Response of geomorphic and geological processes to insufficient and ample sediment supply along the upper continental slope in the north-western South China Sea

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We document upper slope sedimentary process and strata on the passive margin of the north-western South China Sea (SCS) using multibeam bathymetry and high-resolution seismic data. The upper slope can be divided into two segments based on geomorphology, strata, and sediment supply. (1) The east segment is characterised by deep incised canyons and gullies, and slope failure. Submarine canyons with both U- and V-shaped morphology (13–28 km long $\times$ 2–4 km wide) are oriented NNE–SSW or NNW–SSE and are approximately perpendicular to the slope. Erosion is dominant, with escarpments, slumps, and several mass transport deposits (MTDs). Shelf-margin clinoforms show strongly upward vertical aggradation with time and are strongly aggradational in style. Since 5.5 Ma, the shelf break line migrated southwards and then retreated to its present position. The segment is classified as erosion-dominated due to insufficient sediment supply. (2) The west segment has a smooth surface, gentle gradient, and a strongly progradational style, with MTDs triggered by high sedimentation rates. Shelf-margin clinoforms display a combination of progradational and aggradational stacking patterns. The shelf break line migrated southwards with time. The segment is classified as deposition-dominated, resulting from plentiful sediment supply. Depositional models have been constructed for each segment: a constant shelf break model with insufficient sediment supply in the east, and a migration shelf break model with plenty sediment supply in the west. This case study contributes to the understanding of the upper slope sedimentary process and stratigraphic style under different sediment supply conditions.

1. Introduction

The upper continental slope is characterised by unique hydrodynamic conditions and sedimentary processes. The dynamics and the fate of sediment transferred from the continents to the marine environment have been studied throughout the world

in the last few decades. Integrated research has been carried out to describe and quantify shelf sediment export on various continental margins (e.g., Kristoffersen *et al.* 2000; Puig *et al.* 2003; Cristian *et al.* 2009; Miller and Kuehl 2010). For progradational margins, Miller and Kuehl (2010) have shown progradation rates tend to correlate with

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sediment supply and that increasing rates commonly imply larger volumes of sand being brought to the deep-water basin floor. Studies of modern Quaternary systems have demonstrated that fan volume is directly related to river discharge (Wetzel 1993; Sømme *et al.* 2009). Research has also indicated that shelf-margin aggradation and progradation is a function of the space created by relative sea level and basin sediment supply (Campbell 2005). Repeated sediment supply to the continental shelf causes individual clinoforms to migrate basinwards in aggradational and progradational steps (Carvajal *et al.* 2009).

For this study, the upper continental slope of the north-west South China Sea (SCS) in the area of the Qiongdongnan Basin (QDNB), was chosen as a natural laboratory to document shelf-margin sediment transport processes for two reasons. First, plentiful survey data is available, and second, there are variations in geomorphology, and sediment process and supply, from west to east along the margin. Sediment supply is a major external control on shelf-margin growth, architecture, and has the potential to produce deep-water sandstones.

Mass transport deposits (MTDs), which include slides, slumps and debris flows, are well developed in the continental slope. MTDs often comprise greater than 50% of the Quaternary stratigraphy in these settings (Garziglia *et al.* 2008; Moscardelli and Wood 2008), and seismic data suggest that MTDs are also important sedimentary process in the slope of the north-west SCS (Wang *et al.* 2013). For instance, new research shows that two types of MTDs, detached and regional attached, occur along the north-west continental slope (Gong *et al.* 2014). The former results from small-scale mass-wasting processes induced by regional tectonic events and gravitational instabilities on canyon margins, while the latter are triggered by high sedimentation rates, with oversteepening of the slope by shelf-edge deltas, and seismicity (Gong *et al.* 2014). Also, research by Shang *et al.* (2015) on the Central Canyon of the QDNB has shown that in the west segment, turbidite deposits and MTDs with sufficient sediment supply resulted in canyon infilling before 3.8 Ma. However, in the east segment, a combination of insufficient sediment supply and differential subsidence by deep-seated faults delayed canyon infilling (Shang *et al.* 2015).

Submarine slopes are highly variable on both the modern seafloor and subsurface (Mutti and Normark 1987, 1991), and within the study area, geomorphology and strata are different in the west and east segments of the continental upper slope. This variation may induce different dynamic processes, such as sediment supply and subsidence rate within the same relative sea level changes.

In this study, we use new 2D seismic and bathymetric data to study geological processes at the upper continental slope of the SCS (figures 1 and 2). The aims of the study were to identify the principal mechanisms controlling shelf-slope geomorphology and sediment exchange and to investigate the role of the continental upper slope as a preferential pathway for exporting sediment from the shelf to deep slope and basin. We also examine the impact of insufficient and plentiful sediment supply on geological processes, the role of sediment supply in shelf-margin growth, and the supply signatures in margin strata.

2. Tectonic setting and sequence stratigraphy

2.1 Tectonic setting and basin evolution

The QDNB is one of the most important hydrocarbon-bearing basins in the north-western SCS (e.g., Li and Zhu 2005; Peng *et al.* 2006), and covers an area of 45,000 km² (Shi *et al.* 2013). The NE–SW oriented QDNB is a Cenozoic sedimentary basin with greater than 10-km sediment thickness (Xie *et al.* 2008). The basin is divided from the Yinggehai Basin (YGHB) along the Red River Fault Zone (RRFZ) in the west and separated from the Pearl River Mouth Basin in the north-east by volcanic uplift.

The opening of the SCS is linked with extrusion of the Indochina Block and associated left-lateral slipping of the RRFZ between 35 and 17 Ma, driven by the collision between India and Asia (e.g., Leloup *et al.* 2001; Tapponnier *et al.* 2001; Gilley *et al.* 2003). The QDNB forms the western end of the northern margin of the SCS, which was formed by rifting followed by seafloor spreading along a WSW–ENE axis starting around 30 Ma in the north-western area (e.g., Taylor and Hayes 1980; Clift *et al.* 2001; Yan *et al.* 2001; Zhou *et al.* 2002).

The QDNB underwent rifting from 50.0 to 21.0 Ma, thermal subsidence from 21.0 to 10.5 Ma, and rapid subsidence from 10.5 to 0 Ma (Hu *et al.* 2013; Shi *et al.* 2013). Since the post-rift thermal stage, the QDNB has been filled with a thick sequence of marine sediments that are dominated by mudstones, with occasional turbidite channel and submarine fan sandstone bodies in the Miocene to Pliocene (Xie *et al.* 2006).

The RRFZ directly controlled sedimentation and deformation of the western QDNB. Previous studies have shown that the RRFZ experienced sinistral strike-slip from 35 to 20 Ma (Leloup *et al.* 1995) and shifted to dextral movement after ca. 5 Ma (Allen *et al.* 1984; Leloup *et al.* 1995; Sun *et al.* 2003). Due to the variable activity of the RRFZ,

Figure 1. Location of major Cenozoic basins in the north-west South China Sea margin. Abbreviations. BBWB: Beibuwan Basin; YGHB: Yinggehai Basin (also named Song Hong Basin); QDNB: Qiongdongnan Basin; ZJNB: Zhongjiannan Basin (also named Phu Khanh Basin); LP: Leizhou Peninsula; XU: Xisha Uplift; GU: Guangle Uplift; RRSZ: Red River Shear Zone; EVBF: East Vietnam Boundary Fault. Map is modified after Wang *et al.* (2013). The seaward location of the Red River Shear Zone is modified after Zhu *et al.* (2009).

the western part of the basin has experienced more complicated tectonics than the eastern segment, where tectonic activity largely ceased (He *et al.* 2013). Even in the rapid subsidence stage, only a few major faults reactivated; reactivation of the RRFZ in the Yinggehai area and extensional faults in the QDNB area resulted in the formation of slope clinoforms during the post-rifting stage (Xie *et al.* 2006, 2008). Anomalously high rates of post-rift subsidence resulted in the formation of the slope system and elevated sedimentation rates (400–800 m/Ma) in the QDNB (Zhu *et al.* 2011).

The western QDNB is mainly characterised by progradational slope clinoforms, which result in a rapid seaward (and south-east-ward) shift of the shelf-slope break due to high rates of sediment supply. In contrast, the eastern QDNB shelf-margin shows a vertical aggradational or minor progradational pattern due to insufficient sediment

supply (Xie *et al.* 2008). Unlike traditional passive continental margin basins, the QDNB underwent a tectonic reactivation phase from the latest Miocene (5.5 Ma) to Quaternary, with anomalously high rates of post-rifting subsidence (Xie *et al.* 2006). Based on morphologic features and stratigraphic framework, the continental slope system in the QDNB can be classified into four types, prograding, slumping, channelizing, and wide-gentle, from west to east (Su *et al.* 2014).

2.2 Sequence stratigraphy

The oldest sedimentary sequence drilled in the QDNB is the Yacheng Formation of the lower Oligocene. Interpretation of seismic data, however, has shown older, Eocene sequences are widely spread in the rifted areas of the QDNB. Hence, QDNB sedimentary sequence, from bottom to top,

Figure 2. (a) Location of high resolution seismic data. The thick black lines show the seismic profiles discussed in the paper. Faults A, B, C and D show the distribution of the Red River Shear Zone at 5.5 Ma (modified after Zhu *et al.* 2009). (b) 3D view of upper continental slope in the study area. For abbreviations, see figure 1.

comprises of Eocene, Yacheng Formation (early Oligocene), Lingshui Formation (late Oligocene), Shanya Formation (early Miocene), Meishan Formation (Middle Miocene), Huangliu Formation (Late Miocene), Yinggehai Formation (Pliocene), and Ledong Formation (Quaternary) (Xie *et al.* 2008; Wu *et al.* 2009; Yuan *et al.* 2009; Shi *et al.* 2013).

Based on seismic profiles in the shelf and slope areas, previous research has identified and dated eight regional seismic reflectors, which are T100 (50 Ma), T80 (36 Ma), T70 (30 Ma), T60 (21 Ma), T50 (15.5 Ma), T40 (10.5 Ma), T30 (5.5 Ma), and T20 (1.8 Ma) (figure 3B) (Xie *et al.* 2008; Wu *et al.* 2009).

Based on subsidence history (Zhao *et al.* 2013) and tectonic divergence (Zhang *et al.* 2013), seismic reflector T40 (10.5 Ma) is recognised as an important surface in the QDNB. The slope basin has experienced a very rapid subsidence rate since 10.5 Ma. Post-rift sequences in the deep-water

QDNB consist mainly of fine-grained hemipelagic sediments, dominantly silt, fine sandstone, and mudstone (Xie *et al.* 2008; Wu *et al.* 2009).

3. Data and methodology

This study utilises high-resolution 2D seismic reflection profiles and bathymetric data collected by the Guangzhou Marine Geological Survey (GMGS) in 2010–2011 to investigate the spatial-temporal variation of the dynamic upper continental slope processes. The survey covered an area of ca. 18000 km². Seismic data were acquired using a GI-gun source (210 cu in.), which was shot at a distance of approximately 55 m with an air pressure of 150 bars (2000 psi). The data were received by a 55 m long Syntron GEOSENSE48 streamer equipped with separately programmable hydrophone subgroups from R/V Fendou 5. Positioning was determined on the basis of a differential

Figure 3. (a) Seismic profile across the shelf and upper slope. The location is given in figure 2(a). (b) Stratigraphic column of the Qiongdongnan Basin and major tectonic events affecting the South China Sea. The ages of seismic surfaces are based on previous research (modified from Xie *et al.* 2008; Wu *et al.* 2009; Yuan *et al.* 2009; Zhu *et al.* 2009; Shi *et al.* 2013).

global positioning system. Data were digitally recorded at a sampling frequency of 4 kHz over 7 s time intervals and a vertical resolution of ca. 2 m. Seismic velocities were set as follows: seawater, 1500 m/s; shallow depositions since 10.5 Ma, 1750 m/s for simple time-depth conversions. The vertical scale on all the seismic profiles illustrated in this

paper is 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 centre of Guangzhou Marine Geological Survey.

Multibeam bathymetry data used for this study were collected during a geological survey cruise

by the GMGS in 2008. The data were acquired using R/V Haiyang 4, equipped with a hull-mounted Simrad EM1002 95 kHz system ($2^\circ \times 2^\circ$ configuration). The multibeam data were corrected for heading, depth, pitch, heave, and roll. Post-processing was performed with the Hydrographic Information Processing System (version 7.1), a submarine mapping software developed by CARIS. A 100×100 m bathymetric grid was produced for the shelf break zone area, and visualisation of the bathymetric data was conducted using Golden Software Surfer (v 9.7.543) and Global Mapper (v 11.02).

4. Results

4.1 Upper slope geomorphology

Canyons and gullies are prominent features of the upper slope; however, they have been defined in different ways in literature. 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). Submarine canyons were defined by Shepard (1965) as V-shaped and cut into rock walls, although studies on slope margins around

Figure 4. (a) Slope gradient combined with shaded relief of the multibeam bathymetry survey area. The location is given in figure 2(a). (b) Shaded relief image showing canyons and gullies with indication of cross-sections. The bathymetric contours are spaced every 200 m. (c) 3D shaded relief map of survey area. (d) Vertical profiles across the slope. See (b) for locations.

the world have described canyons as U-shaped and broad V-shaped (Jobe *et al.* 2011; Iacono *et al.* 2014). Hence, shape ('V' versus 'U') is not a consistent criterion to discriminate slope canyons from gullies. In this paper, we differentiated slope gullies from canyons on the basis of depth and length rather than shape, with gullies defined as ~ 300 m or less in depth and < 10 km in length, while canyons were ~ 300 m or more in depth and > 10 km in length.

The multibeam bathymetric dataset clearly revealed the geomorphic variability of the upper slope in the north-western SCS. Where water depth

was under 200 m, the seafloor gradient was rather flat, the gradient gradually steepened with water depths between 200 and 1000 m, and in the deep basin, with water depths of 1000 m, the gradient flattened again (figure 2b).

Based on distinctive geomorphic characteristics, the upper slope has been divided into two segments: (1) east segment dominated by deep incised canyons and gullies, and (2) west segment with relatively flat topography (figure 2b). The detailed geomorphic characteristics of the two segments are described below.

Figure 5. (a) Slope gradient combined with shaded relief of multibeam bathymetry survey area. The location is given in figure 2(a). (b) Shaded relief image showing gullies with indication of cross-sections. The bathymetric contours are spaced every 200 m. (c) 3D shaded relief map of survey area. (d) Vertical profiles across the slope. See (b) for locations.

Table 1. Characteristics of gullies and canyons on the shelf break zone in the study area.

Segment of shelf break zone	Cross-section	Water depth (m)	Orientation	Width (km)	Length (km)	Incision depth (m)
Figure 3	U/V-shaped	400–1800	NNE–SSW or NNW–SSE	2–4	13–28	250–500
Figure 4	U/V-shaped	400–800	NW–SE	2–8	6	100–300

Figure 6. (a) Slope gradient combined with shaded relief of multibeam bathymetry survey area. The location is given in figure 2(a). (b) Shaded relief image showing the smooth floor of the shelf break zone with indication of cross-sections. The bathymetric contours are spaced every 200 m. (c) 3D shaded relief map of survey area. (d) Vertical profile across the slope. See (b) for the locations.

4.1.1 East segment

The east segment was approximately 30 km wide, with a relief of 1100 m and water depth ranging from 180 to 1800 m (figure 2). Slope gradient was approximately 1° where water depth was <200 m

or >1200 m. Mean slope gradient was approximately 10°, with a maximum gradient of 15° at water depths of 200–1200 m (figures 4a, 5a).

Submarine gullies and canyons were developed in the east segment. V-shaped canyons, mostly 28 km long and 2–4 km wide with a maximum

incision depth of 500 m, were oriented in the NNE–SSW direction. Straight canyons incised the slope around the 400 m depth contour, forming a deep incision across the upper slope and extending down to the lower slope at 1800 m depth (figure 4, table 1). Canyon heads showed a very complex geomorphology with multiple, slightly incised branches in the upper slope. Canyon wall gradients exceeded 15° in some places.

A series of parallel gullies, trending in a NNW–SSE direction, were found at water depths of 200–1800 m. The gullies had U-shaped channels, 7–10 km long and 3–4 km wide, and tended to increase in depth along down slope with a maximum incision depth of approximately 300 m (figure 4, table 1). Gully wall gradients exceeded 10° in some places, and gully size decreased to the west. Gully heads were located at ~ 400 m water depth.

Other gullies, oriented in a NW–SE direction, had a U- or V-shaped cross-section and were located at 400–800 m water depth. The U-shaped gullies reached up to 8 km in width and 5 km in length with a maximum incision of 300 m, while the V-shaped gullies were narrower, 3–4 km wide, and a little shallower, with a maximum incision of 250 m (figure 5, table 1).

4.1.2 West segment

The seafloor in the west segment was generally flat with a mean gradient of ca. 2° , however, the gradient steepened at water depths of 400–700 m. No gullies or canyons were observed, but there were some small depressions, approximately 3 km wide and 50 m deep (figure 6).

4.2 Slides, slumps, and MTDs

The high-resolution 2D seismic reflection profiles revealed that slides, slumps and MTDs were well developed within the upper Ledong Formation. Slides and slumps, characterised by chaotic seismic facies (figures 7, 8), were well developed on high-gradient slopes ($>5^\circ$) in the east segment. Slides, failure surfaces, and escarpments were identified on the northern slope of the east segment. Canyons and gullies wall were over-steepened ($>8^\circ$) where slide scars and slumps occurred (figure 7, 8). More distinctly continuous reflections, large lateral variations in reflector spacing, and frequent reflector terminations were interpreted as representing interleaving, refilled minor slide scars. Small steps in seafloor topography on the continental slope, and

Figure 7. Seismic profile across east segment of upper continental slope. The section shows the late Quaternary canyon, normal fault, slumps and slide escarpment in the continental slope (for location, see figure 2a). Two mass transport deposits are characterised by chaotic half-transparent, low-amplitude seismic facies in the continental slope.

Figure 8. Seismic profile across the east segment of upper continental slope. The section shows the late Quaternary gully, small-scale fault, slumps and slide escarpment in the continental slope (for location, see figure 2a). Five mass transport deposits are characterised by discontinuous, chaotic, low-amplitude variable seismic facies in the continental slope.

Figure 9. Seismic profile across the east segment of upper continental slope. The section shows the late Quaternary slumps and slide escarpment in the continental slope (for location, see figure 2a). Three mass transport deposits are characterised by half-transparent, low-amplitude seismic facies in the continental slope.

reflector truncations in deeper water indicated that small-scale faulting was common (figure 8). In the scar area, the seafloor was slightly uneven with an undulating topography, which indicated erosion processes. Most of the collapsed sediment had

apparently moved to the south-east, where minor slump blocks protruded above the seafloor.

At the eastern margin of the upper slope basin, there were escarpments of ca. 200–300 m relief (figure 9) ranging up to ca. 600 m relief, with

associated MTDs found directly to the south-east. The slides had partially moved downslope of their original position, as large blocks from the grounding line had been fragmented into numerous small gravity-driven masses that flowed downslopes. The size of the slides in the east segment tended to decrease westwards, and no obvious slides were found in west segment (figure 10).

MTDs were identified from single-channel seismic profiles mainly developed in the upper slope. Several MTDs had incoherent facies or internal reflectors that appear severely deformed. The two-way-travel time thickness of the MTDs ranged from ~ 31 to 250 m (table 2). The MTDs were identified on the basis of unique seismic characteristics which included chaos, lack of continuity, translucence, brightness, and the presence of structures such as escarpments, normal faults and thrust faults (figures 7–10). The basal surface of the chaotic or strong reflective unit was an obvious high-amplitude, negative polarity reflective event. We interpreted the basal shear surface as the MTD slide plane (figures 7–10, table 2). Thus, MTDs were identified as seismic intervals of distorted and discontinuous reflections, which were bounded above, below, and laterally by continuous or strong deformed reflections. Two different MTD seismic facies were identified: (1) small-scale chaotic, low-amplitude reflections with variable seismic reflection continuity, and irregular shape; (2) chaotic, low-amplitude, and semi-transparent seismic reflections with sheet shape.

4.3 Rates of shelf-margin progradation and aggradation

The multibeam seismic profile (figure 11) shows that the stratigraphy of the western margin of the QDNB is dominated by giant Pliocene-Quaternary foresets, which indicate huge sediment input from the Red River and Hainan Island. The western shelf break point migrated a horizontal distance of ca. 27 km since 5.5 Ma (figure 11a), while the east segment shelf break point migrated < 2 km (figure 11b). The shelf-margin stacking pattern was dominated by vertical aggradation, with slight retrogression in the eastern QDNB.

Based on the observations above, the shelf-margin clinoforms documented in this study have been systematically characterised in terms of growth-trajectory angles (G_{ct}), aggradation to progradation ratios (A/P), geometries, and architectural styles:

$$G_{ct} = \tan^{-1} \left(\frac{A}{P} \right) \quad (1)$$

$$\frac{A}{P} = \frac{dy}{dx}, \quad (2)$$

where dy is the vertical component (vertical aggradation) and dx is the lateral component (lateral progradation) of clinoform-growth trajectories. The main clinoform-growth styles of the west and east segment are described below.

This western shelf-margin clinoform shelf-edge (red dots in figure 3a) was strongly progradational through time (blue dashed lines in figure 11a), exhibiting a flat to slightly rising trajectory trend.

Figure 10. Seismic profile across the west segment of upper continental slope (for location, see figure 2a). Three mass transport deposits are characterised by chaotic, low-amplitude variable seismic facies in the continental slope.

Table 2. Characteristics, depositional topography, source area and causal mechanisms of upper strata mass transport deposits (MTDs) in Qiongdongnan Basin, along the north-western South China Sea margin.

Seismic lines		Maximum thickness (m) (m, v=1750 m/s)	Seismic characteristics	Depositional topography	Source area	Triggering mechanisms	Segment location
Figure 7	MTD1	31	Escarpment, chaotic, half-transparent, low-amplitude reflections, normal fault	Topographic confinement	Canyon/gully margins	Local instabilities on canyon/gully margins and regional tectonic events	East segment
	MTD2	51	Escarpment, discontinuous, half-transparent, low-amplitude reflections, normal fault				
Figure 8	MTD1	108	Half-continuous, chaotic, small-scale chaotic, sheet-shaped, small-scale normal fault	Topographic confinement	Canyon/gully margins	Local instabilities on canyon/gully margins and regional tectonic events	East segment
	MTD2	95	Discontinuous, chaotic, low-amplitude variable seismic reflection continuity, sheet-shaped				
	MTD3	115					
	MTD4	66					
	MTD5	88					
Figure 9	MTD1	34	Half-transparent, low-amplitude reflections, sheet-shaped	Semi-confined settings	Upper slopes	Local instabilities	East segment
	MTD2	45					
	MTD3	53					
Figure 10	MTD1	50	Discontinuous, chaotic, low-amplitude variable seismic reflection continuity, sheet-shaped	Unconfined settings	Upper slopes	High sedimentation rates Rapid shelf-edge deltas progradation High sedimentation rates	West segment
	MTD2	250					
	MTD3	50

Figure 11. Interpretation of the multi-channel seismic profile. Inset map shows position of the seismic line. (a) Thick, mostly Plio-Pleistocene foresets migrating south into deep-water. The shelf break mainly developed since 10.5 Ma (modified from Clift and Sun 2006). Location is shown in the inset map. (b) Vertical aggradation with slight retrogression of the shelf break since 5.5 Ma (modified from He *et al.* 2013).

Shelf-edge aggradation was appropriately 1500 m, with a seaward progradation of 43 km (figure 3a, table 3). The G_{ct} for the west segment clinoforms was close to 0 (table 3), with low A/P (<0.07). Gong *et al.* (2015) showed that strongly progradational shelf-margin clinoforms such as these have a characteristic height of 1300 m and a migration distance up to 40 km. They are characterised by oblique progradational clinoforms that show toplap, erosional terminations at their uppermost level in the proximal reaches of the oldest unit, but sigmoidal clinoforms with very slight aggradation in the distal reaches (Gong *et al.* 2015).

The eastern shelf-margin clinoform topset-slope rollovers (indicated by red dots in figure 11b) were associated with strongly upward aggradation shelf-margin clinoforms with predominantly upward aggradation (blue dashed lines in figure 11b) and a steeply rising trajectory. The maximum aggradation relief for this style of clinoform-growth can reach up to 1500 m, with progradation distance

ranging from -320 to 300 m (table 3). Ranges of G_{ct} and A/P for this clinoform-growth style were 70° – 75° and 0 to -2.8 , respectively (table 3).

Strongly aggradational shelf-margin clinoforms are typified by a short migration distance of <1 km. They are made up of successive sigmoidal progradational packages, each of which contain thick topsets and downlap terminations and are characterised by a lack of toplap truncations. Strongly aggradational shelf-margins are sometimes associated with faults, and individual upward prograding shelf-margin clinoforms sometimes lie directly on a concave-up glide plane (Gong *et al.* 2015).

5. Discussion

5.1 Post-rift changes in tectonic subsidence rate

Research by Cong *et al.* (2013) using the Airy equilibrium model, which is based on a

Table 3. Characteristics of progradation and aggradation at the upper slope of the north-west SCS. Vertical aggradation (A) and lateral progradation (P) are based on the beginning and end of clinoform rollovers, respectively. Distances of each growth style are indicated by blue lines shown in figures 3(a), 11.

Location	Seismic sections	A (m)	P (m)	dy/dx	G_{ct}	Time interval	Trajectory styles	AR (m/Ma)	PR (km/Ma)	Stratal stacking patterns
West segment	Figure 3(a) Figure 11(a)	1300	43000	0.035	2.0°	1.8 Ma to present	Slightly rising	789.4	22.63	Progradational and aggradational
		360	8000	0.045	2.5°	10.8 to 5.5 Ma	Flat to slightly rising	63.15	1.40	Progradational
		800	15000	0.053	3.0°	5.5 to 1.8 Ma	Slightly rising	242.42	4.54	Progradational and aggradational
		750	10000	0.075	4.3°	1.8 Ma to present	Slightly rising	375.0	5.0	Progradational and strongly aggradational
East segment	Figure 11(b)	1500	0	0	0°	13.8 to 5.5 Ma	Steeply rising	152.94	0	Dominantly aggradational
		1200	300	-4	75°	5.5 to 1.8 Ma	Steeply rising	363.63	0.09	Dominantly aggradational
		900	-320	-2.8	70°	1.8 Ma to present	Steeply rising	450.0	-0.16	Dominantly aggradational

AR: rates of shelf-edge aggradation; PR: rates of shelf-edge progradation; and G_{ct} : angles of growth trajectories.

tectono-sedimentary analysis, indicates that tectonic subsidence has played a dominant role in the northern continental slope of the SCS since the Late Miocene. Centres of subsidence in the north-western SCS are located in the Central Depression Belt of the QDNB, but there were differential subsidence rates inside the basin. Modelling results showed a higher subsidence rate in the western part of the basin than the eastern (Cong *et al.* 2013). For example, the west segment rate was ca. 75–105 m/Ma and east segment ca. 25–75 m/Ma between 5.5 and 1.8 Ma (figure 12). The higher subsidence rate of the west segment provides more sediment accumulation space which supports the development and progradation of slope clinoforms. Slope margin formation was initiated in the offshore Hainan Island area in the Late Miocene (Chen *et al.* 1993), and significant progradational packages of slope sediments began to prevail in the QDNB in the Early Pliocene (Xie *et al.* 2006). The thickest deposits are found in the western QDNB during the Plio-Pleistocene due to a general southward migration of depocenters over time (Clift and Sun 2006).

5.2 Sediment supply

The distribution of slope clinoforms in the QDNB appears to be associated with faults (figure 1). Deep faulting seems to constrain the initial formation of the slope, although faults do not cross the overlapping shelf-slope deposits (figure 3). Tectonic and thermal subsidence produce the necessary spaces for sediment to infill. Although initial development of slope architecture was influenced by tectonic movement, it is thought that the primary control on slope clinoform geometry was sediment supply by major river systems. Previous research has indicated that sediment supply rate is a major factor in the evolution of deep-water sedimentary environments. Obviously, a sedimentary environment will never become deep-water if sediment supply is too great (Wang *et al.* 2015), however, ample sediment supply rapidly results in development of progradational slope clinoforms extending a large distance in shelf-slope areas (Xie *et al.* 2008).

In the Late Miocene (5.5 Ma), the Tibetan Plateau underwent a phase of rapid uplift, and this, combined with its mountainous relief, potentially provided vast amounts of sediment to the western QDNB through the Red River (Wang 1999; Shi *et al.* 2013). The Red River's highly seasonal water (120 km³/yr) and sediment discharges make it one of the major fluvial suppliers in Southeast Asia (Pruszek *et al.* 2002; Tanabe *et al.* 2003). Detrital zircon grains from the drilling of three sandstones in the Upper Miocene Huangliu Formation in the

Figure 12. Isolines of tectonic subsidence rates (m/Ma) on the north-western continental margin of the South China Sea from 5.5 to 1.8 Ma (modified from Cong *et al.* 2013).

western part of the Central Canyon were analysed by LA-ICP-MS for U–Pb ages. The results suggest that the paleo-Red River system dominantly fed the western part of the QDNB in the Late Miocene (Chen *et al.* 2015). Detailed analyses of chondrite-normalised rare earth element distribution (Shao *et al.* 2010) and 3-D seismic amplitude extraction map (Zhu *et al.* 2009) showed that Hainan Island is also a main source for the QDNB. The Hainan Island provenance began to develop in the Early Oligocene and had become a major source for the QDNB from the Middle Miocene to the present (Liu *et al.* 2015). In the northern QDNB, sediments from Hainan Island have been transported onto the slope and basin floor and deposited as fans (Wang *et al.* 2015).

Reconstructions suggest sediment supply peaked in the Middle Miocene, reduced between 14 and 10.3 Ma to reach a low in the late Miocene, and then rose again in the Pliocene–Pleistocene in the north-western SCS (Clift and Sun 2006). The calculations of Clift and Sun (2006) show a maximum sediment thickness of 2500 m and a high sediment rate in the western QDNB during the Pliocene to the Recent period (figure 13). Additionally, research by Zhu *et al.* (2009) indicated that sedimentation rates in the western QDNB were up to 1.2 mm/a.

Rapid sediment supply and high sedimentation rates tend to compensate channels and canyons (Saller and Dharmasamathi 2012; Ma *et al.* 2015), leading to more gentle slope profiles, as is evident in the western segment. Significant progradational reflection packages of slope sediments have developed since the Early Pliocene in the western QDNB

(Xie *et al.* 2008). The eastern QDNB is subject to less efficient sediment supply as it is approximately 400 km to its nearest source in the Pearl River, and the slope system in this part of the basin shows a sub-vertical stacking pattern with a slight progradation characterised by abundant gravitational faults, rollover structures, and slump deposits (Xie *et al.* 2008).

5.3 Temporal and spatial variations in the shelf break

Based on tectonic subsidence rates (Cong *et al.* 2013), it can be estimated that the shelf break in the west segment occurred at 10.5 Ma, later than that in the east segment (figure 12). West segment shelf-margin evolution can be divided into three stages, based on growth style characteristics: slight progradation between 10.5 and 5.5 Ma; progradation and aggradation between 5.5 and 1.8 Ma; and progradation with strong aggradation from 1.8 Ma to present. The east segment shows a different, dominantly aggradational, style over time; the shelf-margin stacking pattern is dominated by vertical aggradation with slight retrogression.

Spatially, the horizontal migration distance of the shelf break differs from west to east. West segment stratigraphy is dominated by giant Pliocene–Quaternary foresets, which are a response to huge sediment input from the Red River and Hainan Island. The west segment shelf break line migrated southwards a maximum distance of ca. 250 km from 5.5 Ma to present, at a rate of 45.5 km/Ma. In the east segment, however, the shelf break

Figure 13. Isopach maps of some of the major stratigraphic units in the southern Yinggehai and Qiongdongnan basin (QDNB) region (modified after Cliff and Sun 2006). (a) Pliocene–Recent, (b) upper Miocene. Note southerly migration of depocenter into the Qiongdongnan basin during the Pliocene. Strata unit thicknesses are in meters. The purple dashed line is the border of the QDNB.

line migrated to the south only a short distance, between 5.5 and 1.8 Ma, and then retreated from 1.8 Ma to present (figure 14).

Previous research has indicated that average progradation and aggradation rates vary with water depth, with rates of ca. 17 km/Ma and ca. 100 m/Ma at water depths <1000 m and >1000 m, respectively (Carvajal *et al.* 2009). The seismic profiles in this study suggest that upper slope progradation and aggradation rates in the north-western SCS are higher than in other marginal seas in the world.

5.4 Depositional models with insufficient and ample sediment supply

In most of the upper slope and base environment, slump deposits and MTDs with deformation

structures are dominant. Seismic profiles show that a number of gravitational slip faults and slump deposits formed in the east segment. MTDs are confined within submarine canyons/gullies, suggesting that large-scale and high-energy sediment gravity flows were the principle process at the time of MTD emplacement (figures 7, 8). Sediment gravity currents travelling along the long axis of the submarine canyon/gully are interpreted to have induced small collapses and local instabilities on canyon/gully margins, resulting in small-scale mass-wasting processes and MTDs composed of collapsed canyon margin sediments (table 2).

MTDs also occur at extensive headwall escarpments, recognised in the northern part of the slope and downslope to the south. Small-scale faulting is developed inside the MTDs (figure 8), which is suggested as originating during gravity-driven slope collapse (table 2). The gradient of the upper slope tends to be less rugose with lower degrees of deformation (figures 9, 10). It is likely that the overall low deformation of these margins results directly from their smaller scale and resultant low mass, which has decreased potential to induce significant gravity-driven deformation (figure 10).

MTDs are also associated with deformed shelf-edge deltas (figure 10). The rapid progradation of shelf-edge deltas may lead to the development of gravitational instabilities and large-scale sediment failures in distal parts as the delta slope merges with the basin margin slope. This is expressed in the disrupted and deformed seismic reflection configurations from the terminal end of shelf-edge deltas (figure 10). These observations support the interpretation that deformed shelf-edge deltas are MTD source areas (table 2).

The differences in geomorphology and geometry of the west and east segments of the QDNB slope margin indicate that there are different sediment processes operating. Possible depositional models for each segment have been constructed: a constant shelf break model with insufficient sediment supply; and a migration shelf break model with ample sediment supply.

5.4.1 Constant shelf break model

This model applies to the east segment, which is characterised by insufficient sediment supply (figure 15). The erosion rate is higher than the rate of sediment accumulation, causing slope gradients to steepen with time. Consequently, a large number of gravity-driven faults, slumps, MTDs, and erosional surfaces are able to develop within the slope zone. A series of late Quaternary submarine canyons/gullies developed in the eastern shelf-margin of the QDNB indicating deficient sediment supply and erosional slope environments (Xie *et al.*

Figure 14. Shelf break line migration direction and terrigenous sediment sources from the Red River, Hainan Island, and Pearl River (modified from Xie *et al.* 2008; Wang 1999; Liu *et al.* 2013; Shi *et al.* 2013). The dashed arrows show the direction of sources from the Red River, Hainan Island, and Pearl River, respectively. The dotted coloured lines show the shelf break line at 5.5, 2.9, 1.8 and 0 Ma, respectively. The dashed line is the border of the Qiongdongnan basin (QDNB).

Figure 15. Constant shelf break model in the east segment. The model shows strong erosion of the bottom current and insufficient sediment input, resulting in slumping and back step of the east shelf break zone. The east segment is an erosion-dominated slope.

2008). The canyons are generally oriented NW–SE, approximately perpendicular to the slope. A possible hypothesis for the initiation of these canyons

is the backstepping of failures at the shelf break that may be related to minor faulting in the shelf-margin, with subsequent headward erosion. MTDs

Figure 16. Progradation shelf break model in the west segment. The model shows the smooth sea floor of the western shelf break zone resulting from large sediment supply. The west segment is a deposition-dominated slope.

and slumps were also well developed on the eastern upper slope due to canyon margin or head failure.

Previous research has suggested that the development of submarine canyons in the eastern segment of the upper slope is also due to bottom current activity resulting from the South China Sea Warm Current (He *et al.* 2013). It seems that the shelf break zone was eroded by the bottom current and collapsed under gravity, causing the canyon wall MTDs. The shelf break line migrated southwards and then retreated a short distance. Therefore, the east segment may be classified as an erosion-dominated slope.

5.4.2 Migration shelf break model

This model was developed in the west segment. The upper slope accumulated great thicknesses of sediment, with progradational and aggradational slope clinoforms. Based on stratigraphic architectures and sequence geometry, the progradational slope clinoforms associated with a rapid seaward shift of the western shelf break zone is thought to result from significant sediment supply, mainly from the Red River and Hainan Island. Sediment accumulation is stronger than erosion, leading the shelf break line to prograde southwards a great distance, and preventing the development of canyons and gullies in this segment. The west segment may be classified as a deposition-dominated slope (figure 16).

6. Conclusions

- (1) On the basis of an integrated analysis of data from multibeam bathymetry, seismic profiles, and previous research, slope processes in the west and east segment of the upper continental slope were identified. Each segment was characterised by distinctive geomorphology, sequence geometries, and sedimentary processes, which may reflect differences in upper slope depositional processes.
- (2) Two main growth styles of shelf-margin clinoforms were recognised: a strongly progradational style with low G_{ct} ($<4^\circ$), low A/P (<0.07), long migration distance (>40 km); and a strongly aggradational style, with high G_{ct} ($>70^\circ$), high A/P (>4), and short migration distance (<300 m).
- (3) The east segment of the upper slope was classified as an erosion-dominated slope, resulting from insufficient sediment supply. The segment was dominated by canyons and gullies, which decreased in size to the east. Erosion escarpments and slumps were also well developed. Several MTDs were identified in the upper slope of the QDNB, induced by gravitational faults, erosion, and instabilities on canyon margins. Shelf-margin strata and clinoforms showed strong vertical aggradation with time. The shelf break line migrated a short distance to the south between 5.5 and 1.8 Ma and then retreated from 1.8 Ma to present.
- (4) The west segment was classified as a deposition-dominated slope, resulting from sufficient sediment supply close to the source area. The west segment was characterised by a smooth floor, a gentle gradient, and lack of canyons and gullies. Also, no erosion, escarpments, or slumps were found. Several MTDs, created by mass-wasting processes triggered by high sedimentation rate and rapid shelf-edge progradation, were identified. The shelf-edge of the shelf-margin clinoform was progradational through time and displayed a combination of progradational and aggradational stacking patterns. The west segment of the shelf break line continuously migrated to the south since 5.5 Ma.
- (5) Two depositional models, constant shelf break and migration shelf break, were constructed.

The models reflect the significant effect of sediment supply on the upper slope formation and evolution in the north-western SCS. A complicated shelf-margin geomorphology was revealed in the study area, controlled by sediment supply. Variations in the shelf break reflected differences in the balance between sedimentation and erosion. The paper provides an overview of upper slope characteristics and a scientific base for future research in the study area. Additional investigation and research work are needed for a more detailed understanding of the mechanisms of the upper slope sedimentary process, using techniques such as gravity sampling and in situ continuous hydrodynamic measurement.

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