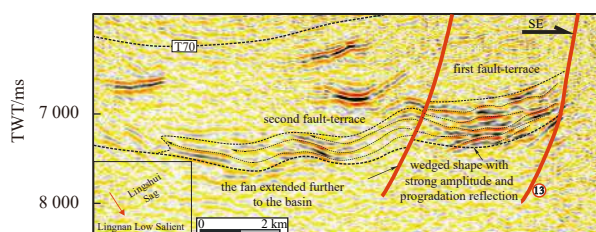
known to be beneficial to the development of coal-bearing successions (Lv et al., 2014, 2020; Li et al., 2018). These areas serve the role of source rock in the Qiongdongnan Basin (Li et al., 2010). The results in this study may potentially assist in improving the predictions of reservoirs and coal-measure source rocks, particularly in deep-water areas lacking borehole information data.

## 6 Conclusions

In the central part of the deep-water areas of the early Oligo-



**Fig. 14.** No. 13 Fault and the secondary fault formed step fault belt, and influenced the extension scale of the basin-marginal fans. The location of No. 13 Fault is shown in Fig. 1.



**Fig. 15.** The extension scale of the basin-marginal fan was controlled by the step fault belt. The step fault belt presented ladder-like profile, and the fan showed wedged shape with strong amplitude and progradation reflection in the seismic profile.

cene Qiongdongnan Basin, the synsedimentary faults had generated three types of characterized paleogeomorphology: transverse anticlines, fault ditches, and step-fault belts. It was confirmed in this study that by influencing the paleogeomorphology, the syndepositional faults had further controlled the basin-marginal fans.

In addition, the transverse anticlines had controlled the positions and distributions of the fans, and the fault ditches may have served as the source channels or had possibly influenced the distribution directions of the fans. The step-fault belt in the study area had changed the lateral extension scales of the fans.

#### Acknowledgements

We thank the Beijing Research Center of CNOOC (China) Co., Ltd. for providing the data used in this study.

#### References

- Athmer W, Luthi S M. 2011. The effect of relay ramps on sediment routes and deposition: A review. *Sedimentary Geology*, 242(1–4): 1–17
- Hou Yuguang, He Sheng, Ni Jun'e, et al. 2012. Tectono-sequence stratigraphic analysis on Paleogene Shahejie Formation in the Banqiao sub-basin, Eastern China. *Marine and Petroleum Geology*, 36(1): 100–117, doi: [10.1016/j.marpetgeo.2012.06.001](https://doi.org/10.1016/j.marpetgeo.2012.06.001)
- Howell J A, Flint S S. 1996. A model for high resolution sequence stratigraphy within extensional basins. In: Howell J A, Aitken J F, eds. *High Resolution Sequence Stratigraphy: Innovations and Applications*. Geological Society, 104(1): 129–137
- Jolley D W, Morton A C. 2007. Understanding basin sedimentary provenance: evidence from allied phytogeographic and heavy mineral analysis of the Palaeocene of the NE Atlantic. *Journal of the Geological Society*, 164(3): 553–563, doi: [10.1144/0016-](https://doi.org/10.1144/0016-76492005-187)

[76492005-187](https://doi.org/10.1144/0016-76492005-187)

- Lei Chao, Alves T M, Ren Jianye, et al. 2019. Depositional architecture and structural evolution of a region immediately inboard of the locus of continental breakup (Liwan Sub-basin, South China Sea). *GSA Bulletin*, 131(7–8): 1059–1074, doi: [10.1130/B35001.1](https://doi.org/10.1130/B35001.1)
- Lei Chao, Ren Jianye. 2016. Hyper-extended rift systems in the Xisha Trough, northwestern South China Sea: Implications for extreme crustal thinning ahead of a propagating ocean. *Marine and Petroleum Geology*, 77: 846–864, doi: [10.1016/j.marpetgeo.2016.07.022](https://doi.org/10.1016/j.marpetgeo.2016.07.022)
- Lei Chao, Ren Jianye, Pang Xiong, et al. 2018. Continental rifting and sediment infill in the distal part of the northern South China Sea in the Western Pacific region: Challenge on the present-day models for the passive margins. *Marine and Petroleum Geology*, 93: 166–181, doi: [10.1016/j.marpetgeo.2018.02.020](https://doi.org/10.1016/j.marpetgeo.2018.02.020)
- Li Wei, Dong Yunpeng, Guo Anlin, et al. 2013a. Chronology and tectonic significance of Cenozoic faults in the Liupanshan Arcuate Tectonic Belt at the northeastern margin of the Qinghai-Tibet Plateau. *Journal of Asian Earth Sciences*, 73: 103–113, doi: [10.1016/j.jseaes.2013.04.026](https://doi.org/10.1016/j.jseaes.2013.04.026)
- Li Xue, Zhang Jinliang, Xie Jun, et al. 2015. Sedimentary and sequence-stratigraphic characteristics of the lower second member, Shahejie formation, M1 block, Wenmingzhai oilfield, Dongpu depression, China. *Arabian Journal of Geosciences*, 8(8): 5397–5406, doi: [10.1007/s12517-014-1579-4](https://doi.org/10.1007/s12517-014-1579-4)
- Li Xue, Zhang Jinliang, Yuan Yong, et al. 2013b. Sequence stratigraphic analysis and integrated 3D geological modeling of M1 block, Wenmingzhai oilfield, Dongpu depression, China. *Central European Journal of Geosciences*, 5(3): 374–386
- Li Zengxue, He Yuping, Liu Haiyan, et al. 2010. Sedimentology characteristics and coal forming models in Yacheng Formation of Qiongdongnan Basin. *Acta Petrolei Sinica (in Chinese)*, 31(4): 542–547
- Li Zengxue, Wang Dongdong, Lv Dawei, et al. 2018. The geologic settings of Chinese coal deposits. *International Geology Review*, 60(5–6): 548–578
- Liao Jihua, Wang Hua, Lv Ming, et al. 2016. Evolution of syndepositional faulting and its controlling effect on sedimentary filling in Songnan-Baodao sag of Qiongdongnan basin, South China Sea. *Journal of China University of Mining & Technology (in Chinese)*, 45(2): 336–346
- Lin Changsong, Zheng Herong, Ren Jianye, et al. 2004. The control of syndepositional faulting on the Eocene sedimentary basin fills of the Dongying and Zhanhua Sags, Bohai Bay Basin. *Science in China Series D: Earth Sciences*, 47(9): 769–782, doi: [10.1360/03yd0203](https://doi.org/10.1360/03yd0203)
- Lin Haitao, Ren Jianye, Lei Chao, et al. 2010. Tectonic transfer zone of No.2 Fault and its controls on sandbody distribution in the Qiongdongnan Basin. *Geotectonica et Metallogenia*, 34(3): 308–316
- Liu Entao, Wang Hua, Li Yuan, et al. 2015. Relative role of accommodation zones in controlling stratal architectural variability and facies distribution: Insights from the Fushan Depression, South China Sea. *Marine and Petroleum Geology*, 68: 219–239, doi: [10.1016/j.marpetgeo.2015.08.027](https://doi.org/10.1016/j.marpetgeo.2015.08.027)
- Loucks R G, Ruppel S C. 2007. Mississippian Barnett Shale: Lithofacies and Depositional setting of a deep-water shale-gas succession in the Fort Worth Basin, Texas. *AAPG Bulletin*, 91(4): 579–601, doi: [10.1306/11020606059](https://doi.org/10.1306/11020606059)
- Lv Dawei, Chen Jitao. 2014. Depositional environments and sequence stratigraphy of the Late Carboniferous–Early Permian coal-bearing successions (Shandong Province, China): Sequence development in an epicontinental basin. *Journal of Asian Earth Sciences*, 79: 16–30, doi: [10.1016/j.jseaes.2013.09.003](https://doi.org/10.1016/j.jseaes.2013.09.003)
- Lv Dawei, Chen Jitao, Li Zengxue, et al. 2014. Controlling factors, accumulation model and target zone prediction of the coal-bed methane in the Huanghebei Coalfield, North China. *Resource Geology*, 64(4): 332–345, doi: [10.1111/rge.12044](https://doi.org/10.1111/rge.12044)
- Lv Dawei, Li Zengxue, Wang Dongdong, et al. 2019. Sedimentary model of coal and shale in the Paleogene Lijiaya formation of

- the Huangxian Basin: Insight from Petrological and geochemical characteristics of coal and shale. *Energy & Fuels*, 33(11): 10442
- Lv Dawei, Song Ying, Shi Longqing, et al. 2020. The complex transgression and regression history of the northern margin of the Palaeogene Tarim Sea (NW China), and implications for potential hydrocarbon occurrences. *Marine and Petroleum Geology*, 112: 104041, doi: [10.1016/j.marpetgeo.2019.104041](https://doi.org/10.1016/j.marpetgeo.2019.104041)
- Posamentier H W, Jervey M T, Vail P R. 1988. Eustatic controls on clastic deposition I—Conceptual framework. In: Wilgus C K, Hastings B S, Posamentier H, et al, eds. *Sea-Level Changes: An Integrated Approach*. Houston: SEPM, 109–124
- Qi Jiafu. 2007. Structural transfer zones and significance for hydrocarbon accumulation in rifting basins. *Marine Origin Petroleum Geology (in Chinese)*, 12(4): 43–50
- Ravnås R, Steel R J. 1998. Architecture of marine Rift-Basin successions. *AAPG Bulletin*, 82(1): 110–146
- Song Guangzeng, Wang Hua, Gan Huajun, et al. 2014. Paleogene tectonic evolution controls on sequence stratigraphic patterns in the central part of deepwater area of Qiongdongnan Basin, northern South China Sea. *Journal of Earth Science*, 25(2): 275–288, doi: [10.1007/s12583-014-0433-7](https://doi.org/10.1007/s12583-014-0433-7)
- Song Guangzeng, Wang Hua, Wang Zhenfeng, et al. 2020. Sequence stratigraphic architectures and responses to syndepositional tectonic evolution in the Paleogene Lingshui Sag, Qiongdongnan Basin, northwestern South China Sea. *International Geology Review*, 62(7–8): 1036–1056, doi: [10.1080/00206814.2019.1579675](https://doi.org/10.1080/00206814.2019.1579675)
- Sun Qiliang, Wu Shiguo, Lü Fuliang, et al. 2010. Polygonal faults and their implications for hydrocarbon reservoirs in the southern Qiongdongnan Basin, South China Sea. *Journal of Asian Earth Sciences*, 39(5): 470–479, doi: [10.1016/j.jseas.2010.04.002](https://doi.org/10.1016/j.jseas.2010.04.002)
- Vail P R, Mitchum R M, Thompson S. 1977. Global cycles of relative changes of sea level. In: Payton C E, ed. *Seismic Stratigraphy: Application to Hydrocarbon Exploration*. Tulsa: AAPG Memoir, 26: 99–116
- Wang Dongdong, Shao Longyi, Li Zhixue, et al. 2016. Hydrocarbon generation characteristics, reserving performance and preservation conditions of continental coal measure shale gas: A case study of Mid-Jurassic shale gas in the Yan'an Formation, Ordos Basin. *Journal of Petroleum Science and Engineering*, 145: 609–628, doi: [10.1016/j.petrol.2016.06.031](https://doi.org/10.1016/j.petrol.2016.06.031)
- Wang Jiahao, Wang Hua, Ren Jianye, et al. 2010. A great oblique transition zone in the central Huanghua Depression and its significance for petroleum exploration. *Acta Petrolei Sinica (in Chinese)*, 31(3): 355–360
- Yang Renchao, Jin Zhijun, van Loon A J, et al. 2017. Climatic and tectonic controls of lacustrine hyperpyncite origination in the Late Triassic Ordos Basin, central China: Implications for unconventional petroleum development. *AAPG Bulletin*, 101(1): 95–117, doi: [10.1306/06101615095](https://doi.org/10.1306/06101615095)
- Zhang Gongcheng. 2010. Tectonic evolution of deepwater area of northern continental margin in South China Sea. *Acta Petrolei Sinica (in Chinese)*, 31(4): 528–533, 541
- Zhang Gongcheng, Mi Lijun, Wu Shiguo, et al. 2007. Deepwater area—the new prospecting targets of northern continental margin of South China Sea. *Acta Petrolei Sinica (in Chinese)*, 28(2): 15–21
- Zhang Gongcheng, Qu Hongjun, Liu Shixiang, et al. 2015. Tectonic cycle of marginal sea controlled the hydrocarbon accumulation in deep-water areas of South China Sea. *Acta Petrolei Sinica (in Chinese)*, 36(5): 533–545
- Zhang Jinliang, Liu Shasha, Li Jingzhe, et al. 2017. Identification of sedimentary facies with well logs: an indirect approach with multinomial logistic regression and artificial neural network. *Arabian Journal of Geosciences*, 10(11): 247, doi: [10.1007/s12517-017-3045-6](https://doi.org/10.1007/s12517-017-3045-6)
- Zhao Zhongxian, Sun Zhen, Sun Longtao, et al. 2018. Cenozoic tectonic subsidence in the Qiongdongnan Basin, northern South China Sea. *Basin Research*, 30(S1): 269–288
- Zhao Zhongxian, Sun Zhen, Wang Zhenfeng, et al. 2015a. The high resolution sedimentary filling in Qiongdongnan Basin, northern South China Sea. *Marine Geology*, 361: 11–24, doi: [10.1016/j.margeo.2015.01.002](https://doi.org/10.1016/j.margeo.2015.01.002)
- Zhao Zhongxian, Sun Zhen, Wang Zhenfeng, et al. 2015b. The mechanics of continental extension in Qiongdongnan Basin, northern South China Sea. *Marine Geophysical Research*, 36(2–3): 197–210