The Thesis Committee for Bingjie Zhang
Certifies that this is the approved version of the following thesis:

The Variability of shelf-margin morphology and controlling factors: a case study of a northwestern South China Sea shelf-margin

APPROVED BY
SUPERVISING COMMITTEE:

Ronald J. Steel, Supervisor

William L. Fisher

Chenglin Gong

The Variability of shelf-margin morphology and controlling factors: a case study of a northwestern South China Sea shelf-margin

by

Bingjie Zhang

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Abstract

The Variability of shelf-margin morphology and controlling factors: a case study of a northwestern South China Sea shelf-margin

Bingjie Zhang, MSEER

The University of Texas at Austin, 2018

Supervisor: Ronald J. Steel

A shelf-margin from Qiongdongnan Basin, northwestern South China Sea was studied. Geometric parameters (clinoform heights, lengths, forest inclinations) and accretion rates (progradation rates and aggradation rates) were measured, shelf-edge trajectories were depicted, and ancient sediment flux across the shelf-edge area were calculated using Petter et al 2013 methodology. The shelf-margin was divided into three depositional packages in terms of different shelf-margin growth patterns. The lower most depositional package (10.5 - 5.5 My) exhibits strong progradation tendency but minimum to even negative aggradation, which is likely due to the anomalous post-rift subsidence that occurred along the northern Qiongdongnan Basin during Middle Miocene to Late Miocene. In contrast, the upper most package (1.9 My - present) mainly grew vertically and managed to maintain a relatively high-rising trajectory because the shelf had become very wide (200 – 280 Km, Xie et al 2008) since Late Miocene and the sediment supply was highly insufficient and fine-

grained. It is also likely that this very high supply rate of mud results at least partly from along-strike mud delivery, possibly as littoral fluid mud plumes, from the mouth of the Red River Delta. The middle package exhibits somewhat a mixed progradational and aggradational character with moderate clinoform dimensions and moderate accretion rates, which is likely to be a result of a reasonable balance between supply and accommodation.

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Introduction

Shelf-margins – sediment prisms that accrete basin-ward toward the deep-water area of an ocean sink, have historically received much attention from researchers, including both modern and ancient margins (e.g. O'Grady et al 2000, Carvajal & Steel 2006, Henriksen et al 2009, Olariu & Steel 2009). Although the geological term "shelf" commonly refers to "continental shelf" which represents the very gently dipping underwater landmass forming at the margin of a continent, Swift & Thorne (1991), Johannessen & Steel (2005) and Helland Hansen et al (2012) argued that the term "shelf" should not be restricted only to continental margins, but rather be used to describe any accretionary (widening), shallow- water platforms building out to water depth of over 200m, in any type of sedimentary basins. Therefore, margins of rift and foreland basins, and even non-marine deep lake basins are also included. The term 'shelf-margin' refers to the whole clinoformal morphological profile, consisting of "shelf", "deep-water slope" and "basin floor" segments (Figure 1).

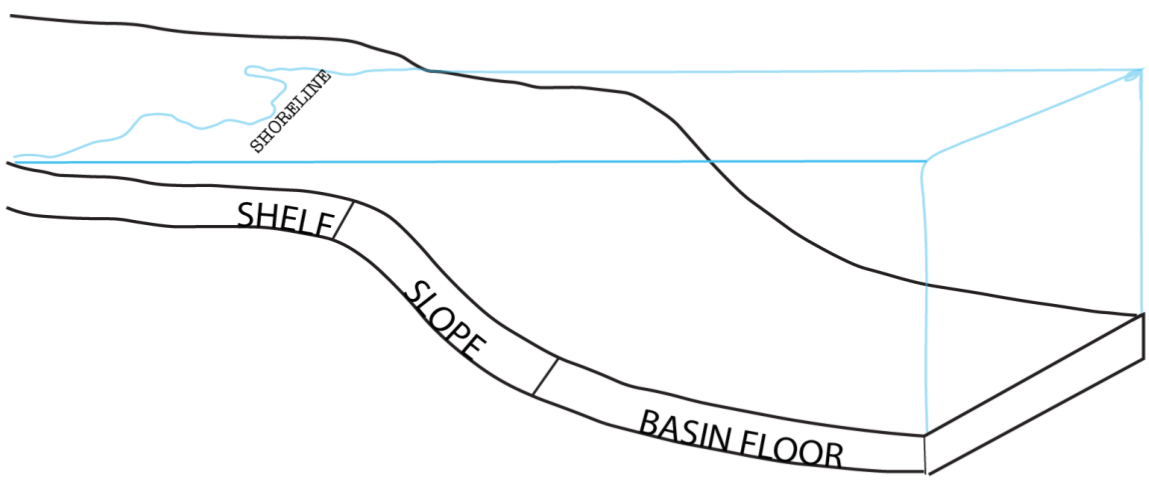

Figure 1. Three segments of a typical shelf-margin

Shallow marine sediments are stored on and dispersed through shelf-margins before ultimately being transported to deep-water areas. Further, shelf-margin geometry, along with marine processes, plays an important role in the nature and distribution of these shallow marine sediments and provides information and signals that help to predict the characters and location of sediments in deep water regions. Therefore, it is critical to quantify the geometries and shapes of shelf-margin prisms and to understand the possible controlling factors behind the variation of shelf-margin morphology.

A variety of factors influence the geomorphology of shelf-slope-basin floor zones, including tectonism, sea-level changes, sediment supply rates, current-controlled processes among others. With the aid of high-resolution, spatially-dense three-dimensional seismic data, and combined with lithological and biostratigraphic information extracted from well logs and cores, multiple researchers have been able to conduct studies to unravel the roles of factors mentioned above in the construction of such shelf-margins by utilizing the architectural and stratigraphic detail provided by the resulting integrated depositional framework (e.g. Posamentier & Kolla 2003)

The basic morphological element of a shelf-margin is the clinoform. The term ‘clinoform’ was originally introduced by Rich (1951) to define the inclined, basin-ward dipping stratigraphic surface that extends from the outer edge of the topset to the bottom of the foreset slope in the deep-water basin. Steel & Olsen (2002) extended the definition of clinoform, which leads to the current commonly-accepted new definition of clinoform – a sloping depositional surface consisting of a seaward-dipping segment (foreset) and two gently dipping segments that connect the foreset to both landward (topset) and basin-ward (bottomset) directions (Figure 3).

However, it should be noted that the clinoform is a common depositional morphology occurring in subaerial, shallow-marine and continental-margin environments over a range of spatial scales (1-10^4m, Wolinzky & Pratson, 2007; Helland-Hansen & Hampson, 2009). Smaller subaerial and subaqueous deltaic-scale clinoforms are typically tens of meters with up to a hundred meters in height, while larger continental-margin clinoforms can have heights up to thousands of meters (Johannessen & Steel, 2005). Not to be confused with deltaic-scale clinoforms, the shelf-margin geometry description part of this study centers on the morphology of continental-margin scale clinoforms (typically hundreds of meters), trying to quantify the geometry by measuring clinoform dimensions (clinoform height, length, foreset dip), determining clinoform stacking patterns and inferring clinoform growth styles. Furthermore, analysis of shelf-trajectory trend and calculation of progradation and aggradation rate were also conducted in this study to achieve a more comprehensive quantification of shelf-margin morphologies.

This work utilized a Cenozoic shelf-margin located at the northwestern South China Sea as a case study. The quantification of various geometries displayed by this shelf-margin, identification and analysis of possible controlling factors in shaping different surfaces within the margin and in addition, utilization of a methodology described by Petter et al 2013 in an attempt to evaluate paleoflux of sediment across the margin, all contributed to a better understanding of the northwestern South China Sea shelf-margin’s current state as well as some critical ancient events that occurred.

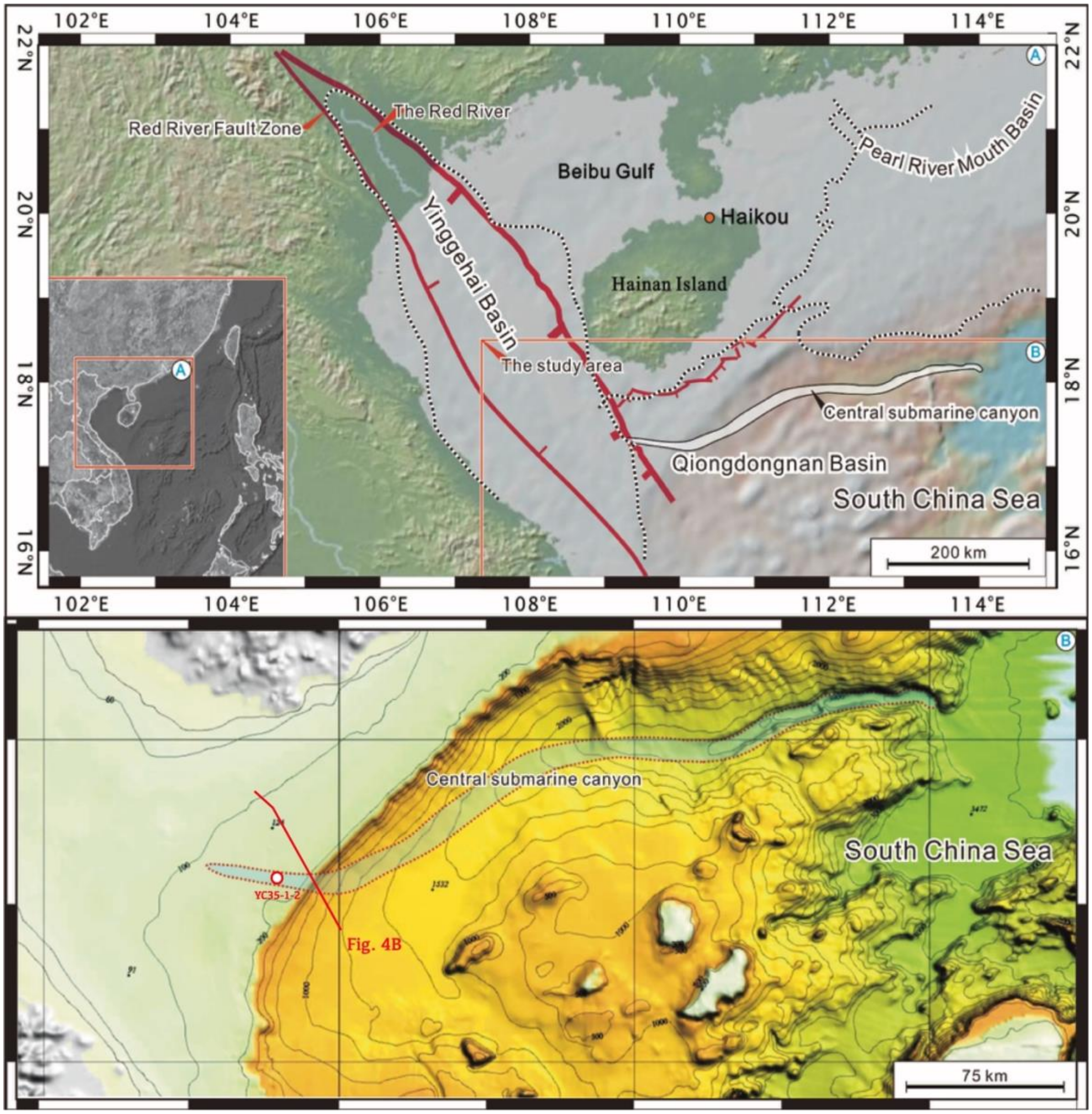

Figure 2. Map showing the study area along the northwestern shelf-margin of South China Sea. A) shows the relative location of Qiongdongnan Basin and Yinggehai Basin. B) shows the location of the seismic line and Well YC35-1-2.

Geological setting

The studied margin lies in the junction of two Cenozoic basins, the Qiongdongnan basin and the Yinggehai basin, which are separated by a major boundary fault the No. 1 fault (Xie et al 2008; Gong et al 2015; Fig 2). The northwestern-southeastern No. 1 fault appears to connect to the Red River fault zone. To the east the study area is adjacent to Pearl River Mouth basin. The formation of Qiongdongnan basin is believed to relate to the opening of South China Sea (Ru and Pigott 1986), while the formation of Yinggehai basin has been open to some debates (e.g. Guo et al 2001; Gong and Li 1997; Li et al 1998). In general, however, the Yinggehai basin is believed to belong to a transtentional system whose formation is closely related to the Red River Fault Zone.

As Xie et al (2008) suggested, both of the two basins underwent two tectonic evolutionary stages, namely a Paleocene – Early Oligocene rifting stage and an Early Miocene – Quaternary post-rifting stage. And thusly generated two supersequences, a syn-rift supersequence from Paleocene to Early Oligocene and a post-rift supersequence from Early Miocene to Quaternary as the basin infill of the Yinggehai basin and Qiongdongnan basin (Gong et al 2015). The clinoforms studied herein are of Upper Miocene – Quaternary age. Tectonic reactivation took place along the northern South China Sea margin by the Late Miocene, which is believed to have controlled the formation and evolution of the continental slope system in the study area (Xie et al 2006).

Dataset and methodology

2D SEISMIC LINE AND WELL LOG

This study utilized the information from a 2D seismic profile and a well log by China National Offshore Oil Corporation Ltd (CNOOC). See the location of the seismic line and the well on Figure 2. The seismic profile was used to identify a series of shelf-margin clinoforms (Figure 4b), to quantify clinoform geometries (Table 1), and to characterize clinoform growth styles. The well log was used herein to provide lithological information, and several unique depositional features developed in a mixed mud-sand unit were recognized based on the different well log patterns they exhibit (Figure 8).

DEFINITION OF MORPHOMETRIC PARAMETERS OF CLINOFORMS

A rollover point occurs where there is an evident change of seafloor slope from topset to foreset (Fig 3), and along with the toe of slope where the seafloor slope significantly decreases from foreset to bottomset, they define the clinoform height (m) and length (km) (Fig 3). Foreset dip (a) is the angle measured on the right triangle defined by clinoform height and length (Fig 3).

Shelf-edge trajectory provides critical information regarding sea level changes, margin growth styles and so forth, and can be depicted by connecting adjacent clinoform rollover points. The vertical portion of the shelf-edge trajectory within two adjacent clinoforms defines the aggradation distance, and the horizontal portion defines the progradation. Aggradation rate (m/ Ma) and progradation rate (Km/ Ma) can be calculated by dividing aggradation and progradation by the corresponding time intervals.

In this study, clinoform heights, lengths, foreset dip (ə) were measured, progradation rate and aggradation rate were calculated using the age information derived from the well data, and shelf-edge trajectories were depicted in order to quantify shelf-margin geometries.

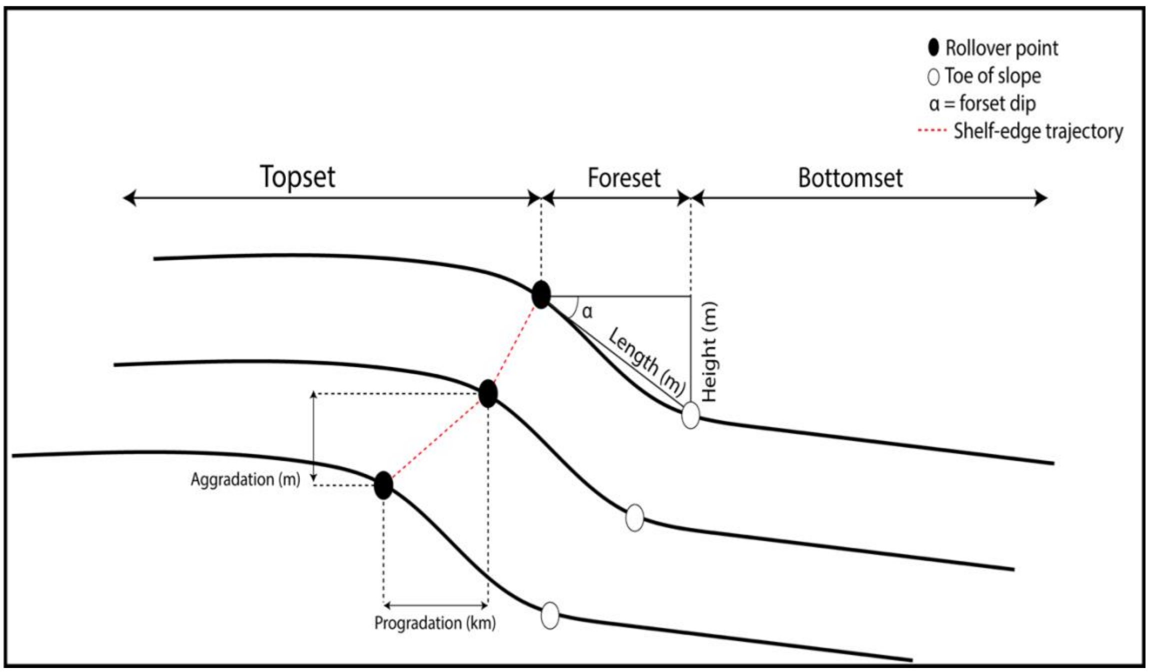

Figure 3. Sketch showing an idealized clinoform profile with clinoform geometries and morphometric parameters.

Description of shelf-margin geometries

Gong et al 2015 identified three depositional packages, namely strongly progradational, mixed progradational and aggradational, and strongly aggradational packages based on the growth styles displayed by clinoforms within each package. The strongly progradational package consists of clinoforms that exhibit a dominantly progradational growth style, with a characteristic long progradation distance and negative aggradation. The strongly aggradational package, on the other hand, is characterized by a distinctly high aggradation rate and rising shelf-edge trajectory trend. The mixed progradational and aggradational package, relative to the former two, developed moderately both vertically and horizontally (basin-ward). Three regionally important unconformities, namely BSA, BLP and BHP were recognized (Gong et al,2015), which serve as the bounding surfaces at the base of strongly progradational, mixed progradational and aggradational and strongly aggradational package, respectively. The corresponding ages of three unconformities are 10.5 Ma, 5.5 Ma and 1.9 Ma. The three packages differentiate from each other not only by stacking patterns, but also by clinoform dimensions (clinoform height H_c, length L_c, foreset dip ∂) and unique seismic facies developing downdip of the slopes of each package.

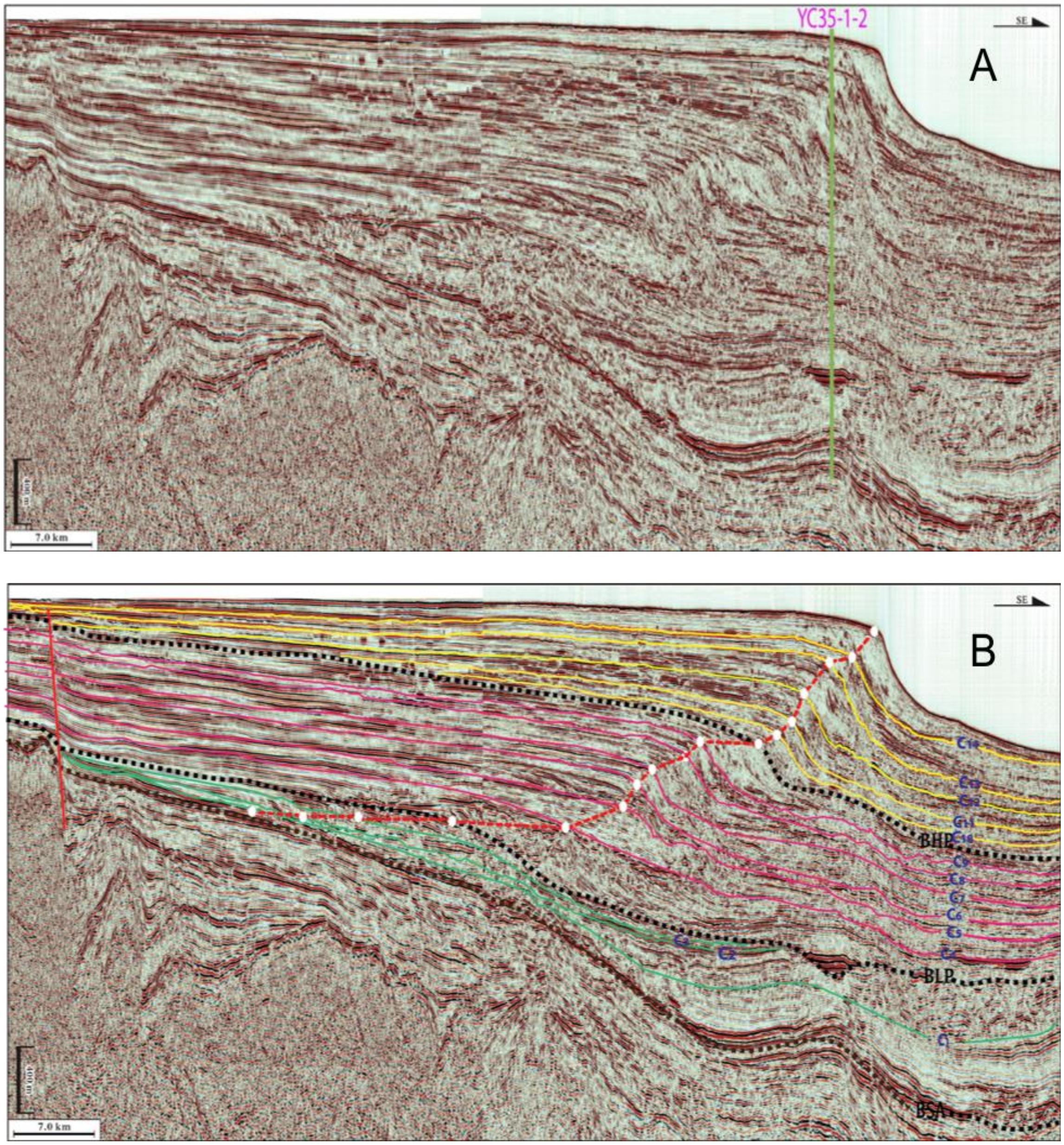

Figure 4: Uninterpreted and interpreted seismic profiles. Top is the uninterpreted seismic profile with extrapolated Well YC35-1-2. See figure 2 for the real location of YC35-1-2. Bottom interpreted seismic profile shows the interpretations of individual clinoforms within three depositional packages, shelf-edge rollover points and shelf-edge trajectory.

Depositional package	Surfaces	Age (Ma)	Height (m)	Length (km)	Forest dip (°)	Aggradation (m)	Progradation (km)	Aggradation rate (m/Ma)	Progradation rate (km/Ma)
Strongly aggradational	seabed	0	480	4.2	6.52	684.81	11.66	360.43	6.14
	14		453	5.6	4.62				
	13		426.67	4.55	5.36				
	12		346.67	3.15	6.28				
	11		293.33	3.15	5.32				
	10		293.33	3.5	4.79				
	BHP	1.9	266.67	2.8	5.44				
Mixed progradational and aggradational	9		373.33	4.9	4.36	548.22	24.77	152.28	6.88
	8		293.33	3.15	4.47				
	7		213.33	3.75	3.26				
	6		240	3.15	4.36				
	5		186.67	3.15	3.39				
	4		133.33	2.1	3.63				
	BLP	5.5	373.33	9.45	2.26				
Strongly progradational	3		157.43	9.1	0.99	-26.65	39.8	-5.33	7.96
	2		171.43	11.9	0.83				
	1		142.86	15.05	0.54				
	BSA	10.5	112.53	17.15	0.38				

Table 1. Summary of geometric measurements of seismic surfaces interpreted from northwestern South China Sea shelf-margin.

STRONGLY PROGRADATIONAL PACKAGE

The strongly progradational shelf-margin clinoforms are characterized by a lack of topsets in the upper most level of proximal reaches and show toplap or truncations instead (Figure 5). Seismic reflections associated with the foresets can be chaotic in places while laterally equivalent seismic reflections of the bottomsets show low to high amplitude, continuous character (see Figure 4 the lower most package bounded by BLP above and by BSA at the base). Due to the strongly progradational character of this package, the shelf-edge trajectory shows a flat to falling trend, with a negative aggradation value and a seaward progradation of tens of kilometers. The thickness of the slope section is relatively uniform but increases toward the basin floor direction (Figure 4).

Individual clinoforms within the strongly progradational package have a characteristic low height of < 200 m and a long length of up to 20km. Foreset angles are characterized by relatively small foreset inclination value of less than 1° (Table 1).

The strongly progradational section appears on the well-log data as low gamma ray, blocky log pattern (Fig 8), with a thickness of approximately 800 m. This package was interpreted as a sand-rich unit and appears to have bypassed sand to the slope and basin floor regions.

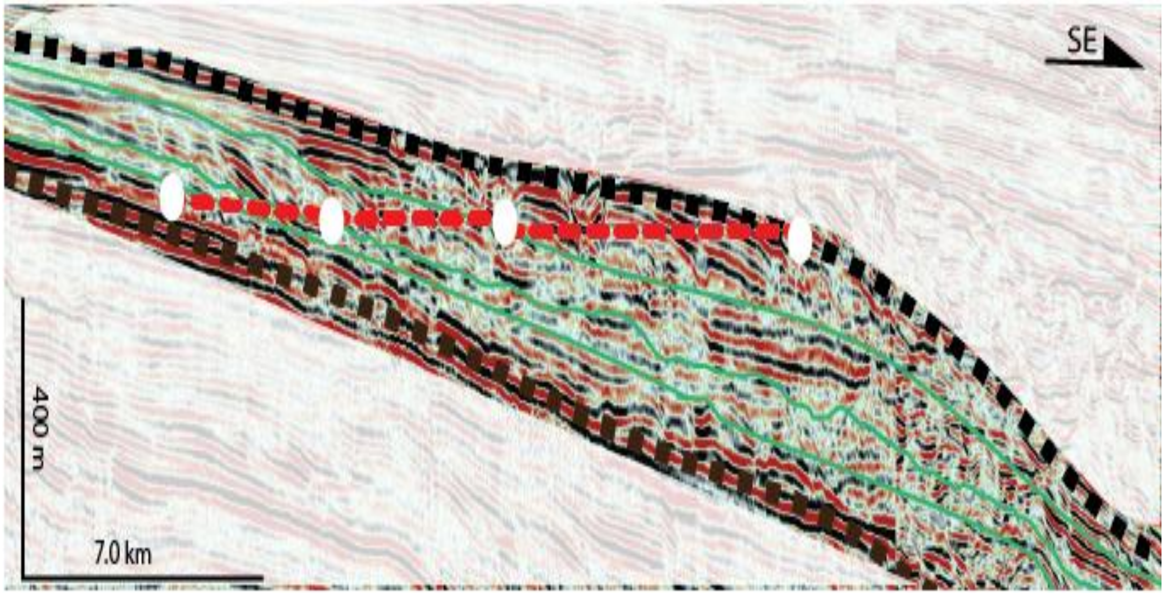

Figure 5. Seismic cross section through the strongly progradational package in the shelf-edge area.

MIXED PROGRADATIONAL AND AGGRADATIONAL PACKAGE

Unlike clinoforms within the strongly progradtional package which lack topsets, this type of package consists of clinoforms with significant vertical accretion, i.e. topsets in the proximal reaches of the clinoforms (Figure 6). These topsets of clinoforms within the mixed progradational and aggradational package are characterized by medium to high amplitude, continuous seismic reflections, while deep-water slopes and bottomsets show medium to high, semicontinuous to continuous reflections (Figure 6). Characterized by both vertical and basin-ward accretion, the shelf-edge displays a slightly rising trend, with an aggradation value of hundreds of meters and a progradation of tens of kilometers. The thickness of the entire package reaches the maximum of up to 1727 m at the shelf-edge and decreases both landward and basin-ward.

The mixed progradational and aggradational shelf-margin clinoforms are characterized by moderate height of 200-400 m and length with an average of 3.95 km. The foreset inclination values are within the range of 2°-4.5° (Table 1).

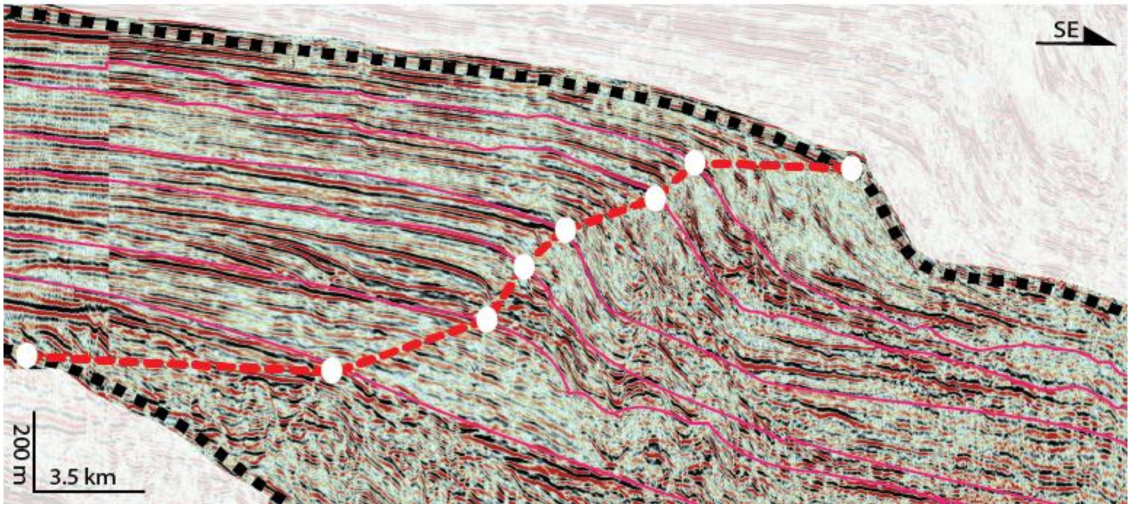

Figure 6. Seismic cross section of the mixed aggradational and progradational package shelf-edge area.

A number of depositional features (shelf-edge delta, slope channel / submarine canyon and mass-transport complex) are speculatively interpreted on the well log based on different log patterns that each feature exhibits (Fig 8). At the bottom of the package, the gamma ray value gradually increases up to 200 m, indicating a fining upward unit which might be reasonable to interpret as a large slope channel or a submarine canyon system. According to Gong et al 2011, this unit has been recognized and termed as the Central submarine canyon system. The gradually decreasing upward gamma ray log patterns correspond to coarsening upward units which were interpreted as prograding shelf-edge deltas, and relatively uniform, low gamma units correspond to mud-dominated, mass-transport complexes. Further up above the bottom submarine canyon, shelf-edge deltas and mass-transport complexes developed alternately (Fig 8). 6 individual shelf-edge deltas with an average thickness of 120 m were recognized, which contribute sand volume to the mixed mud-sand package. Mass-transport complexes, on the other hand, were less developed and more scattered, reaching a thickness of 250 m. These complexes increase the mud ratio of this package accordingly.

STRONGLY AGGRADATIONAL PACKAGE

Seismic reflections associated with topsets, foresets and bottomsets of clinoforms within the strongly aggradational package show little difference from the mixed progradational and aggradational package. The main differences between these two packages lie in the shelf-edge trajectory trend, which shows stronger rising in the aggradational package (see Fig 4 the upper most package bounded by BHP at the base). In addition, the topsets in this package are slightly thicker than the package below (Figure 7). Aggradation of the clinoforms within the strongly aggradational package can reach up to hundreds of meters and progradation distance reaches tens of kilometers. The thickest part (1545 m) occurs at the shelf-edge area.

The strongly aggradational package consists of the highest clinoforms (up to 480m) with relatively short, individual progradational lengths (an average of 3.8km). A characterized high foreset inclination (within the range of 4.5 to 6.5 degrees) is characteristic of each clinoform within the package (Table 1).

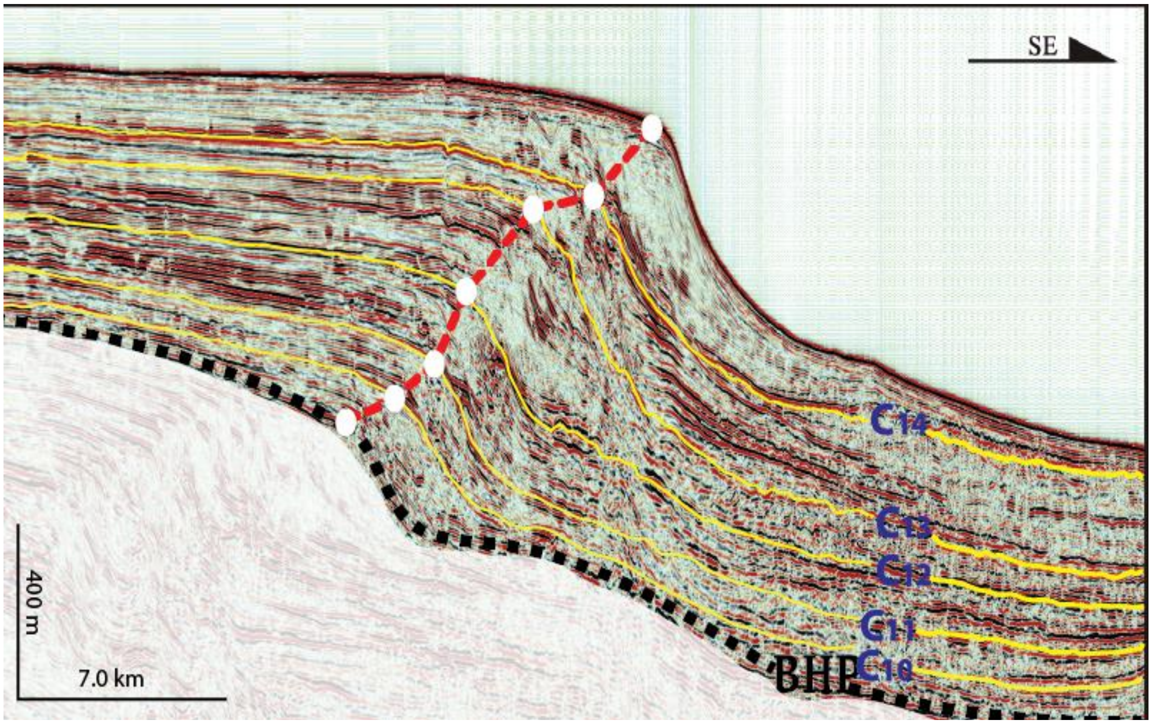

Figure 7. Seismic cross section showing the shelf-edge area of the strongly aggradational package.

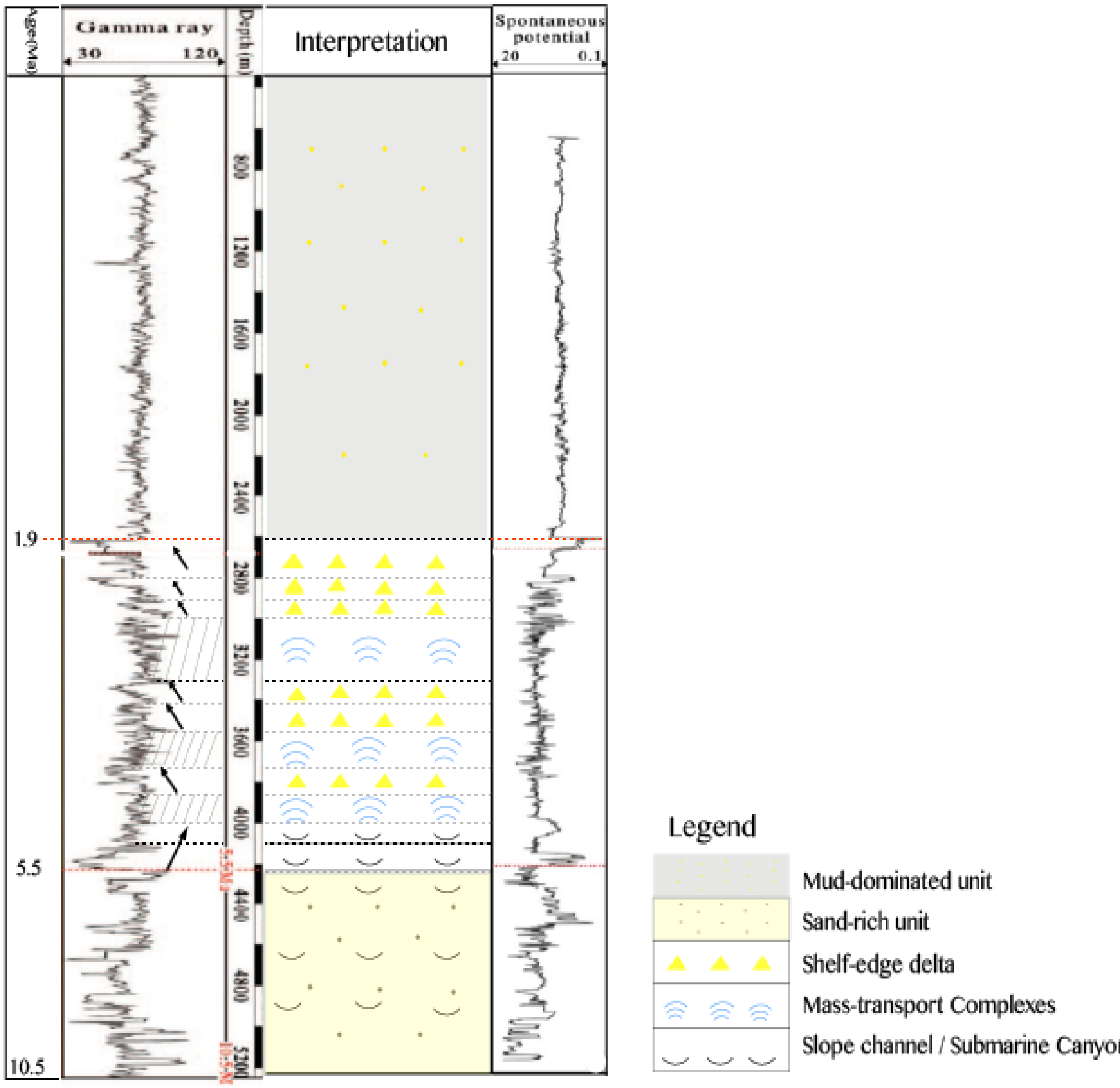

Figure 8. Gamma ray and spontaneous potential well-log curves of Well YC35-1-2 and the interpretation of depositional features according to their well-log patterns.

Categorization of shelf-margins based on seafloor inclinations

Several methods have been proposed to classify modern continental-shelf passive margin morphologies by measuring clinoform inclinations (e.g. O'Grady et al 2000; Adam & Schlager 2000). Similar approaches have been applied to ancient shelf-margins in tectonically active basins (e.g. Salazar et al 2016). In this study, a methodology developed by O'Grady et al (2000) was applied to clinoforms within a shelf-margin in the Northwestern Qiongdongnan basin, taking into consideration that Qiongdongnan basin underwent tectonic reactivation by the Late Miocene, which controlled the formation and evolution of the shelf-margin clinoforms.

Since individual clinoforms within a single depositional package exhibit similar growth styles and clinoform inclination distribution, only the inclination of the bounding surfaces (BSA, BLP, BHP and the seabed) of these packages were measured, and plots showing slope degrees versus depth were depicted (Figure 9). The initial results of the slope patterns of BSA and BLP are aligned with the O' Grady et al (2000) classification of Steep & Rough category of clinoform morphology, whose inclinations are relatively variable and scattered with the maxima reach up to 4.5º (Figure 9. a, b). This type of clinoform presents a segment of constant, relatively high-angle slopes instead of a narrow peak. It is usually associated with low sediment supply (O'Grady et al 2000) and exhibits exposed and truncated architecture with higher canyon incision (Figure 4) than the other types. However, since the analysis was conducted on the undecompacted BSA and BLP which have undergone tectonic tilting and sediment compaction during the burial period, the results may have been biased and thusly cannot represent the true seafloor slope patterns of the BSA and BLP surface.

Unlike BSA and BLP, BHP and the seabed were shallow-buried and were likely less impacted by tilting and sediment compaction. Further, BHP and the seabed developed more defined slope maxima (Figure 9. c, d) that reach up to 7º and 9º, respectively. Although the maxima of BHP and the seabed exceed the average maxima measured by O'Grady et al (2000) for the Sigmoid category, their morphologies, of which slopes gradually increase to the maxima and decrease below the maxima, are closely aligned with the description of the sigmoid margin type. Thus, it is suggested that BHP and the seabed are reasonable to be categorized as the Sigmoid type defined by O'Grady et al (2000). This category indicates conditions of high sediment supply and low canyon incision degree. With the support of strong and stable substrate, the sigmoid margins BHP and the seabed managed to attain steeper slope gradients than the underlying margins BSA and BLP (Figure 4).

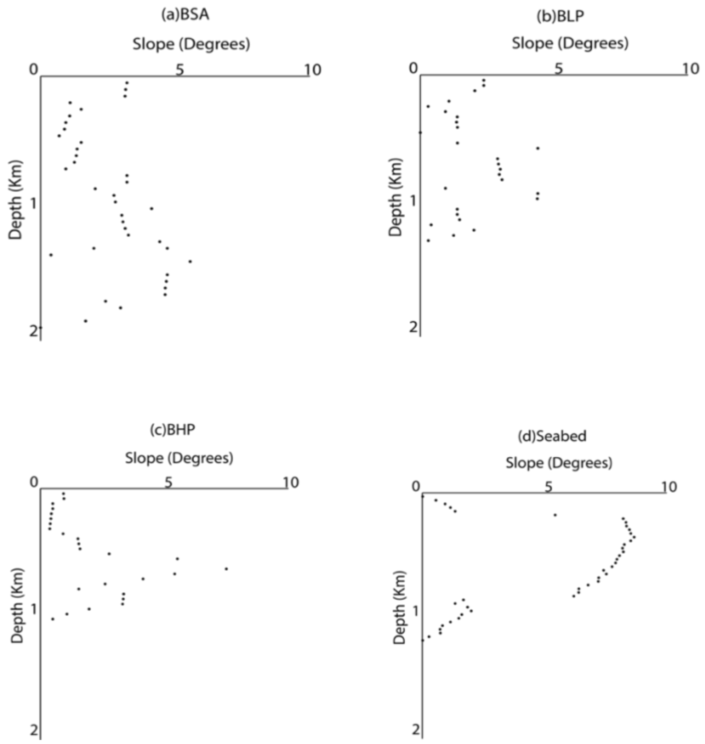

Figure 9. Plots showing slope degrees versus depth of four bounding surfaces a) BSA b) BLP c) BHP d) Seabed.

Calculation of sediment flux

A methodology developed by Petter et al (2013) of estimating sediment flux from ancient shelf-margin successions was utilized on the seismic data. Instead of using this method on individual clinoforms which would be too thin to be imaged, this study treated the three deposition packages as thick clinothem sets and estimated sediment flux across each set. The whole process of the estimation of the strongly aggradational package sediment flux is shown as an example (See Figure 10, Figure 11 and Figure 12).

The essence of the Petter et al 2013 methdology is the use of clinothem dimensions (clinothem thickness and clinoform elevation) and accretion rates (progradaiton rate and aggradation rate), combined with the sediment flux calculation equation derived by Petter et al 2013. The clinothem thicknesses were measured as the vertical distances between the upper and bottom bounding surfaces of the clinothem set, with a horizontal interval of 1.75 km. The clinoform elevations were measured as the upper bounding surface elevation relative to an arbitrarily chosen underlying datum. The clinothem thickness as well as clinoform elevation corresponding to the basin position are shown in figure 10 and 11.

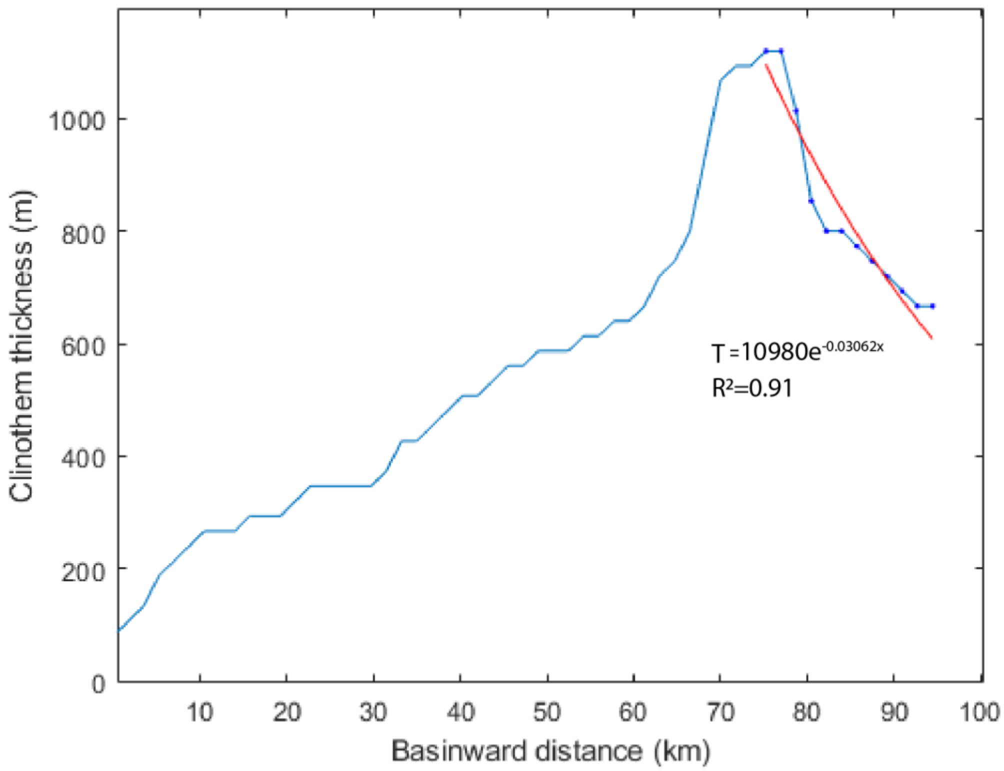

Figure 10. Clinothem thickness versus basin position with an exponential decay function showing the thinning trend of the clinothem from shelf-edge toward the deep basin direction.

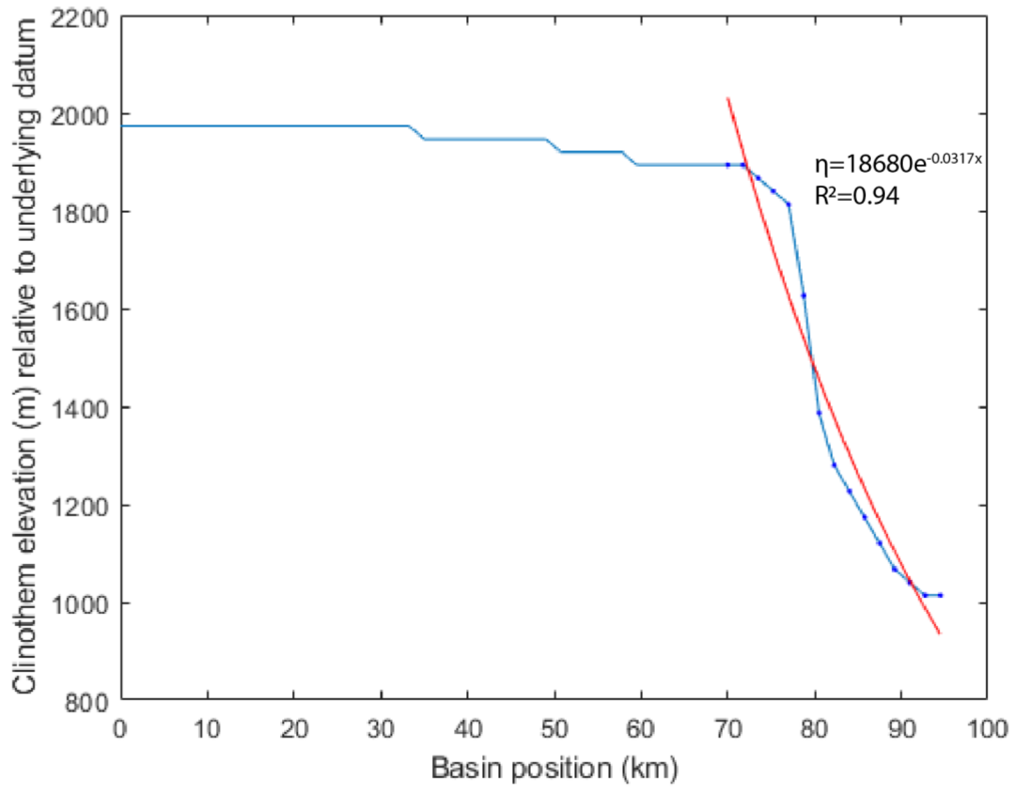

Figure 11. Clinoform elevation versus basin position. Note that the elevation also exhibits an exponential decay pattern after passing the shelf-edge position.

Relevant equations and parameters are shown in Table 2. The calculation process of the sediment flux across the strongly aggradational shelf-edge is shown in the Figure 12 flowchart. The calculation results in a value of 61m^2/yr. Potential sources of error include imprecise bed concentration input (maximum error is around 30% due to grain size, sorting and cement distributions of the deposits, Petter et al 2013), decreasing clinoform height induced by burial and sediment compaction, and spatial variability of subsidence and loading (Petter et al, 2013).

Equation/parameter	Description	Unit
$q_s(x_{SE})=e_{bed}*(P*\eta_{SE}+A*x_{SE})$	Equation of the calculation of sediment flux at shelf-edge	NA
e_{bed}	Bed concentration (i.e., 1-porosity)	NA
η	Clinoform elevation	m
T	Clinothem thickness	m
T_0	Clinothem pinchout thickness (use 5m)	m
a	Initial coefficient	NA
b	Decay constant	NA
X_d	Pinchout position	m
η_d	Pinchout elevation	m
x_{SE}	Position of shelf-edge	m
η_{SE}	Elevation of shelf-edge	m
x_{adjSE}	Distance between shelf-edge and pinchout position	m
na_{djSE}	Elevation difference between shelf-edge and pinchout position	m
P	Progradation rate	Km/my
A	Aggradation rate	m/my

Table 2. Petter et al 2013 methodology equation and parameters summary.

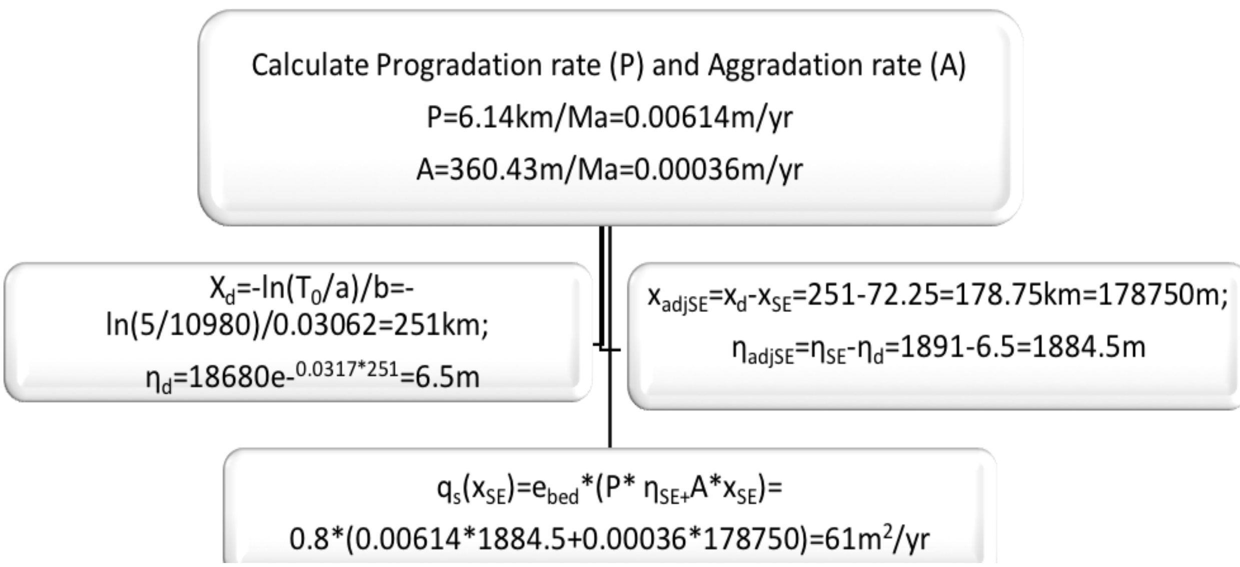

Figure 12. Flowchart showing the calculation process of the sediment flux across the shelf-edge of the Strongly aggradational package.

In addition, sediment flux of the mixed aggradational and progradational package was calculated using the same method and process (see Fig 13 and Fig 14). The calculated value is 39 m^2/ yr, which has the same order of magnitudes as the strongly aggradational shelf-edge sediment flux.

Since the clinothem thickness of the strongly progradational package does not exhibit an exponential thinning trend, but rather an overall increasing trend (Fig 15), the Petter et al 2013 is not applicable in this case.

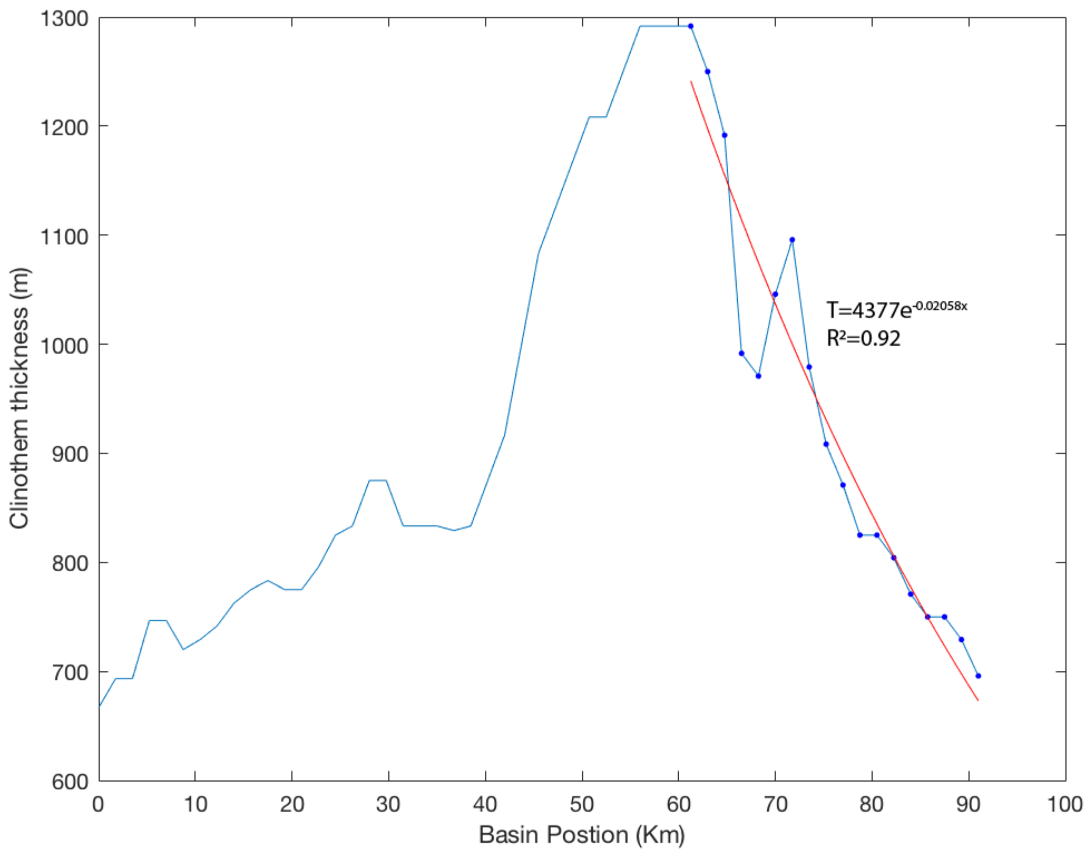

Figure 13. Clinothem thickness versus basin position of the mixed aggradational and progradational package, plus the exponential function of the thickness from the shelf-edge position to the deep basin.

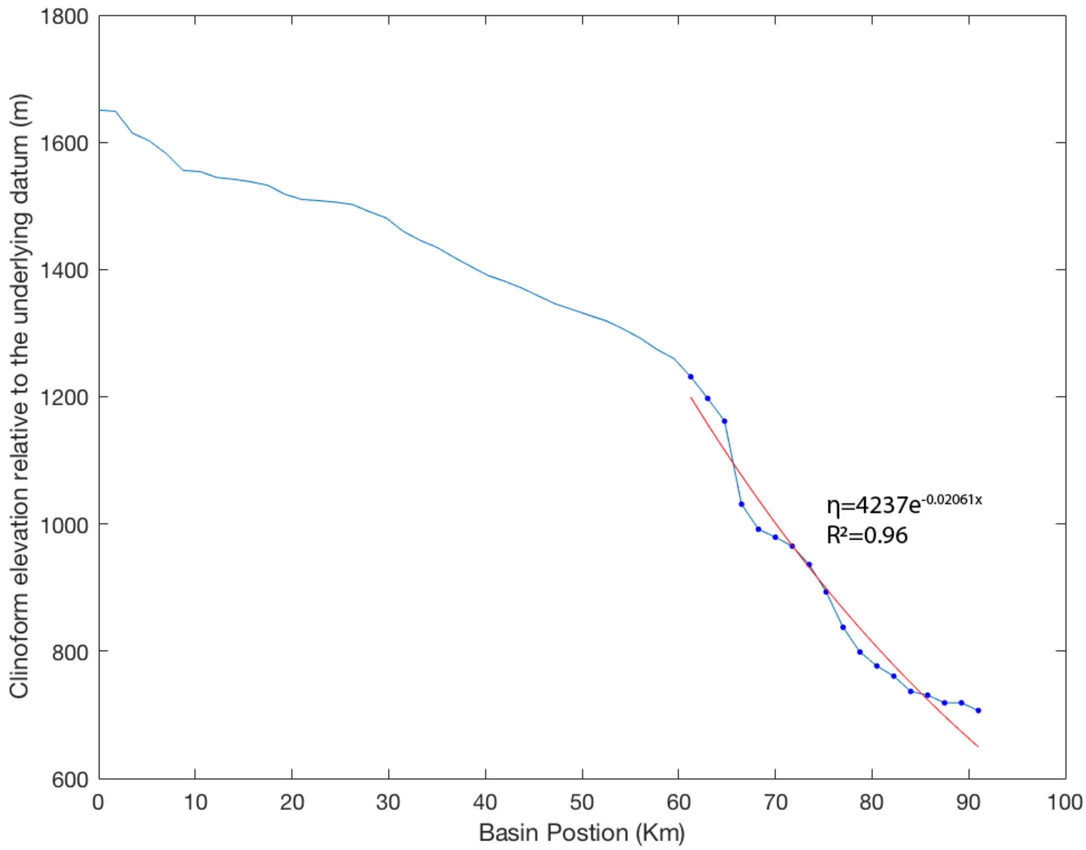

Figure 14. Clinoform elevation versus basin position as well as the exponential trend of the elevation across the shelf-edge in the mixed aggradational and progradational package.

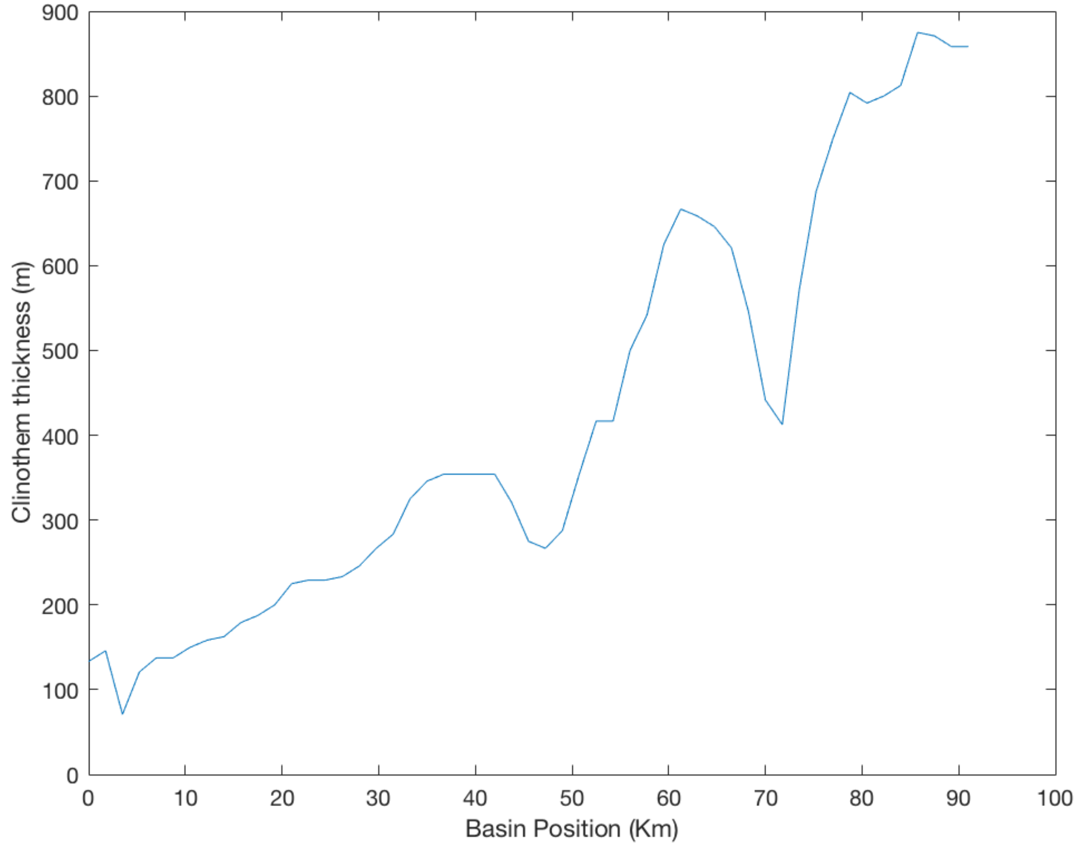

Figure 15. The thickness of the strongly progradational package clinothem showing an overall increasing trend.

Discussion

Typically, two major controlling factors namely sediment supply (Qs) and accommodation space together contribute to the variability of shelf-margin morphology. Sediment supply and accommodation, in turn, consist of minor influencing factors that may or may not take into effect in specific cases. Researchers have demonstrated that changes of sediment supply can be attributed to changes of climate, the tectonic relief of source area, and catchment area, while accommodation change is usually caused by subsidence/uplift, eustatic sea-level change, and sediment compaction. I will discuss the roles that each controlling factor may have played in the formation and development of the northwestern South China Sea shelf-margin morphology, attempting to infer the dominant controlling factor during the development of each of the three depositional packages.

CONTROLLING FACTORS FOR THE MORPHOLOGY OF STRONGLY PROGRADATIONAL PACKAGE

Anomalous post-rift subsidence is commonly computed as the difference between the actual post-rift subsidence and the modeled post-rift subsidence based on exponential thermal cooling following earlier lithospheric thinning events (Xie et al, 2006). Widespread anomalous post-rift subsidence along the northern South China Sea margin since Late Miocene has been reported by several researchers (e.g. Lithgow-Bertelloni and Gurnis, 1997; Wheeler and White, 2000). In the deep-water area the anomalous subsidence is about 900-1200 m, which is much higher than that in the present shelf area (about 300-700 m) (Xie et al, 2006). Therefore, extra accommodation space was created in the abyssal area which may have driven the sediments to bypass the shelf to basin floor, especially during the formation of the strongly progradational package.

Several possible causes of anomalous post-rift subsidence have been proposed (e.g. Kooi and Cloetingh, 1989; Burgess et al., 1997). Dynamic topography – the subsidence or uplift of continents induced by mantle convection, has been predicted using mantle convection models in the southeast Asia (e.g. Lithgow-Bertelloni and Gurnis, 1997) and therefore can be presumed to be a possible origin of the anomalous post-rift subsidence of the northwestern South China Sea margin. However, according to Xie et al (2006), the computed negative dynamic topography is relatively weak (less than 300 m) along the margin and insufficient to explain the total discrepancy between the observed and predicted tectonic subsidence, especially in the abyssal area where the calculated anomalous post-rift subsidence is 900-1200 m. Thus, there must be some other mechanisms in addition to the dynamic topography effects that have contribute to the anomalous subsidence.

Miocene – Recent basalts were observed in southern China (Liang and Liu, 1990) as an evidence of the occurrence of late magmatic events, which likely have interrupted lithospheric cooling processes and induced a new phase of thermal cooling subsidence in the abyssal area of the northern South China Sea margin (Xie et al, 2006). Lüdmann and Wong (1999) believe that a basalt intrusion occurred around 17 Ma and induced a short-period uplift but followed by a new thermal cooling subsidence immediately. A number of volcanoes and igneous rocks in the middle/upper crust along the northern South China Sea margin have been identified by Wang et al (2006). The thermal relaxation and lithospheric contraction induced by late magmatic events are believed to be the main factors behind the excess post-rift subsidence in the abyssal northwestern South China Sea margin.

CONTROLLING FACTORS FOR THE MORPHOLOGY OF STRONGLY AGGRADATIONAL PACKAGE

A very wide shelf of 200-280 km developed since the Late Miocene for the shelf-margin in the Qiongdongnan Basin area (Xie et al., 2008) and from the Pleistocene to Present sediments were highly insufficient compared to the rapid relative sea-level rise, which caused the sediments to mostly store on the shelf instead of prograding into the basin floor area. Because of the hight rate of vertical aggradation, the slope gradually became over-steepening and exceeded the critical angle of an equilibrium profile, which resulted in erosion, slumping and mass transport complexes, as is shown by the chaotic seismic reflections seen in the deep-water slope in front of the strongly Aggradational package.

The Red River, located in northwest of the Qiongdongnan Basin, is the main source of sediments supplied to the northwestern Qiongdongnan shelf-margins. The evolution of the margin has been affected by the associated Red River Fault Zone (see the location on Fig 2). As the shelf-margin prograded toward the southeast, the shelf gradually widened and the distance from the Red River continually increased, which made the progradation of the shelf-margin to the deep-water area increasingly difficult.

In addition, the high gamma ray values exhibited by the strongly Aggradational package on YC35-1-2 well-log (Fig 8) clearly indicate a very strong supply of shelf-parallel transported and mud-rich currents from the Red River. The littoral muddy currents (possibly fluid mud), along with a very wide shelf and highly insufficient sediment supply, resulted in a muddy, predominantly aggradational, and slumping well-developed shelf-margin.

Conclusion

As a common widely occurring geomorphology at continental margins, deep-water sedimentary basins, and non-marine lake basins, shelf-margins have received extensive attention from researchers. The variable morphologies and geometries exhibited by distinct shelf-margins have been a study focus because the morphology of a shelf-margin can provide critical insights to important issues, such as the amount of sediments bypassing the shelf-edge area and ending up in the basin floor. Therefore, it is useful to quantify the morphology of a shelf-margin and to infer the possible controlling factors that produced its changing architecture and geometry through long time intervals.

This study analyzed a shelf-margin from Qiongdongnan Basin, northwestern South China Sea, quantified its geometry in terms of clinoform height, clinform length, foreset inclination and shelf-edge trajectory and grouped the clinoforms into three depositional/stratigraphic packages based on clinoform growth styles. A method developed by O'Grady et al 2000 to categorize shelf-margins based on seafloor slope distribution patterns was tested. Although this method appears to be practical when applied to modern, shallow-buried shelf-margins, it may not be very useful with ancient margins as they have undergone long-term burial and tilting and the preserved morphology may not reflect the original shape during deposition. The same issue arose when the method developed by Petter et al 2013 was utilized in this study as an attempt to calculate paleo sediment flux across the shelf-edge. This method also seems to work better with relatively recent shelf-margins than ancient ones, as the former usually preserve the actual shapes without too much deformation.

Anomalous post-rift subsidence since the Late Miocene was associated with the initial formation of the continental slope system of the northwestern Qiongdongnan Basin (Xie et al., 2006). Higher anomalous post-rift subsidence in the abyssal area drove the sediments to bypass the shelf-edge and prograde toward the deep-water area, which controlled the formation of the strongly progradational package. Possible origins of the anomalous subsidence include dynamic topography and late magmatic events (Xie et al., 2006).

A very wide shelf of up to 200-280 km that developed in the present shelf area and highly insufficient, muddy sediment supply from the Red River may have contributed to the strongly aggradational character of the upper most Late Pleistocene to Recent depositional package. A large amount of shelf-parallel mud-rich, shallow-water currents were probably supplied to the strongly aggradational package and may have helped the shelf-margin maintain a steep slope, as can be seen on the margin profile in Figure 4 and Figure 7.

This work shows that a changing dynamic stratigraphy during the last 10 My on a South China Sea margin can be explained mainly by subsidence, changing sea-level and sediment supply rates during the period.

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