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Sedimentary evolution and control factors of the Rizhao Canyons in the Zhongjiannan Basin, western South China Sea

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Abstract

Submarine canyon is an important channel for long-distance sediment transport, and an important part of deep-water sedimentary system. The large-scale Rizhao Canyons have been discovered for the first time in 2015 in the continental slope area of the western South China Sea. Based on the interpretation and analysis of multi-beam bathymetry and two-dimensional multi-channel seismic data, the geology of the canyons has however not been studied yet. In this paper, the morphology and distribution characteristics of the canyon are carefully described, the sedimentary filling structure and its evolution process of the canyon are analyzed, and then its controlling factors are discussed. The results show that Rizhao Canyons group is a large slope restricted canyon group composed of one east–west west main and nine branch canyons extending to the south. The canyon was formed from the late Miocene to the Quaternary. The east–west main canyon is located in the transition zone between the northern terrace and the southern Zhongjiannan Slope, and it is mainly formed by the scouring and erosion of the material source from the west, approximately along the slope direction. Its development and evolution is mainly controlled by sediment supply and topographic conditions, the development of 9 branch canyons is mainly controlled by gravity flow and collapse from the east–west main canyon. This understanding result is a supplement to the study of "source-channel–sink" sedimentary system in the west of the South China Sea, and has important guiding significance for the study of marine geological hazards.

Key words: canyon, geomorphology, sedimentary evolution, control factors, Zhongjiannan Basin, western South China Sea

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1 Introduction

A submarine canyon is a common large-scale underwater geomorphological unit that occurs on the continental margin (Harris and Whiteway, 2011). It is a long, narrow, and deep negative topography cutting through the seafloor. A canyon can extend hundreds of kilometers into the deep sea area (Shepard, 1981). As an important channel for terrestrial clastic sediments to the deep-sea plain (Babonneau et al., 2002; Laursen and Normark, 2002; Popescu et al., 2004), it becomes an important bridge for the continent-sea connection, which is an important part of the source-transportation-sink system. The canyon system contains abundant geological information, such as sea-level change (McHugh et al., 2002; Gingele et al., 2004; Antobreh and Krastel, 2006). In recent years, with the rapid development in research of deep-water sedimentary systems (Micallef et al., 2014; Popescu et al., 2004), and deep-water oil (McDonnell et al., 2008) and gas and gas hydrate exploration (Davies et al., 2012) in sea areas, these canyon systems have been paid more attention.

A large amount of research has been conducted on the canyons that are developed on the continental margin of the northern South China Sea (Lofi et al., 2005; Xie et al., 2012; Wu and Qin, 2009; Su et al., 2014; Shang et al., 2015; Chen et al., 2020). Submarine canyons can be divided into two types based on topography (Table 1). The one is a large-scale canyon dominated by a main canyon with less developed branch canyons (Ding et al., 2013; Xu et al., 2014; Yin et al., 2015; Luo et al., 2018; Sun et al., 2020). The other is comblike canyons that are composed of several small and short canyons (Chen, 2014; Liu et al., 2016; Nie et al., 2017; Yi et al., 2020; Sun et al., 2022). Based on its development position, shape, and genesis, the canyons can be divided into continental erosion canyons and slope-confined submarine canyons (Harris and Whiteway, 2011). The continental erosion canyon is generally related to onshore rivers or deltas, such as the south Taiwan Shoal submarine canyon that is linked to the Hanjiang River and the Zhujiang River Estuary canyon that is linked to the Zhujiang River. They are mainly formed due to the

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Table 1. Genetic classification of main canyons in the South China Sea

Classification basis	Major characteristics	Typical example
Geomorphic morphological characteristics	Large-scale canyon dominated by a main canyon with less developed branch canyons	Taitung Canyon, Taiwan Canyon, Dongsha Canyon, Zhujiang River Estuary Canyon, Penxi Canyos
	Composed of several small and short canyons	Penghu Canyons, Yitong Canyons, Xishabei Canyons
	It is composed of the main canyon and multiple branch canyons	Rizhao Canyons
Development location, genesis	The continental erosion canyon is generally related to onshore rivers or deltas	Taiwan Shoal submarine canyon, Zhujiang River Estuary Canyon, Dongsha Canyon
	The head is developed only in the continental slope area, usually related to the turbidity current events, gravity-flow transport, traceable slump, and bottom current	Shenhu Canyons, Rizhao Canyons

undercutting effect triggered by a reduction of sea level, while slope-confined submarine canyons are also known as "headless or blind canyons". The head is developed only in the continental slope area, which extends along the slope into a deep-sea basin. Its formation and evolution are usually related to the turbidity current events, gravity-flow transport, traceable slump, and bottom current (Chen, 2014).

In recent years, with the availability of high-precision geophysical data, many quaternary channels/canyons have been identified in Zhongjiannan Basin, and a series of understandings have been made on their morphological characteristics, sedimentary filling and evolution process. Luo et al. (2018) identified a large submarine canyon in the middle of the basin and believed that the canyon has obvious segmented characteristics, which is mainly affected by erosion sedimentation, fault activity and sea level change. Yu et al. (2021) analyzed the pockmarks and its surrounding channels in Zhongjiannan Basin and considered that in addition to gravity flow, oceanographic processes can also play an important role in the formation of submarine channels. The Rizhao Canyons are distributed in the west of Zhongjiannan Basin. Previous studies on the Rizhao Canyons have not been carried out. In this paper, the shape, structure, formation and evolution of the canyon are studied, which enriches and improves the understanding of the source-channel-sink system around the Zhongjiannan Basin.

So far, the deep-water sedimentary system of the Zhongjiannan Basin in the western South China Sea has been relatively little studied and is limited to geological and geophysical data. Based on high-resolution 2D seismic and multibeam data, we carried out this research. The main aims of this work are: (1) to describe the morphology variation and the sediment filling characteristics of the large-scale canyons in the Zhongjiannan Basin, (2) to establish the development pattern of the canyon system and (3) to discuss the main factors controlling canyon formation. The research results will provide an important scientific basis for the research of source-sink system processes and environmental geological disasters in the western South China Sea.

2 Regional geological background

The canyons of the western South China Sea are distributed on the continental slope area of the northwestern Zhongjiannan Basin. The continental shelf in the west is a narrow strip, distributed along the north-south direction. The eastern continental slope changes from a north–south to a north–easterly direction. The slope from the northwest to the southeast is descending, and the water depth is about 300–1 500 m. The Zhongjiannan Basin is located in the eastern part of the continental region of the Indo-China Peninsula. The Yinggehai Basin and the Guangle Uplift areas are situated to the north. The Zhongxisha Uplift area is to the east. The southwest sub-basin is at the southeastern side, and its southwestern side is near the Wan'an Basin (Fig. 1a). The western side is adjacent to the Zhongjian Fault with south–north trending strike-slip fault occurring in the western margin (Gao and Chen, 2006). The effect of the tectonic zone on the structural control and sedimentary evolution of the Zhongjiannan Basin is most obvious (Fyhn et al., 2009). It is located at the fold of the continental slope, which is a large-scale hidden fault. It is fractured into the middle–late Miocene strata and controls the formation pattern of the continental shelf-continental slope in the western South China Sea. The Wa'nan movement (Yao et al., 2018), which occurred during the late Miocene to the early late Miocene, was the most intense tectonic movement in the basin. It resulted in a rise of the crust, strong deformation losses, folding of strata, a large decline in sea level, and the development of submarine canyons and channels. In the late Miocene–Anthropogene, the basin entirely subsided, and the upper strata showed an overall sheet drape with parallel structure reflection characteristics, mainly developing marine sediments. The present tectonic and sedimentary patterns were formed at that time (Zhong and Gao, 2005).

3 Data source

The two-dimensional multi-channel seismic data used in this study were collected in 2001 by the R/V *Tanbao* ship. The number of channels was 128, the total seismic source capacity was 2 250 cu.in. (1 cu.in.=16.387 037 cm^3), the detection point distance was 12.5 m, sampling rate was 2 ms, and the shot point spacing was 50 m. The seismic frequency bandwidth of the study horizon was between 30–45 Hz. In 2013, it was reprocessed through amplitude recovery, prestack noise suppression, multiple suppression, deconvolution processing, velocity analysis, prestack time migration imaging, post stack processing and other technical methods. The quality of reprocessed seismic data was improved to its maximum, meaning that the stratum structure and reflection characteristics of the tectonics can be identified from the shallow to the deep strata. The seismic profile data obtained by the latest processing software and methods meet the requirements of this study and provide important basic data for studying the Zhongjiannan Basin.

4 Result

4.1 *Sequence stratigraphic division*

Referring to the previous stratigraphic division scheme in the southwest basin of the South China Sea and the publicly published data in Vietnam, taking fully into account the regional sedimentary tectonic evolution background, and using the publicly published literature (Zhong and Gao, 2005; Gao and Chen, 2006; Fyhn et al., 2009), this paper combines the 121-CM-1X Well drilling data and cross well seismic profile in the western shelf

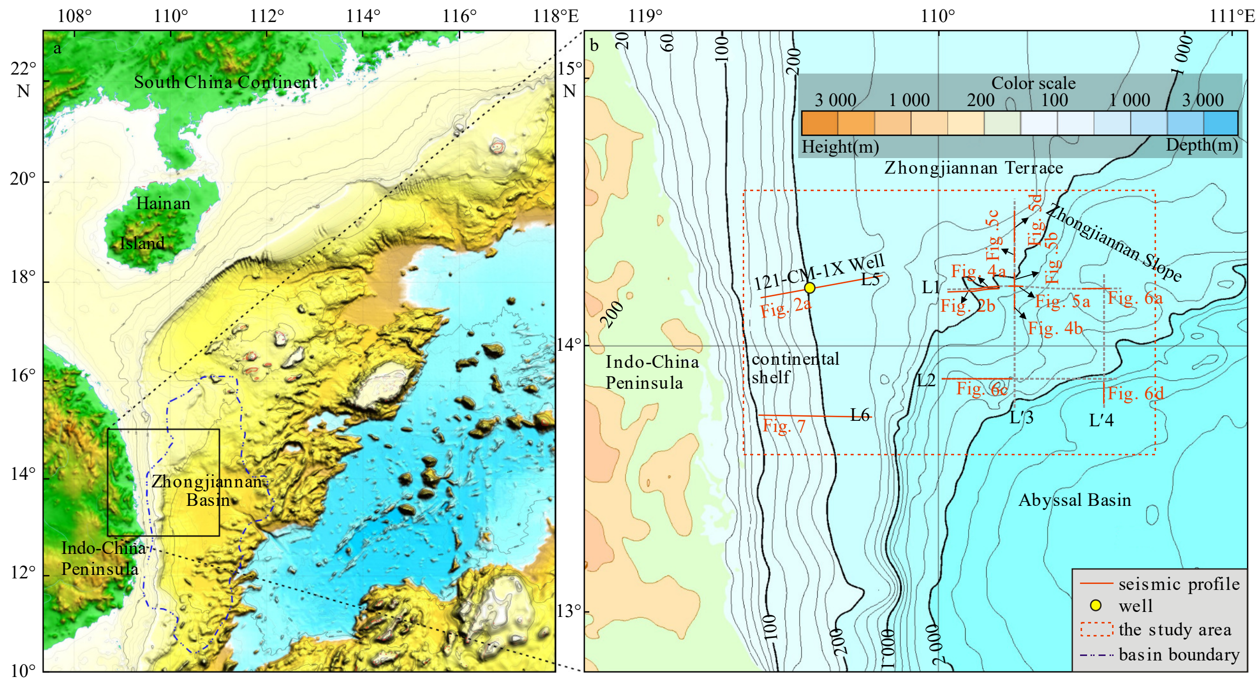


Fig. 1. Geographical location of Zhongjiannan Basin study area (a) and bathymetric contour map of the study area and its periphery (b) (Yang et al., 2015).

area to identify the typical seismic interface and divided stratigraphic sequence, then the seismic boundary is pulled to the seismic profile of the study area, so as to establish the sequence stratigraphic framework of the area.

The division of seismic sequence in this paper is further than that of predecessors. Four seismic boundaries (Fig. 2) are identified, including T_0 (seabed), T_1, T_2 and T_3 interfaces. Three sequences are divided: Sequence A (interface T_0–T_1) is the Quaternary, Sequence B (interface T_1–T_2) is Pliocene, and Sequence C (interface T_2–T_3) is Pliocene.

Interface T_3 corresponding to Wan'an tectonic movement shows stratum deformation and erosion. It is an important unconformity under the background of regional large-scale sea-level decline (Yao et al., 2018). It is characterized by medium-high frequency, medium continuity, two-phase and strong amplitude reflection. There are truncation and erosion characteristics under the interface and obvious onlap fill characteristics above it.

Interface T_2 is characterized by high continuity, strong amplitude, stability and straightness. Incised valley is locally developed on the interface, and onlap, downlap and truncation phenomena are seen. Interface T_1 is bidirectional, highly continuous and strong amplitude. The interface is flat and stable, showing disconformable-conformable contact, and most of them are incised valley.

Sequence C is a set of drape deposits that entered the stable depression stage in the late Miocene, with a large number of downlap and divergent reflection, local stratum deformation, medium-low continuity or chaotic reflection, and strong-medium weak amplitude. The Pliocene of Sequence B is dominated by medium-high frequency, medium-strong amplitude, medium-high continuity and parallel-subparallel reflection. The local strata are crumpled and deformed, showing low continuous or chaotic reflection with strong-medium weak amplitude. Most of them are in parallel unconformity contact with the upper and lower strata, and a large number of downcut valleys are de-

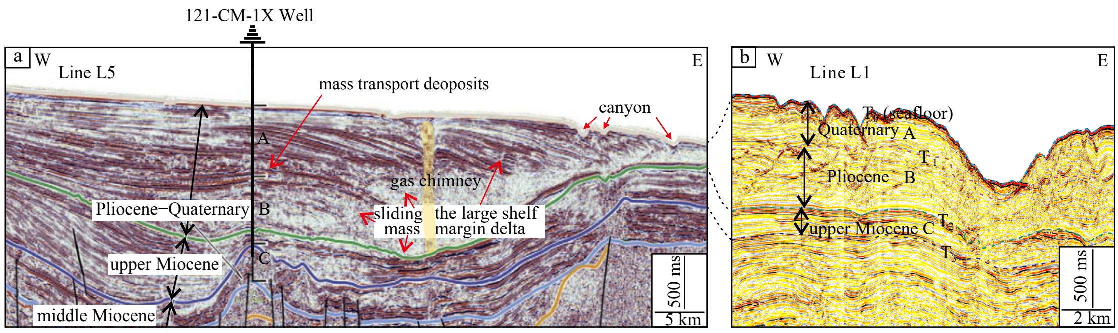


Fig. 2. Sequence stratigraphic division in the seismic line L5 passing through drilling 121-CM-1X Well, according to Fyhn et al. (2009) (a) and sequence stratigraphic division in the seismic survey line L1 in the study area (b). According to the calibration of 121-CM-1X drilling data, Sequence A is Quaternary, Sequence B is Pliocene, and Sequence C is Pliocene. The locations of the seismic line L5 and L1 are marked on Fig. 1b.

veloped. The Quaternary of Sequence A is dominated by high frequency, medium-weak amplitude, medium-high continuity, parallel-subparallel or filling facies reflection, and mostly in parallel unconformity contact with the underlying strata.

4.2 *Morphological characteristics*

The Rizhao Canyons in the western South China Sea are distributed on the Zhongjiannan Slope, with the main canyon occurring in the east–west direction and multiple branch canyons connecting with the main canyon in the direction of the southern slope (Fig. 3) and extending into the deepwater area of the Zhongjiannan Basin. The canyon head is developed in the upper continental slope, which is not connected with onshore rivers and belongs to a continental slope restricted submarine canyon. The transition zone of the north Zhongjian Terrace to the south Zhongjiannan Slope is a narrow strip, distributed in a north-easterly direction, while the main canyon extends parallel to the transition zone. The total length of the main canyon is over 70 km, with a width of 1–2.3 km. The cross-section of the undercutting canyon is a V-type and a U-type, and the undercutting depth is 40–241 m. The waterbody deepens from the west to the east. The main canyon is mainly divided into three sections: the upper section in a west–easterly direction, the middle section with a southwest-northeasterly direction, and the lower section with a west–east trend. At the end of the main canyon, a branch canyon is divided to the north and extends along the topographic transition zone. The end of the middle section extends to the south and converges with the main canyon.

The main canyon on the south side of the Rizhao Canyons is connected with a multi-head branch canyon, named C1–C9 from the west to the east (Fig. 3). According to the direction of the branch canyon, they can be divided into ① A N–S strike group of western canyons C1, C2 and C3; ② A NW–SE strike group of eastern canyons (C4–C9) and NWW–SEE strike (only canyon C9). As a whole, the upper branch canyon has the characteristics of changing from N–S to NW–SE and then to NWW–SEE from the west to the east. The canyons C2, C3, C4, and C5 in the middle of the canyons are large and have multiple and complicated branch channels. The canyon scale gradually decreases towards the east and the branch channels decrease until no branches are left.

4.3 *Sedimentary structure of canyon system*

Based on the existing two-dimensional multichannel seismic profiles in the western South China Sea, the sedimentary and structural characteristics of the canyon system were identified, and the sedimentary structure inside, around, and outside the canyon outlet is described in detail (Table 2; Fig. 4). The evolutionary process and spatial distribution of the canyon filling are discussed. Finally, the development of the canyon system in this region is established.

4.3.1 *Gravity flow sedimentation at the bottom boundary of the canyon*

The bottom boundary of the canyon is T3 interface, below which a parallel continuous reflection group, which has a truncation in relation to the interface. Above the interface is a chaotic or low continuous reflection sedimentation within the canyon boundary. The periphery outside the boundary is generally a medium continuous reflection group, which is onlap or downlap interface (Figs 4a, 4b, 5a and 5b). This interface is the initial surface of gravity flow erosion. The bottom and periphery of the canyon is a set of medium and weak amplitude, chaotic-low continuous reflection sedimentation occurrences (Table 2a; Fig. 5b). The interior shows the secondary accumulation characteristics of folds and deformation, which can be eroded, belonging to gravity flow sediment. *In-situ* continuous reflection strata without erosion and transformation can be seen nearby (Fig. 5a). The initial erosion of the gravity flow was mainly in the late Miocene, dominated by sediment transport of gravity flow. Its energy is strong, and it erodes *in-situ* continuous strata, and further forms a weak zone (Wu et al., 2011). It can more easily produce erosion valleys, forming the initial negative topography. Therefore, it is speculated that Rizhao Canyons began to develop from the late Miocene.

4.3.2 *Canyon filling structure*

Based on the detailed description of the sedimentary characteristics of the inner canyon of the two-dimensional seismic profile, the process of upfill of the canyon was analyzed by comparing the sedimentary characteristics of the upper-middle-lower section of the single-branch canyon with those of each branch canyon. The undercutting cross-section morphology of the canyon is mainly V-shaped and U-shaped, and partly W-shaped (Table 2g).

Canyon C4 is the largest one of the branch canyons. C4 and C5 both have several small channels flowing into them. The undercutting morphology of their cross-sections was V-shaped in the early stage, which was later filled with sediment. The morphology is now U-shaped valleys with flat bottoms (Fig. 6a). The

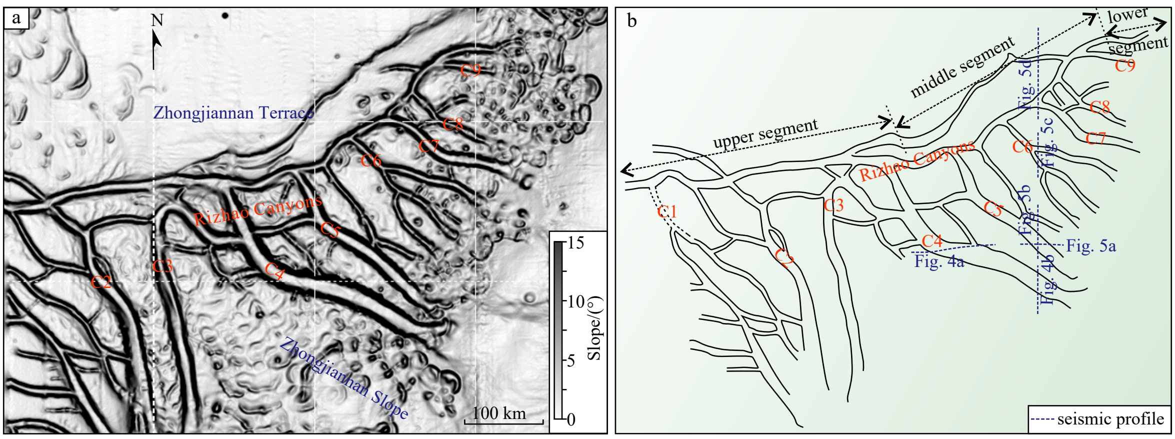
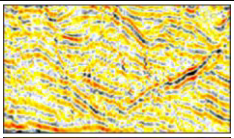
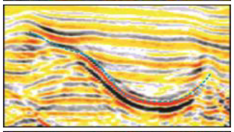
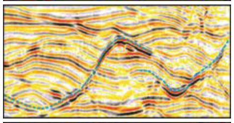
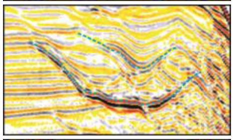
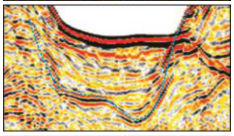
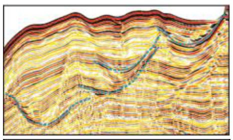
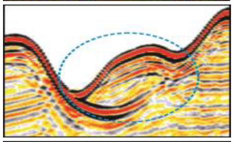
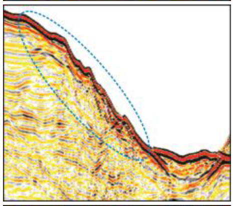
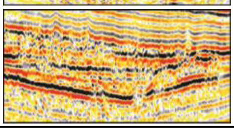


Fig. 3. Topographic slope map of Rizhao submarine canyon (a) and sketch of canyon shape (b) (the location is shown in Fig. 1b).

Table 2. Typical seismic facies analysis and corresponding sedimentary facies interpretation of canyon system

Serial No.	Line No.	Seismic profile	Seismic reflection characteristics	Sedimentary facies	Origin
a	L1		low continuous reflection and chaotic reflection	gravity flow deposit	gravity flow
b	L1		parallel reflection	channel-fill facies	turbidity current
c	L1		medium-high continuous and two-way onlap reflection		
d	L′3		medium continuous and two-way onlap reflection		
e	L′3		medium-low continuous reflection		
f	L′3		medium-high continuous onlap reflection		channel migration gravity flow
g	L1		medium continuous reflection	slump mass	gravity flow
h	L1		medium continuous reflection in the upper part, chaotic reflection in the lower part	slump mass, sliding mass	
			chaotic reflection filling in the channel	channel-fill facies	turbidity current
i	L′4		local strong amplitude continuous-low continuous reflection	deep water fan	

interior shows multi-stage sedimentary filling characteristics. In the upper and middle sections of canyon C4, the submarine undercutting valley depth was 333 m and 319 m, respectively, and the lower filling thickness was 1.3 s and 1.26 s (two-way reflection time), respectively (Figs 4a, b). In the middle section of canyon C5, the submarine undercutting valley depth was 291 m and the lower filling thickness was 0.74–0.89 s (two-way reflection time), respectively (Figs 5a, b). Due to the constant erosion in the canyon, a multi-period channel superposition with lateral migration and vertical accretion filling was formed. The undercutting width decreased gradually from the old to the new channel. The bottom of each period of the channel erosion showed a concave and strong amplitude reflection, which indicated that the bottom of the channel was generally dominated by coarse-grained retained sediment, and the inner filling was mainly chaotic reflection, followed by medium continuous reflection, medium-strong amplitude, and one-way/two-way onlap reflection. The slope of the canyon wall was steep with a general slope of 15°–20°, the sidewall has developed a step fault, and is gradually sliding to the canyon slope according to the step-by-step explanation of the fault development (Figs 4a,5b). The scoured and collapsed sediments of the canyon wall slide along the sidewall to the canyon bottom, showing strong amplitude and chaotic structure reflection (Table 2h; Figs 4, 5a, 5b).

There was only one main canyon in the head of canyon C6, and 3 branch channels were divided downstream. As shown in Fig. 5c, in the upper section of the incising canyon C6, the undercutting valley was V-shaped, the maximum undercutting depth was about 198 m, and the filling thickness was 0.8 s. The canyon bottom showed strong amplitude reflection, which was clear and easy to be identified. The whole channel was divided into four stages. The internal channel was mainly medium-strong amplitude, chaotic or low continuous reflection filling, and the main axis direction of the channel showed northward migration. In the lower sections of canyons C6–C8 (Fig. 6a), the submarine undercutting depth was usually 100–200 m, the local maximum depth

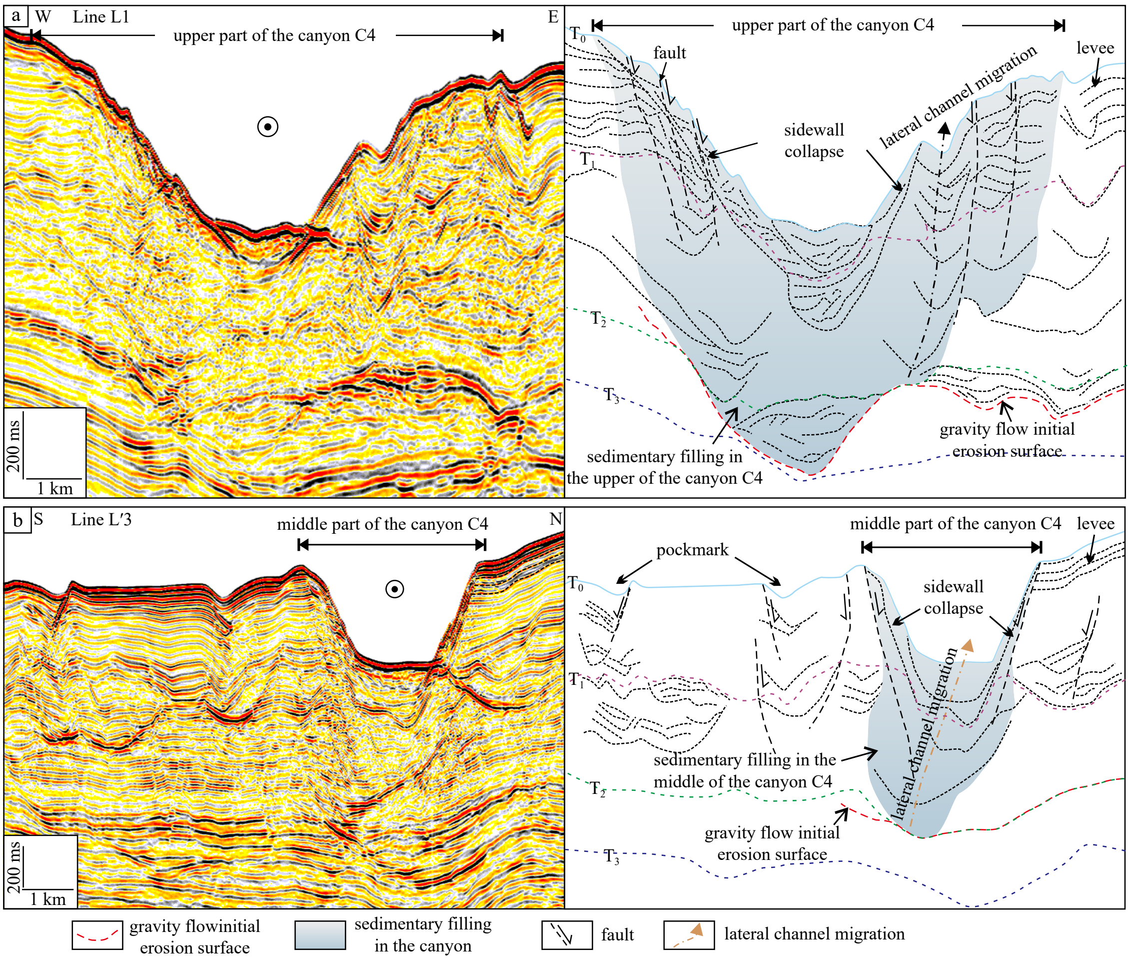


Fig. 4. Seismic profile and interpretation of the canyon C4, upper part (a) and middle part (b) (profile location is shown in Figs 1b and 2).

could reach 293 m, and the filling thickness of the canyon was thin, which was usually about 0.2 s. Inclined accumulation occurred along the canyon wall due to the slump/slip effects of the canyon sidewall (Table 2g; Fig. 6a). The interior was mainly characterized by strong amplitude and medium continuous reflection. There was also chaotic reflection filling, which might be due to denudation of sediment of the canyon sidewall or a turbid current that brought sediment into the canyon channel.

In the middle section of the main canyon, valley ① in Fig. 5d, the section morphology was U-shaped, the undercutting depth was about 276 m, and the filling thickness below the valley was about 1s, which mainly showed medium-low continuous reflection sedimentation (Fig. 5d). The undercutting valley ② in Fig. 5d was V-shaped and the undercutting depth was 128 m. There were whole strata slip filling with medium-high continuous and sub-parallel reflection inside valley ③ in Fig. 5d. In the north branch of the main canyon, the V-shaped undercutting valley with a depth of 150 m (valley ④ in Fig. 5d) could be seen, and no internal filling was found.

In a word, the water depth of the single branch canyon gradually deepened from the upper, middle, and lower sections, the width of the canyon top decreased, the width of the canyon bottom increased, the submarine undercutting depth decreased, and the filling thickness of the canyon decreased. At the same time, the bottom filling characteristics of the lower section of the canyon were different from that of the upper and middle sections, and there was no obvious erosive sediment in the lower section of the canyon bottom. The results showed that the sediment supply of the lower section was less than that of the upper and middle sections, and the transport velocity of sediments decreased, leading to the reduction of erosion and its undercutting ability, which was dominated by wall slump/slip of the canyon wall and sedimentary filling in the canyon by turbid currents. The main function of the upper and middle sections was erosion undercutting and sedimentary filling, while that of the lower section was undercutting. From canyon C4 eastward to canyons C5, C6, C7 and C8, the canyon scale gradually reduced. The canyon boundary is mostly controlled by faults, and slumps or slips occur in the canyon side walls and are affected by slope and gravity. In the canyon, multi-stage channel undercutting and filling were developed, and the main axis of the channel had migration characteristics, which mainly experienced the sedimentation process of erosion, filling, re-erosion, and re-filling.

4.3.3 *Canyon bank sedimentation*

The banks on both sides of the canyon erosion boundary showed parallel-sub-parallel structures with medium amplitude and high continuous reflection, but they were washed and filled by several channels. For example, compared with the filling in canyon C4, the filling and sedimentation continuity of the upper channel of the bank was better, which mainly included parallel structures (Table 2b), two-way onlap (Table 2c, 1d), one-way on-

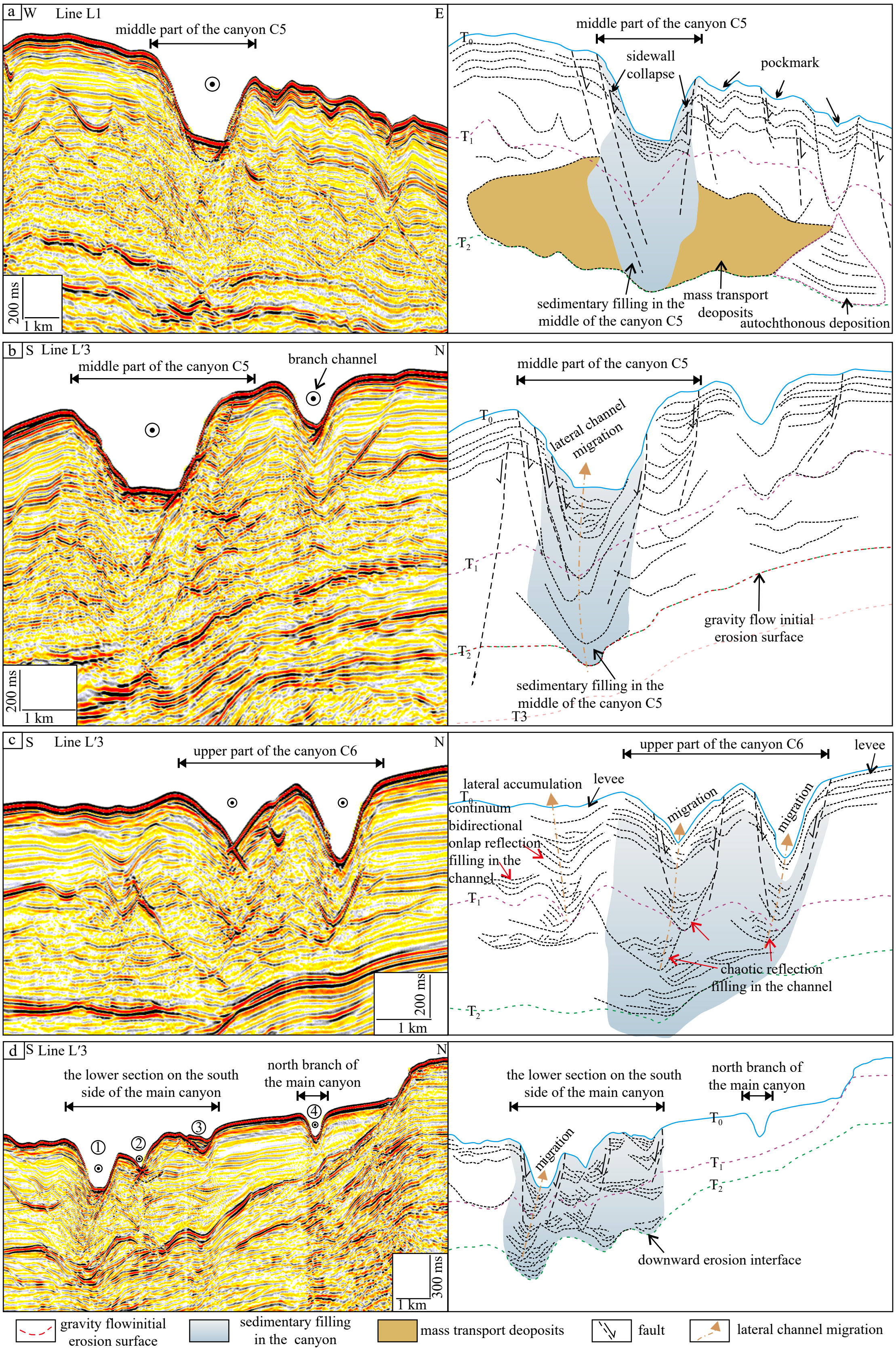


Fig. 5. Seismic profile and interpretation of the canyons C5, C6, and main canyon, middle part of C5 on seismic profile L1 (a), middle part of C5 on seismic profile L′3 (b), upper part of C6 on seismic profile L′3 (c) and the main canyon on seismic profile L′3 (d) (profile location is shown in Figs 1b and 2).

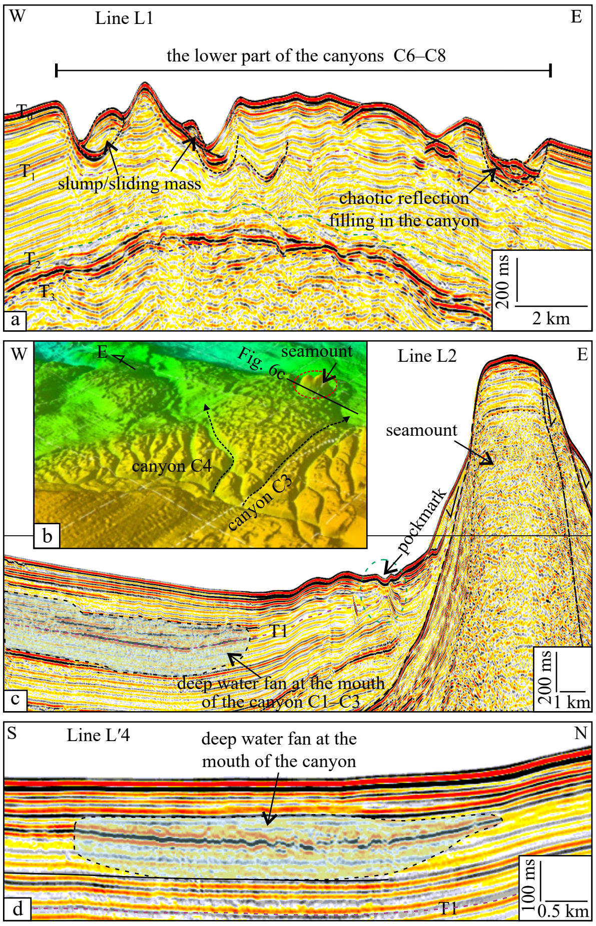


Fig. 6. Seismic line L1 across the lower section of canyons C6–C8 (a), local topographic map of canyons area (b), seismic survey line L2 across the downstream of canyons C1–C3 and the mouth (c) and seismic line L′4 across the downstream of the canyons and the mouth (d) (see Fig. 1b for profile location).

lap (Table 2f), and medium-high continuous reflection. The upper channel in the canyon and both sides of the bank showed eastward and northward migration (Table 2f) as well as lateral accretion characteristics. Many small-scale concave valleys also developed on the seabed side of the bank, which are geomorphologically called “seabed pockmarks”. Since the underlying strata were sunken (Figs 4b, 5b), a set of seismic reflection characteristics of “undulation” can be seen on the bank (Fig. 5a).

4.3.4 *Canyon outlet sedimentation*

In the lower reaches and the mouth of the canyons, the water depth was 1 584–1 713 m, and a lenticular fan was developed. The interior mainly showed medium-low continuous reflection, showing thrust faults, folds, and flexure (Fig. 6). Strong amplitude reflection (Table 2i; Figs 6c, d) can be seen locally. The peripheral strata mainly showed continuous parallel structure reflection, showing a discordant contact, belonging to deep water fan sedimentation due to turbid currents. As shown in Figs 6b and c, the outcropping seamount was located 5 km to the east of the fan. It is possible that due to the shielding effect of the seamount, the fan did not expand to the east. The results showed that the canyon was the major transportation channel for sediment transported by gravity flow. The sediment was continuously transported in the form of turbid current after arriving at the outlet of the canyon. The sediment was removed and the Pliocene–Quaternary deepwater fan was developed from the vast and deep-sea area which extended to the mouth of the canyon.

There are three types of sedimentation in the canyon. First, turbidity sedimentation and gravity flow sedimentation with strong amplitude reflection characteristics, weak continuity, and chaotic structure. They are axial sediment filling in the canyon, vertically developing multiple erosion channel bottom interfaces, which can be divided into multi-stage erosion-filling cycles (Figs 4 and 5). Second, there is sediment instability in the canyon sidewalls. There are always chaotic reflection structures on the wall of two sides of the canyon. Because of the steep canyon side wall topography, the sediment instability caused by gravity forms the step-by-step declining topography inside the canyon. At the same time, sediment from the canyon wall was exfoliated close to the canyon bottom by erosion, forming the chaotic reflection filling of the canyon bottom (Figs 4, 5a and 5b). Third, slip sediment with better continuity, medium, and strong amplitude reflection characteristics, mainly represent the overall slip of the canyon sidewall or bank sedimentary layer, show inclined accumulation filling in the submarine canyon (Fig. 5d③). In the canyon system, the channel undercutting the erosion subface and the strong amplitude formation both correspond to turbid current sedimentation. The gravity flow sedimentation corresponding to chaotic reflection can indicate the inner axial sediment filling characteristics in the canyon. The results showed that the submarine canyons are an important channel for sediment transport in this area, which can further transport continental marginal sediments to the lower continental slope, and even to the deep-sea area, where a deep-water sediment fan has been developed.

5 Discussion

5.1 *Sedimentary evolution of the canyon system*

The provenance of the study area was mainly composed of sediments from the continental regions of the western Indo-China Peninsula, and there may be a small number of Red River sediments from the north. A W–E seismic profile of the continental shelf in west China that from the beginning of the late Miocene (Zhong and Gao, 2005; Gao and Chen, 2006; Fyhn et al., 2009), shows that continental shelf slopes continuously migrated to the eastern sea area. The continental shelf margin showed obvious progradational features, and large-scale continental shelf marginal deltas, slumps, and block transport complexes were deposited (Figs 2a and 7). This indicated that the sediment source mainly came from the west and the supply was sufficient. In this way, under the inducement of continental marginal sediment, large-scale sediment flows with strong erosion occurred, resulting in erosion of the underlying strata. The early sediment flows eroded the regional strata of the transition zone between the north fault-step zone and the Zhongjiannan Slope, undercutting the canyon from east to west, and beginning to develop the embryo of the main canyon. When a large amount of sediment was transported to the east rapidly, it exceeded the carrying capacity of the incised valley, broke the sidewall in the downward slope direction, i.e., the south side of the canyon wall, and then eroded toward the south to form a series of branch valleys which are connected, demonstrating a net and dispersing the transportation quantity of sediment in the main canyon. Because the east–west slope of the main canyon was flat at about 0.1°–0.8°, the southern slope was relatively steep at 1.0°–2.1° (Fig. 8). The sediment was more easily transported to the deep basin area through the southern branch canyon, which makes the previously de-

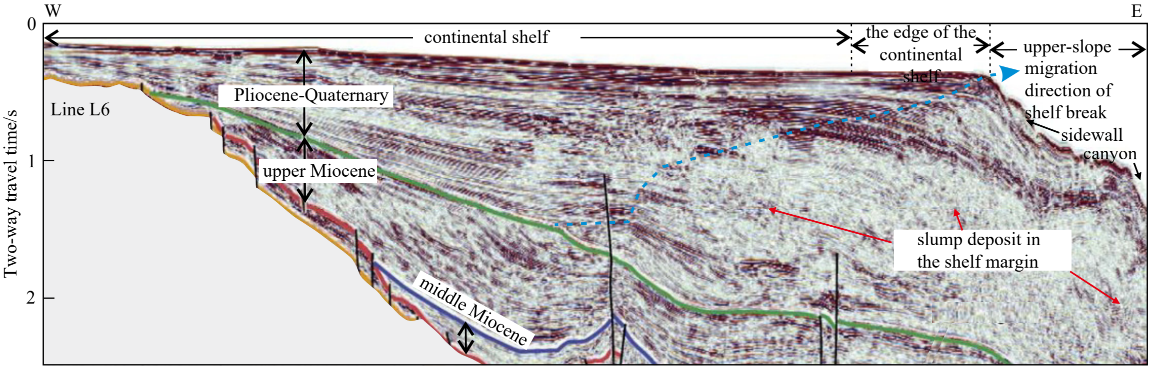


Fig. 7. The interpretation of seismic profile L6 across the continental shelf and the upper slope in the west of the study areas (modified from Fyhn et al. (2009); location of lines is shown in Fig. 1b).

veloped main canyon scale (such as the width of the canyon top, the undercutting depth, and the filling thickness) smaller than that of the branch canyon. Formed canyons showed the main canyon connected with multi-branch interlacing network features, demonstrating distinct features with the principal main canyon or several parallel short comb-like canyons in the northern South China Sea.

The vertical sedimentary characteristics of the canyon show chaotic reflection gravity flow sedimentation at the early canyon bottom in the early late Miocene. During the Pliocene Quaternary period, multi-stage erosion-filling cycles occurred in the upper canyon, in which the upper and middle sections of the canyon were dominated by undercutting and filling, and the lower section was dominated by erosion. At the same time, the undercutting by erosion of main and branch canyons decreased from the west to the east. Sediment was unstable due to the steep sidewalls, forming terraced slopes towards the canyon. Sediments were exfoliated to the bottom of the canyon, showed by chaotic reflection filling. The whole canyon wall sediment also slipped, forming slip sediment and inclined accumulation and filling in the canyon. The two sides of the canyon bank mainly consisted of vertical accretion and showed an extensively developed seabed pockmarking. Sediment that was transported through the canyon to the deep basin area in the downstream-mouth of the canyon, was unloaded and deposited to form a deepwater fan.

From late Miocene to Quaternary period, the western continental shelf area and the northern Red River continuously provided a large amount of sediments to the study area. Due to the strong erosion of sediments by gravity flow, erosion valleys appeared on the seabed, which further developed into canyons and became the transportation channel of sediments. The sediments were continuously transported to the deep-sea area, and the sediments were bound in the canyon until the end of the canyon in the deep-water area. Finally, it got rid of the constraints of the canyon sidewall and dispersed in a fan, forming a deep-water fan deposition, which formed a complete “source channel sink” sedimentary system.

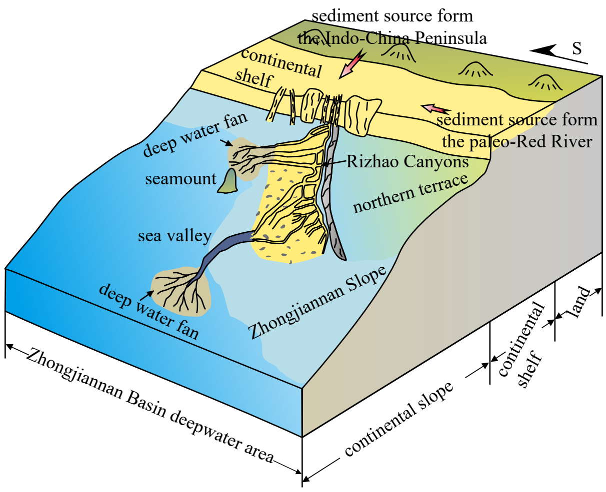


Fig. 8. Sedimentary development pattern of the Rizhao Canyons.

5.2 *Control factors of the canyon system*

The formation of a canyon is also the result of the interaction and mutual effects of multiple factors such as tectonic activities, topographic conditions, provenance supply, sedimentation, and sea-level changes. However, single or multiple factors play a leading role (Chen et al., 2020; Wu and Qin, 2009; Ding et al., 2013). Many canyons with a clear and simple main axis are controlled by tectonic activities, including the Taitung Canyon, the Taiwan Canyon, the Zhujiang River Estuary canyon, and the Zhongyang Canyon (Su et al., 2014). The Penxi Canyon is mainly affected by the negative topography of a pre-existing landform (Luo et al., 2018). There are canyons with abundant provenance supply and strong sedimentation, such as the Penghu Canyon, the Dongsha Canyon (Wang et al., 2021) and the Shenhu Canyons (Wu et al., 2011).

5.2.1 *Sediment supply*

The large-scale sediment source supply causes the slope break belt to migrate forward, forming a fan and the prograding body. This is a prerequisite for channel formation, which shows that the quantity of sediment supply is the main controlling factor of the canyon formation and evolution (Yuan et al., 2010).

From the perspective of topography, the main canyon extended from the upper continental slope area outside the western continental shelf towards the east, while branch canyons all developed from the main canyon towards the south. At the same time, no fan or other canyon/channel converged on the north side of the canyons. The continental marginal sedimentary system shows obvious prograding characteristics on the east–west seismic profile of the continental shelf margin area (Fig. 6). It was inferred that these canyons had a unified material source. Their provenance of the sediment is from the west, and the sediment supply was plentiful.

When a large amount of sediment was transported along the continental slope direction, the downward erosive sediment flow would be formed, resulting in erosion of the underlying strata (Sanchez et al., 2012; Li et al., 2015). For example, the undercutting valley (Fig. 4a) that developed on the interface of the canyon bottom, confirmed the erosion effect of the sediment flow. If the strongly prograded continental shelf marginal system experienced a high water level stage, it would bring more sediments, which could further aggravate the erosion and form submarine canyons. With a sufficient supply of sediment, the strong sediment flow led to the canyon landform becoming more prominent (Liu et al., 2016). This meant that the erosion of the canyon continuously increased and that the canyon undercutting was deeper and wider. The lower part of the upper and middle sections of canyons C4 and C5 were also V-shaped, indicating that erosion of the canyon was strong in the early stage of canyon formation. The canyon side walls were however steep, causing sediment instability and slip/slump accumulation towards the canyon bottom (Figs 4a and 6a). The top width of the upper segment of the main canyon is 65 m, and the lower section is narrowed to 7 m, At the same time, the top width of the cross sections of C2, C3 and C4 branch canyons in the west is larger, which is 25–49 m, while the top width of the cross section of C4–C9 branch canyons in the northeast is smaller and smaller (the narrowest part is 2 m). Starting from the head of the upstream canyon, the sediment transported by the main canyons is divided into two parts in the upstream. One part is transported to the downstream of the main canyon in the east, and the other part is transported to each branch canyon in the south, which gradually disperses and weakens the action intensity of gravity flow, and reduces the depth and width of undercut erosion. Therefore, the development of Rizhao Canyon group is directly affected by the sediment sources supply and gravity flow erosion.

5.2.2 *Topographical conditions*

The development location and trend of Rizhao Canyons in the western South China Sea were directly controlled by topographic characteristics, which were mainly reflected in two aspects: the topographical slope and the change in water depth. The study area showed that the topographical characteristics with north high-south low, west high-east low, and the water body deepening to the east and southeast. To the west was a narrow continental shelf and to the east was a continental slope. The water depth line close to the western continental shelf area is oriented in a nearly S–N direction, and the head of the main canyon in the study area (nearly 300 m deep) was developing vertically to the isobath along an east–west direction. Then it extended to the east, and the trend was in line that of the topographical transition zone of the Zhongjian Terrace and the Zhongjiannan Slope (SW–NE), basically along the transition zone or close to it, all the way down to the eastern slope direction (with a slope of about 0.5°), extending to the deepwater area (with a water depth of 1 300 m). The north side of the canyon distribution area was the flat Zhongjian Terrace (with a slope of about 0.2°), and the south side was the Zhongjiannan Slope (with a slope of about 1.0°–1.7°). The northern part of the slope has a relatively large slope and high terrain, and extends to the south. The branch canyon spread over the slope and extended into the deepwater area of the Zhongjiannan Basin (with a water depth of over 1 500 m).

The Rizhao Canyons are mainly controlled by material source supply and topographic conditions. The material source supply becomes the material basis and power source of Rizhao Canyons development. The topographic conditions directly control the development of canyon. Therefore, it is considered that Rizhao Canyons belong to slope-confined submarine canyons (Table 1) and become an important channel for sediment transport in the western South China Sea.

6 Conclusions

The Rizhao Canyons is a set of large-scale continental slope-restricted canyons in the western South China Sea. It is mainly distributed on the Zhongjiannan Slope with a slope of 1°–2° and a water depth of 359–2 234 m. The canyon is composed of one main canyon and nine main branch canyons. The main canyon has a total length of more than 70 km, generally extending along an E–W direction, and finally into the eastern lower slope area with a water depth of 1 064 m eastward. The south side of the main canyon is directly connected with several branch canyons extending along the S, SE, and SEE directions. The whole canyon shows the distribution structure characteristics of one main canyon and many branch canyons and finally converges into the basin area.

The canyons developed in the late Miocene–Quaternary period and display undercutting and filling characteristics. Its sedimentary structure mainly includes ① the canyon bottom is a set of gravity sedimentation flows with fold deformation and chaotic reflection characteristics; ② the canyon shows undercutting and filling effects, demonstrating the characteristics of multi-stage cycle superposition and principle axis migration; ③ the canyon bank shows vertical accretion characteristics, and seabed pockmarking is commonly seen in localised areas, and ④ deep-water fan sedimentation with medium-strong amplitude reflection is developed in the lower reaches and mouth of the canyon system.

The formation and evolution of the canyon are influenced by many factors, such as topographical conditions, provenance supply, sea-level change, and tectonic activities. The development of the Rizhao Canyons is mainly controlled by provenance supply and topographic conditions. A large number of sediments from the western Indo-China Peninsula enter the continental slope across the continental shelf margin from the east, which provides the material basis for the formation of erosive sediment flow. Influenced by the sediment supply and the changes in continental slope and water depth, the sediment flow erodes the seabed, leading to the development of the canyon embryo and the extension of the canyon into the deep basin area, which promotes the sedimentation of the canyon system.

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