Occurrence of submarine canyons, sediment waves and mass movements along the northern continental slope of the South China Sea

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In this study, we reveal a series of newly discovered submarine canyons, sediment waves, and mass movements on a flat and smooth seafloor using high-resolution, multi-beam bathymetry and shallow seismic surveys along the northern slope of the South China Sea. We also describe their geomorphology and seismic stratigraphy characteristics in detail. These canyons display U-shaped cross sections and are roughly elongated in the NNW–SSE direction; they are typically 8–25 km long, 1.2–7 km wide, and form incisions up to 175 m into Pliocene–Quaternary slope deposits at water depths of 400–1000 m. Slide complexes and the sediment wave field are oriented in the NE–SW direction and cover areas of approximately 1790 and 926 km², respectively. Debris/turbidity flows are present within these canyons and along their lower slopes. Detailed analysis of seismic facies indicates the presence of six seismic facies, in which Cenozoic strata located above the acoustic basement in the study area can be roughly subdivided into three sequences (1–3), which are separated by regional unconformities (Tg, T4, and T3). By combining these data with the regional geological setting and the results of previous studies, we are able to determine the genetic mechanisms used to create these canyons, sediment wave field, and mass movements. For example, frontally confined slide complexes could have been influenced by high sedimentation rates and high pore pressures. A series of very large subaqueous sediment waves, which record wavelengths of 1.4–2 km and wave heights of 30–50 m, were likely produced by interactions between internal solitary waves and along-slope bottom (contour) currents. Canyons were likely initially created by landslides and then widened laterally by the processes of downcutting, headward erosion, and active bottom currents and debris/turbidity flows on canyon floors. We therefore propose a three-dimensional model to describe the development of these mass movements, the sediment wave field, and canyons. The four stages of this model include a stable stage, followed by the failure of the slope, and subsequent formations of the sediment wave field and canyons.

Keywords. South China Sea; canyons; sediment waves; mass movements; continental slope.

1. Introduction

Mass movements, such as slides, liquefied-flow/debris-flow deposits, and turbidity currents, are recorded along continental margins around the world (e.g., Shor and Piper 1989; Weaver *et al.* 2000; Locat 2001; Qin *et al.* 2015). The formation of a mass movement is complicated and is often linked to factors such as high sedimentation rates, unfavourable soil layering, earthquakes, or climate variability, which affect sedimentation processes, erosion/oversteepening, and fluid flow (e.g., gas, hydrates) (Pecher *et al.* 2005; Bangs *et al.* 2010; Li *et al.* 2013; Qin *et al.* 2015). Additionally, mass movements can be affected by a combination of these factors (Locat and Lee 2002; Masson *et al.* 2006; L'Heureux *et al.* 2013).

Sediment waves are found in shelves, slopes, and abyssal plains in oceans throughout the world (e.g., Ediger *et al.* 2002; Cattaneo *et al.* 2004; Arzola *et al.* 2008; Reeder *et al.* 2011; Gong *et al.* 2012), and typically record meter- to kilometer-scale wavelengths and wave heights of several meters (Wynn *et al.* 2000), with crests that are positive, relative to the surrounding seafloor region. These sediment waves are formed over time as a result of differential deposition or erosion from successive turbidity currents, or can instead be attributed to downslope-flowing turbidity currents and along-slope, bottom-flowing (contour) currents (Wynn and Stow 2002).

Submarine landslides on passive continental margins are predominantly distributed along slopes and are often associated with sediment waves, submarine canyons, or channel systems (e.g., Greene *et al.* 2002; Chaytor *et al.* 2009; Puga-Bernabeu *et al.* 2011; Li *et al.* 2015; Chen *et al.* 2016; Li *et al.* 2016). Although much research has been performed in this field (Lüdmann *et al.* 2005; Gong *et al.* 2012; Chen *et al.* 2014), most studies have used multi-channel seismic data and well data from the continental shelf and slope areas, thereby omitting detailed information about the seafloor geomorphology and shallow seismic sequences of canyons and mass movements along the northern slope of the South China Sea. For example, one study focused on using a 2D multi-channel reflection seismic dataset to define depositional characteristics and processes of along-slope currents related to a seamount, but ignored the additional canyons, sediment waves and mass movements in the study area (Chen *et al.* 2014).

In this study, we document a series of newly discovered submarine canyons, sediment waves and mass movements that developed during the Late Miocene–Quaternary along the northern continental slope of the South China Sea (figure 1). A series of canyons/gullies in this region extend downslope, roughly in the NNW–SSE direction. The lateral spacing between these canyons is generally 2–10 km. Unlike many previously studied canyons and channels, these submarine canyons show no evidence of migration (e.g., Zhu *et al.* 2010; Jobe *et al.* 2011). Submarine slide complexes and a sediment wave field were also discovered in this region. We investigate their morphology and shallow seismic sequence features, and then analyze the relationships between mass movements, sediment waves and canyons to produce a conceptual model to explain their evolution. The objective of this study is to explore the relationship between canyons, sediment waves, and mass movements to better understand sedimentary processes along marginal seas.

2. Geological background

2.1 Geological setting

The South China Sea is a large marginal sea with an area of approximately $350 \times 10^4 \text{ km}^2$ that is located in the western Pacific Ocean. The topography of the northern slope of the South China Sea varies greatly between the shelf and the slope; its water depth ranges between 200 and 2000 m, with the fathom line oriented roughly parallel to the coastline. Seamounts and scarps are well developed, and several sedimentary basins, such as the Qiongdongnan Basin (QDNB) and the Pearl River Mouth Basin (PRMB), extend to the NE–SW with a maximum sedimentary thickness of 10 km (Peng *et al.* 2004) (figure 1). The PRMB, which is located in the central part of the northern margin of the South China Sea, is one of the most important petroliferous basins in the region. The PRMB has experienced ongoing tectonic subsidence beginning in the Middle Miocene (Wu *et al.* 2005). The Pearl River represents a major sediment input point into the northern South China Sea margin (figure 1), delivering approximately 90×10^6 tons of sediments annually to the river mouth (Lüdmann *et al.* 2001).

The general stratigraphic column of the PRMB is shown in figure 2. Paleocene to Lower Oligocene strata comprise fluvial–lacustrine sediments in

Figure 1. Bathymetry map (solid black line) and modern winter surface circulation in the northern South China Sea. The outlines of the Pearl River Mouth Basin and Qiongdongnan Basin are shown with red dashed lines (after Sun *et al.* 2012, 2016). Numbers. 1: Kuroshio Current; 2: South China Sea Branch of Kuroshio; 3: Guangdong coastal current; 4: South China Sea Warm Current; 5: Longshore current; 6: Summer monsoon. The paths of the currents are mainly derived from Fang *et al.* (2009), although the path of the longshore current is from Liu *et al.* (2010). The cyclonic (counter-clockwise) circulation pattern is largely controlled by northeastern winter monsoon winds, whereas the monsoon winds reverse during the summer, resulting in an overall anti-cyclonic circulation. Insert (top left): regional setting of the South China Sea. The study area (black square) is located within the Pearl River Mouth Basin.

discrete rifts; in particular, Eocene sediments contain dark lacustrine mudstones, which represent the major source rocks for hydrocarbons in this area. Upper Oligocene sediments are transitional (coastal and littoral). Neogene strata contain marine formations that constitute a generally transgressive sequence, indicating a trend of sea level rise in the basin that contrasts with the contemporaneous global trend of relative sea level fall (Haq *et al.* 1987) (figure 2). Eight regional seismic unconformities have also been identified and are classified as T2 to T9 and Tg (figure 2). The unconformities T7 (30 Ma) and T6 (23 Ma) are widely considered to represent breakup unconformities separating the lower syn-rift from the upper post-rift mega-sequences in the PRMB (e.g., Xie *et al.* 2013).

2.2 Oceanographic conditions

Previous research suggests that the energetic circulation of the northern South China Sea is complicated due to the influence of the east Asian monsoon and the intrusion of the Kuroshio Current (Su 2004; Xue *et al.* 2004; Fang *et al.* 2005). The ocean currents in the region between the shelf and the slope mainly include the longshore current, the Guangdong Coastal Current (GDCC), the South China Sea Warm Current (South China Sea WC), and the South China Sea Branch of the Kuroshio Current (South China Sea BK) (figure 1) (e.g., Liu *et al.* 2010). The ocean circulation in this region can be divided into surface circulation (occurring at water depths of <350 m), intermediate water circulation (350–1350 m), and

Figure 2. Schematic overview of the major structural and tectonic events in the northern South China Sea since the Paleocene (modified from Li *et al.* 2009; Wang and Li 2009), with the general tectonic evolution history of the Pearl River Mouth Basin (Li *et al.* 2009; Xie *et al.* 2013) and their respective regional sea-level changes (Xu *et al.* 1995; Xie *et al.* 2014) and comparisons to the global range (Haq *et al.* 1987).

deep water circulation (>1350 m) (Chen and Wang 1998).

The surface circulation of the South China Sea is mainly controlled by the east Asian monsoon and strongly influenced by the Kuroshio intrusion (Shaw and Chao 1994; Su 2004; Liu *et al.* 2010). Within the South China Sea, surface (winter) waters are mixed with deep waters from the western Pacific and are returned through the Luzon Strait at upper (summer) and intermediate depths

(Yuan 2002; Qu and Lindstrom 2004; Wang and Li 2009; Xu *et al.* 2014).

The Kuroshio Current is an important western boundary current of the North Pacific Ocean that flows northwards, year-round, along the Philippines and the east coast of Taiwan. When this current passes through the Luzon Strait, one branch of the Kuroshio Current intrudes into the north-eastern South China Sea, thus strongly affecting the circulation pattern of the South China Sea

(figure 1). The intermediate water circulation in the northern South China Sea is considered to be anti-cyclonic and is commonly referred to as the Kuroshio Current, which may contain a local component of the South China Sea warm current (Wang *et al.* 2010; Gong *et al.* 2012).

The South China Sea deep water circulation has been proven to be cyclonic (Shao *et al.* 2007; Wang *et al.* 2010; Gong *et al.* 2012; Li *et al.* 2013). This circulation is influenced by the intrusion of southward-flowing North Pacific deep water through the Bashi Channel (e.g., Lüdmann *et al.* 2005; Gong *et al.* 2012), where the average bottom current velocity exceeds 0.15 m/s and the maximum velocity reaches 0.3 m/s at water depths of 2500–2600 m (e.g., Xie *et al.* 2009).

Some researchers have suggested that the circulation system of the South China Sea has existed since the Middle Miocene (Zhao 2005; Zhu *et al.* 2010; He *et al.* 2012). Consequently, modern oceanographic conditions can be useful analogues for deducing ancient hydrodynamic processes.

3. Data and methods

Multi-beam bathymetry data from the study area were acquired by using the R/V FENDOU-5 in 2008, equipped with a hull-mounted Simrad EM1002 95 kHz system ($2^\circ \times 2^\circ$ configuration). Multi-beam data were corrected for heading, depth, pitch, heave and roll. Post-processing was conducted using the CARIS HIPS system (version 7.1), which is a submarine mapping software system. A 100×100 m bathymetric grid of the shelf break zone area was produced, and visualization of the bathymetric data was conducted using Golden Software Surfer (v9.7.543) and Global Mapper (v11.02).

A multi-channel seismic dataset was acquired using a 3000-m long streamer with 240 channels (using a trace interval of 12.5 m), as well as a tuned air gun source with a total volume of 8×20 in³ and a shot interval of 25 m. The sampling interval was defined as 1 ms. The streamer depth and source depth were defined as 5 and 3 m, respectively, and the dominant frequency of the data was approximately 80 Hz within the shallowest 1500 m of the water depth. These data were then processed using the Echos (Focus) 1.0 software. The high-resolution single-channel seismic source used to acquire these data was a 210 in³ GI-Gun that was shot at a distance of ~ 55 m and operated at a

high air pressure of 150 bar (2000 psi). Data were acquired using a 55-m long Syntrol GEOSENSE48 streamer equipped with separately programmable hydrophone subgroups. These data were digitally recorded at a sampling frequency of 4 kHz over 3 s time intervals. In this study, the average velocity of the water column is defined as 1519 m/s, and the vertical scale on all seismic profiles illustrated in this paper represents a two-way travel time. All original data were converted to the Society of Exploration Geophysicists (SEG-Y) format and further processed using Geovation 2D software at the data processing center of the Guangzhou Marine Geological Survey.

4. Results

4.1 Morphological descriptions

In cross-section, gullies are V- or U-shaped and are typically narrower, shorter and of lower relief than submarine canyons (Field *et al.* 1999; Jobe *et al.* 2011; Lonergan *et al.* 2013). Shepard (1965) determined that submarine canyons are V-shaped and cut into rock walls, whereas other canyons in global slope margins range from U-shaped to broadly V-shaped (Jobe *et al.* 2011; Iacono *et al.* 2014). Therefore, shape (i.e., V-shaped *vs.* U-shaped) is not a consistent criterion for discriminating between slope canyons and gullies. In non-technical terms, a ‘canyon’ is defined as a ‘deep valley or gully’ (Random House Webster’s College Dictionary, 2000). In this paper, we differentiate between slope gullies and canyons on the basis of length and depth, rather than shape: gullies are 0–100 m deep and <15 km long, whereas canyons are deeper than ~ 100 m and longer than 15 km.

Analysis of a shaded seafloor image of the study area constructed using multi-beam bathymetry data reveals a mutually parallel network of submarine canyons and gullies (figure 3). The average gradient of the continental slope is 0.68° , although a marked change (16° – 26°) occurs along the flanks of the canyon walls (figure 4). Submarine canyons and gullies that are oriented downslope and record variable morphology comprise the major physiographic features of the flat upper continental slope in the study area (figures 3 and 4). Numerical measurements of individual canyons/gullies (i.e., length, width, canyon relief and maximum slope gradient) are shown in table 1. Most canyons cut into the upper slope, are deeply incised and are commonly U-shaped (figures 3–4).

Figure 3. Bathymetric relief image of the study area, showing the network of canyons and gullies. Bathymetric contours are spaced every 100 m at water depths <1000 m. Brown dashed lines indicate the sediment wave field; blue and black lines represent the multi-channel and single channel seismic profiles, respectively.

The study area contains two larger canyons (C1 and C2) that are approximately 5–7 km wide (but become as narrow as 4 km towards the canyon heads), and approximately 24 km long. These canyons record a general NNW–SSE orientation, but turn slightly northward at a water depth of 500 m. The canyon heads do not indent towards the inner shelf; instead, they initiate at a water depth of 400 m. The two canyons exhibit a straight course and disappear at a water depth of 900 m. The wide and flat bottoms of the canyons are incised by a U-shaped axial thalweg up to 175 m deep below their adjacent upper flank shoulders, with their sidewalls dipping up to approximately 12° (table 1, figure 4). The eastern flanks of these canyons are typically steeper than the western flanks. The dips of these canyons range from 4° to 12.58°, with most dips falling between 5° and 9°. Although the two

canyons record similar shapes, lengths, widths and incision depths, the bottom of canyon C2 is wider than that of canyon C1. Canyon C1 displays a small branch on the western sidewall; this narrow, linear branch is approximately 60 m deep, located at a water depth of 477–647 m, and is oriented in the NNW–SSE direction (figures 3 and 4).

Five additional finger-shaped smaller canyons/gullies, each about 8–19 km long, also occur at water depths of 450–1000 m. Canyon C3 and Gully C4 record similar ‘pear-shaped’ outlines on the upper slope of the study area. Canyon C3 is located at a water depth of 700–1500 m and extends to the lower slope, whereas Gully C4 is shorter and narrower than Canyon C3. Gullies C5 and C6 are also parallel, and both trend in the NNW–SSE direction. Gully C6 becomes wider downslope towards its end at a water depth of 600 m. Its sidewalls

Figure 4. Slope gradient map of the study area with vertical cross profiles. The locations of the profiles are in the upper map.

record slope gradients of $\sim 4.5^{\circ}$ – 8.6° (table 1, figure 4). Gully C7 is located at a water depth of 500–700 m and is parallel to Canyon C2 to the west (figures 3 and 4).

Multi-beam bathymetry data demonstrate the presence of sediment waves in the study area. These bathymetry data indicate that the water depths in the sediment wave field are 500–900 m. Sediment waves are oriented NE–SW and cover a total area of approximately 926 km^2 , with a maximum length of 85 km and a maximum width

of 14.8 km. The seafloor between the waves is smooth and slopes approximately 2° – 4° towards the southeast; the steepness of the slope where sediment waves are found is approximately 3° – 5° . Observed wavelengths in this field vary from 1.4 to 2 km, with wave heights of 30–50 m. Sediment waves begin to form after the slope steepens beyond a slope angle of approximately 2° , and this wave field disappears on gentler slopes with slope angles of $<2^{\circ}$ (figures 3 and 4). The sediment waves on the central field also appear to be

Table 1. Summary of main metric parameters of canyons and gullies.

Location	Length (km)	Head water depth (m)	Orientation	Width of top (km)	Width of bottom (km)	Maximum incision (m)	Maximum slope angle of side walls	Shape	Type
C1	25	477	NNW-SSE	4–5	1.3–1.7	175	10.2°	Wide base	Canyon
C2	24	470	NNW-SSE	5–7	1–2.5	175	12.2°	Wide base	Canyon
C3	21	671	NNW-SSE	2–3	1–1.2	100	8.7°	Finger pear	Canyon
C4	8	792	NNW-SSE	1.4–2	0.5–0.7	60	6.1°	Finger pear	Gully
C5	8.9	500	NNW-SSE	1.7–2	0.5–0.9	40	5.4°	Finger linear	Gully
C6	11	500	NNW-SSE	2–3.7	1.2–1.9	80	5.6°	Finger wide base	Gully
C7	9.5	540	NNW-SSE	1.2	0.7–1.0	35	5.5°	Finger linear	Gully

interrupted by the presence of some incipient submarine canyon heads (figures 3 and 4). Overall, the sediment waves covering the continental slope record rounded crests and wide troughs; they are parallel to sub-parallel, and occasionally bifurcate the bathymetric contours.

4.2 Stratigraphy

4.2.1 Seismic facies

We are able to distinguish six main seismic facies based on seismic reflector characteristics and geometric data (table 2). A well-stratified facies (facies 1) is interpreted to comprise hemipelagic sediments (H), due to the presence of widespread, continuous reflectors of a uniform seismic nature infilling irregular topography. Facies 1 is observed within sequences 1, 2, and 3. A weak-to-moderately stratified facies (facies 2) is characterized by subparallel-to-parallel, variable amplitude reflectors with poor-to-moderate continuity. This facies contains locally transparent and/or chaotic seismic zones. We therefore interpret facies 2 to comprise mixed turbidity/hemipelagic sediments (MTH); this facies is observed within sequence 2. Facies 3 is characterized by a structureless-to-chaotic facies, low-to-moderate amplitudes, short reflectors, and near-transparent zones. We therefore interpret facies 3 to reflect debris/turbidity deposits formed by mass-transported hemipelagic sediments (TH). Facies 3 is developed in sequence 3. Facies 4 has a distinct, lens- or wedge-shaped external form and exhibits chaotic and discontinuous internal seismic characteristics, but mainly occurs along or near the base of the canyon and the slope region. The lens-shaped external form, along with the lack of a coherent internal structure, is thus interpreted to reflect a series of slide complexes (SD). This facies is observed within sequences 1, 2, and 3. Facies 5 displays a U-shaped geometry and is filled by a chaotic facies. Facies 5 is observed within sequences 1, 2, and 3 and is interpreted to reflect buried channel (C) deposits that formed within a high-energy setting. Facies 6 records wave-like structures and a regular, rhythmic bedding morphology with continuous or near-continuous reflections. This facies is observed within sequences 2 and 3 and is interpreted to reflect sediment waves (SDW) that formed from the interaction of various depositional and gravity deformation processes.

Table 2. Summary of seismic facies characterizing the dominant seismic sequences.

Seismic appearance	Facies	Seismic reflector characteristics	Geological interpretation	Observed in sequences
F1	Well-stratified, widespread, continuous reflectors with uniform seismic characteristics	Hemipelagic sediments (H)	Sequences 1, 2, 3
F2	Weakly-to moderately stratified, subparallel-to-parallel, variable amplitude reflectors with poor-to-moderate continuity	Mixed turbidite/hemipelagic sediments (MTH)	Sequence 2
F3	Structureless-to-chaotic, low-to-moderate amplitude, short reflectors and nearby transparent zones	Debris/turbidity deposits formed by mass-transport of hemipelagic sediments (TH)	Sequence 3
F4	Distinct, lens- or wedge-shaped external form, chaotic and discontinuous internal seismic characteristics	Slide complex (SD)	Sequences 1, 2, 3
F5	U-shape incised fill of chaotic facies	(Buried) Channel (C)	Sequences 1, 3
F6	Wave-like structures, regular, with continuous or near-continuous reflections	Sediment waves (SDW)	Sequences 2, 3

4.2.2 Structure of Late Cenozoic strata

Three regional unconformities, namely the Tg (65 Ma), T4 (11.5 Ma), and T3 (5.3 Ma) unconformities, and sedimentary sequences that overlie the basement can be identified in seismic profiles obtained within the study area (figures 5 and 6) based on published regional seismic stratigraphy data, general stratigraphic columns (figure 2) (Sun *et al.* 2008; Li *et al.* 2009; Wang and Li 2009; Yuan *et al.* 2009; Ding *et al.* 2011) and correlations with nearby 2D seismic lines (Chen *et al.* 2014). The pre-Cenozoic basement is located underneath the Tg unconformity, whereas Paleogene–Middle Miocene deposits are present between the Tg and T4 unconformities and Late Miocene deposits exist between the T4 and T3 unconformities. The T3 unconformity and the seafloor mark the boundaries of Pliocene–Quaternary strata.

The Tg sequence boundary likely represents the top of a lava intrusion produced by magmatic activity occurring within the Cenozoic period during the syn-spreading of the PRMB. Reflectors characterized by chaotic, discontinuous, and low-reflection amplitudes represent the acoustic basement in the seismic data. This basement is buried underneath a thick cover of sediment (varying between 1.4 and 2-s two way travel time (TWT) in thickness) that is only exposed near the seamount (figure 6).

The thick Cenozoic succession above the acoustic basement can be roughly subdivided into three sequences, which are separated by the regional T4 and T3 unconformities. The lower sequence 1, which is located between Tg and T4, is interpreted to be Paleogene–Middle Miocene in age. The T4 angular unconformity is widespread and is only absent at seamounts. Sequence 1 is distributed at a relatively even thickness from the west to the east but thins to the southeast. The seismic reflections within sequence 1 generally display hummocky clinoform reflectors with very high amplitudes but relatively low continuity, and it ultimately pinches out against the seamount. Displaced reflectors within sequence 1 are commonly accompanied by a series of normal faults that displace sediments up to T3 (figures 5 and 6). The folded and faulted lower sequence 1 reflects the occurrence of extensive tectonic activity during the post-rift stage of the basin. Based on the wide distribution of these strata and their low degree of internal deformation, we infer that they formed within a relatively stable hemipelagic depositional environment (facies 1).

The Late Miocene sequence 2 overlaps sequence 1. Sequence 2 mainly consists of continuous, sub-parallel to parallel, and generally low but locally variable amplitude reflectors that overlap the T4 unconformity. In general, the sequence contains low amplitude reflectors at its base, which are overlain by a higher-amplitude, continuous reflector. Seismic reflections appear to comprise relatively continuous but locally chaotic and discontinuous reflectors, and a thin, transparent layer can also be observed. Sequence 2 is ~500-m thick and is more consistent in its thickness in the SW–NE direction than sequence 1, which decreases in thickness towards deep-water areas. A chaotic and discontinuous deposit approximately 200-m thick and 85-km wide can also be observed in the uppermost part of sequence 2, beneath the canyons. Sequence 2 is dominated by facies 2 (MTH) and facies 3 (SD) (figures 5 and 6).

Sequence 3, which is the youngest sequence, records a series of continuous, sub-parallel reflectors with slightly higher amplitudes that are recorded in sequence 2. Sequence 3 is approximately 250-m thick and maintains a relatively stable thickness in the SW–NE direction before decreasing towards the deep-water area. Close to the canyons, the seismic reflections in sequence 3 exhibit newly developed incision features with locally chaotic or discontinuous reflectors. The basal reflectors within sequence 3 downlap onto the boundary with sequence 2 (between the chaotic and discontinuous reflectors); this sequence is overlain by continuous parallel or subparallel reflectors. The seismic facies of sequence 3 is dominated by facies 1 (H), facies 3 (TH) and facies 6 (SDW) (figures 5 and 6). Seismic facies 5 is also observed within sequence 3 in the form of small and inconsistent incisions (figure 5c).

4.2.3 Slide complexes

Seismic data clearly indicate that slide complexes developed during three periods:

- (i) the end of the formation of sequence 1, prior to 11.5 Ma;
- (ii) the beginning or middle of the formation of sequence 2, between 5.3 and 11.5 Ma; and
- (iii) the end of the formation of sequence 2 or the beginning of sequence 3, ca. 5.3 Ma.

In this study, we focus on the slide complexes at the top of sequence 2.

Figure 5. (a) Interpreted 2D multi-channel seismic line M1, showing canyons that have eroded into Quaternary deposits and the chaotic, discontinuous slide complexes under the canyon. Purple line: interpreted top of the lava intrusion; brown line: interpreted Late Miocene base; yellow line: interpreted base of Pliocene deposits; red line: faults; blue line: limit of the slide complexes. SD: Slide complex; MTH: Mixed turbidite/hemipelagic sediments; H: Hemipelagic sediments; C: (buried) channel. (b) Seismic line without interpretation. (c) Enlarged map of the canyon area. The locations of the seismic profile M1 are the same as in figure 3.

Figure 6. **(a)** Interpreted 2D multi-channel seismic line M2, showing the canyons, sediment waves, and slide complexes. See figure 5(a) for colour legends. SD: Slide complex; MTH: Mixed turbidite/hemipelagic sediments; H: Hemipelagic sediments; SDW: Sediment waves. **(b)** Seismic line without interpretation. The location of seismic profile M2 is the same as in figure 3.

Slide complexes in this region are oriented to the NE–SW, with a mean thickness of approximately 200 m and a maximum thickness of approximately 348 m in the toe region, which is located in the downslope area. These slide complexes cover an area of approximately 1790 km², with a length of 93 km, width of 24 km, and a volume of approximately 360 km³ (figure 12). According to the seismic line HD2, the wedge containing these slide complexes developed 230–358 m below the sea floor (mbsf). The slide complexes are approximately 133-km thick and 8.5-km wide and

are located at a water depth between 440 and 638 m (figure 7). The sizes of the slide complexes increase to the east. Lens or slabby slide complexes are located at water depths between 330 and 600 m at 200–355 mbsf, with a width of 17–24 m and a thickness of 136–348 m (figures 8–10, table 3).

High-resolution seismic data clearly reveal detailed information about the structure and characteristics of these slide complexes (figures 7–10). Seismic data record the highest amplitudes and continuous parallel reflectors within sequence 3

Figure 7. (a) Interpreted single-channel seismic reflection profile HD2. Sediment waves, slide complexes and debris/turbidity flows are shown in profile HD2. SD: Slide complex; MTH: Mixed turbidite/hemipelagic sediments; H: Hemipelagic sediments; SDW: Sediment waves; C: (buried) channel. (b) Uninterpreted profile HD2. (c) Enlargement of the slide complexes. (d) Enlargement of debris/turbidity flows. The location of seismic profile HD2 is the same as in figure 3.

outside the region of the canyons (figures 7–11). Closer to the canyons, slide complexes are characterized by thin, chaotic, and discontinuous reflectors that allow landslides to be distinguished from the undeformed hemipelagic units in the background. A given landslide mass thickens towards the toe region, and its upper boundary does not bulge appreciably above the regional undeformed slope datum. This observation suggests that the slide complexes did not once form a major positive topographic feature over the coeval seafloor (figures 7–11).

Analysis of strike-oriented seismic profiles reveals that the lateral margins of the slide complexes are generally abrupt and that there are steep limits between highly chaotic seismic facies within the landslide mass and the outer undeformed strata. These characteristics of the slide complexes thus confirm that the bulk of each landslide deposit is entrenched within the surrounding strata (figure 5).

The heads of the slide complexes are wedge-shaped and pinch out in the direction of the upper slope. Some downcutting channel facies can also

Figure 8. (a) Interpreted single-channel seismic reflection profile HD3 through Canyon C1. Sediment waves, slide complexes, and debris/turbidity flows are shown in profile HD3. SD: Slide complex; MTH: Mixed turbidite/hemipelagic sediments; H: Hemipelagic sediments; SDW: Sediment waves; C: (buried) Channel. (b) Uninterpreted profile HD3. (c) Enlargement of the sediment waves. (d) Enlargement of debris/turbidity flows. The location of seismic profile HD3 is the same as in figure 3.

be observed at the head area of the landslide mass. No obvious headscarps are observed at these slide complexes (figures 7–10).

Toes of the slide complexes are distinctly characterized by an abrupt change from the highly disturbed seismic facies within the landslide mass to the outer continuous reflections at the base of the slope. However, some moderately continuous reflections do exist within the landslide mass and are similar to the undisturbed strata outside the slide complexes. This correlation suggests that

some deposits have been deformed and transported within the landslide, but still preserve their primary stratification (figure 11).

In general, we are able to continuously trace a basal shear surface that exhibits remarkable lateral variations in its seismic amplitudes and geometries. This surface forms a continuous, flat, and strong seismic amplitude reflection that is conformable with the underlying strata. However, locally, this surface ramps up and down the stratigraphy to create a series of staircase-like geometries,

Figure 9. (a) Interpreted single-channel seismic reflection profile HD4 through Canyon C2 and Gully C7. The slide complexes, debris/turbidity flows and sediment waves are shown in the profile HD4. SD: Slide complex; MTH: Mixed turbidite/hemipelagic sediments; H: Hemipelagic sediments; SDW: Sediment waves; C: (buried) Channel. (b) Uninterpreted profile HD4. (c) Enlargement of the sediment waves. (d) Enlargement of debris/turbidity flows. The location of seismic profile HD4 is the same as in figure 3.

in which one can observe clear reflection terminations (figures 7–11). The most probable direction of translation is approximately NW–SE along the basal shear surface base of the seismic features described above.

4.2.4 Seismic structure of sediment waves

According to bathymetric data, sediment waves are present along the slope of the seafloor at a water

depth of 500–900 m. Here, we use single-channel seismic profiles to characterize the internal structure of these sediment waves. The seismic profiles display concave-up sediment wave packages. Analysis of high-resolution seismic data also demonstrate that buried, vertically stacked, successive sediment wave packages can also be observed within the Pliocene–Quaternary deposits above the area of the slide complexes (figures 7–10). The basal boundary contains channel-like incisions, as seen in facies 5.

Figure 10. (a) Interpreted single-channel seismic reflection profile HD5. The slide complexes are shown in profile HD5. SD: Slide complex; MTH: Mixed turbidite/hemipelagic sediments; H: Hemipelagic sediments; SDW: Sediment waves. (b) Uninterpreted profile HD5. (c) Enlargement of the slide complexes. The location of seismic profile HD5 is the same as in figure 3.

Table 3. Parameters of slide complex features in the study area.

Size on profiles	HD2	HD3	HD4	HD5
Water depth range (m)	440–638	359–592	330–754	400–600
Shape	Wedge	Slabby	Lens	Lens
Depth range (mbsf)	230–268	200–270	50–173	296–355
Width in profile (km)	13	24	24	17
Max. thickness (m)	133	136	348	189

Figure 11. Seismic profile through the slide complexes (see figure 10 for location). The toe region appears as the downslope boundary between the chaotic seismic facies of the slide complexes and the continuous reflection of the base of the slope. The clear frontal ramp and the mass of the slump are buttressed against the downslope strata.

Successive incisions from the base of sequence 3 are observed throughout the entire post-T3 sequence. Some sediment waves are also found inside the slide complexes, thus indicating that some of the slide complex deposits may include deformed sediment waves (figures 7–10).

Seismic reflections inside these sediment wave packages are similar between waves, and internal reflectors can be traced across the crests and troughs of each sediment wave along the seismic profiles (figures 7–10). In the sediment wave field, the downslope flank of one wave meets the upslope flank of the next lower wave, and sediment waves record fairly continuous and parallel seismic reflections with moderate to high amplitudes. Sediment waves also record upper-slope lateral migration. Individual sediment waves exhibit thicker sediment packages on upslope flanks and crests than they do on downslope flanks (figure 10c). Additionally, the gradient of the southern slope is greater than that of the northern slope (figure 4), which suggests that the waves within these wavy sediments experienced minor erosion on their southern flanks.

Seismic profiles and swath-bathymetry maps do not record headwall scarps on the upper continental slope, and also record a lack of compressional features at the toe of the sediment wave field. This observation indicates that gravity deformation was likely not the mechanism forming these sediment waves (Lee *et al.* 2002). Instead, based on their wave dimensions, it is more likely that these

sediment waves were produced by a dominant bottom current.

4.2.5 Canyons/gullies

The seismic reflections within the canyons demonstrate the existence of erosional and infill processes within the study area (figure 5c). The steep flanks of the canyons record little accumulation of deposits within the thalweg, thus suggesting that erosional processes have occurred here. Deposits along the thalweg can be observed in Canyons C1 and C2 and Gully C6 (figure 5c). The basal surfaces of these canyons are characterized by continuous and strong amplitude reflections, and thalweg deposits are marked by parallel, high-amplitude, continuous reflections that onlap the basal surface. Although the northeastern flanks are often partially re-eroded, strata in the southwestern flanks of the gullies are usually better preserved and less steeply inclined. The seismic characteristics of laterally inclined slide packages, which are located on the southwestern flank of the canyon, are dominated by low-amplitude, moderately continuous, oblique and sigmoidal reflections. These reflections dip to the northeast and downlap onto deposits along the thalweg or a basal erosional discontinuity (figure 5c). Canyon margin deposits comprise high-continuity reflections with variable amplitudes and are truncated by basal erosional discontinuities (figure 5c).

4.2.6 Debris/turbidity flows

The seafloor at the downslope end of the canyons is completely smooth and flat at a depth of 1000 m. A debris/turbidity flow province is associated with the canyon and its downslope run-out area. Seismic data reveal the presence of a well-defined sedimentary unit up to ~10-m thick, which disappears upslope towards the head of the canyon. The seismic facies of the debris/turbidity flows is characterized by a reflection-free to chaotic, irregular, and low-amplitude pattern. This facies is typical for debris-flow deposits, and clearly contrasts with the horizontally stratified, high-amplitude facies with continuous reflectors observed in the strata below (figures 7–9). These debris/turbidity flows also disappear outside the canyon mouth area, which indicates that the debris/turbidity flows record a closed relationship with the canyons (figure 10).

5. Discussion

5.1 Processes leading to the slide complexes in the Late Miocene

Here, we summarize the most important observations from our seismic interpretation of the slide complexes in the previous sections, which provide a basis for the discussion below:

- (1) The region of the slide complexes is marked by its wedge-like shape and downslope topography. The toe region is dominated by a thrust belt, in which thrusts cut upwards across the entire thickness of the landslide and ramp upwards from the basal shear surface. The toe region is laterally and frontally confined and is delimited by a series of abrupt and relatively steep (dipping approximately 20°) ramps separating the toe region from the stratigraphically equivalent and undeformed slope section (figure 11).
- (2) Although these slide complexes are mainly characterized by chaotic and discontinuous facies, the presence of some individual and moderately continuous reflections within the landslide masses allows us to produce correlations between internal features, particularly in the HD2 and HD4 seismic lines. Additionally, some incision channels have developed inside the head region of the slide complexes. These channels seem to trend in the along-slope direction (figures 7 and 9).

Using the definitions of Jose *et al.* (2006), observations (1) and (2) demonstrate that the slide complexes in this study are frontally confined. The slide complexes exhibit well-preserved internal stratification and a toe region buttressed by the ramp, which implies a relatively modest downslope transfer of sediment. This downslope translation stopped when the stress that developed from the landslide mass became lower than the strength of the foreland.

Given the lack of wells drilled in this area, we can use seismic data and the sedimentary environment in the upper slope, along with the overlying sedimentary wave field, to estimate that the deposits involved in the slide complex may originally have been turbidity, density or contour current deposits.

Although it is difficult to determine sedimentation rates during the Late Miocene–Quaternary due to the lack of deep water wells, seismic profiles (figures 5 and 6) demonstrate that the time thickness from the Pliocene to the present (5.3–0 Ma) reached a maximum value of 300 ms (with a sediment rate of approximately 56 ms/Ma), whereas the time thickness from the Late Miocene to the Pliocene (11.5–5.3 Ma) reached a maximum value of 500 ms (with a sediment rate of ~80 ms/Ma), and the time thickness of the preceding period (65.5–11.5 Ma) reached a maximum value of 800 ms (with a sediment rate of approximately 15 ms/Ma). These results indicate that the sedimentation rate increased significantly after the Late Miocene. Additionally, the sediment thickness of sequence 2 in the area of the slide complexes is larger than that at the lower slope and in the SW area of profile M1. This observation further indicates that sedimentation rates were higher from 11.5 to 5.3 Ma.

Previous research has demonstrated that sea level decreased during the Late Miocene (figure 2). This trend is directly related to increased erosion rates and source delivery to the slope area. Because the Paleo-Pearl River was the major drainage system supplying sediments to the shelf and slope of the PRMB, the enormous terrigenous supply of the Paleo-Pearl River may have been responsible for the high sedimentation rates along the slope during these sea-level lowstands (Wang *et al.* 2000). Additionally, the rapid sediment accumulation of sequence 2 (11.5–5.3 Ma) likely produced the high pore pressures and weak cementation.

5.2 Sediment wave fields

Two sediment wave fields were also identified on the slope of the South China Sea near southwestern Taiwan. One sediment wave field is located on the lower slope and is generally oriented perpendicular to the direction of down-slope gravity flows and the canyon axis. Another sediment wave field is located more basinward on the continental rise, where along-slope bottom (contour) currents are vigorous and most likely dominate over diluted turbidity currents, resulting in the production of vertically aggraded sediment waves (table 4) (Gong *et al.* 2012).

Symons *et al.* (2016) indicated that large-scale sediment waves have wavelengths of 300–7200 m and wave heights of 5–220 m. Very large subaqueous sand waves, with amplitudes exceeding 16 m and wavelengths exceeding 350 m, have also been discovered on the upper continental slope of the northern South China Sea, at water depths ranging from 160 to 600 m. These very large sand waves are formed by internal solitary waves, which are generated from tidal forcing on the Luzon Ridge in the eastern South China Sea (table 4) (Reeder *et al.* 2011).

Therefore, the sediment waves in this study are likely large-scale waves. The base of the wave field is defined by an initiation surface, which is characterized by a high-amplitude reflection corresponding to the regional unconformity T3 (figure 10), and the top of the wave field is defined by the seafloor crests. The strata underlying the initiation surface record chaotic seismic reflections with variable amplitudes that are interpreted to be slide complexes (figures 7–9).

The crests of the sediment wave field are parallel or subparallel to the bathymetric contour lines (figure 3). These continuous, parallel to subparallel, internal seismic-reflection configurations indicate the occurrence of active vertical aggradation, rather than up-slope migration (figure 10c). Over longer time scales (observed in the seismic profiles), from approximately 5.3–0 Ma, this wave field migrated, which suggests the presence of lasting bottom flow activity. The sediment wave field laterally evolved approximately 30 km along the slope in the SW direction and 560 m in the vertical direction.

The sediment wave field in this study has the following geomorphologic and seismic characteristics: (1) sediment waves are classified as ‘large-scale’

based on their wavelengths and heights; (2) sediment waves occur on the upper continental slope, where the water depth ranges between 500 and 900 m, and are thus not subjected to the influence of shallow- or deep-water generation mechanisms.

Previous research indicates that intermediate water sweeps the northern margin of the South China Sea from west to east (Wang and Li 2009; Xie *et al.* 2009; Li *et al.* 2013) and can occur at water depths between 350 and 1500 m (Chen and Wang 1998; Zhu *et al.* 2010; Wang *et al.* 2013; Xie *et al.* 2013). Additionally, research by Ramp *et al.* (2004) indicates that the South China Sea hosts the world’s largest observed internal solitary waves. These internal solitary waves are generated by tidal forcing on the Luzon Ridge on the east side of the South China Sea, and propagate west across the deep basin (Lien *et al.* 2005; Chang *et al.* 2006).

In the absence of any other likely mechanism, we propose that internal solitary waves, as discussed by Symons *et al.* (2016), represent the most likely mechanism for the resuspension and transport of sediment, as well as the subsequent formation of sediment waves in this area. The presence of an along-slope (contour) current could also have affected the formation of these sediment waves, based on the orientation and migration time scale of the sediment wave field (table 4).

5.3 Canyons and gullies

A series of parallel canyons and gullies, which trend in the NNW–SSE, NNE–SSW, and NE–SW directions and are thus oriented approximately perpendicular to the slope, were discovered along the northern slope of the South China Sea at water depths of 400–1800 m (He *et al.* 2014; Li *et al.* 2015, 2016; Chen *et al.* 2016). These canyons may have been formed by the backstepping of failures at the shelf break, which may be related to minor faulting in the shelf margin followed by subsequent headward erosion. Mass transport deposits (MTDs) and slumps are also well developed on the slope area due to canyon margin or head failure. The results of previous research have also indicated that submarine canyons on the northern slope of the South China Sea record different upper slope stabilities, which are related to the presence of submerged reefs and sedimentary undulations (Li *et al.* 2016).

The canyons and gullies distributed on the northern, over-steepened slope of the QDNB area are linear, approximately 6–28 km long and

Table 4. Examples and comparison of sediment wave fields observed in the continental slope of the northern South China Sea.

Longitude/ latitude	Water depth range (m)	Slope gradient (°)	Wave length range (m)	Wave height range (m)	Sediment wave field characteristics	Formation process	References
Upper continental slope, northeastern South China Sea							
20–22°N 117.2°–117.8°E	250–600	2–0.3	280–350	3–16	Closely spaced dunes whose size and structure change across the field (downslope) with changes in the slope gradient	Shoaling deep-water internal solitary waves	Reeder <i>et al.</i> (2011)
Slope off southwestern Taiwan, northeastern South China Sea							
21–21.6°N 119.3°–119.7°E	Field 1: 3000–3200	5.6	500–4000	7–117	Individual sediment waves that usually display an asymmetrical morphology with thicker, steeper, and shorter up-slope flanks, whereas those on the down-slope flanks are thin and less well-layered	Along-slope bottom (contour) currents that are associated with the intrusion of the North Pacific Deep Water into the South China Sea	Gong <i>et al.</i> (2012)
	Field 2: 3200–3400	1.6	1500–5400	<110	Continuous, parallel or subparallel reflections on both flanks of the sediment waves	Flowing bottom (contour) currents that are induced by the intrusion of the North Pacific Deep Water into the South China Sea	
Upper continental slope, northern South China Sea							
18.5–19.3°N 112.7°–113.5°E	600–900	2–4	1400–2000	30–50	Seismic-reflection nature is similar between waves, and internal reflectors can be traced across the crests and troughs of each sediment wave along both seismic profiles	Interactions of along-slope bottom (contour) currents and internal solitary waves	This study

2–8 km wide, and record a maximum incision depth of 500 m. These canyons and gullies are oriented in the NNW–SSE, NNE–SSW, and NW–SE directions, with slope gradients of approximately 1–10° (table 5). The heads and flanks of these canyons are carved by numerous gullies, which are relatively abundant towards the upper part of the slope, but are generally absent at its base (Li *et al.* 2015). The existence of gullies indicates that erosional processes were strongly developed inside these submarine canyons (Li *et al.* 2015). Local sediment failure in canyon heads and walls are interpreted to have generated MTDs above basal channel-lag deposits (Li *et al.* 2015; Chen *et al.* 2016). Multi-beam bathymetry and high-resolution seismic data reflect the instability of the slope, as well as the presence of well-developed Miocene–Quaternary recurrent MTDs near the canyons on the northern slope of the QDNB (Li *et al.* 2015). The presence of earthquake activity and high sedimentation rates occurring after the Late Miocene represent important preconditioning factors for the development of recurrent MTDs in the northern slope of the QDNB (Li *et al.* 2015). Furthermore, erosion-dominated, over-steepened slopes created by insufficient sediment supply are more common in larger canyons and gullies (Chen *et al.* 2016) (table 5).

Numerous submarine landslides and a series of downslope-extending canyons are also well-developed in the middle northern continental slope of the PRMB area, where slope gradients are approximately 10°–15° (He *et al.* 2014; Li *et al.* 2016) (table 5). These canyons are characterized by their linearity and regular spacing (Li *et al.* 2016). Bathymetric and chirp data further reveal that axial incisions and landslides represent the main geological processes controlling the morphology and evolution of these canyons. In general, canyon slope gradients and maximum canyon relief values are controlled by mass transport activity and the consequent formation of sediment gravity flow deposits (Li *et al.* 2016).

The canyons and gullies in the study area are located at shallow water depths than the canyons found on the northern slope of the QDNB and the middle slope of the PRMB (table 5). Additionally, the length, width and maximum incision depths of the canyons in the study area are generally smaller than those on the northern slope of the QDNB and the middle slope of the PRMB. The mean slope gradient of the canyon area is also gentler, ranging from 0.3–0.8° (table 5).

Analysis of bathymetric data and seismic profiles reveals that three main processes that have influenced the evolution and morphology of the canyons in this study: (1) canyon head slumps; (2) axial incisions and landslides; (3) active bottom currents and debris/turbidity flows on canyon floors.

Slumps are mostly developed around the upper and middle reaches of the canyons, with some occurring in canyon head regions, and a few occurring in the lower reaches of the canyons (He *et al.* 2014). Bathymetric data indicate that some small scars appear at the heads of canyons C1 and C2 (figure 4), and geomorphology data suggest that slumps have caused sediment collapse in the canyon head area. The lack of obvious gullies carved at the heads of these canyons is not similar to the canyons on the northern slope of the QDNB (Li *et al.* 2015). This observation suggests that the slumps of the C1 and C2 canyon heads are relatively weak or young, and have not had enough time to fully develop into gullies.

Previous studies have demonstrated that recurrent axial incisions can widen and deepen canyons (Zhu *et al.* 2010; Li *et al.* 2015). In this study area, canyon head erosion produces downslope gravity flows, which in turn produce axial incisions. These canyons are supposedly created by landslides occurring on steeper sites of the continental slope, as canyon downcutting or incision profoundly influences the occurrence and preservation of landslides. Additionally, canyon incisions steepen canyon walls to produce landslides, which explains why most landslides are distributed along canyon flanks (He *et al.* 2014). Seismic profiles indicate that the southwestern flank walls of these canyons are characterized by thalweg-parallel slide deposits, whereas their northeastern flank walls are characterized by erosion. The average slope gradient of the western canyon walls is smaller than that of the eastern ones, which is also similar to that of the middle slope of the PRMB. Erosion of the northeastern flank indicates that landslides are important factors controlling canyon shape in the study area. Previous studies have revealed that most MTDs on canyon walls produce a step-like morphology, which indicate that mass wasting occurred more frequently in the middle continental slope of the PRMB (Li *et al.* 2016). There are no step-like terraces on the flanks of the canyons, or large-scale MTDs similar to those found in the mid-to-lower northern slope of the QDNB (Li *et al.* 2015, 2016). Therefore, this analysis

Table 5. Examples and comparisons of canyons and gullies observed in the continental slope of the northern South China Sea.

Water depth (m)	Length (km)	Width (km)	Orientation	Incision depth (m)	Maximum gradient of sidewalls (°)	Slope gradient of (°)	Geomorphology characteristics	Sedimentary characteristics	References
Northern slope of QDNB									
400–1800	6–28	2–8	NNE–SSW NNW–SSE NW–SE	100–500	10–20	1–10	Straight canyons and gullies strike perpendicular to the slope. Heads and flanks of canyons are carved by numerous gullies. Canyon size decreases towards the west	Erosion escarpments, slumps and MTDs are well developed. Gravitational faults, erosion, and instabilities on canyon margins. Multi-erosional basal surface	Li <i>et al.</i> (2015); Chen <i>et al.</i> (2016)
Middle northern slope of PRMB									
500–1500	18–54	0.7–2	N–S	142–397	8–10	1.5–2.5	Straight canyons exhibit east flanks narrower and steeper than west ones. Seafloor is rough and characterized by failure scars. Undulated bedforms are aligned at a low angle or are parallel to regional contours	Mass transport activity, turbidity deposits and sediment gravity flow deposits are also found. Axial incision and landslides are the main geological processes controlling the canyon morphology and evolution. Multi-erosional basal surface	He <i>et al.</i> (2014); Li <i>et al.</i> (2016)
Western northern slope of PRMB									
400–1000	8–25	1.2–7	NNW–SSE	35–175	16–26	0.3–0.8	Finger, linear or wide base canyons and gullies strike perpendicular to the slope. The eastern flanks of canyons are usually steeper than western ones. Large-scale sediment waves are aligned at a low angle or are parallel to regional contours	Slump in the canyon head area. Northeastern flanks have often been partially re-eroded; active and laterally inclined slide packages located at the southwestern flank. Active bottom currents and debris/turbidity flow well developed in the canyon floor. Single erosion basal surface	This study

Figure 12. Spatial distribution of the canyons, sediment wave field, slide complexes and debris/turbidity flows.

indicates that MTDs are relatively weaker in these canyons than they are in canyons on the northern slope of the QDNB and the middle slope of the PRMB.

Zhu *et al.* (2010) described canyons in the South China Sea that were modified by both turbidity and contour currents. This mixed turbidity and contour current regime has also been observed elsewhere (Howe 1996; Damuth and Olson 2001). Although the slope gradient in the study area is more gentle than that observed on the northern slope of the QDNB and the middle slope of the PRMB, seismic profiles also reveal that canyon floors are partially filled with structureless-to-chaotic, low-to-moderate amplitude, short reflectors, as well as nearby transparent data that can be interpreted as debris/turbidity deposits. Some thin debris/turbidity deposits are also found at the mouth of the canyon, which indicates that these canyons were primarily created by landslides (figures 8, 9, and 12). The axis canyon floor is characterized by small-scale sediment bedforms and

landslide debris, which suggests that some reworking of landslide debris by currents has occurred within the canyon. The ridges in the canyon appear to be related to sediment wave crests, thus suggesting that these sediment waves are still active today (figures 7 and 8). Furthermore, bottom currents and turbidity currents are assumed to have been generated by sediment waves (Lonsdale and Hollister 1979; Wynn and Stow 2002). The occurrence of these sediment waves thus indicates that bottom currents and turbidity currents were active along the gentle slope of the canyon floor and greatly influenced the evolution of these canyons and gullies.

Previous research has indicated that canyons developed on the northern slope of the QDNB and the middle slope of the PRMB result from the long-term erosion of a series of incision-infill cycles that began along the continental slope during the Middle Miocene (Sun *et al.* 2012; He *et al.* 2014; Li *et al.* 2015, 2016). Each canyon cycle is characterized by a basal erosional surface at its base. Subsequently,

laterally inclined slide deposits partially infill this erosional base with horizontal onlap geometry (Zhu *et al.* 2010). These canyon fills, characterized by discontinuous high-amplitude reflections, are vertically stacked and migrate eastwards (He *et al.* 2014). However, the canyons in this study area appear to record different seismic facies than those previously found in the QDNB and PRMB, according to high-resolution seismic data. The seismic characteristics of these canyons demonstrate that there are no buried canyons, and therefore that no obvious multi-cycle paleo-erosional bases, or infill sediment with horizontal onlap geometry, appear in sequence 2. These results indicate that the canyons in this study are formed during a single stage. The age of the canyon system remains unknown; we can only determine that these canyons are the most recent canyons to have developed on the upper slope and that their relief is preserved in the sea-floor morphology, which is covered only by Holocene deposits. The bases of the canyons are located in the upper sequence 3, thus implying that the canyons may have first formed during the Quaternary.

The above analysis, as well as comparisons to other canyons along the northern slope of the South China Sea, suggests that the presence of particular morphologies indicates the importance of both head and flank erosion in canyon evolution. The canyons in this study are key examples of a canyon system that is affected by multiple active depositional processes, including erosion, landslides and the influx of debris/turbidity flow and bottom currents. These canyons were initially formed by failure. Debris/turbidity currents within the canyons then significantly eroded and bypassed the upper reach of the canyon, contributing to the development of a basal erosional discontinuity. Vigorous bottom currents then fed mud into the canyons, resulting in the accumulation of laterally inclined packages along the southwestern flank.

5.4 Model of sedimentary processes and morphological development

The presence of slide complexes, the sediment wave field, and canyons indicates that sedimentary processes in the study area are complicated. We present a three-dimensional model diagram illustrating their development in this region, which can be organized as follows (figure 13):

- Stabilization stage (ca. 11.5–5.3 Ma): The rapid sediment accumulation recorded in sequence 2 is triggered by continuous and high rates of sedimentation under lowstand sea levels (figure 13a).
- Failure of the slope (ca. 5.3 Ma): High pore pressures and weak sediment cementation provide the basic conditions for mass transport deposits. The abrupt release of pore pressure along the failure plane and low slope angles cause the *in-situ* movement of slide complexes. Downslope translation stops when the stress developed from the landslide mass becomes lower than the strength of the foreland (figure 13b).
- Formation of the Sediment wave field (ca. 5.3–0 Ma): sediment waves began to form at ca. 5.3 Ma. The development of these sediment waves is probably controlled by along-slope bottom (contour) currents and internal solitary waves. Internal solitary waves decelerate on the upstream wave flank and accelerate on the downstream wave flank. More sediment accumulates on the upstream wave flank, where the flow speed is lower, and the waveform migrates upstream with time. Concurrently, the sediment wave field slowly migrates in the SW direction under the influence of along-slope bottom (contour) currents (figure 13c).
- Formation of the canyons (ca. 2.6–0 Ma): The geomorphological features of the canyon system are obviously the result of erosive sediment flows. Initial landslides occur at steeper sites along the sediment wave field on the continental slope. Canyons begin to form and widen under erosion from bottom currents, turbidity flows and canyon head failures. Failure scars left by these initial landslides develop into gullies, which further evolve into initial canyons to induce successive headward or retrogressive landslide events. At the same time, downcutting and the headward erosion of these canyons increase the slope gradient of the canyon walls, inducing more landslides in both the head regions and sidewalls of the canyons. The entrenched axial thalweg functions as an ‘active zone’ along the canyon, where sediment flows cut into the flat canyon bottom (He *et al.* 2014). The current within the canyons is strong enough to wash away landslide materials, producing debris/turbidity deposits at the canyon mouth and lower slope. Consequently, the canyon widens over time and penetrates farther to the north by headward erosion along

Figure 13. 3D model of the study area showing the initiation and development of the canyon system, sediment waves and mass movements in five stages: (a) stabilization stage; (b) failure of the slope; (c) formation of the sediment wave field; (d) formation of the canyon system; and (e) the present seafloor geomorphology.

the sediment flow path towards the source of the flow (figure 13d). The modern geomorphology of the seafloor is thus the result of the integrated processes of debris/turbidity flows, along-slope bottom currents, and downslope flow (figure 13e).

6. Conclusions

In this study, we investigate the characteristics and distribution of submarine mass movements, sediment wave field, and canyons on the modern seafloor along the northern continental slope of the South China Sea by using high-resolution

2-D seismic profiles and a multi-beam bathymetric map. The main conclusions of this study are as follows:

- Analysis of high-resolution multi-beam bathymetry maps and seismic data reveal that canyons and mass movements are developed along the northern continental slope of the South China Sea. Seismic reflection profiles indicate the presence of six seismic facies: hemipelagic sediments (H), turbidity/hemipelagic sediments (MTH), debris/turbidity deposits (TH), lide complexes (SD), (buried) Channel (C), and sediment waves (SDW). Cenozoic strata located above the acoustic basement in the study area can also be

roughly subdivided into three sequences that are separated by regional unconformities.

- Slide complexes are oriented in the NE–SW direction and cover an area of $\sim 1790 \text{ km}^2$. These slide complexes exhibit a seismic facies that is characterized by a chaotic zone with discontinuous seismic reflections that is bounded by continuous strata of Late Miocene age. The mass movements recorded in sequence 2 were likely caused by high sedimentation rates and pore pressures, which created sediment instability. These slide complexes were frontally confined, causing landslides to undergo restricted downslope translation without overrunning undeformed downslope strata.
- The sediment wave field is oriented in the NE–SW direction and covers an area of approximately 926 km^2 . Very large sediment waves are irregularly spaced between water depths of 500–900 m, with wavelengths of 1.4–2 km and wave heights of 30–50 m. Their wave geometry strongly suggests that the sediment wave field is not related to any major channel-levee systems, instead reflecting a complex origin caused by interactions between internal solitary waves and along-slope bottom (contour) currents.
- The canyon system is oriented in the NNW–SSE direction. These canyons incise into a sedimentary succession of Quaternary age, and presumably originate from gullies that were created by initial landslides at one or more steeper sites on the continental slope. These canyons are elongated upslope by successive retrogressive landslides and are laterally widened by the processes of downcutting, headward erosion and active bottom currents and debris/turbidity flows on canyon floors.
- We propose a 3D model to explain the evolution of the slide complexes, the sediment wave field, and canyons in the study area. The sedimentary processes in this model are complicated, and demonstrate that active bottom currents and debris/turbidity flows have affected the sedimentation and geomorphological evolution of the northern slope of the South China Sea since the Late Miocene.

This imaging of the canyons, sediment wave field and mass movements in this study thus provide new insights into the evolution of the stratigraphy and geomorphology along the upper slope of the South China Sea.

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