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Seismic geomorphology and main controls of deep-water gravity flow sedimentary process on the slope of the northern South China Sea

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The Quaternary continental slope of the Baiyun Sag in northern South China Sea is characterized by a complex topography and abundant gravity flow sedimentation. High-resolution 3-D seismic data in this area allow for a detailed study of the seismic geomorphology and deep-water gravity flow depositional process. The Quaternary continental slope in the northern South China Sea is an above-graded slope. An intraslope basin lies within the above-grade continental slope. Slump, erosion, and deposition processes tend to develop a gentle topography and consequently a graded slope. The upper continental slope, which is above the slope equilibrium profile, is dominated by erosion and slumping. Slides, slumps and erosional channels are developed within this continental slope. The intraslope basin is located below the slope equilibrium profile and is potential accommodation space where sediments transported by gravity flows could be deposited, forming lobe aprons. Under the influence of gravity flow supply, gravity flow duration, continental slope topography, equilibrium profile, and accommodation, a slump-erosional channel-lobe depositional system is developed in the Quaternary continental slope in the Baiyun Sag. The deep-water gravity flow depositional process and the distribution of gravity flow sediments are greatly influenced by the continental slope topography, while the continental slope topography at the same time is reshaped by deep-water gravity flow depositional process and its products. The study of the interplay between the continental slope and gravity flow is helpful in predicting the distribution of the deep-water gravity flow sediments and the variation of sediment quality.

seismic geomorphology, deep water, gravity flow, sedimentary process, South China Sea

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As a result of rising of exploration and development costs and increasingly complex exploration targets, 3-D seismic data now afford an effective tool to reduce risk. High-resolution 3-D seismic data from deep-water sedimentary basins around the world have led to the development of deep-water sedimentology. Much of the increase in our knowledge of deepwater depositional systems has come from observations and interpretations made possible by increasingly quantities of high quality 3-D seismic data [1–5]. Seismic geomorphology is a growing field that involves the study of basin geomorphology and depositional systems using 3-D seismic-derived plan-view images [6]. Seismic geomorphologic analysis leads to the identification, interpretation, and prediction of depositional elements [4, 6–11]. Study of the deep-water deposition is one of the most active fields in sedimentology. The issue that the complex topography controls the deep-water gravity flow depositional

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process has drawn great attention of many geoscientists [5, 12–14]. Active gravity flow depositional systems present on the continental slope, northern South China Sea (SCS) [15–17]. The continental slope on the northern SCS is characterized by a complex slope caused by rifting. The complex seafloor topography has played an important role in controlling the gravity flow depositional processes and distribution of sediments. This article documents the Quaternary slope topography and the main controls on deepwater gravity flow depositional process by interpreting nearly 4500 km^2 of near surface high-resolution 3-D seismic data. Study of seismic geomorphology in this area provides new and critical information for deep-water exploration and development within northern SCS. Seismic geomorphology has become a key tool for geoscientists to identify, interpret, and predict the seabed geomorphology and the main factors involved in the deepwater depositional process [4–9].

1 Geological setting and seismic data

The Baiyun Sag (BYS) is the largest sag in the Pearl River Mouth Basin (PRMB) in northern continental slope of SCS, with a maximum thickness of sediment over 11 km. The BYS has an area of over 2.1×10^4 km^2 and a water depth ranging from 200 to 2000 m (Figure 1(a)). The BYS is subdivided into two subsags by the Baiyun low uplift: the main BYS with a width about 80 km and the Liwan Sag (LWS) with a width about 70 km (Figure 1(b)). Major boundary faults of the main BYS are the long active faults. The tectonic evolution of the BYS can be divided into three phases: the rifting phase, the depressive phase and the differential uplifting-subsiding phase [18]. The depositional environment in BYS changed from a shallow-water shelf to a deep-water slope at 23.8 Ma [19]. An intraslope basin was formed on the slope of northern SCS. Recent re-

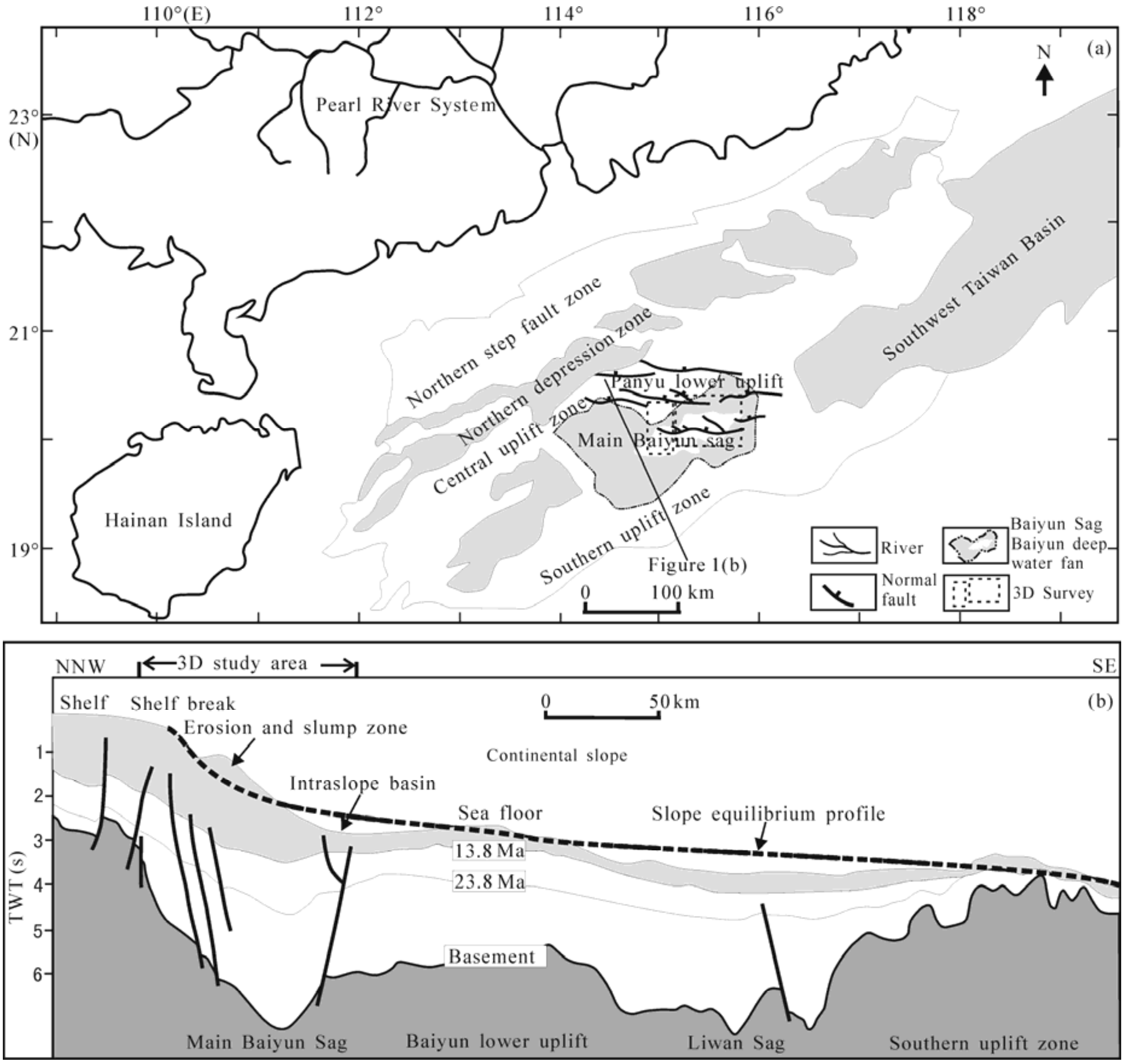

Figure 1 Basemap of BYS (a) and regional geologic profile (b).

search has revealed that multiple submarine fans exist on the Baiyun deep-water area [20–22].

The study area is located in the main BYS. Two 3-D seismic surveys cover a total area of approximately 4500 km^2 (Figure 1(a)). Seismic data from the shallow Quaternary sedimentary formations have a wide frequency band. The frequency ranges from 3 to 80 Hz with the dominant frequency reaching 45 Hz. High-resolution 3-D seismic data and imaging techniques are used to identify and predict the deep-water sedimentary systems and their main controlling factors. The objective of this paper is to discuss the main controls of the Quaternary slumps- erosion channels- and lobe depositional systems of the BYS by analyzing the high-resolution 3-D seismic data.

2 Topography of the continental slope in BYS

BYS lies in the continental slope of the northern SCS. Gravity flow deposition started from Neogene in this area [20–22]. The 3-D seismic survey is located in the main BYS (Figure 1(b)). A large scale intraslope basin was formed on the slope of northern SCS in response to the fault activities before 23.8 Ma (Figure 1(b)). Complex topography of the study area can be divided into an erosional channel zone and an intraslope basin zone (Figure 2). Many submarine erosion channels were developed in the erosion channel zone, with a large number of continental slope slumps and channel wall slumps. The intraslope basin is located in front of the erosion channel zone. Multiple overlying lobes were formed in the intraslope basin with a gentle topography. Multiple submarine erosional channels are identified on the upper continental slope. Overlying lobes were developed at the terminals of the submarine erosion channels. The slump-erosion channel-lobe depositional system was developed in Quaternary continental slope in BYS (Figure 2).

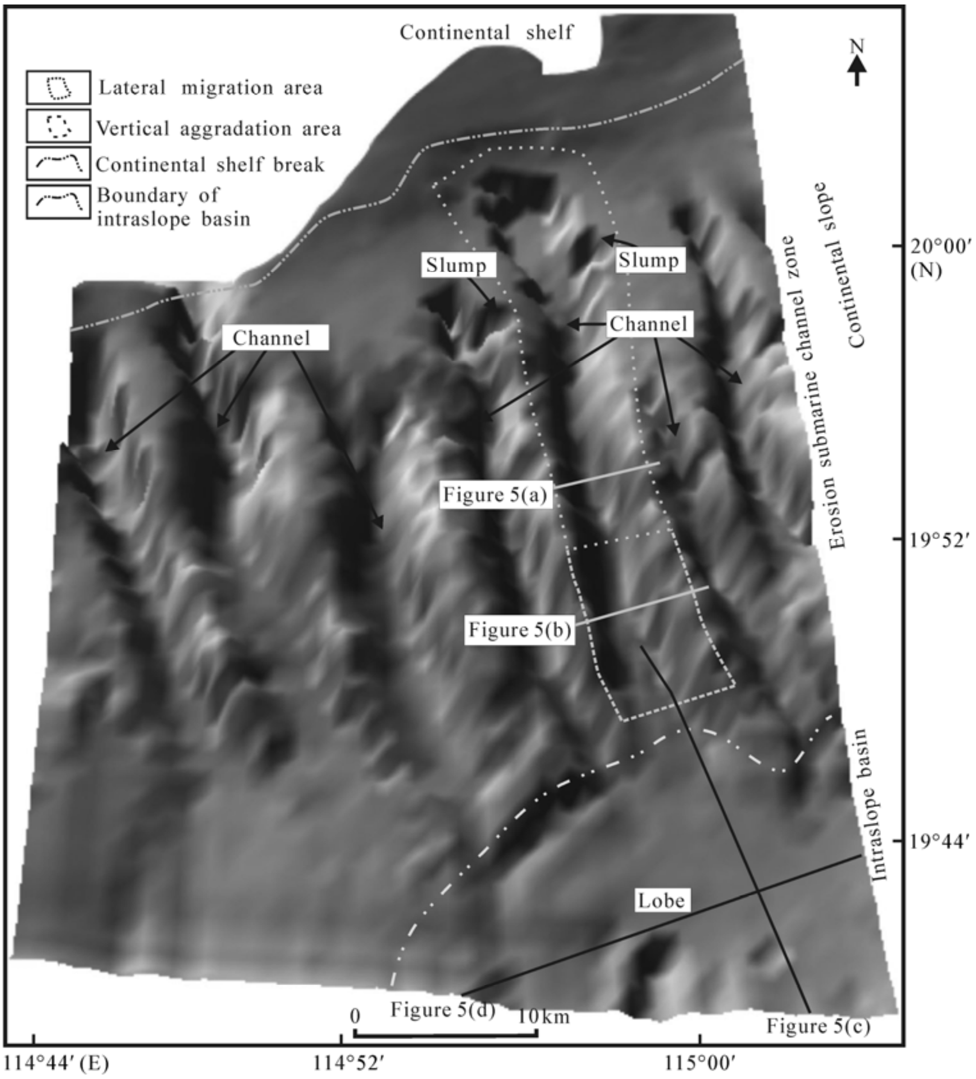

Figure 2 Quaternary slope topography of the study area, BYS.

3 Slope equilibrium profile and accommodation types

The slope equilibrium profile is an imagined surface, where sediment deposition and erosion are in equilibrium. Spaces below this surface are accommodation spaces where sediments transported by gravity flows are deposited, whereas the strata above this surface tend to be eroded away. Erosion intensity is determined by the power of the gravity flows and the characteristics of the continental slope [12]. The slope equilibrium profile is controlled primarily by slope topography and varies along with the development of the slope topography. The slope equilibrium profile is approximately a trend surface of the slope topography. The trend surface is computed by fitting a slowly changing 3-D surface to the bathymetry data [23]. The slope equilibrium profile in this study area is a slowly changing 3-D trend surface between the shelf break and toe-of-slope. Areas above the slope equilibrium profile are potential erosion zones. In contrast, areas below the slope equilibrium profile are potential deposition zones (Figure 1(b)). Continental slopes can be divided into graded slope and above-graded slope on the basis of topography [12, 24]. The Quaternary continental slope of the BYS, which is above-graded slope, is characterized by a complex topography. The upper continental slope above the slope equilibrium profile is a potential erosion zone or slump zone. The intraslope basin below the slope equilibrium profile is a potential deposition zone (Figure 1(b)). The slope accommodation is determined by the slope equilibrium profile and seafloor of the intraslope basin. Slump, erosion, and deposition tend to produce a gentle topography and consequently a graded slope. The upper continental slope of the BYS lies above the slope equilibrium profile. Erosion from gravity flow, slope slump, and channel wall slump tend to produce a graded slope (Figures 1(b), 2 and 3). The sea floor of the slump (erosion) area lies above the slope equilibrium profile. Slope slumping and gravity flow erosion work to form a gentle topography and consequently a graded slope. Slides, slumps, and erosional channels were developed within this continental slope (Figure 3(b) and (c)).

Slope slump is triggered by gravitational instability of the continental slope (Figures 2, 3(a) and (b)). Submarine landslides move along the continental slope. Down-slope sliding is approximately parallel to the dip of the continental slope (Figure 3(b)). The strike of the slump scars is approximately parallel to the strike of the continental slope. 3-D seismic data have revealed complex deformation in the area with no erosional channels (Figure 3(a)). Erosional channels are formed in this area with active gravity flow. Oversteepened walls were caused by the erosion from the gravity flow. Slumping was triggered by gravitational instability of the submarine channel walls. Slump scars were parallel with the strike of the submarine channel (Figures 3(a), 4). The polygonal faults were formed by the interaction of the early down-slope slump and the later slumping of the submarine channel wall (Figure 4).

It is difficult to explain the development and evolution of the polygonal faults observed in 3-D seismic data with only a regional tectonic stress field. Deformation is controlled by the gravity instability induced by sediment unloading [25]. Sediment unloading and gravity slide are the main controls of the deformation. The deformation in the Quaternary continental slope of the BYS might develop under conditions where a regional tectonic stress field is weak or absent and was triggered by gravitational instability due to increasing depositional load. The local stress field was influenced by the lateral lithological discontinuity that had influence on the strain distribution. The polygonal fault is a result of slumps in different directions and is influenced by a combination of both submarine channel erosion and gravitational sliding (Figure 4). The Quaternary continental slope of the northern SCS is above-graded slope. Gravity flow erosion and gravitational sliding tend to form a gentle topography and consequently a graded slope.

4 Submarine sediment types and sedimentary facies

Many slides, erosional channels, and lobes are developed in the Quaternary continental slope of the BYS (Figure 3(a)). Slumping is triggered by gravitational instability of the continental slope and the submarine channel walls. The slides vary in shape and size. In general, the diameter of slide is less than 2 km (Figures 3(b), 4). The slide is composed mostly of similar compositions to the continental slope and submarine channel wall. Due to a low sediment supply, sedimentation on the continental slope of north SCS is dominated by fine-grained sediments. Submarine gravity flow channels were dominated by erosion and bypass. The lithology of the slides is rich in mud. The dominant lithology of the slides is mud-rich mudstone.

Multiple submarine erosion channels are identified along the slope direction (Figures 2, 3(a)). These submarine erosion channels are characterized by “V”-shape or “U”-shape on seismic profile (Figure 5). The coarse-grained lags on the channel bases make a distinctive high-amplitude seismic reflector (Figure 5(a)). Submarine channel deposits are composed of mass transport deposits (MTDs) and pelagic drapes (Figure 5). The MTDs show weak- moderate, discordant to chaotic amplitude reflectors on seismic profile. Pelagic drape sediments are characterized by low amplitude, parallel to sub-parallel seismic reflectors. Slides are resulted from the failure of the submarine channel walls (Figure 5(a)).

Submarine erosional channels are the major conduits for the transportation of coarse-grained sediment into deep wa-

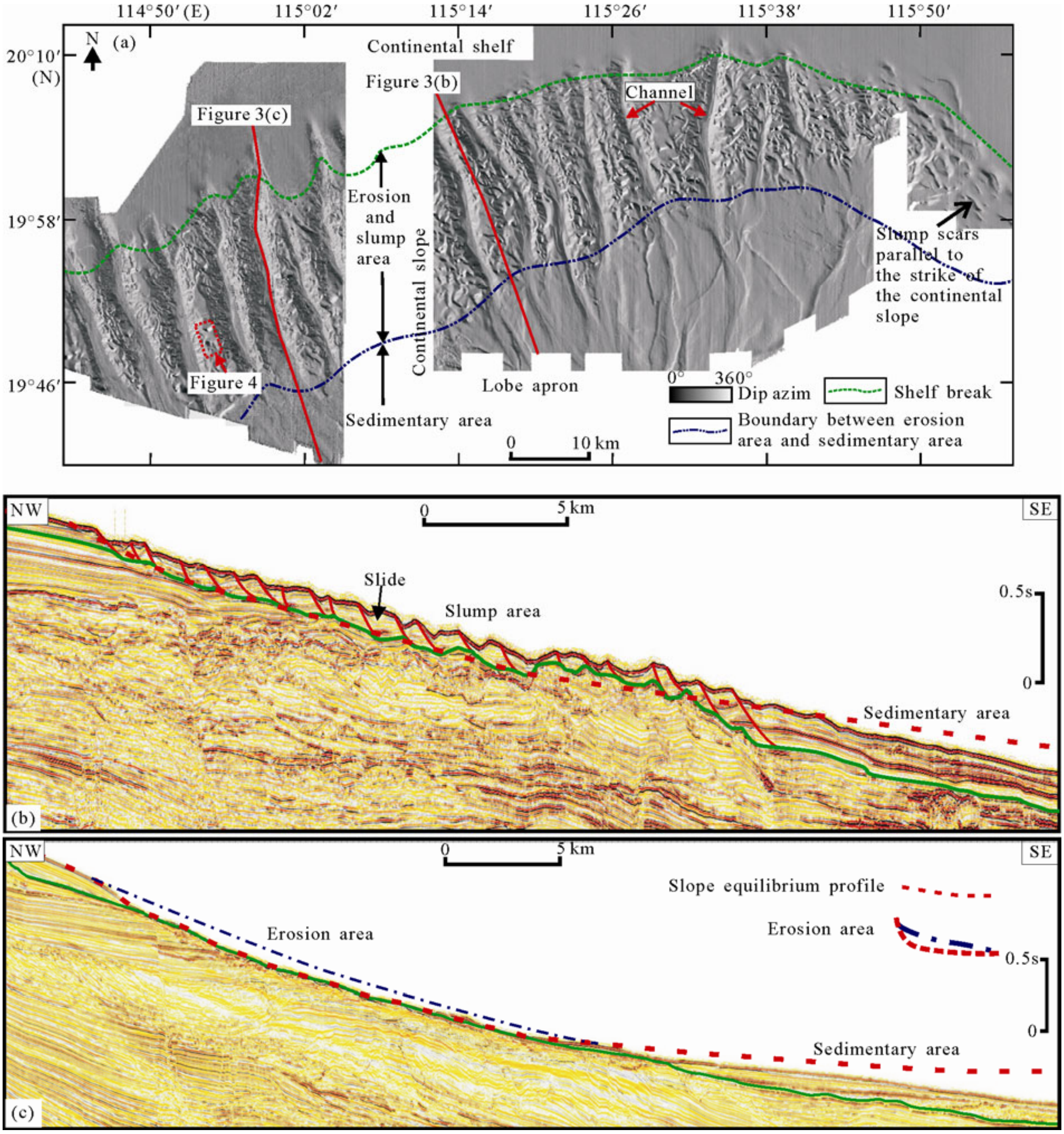

Figure 3 3-D image showing the slump-erosional channel-lobe systems in BYS. (a) Dip and azimuth map of the sea floor; (b) seismic profile via the inter channel area; (c) seismic profile along the channel thalweg.

ter. Most coarse-grained sediments were transported to the toe of the continental slope or deep-sea plain by gravity flow. Part of the coarse-grained sediments is composed of the basal lag deposits. Hemipelagic mud was deposited in the submarine erosion channels mostly during periods of gravity-flow depositional quiescence. Submarine channel wall slumping was developed due to channel wall instability caused by the long period erosion of the gravity flow. Slides are common within submarine erosion channels. Slides in a channel fill are in part derived from the channel walls but also have undergone a long-distance transport along the channel. Parts of slides are transported by gravity flow to the terminal of the channel and form the lobate MTDs.

A near-surface, 3-D seismic data set from the continental slope, BYS, reveals the migration-aggradation history of submarine channels (Figures 2, 5). Submarine channels, located in the lateral migration area, are characterized by lateral migration of the channel (Figure 5(a)). Lateral accretion units represent a gradual lateral change in the position of a channel. Lateral migration of submarine channels results in deposition (accretion) on the inner side of the channel bend and erosion on the outer side of the channel bend.

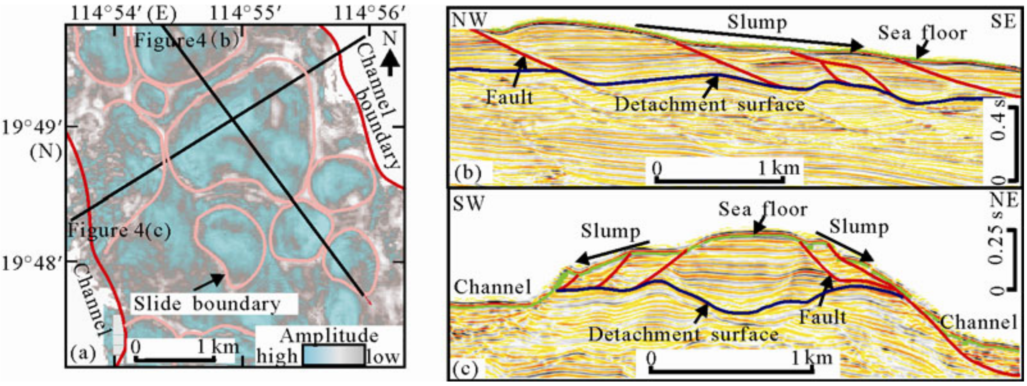

Figure 4 Polygonal fault pattern in Quaternary, BYS. (a) RMS attribute at seabed + 40 ms; (b) slumps along the slope; (c) slumps of the channel wall.

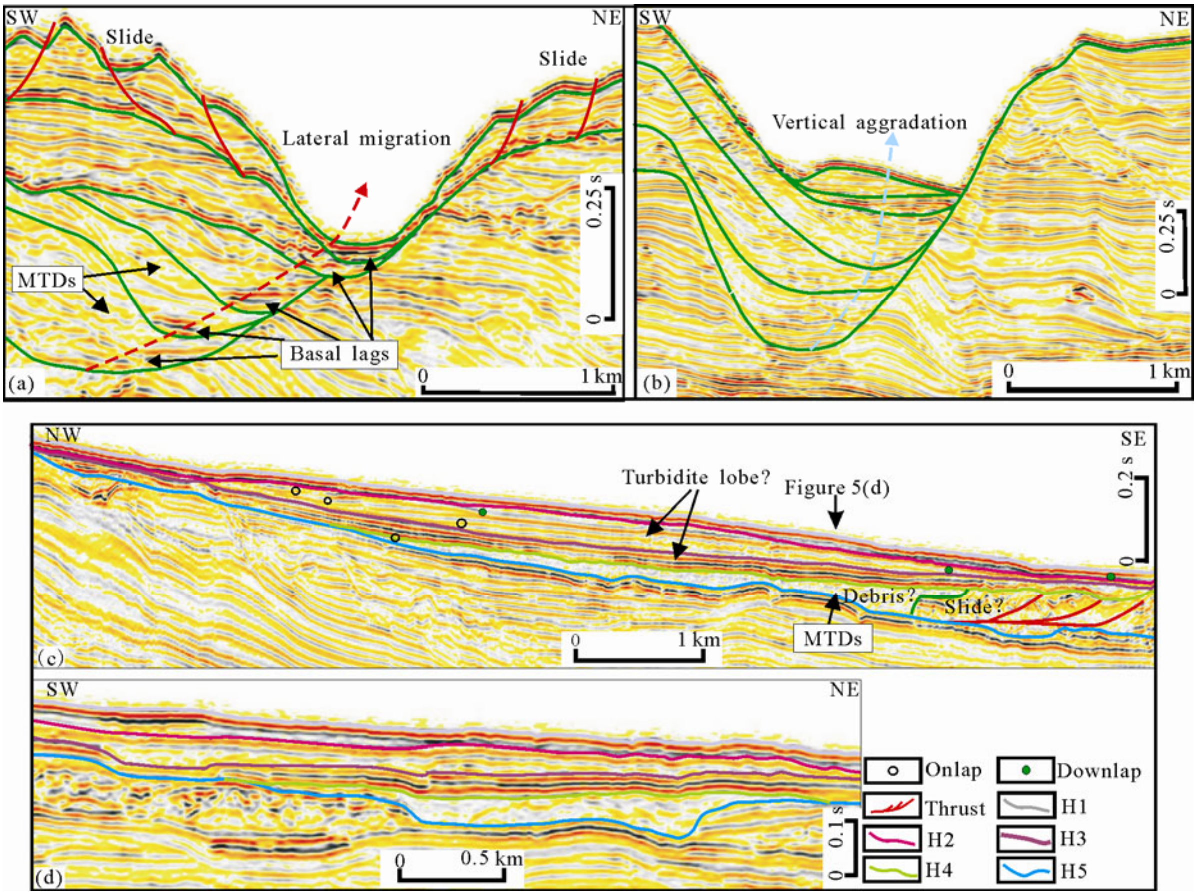

Figure 5 Typical seismic profiles showing the Quaternary channel-lobe deposit system in BYS. (a) Typical seismic profile showing the channel migration; (b) typical seismic profile showing the channel aggradation; (c) seismic profile across the lobe in dip direction; (d) seismic profile across the lobe in strike direction.

Submarine channels in the vertical aggradation area are characterized by vertical aggradation (Figure 5(b)). The sinuosity of a channel characterized by lateral migration is higher than that of a channel characterized by vertical aggradation. In general, the degree of submarine channel sinuosity is related to slope gradient along the channel and the percentage of silt/clay in the channel-fill sediment. Steep channel slope gradients tend to develop channels with a low sinuosity. Channels filled with fine-grained sediment are commonly characterized by a high sinuosity.

The seafloor of the intraslope basin lies below the slope equilibrium profile. The slope accommodation is controlled by the slope equilibrium profile and seafloor (Figure 1(b)). Gravity flows within the upper slope submarine channels are characterized by erosion and sediment bypass. A lobe forms at the terminal of each submarine channel. Several lobes compose a lobe apron. A deepwater sediment sequence is recognized through a typical seismic facies analysis of the formations between the seismic horizons H1 and H5 (Figure 5(c) and (d)). The lower formation is composed of MTDs, which are characterized by transparent chaotic seismic facies and high-amplitude chaotic reflections. Thrust blocks at the front of MTDs reflect a localized contraction. The MTDs are composed mostly of rocks similar to those of continental slope or local uplift. Variations of the seismic amplitude within the MTDs may reflect the change of the lithology and flow state (Figure 5(c). The MTDs are overlain by high amplitude, parallel or sub-parallel seismic reflections, which are interpreted to be turbidity lobes. The upper lobe in the slope direction has medium amplitude, sigmoidal reflection configuration (Figure 5(d)). Seismic reflection terminations such as onlap and downlap are observed in the seismic data.

5 Evolution of the deep-water gravity flow deposit system in BYS

5.1 Relationships between seismic facies and depositional processes

Deep-water depositional elements are revealed by high-resolution 3-D seismic reflections. Different seismic configurations indicate different sedimentary processes and record a variety of accommodation-filling successions [26]. A typical deep-water channel-lobe depositional system in response to active gravity flow is developed in the Quaternary strata of the study area (Figure 3(a)). As is shown in seismic profiles along the longitudinal axis of the depositional lobe (Figure 5(c)), basal chaotic sigmoidal seismic reflections are interpreted to be the progradational deposits composed of MTDs at the terminal of submarine channel (Figure 6(a)). The high amplitude, parallel to subparallel seismic facies are interpreted to be the aggradational turbidite lobes (Figure 6(b)). Medium amplitude, sigmoidal seismic reflections with typical onlap reflections probably represent the retrogradational lobe as a result of the waning turbidity current (Figure 6(c)). The three types of deposits inferred from seismic facies constitute the filling of the intraslope basin. The MTDs were transported long distance and deposited in the front of the intraslope basin. Due to the rough topography of basal MTDs and a relatively reduced sediment supply, the two upper lobes migrated headward.

5.2 Vertical evolution of the submarine channel-lobe deposit system

Due to the influence of the rifting, the continental slope on the northern SCS exhibits a complex slope and a large scale intraslope basin was developed (Figures 1(b), 7(a)). The continental slope of the northern SCS is classified as an above-grade slope, because the sea floor of the continental slope is not consistent with the slope equilibrium profile (Figure 7(a)). The transition from an above-graded slope to a graded slope is made by the erosion, slump, bypass, and deposition. The upper slope is dominated by slump, erosion, and bypass. A lot of erosion submarine channels were developed because the sea floor lies above the slope equilibrium profile (Figures 1(b), 3(a)). In the situation that the sea floor lies below the slope equilibrium profile (Figure 1(b)), the intraslope basin provides the slope accommodation space for gravity flow deposition. Because the accommodation space is greater than sediment supply, the intraslope basin is dominated by gravity-flow deposition. Confined gravity flow is contained in a basin too small to allow multidirectional flows [5, 27]. Due to the limit of the submarine channel walls, the gravity flows that bypass, erode, and are

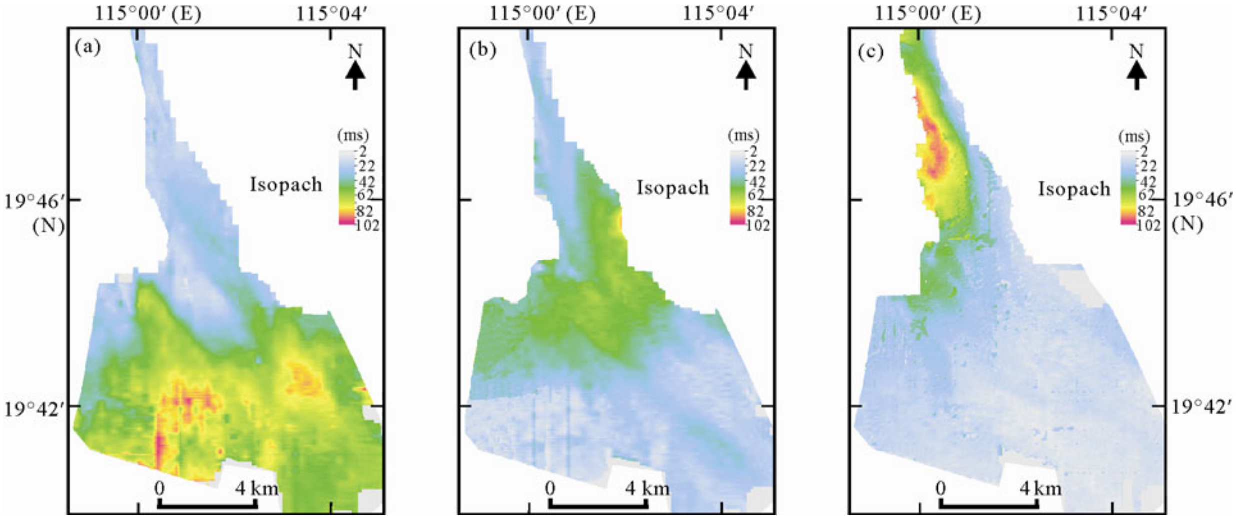

Figure 6 Isopach maps of the lobes in different stages. (a) Isopach map of the H4-H5; (b) isopach map of the H3-H4; (c) isopach map of the H2-H3.

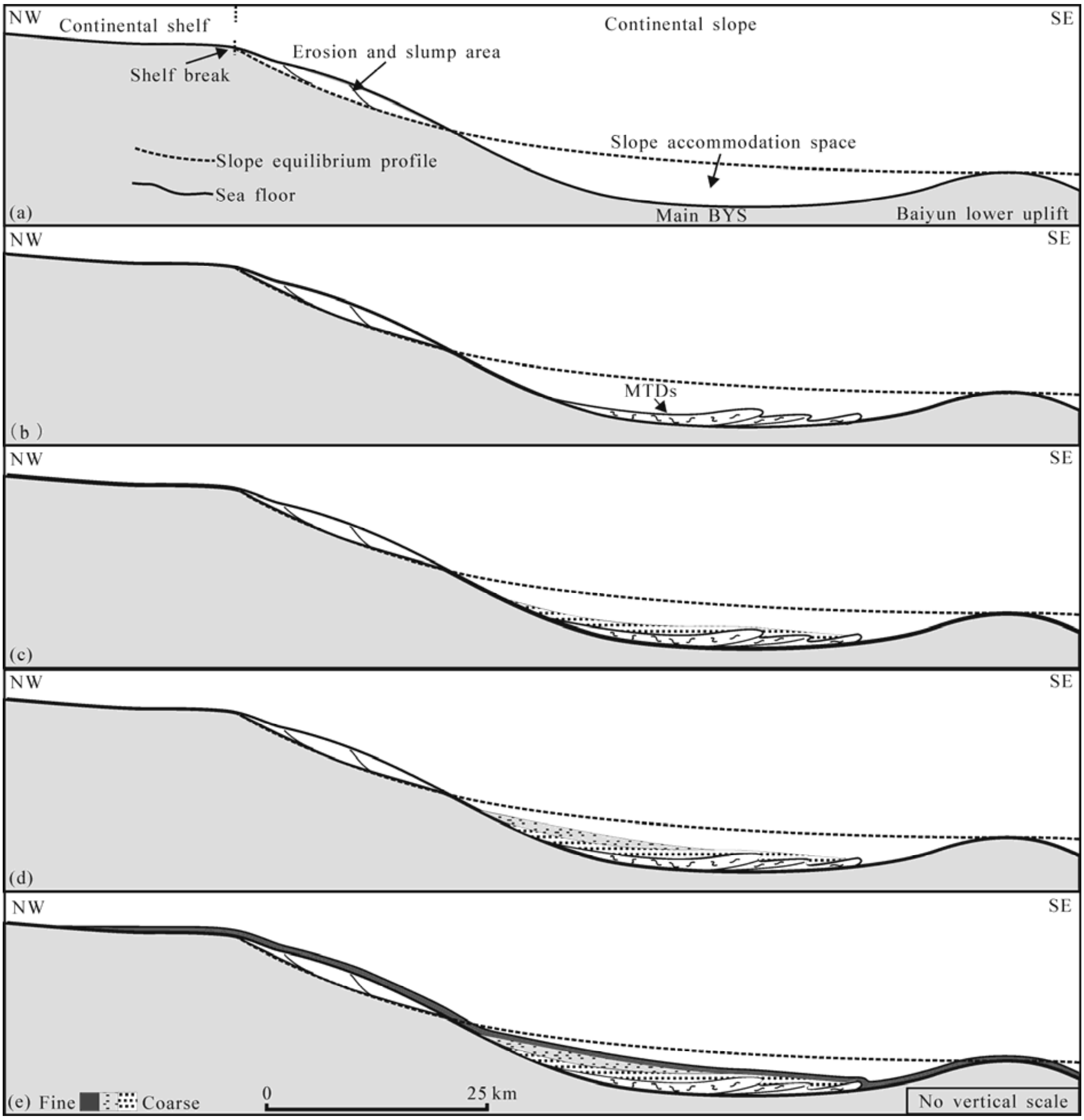

Figure 7 Profiles illustrating the evolution of the channel-lobe system.

deposited within the upper slope submarine channels are confined gravity flows. When the gravity flows reach the intraslope basin, which provides an accommodation space larger than sediment supply, the gravity flows will fill the accommodation space and then change into unconfined gravity flows forming the depositional lobes.

The gravitational instability of the shelf margin and upper continental slope result in the slumps, which will produce gravity flows. Gravity flows erode and bypass the submarine channels and deposit lobate-shaped MTDs at the terminal of submarine channels (Figure 7(b), white layer with curved lines). Thrust slides within the MTDs indicate a local contraction (Figure 5(c)). The MTDs deposited in the intraslope basin have a lobate shape (Figure 6(a)). At this stage, the gravity flow deposits that are characterized by progradation developed the slides, and debris flow dominated submarine channel- lobe apron system (Figure 7(b)). The upper continental slope is a major erosion zone because the sea floor lies above the slope equilibrium profile. Continuous erosion of the gravity flow within the submarine channels results in oversteepened channel walls and consequently channel wall slumps. An intraslope basin provides the slope accommodation space for the slides caused by slumping along the slope direction, slumping of submarine channel walls, and the slumping of the shelf margin. Because the slope accommodation space was larger than the volume of gravity flow, the lobate MTDs were formed in the intraslope basin. The MTDs originated from the slumps of shelf margin, continental slope, and submarine channel walls. The MTDs are composed of the same lithologies as those of the continental slope and shelf margin sediments. Generally, most MTDs are interpreted to be shale-rich.

Thrusting within the MTDs resulted in a rough topography and produced many minibasins. Subsequent gravity flows were deposited within the minibasins on the surface of the MTDs (Figure 7(c), white dotted layer). The persistent gravity flow formed the aggradational lobe within the early minibasins. Coarse-grained sediments were transported to the intraslope basin through the upper slope submarine channels.

Due to the waning of the gravity flow, sediments were deposited headward and formed the retrogradational lobe (Figure 7(d), gray dashed layer). The gravity flow formed lobate-shaped sediment bodies at the terminals of the submarine channels, which onlap the continental slope.

During the quiescent stage of gravity flow, the older lobes were overlain by pelagic deposits (Figure 7(e)). Gravity flow ceased at this stage. The entire slope topography was covered by a drape of pelagic sediment, which was nearly uniform because pelagic deposition is not influenced by the slope topography, the slope equilibrium profile, and the accommodation space. A typical deepwater depositional cycle, which is MTDs-lobe-pelagic drape sediments, is observed in the study area.

5.3 Plain view evolution of the submarine channel-lobe systems

The sea floor of the upper slope lies above the slope equilibrium profile. Confined gravity flows are characterized by erosion and sediment bypass in the upper slope submarine channel. Confined gravity flow was transformed into unconfined gravity flow and developed lobate deposits within the intraslope basin, which provided accommodation space for gravity flow deposition (Figure 8).

(1) Depositional evolution of the deep-water gravity flow can be divided into four stages. Progradational stage, aggradational stage, retrogradational stage, and a quiescent stage of gravity flow. The lithology of the continental slope is dominantly pelagic drape sediments deposited during periods of gravity flow depositional quiescence.

(2) Progradational stage (Figure 8(a)). An intraslope basin was formed in the Quaternary continental slope of the BYS. Because the seafloor of the upper continental slope lies above the slope equilibrium profile, there is no slope accommodation in the upper continental slope. The upper continental slope is characterized by slump and erosion. The intraslope basin provides an accommodation space for gravity flow deposition. The slump-erosion channel-lobate progradational mass-transport depositional system was developed in Quaternary continental slope in BYS. During this stage, the erosional submarine channels were the major conduits for the transportation of coarse-grained sediment into deep water. Slope accommodation in the intraslope

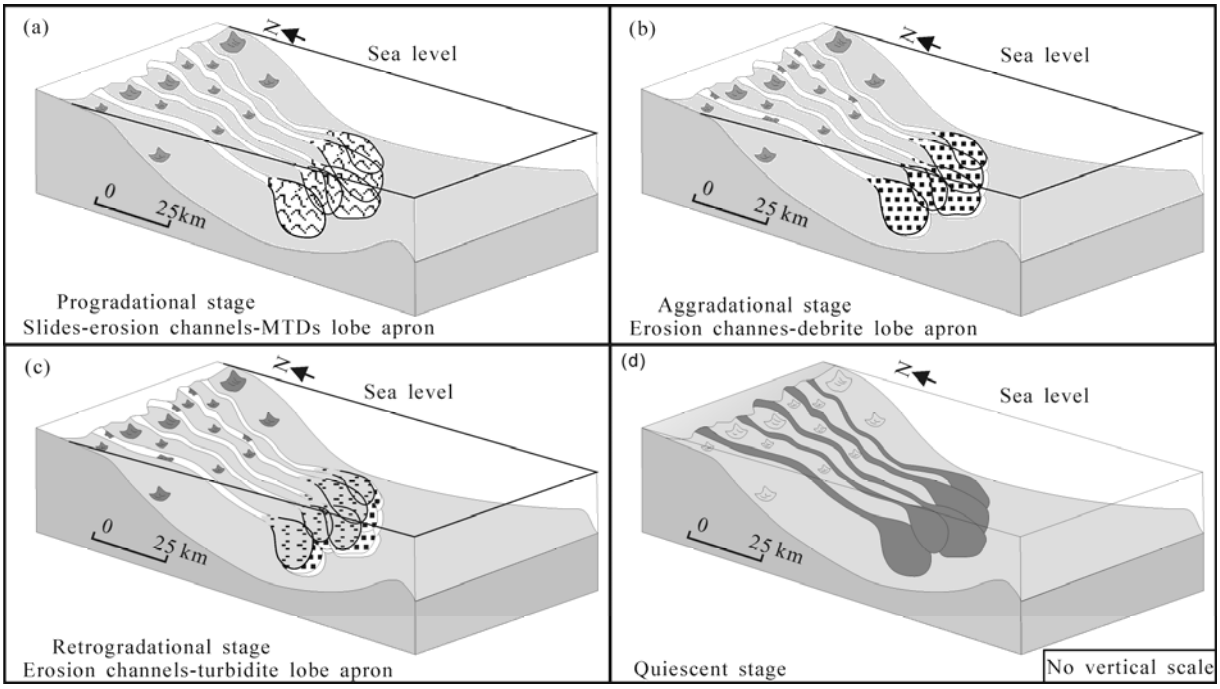

Figure 8 Planar maps showing the spatial evolution of the channel-lobe system.

resulted from slumps along the slope dip direction and the channel wall slump developed the debris-dominated basin exceeded the volume of the gravity flow. Confined gravity flow was transformed into unconfined gravity flow and developed the lobes that are composed of mass- transport deposits, such as slides and debris. MTDs were lobate deposits in the intraslope basin. The volume of the gravity flow resulted from the failure of the upper slope and channel walls was smaller than the accommodation space of the intraslope basin, and thus the gravity flow formed lobate deposits at the terminal of submarine erosion channels. Individual lobes merge with adjacent lobes to form a continuous and more extensive apron (Figures 3(a), 8(a)). Several minibasins are present, indicating irregular bathymetry caused by local contraction within the lobate MTDs (Figures 5(c), 7(b)).

(3) Aggradational stage (Figure 8(b)). Gravity flow composed of coarse-grained sediments from the continental shelf margin passed through the submarine channel. Oversteepened walls were formed by the erosion of the gravity flow. Slumping was triggered by gravitational instability of the submarine channel walls. Polygonal faults were formed by the interaction between the slumps along the slope direction and the channel wall slumps. Gravity flows were confined in the older minibasins. Erosion channels-aggradational lobe apron systems were formed during this stage.

(4) Retrogradational stage (Figure 8(c)). The early slumping, erosion, and deposition produced a gentle slope topography. The slope equilibrium profile varies along with the slope topography. When the supply and strength of the gravity flow were weak, gravity flow deposits onlapped the slope, producing the retrogradational lobe apron at the terminals of the submarine channels.

(5) Quiescent stage of gravity flow (Figure 8(d)). Gravity flow became rare or ceased at this stage. The predominantly pelagic deposits commonly draped the entire slope topography.

6 Conclusions

High-resolution 3-D seismic data and seismic imaging techniques are used to analyze the evolution of the gravity flow deposit systems on the continental slope of northern SCS. The research is helpful in predicting the distribution and quality of the deep-water gravity flow sediment.

The Quaternary continental slope of the northern SCS is an above-graded slope. The intraslope basin lies within the above-grade continental slope. Slump, erosion and deposition tend to produce a gentle topography and consequently a graded slope. The upper continental slope above the slope equilibrium profile is dominated by erosion and slumping. Slides, slumps, and erosional channels were developed within this continental slope. The intraslope basin below the equilibrium profile provided an accommodation space for gravity flow sediments to deposit. Lobe apron was developed within this basin. Under the influence of the gravity flow supply, gravity flow duration, continental slope topography, equilibrium profile, and accommodation, a slump-erosion channel-lobe depositional system developed in Quaternary continental slope in BYS.

Gravity flow sediment supply, duration, continental slope topography, equilibrium profile, and accommodation are the main controlling factors for the variation of deepwater gravity flow depositional system. It is unrealistic to accurately summarize and predict the gravity flow depositional system with any single model.

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