

High-resolution sequence architecture and depositional evolution of the Quaternary in the northeastern shelf margin of the South China Sea

Hanyao Liu¹, Changsong Lin^{1*}, Zhongtao Zhang², Bo Zhang², Jing Jiang¹, Hongxun Tian¹, Huan Liu¹

¹ School of Ocean Sciences, China University of Geosciences, Beijing 100083, China

² Shenzhen Branch of CNOOC Ltd., Guangzhou 518000, China

Received 5 December 2017; accepted 9 February 2018

© Chinese Society for Oceanography and Springer-Verlag GmbH Germany, part of Springer Nature 2019

Abstract

The northeastern shelf margin of the South China Sea (SCS) is characterized by the development of large scale foresets complexes since Quaternary. Based on integral analysis of the seismic, well logging and paleontological data, successions since ~3.0 Ma can be defined as one composite sequence, consist of a set of regional transgressive to regressive sequences. They can be further divided into six 3rd order sequences (SQ0–SQ5) based on the Exxon sequence stratigraphic model. Since ~1.6 Ma, five sets of deltaic systems characterized by development of wedge-shaped foresets complexes or clinoforms had been identified. High-resolution seismic data and the thick foresets allowed further divided of sub-depositional sequences (4th order) of regression to transgression, which is basically consistent with published stacked benthic foram O-isotope records. Depositional systems identified in the study area include deltaic deposits (inner-shelf deltas and shelf-edge deltas), incised valleys, and slope slumping massive deposits. Since ~1.6 Ma, clinoforms prograded from the southern Panyu Lower Uplift toward the northern Baiyun Depression, shelf slope break migrated seaward, whereas the shelf edge of SQ0 migrated landward. The development of incised valleys in the continental shelf increased upward, especially intensive on the SB3 and SB2. The slumping massive deposits increased abruptly since SB2, which corresponds to the development of incised valleys. The evolution of depositional systems of continental slope mainly controlled by the combined influence of sea level changes, tectonic movements, sediment supply and climate changes. Since ~3.0 Ma, relative sea level of the northern SCS had been experienced transgression (~3.0 Ma BP) to regression (~1.6 Ma BP). The regional regression and maximum transgressions of the composite sequences were apparently enhanced by uplift or subsidence related to tectono-thermal events. In addition, climatic variations including monsoon intensification and the mid-Pleistocene transition may have enhanced sediment supply by increasing erosion rate and have an indispensable influence on the development of the incised valleys and 5 sets of deltaic systems since ~1.6 Ma.

Key words: sequence architecture, depositional systems, continental slope, Quaternary, Zhujiang (Pearl) River Mouth Basin

Citation: Liu Hanyao, Lin Changsong, Zhang Zhongtao, Zhang Bo, Jiang Jing, Tian Hongxun, Liu Huan. 2019. High-resolution sequence architecture and depositional evolution of the Quaternary in the northeastern shelf margin of the South China Sea. *Acta Oceanologica Sinica*, 38(5): 86–98, doi: 10.1007/s13131-019-1442-2

1 Introduction

The South China Sea (SCS), the largest marginal basin on the continental margin of Southeast Asia, has attracted special attention for Earth scientists world-wide because of its particular location (interactions among three large plates: Indian, Pacific and Eurasian) and its oil and gas potential (Chen et al., 1993; Gong and Li, 2004; Jiang et al., 2017; Lin et al., 2017; Lüdmann and Wong, 1999; Wang and Li, 2009; Wang et al., 2003, 2014). The study area of this paper located around the Panyu Lower Uplift–Baiyun Depression, northern shelf margin of the SCS.

The shelf margins, transitional zone from the continental shelf to the deep sea, are important areas of sedimentary geology and marine sedimentary process studies (Lin et al., 2017). A large quantity of sedimentary studies showing that the development and depositional evolution of shelf margin are not only related to sea level variations, but also basin tectonism, sediment supply

and climatic changes (Lin et al., 2001; Alves et al., 2014). Over the past few years, the northern margin of the SCS has been the subject of detailed investigations, many studies have focused on the development and depositional characteristics on Oligocene–Miocene strata, comprising distribution of depositional systems, sequence architecture, depositional evolution, and controlling factors (Dong et al., 2008; Jiang et al., 2017; Wu and Xu, 2010; Liu et al., 2011; Xie et al., 2009; Zhu et al., 2011). However, for the Quaternary strata on the northern margin of the SCS, only few studies related to the high-resolution sequence stratigraphy (Chen et al., 1993; Huang et al., 1995; Ge et al., 2012; Kou, 1990; Kou and Du, 2010; Liu et al., 2011; Lüdmann et al., 2001; Zhuo et al., 2015), particularly their responses to sea level changes, basin tectonism, sediment supply and climate changes.

This paper focus on the continental margin systems, established the sequence architecture and depositional evolution

Foundation item: The National Natural Science Foundation of China under contract Nos 91328201, 91528301 and 41130422.

*Corresponding author, E-mail: lincs58@163.com

model since ~3.0 Ma, further created the high-resolution depositional sequences (4th order) since ~1.6 Ma, aimed to reveal their relationship to the sea level, tectonic setting, sediment supply and climatic changes of the Quaternary in the northern SCS, which has an important Guiding significance for studies in continental margin basins.

2 Geological setting

Located in the northeastern of the SCS, Zhujiang (Pearl) River Mouth Basin (ZRMB) is one of the most important petroliferous basins in China. With a general strike of SW–NE, the ZRMB is about 800 km long and 300 km wide, covering an area of more than 175 000 km² (Chen, 2000). From the north to south, the ZRMB consists of five tectonic units: the Northern Depression Belt, the Central Uplift Belt, the Southern Depression Belt, and the Southern Uplift Belt (Gong and Li, 2004; Wang and Li, 2009). The shelf margin of present day located between the Panyu Lower Uplift and the northwestern of Baiyun Depression (Fig. 1). Panyu Lower Uplift, with an area of ~7 500 km², has a total water depth around 100–200 m, located in the middle of the Central Uplift Belt. The Baiyun Depression, with an area of ~25 500 km², filled with more than 10 000 m deposits.

During the Baiyun event (~23.8 Ma BP), the deep mantle of the Baiyun Depression started rising, resulting intensive thermal subsidence, further causing the shelf slope moved to the location of present day abruptly (Ding et al., 2013; Pang et al., 2009; Sun et al., 2008; Xie et al., 2014). About 6.5 Ma BP, collision between the Luzon Arc and Eurasian Plate resulted the uplift of Taiwan, further causing a series of neotectonic activities in the SCS (Huang et al., 1997) (Fig. 2). In addition, two main collision phases on the northern SCS was identified at 5–3 Ma and 3–0 Ma, respectively, accompanying stress regime transformed from compression into transtension (Lüdmann and Wong, 1999). Regionally, in the ZRMB, the Liuha Movement at the end of the Pliocene–early Pleistocene, was characterized by uplift, faulting, folding and denudation of the Quaternary strata, also related to the arc-continent collision (Wu et al., 2004).

Since ~3.0 Ma, the northern SCS had experienced an extensive transgression. Afterward, ~1.6 Ma, started a regression in general, enhanced the preservation of the Quaternary geological records in the study area (Jiang et al., 2017). In the ZRMB, the thickness of Quaternary strata increased seaward, varies between 100 m and 400 m on the continental shelf, reaching a peak of ~600 m at the distal shelf margin (Jiang et al., 2017; Lüdmann et al., 2001). The age frame of Quaternary was founded using the dating data of shallow boreholes (ZQ1–ZQ4), and the paleontological data from local well loggings (Fig. 2) (Feng et al., 1996; Qin, 1996; Zhuo et al., 2015).

During the Quaternary, as the onsets of the northern hemisphere ice sheet (~3.2–2.5 Ma), climate and the monsoon became intensive variable with glaciation to inter-glaciation cycles (Huang et al., 2005; Wang et al., 2003, 2014). One of the most important events about Quaternary climate is the mid-Pleistocene Transition, which marks the dominant climate periodicity extended from 41 ka to 100 ka (Martin et al., 2008; Prell, 1982) (Fig. 2).

3 Research methods

In recent years, due to petroleum and hydrocarbon exploration activities, also resource investigations of the government, abundant data have been obtained in the SCS. Extensive seismic, well logging, shallow boreholes and paleontological data provided the basis for the comprehensive study of sequence architecture and depositional evolution. Five zero phase 3D seis-

mic volumes involved in this study, 3D seismic volumes A and B cover an area of ~1 200 km² and ~13 000 km², respectively (Fig. 1c), which have a dominant frequency of 30–60 Hz, resulting in a vertical resolution of ~10 m assuming the seismic velocities of 1 600 m/s (Zhou et al., 2015; Zhuo et al., 2015). Numerous 2D seismic lines linking between 3D surveys A and B have a vertical resolution ~20 m (Zhou et al., 2015; Zhuo et al., 2015). Using Geoframe et al. software of seismic interpretation, all of these seismic and well-logging data can be integrated well.

Using the integrated data with seismic and well logging, we firstly established sequence stratigraphic framework in the light of the guideline of sequence stratigraphy (Catuneanu et al., 2009). In seismic profiles, the characteristic of sequence boundaries can be interpreted as unconformities, such as onlap, downlap, toplap, truncation, downcutting and variations of stratigraphic stacking patterns (Jiang et al., 2017; Lin et al., 2001, 2017; Lin, 2009). By analyzing the shapes and combination types of well logging data (lithology; GR: natural gamma ray; DT: acoustic log), internal sequence boundaries and depositional systems tracts can be further determined. The age of major unconformities can be constrained by dating data of published shallow boreholes ZQ3 (Feng et al., 1996) (Fig. 3) and biostratigraphic age data of calcareous nannofossil and foraminifera (Gong and Li, 2004; Qin, 1996) (Fig. 2). The identification of depositional systems mainly based on the analyses of seismic and log-lithology facies (Mitchum et al., 1985; Vail et al., 1977a, b), 3D seismic amplitude slices, and geomorphological structure according to the predecessors' summary (Li et al., 2011; Gong et al., 2013, 2016).

4 High-resolution sequence stratigraphic framework

4.1 Sequence classification and age constrain

Depositional sequences are composed of a series of depositional sequences of various orders, which corresponds to the division of the sequence stratigraphic units (Lin, 2009). The division of sequence stratigraphic units of various orders is on the basis of their duration (Mitchum et al., 1985; Vail et al., 1977a, 1991). Major unconformities identified in the study area contain one 2nd order (T0) and six 3rd order sequence boundaries (SB0–SB5), which can divide the Quaternary strata into six 3rd order sequence units (SQ0–SQ5). Within the 3rd sequences, flooding surfaces and internal unconformities (high frequency sequence boundaries) also can be recognized which further divided SQ0–SQ5 into more than 20 high frequency sequences.

In order to determine the chronostratigraphic framework, the age of the major unconformities (T0, SB0–SB6) had been constrained. Previous studies about shallow boreholes ZQ1–ZQ4 provided accurate dating data (Feng et al., 1996). Fortunately, ZQ3 just located in the 3D seismic volume A, which provided the possibility of the accurate well-seismic calibration. The SB3 was identified at a depth of 117 m which almost corresponds to the Brunhes-Matuyama palaeomagnetic reversal boundary (ca. 780 ka) of ZQ3, and the SB2 was identified at a depth of 85 m which could placed between (469.011±23.451) ka to (337.157±16.858) ka BP (Fig. 3). Likewise, SB1 ranges from (235.025±11.751) ka and (48.023±2.401) ka BP, and the SB0 lies from (48.023±2.401) ka BP to present (Fig. 3). The result was comparable to the chronostratigraphic framework of Zhuo et al. (2015). The age of the major unconformities (SB0–SB3) in the main study area (3D seismic volume B) can be further determined by the calibration of 2D seismic profiles linking between 3D surveys A and B (Fig. 4). Although, ZQ3 did not penetrate the early Pleistocene strata, the

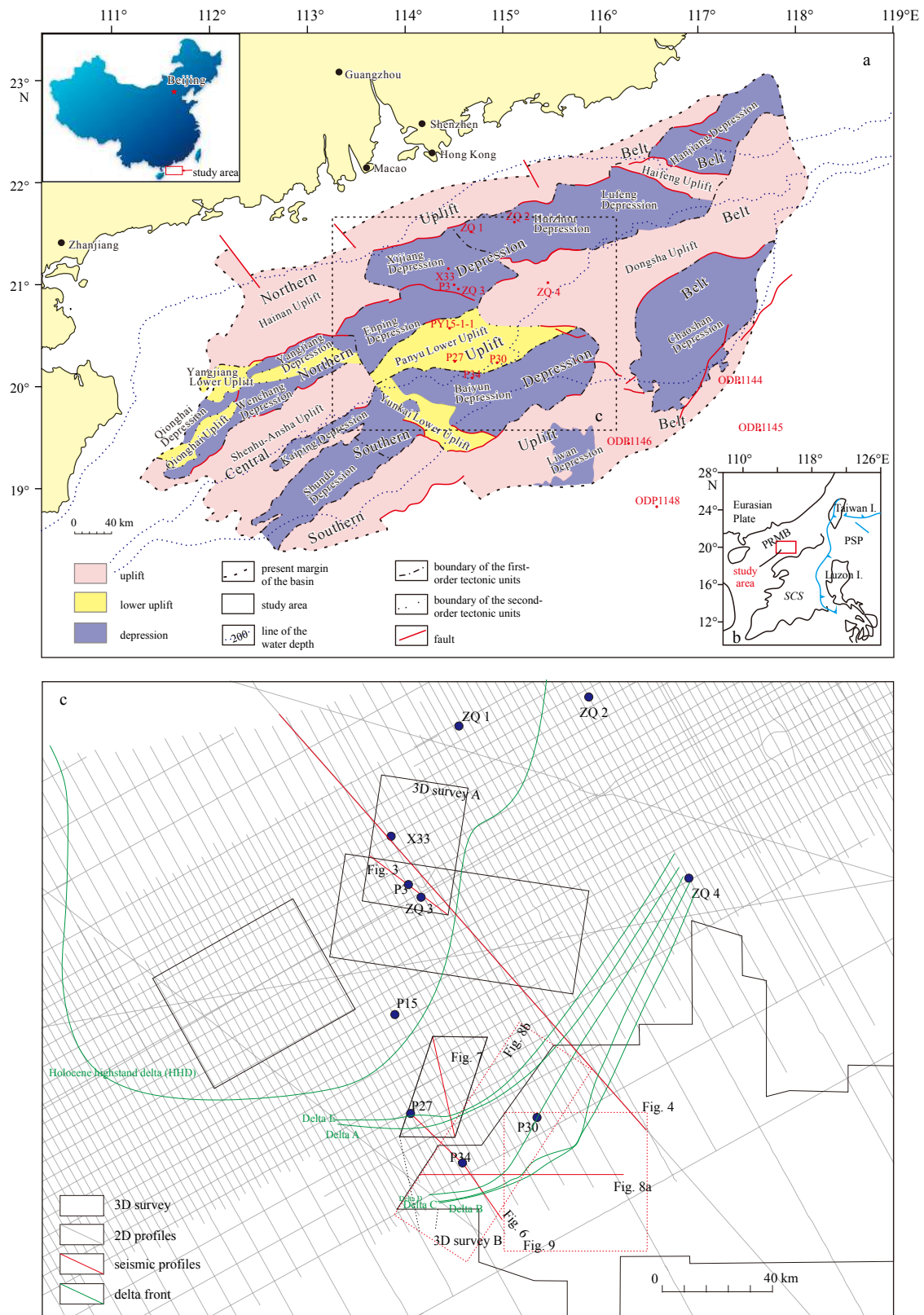


Fig. 1. The location of the South China Sea and distribution and tectonic unit division of the Zhujiang River Mouth Basin (a). The tectonic setting of the South China Sea modified from Lin et al. (2017) is shown in (b). Attached maps (c) showing the location of seismic and borehole data used in the paper, the evolution of the Quaternary paleo-delta front are mapped in Fig. 1c, the position of Holocene highstand delta is according to Pang et al. (2009). SCS: South China Sea; ZRM: Zhujiang River Mouth Basin; PSP: Philippine Sea Plate.

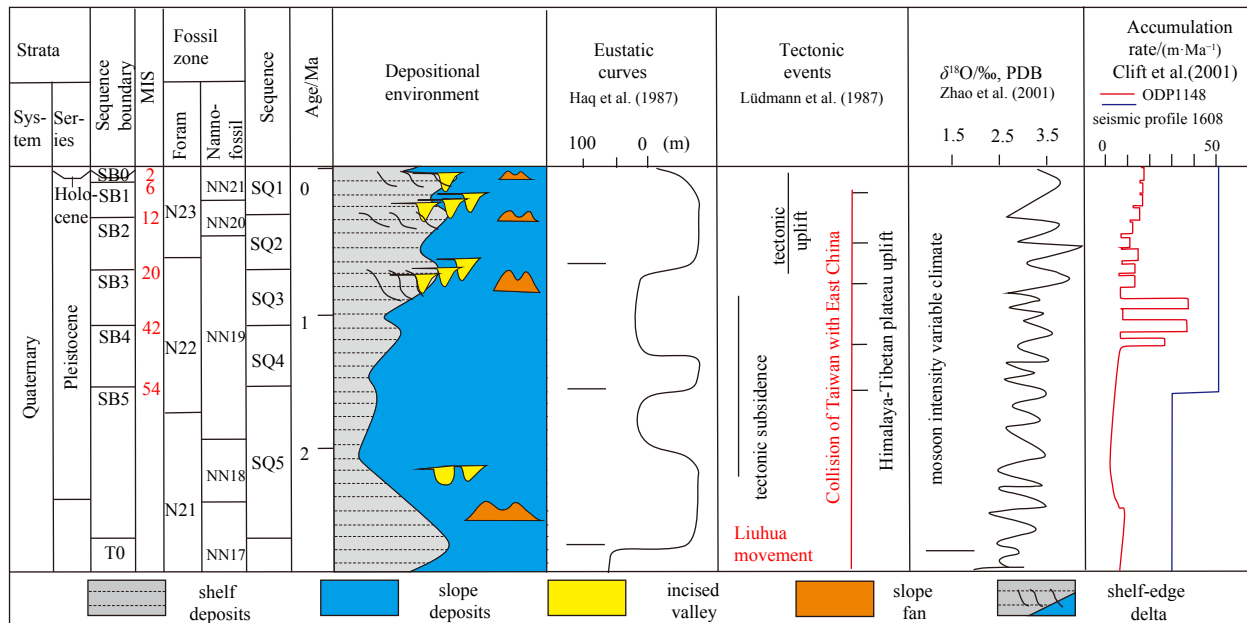


Fig. 2. Summarize of sequence classification, depositional evolution and geological setting of the Quaternary in the Zhujiang River Mouth Basin.

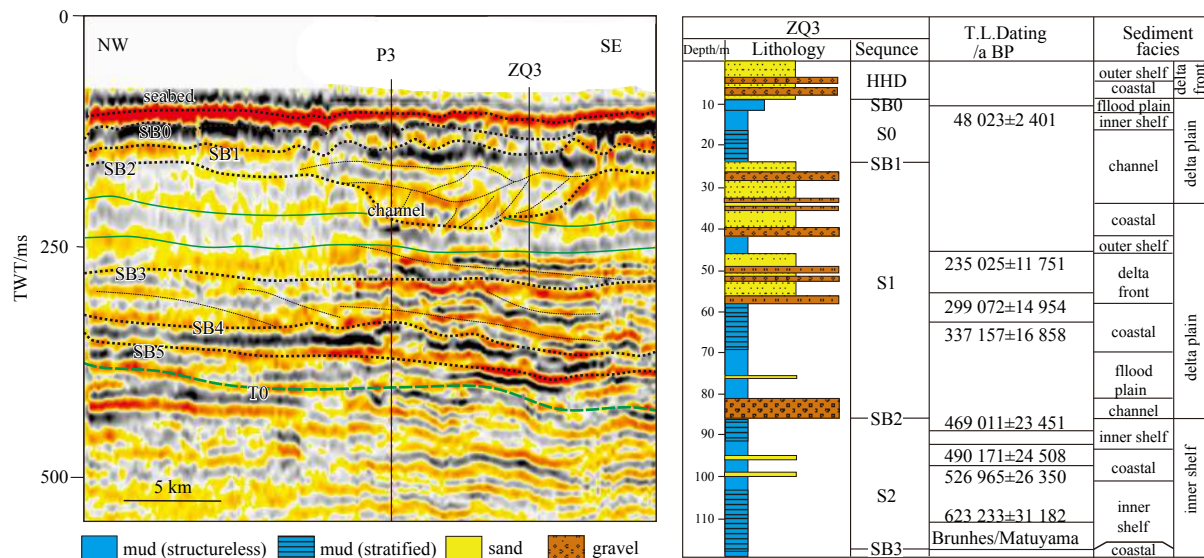


Fig. 3. Dating data and environment of shallow boreholes ZQ3 (after Feng et al. (1996); and Zhuo et al. (2015)) with inner shelf seismic profile, the age framework since mid-Pleistocene of study area are established using the well-seismic calibration. See Fig. 1c for location of seismic profile and well loggings.

age of SB4, SB5 and T0 can be constrained by the biostratigraphic age data in the study area (Fig. 5). According to the paleontological data of P3, P27, P34 from the internal data of the China National Offshore Oil Corporation, T0 was considered as the base of the Quaternary and have an age between 3.0–2.5 Ma, similarly, the age of SB5 and SB4 were identified as ~1.6 and ~1.3 Ma, respectively. As the stacked benthic foram O-isotope records are a good proxy for the amplitude of sea level cycles during the Quaternary, the sequence boundaries can be related to the lowstand of the marine O-isotope stages (Anastasakis and Piper, 2013; Imbrie et al., 1993). Thus, the age of sequence boundaries (including internal high frequency sequence boundaries) can be further assumed corresponding to the O-isotope curve, resulting se-

quence boundaries SB0 to SB5 are assumed relating to the lowstand of MIS 2, MIS6, MIS12, MIS20, MIS 42, MIS54, respectively (Figs 2 and 6).

The basal boundary T0 characterized by large scale erosion or angular unconformity. In the 3D seismic profiles: T0 extended to the whole study area showing strong amplitude, high frequency and strong continuity parallel reflection features; Around the Dongsha Uplift, the Pliocene strata was mostly eroded and the angular unconformity had been strengthened. In the well logging profiles: Lithology and logging data around T0 shows an abrupt change, GR curve formed funnel-shape (Fig. 5). Depositional sequences since ~3 Ma can be defined as one regional transgressive to regressive sequence. Sequence boundaries SB0 to SB5

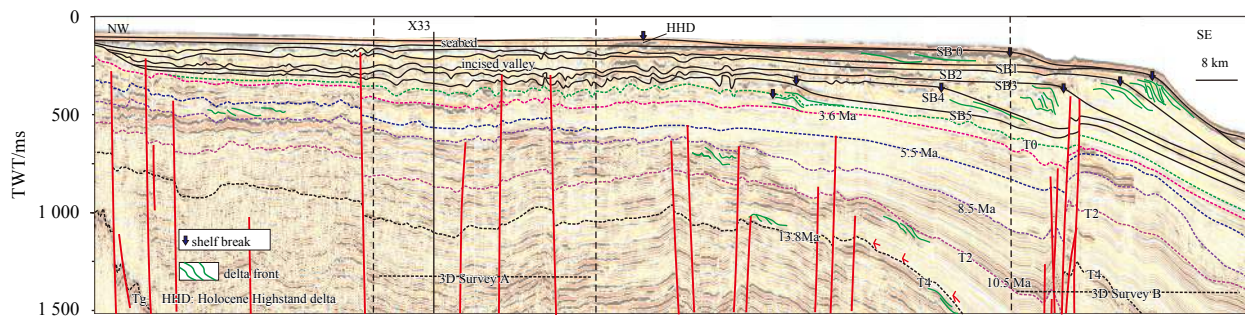


Fig. 4. Illustration of 2D seismic profiles linking between 3D Survey A and B showing the age framework and depositional evolution. See Fig. 1c for location of seismic profile and well loggings.

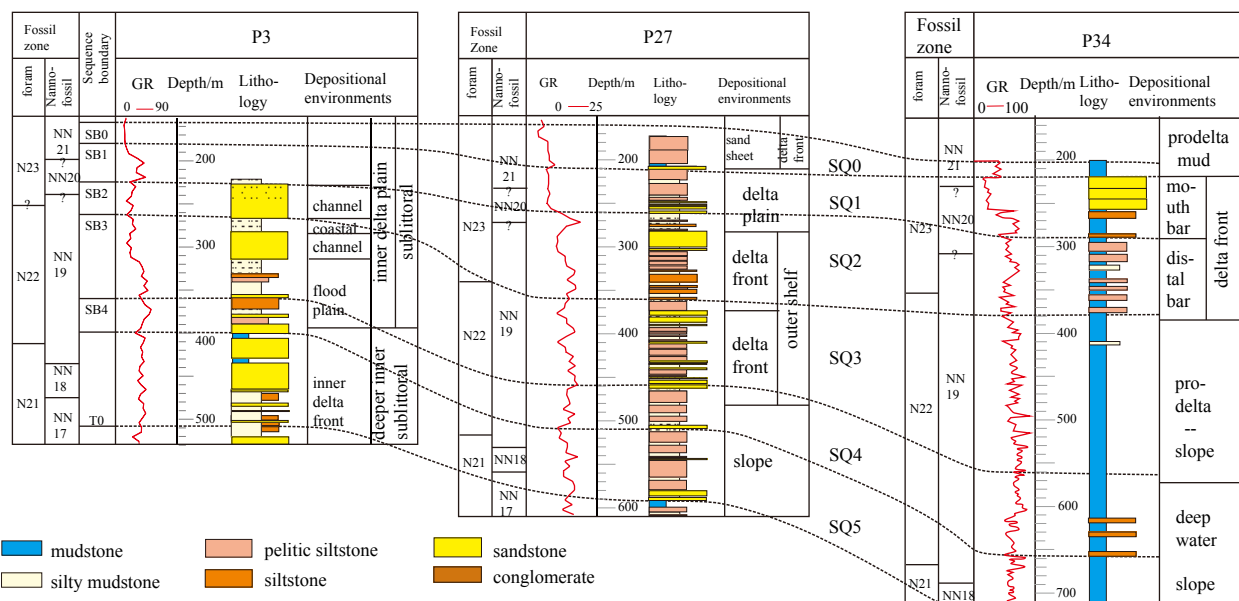


Fig. 5. Sequence classification and depositional environment of well loggings using the biostratigraphic age data and well-seismic calibration (Gong and Li, 2004; Qin, 1996). See Fig. 1c for the location.

extended extensively, which divided Quaternary strata into six 3rd order sequences (SQ5–SQ0) with a cycle ~0.4 Ma (Fig. 6). Since SB5, five sets of high-angle prograding clinoforms (SQ4–SQ0) had been identified. Along the unconformities (SB0–SB5), with the relatively strong amplitudes and subparallel reflections, similar features had been found in the seismic profiles, such as toplap contacts or truncation and downcutting at the top of the clinoforms; downlap contacts at the bottom of the base; and onlap contacts against the slope. In addition, lithology and logging data commonly show an abrupt change along the unconformities in the well logging profiles (Fig. 5). Within SQ5–SQ0, four maximum flooding surfaces (MFS) had been identified through tracing the onlap point. Commonly, the MFS extended extensively and easily merged with the sequence boundaries except in the incised valleys and slope area (Fig. 6). High-resolution seismic data and the thick progradational clinoforms since SB5 (~1.6 Ma) allowed the further divide of sub-depositional sequences of regression to transgression. The 4th order sequences bounded by internal high frequency sequence boundaries, which terminate by minor toplap and downlap against the top and bottom of 3rd sequence boundaries (Fig. 6). Minor onlap contacts also can be identified against the slope (Fig. 6). The internal boundaries can be tracked on a large scale within the 3rd

sequence around southern Panyu Lower Uplift to northern Baiyun Depression (Fig. 6).

4.2 Sequence architecture (SQ0–SQ5)

Six 3rd order sequences (SQ5–SQ0) had been identified in the study area since ~3 Ma, which characterized by the development of high-angle clinoforms (Figs 6–8). Within SQ5–SQ0, depositional systems are basically consistent with the Exxon sequence stratigraphic model (Vail, 1987), highstand, transgressive and lowstand systems tracts can be identified. SQ5 mainly feature as high-frequency parallel seismic reflections representing extensive transgressive to highstand systems tracts, which can also be documented by borehole and logging data, while lowstand systems tracts mainly appear within the incised valleys and upper slope as slumping massive deposits (Figs 6–8). SQ4–SQ0 display the similar architectures which mainly characterized by the rapid development of a series of high-angle progradational clinoforms on the continental shelf to shelf edge zone representing the highstand systems tracts and the incised valleys and slumping massive deposits on the upper slope representing lowstand systems tracts. While the transgressive systems tracts usually characterized by thin layers of strong amplitude seismic reflections overlying the highstand systems tracts which indicated the rapid

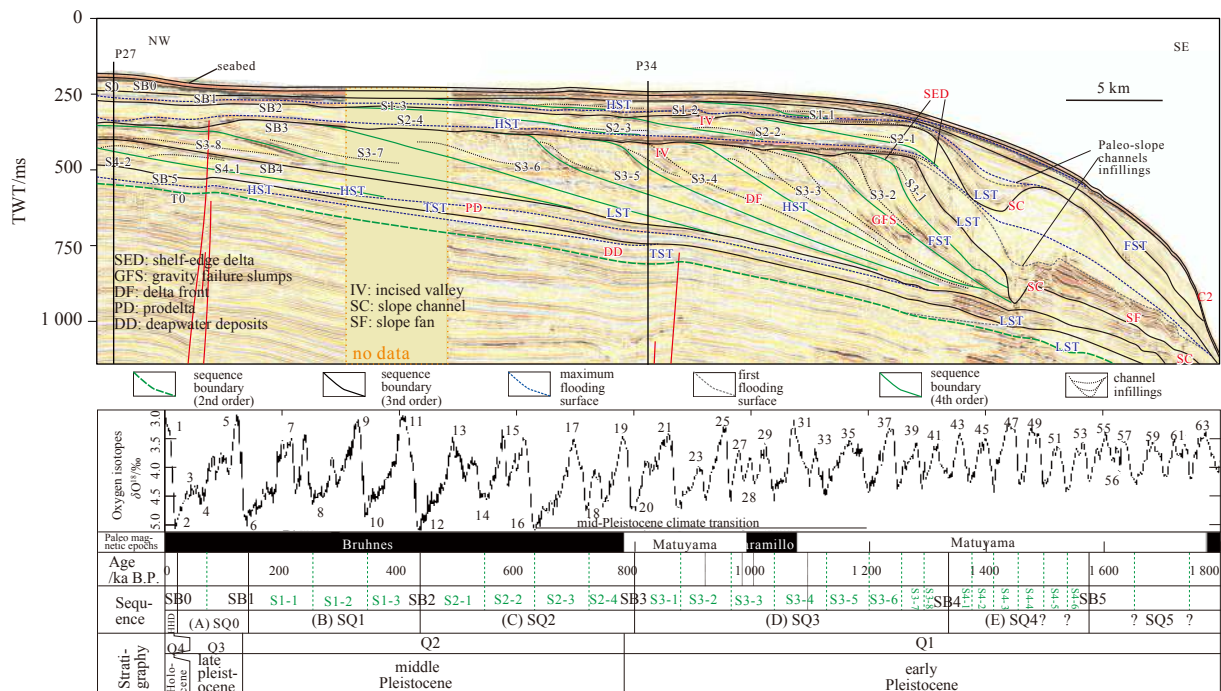


Fig. 6. High-resolution sequence stratigraphic framework of seismic profile in the outer-shelf to shelf margin zone with the constrain of stacked benthic foram O-isotope records (Lisiecki and Raymo, 2005). See Fig. 1c for the location.

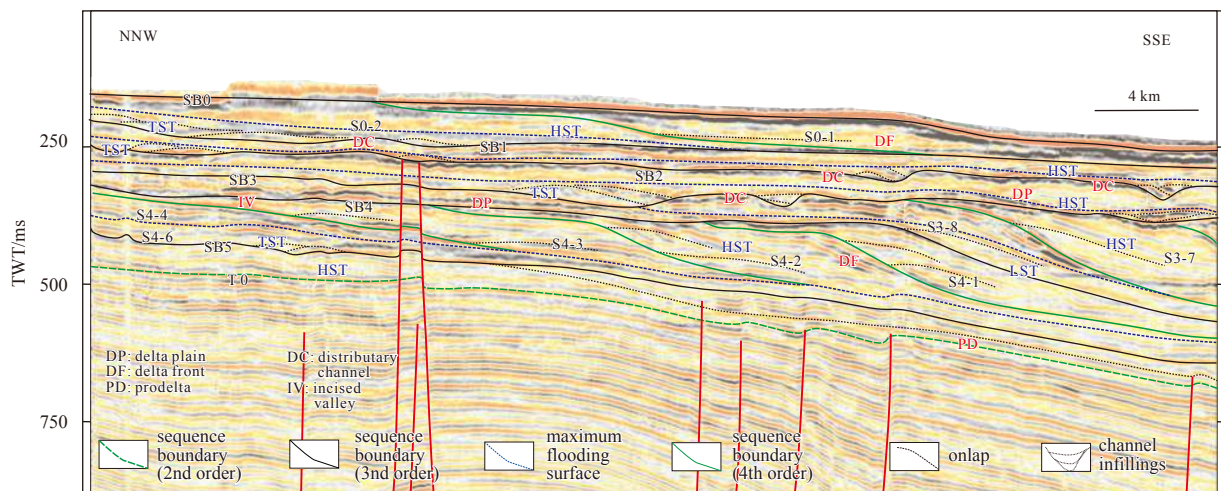


Fig. 7. High-resolution sequence stratigraphic framework of seismic profile in the mid-shelf zone, sequence architecture and depositional evolution are shown in the profile. See Fig. 1c for location of seismic line.

transgression, sometimes they are too thin to identify (Figs 6–8). In addition, forced falling stages can be identified at the end of highstand stages divided by the forced regression surface (Lin, 2009). Since SB5, a total of five sets of high-angle prograding clinoforms (SQ4–SQ0) can be interpreted as five sets of progradational delta to shelf-edge delta systems which feature oblique-tangential seaward-dipping seismic reflections and coarsening-upward well-logging patterns. From inner shelf to the shelf edge, the internal structure of the clinoforms usually characterized by the general increasing of the dipping angle and the thickness of foresets, display a transition from a regular toplap to declining-of-flap structures, indicated the general falling of relative sea level and abundant sediment supply.

Within SQ4–SQ0, the thick progradational clinoforms had

been further divided into 23 sub-depositional sequences of regression to transgression, the internal sequences mainly formed by progradational wedges with the average seaward-dipping angle $\sim 1^\circ$ – 3° which indicated the minor regression of sea level, minor transgression also can be identified through the onlap contacts against the slope (Figs 6–8). The stacked benthic foram O-isotope records are a good proxy for the minor sea level fluctuations, which can be a contrast to the internal sequences. In SQ4, however, because of the limit of 3D seismic data, internal sequences cannot be identified completely, only 4–5 minor progradational wedges are visible (Fig. 7), causing the difficulty of comparing with the stacked benthic foram O-isotope records. Fortunately, since SB4, the prograding complexes (SQ3–SQ0) had prograded into southern Panyu Lower Uplift to northern Baiyun

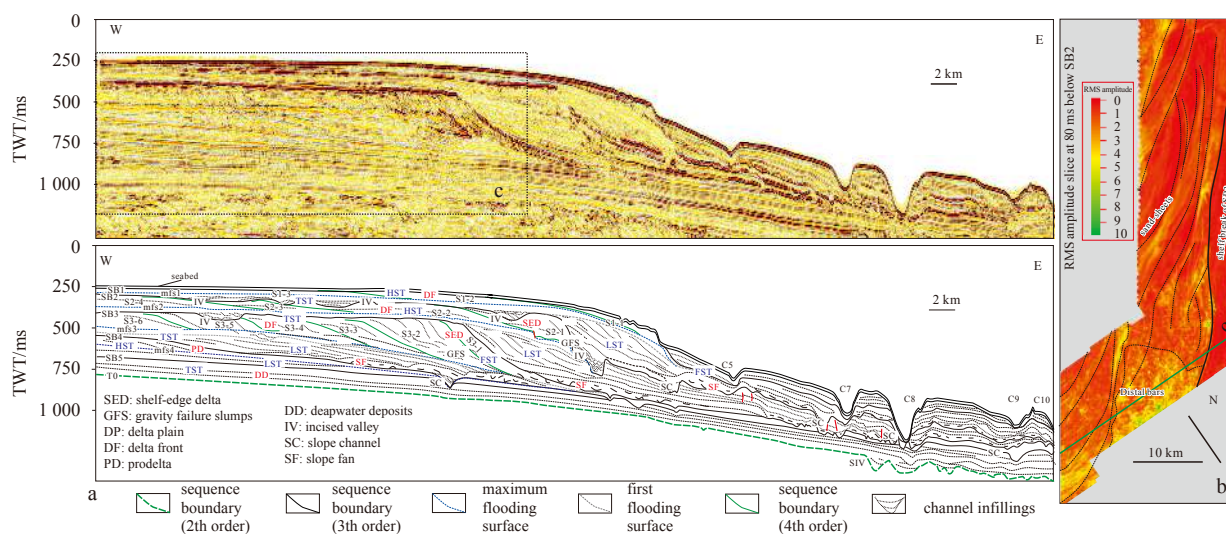


Fig. 8. High-resolution sequence stratigraphic framework of seismic profile in the outer shelf to shelf margin zone. The sequence architecture and depositional evolution consist of deltaic deposits, incised valleys, upper slope gravity failure slumps are shown in (a). The RMS amplitude slice (b) at 80 ms below SB2 display the delta front of SQ3 consisting of distal bars and sheet-like sand bar deposits. See Fig. 1c for location of the seismic line and RMS slice.

Depression, which just located in the 3D seismic survey B. SQ3 features large scale prograding complexes with ~100–400 m height, which can be divided into 8 internal sequences formed by progradational wedges (S3-8 to S3-1); Comparing with SQ3, SQ2 and SQ1 had prograded slightly basinward, the thickness and seaward-dipping angle of internal progradational foresets reduced relatively, SQ2 with the average height of ~100 m can be divided into 4 progradational wedges (S2-4 to S2-1), SQ1 with the average height of ~60 m can be divided into 3 progradational wedges (S1-3 to S1-1); SQ0 displays single progradational wedge which retrograded landward comparing with SQ1 indicating the transgression right after SB1 (Fig. 6); Holocene deposition barely found in the study area, the Holocene Zhujiang River Delta had been restricted within the inner-shelf (Lüdmann et al., 2001) (Fig. 1c, 4). Since 3rd order sequence boundaries SB0 to SB4 are related to the lowstand of MIS 2, MIS6, MIS12, MIS20, MIS 42, respectively, with comparing to the stacked benthic foram O-isotope records, the amount of 4th order sequence boundaries equals to the amount of the lowstands of the O-isotope stage within the 3rd sequences (SQ3–SQ0) (Fig. 6). As the sequence boundaries can be related to the lowstand of the marine O-isotope stages (Anastasakis and Piper, 2013; Imbrie et al., 1993), all these internal progradational wedges are considered corresponding to the lowstand of the O-isotope stage, which indicate the sea level changes of orbital scale cycles. Within SQ3, the high frequency of internal sequences show a transition from ~41 ka to ~100 ka, within SQ2 to SQ0, the sub-sequences are dominated by the cycle of ~100 ka (Fig. 6).

5 Depositional systems and Evolution

5.1 Deltaic deposits

The Quaternary strata are characterized by the development of a series of progradational clinoforms from outer shelf to shelf margin. Since SB5, five sets of high-angle prograding clinoforms (SQ4–SQ0) had been identified which embody five sets of progradational deltaic systems (E–A) representing delta to shelf-edge delta. Based on the well logging and seismic data, three del-

taic depositional facies have been recognized: (1) delta plain (inter distributary plains and distributary channels); (2) the prograding delta front (proximal river mouth bars, distal bars and sand-sheets); and (3) prodelta muddy deposits. Delta plain deposits display a parallel to sub-parallel and small channel-shaped seismic structure which represent inter-distributary plains and distributary channels (Figs 3, 4 and 7). The well logging usually shows fining-upward cycle, which is dominated by siltstone, while the channels commonly fill with sandstone (Figs 3 and 5). The end of delta plain lobe generally link with mouth bar deposits representing the proximal delta front zone. Delta front deposits display thick imbricate, S-shaped to tangential progradational foresets or clinoforms seismic reflections and coarsening-upward well logging patterns, whose major lithology slightly finer than the delta plain (Figs 5, 6 and 8). Proximal river mouth bars, distal bars and sand-sheets deposits have been identified within the delta front. Proximal river mouth bars deposits are dominated by sandstone with a funnel-box shaped GR curve (Fig. 5); At the end of delta front, distal bars feature coarsening-upward prograding complexes which are dominated by (pelitic) siltstone (Fig. 5); sand-sheets are also identified at the distal front characterized by sheet-like bars of pelitic siltstone, RMS amplitude slices indicate that the delta front is dominated by a series of lobe-shaped sand-sheets and distal bars (Fig. 8b). Prodelta deposits commonly prograded into the slope zone or bathyal environment with parallel to subparallel and dome-shaped seismic reflections dominated by mudstone with a high GR value (Figs 5, 6 and 8). From inner-shelf to shelf margin, the main environment of Quaternary transform from sublittoral of inner delta plain with channels to slope-deep water of prodelta, lithology became finer overall (Figs 3–5).

The phase of sea level can determine the type and the nature of the delta. The inner-shelf delta, which developed in nearshore environments on the inner-shelf usually formed in the highstand, whereas the shelf-edge delta characterized by thick clinoforms which prograded into the continental margin usually formed in the forced falling to lowstand stage (Carvajal et al., 2009; Dixon et al., 2012; Henriksen et al., 2009; Porębski and Steel, 2001, 2003).

Deltas E and A which corresponds to the sea level fall of MIS 42 and MIS 2, respectively, are assumed to be inner-shelf delta by the interpretation of seismic data. The progradation of deltas E and A are relatively weak cause the main part of them mainly developed on the inner-shelf, the delta front of them are identified on the Panyu Lower Uplift with a height ~60 m and ~80 m which characterized by subparallel to S-shaped seismic reflections (Fig. 7). With abundant sediment supply, Deltas D, C and B are prograded seaward into the shelf margin zone rapidly during the forced falling stage, which can be interpreted as shelf-edge deltas. Shelf-edge deltas and clinoforms generated by shelf margin accretion are quite different, except the two types coincide when deltas reach the shelf edge (Porębski and Steel, 2001, 2003). Delta D feature thick S-shaped to oblique-tangential seaward-dipping seismic reflections and coarsening-upward well-logging patterns forming during the lowstand of MIS 20, the deltaic progradational beds are approximately 200 m thick and can be distinguished from the underlying shelf-edge clinoforms (Figs 6 and 8). Delta C and B showing the similar structure are relatively thin, but their delta fronts display the even more rapid progradation than D, which related to the sea level fall of MIS 12 and MIS 6, respectively (Figs 6 and 8). The sub-sequences within these deltaic foresets are also identified representing the sea level changes of orbital scale cycles (Fig. 6). Based on 3D and 2D seismic data, the position of these five delta front (E–A) have been mapped showing the evolution of the paleo-delta (Fig. 1c), where the delta front E to B prograded from the southern Panyu Lower Uplift toward the northern Baiyun Depression, and shelf slope break migrated seaward, whereas the delta front A return to the inner shelf. Holocene highstand delta is considered as a bay delta, which had been constrained into the inner shelf because of the strong longshore currents and wave action (Lüdmann et al., 2001).

5.2 Incised valleys and slumping massive deposits

On the outer shelf, intensive incised valleys developed responding to the 3rd sequence boundary during the lowstand stage. In the seismic profiles, incised valleys commonly feature U-shaped and V-shaped with the depth about tens of meters, and with the width about tens of kilometers (Figs 6 and 8). Internal fillings which can be divided into sub-units usually display a single-story to multistory asymmetric structure and mainly migrated seaward (Figs 6 and 8). In the well-logging profiles, incised valleys commonly show low GR values and sudden changes of lithology (Fig. 5). Since Quaternary, the incised valleys have become more and more intensive upwards, especially on SB3 and SB2 (Fig. 8).

The slumping massive deposits or slope slumps developed on the upper slope during lowstand stage. According to the seismic profiles, the slumping massive deposits migrated basinward in general and increased within SQ3–SQ1 and characterized by strong amplitudes and chaotic reflections with an average thickness of ~30 m (Figs 6 and 8), which are considered to be related with the development of shelf-edge deltas. The RMS amplitude slices at 20 ms upon SB3 and SB2 show that the slumps of shelf-edge delta fronts stepped over the shelf break zone and transport into the slope channels zone, cover an average area of ~500 km² and increased abruptly since SB2, which corresponds to the development of incised valleys (Fig. 9). Small gullies were identified in the head of the slumping massive deposits linking between the shelf-edge delta and the slumping massive deposits, indicated the process of the slumping-gravity flow.

Slumping-gravity flow transport along the front edges which

play an important sediment supply for slope fan deposits have been identified in the western part of study area based on the integral analysis of the seismic data. The slumping massive deposits of shelf-edge deltas are considered as the major sediment supply for slope fans, which are caused by the extensive erosion of the shelf area and the gravity imbalance of the rapid progradational shelf-edge deltas during the sea level fall. The progradation of SQ4 and SQ0 are limited, causing the thin strata during these periods in the slope area. SB5 and SB4 usually merge with SB3 and SB0 merge with SB1 in the seismic profiles (Figs 6 and 8).

6 Controls on sequence architecture and depositional evolution

6.1 Sea level changes and tectonics

The relative sea level changes are the central cause of the development of depositional cycles and sequence architecture (Lin, 2009). The sea level changes reflected in the seismic structure are almost match with the stacked benthic foram O-isotope records, in particular, the major sequence boundaries are commonly consistent with regression events and correlated with low $\delta^{18}\text{O}$ values (Fig. 6). The development of T0 was considered to correspond to the declining sea levels caused by the onset of the Arctic ice-sheet development (Wang et al., 2014), an increase by ~1.9‰ of $\delta^{18}\text{O}$ at the same period is recorded in ODP Site 1148 (Zhao et al., 2001) (Fig. 2); The development of SB5 and SB3 are consistent with the global sea level falls related to Haq et al. s' (1987) sea level change curve (Fig. 2), which indicates that development can be correlated globally; The development of SB2 and SB0 are assumed corresponding to the ice-sheet expansion of the Mid-Brunhes Event (MBE) and LGM, which both display larger-amplitude changes in $\delta^{18}\text{O}$ records (Wang et al., 2014) (Figs 6 and 10). The depositional evolution is also consistent with the transgression to regression cycles, deltaic deposits featuring progradational clinoforms are formed during highstand to falling stage, with the sea level continue to fall, resulted the extensive erosion on the shelf area forming incised valleys and slumping massive deposits.

Tectonic subsidence/uplift is believed to be the major control for the development of sequences. The tectonic subsidence may enhance the process of deposits, whereas the uplift could enhance the relative sea level falls and further strengthen the progradation of deposits. Since ~3.0 Ma, the collision between Luzon Arc and east China had been identified (Lüdmann and Wong, 1999), Liuha Movement at the end of the Pliocene–Early Pleistocene is considered to be correlated with the collision of Taiwan with Luzon Arc (Wu et al., 2004). These arc-continent collisions resulted the uplift, faulting, folding and denudation of the Quaternary strata along with T0 in the seismic profiles, especially around the Dongsha Uplift zone. The extensive transgression strata in SQ5 characterized by the shelf-break zone migrated landward intensively which differs with the trend of Haq et al. s' (1987) sea level change curve, are considered as the result of a high rate of regional tectonic subsidence at that time (Li et al., 1999; Jiang et al., 2017).

The relative sea level changes are considered as the sum of the eustatic and tectonic contributions. Since ~1.6 Ma, since 0.10‰–0.11‰ changes in $^{16}\text{O}/^{18}\text{O}$ ratio represent approximately 10 m in sea level change (Chiocci et al., 1997), and the relative sea level curve in the study area can be obtained from seismic data based on $v=1\ 500\ \text{m/s}$, thus the tectonic contribution could be computed as a first approximation using the correlation between the present locations of the 5 sets of delta fronts and the stacked

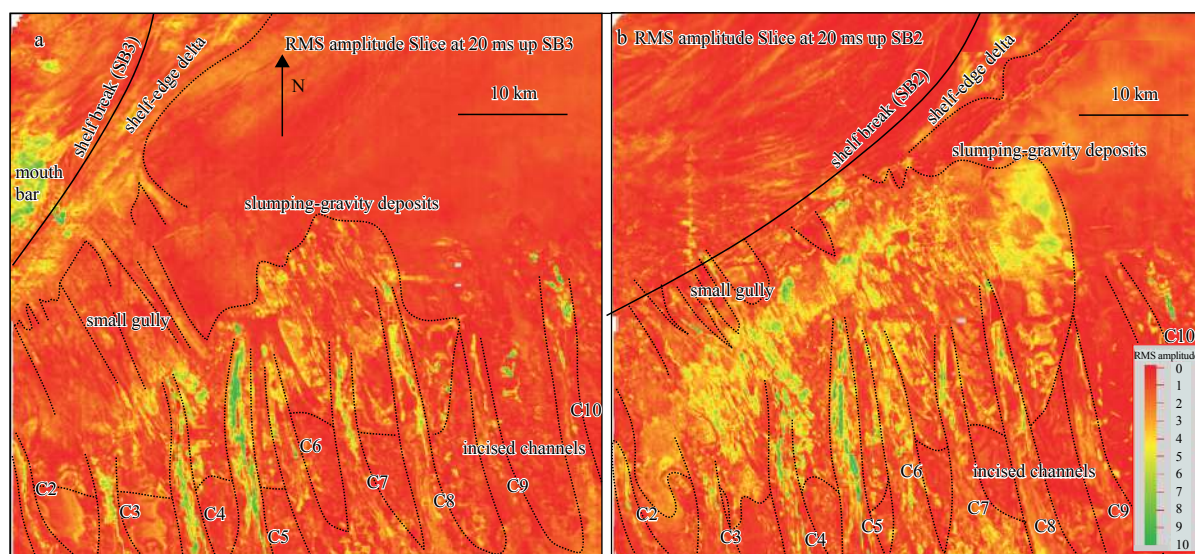


Fig. 9. RMS amplitude slices at 20 ms up SB3 and SB2 showing the evolution of slumping massive deposits from SQ3 to SQ2, note the slumping massive deposits increased abruptly since SB2. See Fig. 1c for the location.

benthic foram O-isotope records without consideration of the influence of sediment loading, compaction and erosion (Lüdmann et al., 2001). The result shows a subsidence rate ~ 76 m/Ma during the period of SQ3, and then three uplift phases during SQ2–SQ0 (Fig. 10). The tectonic subsidence may enhance the deposits of thick strata of SQ3, whereas the uplift could enhance the relative sea level falling and further strengthen the progradation of clinoforms of SQ2–SQ0.

6.2 Sediment supply and climate changes

Sediment supply is critical to the depositional architecture and can determine the patterns of deposits in all sedimentary basins (Catuneanu, 2006). In the study area, Quaternary strata is quite thick (~ 200 – 600 m), which is considered to be enhanced by the tectonic subsidence (see Section 6.1) and abundant sediment supply. Based on the previous studies on seismic profiles in the ZRMB and ODP1148, the sedimentation rates peaked during the Pleistocene (reaching 50.7 and 49.01 m/Ma, respectively) (Clift et al., 2002) (Fig. 2), which are consistent with the onset of the progradation of shelf-edge clinoforms. The abundant sediment supply may be correlated with the uplift and denudation of Western Yunnan Plateau during the Quaternary, which could have supplied large amounts of sediments to the South China Sea Basin (Wang et al., 1999). Furthermore, the increases in sedimentation rates were recorded at ~ 2 – 4 Ma around the globe, implying increased erosion rates (Nott and Roberts, 1996; Oline et al., 1999; Zheng et al., 2000; Zhang et al., 2001). The extreme climate changes during Quaternary might result in a frequent and abrupt change of temperature, precipitation and vegetation, which prevented fluvial and glacial systems from establishing equilibrium states and caused more incisions and denudations of surfaces, and further provided abundant sediment supply (Zhang et al., 2001).

Pleistocene climate started with the onset of the Arctic ice-sheet development, which differs from a stable and warm-wet climate before Quaternary, characterized by an extreme climate with frequent and high-amplitude cycles of glaciation to interglaciation (Huang et al., 2005; Zhang et al., 2001). According to the previous studies in the SCS (Luo and Sun, 2013; Tang et al.,

2004; Zhang et al., 1997; Zhang and Long, 2008), the climate changes are related to glacio-eustatic changes and can further cause the sea level changes, which constrained the depositional cycles and sequence architecture (see Section 6.1). In addition, the extreme climate changes and abundant sediment supply are considered to enhance the progradation of the clinoforms and the development of incised valleys, which further resulted the deposits of slope slumps during Quaternary (Zhang et al., 2001).

6.2.1 The mid-Pleistocene transition

The mid-Pleistocene transition (MPT), as a significant climate event in the Quaternary, marks the dominant climate periodicity extended from 41 ka to 100 ka (Martin et al., 2008; Prell, 1982). The SCS probably was more sensitive to the MPT than the open ocean (Wang et al., 2014). It is clear now the MPT covered a long time interval from ~ 1.2 Ma to ~ 0.6 Ma and centered on ~ 0.9 Ma, which can be seen in the stacked oxygen isotope records (Figs 6 and 10) (Lisiecki and Raymo, 2005; Elderfield et al., 2012; Shackleton, 1987). Along with the completion of MPT, the amplitude and duration of eustatic changes increased abruptly (Zhuo et al., 2015), which caused the extensive formation of progradational clinoforms and incised valleys. In the seismic profiles, SB3 are considered to be constrained by the MPT. The depositional architecture before SB3 are relative stable and can be divided into more 4th sub-sequences with 41–100 ka cycles; After SB3, besides the 4th sub-sequences are mainly constrained by 100 ka, the clinoforms prograded farther seaward into the shelf-margin forming shelf-edge deltas, and the incised valleys developed more intensively along the sequence boundaries, further causing the development of slumping massive deposits (Figs 9 and 11).

6.2.2 The East Asian monsoon

With the intensive climate variations, the relationship between monsoon of SCS and glaciation to inter-glaciation cycles became closer, and the winter monsoon had been strengthened intensively (Wang et al., 2003), in particular, the East Asian monsoon system had an important influence on climate in the SCS and the surrounding areas (Zhisheng et al., 2001). Besides the boreal ice sheet growth, the East Asian monsoon is linked to the

phases of Himalaya-Tibetan plateau uplift (Prell and Kutzbach, 1987), the warm-wet South Asian air mass was considered to be blocked by the plateau uplift and further strengthened the cold-dry climate of East Asian monsoon (Clift et al., 2008; Meng et al., 2011). According to the micropaleontological and palynological studies, the East Asian winter monsoon enhanced in 3.2–2.2 Ma, and strengthened at ~1.7, 1.3, 0.9, 0.45 and 0.15 Ma (Jian et al., 2001; Jian and Huang, 2003), which are almost consistent with the major sequence boundaries in the study area. The East Asian monsoon intensification events are considered to result cooler and drier climate conditions and correlated to the increased magnitude of sea level fall (Zhuo et al., 2015), which further caused the onset of intensive development of the progradational clinoforms and incised valleys (Fig. 11).

7 Conclusions

(1) Regional unconformity T0 and six local unconformities SB5–SB0 characterized by onlap, downlap, toplap, truncation, downcutting, divided the Quaternary strata into six 3rd order sequences (SQ0–SQ5). Twenty-three 4th order sub-sequences can be further divided within the large scale progradational complexes or clinoforms of SQ4–SQ0. The chronostratigraphic framework of 4th sequences is constructed by correlating the unconformities with the lowstand of the stacked benthic foram O-isotope records.

(2) The Quaternary strata are characterized by a series of high-angle foresets complexes or clinoforms. Deltaic deposits, incised valleys, and slope slumping massive deposits are recognized in the Quaternary strata. Deltaic deposits have been interpreted into two types: a. inner shelf deltas which display relatively weak progradation (Deltas E and A); and b. shelf-edge delta which are prograded seaward into the shelf margin zone (Deltas D, C and B). Three deltaic depositional facies have been recognized: a. delta plain (interdistributary plains and distributary channels); b. the prograding delta front (proximal river mouth bars, distal bars and sand-sheets); and c. prodelta muddy deposits. The depositional evolution in the study area has been reconstructed based on the integral analysis of seismic data. Since SQ4–SQ1, Deltas E–B prograded from the southern Panyu Lower Uplift toward the northern Baiyun Depression, shelf slope break migrated seaward, whereas Delta A return to the inner shelf. The development of incised valleys in the continental shelf increased upward, especially intense on the SB3 and SB2. The slumping massive deposits increased abruptly since SB2, which corresponds to the development of incised valleys.

(3) The tectonic curve since SB4 was established by the correlation between the present locations of the 5 sets of delta fronts and the stacked benthic foram O-isotope records. The sequence architecture and depositional evolution in the study area were controlled by the combined influence of sea level changes, tectonism, sediment supply and climate changes. Besides the control of global sea level changes, the tectonic subsidence may enhance the deposits, whereas the uplift could enhance the relative sea level falls and further strengthen the progradation of deposits. Furthermore, the abundant sediment supply and intensive climate changes since Quaternary are considered to enhance the development of 5 sets of progradational clinoforms and incised valleys since SB5, especially SQ3 to SQ1.

Acknowledgements

We sincerely thank the China National Offshore Oil Corporation for providing the subsurface data and supporting of this work.

References

- Alves T M, Bell R E, Jackson A L, et al. 2014. Deep-water continental margins: geological and economic frontiers. *Basin Research*, 26(1): 3–9, doi: [10.1111/bre.2014.26.issue-1](https://doi.org/10.1111/bre.2014.26.issue-1)
- Anastasakis G, Piper D J W. 2013. The changing architecture of sea-level lowstand deposits across the Mid-Pleistocene Transition: South Evoikos Gulf, Greece. *Quaternary Science Reviews*, 73: 103–114, doi: [10.1016/j.quascirev.2013.04.018](https://doi.org/10.1016/j.quascirev.2013.04.018)
- Carvajal C, Steel R, Petter A. 2009. Sediment supply: The main driver of shelf-margin growth. *Earth-Science Reviews*, 96(4): 221–248, doi: [10.1016/j.earscirev.2009.06.008](https://doi.org/10.1016/j.earscirev.2009.06.008)
- Catuneanu O. 2006. *Principles of Sequence Stratigraphy*. Canada: Elsevier Science, 1–16
- Catuneanu O, Abreu V, Bhattacharya J P, et al. 2009. Towards the standardization of sequence stratigraphy. *Earth-Science Reviews*, 92(1–2): 1–33
- Chen Cangmin. 2000. Petroleum geology and conditions for hydrocarbon accumulation in the eastern Pearl River Mouth Basin. *China Offshore Oil and Gas (Geology)* (in Chinese), 14(2): 73–83
- Chen P P H, Chen Z Y, Zhang Qimin. 1993. Sequence stratigraphy and continental margin development of the northwestern shelf of the South China Sea. *AAPG Bulletin*, 77(5): 842–862
- Chiocci F L, Ercilla G, Torre J. 1997. Stratal architecture of western Mediterranean margins as the result of the stacking of quaternary lowstand deposits below ‘glacio-eustatic fluctuation base-level’. *Sedimentary Geology*, 112(3–4): 195–217
- Clift P, Lee J I, Clark M K, et al. 2002. Erosional response of South China to arc rifting and monsoonal strengthening: A record from the South China Sea. *Marine Geology*, 184(3–4): 207–226
- Clift P D, Hodges K V, Heslop D, et al. 2008. Correlation of Himalayan exhumation rates and Asian monsoon intensity. *Nature Geoscience*, 1(12): 875–880, doi: [10.1038/ngeo351](https://doi.org/10.1038/ngeo351)
- Ding Weiwei, Li Jiabiao, Li Jing, et al. 2013. Morphotectonics and evolutionary controls on the Pearl River Canyon system, South China Sea. *Marine Geophysical Research*, 34(3–4): 221–238
- Dixon J F, Stee R J, Olariu C. 2012. River-dominated, shelf-edge deltas: delivery of sand across the shelf break in the absence of slope incision. *Sedimentology*, 59(4): 1133–1157, doi: [10.1111/sed.2012.59.issue-4](https://doi.org/10.1111/sed.2012.59.issue-4)
- Dong Wei, Lin Changsong, Qin Chenggang, et al. 2008. High resolution sequence framework, depositional pattern and litho-stratigraphic traps of Hanjiang formation in Panyu Uplift, Pearl River Mouth Basin. *Geoscience (in Chinese)*, 22(5): 794–802
- Elderfield H, Ferretti P, Greaves M, et al. 2012. Evolution of ocean temperature and ice volume through the mid-Pleistocene climate transition. *Science*, 337(6095): 704–709, doi: [10.1126/science.1221294](https://doi.org/10.1126/science.1221294)
- Feng Zhiqiang, Feng Wenke, Xue Wanjuan, et al. 1996. Evaluation of Marine Geologic Hazards and Engineering Geological Conditions in the Northern South China Sea (in Chinese). Nanjing, China: Hehai University Publishing House, 177–178
- Ge Huangmin, Li Qianyu, Zhong Guangfa, et al. 2012. High resolution Quaternary seismic sequence stratigraphy and paleoenvironmental evolution in the northern South China Sea. *Marine Geology & Quaternary Geology (in Chinese)*, 32(4): 49–60
- Gong Zisheng, Li Sitian. 2004. *Dynamic Research of Oil and Gas Accumulation in Northern Marginal Basins of South China Sea* (in Chinese). Beijing: Science Press, 1–50
- Gong Chenglin, Wang Yingmin, Steel R J, et al. 2016. Flow processes and sedimentation in unidirectionally migrating deep-water channels: From a three-dimensional seismic perspective. *Sedimentology*, 63(3): 645–661, doi: [10.1111/sed.2016.63.issue-3](https://doi.org/10.1111/sed.2016.63.issue-3)
- Gong Chenglin, Wang Yingmin, Zhu Weilin, et al. 2013. Upper Miocene to Quaternary unidirectionally migrating deep-water channels in the Pearl River Mouth Basin, northern South China Sea. *AAPG Bulletin*, 97(2): 285–308, doi: [10.1306/07121211159](https://doi.org/10.1306/07121211159)
- Haq B L, Hardenbol J, Vail P R. 1987. Chronology of fluctuating sea levels since the Triassic. *Science*, 235(4793): 1156–1167, doi: [10.1126/science.235.4793.1156](https://doi.org/10.1126/science.235.4793.1156)
- Henriksen S, Hampson G J, Helland-Hansen W, et al. 2009. Shelf edge and shoreline trajectories, a dynamic approach to stratigraphic

- analysis. *Basin Research*, 21(5): 445–453, doi: [10.1111/bre.2009.21.issue-5](https://doi.org/10.1111/bre.2009.21.issue-5)
- Huang Baoqi, Jian Zhimin, Zhao Quanhong, et al. 2005. Variations in deep-water masses from the northern south China Sea since the late Pliocene. *Earth Science—Journal of China University of Geosciences (in Chinese)*, 30(5): 529–533
- Huang Chiyue, Wu Weiyu, Chang C P, et al. 1997. Tectonic evolution of accretionary prism in the arc-continent collision terrane of Taiwan. *Tectonophysics*, 281(1–2): 31–51
- Huang Zhenguo, Zhang Weiqiang, Chai Fuxiang. 1995. The submerged Zhujiang delta. *Acta Geographica Sinica (in Chinese)*, 50(3): 206–214
- Imbrie J, Berger A, Boyle E A, et al. 1993. On the structure and origin of major glaciation cycles 2. The 100,000-year cycle. *Paleoceanography*, 8(6): 699–735, doi: [10.1029/93PA02751](https://doi.org/10.1029/93PA02751)
- Jian Zhimin, Huang Wei. 2003. Rapid climate change and high-resolution deep-sea sedimentary records. *Advance in Earth Sciences (in Chinese)*, 18(5): 673–680
- Jian Zhimin, Wang Pinxian, Zhao Quanhong, et al. 2001. Late pliocene enhanced east asian winter monsoon: evidence of isotope and foraminifers from the northern south china sea. *Quaternary Sciences (in Chinese)*, 21(5): 461–469
- Jiang Jing, Shi Hesheng, Lin Changsong, et al. 2017. Sequence architecture and depositional evolution of the Late Miocene to quaternary northeastern shelf margin of the South China Sea. *Marine and Petroleum Geology*, 81: 79–97, doi: [10.1016/j.marpetgeo.2016.12.025](https://doi.org/10.1016/j.marpetgeo.2016.12.025)
- Kou Yangqi. 1990. Ancient River Channels in the northern South China Sea shelf and engineering geologic significance. *Marine Geology & Quaternary Geology (in Chinese)*, 10(1): 37–45
- Kou Yangqi, Du Deli. 2010. Sedimentary features of shallow ancient river channels on the northern shelf of the South China Sea. *Acta Geologica Sinica (in Chinese)*, 8(1): 85–98
- Lüdmann T, Wong H K. 1999. Neotectonic regime on the passive continental margin of the northern South China Sea. *Tectonophysics*, 311(1–4): 113–138
- Lüdmann T, Wong H K, Wang Pinxian. 2001. Plio-Quaternary sedimentation processes and neotectonics of the northern continental margin of the South China Sea. *Marine Geology*, 172(3–4): 331–358
- Li Fei, Cheng Rihui, Wang Gongsheng, et al. 2011. Application of seismic attribute analysis to study sedimentary systems of the Yingcheng formation, lower cretaceous, Shiwu Oilfield. *Journal of Jilin University (Earth Science Edition) (in Chinese)*, 41(S1): 54–59
- Li Sitian, Lin Changsong, Zhang Qiming, et al. 1999. Episodic rifting of continental marginal basins and tectonic events since 10 Ma in the South China Sea. *Chinese Science Bulletin*, 44(1): 10–23, doi: [10.1007/BF03182877](https://doi.org/10.1007/BF03182877)
- Lin Changsong. 2009. Sequence and depositional architecture of sedimentary basin and process responses. *Acta Sedimentologica Sinica (in Chinese)*, 27(5): 849–862
- Lin Changsong, Eriksson K, Li Sitian, et al. 2001. Sequence architecture, depositional systems, and controls on development of lacustrine basin fills in part of the Erlan basin, northeast China. *AAPG Bulletin*, 85(11): 2017–2043
- Lin Changsong, Lu Jinyan, Cai Shixiang, et al. 2001. Depositional architecture and developing settings of large-scale incised valley and submarine gravity flow systems in the Yinggehai and Qiongdongnan basins, South China Sea. *Chinese Science Bulletin*, 46(8): 690–693, doi: [10.1007/BF03182838](https://doi.org/10.1007/BF03182838)
- Lin Changsong, Jiang Jing, Shi Hesheng, et al. 2017. Sequence architecture and depositional evolution of the northern continental slope of the South China Sea: responses to tectonic processes and changes in sea level. *Basin Research*, 30(1): 568–595
- Lisiecki L E, Raymo M E. 2005. A Pliocene-Pleistocene stack of 57 globally distributed benthic $\delta^{18}\text{O}$ records. *Paleoceanography*, 20(1): PA1003
- Liu Baojun, Pang Xiong, Yan Chengzhi, et al. 2011. Evolution of the Oligocene-Miocene shelf slope-break zone in the Baiyun deep-water area of the Pearl River Mouth Basin and its significance in oil-gas exploration. *Acta Petrolei Sinica (in Chinese)*, 32(2): 234–242
- Luo Yunli, Sun Xiangjun. 2013. Vegetation evolution and its response to climatic change during 3.15–0.67 Ma in deep-sea pollen record from northern South China Sea. *Chinese Science Bulletin*, 58(3): 364–372, doi: [10.1007/s11434-012-5374-x](https://doi.org/10.1007/s11434-012-5374-x)
- Martin J H, Pillans B, Farquhar S A. 2008. The Early-Middle Pleistocene Transition: Characterization and proposed guide for the defining boundary. *Episodes*, 31(2): 255–259
- Meng Xianwei, Xia Peng, Zheng Jun, et al. 2011. Evolution of the East Asian monsoon and its response to uplift of the Tibetan Plateau since 1.8 Ma recorded by major elements in sediments of the South China Sea. *Chinese Science Bulletin*, 56(6): 547–551, doi: [10.1007/s11434-010-4258-1](https://doi.org/10.1007/s11434-010-4258-1)
- Mitchum R M Jr. 1985. Seismic stratigraphic expression of submarine fans. *AAPG Special Volumes*, 167: 117–136
- Nott J, Roberts R G. 1996. Time and process rates over the past 100 m.y.: A case for dramatically increased landscape denudation rates during the late Quaternary in northern Australia. *Geology*, 24(10): 883–887, doi: [10.1130/0091-7613\(1996\)024<0883:TAPROT>2.3.CO;2](https://doi.org/10.1130/0091-7613(1996)024<0883:TAPROT>2.3.CO;2)
- Oline H B, Eldholm O, Skogseid J. 1999. Cenozoic evolution of the northern Vøring margin. *Geological Society of America Bulletin*, 111(12): 1792–1807, doi: [10.1130/0016-7606\(1999\)111<1792:CEOTNV>2.3.CO;2](https://doi.org/10.1130/0016-7606(1999)111<1792:CEOTNV>2.3.CO;2)
- Pang Xiong, Chen Changmin, Zhu Ming, et al. 2009. Baiyun movement: a significant tectonic event on Oligocene/Miocene boundary in the northern South China Sea and its regional implications. *Journal of Earth Science*, 20(1): 49–56, doi: [10.1007/s12583-009-0005-4](https://doi.org/10.1007/s12583-009-0005-4)
- Porębski S J, Steel R J. 2001. Delta types and sea level cycle. *AAPG Annual Convention*, 10: A160
- Porębski S J, Steel R J. 2003. Shelf-margin deltas: their stratigraphic significance and relation to deepwater sands. *Earth-Science Reviews*, 62(3–4): 283–326
- Prell W L. 1982. Oxygen and carbon isotope stratigraphy for the quaternary of Hole 502B: evidence for two modes of isotopic variability. In: *Initial Reports of the Deep Sea Drilling Project*. Washington: U.S. Government Printing Office, 68: 455–464
- Prell W L, Kutzbach J E. 1987. Monsoon variability over the past 150,000 years. *Journal of Geophysical Research*, 92(D7): 8411–8425, doi: [10.1029/JD092iD07p08411](https://doi.org/10.1029/JD092iD07p08411)
- Qin Guoquan. 1996. Application of micropaleontology to the sequence stratigraphic studies of late Cenozoic in the Zhujiang River Mouth Basin. *Marine Geology & Quaternary Geology (in Chinese)*, 16(4): 1–18
- Shackleton N J. 1987. Oxygen isotopes, ice volume and sea level. *Quaternary Science Reviews*, 6(3–4): 183–190
- Sun Zhen, Zhong Zhihong, Zhou Di, et al. 2008. Dynamics analysis of the Baiyun Sag in the Pearl River Mouth Basin, North of the South China Sea. *Acta Geologica Sinica*, 82(1): 73–83
- Tang Song, Shao Lei, Zhao Quanhong. 2004. Characteristics of clay mineral in South China Sea since Oligocene and its significance. *Acta Sedimentologica Sinica (in Chinese)*, 22(2): 337–342
- Vail P R. 1987. Seismic stratigraphy interpretation using sequence stratigraphy, Part 1: seismic stratigraphy interpretation procedure. In: Bally A W, ed. *Atlas of Seismic Stratigraphy*. Tulsa, OK: AAPG Studies in Geology, 27: 1–10
- Vail P R, Audemard F, Bowman S A, et al. 1991. The stratigraphic signatures of tectonics, eustasy and sedimentology—an overview. In: Einsele G, Ricken W, Seilacher A, eds. *Cycles and Events in Stratigraphy*. Berlin: Springer-Verlag, 617–659
- Vail P R, Mitchum R M, Todd R G, et al. 1977a. Seismic stratigraphy and global changes in sea level. In Payton C E, ed. *Seismic Stratigraphy—Applications to Hydrocarbon Exploration*. Tulsa: American Association of Petroleum Geologists, 26: 49–212
- Vail P R, Mitchum R M, Todd R G, et al. 1977b. Seismic stratigraphy and global changes of sea-level, Part 9. Seismic interpretation of elastic depositional fades. In: Payton C E, ed. *Seismic Stratigraphy—Application to Hydrocarbon Exploration*. Tulsa: American Association of Petroleum Geologists, 26: 83–97

- Wang Pinxian, Jian Zhimin, Zhao Quanhong, et al. 2003. Evolution of the South China Sea and monsoon history revealed in deep-sea records. *Chinese Science Bulletin*, 48(23): 2549–2561, doi: [10.1360/03wd0156](https://doi.org/10.1360/03wd0156)
- Wang Pinxian, Li Qianyu. 2009. *The South China Sea: Paleoceanography and Sedimentology*. Netherlands: Springer, 1–50
- Wang Pinxian, Li Qianyu, Tian Jun. 2014. Pleistocene paleoceanography of the South China Sea: Progress over the past 20 years. *Marine Geology*, 352: 381–396, doi: [10.1016/j.margeo.2014.03.003](https://doi.org/10.1016/j.margeo.2014.03.003)
- Wang Guozhi, Wang Chenshan, Zeng Yunfu. 1999. Sedimentary Evidence of the Western Yunnan Plateau Uplift since Miocene. *Bulletin of Mineralogy, Petrology and Geochemistry* (in Chinese), 18(3): 167–170
- Wu Shiguo, Liu Zhan, Wang Wanyin, et al. 2004. Late Cenozoic neotectonics in the Dongsha islands region and its responds to collision between Chinese continental margin and Luzon. *Oceanologia et Limnologia Sinica* (in Chinese), 35(6): 481–490
- Wu Jinggu, Xu Qiang, Zhu Yanhe. 2010. Generation and evolution of the shelf-edge delta in Oligocene and Miocene of Baiyun Sag in the South China Sea. *Earth Science* (in Chinese), 35(4): 681–690
- Xie Lihua, Lin Changsong, Dong Wei, et al. 2009. High-resolution sequence stratigraphy of Zhujiang Formation and Zhuhai formation in Panyu low uplift of the Zhujiang River mouth basin. *Geology in China* (in Chinese), 36(2): 366–377
- Xie Hui, Zhou Di, Li Yuanping, et al. 2014. Cenozoic tectonic subsidence in deepwater sags in the Pearl River Mouth Basin, northern South China Sea. *Tectonophysics*, 615–616: 182–198
- Zhang Yulan. 2008. Sporopollen and algae in Core C4 of northern South China Sea and its paleoenvironment. *Journal of Tropical Oceanography* (in Chinese), 27(6): 44–48
- Zhang Xunhua, Li Yancheng, Qi Zhenhua, et al. 1997. An approach to the formation and evolution model of South China Sea Basin. *Marine Geology & Quaternary Geology* (in Chinese), 17(2): 1–7
- Zhang Peizhen, Molnar P, Downs W R. 2001. Increased sedimentation rates and grain sizes 2–4 Myr ago due to the influence of climate change on erosion rates. *Nature*, 410(6831): 891–897, doi: [10.1038/35073504](https://doi.org/10.1038/35073504)
- Zhao Quanhong, Jian Zhimin, Wang Jiliang, et al. 2001. Neogene oxygen isotopic stratigraphy, ODP Site 1148, northern South China Sea. *Science in China Series D: Earth Sciences*, 44(10): 934–942, doi: [10.1007/BF02907086](https://doi.org/10.1007/BF02907086)
- Zheng Hongbo, Powell C M, An Zhisheng, et al. 2000. Pliocene uplift of the northern Tibetan Plateau. *Geology*, 28(8): 715–718, doi: [10.1130/0091-7613\(2000\)28<715:PUOTNT>2.0.CO;2](https://doi.org/10.1130/0091-7613(2000)28<715:PUOTNT>2.0.CO;2)
- Zhisheng A, Kutzbach J E, Prell W L, et al. 2001. Evolution of Asian monsoons and phased uplift of the Himalaya-Tibetan plateau since Late Miocene times. *Nature*, 411(6833): 62–66, doi: [10.1038/35075035](https://doi.org/10.1038/35075035)
- Zhou Wei, Wang Yingmin, Gao Xianzhi, et al. 2015. Architecture, evolution history and controlling factors of the Baiyun submarine canyon system from the middle Miocene to Quaternary in the Pearl River Mouth Basin, northern South China Sea. *Marine and Petroleum Geology*, 67: 389–407, doi: [10.1016/j.marpetgeo.2015.05.015](https://doi.org/10.1016/j.marpetgeo.2015.05.015)
- Zhu Yanhe, Zhu Weilin, Xu Qiang, et al. 2011. Sedimentary response to shelf-edge delta and slope deep-water fan in 13.8 Ma of Miocene epoch in Pearl River Mouth Basin. *Journal of Central South University (Science and Technology)* (in Chinese), 42(12): 3827–3834
- Zhuo Haiteng, Wang Yingmin, Shi Hesheng, et al. 2015. Contrasting fluvial styles across the mid-Pleistocene climate transition in the northern shelf of the South China Sea: Evidence from 3D seismic data. *Quaternary Science Reviews*, 129: 128–146, doi: [10.1016/j.quascirev.2015.10.012](https://doi.org/10.1016/j.quascirev.2015.10.012)