



Original Paper

Quaternary spatiotemporal evolution and multi-factor driving mechanisms of continental slope canyon–fan systems in Baiyun sag, Pearl River Mouth Basin, South China Sea



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ABSTRACT

As potential targets for deep-sea hydrocarbon exploration, continental slope canyon–fan systems preserve records of sea-level fluctuations and paleoclimatic changes. The Quaternary canyon–fan system in the Baiyun sag represents a potential reservoir for sand-rich deposits. However, the mechanism governing its Quaternary spatiotemporal evolution, which is influenced by multiple factors, remains unclear, significantly constraining the prediction accuracy of sand-rich deposits in this area. Based on three-dimensional (3D) seismic, drilling/logging, and paleontological datasets, a Quaternary isochronous stratigraphic framework was established for the northern continental slope of the Baiyun sag. Seismic interpretation techniques were employed to delineate the morphology and architecture of slope canyon group and associated slope fans, which enabled the development of a spatiotemporal evolutionary pattern for canyon–fan systems and the revelation of their multifactorial driving mechanisms. Our study demonstrates that: (1) Within the Quaternary target strata, one second-order (T_0) and five third-order sequence boundaries (SB1–SB5) have been identified, leading to the delineation of five third-order sequence units (Sq1–Sq5) with distinct structural characteristics; (2) Sedimentary geomorphic units such as shelf-margin deltas, submarine gullies, canyons, and slope fans have been recognized, collectively forming a complete deep-water source-to-sink (S2S) system; (3) The evolution of canyon–fan systems commenced during the canyon–fan formation stage (Stage 1) under a transgressive background, progressed through the peak stage of canyon incision and fan progradation (Stages 2–3) under a regressive background, and culminated in the canyon–fan decline stage (Stage 4) under another transgressive background; (4) Macroscopic factors, including tectonic activity and climate–sea level changes, controlled sediment supply and the development of canyon–fan systems, while local factors such as sediment provenance patterns and the distance between canyons and the shelf margin regulated the structural configuration and spatial distribution of these systems. The dominant controlling factors undergo shifts over time. Elucidating the spatiotemporal evolutionary patterns of Quaternary continental slope canyon–fan systems, revealing their multifactorial driving mechanisms, and deepening the understanding of dynamic processes within deep-water S2S systems will provide a theoretical basis for subsequent predictions of sand-rich deposits and offer a practical paradigm for global canyon–fan research.

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1. Introduction

On a macroscopic scale, the geomorphic units on the Earth's surface can be divided into erosional landforms and depositional landforms. Erosional products originate from erosional landforms.

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The process by which these products are transported and eventually deposited in sedimentary areas or catchment basins is termed the source-to-sink (S2S) system. Gong et al. (2021a) classified the S2S system into two major categories: the proximal (shallow-water) S2S system and the distal (deep-water) S2S system. Among them, the shelf margin-slope serves as a crucial conduit for the transfer of materials and energy connecting the shallow-water shelf (source area) and the deep-water basin (sink area) (Lin et al., 2015). As an integral part of deep-water S2S systems (Harris and Whiteway, 2011; Gong et al., 2021b), it preserves records of sequence architecture, sea-level fluctuations, and paleoclimatic conditions (Gong et al., 2016; Lin et al., 2018a). Continental-slope canyons, acting as pathways for the transport of terrigenous clastics to the deep sea, along with their infill deposits and distal slope fans, represent potential hydrocarbon reservoirs in deep-water settings (Zhao et al., 2012; Jobe et al., 2017; Kneller et al., 2020; Zhu et al., 2023; Gong et al., 2024). Consequently, the shelf margin-slope not only constitutes a natural laboratory for geodynamic research (Lin et al., 2018b), but also serves as a strategic target for deep-water hydrocarbon exploration (Wang et al., 2022), with canyon-fan systems attracting particular attention due to their hydrocarbon exploration potential.

Continental slope canyons, which are common geomorphic features along continental margins, are characterized by an elongated negative relief with V- or U-shaped profiles. They can extend several to over 10 km in width and hundreds of meters in depth, often terminating in fan-shaped or broom-like sedimentary deposits (Harris and Whiteway, 2011). Canyons are classified into “shelf-incising” and “slope-confined” types based on whether the canyon head incises through the shelf and its connectivity to river systems (Harris and Whiteway, 2011; Jobe et al., 2011). The former originates from the continental shelf and erodes it, with the canyon head generally connected to areas with a high supply of coarse-grained sediments; the latter originates from the continental slope and generally lacks a supply of terrigenous clastic sediments. Although the Quaternary canyon group on the continental slope of the Baiyun sag falls into the “slope-confined” category, the development of submarine gullies connects the canyons with the shelf area, providing the canyon group with an adequate sediment supply. Early research in this area, constrained by data quality and technological limitations, primarily focused on seabed geomorphic descriptions (Ding et al., 2013b), Miocene channel characteristics (Gong et al., 2013), and the impact of canyon migration on gas hydrate accumulation (Wang et al., 2014). Moreover, significant controversies persist regarding the genesis mechanisms of these canyons. For instance, Zhu et al. (2010) proposed a depositional model involving “lowstand turbidity current erosion and highstand bottom current reworking”, emphasizing the interactive control of turbidity and bottom currents on canyon evolution (Ding et al., 2013a; Gong et al., 2013). In contrast, Liu et al. (2016) highlighted morphological and genetic differences between Late Miocene channels and present-day canyons, arguing against a unified model for their interpretation.

Advancements in high-quality data acquisition and deep-sea exploration technologies have enabled a more profound revelation of the controlling mechanisms underlying the spatiotemporal evolution of canyon-fan systems (Liu et al., 2019b). However, the controlling factors at different temporal scales exert significantly varying influences on the evolution of canyon-fan systems. Tectonic activity, climate change, and sea-level fluctuations are macroscale controlling factors, typically operating on a million-year timescale: tectonic activities can dictate canyon orientation by creating fracture planes in stratigraphy that are prone to erosion, thereby establishing the geomorphic conditions for canyon development (Ding et al., 2013b). Global Pleistocene

climate-sea level fluctuations exhibited high-frequency, high-amplitude variations, with asymmetric patterns of rapid transgression and slow regression significantly influencing erosion-deposition processes on continental slopes. For instance, the formation of the Danube Canyon in the Black Sea has been linked to debris flow erosion triggered by regression (Popescu et al., 2004). Additionally, relatively localized factors, such as gas hydrate dissociation (Davies et al., 2012; Ma et al., 2025) and sediment waves (Wang et al., 2023), also influence canyon-fan evolution. These factors typically operate on a smaller timescale, yet the association between sediment waves and canyon genesis remains controversial (Gong et al., 2023). Currently, the coupling mechanisms among these multifaceted factors in controlling the spatiotemporal evolution of canyon-fan systems remain unclear, necessitating further in-depth research.

The Quaternary canyon-fan system in the Baiyun sag represents a potential reservoir for sand-rich deposits. However, its complex evolutionary processes and controlling mechanisms remain poorly understood, thereby constraining the accuracy of sand-rich deposit predictions in this region. This study focuses on the Quaternary continental slope canyon-fan system in the Baiyun sag. It intends to utilize high-resolution seismic data, drilling and logging information, as well as paleontological records, employing sequence stratigraphic methods and seismic interpretation techniques to thoroughly unveil its spatiotemporal evolution patterns and the coupled control mechanisms of multiple factors. The research aims to provide a solid geological basis for subsequent precise prediction of sand-rich deposits in this area, while also offering a practical example that can be referenced for studies on similar deep-water canyon-fan systems worldwide.

2. Geological setting

2.1. Regional geological overview

The northern continental slope of the South China Sea (SCS) stretches from the southwestern tip of Taiwan in the east to the eastern entrance of the Xisha Trough in the west. It is characterized by a broader western portion and a narrower eastern portion, generally trending in a NE direction. The boundary between this slope and the deep-sea plain lies at a water depth ranging from 3400 m to 3700 m. The Baiyun sag in the Pearl River Mouth Basin serves as the depositional center within the Shenhu area, with a maximum thickness exceeding 6 km and an area of approximately 25,000 km². Most of the water depth in the Baiyun sag ranges from 500 m to 2000 m, while a series of submarine canyons have developed at water depths of approximately 600–1600 m on the northern continental slope of the Baiyun sag. These canyons exhibit distinct linear submarine negative relief features, generally trending in a NW–SE direction, with some even oriented in a N–S direction (Fig. 1).

The circulation system in the SCS is relatively complex, displaying an overall “sandwich-like” vertical structure, which can be further divided into surface water, intermediate water, and deep water. The Kuroshio, an important western boundary current in the North Pacific Ocean, has a maximum influence depth of approximately 800 m. It enters the SCS through the Luzon Strait in a clockwise direction (Xue et al., 2004) and further evolves into the northeastward-flowing South China Sea Warm Current (SCSWC). The SCSWC primarily moves along the continental shelf of the SCS and constitutes the main body of the western boundary current in the SCS (Zhu et al., 2010). Zhu et al. (2010) indicated that the canyon migration on the northern slope of the Baiyun Sag in the Pearl River Mouth Basin is mainly attributed to the SCSWC flowing

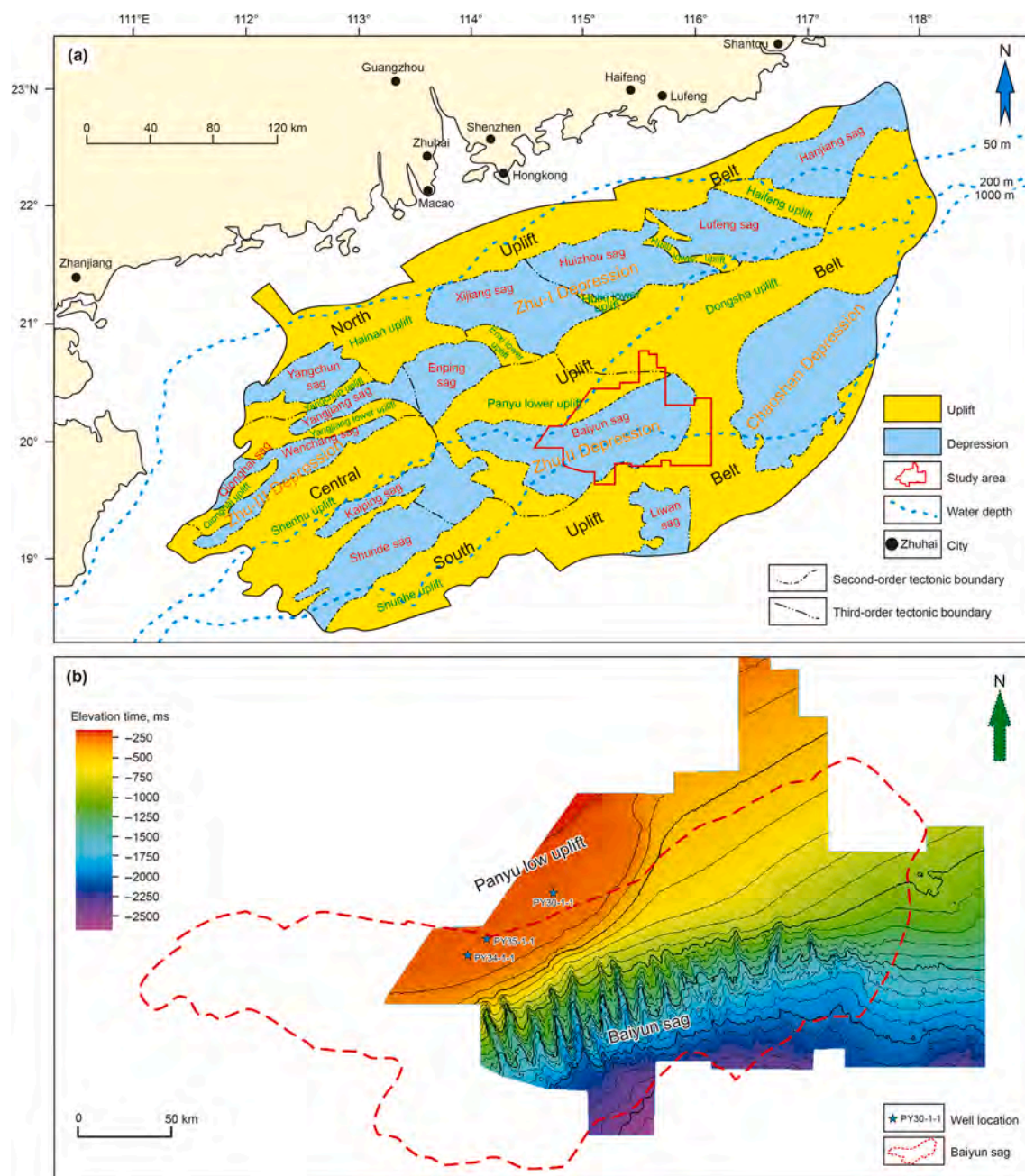


Fig. 1. (a) Tectonic units of the Pearl River Mouth Basin in the SCS (after Wu et al., 2020), (b) seabed geomorphic map of the Panyu low uplift–Baiyun sag.

northeastward along the intermediate water on the continental slope.

2.2. Tectonic evolutionary history

The Baiyun sag in the Pearl River Mouth Basin can be divided into three tectonic evolutionary stages from bottom to top: the extensional fault-depression stage from the Early Eocene to Late Oligocene, the depression stage from the Late Oligocene to Middle Miocene, and the regional subsidence stage since the Late Miocene (Liu et al., 2011). From the Late Miocene to the Quaternary, the basin experienced increased subsidence, primarily due to isostatic compensation resulting from deep mantle uplift, which led to the deposition of extremely thick strata (Zhang, 2010), including the

Yuehai Formation, Wanshan Formation, and Quaternary deposits. During the Late Miocene, NE- and NEE-trending faults were gradually replaced by NWW- and EW-trending faults, which exerted control over shallow fault block activities. Concurrently, numerous near-EW- and NW-trending strike-slip fault zones and NWW-trending extensional fault zones were newly formed, with some faults even cutting into the rift-related strata, further fragmenting the basin and resulting in its present-day complex structural configuration (Hu, 2019).

2.3. Sedimentary stratigraphic characteristics

The strata in the Pearl River Mouth Basin, from bottom to top, consist of the Paleocene Shenhu Formation, Eocene Wenchang and

Enping formations, Oligocene Zhuhai Formation, Miocene Zhujiang, Hanjiang, and Yuehai formations, Pliocene Wanshan Formation, and Quaternary deposits (Fig. 2). Among these, the Miocene and Pliocene strata represent deep-water slope deposits (Shao et al., 2013). The Pliocene Wanshan Formation predominantly features medium- to fine-grained sandstone interbedded with mudstone. Influenced by burial depth, it exhibits relatively low diagenesis and contains abundant bioclasts. The grain size gradually coarsens upward, displaying classic inverse grading characteristics. Quaternary sediments primarily consist of deep-marine shale, mudstone, siltstone, and minor sandstone (Li, 2012).

3. Data and methodology

3.1. Seismic and well data

The 3D seismic survey area in this study covers approximately 1600 km². The dominant frequency of the shallow strata is around 50 Hz, with a seismic data processing bin size of 12.5 m × 25 m and a vertical sampling interval of 4 ms. The seismic data exhibit strong reflection energy, clear imaging, and relatively high resolution. Given the propagation velocity of shallow seismic waves at approximately 1600 m/s, the vertical resolution of the seismic data is estimated to be around 8 m, which meets the requirements of this study.

Additionally, in the Panyu low uplift area, only wells PY35-1-1, PY34-1-1, and PY30-1-1 have penetrated the Quaternary strata. Each of these wells contains paleontological data suitable for dating, providing crucial chronostratigraphic calibration for identifying sequence boundaries.

3.2. Methodology

To clarify the spatiotemporal evolutionary processes and controlling mechanisms of the continental slope canyon–fan system, this study employs the following research methods.

(1) Based on sequence stratigraphic theory (Vail et al., 1977; Wang et al., 2025a), key sequence boundaries within the study

area were systematically identified through a comprehensive analysis of seismic, drilling and logging data. Sequence boundaries encompass unconformities, maximum flooding surfaces, etc., with their primary identification markers including seismic reflection termination relationships (Catuneanu, 2002; Olabode and Adekoya, 2008), abrupt changes in logging curves or lithology (Di Celma et al., 2010), and differences in seismic facies characteristics (Wang et al., 2025a). These sequence boundaries exhibit regional comparability and isochronicity, and thus the precise identification of key sequence boundaries enables the establishment of an isochronous stratigraphic framework for the study area.

Based on the identification results of sequence boundaries, combined with drilling and logging data, paleontological data, and previous research findings, precise chronostratigraphic calibration of sequence boundaries was conducted. By utilizing drilling data from wells that penetrated the Quaternary in the study area and planktonic foraminiferal data, the relative ages of some key sequence boundaries can be determined. However, due to the limited number of wells in the study area, the positions of all sequence boundaries could not be determined. Therefore, previous research data were cited to calibrate the ages of the remaining sequence boundaries (Feng et al., 1996; Liu et al., 2019a). The construction of a high-resolution chronostratigraphic framework can constrain the evolutionary chronology of canyon–fan systems, establish correlations between sedimentary sequences and macro-events such as global sea-level changes and regional tectonic activities, and provide geological evidence for exploring the controlling factors of deep-water sedimentary evolution.

(2) Seismic attributes and seismic profile analyses are utilized to identify and delineate the sedimentary characteristics and internal filling architectures of the canyon–fan system (Wang et al., 2025b). Variance attributes are employed to define canyon boundaries and the positions of shelf margins, while RMS amplitude attributes are used to characterize the distribution range of fan bodies and the filling architectures of canyons. Building on this, seismic profile interpretation and stratigraphic slicing techniques are combined to systematically analyze the sedimentary

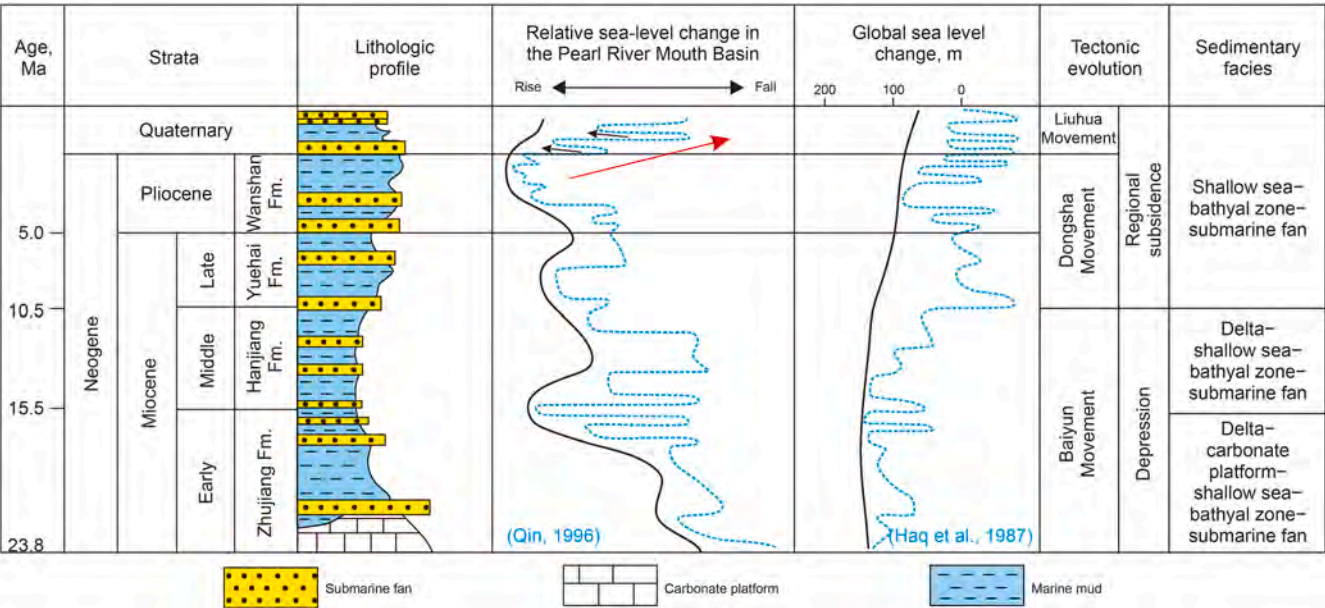


Fig. 2. Comprehensive tectono-stratigraphic column of the Pearl River Mouth Basin (after Haq et al., 1987; Qin, 1996; Shi et al., 2014).

evolutionary processes of the canyon–fan system during different sequence stages, enabling a transition from static characterization to dynamic evolutionary research.

4. Results

4.1. Construction of isochronous stratigraphic framework for the shelf margin–continental slope

4.1.1. Identification of key sequence boundaries

Seismic reflection termination relationships include onlap, downlap, toplap, and truncation, which serve as key diagnostic features for identifying seismic reflection boundaries as isochronous depositional boundaries. Toplap and truncation generally indicate the top boundaries of sequences, whereas onlap and downlap typically mark the base boundaries of sequences (Abbas et al., 2018; Fonseca et al., 2020; Wang et al., 2025a). However, when sea-level fluctuations exert minimal influence on deep-water deposition, seismic reflection termination relationships may exhibit weak or indistinct characteristics. In such cases, sequence boundaries can be identified using variations in seismic facies and abrupt changes in logging curves. Based on these criteria, one second-order (T_0) and five third-order sequence boundaries (SB1, SB2, SB3, SB4, and SB5) were identified within the target interval (Fig. 3).

The T_0 boundary represents a regional unconformity surface. On seismic profiles, it displays reflection characteristics of strong amplitude and high continuity. The event horizon of this interface is straight from the shelf to the shelf margin area. In the slope region, due to erosion by submarine canyons, the undulation of the event horizon increases but remains continuously traceable. In the stratigraphic uplift area, it exhibits angular unconformity (Fig. 3(d) and (e)). Drilling and logging data indicate that the T_0 boundary marks an abrupt lithological change from sandstone to mudstone, with the GR curve showing a funnel shape (Fig. 3(g)). Large-scale transgressive deposits are developed above this boundary.

The SB1 boundary shares similar characteristics with T_0 , featuring straight event horizons and strong-amplitude reflections. However, when transitioning towards the slope, it nearly coincides with SB2. Both the SB2 and SB3 boundaries allow for the identification of the shelf break, displaying reflection characteristics of strong amplitude and high continuity. They show erosional features from the shelf to the shelf margin area and onlap features in the slope region (Fig. 3(a) and (b)). The SB4 boundary is clearly distinguishable in the shelf, showing medium-amplitude and high-continuity reflection characteristics (Fig. 3(f)), but gradually coincides with SB5 after crossing the shelf break. The SB5 boundary represents the present seafloor boundary, displaying strong-amplitude and high-continuity reflection

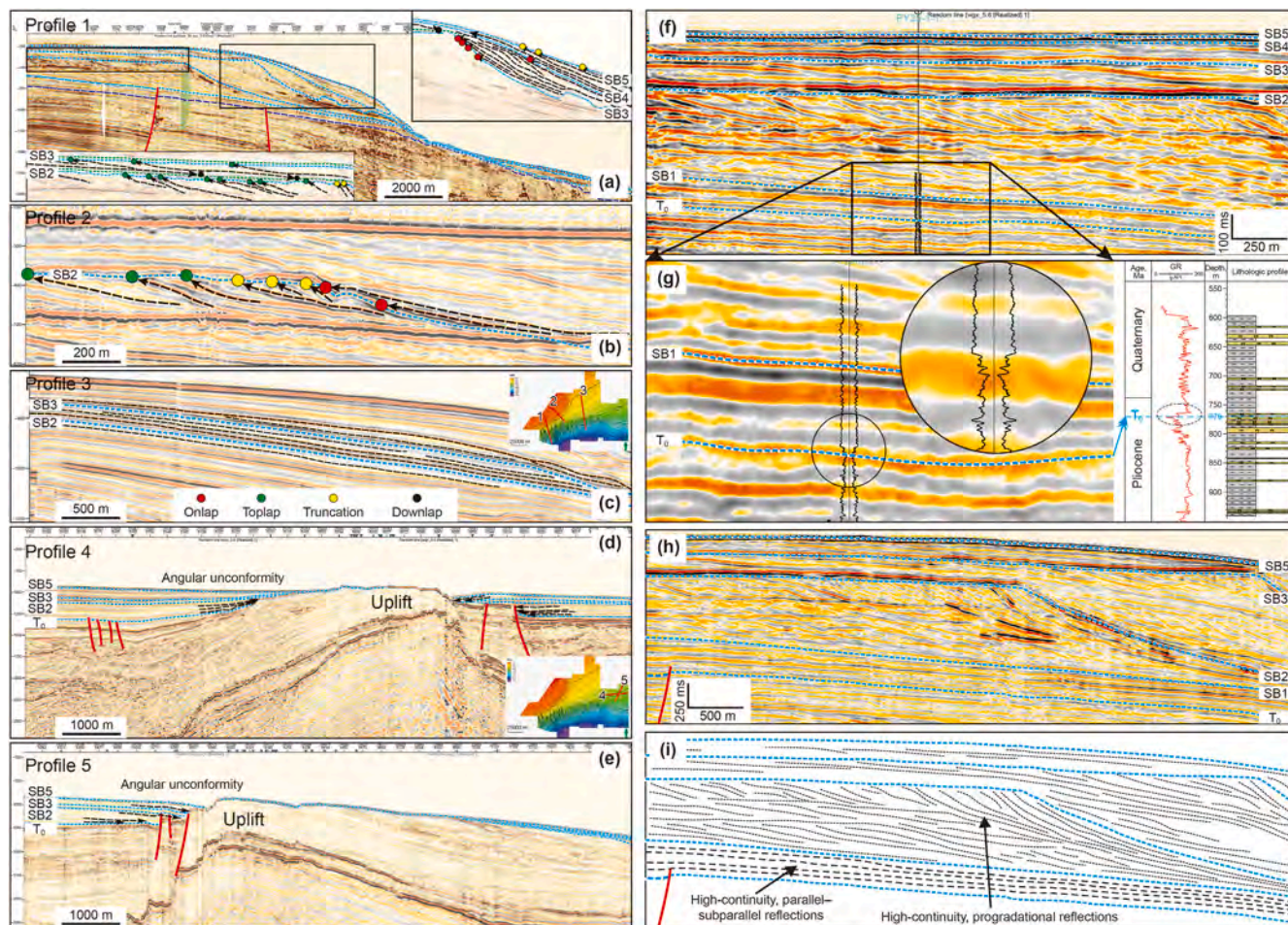


Fig. 3. Schematic diagram of typical identification markers for sequence boundaries. (a–e) Seismic reflection termination relationships, clearly revealing phenomena such as onlap, toplap, truncation, and downlap; (f–g) abrupt changes in logging curves and lithology, with the GR curve showing a funnel shape at the T_0 boundary and the lithology abruptly changing from sandstone to mudstone; (h–i) differences in seismic facies, with the bottom of the target interval exhibiting high-continuity, parallel–subparallel reflection seismic facies, while the upper strata transition to high-continuity, progradational facies.

characteristics due to the significant impedance contrast between the overlying water layer and the underlying strata (Fig. 3).

4.1.2. Sequence units and establishment of high-resolution sequence stratigraphic framework

Based on the aforementioned identification of sequence boundaries, the target interval can be divided into five third-order sequence units (Sq1–Sq5). Consequently, a high-resolution Quaternary sequence stratigraphic framework for the study area has been established (Fig. 4(a) and (b)).

Sq1 is primarily characterized by gently stable, thin-layered deposits that slope slightly seaward. It displays features of medium-amplitude, high-continuity, and parallel reflections. However, it is difficult to identify the reflection termination relationships. Sq2–Sq4 consist of thick deposits with high-angle progradational reflections, showing characteristics of strong-amplitude, medium-continuity, and progradational. Sq5 only shows a certain thickness of deposits below the shelf break, indicating that the sea level was below it. There is limited sediment

thickness from the shelf to the marginal area, and identification is difficult due to resolution constraints (Fig. 4).

Seismic profiles in the study area reveal that the thickness of the Quaternary strata gradually decreases from the SW to the NE (Fig. 4(c)–(f)). The sedimentary thickness of Sq1 varies across different regions but remains generally gentle overall. Sq2 and Sq3 exhibit significant variations, with the shelf margins of these two sequences being close in the SW area but significantly farther apart in the NE area (Fig. 4(e) and (f)). This reflects that the SW area served as the Quaternary depositional center, with sedimentary material decreasing towards the NE area. Additionally, there are substantial regional differences in the positions of the shelf margins across different sequences, indicating that sea-level changes influence the scale of sediment reception in the shelf area (Fig. 4).

4.1.3. Age calibration of key sequence boundaries

In this study, the geological ages of each key sequence boundary were determined (Fig. 5). This determination was achieved by integrating the 24 calcareous nannofossil zones proposed by Martini (1971) and the 23 Late Cenozoic planktonic foraminiferal

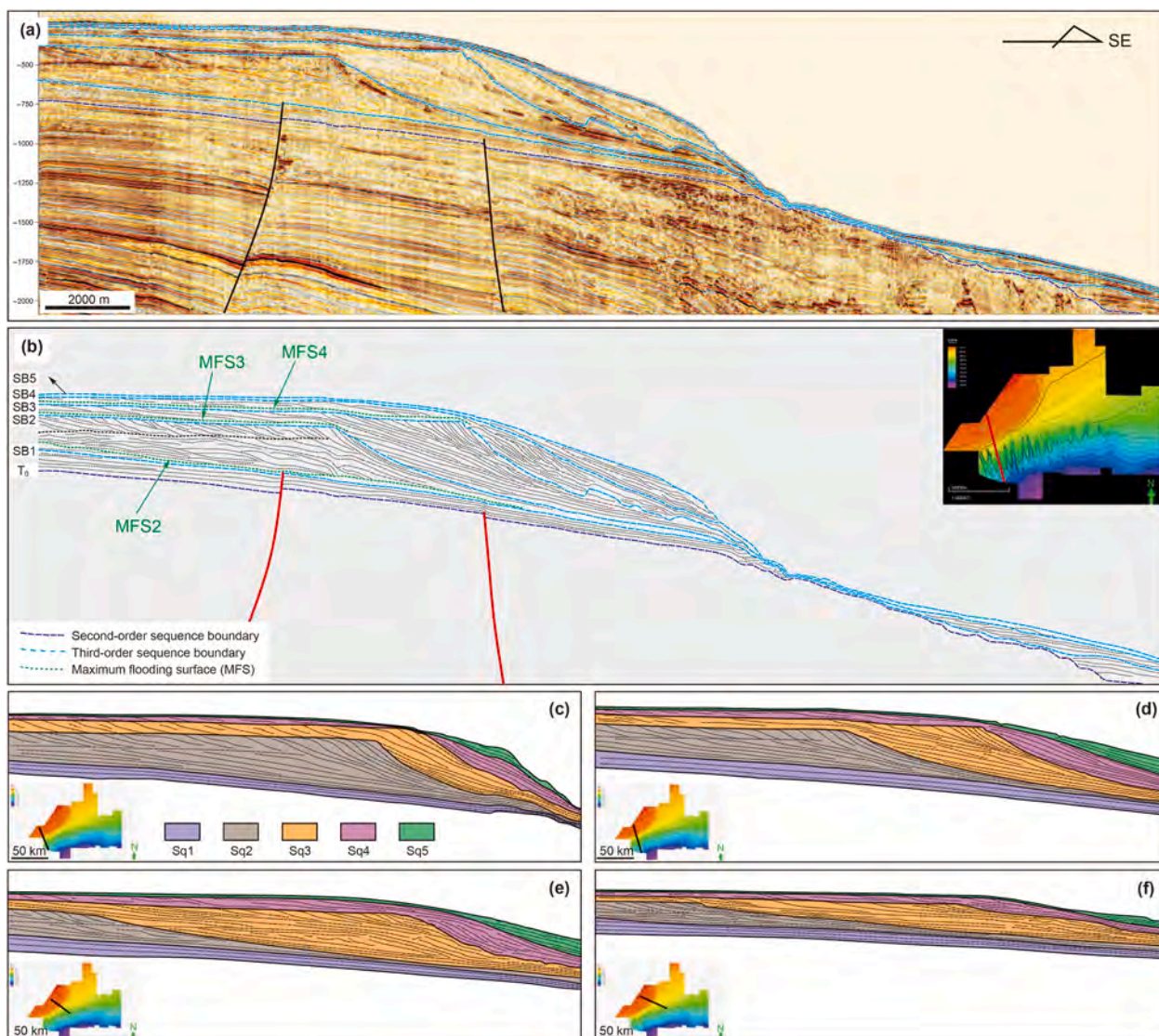


Fig. 4. Construction of a high-resolution Quaternary sequence stratigraphic framework for the shelf margin–continental slope in the Baiyun sag. (a) Original seismic profile, (b) corresponding interpreted profile, (c–f) schematic diagrams of sequence unit structures in different regions of the study area.

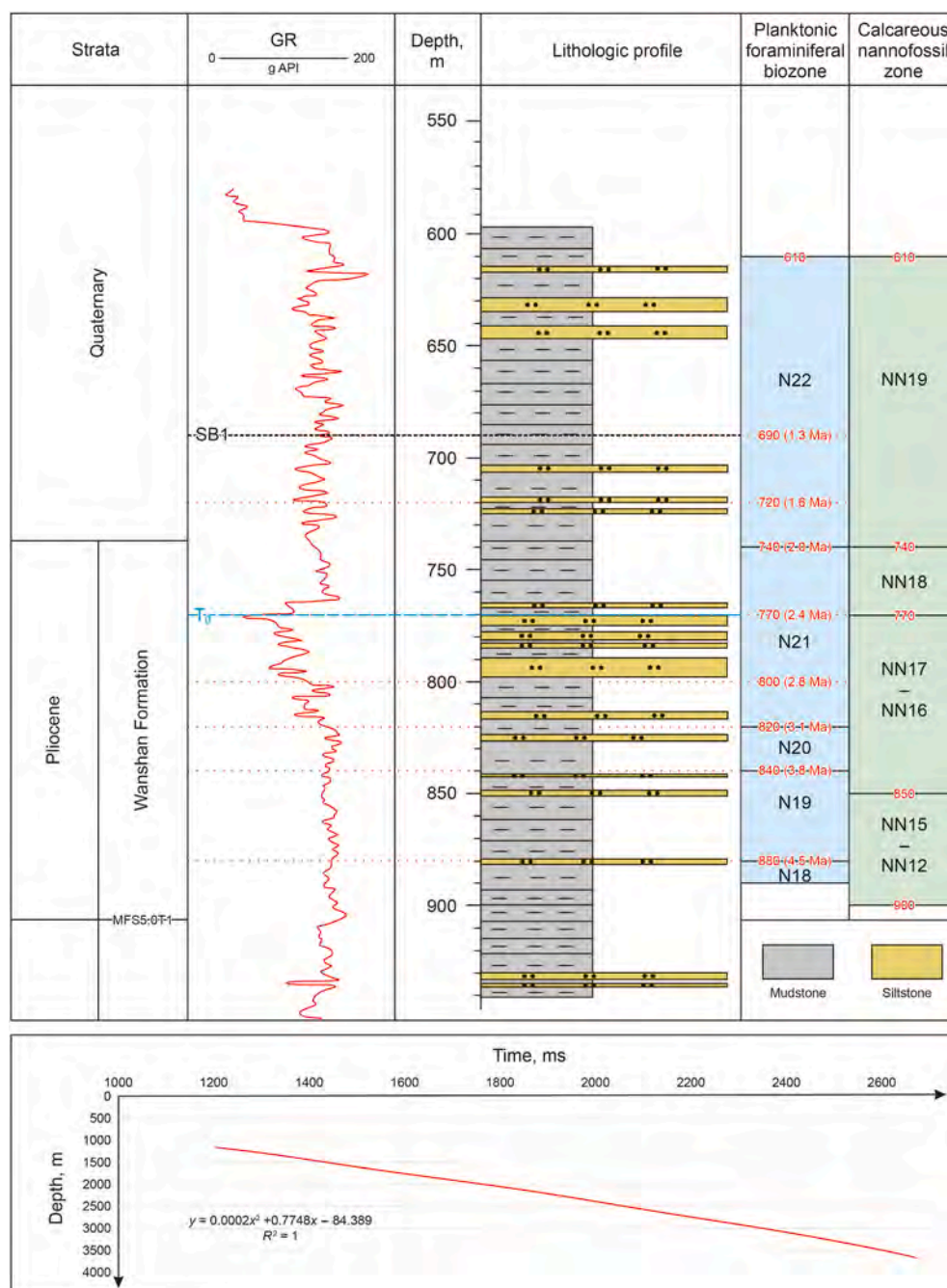


Fig. 5. (a) Comprehensive stratigraphic column chart for sequence stratigraphic analysis of Well PY35-1-1, (b) time-depth relationship curve.

zones divided by Blow (1979). Additionally, the analysis was supplemented with the Last Appearance Datums (LADs) of paleontology identified in the drilling wells of the Pearl River Mouth Basin (Qin, 1996) as well as previous shallow drilling data (Feng et al., 1996).

The logging curves and lithological changes in Well PY35-1-1 indicate that the T_0 boundary is located at a depth of 770 m, which does not coincide with the Quaternary/Pliocene boundary (740 m) (Lin et al., 2018a). The T_0 boundary corresponds to the LAD of *Globigerinoides extremus*, with an age of approximately 2.4 Ma (Fig. 5). Other key planktonic foraminiferal bioevents in this well include: (1) The LAD of *Neogloboquadrina humerosa* is observed at 690 m, with an age of about 1.3 Ma, which is identified as the SB1

boundary through well-seismic correlation; (2) The transition surface where *Pulleniatina obliquiloculata* changes from dextral to sinistral coiling is located at 720 m, corresponding to an age of approximately 1.6 Ma; (3) The transition from sinistral to dextral coiling in *Globorotalia menardii* is observed at 730–740 m depth, corresponding to an age of about 1.8–2.0 Ma. This boundary represents the division between the N22 and N21 zones of planktonic foraminifera in the northern SCS and also serves as the Quaternary/Pliocene boundary (Fig. 5).

Given the limited number of wells drilled into the Quaternary in the study area, the ages of the remaining sequence boundaries need to be calibrated using previous data. This data includes that from Well W1 on the continental shelf and shallow borehole ZQ3

(Feng et al., 1996; Liu et al., 2019a). Paleontological analysis of Well W1 shows that SB1 is located near the LAD of *Neogloboquadrina humerosa*, with an age of approximately 1.3 Ma, consistent with the result from Well PY35-1-1. Shallow drilling data from ZQ3 indicate that SB2 is located near the Brunhes-Matuyama polarity reversal boundary, with an age of about 0.79 Ma (Kong et al., 2012). The ages of SB3 and SB4 are approximately 0.44 Ma and 0.14 Ma, respectively. The seafloor boundary SB5 formed during the lowest sea level of the Last Glacial Maximum, with an age of about 0.029 Ma (Liu et al., 2019a; Miller et al., 2020). Based on the age calibration of the above-mentioned key sequence boundaries, an isochronous stratigraphic framework for the Quaternary in the study area was ultimately constructed.

4.2. Types and sedimentary characteristics of sedimentary geomorphic units on the continental slope

4.2.1. Identification of geomorphic units based on seismic facies analysis

Based on typical seismic profiles from the Panyu low uplift–Baiyun sag area (Fig. 6), a total of eleven types of seismic facies were identified: (a) S-shaped progradational facies with medium- to strong amplitude and moderate continuity; (b) Seismic facies with weak amplitude, low continuity, and blank or no reflections; (c) Lenticular facies with weak amplitude and low continuity; (d) Oblique progradational facies with medium- to strong amplitude and moderate continuity; (e) Onlap filling facies with medium- to strong amplitude and high continuity; (f) Discontinuous and chaotic filling facies with medium to weak amplitude; (g) Sheet-like facies with strong amplitude and high continuity; (h) Seismic facies with chaotic reflections of medium-

to strong amplitude and low continuity; (i) Mound-shaped facies with strong amplitude and high continuity; (j) Seismic facies with subparallel reflections of medium- to strong amplitude and high continuity; (k) Seismic facies with subparallel reflections of medium- to strong amplitude and high continuity.

Different seismic facies and their combinatorial relationships are concrete manifestations of the seismic responses of various sedimentary bodies. By integrating the regional sedimentary context and previous research findings, various sedimentary body types corresponding to different seismic facies have been identified, including shelf (margin) deltas, canyons, gullies, slumps, slope fans, continental slope deposits, lowstand wedges, and contourite deposits (Table 1). The shelf delta front appears as wedge-shaped or lenticular formations with S-shaped or oblique progradational reflections. Multiple stages of progradational superposition form shelf-margin delta complexes, serving as significant sediment source systems. In the continental slope area, mound-shaped, filled, and chaotic reflection seismic facies are related to the scale of terrigenous clastic supply. Under conditions of strong sediment supply, the upper part of the continental slope develops sediment transport systems dominated by slumps, canyons, and gullies, while the lower slope develops sediment accumulation systems represented by slope fans and lowstand wedges.

Although various sedimentary geomorphic units have developed in the continental slope area, considering the research objectives of this paper, continental slope canyons and slope fans are prioritized as the key analysis targets. Sedimentary bodies such as slumps merely serve as auxiliary elements in this study, exerting local impacts on canyons and fans to a certain extent, while more in-depth analyses will be conducted in subsequent research.

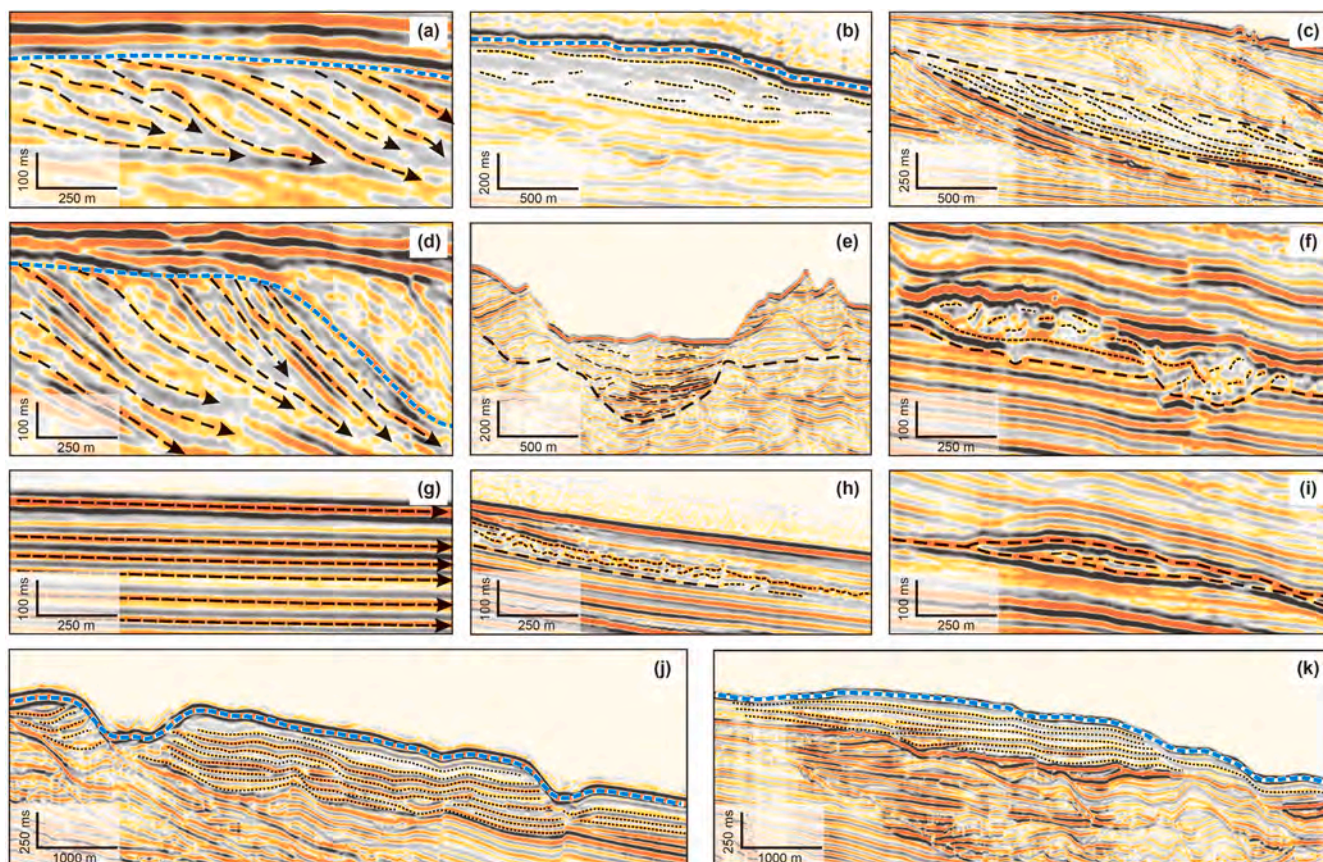


Fig. 6. Typical seismic profile for the identification of seismic facies types in the shelf to continental slope area of the Baiyun sag.

Table 1

Summary of typical seismic facies parameter characteristics and corresponding sedimentary bodies in the Panyu low uplift–Baiyun sag.

Number	Reflection morphology	Reflection configuration	Amplitude	Continuity	Corresponding sedimentary units
a	Lenticular	S-shaped progradational	Medium-strong	Medium	Mid-shelf delta
b	/	Blank	Weak	Low	Prodelta
c	Lenticular	Progradational	Weak	Low	Lowstand wedge
d	Wedge-shaped	Oblique progradational	Medium-strong	Medium	Shelf-margin delta
e	Onlap fill	Parallel–subparallel	Medium-strong	High	Submarine canyon
f	Chaotic fill	Chaotic	Medium-weak	Discontinuous	Submarine gully
g	Sheet-like	Parallel	Strong	High	Slope deposits
h	/	Chaotic	Medium-strong	Low	Slump
i	Mound-shaped	Parallel–subparallel	Strong	High	Slope fan
j	Sheet-like	Subparallel	Medium-strong	High	Contourite deposits
k	Lenticular	Subparallel	Medium-weak	High	Contourite deposits

4.2.2. Continental slope canyon group

Taking advantage of the clear identification of submarine sedimentary body boundaries through variance attributes, 16 canyons have been identified in the continental slope area of the Baiyun sag. These canyons are named sequentially from west to east as C1–C16 (Fig. 7). On the plan view, they exhibit a linear and subparallel, evenly distributed pattern. Based on their morphology, orientation, and internal structural characteristics, the area can be divided into the eastern and western areas of the canyon group (Fig. 7(a)).

The plan views of variance attributes reveal that the shelf margin and the heads of canyons have migrated over time (Fig. 7(e) and (f)). The T_0 boundary does not show the identification of the shelf margin (beyond the data range). From SB2 to SB3, the shelf margin advanced seaward. By SB5, the shelf margin in the SW region retreated landward, while it continued to advance seaward in the NE region (Fig. 7(e)). Statistical analysis of canyon positions at each boundary indicates that their heads generally migrated landward towards the shelf, reflecting continuous headward erosion of the canyons (Fig. 7(f)).

Profiles along the strike of the continental slope (from west to east) demonstrate that the incision depth of the canyons gradually decreases from SW to NE. The deepest incision occurs at the canyon heads, indicating strong gravity-flow incision erosion in the SW region of the study area (Fig. 8). Compared to profile 1, profiles 2 and 3 show a significant reduction in the incision depth in the middle sections of the canyons (Fig. 8(b) and (c)). Profiles perpendicular to the strike of the continental slope (from north to south) reveal that the canyon morphology transitions from a strongly erosive V-shape upstream to a predominantly aggradational U-shape downstream. The incision depth decreases along the downstream direction and reaches a minimum at the canyon termination (Fig. 8(d)).

Given that the development area of the continental slope canyon group is divided into eastern and western areas, a canyon is selected from each area as a typical object for detailed characterization of its internal filling architecture (Figs. 9 and 10). Among them, C2 extends a relatively long distance within the scope of the research data, has a well-preserved structure, and is closest to the shelf margin. Therefore, C2 is chosen as the representative canyon of the western zone of the canyon group (Fig. 9). C15 has a relatively unique strike within the eastern zone of the canyon group and also maintains an intact structure. Hence, C15 is selected as the representative canyon of the eastern zone of the canyon group (Fig. 10).

Canyon C2 exhibits significant incision depth. From upstream to downstream, the erosive force of gravity flows on the underlying strata gradually weakens, and aggradation becomes more pronounced, resulting in an increased thickness of the

downstream strata (Fig. 9(f)). The canyon head has the deepest incision but a narrow width, preserving stable original continental slope strata on both sides. However, the steep slope of the canyon walls, caused by the substantial incision depth, makes the strata on the walls prone to slumping and deposition under gravitational forces (Fig. 9(d)). In the downstream area, the canyon widens, with the strata on both sides showing intermittent characteristics and the development of multi-level terraces. This is attributed to the energy dissipation of the fluid after long-distance transportation, resulting in weakened vertical incision erosion but enhanced lateral erosion (Fig. 9(e) and (f)). Additionally, the canyon head shows a notable unidirectional migration feature, with the thalweg showing the greatest variation, which gradually decreases downstream, ultimately resulting in approximately vertical stratigraphic superposition (Fig. 9).

The head of canyon C15 exhibits strong incision erosion, presenting a narrow and deep V-shape geometry (Fig. 10(d)). The middle section of the canyon widens laterally, with multiple fluid erosion troughs developed on both sides and a relatively thin internal sediment thickness, indicating strong destruction of early sediments by gravity flows and predominantly sediment bypassing (Fig. 10(e)). At the canyon terminus, the erosive effect of the fluid is weak, with only slight negative topographic features observed (Fig. 10(f)). Although profile 4 extends beyond the range of C15, there are still slight negative topographic features along the flow direction in the strata, which generally exhibit strong amplitude, high continuity, and parallel–subparallel reflection characteristics. This reflects that after the sedimentary environment transitions from a strongly confined to an unconfined state, the reduction in flow velocity of the gravity flows leads to sediment settling (Fig. 10(g)).

4.2.3. Slope fan

Since the Quaternary, the thickness between sequence boundaries within the canyons has been relatively thin, with only partial sediment deposition occurring along the canyon axes. This indicates that later fluids have exerted strong scouring effects on the early-deposited sediments, causing them to be resuspended and transported to the deep sea. As a result, a substantial material basis has been provided for the development of slope fans (Figs. 11 and 12).

The distribution of slope fans in sequence unit Sq1 shows significant regional differences. In the western area of the canyon group, at the canyon termini, fan deposits of a certain scale are observable, displaying finger-like or tongue-shaped morphologies. In contrast, in the eastern area of the canyon group, only sporadic fan deposits with indistinct morphologies are developed (Fig. 11(d)). In sequence units Sq5, Sq3, and Sq2, large-scale fan deposits are commonly developed at the termini of canyons. On

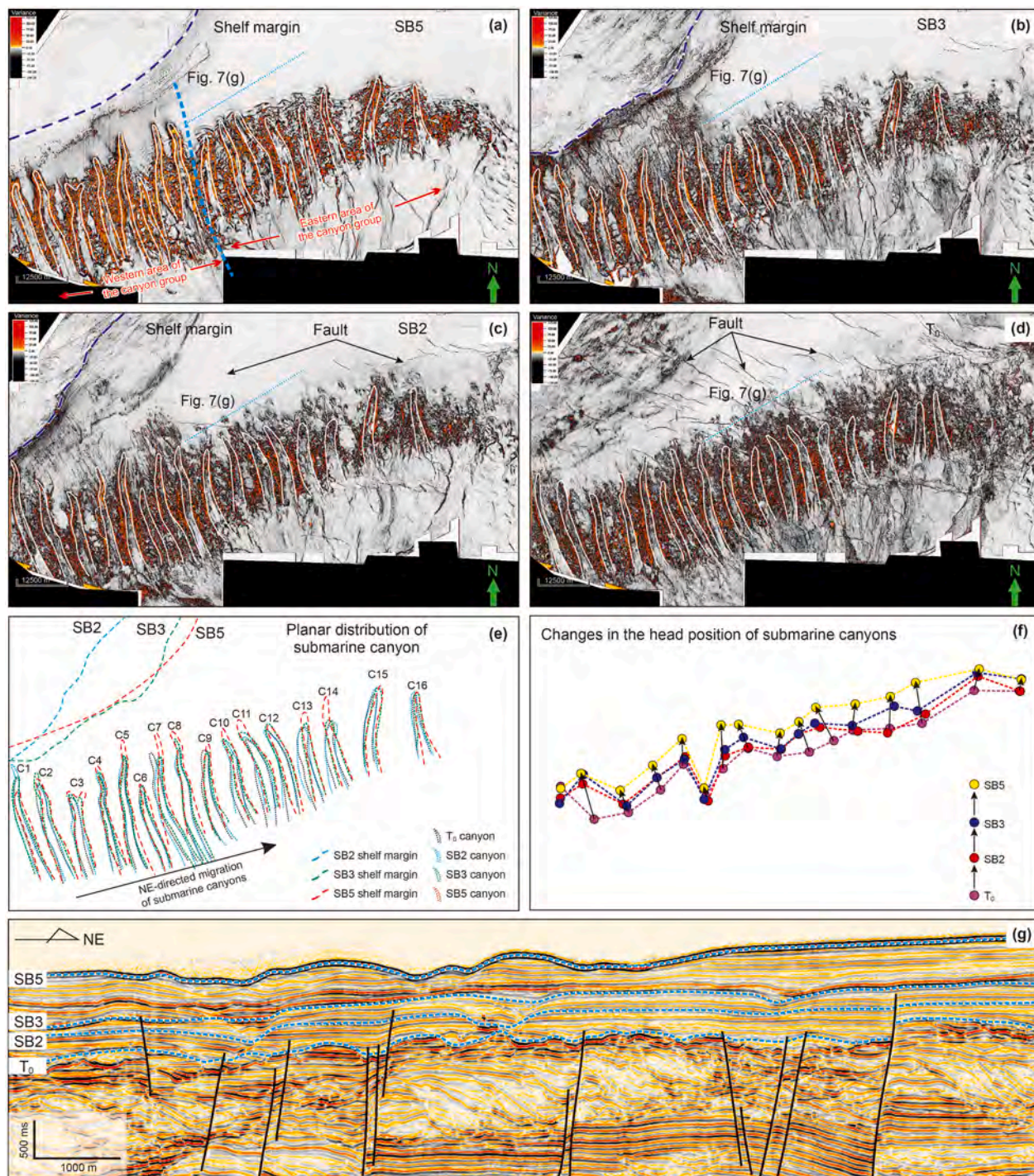


Fig. 7. Schematic diagram showing the planar distribution and head position changes of continental slope canyons in the Baiyun sag during different sequence periods (the location of the study area is shown in Fig. 1). (a–d) Plan views of variance attributes, where submarine canyons exhibit high variance values, facilitating the delineation of their planar morphology; (e) overlay map of canyon positions and distribution map of shelf margin positions during different sequence periods; (f) map illustrating the changes in head positions of canyons during different sequence periods; (g) the seismic profile illustrating the development of faults at different boundaries.

the plan view, they present finger-like or fan-shaped morphologies with extensive depositional ranges (Fig. 11(a)–(c)).

Analysis of typical seismic profiles indicates that upon entering the slope fan development zone, there is a significant increase in sediment thickness for each sequence unit (Fig. 12). This forms a stark contrast with the intense erosional characteristics of submarine canyons. The fan deposits at canyon termini exhibit two types of reflection characteristics on seismic profiles. Type I,

developed at the base of the Quaternary, displays weak amplitude and chaotic reflection features (Fig. 12(d) and (e)). Type II, developed in the middle to upper parts of the Quaternary, shows medium- to strong amplitude, high continuity, and parallel-subparallel reflection characteristics (Fig. 12(a) and (b)). On the plan view, the western area of the canyon group primarily features slope fans with superimposed Type I and Type II, while the eastern area is dominated by Type II slope fans.

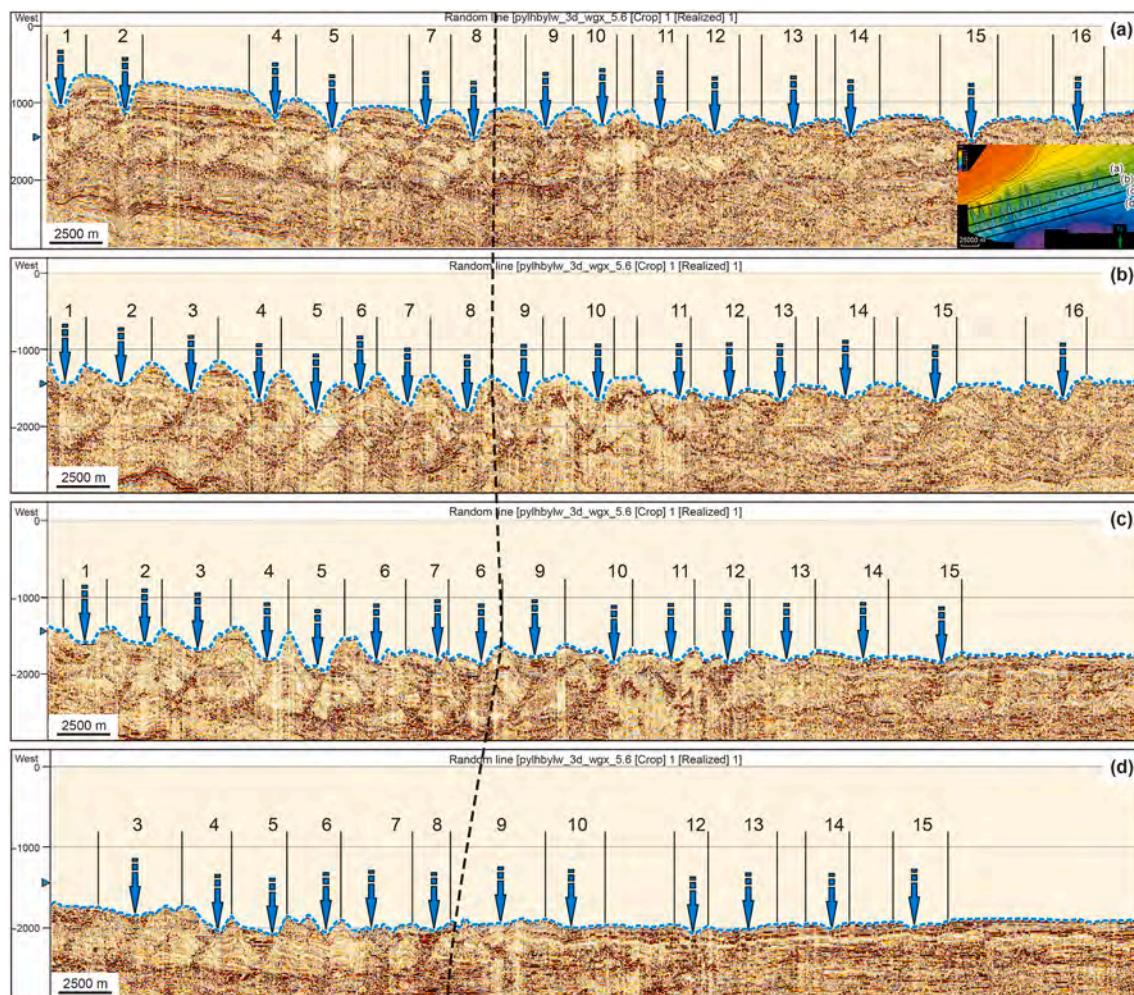


Fig. 8. Profile morphological characteristics at different spatial locations within the continental slope canyon group (the black dashed line serves as the demarcation between the eastern and western areas of the canyon group).

5. Discussion

5.1. Spatiotemporal evolution patterns of continental slope canyon-fan systems

Based on the aforementioned research findings, this study has established a spatiotemporal evolution pattern for canyon-fan systems in the Quaternary continental slope area (Fig. 13). The evolution process of the canyon-fan systems corresponds to different sequence units and can be divided into four stages.

(1) **Stage 1 (corresponding to Sq1, Fig. 13(a)):** A series of submarine canyons with approximately parallel alignments and wide U-shaped cross-sections developed in the continental slope area. This reflects weak incision erosion by the fluid within the canyons (Figs. 9 and 10). During this stage, the shelf margin was distant from the canyons (Fig. 7(d)), indicating that the study area was in a transgressive phase with rising sea levels and limited supply of terrigenous clastic sediments. Popescu et al. (2004) noted that deep-water sedimentation was inactive during transgressions. However, the RMS amplitude attribute map in this study reveals that slope fans of a certain scale still developed in the continental slope area, primarily in the western area (Fig. 11(d)). These slope fans display weak amplitude and chaotic reflections in seismic profiles (Fig. 12(d) and (e)). This may be related to slope strata collapse induced by tectonic activity during the Sq1 period

(Xu et al., 2016). Numerous faults are present at the T_0 boundary (Fig. 7(d)), reducing the stability of the slope strata and leading to collapse. The collapsed material was transported over short distances through the canyons and accumulated at the canyon termini, forming poorly sorted slope fans with chaotic reflections (Fig. 11(d)).

(2) **Stage 2 (corresponding to Sq2, Fig. 13(b)):** The canyon morphology gradually transitions from a wide U-shape to a V-shape (Figs. 9 and 10). Previous studies have investigated the geometric morphology of canyons or channels (Deptuck et al., 2007; Hansen et al., 2017). Hansen et al. (2017) suggested that the morphology of submarine channels offshore Nigeria exhibits either high sinuosity or straight morphology, or significant variations in channel width and depth at different locations, which may be influenced by factors such as sediment supply, substrate properties, and slope topographic gradient. In this study, the morphological transition of the canyon from a U-shape to a V-shape reflects an increase in fluid energy and intensified erosion. The presence of thick prograding structures in seismic profiles suggests that sea level was falling (Fig. 4(a)), with the shelf margin advancing seaward and approaching the canyons (Fig. 7(c)). This transports substantial terrigenous clastic material to the deep-water area (Ding et al., 2013a). Variance attribute maps reveal retrogressive erosion occurring in the canyons, with their heads extending towards the shelf margin (Fig. 7(e) and (f)). Submarine

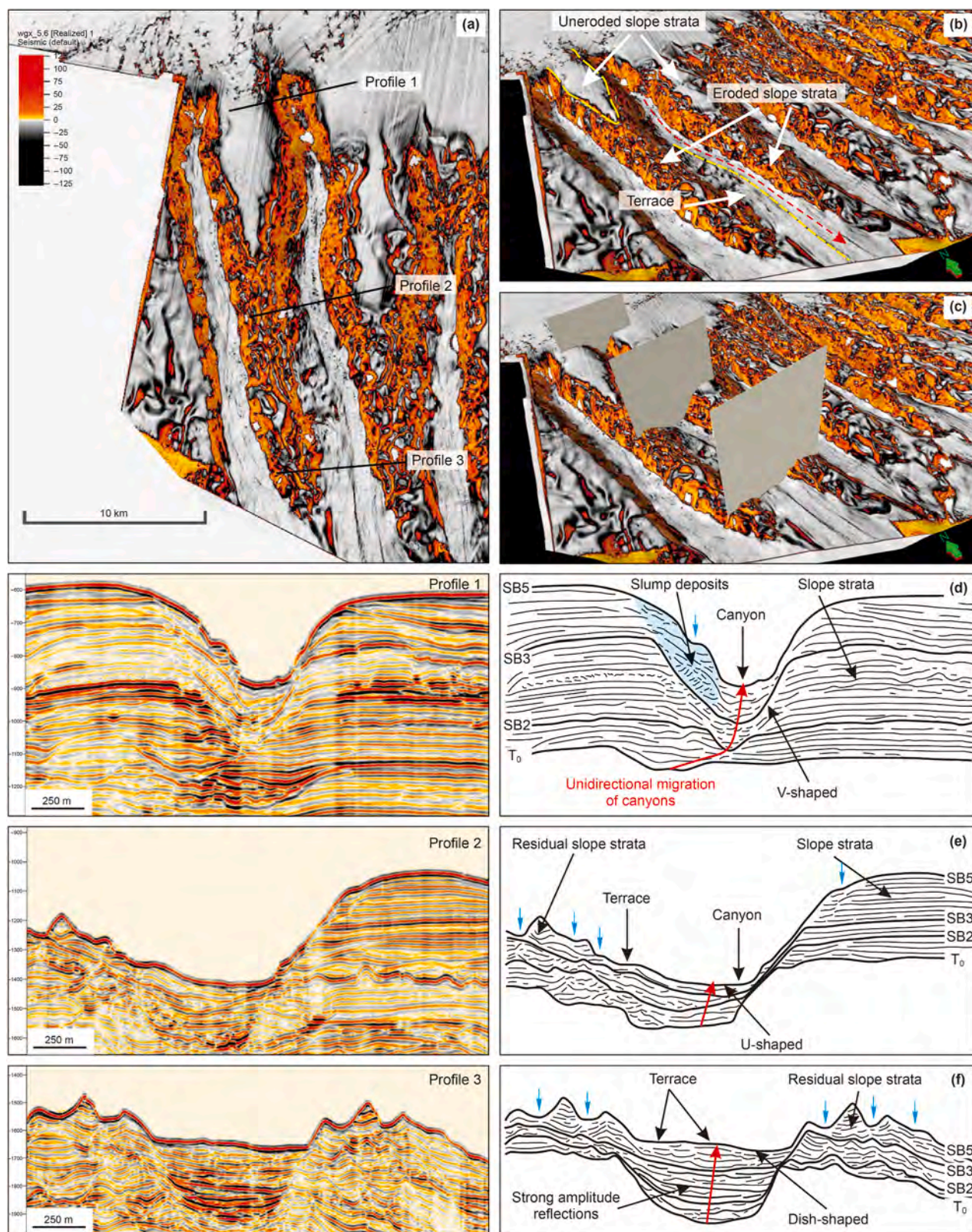


Fig. 9. Analysis of the internal filling architecture of canyon C2. (a–c) Plan view and 3D perspective view of variance attributes; (d–f) seismic profiles and corresponding interpreted diagrams of the upstream, midstream, and downstream sections of canyon.

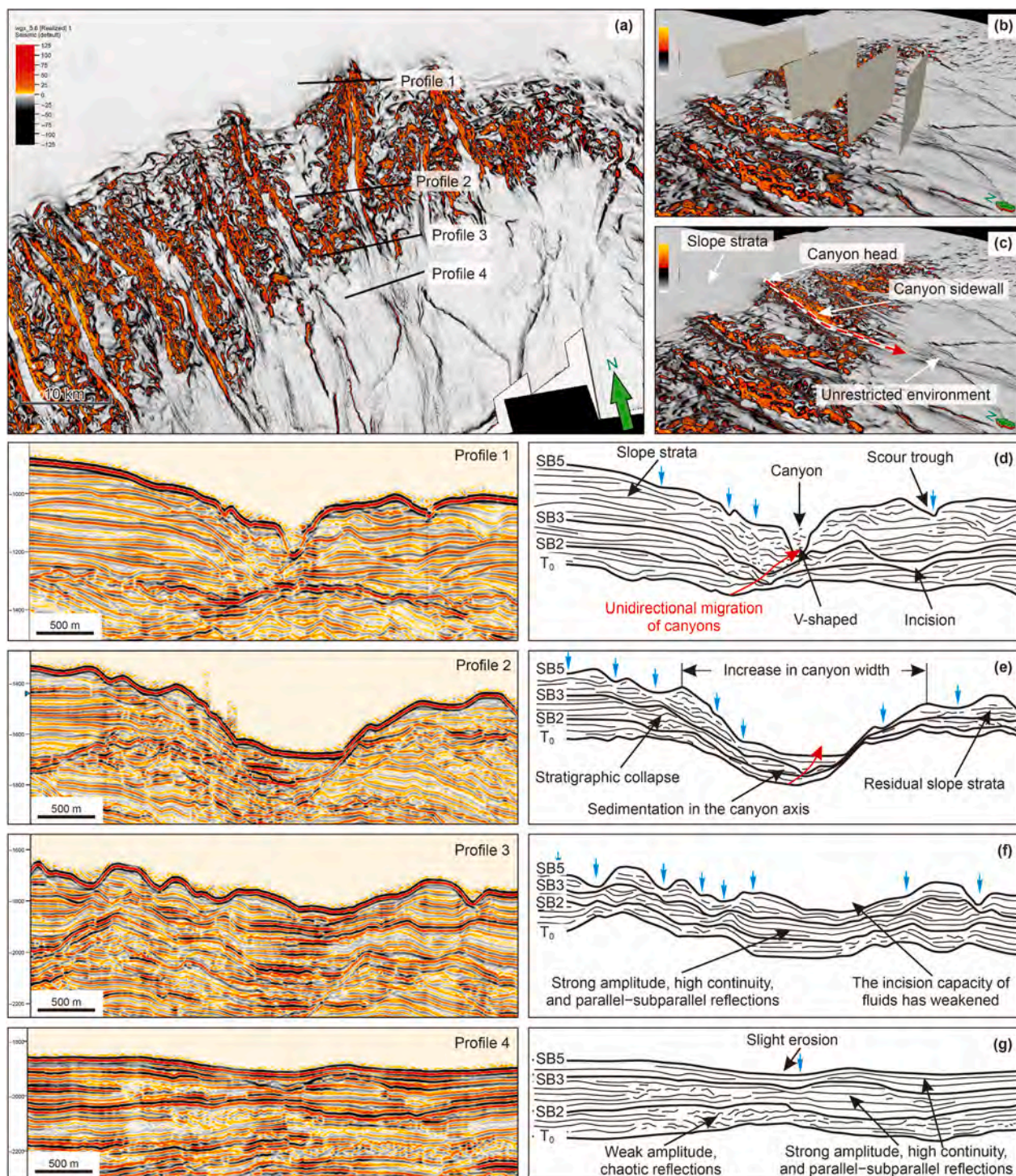


Fig. 10. Analysis of the internal filling architecture of canyon C15. (a–c) Plan view and 3D perspective view of variance attributes; (d–f) seismic profiles and corresponding interpreted diagrams of the upstream, midstream, and downstream sections of the canyon.

gullies develop between the canyon heads and the shelf margin (Fig. 11(c)), serving as channels for transporting terrigenous sediments. RMS amplitude attributes indicate an increase in the scale of fan deposits at the canyon termini in both the eastern and western areas, displaying chaotic and parallel reflection superposition features in seismic profiles (Fig. 12(e)). Stratal slumping on the continental slope induced by tectonic activity is the primary cause of the chaotic reflection deposits at the base, while

subsequent terrigenous clastic sediments from the shelf margin, transported through the canyons, form stable deposits overlying the chaotic reflection fans.

(3) **Stage 3 (corresponding to Sq3, Fig. 13(c)):** This stage exhibits characteristics similar to those of Stage 2. The canyon cross-sections are deep V-shaped (Figs. 9 and 10), indicating a further increase in fluid erosion capacity. Prograding structures in seismic profiles indicate a continued decline in sea level, with

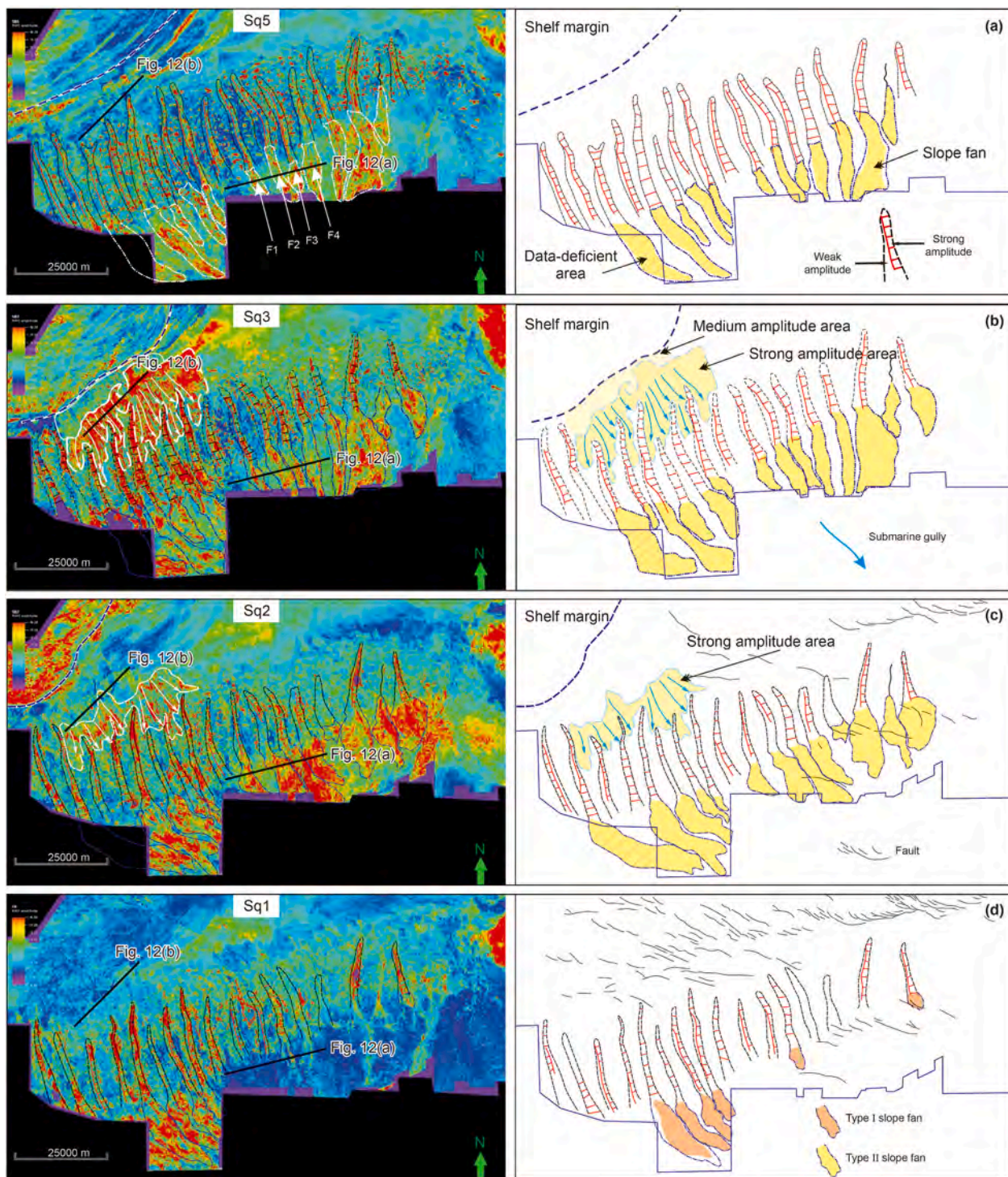


Fig. 11. Schematic diagram showing the planar distribution of slope fans during different sequence periods. The left side presents a plan view of RMS amplitude attribute, while the right side displays the corresponding interpreted diagram. RMS amplitude attributes can be used to identify sedimentary bodies of different properties in deep-water environments (such as distinguishing sandstone from mudstone). High RMS amplitude values represent more sandy deposits, whereas low values typically indicate more muddy deposits.

the shelf margin continuing to advance seaward (Fig. 7(b)). Retrogressive erosion at the canyon heads intensifies, and the development scale of submarine gullies expands (Fig. 11(b)), enhancing sediment transport capacity. RMS amplitude attributes reveal an expansion in the scale of slope fans, which exhibit strong amplitude, high continuity, and parallel reflection features

in seismic profiles (Fig. 12(a) and (b)). These features resemble the seismic characteristics of sandy deposits modified by bottom currents (Wang et al., 2024) and contrast sharply with the earlier chaotic deposits. During this period, tectonic activity weakens, and the continental slope strata stabilize. The slope fans are primarily composed of clastic sediments transported over long

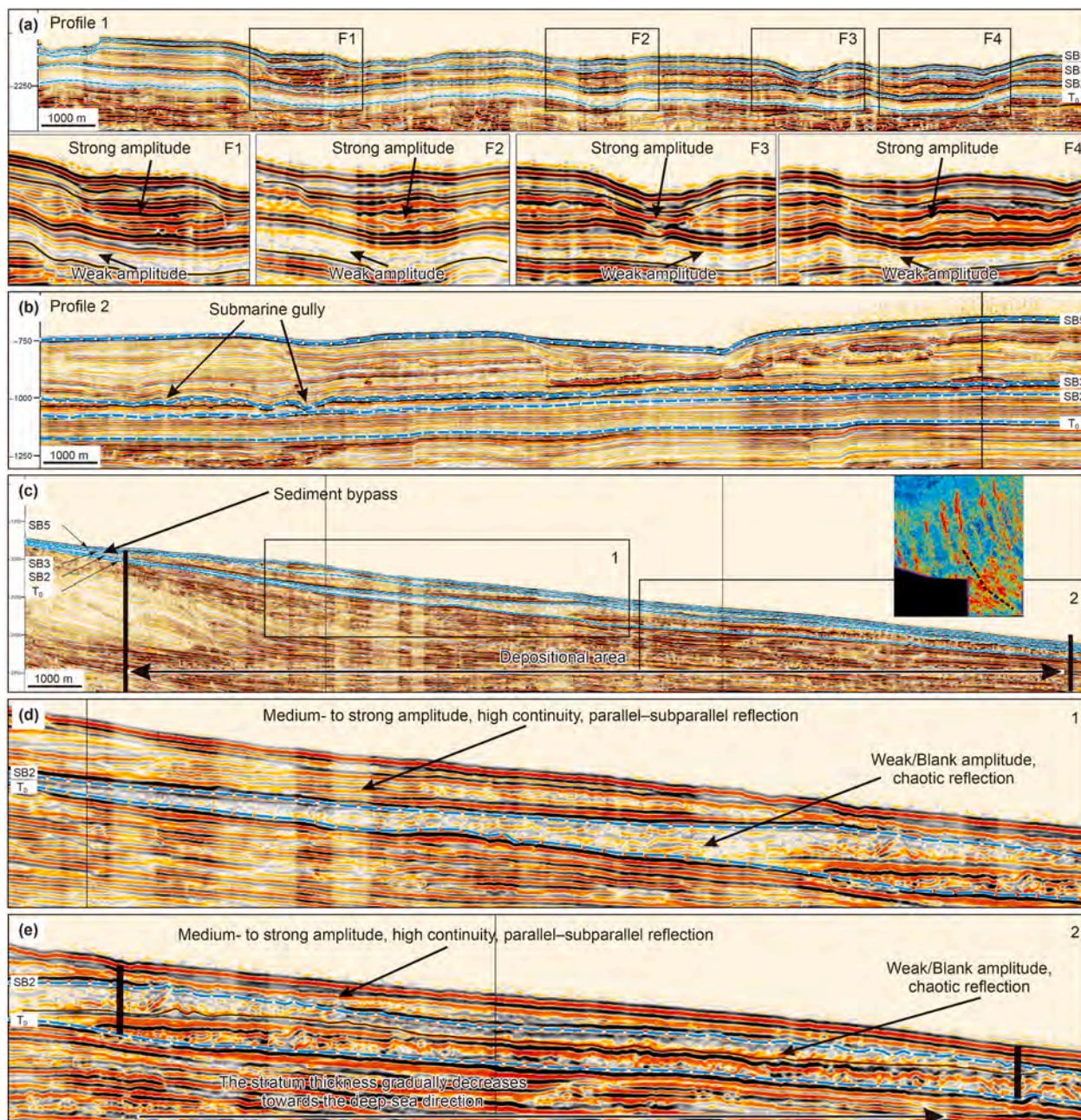


Fig. 12. Typical seismic profiles of slope fans, with the locations of profiles 1 and 2 shown in Fig. 11. (a–b) are seismic profiles parallel to the strike of the continental slope, and (c–e) are seismic profiles perpendicular to the strike of the continental slope.

distances and subjected to sedimentary differentiation from the shelf area, resulting in relatively uniform and continuous reflection structures. The formation patterns of canyons exhibit certain distinctions from those of channel complexes developed on deep-water plains. Wang et al. (2025b) noted in their study on the evolution of large-scale channel systems in the Taranaki Basin, New Zealand, that complex large-scale channel systems do not form abruptly but rather through repeated erosion and filling by gravity flows of different ages, leading to the development of composite channels. The gradual superimposition of these composite channels ultimately results in the formation of intricate channel systems.

(4) **Stage 4 (corresponding to Sq4–Sq5, Fig. 13(d)):** The canyon cross-sections exhibit a narrow V-shape (Figs. 9 and 10). The shelf

strata are relatively thin, and due to limitations in seismic resolution, no seismic reflection termination relationships are observed. During this time, the shelf margin retreats landward (Fig. 7(e)), indicating a rise in sea level. However, RMS amplitude attributes reveal that slope fans still develop at the canyon termini, displaying strong amplitude, high continuity, and parallel reflection features in seismic profiles, albeit on a smaller scale compared to Stage 3. This contradicts the viewpoint of Popescu et al. (2004). The reason is that, despite the rising sea level and landward retreat of the shelf margin, retrogressive erosion at the canyon heads continues, enabling clastic sediments from the shelf margin to still be transported into the canyons, albeit on a reduced scale compared to Stages 2 and 3. Consequently, the scale of slope fans at the canyon termini also decreases accordingly.

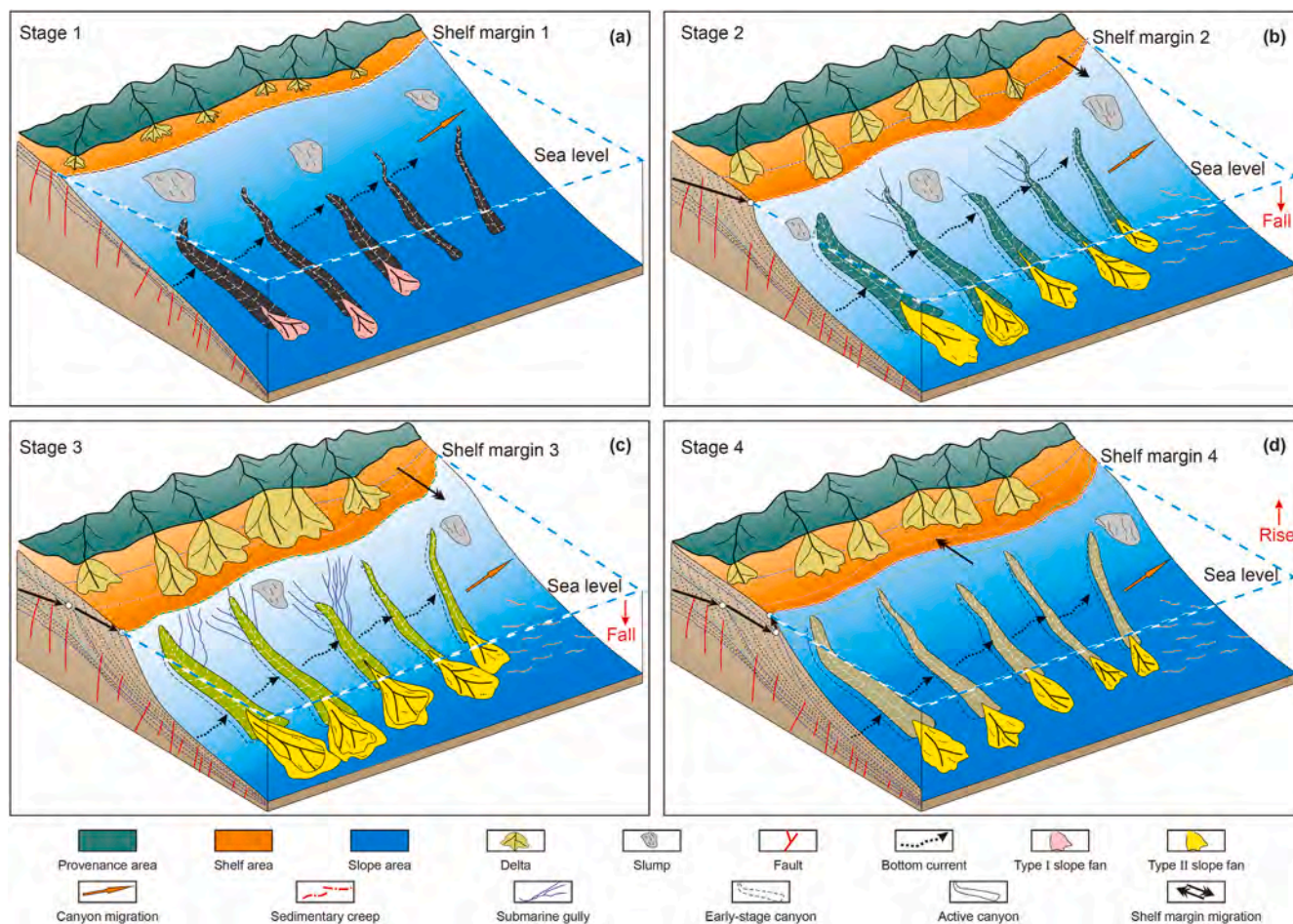


Fig. 13. Schematic diagram of the spatiotemporal evolution of canyon-fan systems.

In summary, this study reveals a distinct cyclical evolutionary pattern of Quaternary canyon-fan systems in the study area, as follows.

- 1) As sea level falls and sediment supply increases, the canyon cross-sectional morphology evolves sequentially from a wide U-shape to a V-shape, deep V-shape, and narrow V-shape, reflecting stage-wise changes in the energy and erosional capacity of gravity flows.
- 2) There are two sets of sediment source systems for slope fan deposition: near-source slope collapse and distal shelf clastics. The evolutionary process indicates a shift in sediment supply mechanisms from being “locally collapse-dominated” to “distally transported-dominated”.
- 3) The complete evolutionary cycle of continental slope canyon-fan systems begins with the formation period (Stage 1) under a transgressive background, develops during the peak period of canyon incision and fan progradation (Stages 2-3) under a regressive background, and terminates with the decline period (Stage 4) under a transgressive background (Fig. 13).

5.2. Controlling factors for the spatiotemporal evolution of continental slope canyon-fan systems

The complexity of deep-water environments means that deep-water sedimentation is inevitably controlled by the synergistic effects of multiple factors (Gee and Gawthorpe, 2006; Wynn et al.,

2007; Hansen et al., 2017; Wu et al., 2018; Li et al., 2020), instead of being independently governed by a single factor. Similarly, the evolution of Quaternary canyon-fan systems in the Baiyun sag is also controlled by the synergistic interaction of multiple factors (Zhu et al., 2010; Gong et al., 2021a). This study reveals that both macroscopic and local factors govern the evolution of Quaternary canyon-fan systems in the Baiyun sag. Macroscopic factors, such as sea-level changes and tectonic activities, collectively control the scale of sediment supply and the development and demise of canyon-fan systems. Local factors, including sediment provenance patterns and the distance between canyons and the shelf margin, jointly modulate the internal structure and distribution scale of canyon-fan systems. This two-tiered control model, characterized by “macroscopic foundation and local adjustment”, shares commonalities with deep-water sedimentary systems in many passive continental margins worldwide (Casalbore et al., 2018). However, the unique coupling patterns and shifts in the dominance of various factors within this study area are distinctive.

5.2.1. Macroscopic factors determine the formation and demise of canyon-fan systems

(1) Tectonic activities

Throughout the four evolutionary stages of the continental slope canyon-fan systems, tectonic activity emerges as the primary factor governing canyon development and fan type (Ding et al., 2013a; Gao et al., 2021). Since the Late Miocene, the Pacific

and Indian Ocean plates have become increasingly active, influenced by adjustments in deep-seated tectonic mechanisms within the Earth, with lower mantle material upwelling to the weak zones at the bottom of the Xisha Trough and accelerating the subsidence of the seafloor around the trough. Yu et al. (2012) pointed out that the average subsidence rate in the Pearl River Mouth Basin during the Pleistocene (approximately 1.8–0 Ma) could reach 73 m/Ma. Rapid basin subsidence is typically accompanied by intense faulting (Wang et al., 2006; Pang et al., 2007; Ding et al., 2009). Faults tend to create weak zones in the strata, which are later preferentially eroded by fluids, leading to the formation of canyons.

During the early stage (Sq1 period), tectonic activity generated numerous NW-trending faults (Fig. 7(d)). Although the strike of slope canyons in the study area is at an oblique angle to that of the faults, the development of faults creates fracture planes of certain scales within the strata, which can be regarded as “negative topography”. These fracture planes control the transport of terrigenous clastic sediments along the fault strike for a certain distance towards the slope. The sediments then accumulate at the canyon heads. Simultaneously, faults undermine the stability of slope strata (Hansen et al., 2017), which is in line with the viewpoint proposed by Ma et al. (2025) that tectonic activities destabilize strata, leading to sediment instability and collapse deposition. This, in turn, triggers larger-scale stratal collapses, ultimately resulting in the development of slope canyons (Fig. 7). The control mechanism governing the evolution of the Miocene deep-water channel–levee systems in the Taranaki Basin, New Zealand, is similar. Tectonic movements are considered a key factor in sediment resuscitation, which increases the flux of terrigenous clastic sediments transported seaward, thereby facilitating the development of large-scale channel–levee systems (Uruski and Warburton, 2015; La Marca and Bedle, 2022; Wang et al., 2025b).

Furthermore, the episodic activation of tectonic activity during the early Sq1 and Sq2 stages directly triggered slope sediment collapse, resulting in the formation of early slope fans (Fig. 12(d) and (e)). After the late stage of Sq2, tectonic activity gradually diminished, reducing its impact on slope stratal stability and leading to a shift in the canyon–fan depositional pattern. This study demonstrates that while tectonic activity was the dominant triggering factor during the early evolutionary stages (early Sq1–Sq2), over time, the deposition of shelf clastics controlled by sea-level changes emerged as the dominant factor governing the evolution of canyon–fan systems.

(2) Climate–sea level changes

The Quaternary glacial–interglacial cycles exhibit high-frequency and high-amplitude climatic fluctuations. During the late Pliocene (approximately 3.5–2.5 Ma), the $\delta^{18}\text{O}$ values increased by 0.99‰, which indicated the formation of the Arctic ice sheet and a global climate transition from a “unipolar ice sheet” to a “bipolar ice sheet” (Zachos et al., 2001). After 2.4 Ma, the Arctic ice sheet expanded, and deep-sea temperatures decreased. Around 0.9 Ma, the $\delta^{18}\text{O}$ values increased again, which signaled a further expansion of the Arctic ice sheet (Jian et al., 2003) (Fig. 14(a)). During the Mid-Pleistocene Climate Transition (1.2–0.5 Ma), the dominant global climate cycle shifted from 40 ka to 100 ka, and the fluctuation amplitudes increased (Wu et al., 2002). This event may be related to the rapid uplift of the Tibetan Plateau at around 1.3 Ma (Fig. 14(a)). The uplift of the Tibetan Plateau reshaped atmospheric circulation patterns. Foraminiferal carbon isotope data from ODP Site 1148 reveal that since the Early Pleistocene, the East Asian winter monsoon has significantly intensified multiple times.

The intensification occurred at approximately 2.2 Ma, 1.7 Ma, 1.3 Ma, 0.9 Ma, and 0.6 Ma (Jian et al., 2003) (Fig. 14(a)). Quaternary clay mineralogical analysis from ODP Site 1146 also confirms that from approximately 2.0 Ma to 1.2 Ma, the northern SCS was primarily influenced by the East Asian winter monsoon. The intensification of the winter monsoon inhibited chemical weathering but promoted physical weathering, thereby increasing the supply of terrigenous clastic sediments and laying a material foundation for the development of deep-water deposits.

Climate change governs sea-level fluctuations, which in turn influence deep-water sedimentary processes. The relative sea-level change curve established by Pang et al. (2007) for the Pearl River Mouth Basin indicates that since 21 Ma, there have been eight occasions when the sea level dropped to near the shelf break at 17.5 Ma, 16.5 Ma, 10.5 Ma, 1.6 Ma, and 0.8 Ma. During the Quaternary, the sea level fell by as much as 120 m, advancing the coastline seaward by approximately 200 km (Jia and Xie, 2006).

During the regression phases (Sq2–Sq3) in the study area, the shelf margin continually advanced seaward, exposing large areas of the shelf. Terrigenous clastic materials were directly transported to the deep-water zone through canyon heads and gullies, which provided an abundant sediment supply for the development of slope canyon–fan systems (Fig. 11(b) and (c)). This finding aligns with the conclusions of Ding et al. (2013a) from studies in other slope regions, and both of them emphasize the pivotal control of sea-level fall on deep-water sedimentation. However, this study reveals that during the transgression phases (Sq4–Sq5), due to canyon headward erosion, terrigenous clastic sediments can still be transported to the slope. This allows slope fans to continue developing, albeit with reduced scales due to the influence of rising sea levels. This phenomenon differs from the viewpoint proposed by Wong et al. (1994) that canyon/channel–levee systems may be inactive during highstand transgressions, which highlights the lag effect and sustaining influence of submarine geomorphic evolution relative to sea-level changes.

5.2.2. Local factors modulate the depositional details of canyon–fan systems

(1) Sediment provenance patterns

Broucke et al. (2004) pointed out that when understanding the formation and evolution of deep-water channels and fans, taking into account temporal variations in sediment supply is crucial, as these variations are primarily influenced by sea-level fluctuations and sediment provenance from the source area. Similarly, Wang et al. (2025b) clarified in their study on deep-water channels in the Taranaki Basin, New Zealand, that the scale and properties of sediment supply are key factors influencing the development process of deep-water channel systems. Consequently, the adequacy of sediment supply has a significant impact on the internal sedimentary architecture of channel systems and the migration processes of individual composite channels, which serves as a direct determinant for deep-sea channels (Gong et al., 2013).

The Quaternary glacial–interglacial cycles were characterized by frequent changes, which lead to relatively high sedimentation rates at the shelf margin in the northern SCS. Research at ODP Site 1148 revealed that the sedimentation rate in the northern SCS during the Quaternary reached as high as 49.01 m/Ma (Clift et al., 2008), and the maximum rate occurred during the Pleistocene. The significant increase in Quaternary sedimentation rates was a global event (Zheng et al., 2000), which was likely influenced by abrupt climate changes that occurred between 4 Ma and 2 Ma (Zhang et al., 2001), resulting in increased erosion of strata.

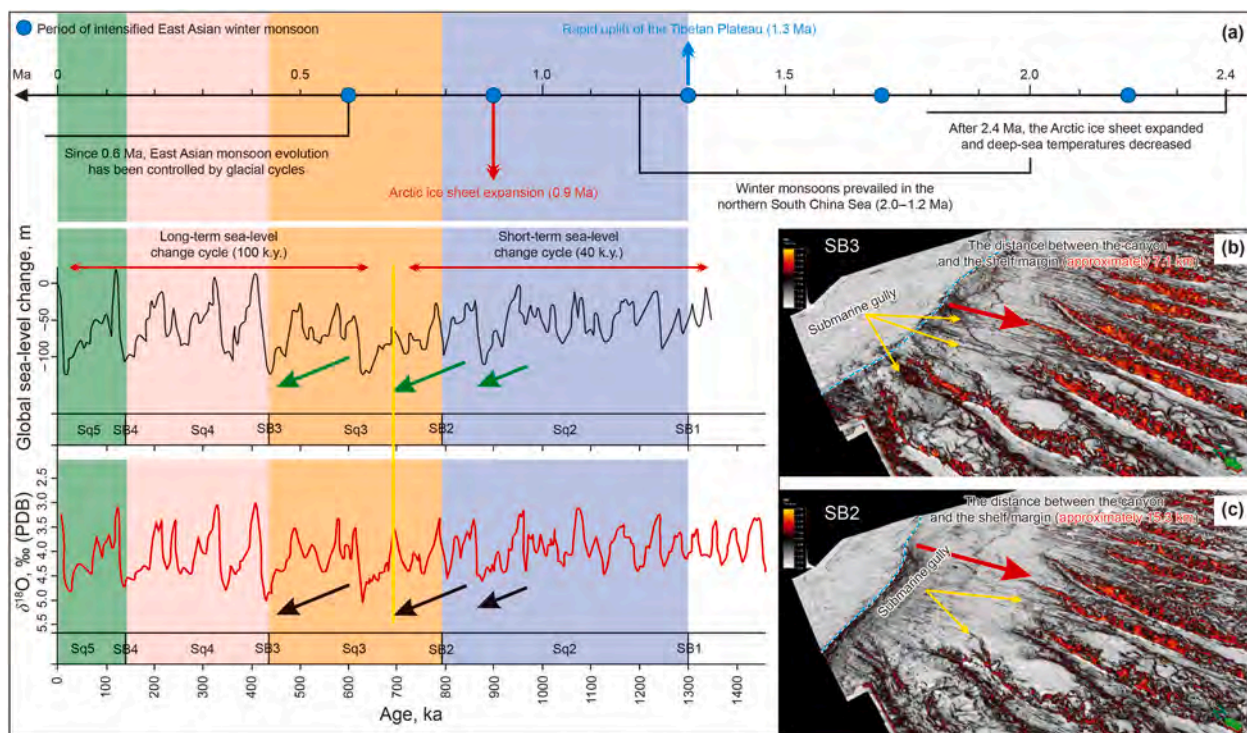


Fig. 14. (a) Climatic event scale for the SCS region (modified from Jian et al., 2003; Yang et al., 2022), benthic foraminiferal oxygen isotope data (modified from Meng et al., 2011), and the global sea-level change curve (modified from Müller et al., 2005); (b–c) schematic diagrams illustrating the distances (red arrows) between canyon heads and shelf margins during different sequence periods.

Vail et al. (1977) proposed that sea-level changes were the primary controlling factor for sequence development and submarine fan formation, and their fluctuations governed the landward-to-seaward transport of sediments, with lowstand systems tracts representing the main stage for submarine fan development. However, a series of studies by Plink-Björklund and Steel (2002), Carvajal and Steel (2006), and Covault and Graham (2010) indicated that submarine fans do not always form during lowstand systems tracts and appear to have no specific relationship with sea-level changes. Besides sea-level fluctuations, factors such as sediment supply controlled by tectonic activity and climate change, as well as paleotopographic variations, are also important influences on submarine fan development (Covault and Graham, 2010). This study has identified two modes of sediment provenance supply. The first is near-source slope collapse, triggered by tectonic activity that causes the collapse of slope strata. This mode is characterized by short sediment transport distances, poor sorting, and weak-amplitude, chaotic seismic reflections (e.g., the Sq1 fan body) (Fig. 12). The second is distal shelf clastics, controlled by climate-sea-level changes, whereby shelf clastic sediments undergo long-distance transport and thorough sorting, exhibiting strong-amplitude, highly continuous, and parallel seismic reflections (e.g., the Sq3 fan body) (Fig. 12). Although this study lacks quantitative characterization of sediment supply flux, the progradational reflection patterns observed in seismic profiles suggest an increase in sediment flux from the Sq1 to Sq4 periods (Fig. 4).

Additionally, Hansen et al. (2017) indicated that the properties of sediment from the source area play a crucial role in shaping the morphology of channels or canyons. Coarse-grained sediments may lead to a reduction in channel sinuosity, whereas fine-grained sediments tend to promote the sinuous development of channels. The continental slope canyons in the Baiyun sag serve as

significant conduits for the transport of terrigenous clastic sediments. The transportation of sediments with varying grain sizes from the shelf to the deep-water plain inevitably influences the morphology and internal filling structure of these canyons.

(2) The distance between the canyon head and the shelf margin

Posamentier et al. (1991) explicitly stated that if a canyon head has already incised through the shelf and reached the modern beach, sediments can be transported to the deep-sea area regardless of sea-level position (Covault and Graham, 2010). This scenario applies to nearly half of the submarine canyons along the tectonically active California continental margin (Normark et al., 2009). When the sediment supply is sufficient to push the delta to the shelf edge, deep-sea sedimentation can occur independently of sea-level fluctuations (Carvajal and Steel, 2009).

“Slope-confined” canyons refer to those with heads terminating in the slope zone and unable to erode upward into the shelf edge. Examples include the Noggin and Ribbon Reef canyon groups off northeastern Australia (Puga-Bernabéu et al., 2013) and the Pliocene–Pleistocene canyon groups off the Ebro River shelf margin (Bertoni and Cartwright, 2005). These canyons develop at locations relatively distant from the shelf edge, so they are less influenced by sea-level changes. Their formation and evolution may be related to turbidity currents or mass transport events (Wynn et al., 2007), sediment instability (Nakajima et al., 2014), and retrogressive slumping (He et al., 2014). Gong et al. (2021a) pointed out that some slope canyons in the Baiyun sag do not connect directly with the shelf margin, yet fan deposits still develop at their distal ends. This may be because the canyon heads capture sediments from coastal currents, which are then transported downstream through intra-canyon channels to form slope fans. However, the canyons in the western part of the canyon

group studied in this research exhibit certain differences from the example provided by Gong et al. (2021a). Although their heads are not directly connected to the shelf edge, large-scale submarine gullies have developed between them (Figs. 11 and 14(b) and (c)). These submarine gullies connect the shelf edge with the submarine canyons, enabling the transport of clastic sediments from the shelf edge to the slope and further into the deep-sea area via the submarine canyons. It should be specifically noted that the distance between the canyon heads and the shelf margin refers to the scope within the western part of the canyon group. In contrast, since the eastern part of the canyon group is located far from the shelf margin, this factor has a negligible impact on the development of its canyons.

The distance between the canyon head and the shelf edge determines the efficiency with which the canyon captures shelf sediments through retrogressive erosion (Fig. 14). When the distance is relatively short (Sq2: approximately 15.3 km; Sq3: approximately 7.1 km), the canyon can efficiently transport shelf-derived sediments to the deep-water area, supporting the development of large fan bodies. Even during transgressions (Sq4–Sq5, approximately 8.3–8.6 km), continuous retrogressive erosion can still “plunder” sediments from the retreating shelf edge, sustaining fan growth, albeit on a reduced scale. This phenomenon highlights the canyon system's ability to actively acquire sediment sources rather than merely passively receiving them. The growth and sedimentation capacity of different canyons may be closely related to their ability to effectively shorten the distance to sediment source areas.

(3) Bottom current activity

The interaction between submarine bottom currents and gravity flows is widely recognized as a key factor influencing deep-water sedimentation. A prominent research focus has been on unidirectionally migrating channels, where canyons undergo lateral displacement either along or against the bottom-current direction under its influence. This phenomenon is notably documented in the Qiongdongnan Basin, Pearl River Mouth Basin, Greenland's Irminger Basin, East Africa's Mozambique Rovuma Basin, and Tanzania Coastal Basin (Rasmussen et al., 2003; Gong et al., 2013; Sansom, 2018; Fonnese et al., 2020).

The submarine canyon group on the continental slope of the Baiyun sag in the SCS exhibits a distinct unidirectional migratory trend (Gong et al., 2013), serving as a globally significant case study of the influence of the bottom current. Notably, canyon migration here occurs in the direction of the bottom current, which contrasts sharply with the counter-current migration observed in East Africa's Ruvuma Basin (Chen et al., 2020). This study identifies contourite drifts through seismic profiles, which are characterized by moderate amplitude and highly continuous reflections (Fig. 6(j) and (k)). Bottom currents constitute the primary driving force for drift formation, which additionally requires a sufficient sediment supply, such as that sourced from submarine channels formed by gravity flows. Without adequate sediment input, even active bottom currents struggle to form contourite drifts with sparse sediment loads. The development of such structures indirectly confirms the presence of abundant sediment provenance in the study area. Furthermore, the unidirectional nature of bottom-current activity significantly influences the internal filling architecture of canyons and slope fans, with pronounced unidirectional migration evident in canyon axes and slope fan positions (Figs. 9, 10 and 13). Consequently, the interplay between bottom currents and gravity flows warrants particular attention in deepwater hydrocarbon exploration.

5.2.3. Coupling mechanism of multiple factors and its research implications

This study identifies a complete deep-water S2S system, with the shelf-margin delta occupying a pivotal position as the “source”. During the canyon–fan formation phase under a transgressive background (Stage 1), the shelf-margin delta provided the initial sediment supply for the canyon–fan system. As continuous regression occurred, the shelf-margin delta offered an increasingly abundant sediment source, leading to more active canyon incision and fan accumulation (Stage 2–3). Conversely, in a transgressive setting, the development scale of the shelf-margin delta gradually decreased, resulting in a reduced sediment supply to the canyon–fan system and its subsequent decline. This series of sedimentary processes fully demonstrates that the development scale and sediment-supply mode of the shelf-margin delta directly dictate the sedimentary characteristics and evolutionary trajectory of the canyon–fan system, serving as a crucial basis for understanding the shelf delta as a significant source of deep-water sedimentary material.

In conjunction with previous studies, it is evident that deep-water sedimentary processes are not controlled by a single factor (Li et al., 2020; Wu et al., 2020; Wang et al., 2025b). Similarly, the evolution of Quaternary canyon–fan systems in the Baiyun sag is also subject to the synergistic control of multiple factors, with the dominant factor varying across different sedimentary stages. During the Sq1 period, the sediment supply was primarily dominated by tectonically induced slope collapses. The Sq2 period represents a transitional phase jointly influenced by tectonic activity (slump deposits) and sea-level fall (terrigenous clastic deposits). In the Sq3 period, the sedimentation shifted to being primarily dominated by terrigenous clastic deposits resulting from sea-level fall. By the Sq4–Sq5 periods, under a background of rising sea levels and weak tectonic activity, the canyon's headward erosion capability became crucial for sustaining slope fan development. This spatiotemporal shift in the dominance of multiple factors distinguishes the deep-water system in this study area from other classic passive continental margin deep-water systems. The slope–fan spatiotemporal evolution model established in this study not only provides a detailed description of the canyon–fan evolution process but also emphasizes the importance of analyzing control mechanisms under the coupling of multiple factors, offering guidance for predicting deep-water sand-rich deposits.

6. Conclusions

- (1) In the Quaternary strata of the study area, one second-order and five third-order sequence boundaries have been identified, leading to the division of five third-order sequence units (Sq1 to Sq5). Sq1 is characterized by gentle, thin-bedded deposits, indicating a stable deep-water environment. Sq2–Sq4 exhibit thick, high-angle prograding reflection configurations, reflecting intense progradation of terrigenous clastics; Sq5 is only identified with deposits of a certain thickness below the shelf break, reflecting restricted sedimentation during a lowstand sea level. The ages of key sequence boundaries have been calibrated using paleontological and shallow drilling data, establishing an isochronous stratigraphic framework for the Quaternary in the study area.
- (2) Various geomorphic units, including shelf (margin) deltas, submarine gullies, canyons, and slope fans, have been identified within the study area. Since the Quaternary, headward erosion has continuously occurred at canyon heads. Two types of slope fans have developed at canyon

termini, with Type I exhibiting weak-amplitude, chaotic reflections and Type II displaying medium- to high-amplitude, highly continuous, parallel-subparallel reflections.

- (3) The evolutionary process of canyon–fan systems shows a good correspondence with sequence units, demonstrating distinct stages. Stage 1 represents the initial formation period of canyon–fan systems under a transgressive background. Stages 2–3 mark the peak period of intense canyon incision and large-scale fan progradation under a regressive background. Stage 4 denotes the decline period of canyon–fan systems under a transgressive background.
- (4) The Quaternary canyon–fan evolution in the Baiyun sag is jointly controlled by macro- and local factors, following a control model of “macro-scale foundation and local-scale adjustment”. Macroscopic factors, such as sea-level changes and regional tectonic activity, control the scale of sediment supply and the development and demise of canyon–fan systems. Local factors, including sediment provenance patterns, the distance between canyons and the shelf edge, and bottom current activity, regulate their internal structures and spatial distribution patterns. These factors act in concert, with the dominant factor shifting during different periods.

CRediT authorship contribution statement

Guang-Xu Wang: Writing – original draft, Software, Methodology, Investigation, Conceptualization. **Jun-Ling Pei:** Writing – review & editing, Methodology, Conceptualization. **Wei Wu:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **Quan Li:** Software, Methodology. **Wei-Qing Liu:** Writing – review & editing, Methodology. **Zhi-Feng Xing:** Methodology, Conceptualization. **Jing Yu:** Investigation, Conceptualization.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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