The late Cenozoic deep-water channel system in the Baiyun Sag, Pearl River Mouth Basin: Development and tectonic effects

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A R T I C L E   I N F O

Keywords: Deep-water channel Active fault Turbidite deposits Deep-water sedimentation Pearl River Mouth Basin

A B S T R A C T

Twenty modern submarine channels and buried channels were examined using high-resolution 3D/2D seismic data in the Baiyun Sag, Pearl River Mouth Basin. The channels were dominantly straight, sub-parallel with one another, and oriented perpendicular to the slope contours. Four stages of the deep-water channel system (DCS) were identified according to seismic facies and spatial distribution. The stages were controlled by sediment input and tectonic activities. DCS I is distributed in the middle of the Baiyun Sag, with small individual channels. DCS II expanded because of decreasing sediment input and stable subsidence of the Baiyun Sag increased the slope. DCS III had the broadest distribution and nearly covered the entire Baiyun Sag. Further decreases in sediment input and the Dongsha Event increased the gravity flow domain and greatly promoted the development of the DCS. DCS IV narrowed to the southwest because the buried channels in the northeastern Baiyun Sag ceased after 5.5 Ma as the result of active fault activity. This study highlights that the channel system plays an important role in recording the sedimentary evolution of the Pearl River Mouth Basin and affects the deep-water resource (hydrocarbon and gas hydrate) distribution.

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1. Introduction

Deep-water channels are common and important sedimentary features in the continental slope and generally develop through four evolution stages: eroding, infilling, overflowing, and sediment covering (Mutti and Normark, 1987, 1991; Navarre et al., 2002; Abreu et al., 2003; Peakall et al., 2007). The channel system contributes to clastic sediment being transported from the shelf to the deep-water basins, which forms significant oil and gas reservoirs (Dixon and Weimer, 1998; Navarre et al., 2002; Mayall et al., 2006; Deptuck et al., 2007; Hutchinson et al., 2008; Vangriesheim et al., 2009; Amos et al., 2010; McHargue et al., 2011; Lonergan et al., 2013). Generally, gravity flows and bottom currents are viewed as the main causes of submarine channels (Abreu et al., 2003; Deptuck et al., 2007; Kane et al., 2007; Di Celma, 2011; Gong et al., 2011; Saller and Dharmasamadhi, 2012).

A series of papers have been published that reveal abundant oil and gas resources, such as gas hydrate and shallow gas, in the northern South China Sea (SCS) (Wu et al., 2007; Gong et al., 2009; Wang et al., 2011; Sun et al., 2012). Deep-water channels in the Baiyun Sag of the Pearl River Mouth Basin (PRMB), northern SCS have been active since the Middle Miocene (Liu et al., 2006; Zhu et al., 2010; Gong et al., 2013). The deep-water channel system (DCS) becomes valuable in hydrocarbon exploration because the channel system plays a very special role in the formation of petroleum source rocks. We conducted the study to determine the evolution of DCS and to investigate the favorable distribution of oil and gas reservoirs.

The channels originated in a period of strong regression (ca. 13.8 Ma), which contributed to voluminous sediment unloading on the shelf edge and triggered widespread gravity flows (Zheng et al., 2007; Zhu et al., 2010; Ding et al., 2013; Gong et al., 2013). Previous studies indicate that the channels form in three stages: (1) erosion by turbidity currents during the relative sea level fall and low-stand, (2) infilling by mass-transport deposits (MTDs) and lateral accretion packages during relative sea level rise, and (3) burying by deep-water mud during the relative sea level high-stand (Zheng et al., 2007; Zhu et al., 2010; Lü et al., 2012; Gong et al., 2013; Li et al., 2013). Previous studies have mainly focused on small 3D seismic surveys, and tectonic controlling factors for channel development are still unclear.
Fig. 1. (a) The tectonic division and geomorphologic map north of the SCS. The location of the paleo-Pearl River Delta (paleo-PRD) and submarine fan from Pang et al. (2007); the red line represents the area affected by the Dongsha Event from Wu et al. (2014). (b) A map of the modern submarine channels; 20 submarine channels are distributed on the slope, with similar geometries. C1–C20: submarine channels on the modern sea floor. (c) The crossing sections of modern submarine channels. The channels show the V-shaped sections in the top (A–A’) and U-shaped sections in the tail (B–B’). See the positions in (b). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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In this study, we identified four stages of the channel system based on the larger 3D seismic surveys. The purposes of this paper are as follows: (1) to reveal the sedimentary characteristics of the deep-water channel system, including the evolution, deposition accumulation area, and sedimentation differentiation; (2) to investigate the key tectonic activities during DCS development; and (3) to establish a sedimentary model of the tectonic effects on DCS development.

2. Regional geological setting

The Baiyun Sag of the PRMB lies on the continental slope along the northern margin of the South China Sea (SCS) (Fig. 1a). It is the largest sag in the PRMB and covers an area of approximately 5000 km² with a water depth of 200–2000 m (Fig. 1b). The DCS, located on the northern slope of the Baiyun Sag, connects the broad shelf and deep-water basin. The paleo-Pearl River Delta (Paleo-PRD) in northwestern DCS was the main material source; submarine fans located in the southeastern DCS were the main sediment pool area (Pang et al., 2007). Furthermore, the Dongsha Event domain, where the region was affected by the Dongsha Movement, is found in the northeastern DCS (Fig. 1a).

2.1. Tectonic events

The Cenozoic evolution of the northern margin of the SCS has been divided into two main stages: (1) rifting and (2) post-rifting (Zhou et al., 1995, 2009). Three main tectonic events occurred in the PRMB during the Cenozoic: (1) the Naihai Event (ca. 30 Ma) ended the basement rifting, after which the PRMB entered a stage of thermal subsidence and deposition (Dong et al., 2009). (2) The Baiyun movement (ca. 23.8 Ma) was a key timeline event in the Baiyun Sag, when the slope break jumped from the south to the north and the sedimentary environment changed from the continental shelf with neritic depositions to the continental slope with deep-water depositions (Pang et al., 2007, 2009). (3) The Dongsha Event (ca. 10.5–5.5 Ma) is generally thought to have had a peak activity at ca. 5.5 Ma and activated a series of faults with an important influence on the study area (Lüdmann and Wong, 1999; Huang et al., 2001; Lüdmann et al., 2001; Wu et al., 2014).

Fig. 2. Seismic stratigraphy, lithology, sedimentary facies and the regional sea level curve in the Baiyun Sag modeled from Li (1993), Wu (1994), Lüdmann and Wong (1999), Yan et al (2001) and Ding et al. (2013).
2.2. Sequence stratigraphy

The Cenozoic strata in the Baiyun Sag exceeded 11 km in thickness over the basement rocks of Cretaceous and Jurassic granites (Pang et al., 2007; Zhou et al., 2009). The rifting sequence consists of Paleocene fluvial-lacustrine facies and upper Oligocene deltaic facies. The post-rifting sequence includes Neogene hemipelagic sedimentary facies. The Early Miocene Zhujiang Formation lithology changes to littoral-neritic sandstones and mudstones and indicates a transition to a slope bathyal sedimentary environment. The sandstones and mudstones with coal beds of the Middle Miocene Hangjiang Formation are typical slope bathyal deposits. The alternating layers of littoral-neritic psephite in the Middle Miocene imply that a strong regression occurred during this period. The lithology of the Late Miocene consists of marine micro-conglomerates with silty mudstones. The silty mudstone and sandstone strata were deposited after 13.8 Ma when the channels were formed and are approximately 2700 m thick (see Fig. 2 for more details).

3. Data and methods

The data used in this study include high-resolution 3D seismic data acquired by the China National Offshore Oil Corporation (CNOOC). The survey covered an area of ca. 2500 km² with a bin size of 12.5 \times 12.5 m² in the cross-line and in-line directions. The frequency bandwidth of the data ranges from 35 to 70 Hz with a dominant frequency of 50 Hz, and the vertical resolution is ca. 10 m. The seismic velocities were set as follows: seawater, 1500 m/s; shallow depostions since 10.5 Ma, 1750 m/s; and deep depostions before 10.5 Ma, 1800 m/s for simple time-depth conversions. The vertical scale for all of the seismic projections before 10.5 Ma, 1800 m/s for simple time-depth conversions.

The analysis of seismic facies and seismic attribute extractions (e.g., root mean square amplitude) contributed to the recognition, detection, and description of the channel deposits. Coherence volume slices were applied to recover the paleo-geomorphology and the seismic root mean square amplitude analysis was used to recognize the distribution of the coarse grain-rich zone. A borehole of LH-1 and log data were used to support the interpretation of the sequence stratigraphy.

4. Results

4.1. Deep-water channels

4.1.1. Modern submarine channels

Modern submarine channels are current analogs of the DCS on the modern seafloor. In the study area, the slope, which had a mean angle of 2–3° between the depths of 250 m and 2000 m, is incised by approximately 20 submarine channels (Fig. 1b). These submarine channels are perpendicular to the slope and have similar geometries. The channels are \textasciicircum 100–350 m deep, \textasciicircum 20–40 km long, and \textasciicircum 3–5 km wide with a V-shaped section at the top and a U-shaped section at the tail (Fig. 1c). They start at the shelf edge that appears at an approximate water depth of 300 m and extend down to \textasciicircum 1800 m depth. The steepest areas in the study survey occur at the channel walls where the mean slope gradient is highest at 6–7°. This morphology extends approximately 140 km from west to east along the slope. The spacing between the channels decreases gradually from 6–13 km to 5–8 km from north to south. Compared to the channels in the eastern region, the western channels are closer to paleo-PRD (Fig. 1). In addition, some channels (e.g., C1 and C20) at the either side of the channel-domain are smaller than the ones in the middle. Channels C19 and C20 on the eastern side are oriented differently than the others (Fig. 1b). A series of failure scars were identified in the channels (Fig. 3). The large scars are mainly distributed on the tops of the channels, with strikes roughly perpendicular to the channels; small scars are mainly distributed on the walls of channels, with strikes roughly parallel to the channels. Small mass-transporting deposits (MTDs) occur at the channel walls and are in close proximity to these scars.

4.1.2. Stages of the DCS

Four third-order sequence boundaries, namely SB13.8 Ma, SB12.5 Ma, SB10.5 Ma, and SB5.5 Ma, were identified according to seismic reflections. The DCS was divided into four evolutionary stages using the sequence boundaries and seismic facies: DCS I
DCS I (13.8–12.5 Ma): buried channels are limited to the middle of the northern slope of the Baiyun Sag (Fig. 5). The embryonic channels have no obvious erosive negative topography. The size of each channel is relatively small and the space between two channels is large (Fig. 6a). The seismic reflections in the channel axis are disordered and unclear, but the areas between channels show continuous and distinct reflections. The channel amplitude varies from being high in the channel axes to being low between the channels (Fig. 4).

DCS II (12.5–10.5 Ma): the domain of DCS II increases slightly compared to DCS I, and the size of the buried channels were larger (Fig. 6b). The seismic reflections were distinct and easily identified in both the channel axes and the area between the channels. The seismic events are parallel and continuous. The seismic reflection amplitude is relatively high especially in the channel axes (Fig. 4).

DCS III (10.5–5.5 Ma): buried channels of this stage are largest during the four developing periods and are distributed over the

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entire northern slope of the Baiyun Sag (Figs. 5 and 6). There were no buried channels in the northeastern Baiyun Sag before 10.5 Ma. Then, a series of small channels originated in this area and lasted until 5.5 Ma when they were infilled and buried by later deposits. The seismic events show weak continuity. The channel amplitude is variable: high in the channel axes and low between the channels (Fig. 4).

DCS IV: (5.5–0 Ma): the biggest characteristics of DCS IV are that the channel domain is narrowed to the southwest (Figs. 4–6). The buried channels ceased in the northeastern Baiyun Sag and abyssal deposits replaced channel deposits (Figs. 5 and 6). In the middle of the northern slope of the Baiyun Sag, channels continue to develop and form modern submarine channels. The seismic events are continuous and distinct with relatively high amplitudes, suggesting a stable sedimentary environment (Fig. 4).

4.2. Active faults in the DCS domain

4.2.1. Fault geometry

The seismic data showed that there were two types of faults on the northern slope of the Baiyun Sag: (1) the main faults are reverse normal faults (dip opposite to the slope), and the others are (2) small forward faults (dip consistent with the slope).

Three fault zones have been active since the Middle Miocene (Figs. 6 and 7). Fault Zone A is the boundary between the Baiyun Sag and the Dongsha Event Domain. It is composed of five main faults and a series of branch faults. The main faults trend NW (F1, F2, and F4) or NEE (F3 and F5) with dips opposite the slopes (Table 2). Some of these faults are “S” (F1) or reverse “S” (F2 and F5) shapes. Feather-like branch faults are distributed en echelon on the tails of the main faults. Fault zone B and C are composed of a series of relatively small faults. The five main faults in Fault Zone A are deep-rooted with large throws, which can extend to the basement (Fig. 8). The dip angles of F1 and F2 are nearly 90°. The dip angles of F3, F4, and F5 decrease with depth. The hanging wall strata are thicker than in the footwalls, indicating that these faults are synsedimentary. The main faults resulted in a break in the strata close to the seafloor, but most of the branch faults were limited to strata older than 5.5 Ma (Fig. 8). The branch faults create flower-like patterns in the tails of faults F3 and F5 and have throws close to zero (Fig. 8d and h).

Fig. 5. (a) A distribution map of the different stages of the DCS. See the position in Fig. 1a. (b) The 3D seismic profile across DCS. The distribution of DCS I was concentrated in the middle slope in the Baiyun Sag, DCS II was slightly expanded basin-ward, DCS III had the broadest distribution, nearly covering the entire slope in the Baiyun Sag, and DCS IV narrowed into south-west. See the position in (a).
4.2.2. Fault parameters

The paleo-fall \( P \) is the difference in the thickness of the strata on both sides of the fault. The paleo-fall rate \( P_r \) is defined as the paleo-fall per unit of time. \( P \) and \( P_r \) describe synsedimentary fault activities well without the defects caused by a strata hiatus.

The paleo-fall and its rate can be computed from the seismic profiles after time–depth conversion (see the computing formula in Fig. 9). For any of the five main faults, we set the middle of the fault as the computing position to present the mean value, and the results are shown in Table 2. Different periods have different features. During the 13.8–12.5 Ma and 12.5–10.5 Ma periods, \( P \) values

<table>
<thead>
<tr>
<th>Table 1</th>
<th>The analysis of the stage division of the DCS.</th>
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<tr>
<td>DCS stages</td>
<td>Periods (Ma)</td>
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<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>DCS I</td>
<td>13.8–12.5</td>
</tr>
<tr>
<td>DCS II</td>
<td>12.5–10.5</td>
</tr>
<tr>
<td>DCS III</td>
<td>10.5–5.5</td>
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<tr>
<td>DCS IV</td>
<td>5.5–0</td>
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Fig. 6. The coherence slice map of the channels in the northern slope in Baiyun Sag. (a) The coherence slice along the horizon at 13.8 Ma. (b) The coherence slice along the horizon at 12.5 Ma. (c) The coherence slice along the horizon at 10.5 Ma. (d) The coherence slice along the horizon at 5.5 Ma. A series of buried channels were distributed in the Baiyun Sag perpendicular to the slope. The channels of DCS I are small and distantly spaced. More channels develop during DCS II. The channels of DCS III are mostly developed and showed the largest sizes. The DCS IV domain narrows into the southwest. In addition, three fault zones (Zone A, B and C) are distributed on the northeastern slope in the Baiyun Sag. See the position in Fig. 1b.

Fig. 7. A distribution map of the active faults since 10.5 Ma in the northern slope in Baiyun Sag. Fault Zone A is composed of five main faults, namely F1, F2, F2, F3, F4 and F5 and their branch faults. In the western tails of the main faults, the branch faults are distributed in echelon and present feather-like styles. The black dotted lines outline modern submarine channels (C12–C20) according to the modern seafloor morphology and the blue dotted lines outline buried channels developed during DCS II and according to the coherence slice. Compared to the buried channel domain, the modern channel domain narrows into the southwest. See the position in Fig. 5.

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of the five faults were low, ranging from two to nineteen meters. However, during the 10.5–5.5 Ma and 5.5–0 Ma period, the $P$ values of the five faults are highest at 100–240 m. Meanwhile, $Pr$ values show a similar trend (Fig. 10).

4.3. Space–time relationship between active faults and channels

These active faults are mainly located on the northeast of the channel domain and are nearly perpendicular to the strikes of the buried channels, which are distributed on the southern side of fault zone A (Figs. 6 and 7). During 10.5–5.5 Ma, channels were developing well on the southern side of fault zone A. However, after 5.5 Ma, the channel domain narrowed in the southwest resulting in a lack of channel generation on the southern side of fault zone A. Some faults, such as F2, have a large cliff on the modern seafloor (Fig. 11). The seismic section (Figs. 4b and 11) across the faults shows widespread MTDs and small channel deposits from 10.5 Ma to 5.5 Ma. However, after 5.5 Ma, stable abyssal deposits buried and covered the sedimentation event.

5. Discussion

5.1. Sediment input and tectonic subsidence increased the slope

Basin subsidence controls the sedimentary accumulation area, and together with sediment input, affects the basin fill succession (Catuneanu, 2006). The differential settlement of the basin and the rate of sediment input control the change of the basin-edge slope gradient. Dong (2008, 2009) confirmed that the deep-water sag in the PRMB entered a relatively stable settlement stage after 23.8 Ma, with accelerated subsidence from 5.5 to 2.6 Ma. Other papers have suggested one rapid subsidence at ca. 17.5 Ma (Shi et al., 2005; Zhou et al., 2009).

During the DCS development, sediment input to the Baiyun Sag showed a rapid stage from 13.8 to 12.5 Ma, a medium sediment input stage from 12.5 to 10.5 Ma, and a slow stage from 10.5 to 0 Ma (Zhou et al., 2009) (Fig. 12). Since 13.8 Ma, sediment input into the Baiyun Sag has decreased, and subsidence has been relatively stable except for one acceleration at 5.5 Ma. Deposition on the slope tends to infill the negative relief and balance the slope gradient. When sediment input decreased, this balancing effect was weakened and the slope increased. The slope has been unstable from 13.8 Ma to the present, promoting the development of deep-water channels. Hence, the DCS domain expanded gradually from DCS I to DSC III.

5.2. The Dongsha event increased the gravity flow domain

The channel region represents the developing turbidity current domain. Deep-water channels on the slope in the Baiyun Sag are dominantly straight and sub-parallel, evenly spaced, and perpendicular to the slope contours. These characteristics reflect the line-source sediment supply. Since the Middle Miocene, the paleo-PRD has been the main sediment source for the deep-water area in the PRMB (Wang et al., 2012; Wu et al., 2012). After 10.5 Ma, the Dongsha Event triggered a series of uplifts, which may have been new erosion areas during the relative sea level low-stand. On the modern seafloor, channels C19 and C20 are close to the Dongsha Event domain, and their orientation is NE–SW, unlike the other channels (Fig. 1b). This illustrates that the Dongsha Uplift affects or changes the strike of the shelf break. Furthermore, the strong uplift increases the fall height between the uplifting zone and the northeastern Baiyun Sag and raises the slope gradient. Above all, the basement uplift that resulted from the Dongsha Event further increased the instability of the slope. Turbidity currents tend to develop in the instable slope under some trigger mechanism such as an earthquake or storm (Galloway and Hobday, 1996). Therefore, the turbidity current domain expanded to the northeastern Baiyun Sag. During the Dongsha Event, compared to the western region, only a small amount of sediment may have been supplied to the eastern Baiyun Sag because it is relatively far from the main material source, the paleo-PRD. Thus, the channels were smaller than that in the western region (Figs. 7 and 12). Due to the passing sediment, slope deposits in the eastern Baiyun Sag were thin. The Dongsha Event expanded the turbidity current domain eastward and increased the channel domain.

5.3. Active fault effects on DCS

5.3.1. Fault activity analysis

The fault growth index ($Q$) is generally applied to evaluate the intensity of synsedimentary fault activities during a certain period, but is inapplicable when strata are absent in the footwalls. $P$ and $Pr$ can describe synsedimentary fault activities well without the defects caused by a strata hiatus.

The synsedimentary fault activities since 13.8 Ma were analyzed using $P$ and $Pr$. All five main faults have similar activation histories: (1) a stable stage from 13.8 to 10.5 Ma, (2) an activated stage from 10.5 to 5.5 Ma and (3) a peak activation period after 5.5 Ma (Fig. 10 and Table 2). For example, F1 had weak activity from 13.8 to 10.5 Ma and its paleo-fall rate during this period was no more than 7 m/Ma. From 10.5 to 5.5 Ma, F1 entered into an active stage, with a paleo-fall of 23.3 m/Ma. After 5.5 Ma, the activity of F1 peaked with an average paleo-fall rate of 33.8 m/Ma.

The activation periods of these synsedimentary faults coincided with the Dongsha Uplift, which is generally thought to have been active from 10.5 to 5.5 Ma and most strongly active at ca. 5.5 Ma (Huang et al., 2001; Wu et al., 2014). Most of the branch faults stop activity at ca. 5.5 Ma. The peak activity of the main faults was slightly later than that of Dongsha Event, implying the activities of the main faults were hysteric to the Dongsha Movement to some extent.

5.3.2. Active fault effects on sedimentation

5.3.2.1. Deposition differentiation. Strong fault activity resulted in large cliffs, which caused deposition differentiation when the sediments were transported across them. Compared with coarse-grained sediments, it was easier for fine-grained sediments to cross the cliff. As shown in Fig. 13, the lower root-mean-square (RMS) amplitude to the south of the F1 and F2 fault zone suggests a fine-grained sediment zone. The RMS amplitude is high to the northeast of the fault zone, implying a coarse-grained sediment

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Table 2

Geometry elements and fault activities of the main synsedimentary faults in the northern east slope of the Baiyun Sag, P: Paleo-fall; Pr: Paleo-fall rate. $P$ and Pr are both faults based on the average value of the fault activities.

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<td>NE</td>
<td>NEE</td>
<td>NEE</td>
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<td>Fault strike</td>
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<td>NW</td>
<td>NEE</td>
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<tr>
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<td>31.8</td>
<td>29.3</td>
<td>43.6</td>
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Fig. 8. The 3D seismic profiles across the synsedimentary faults in the northeastern slope in Baiyun Sag. F2 broke the seafloor and formed a steep cliff. The main fault and branch faults combined to create a series of section styles including ladder-like, “Y”-like, reverse “Y”-like, flower-like and broom-like styles. (a)–(h) Profiles of A–A', B–B', C–C', D–D', E–E', F–F', G–G' and H–H', respectively. See the positions in Fig. 7.
zone. On the western tail of F3, the paleo-fall was small and had little effect on deposition differentiation, thus, the RMS amplitude had no obvious differences at this location (Fig. 13). The branch faults made differentiation complicated and contributed to the local RMS low amplitude area to the north of the main faults.

5.3.2. Deposition accumulation area. There was a prior sediment-accumulating zone (local sedimentary center) to the north of the fault zone, where the sedimentary thickness, since 10.5 Ma, was relatively thicker than the southern side (Fig. 14a). Zone X (Fig. 14a), located west of the deposition thinning area (Fig. 14a), had thicker deposits because it was far from the fault belt and the sediment accumulation area was seldom affected by the synsedimentary faults. After 5.5 Ma, the local sedimentary center was still located north of the fault belt because the synsedimentary faults entered a peak active stage (Fig. 14b). Since 5.5 Ma, fault activity has contributed to the expansion of erosion in the footwalls. Zone Y (Fig. 14b), located between the erosion area and the deposition thinning area, had relatively thicker deposits because the western tail of F3 had a small paleo-fall.

The synsedimentary faults changed the deposition accumulation area by adjusting the fault-fall. When the sediment supply was stable, an accumulation differentiation occurred in the two walls of the synsedimentary faults. The falling hanging walls provided larger deposition accumulation areas.

5.3.3. Active faults limited the boundary of the DCS

After 5.5 Ma, the activities of the small forward faults ceased, but the five synsedimentary faults maintained peak activities, resulting in large cliffs. When the massive amount of transporting sediment across the faults was blocked, the turbidity current weakened and even ceased in some cases (Fig. 11). Under this fault affect, the development of channels northeast of Baiyun Sag was abandoned. Compared to the area of DCS III, the DCS IV domain narrows to the southwest (Figs. 5–7) and shows that active faults limit the boundary of the DCS.

5.4. Interpretation model of the study area

Tectonic activities affected the DCS development. From 13.8 to 10.5 Ma, decreasing sediment input and stable tectonic subsidence increased the slope and the DCS domain expanded gradually (Fig. 15a and b). From 10.5 to 5.5 Ma, the Dongsha Event increased the gravity flow domain in northeastern Baiyun Sag and generated a series of small channels. Furthermore, fault activity produced fragile zones and promoted the development of the DCS. Thus, DCS III had the broadest distribution (Fig. 15c). After 5.5 Ma, a strong main fault activity produced large cliffs, which limited the generation of turbidity currents in northeastern Baiyun Sag; thus, DCS IV narrowed to the southwest (Fig. 15d).

6. Conclusions

(1) Approximately 20 modern submarine channels and a series of buried channels are located in the Baiyun Sag, Pearl River Mouth Basin. The channel depositions are composed of axis bottom-lag deposits, MTDs, lateral accretion packages, and abyssal depositions.

(2) The DCS is divided into four evolutionary stages: DCS I (13.8–12.5 Ma), DCS II (12.5–10.5 Ma), DCS III (10.5–5.5 Ma), and DCS IV (5.5–0 Ma). In the first three stages, the channel domain gradually expanded, and DCS III had the broadest domain. However, the area of DCS IV rapidly narrowed to the southwest. In the modern seafloor, there is no channel development in the northeastern Baiyun Sag.

(3) A series of active faults are distributed in the channel domain. Synsedimentary faults (F1–F5) form a boundary between the Baiyun Sag and the Dongsha Event domain and had two active stages: (i) from 10.5 to 5.5 Ma, deriving from a series of branch faults, and (ii) after 5.5 Ma, with peak activity generating huge cliffs.

(4) Tectonic activities affected channel development are as follows:

(1) An increasing slope promoted the development of the DCS. During channel development, the subsidence rate of the Baiyun Sag was relatively stable, except for an abrupt increase
Fig. 11. The 3D seismic profiles across the northeastern slope in Baiyun Sag. (a) The seismic profile across the synsedimentary faults (F1 and F2). (b) The local enlargement of the profile in (a). The large cliff restrained the sediment transport. The new deposition overlapped regressively on the older strata in the foot side. The small channels were buried by the MTDs. Abyssal depositions replaced the turbidity current after 5.5 Ma. See the position in Fig. 7.

Fig. 12. The rates of sedimentation for the Baiyun Sag. (a) Max Rates of sedimentation; (b) Ave. Rates of sedimentation. The data of the sedimentation rates from Zhou et al. (2009). The rates of sedimentation approximately reflected the sediment input into the Baiyun Sag. Three different stages are shown: (1) rapid deposition (13.8–12 Ma), (2) medium deposition (12.5–10.5 Ma), and (3) slow deposition (10.5–0 Ma).

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from 5.5 to 2.6 Ma. Meanwhile, the sediment input decreased. This resulted in a slope increase that promoted the development of the DCS.

(2) The Dongsha Event increased the gravity flow domain and promoted the development of the DCS. Basement uplifts, triggered by the Dongsha Event, led to strata erosion and regressive overlap. Because it is far from the pale-PRD, sediment unloading in the northeastern Baiyun Sag was relatively lacking. Therefore, the buried channels of DCS III in this location were small.

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(3) Active faults affected the development of the DCS. The fault activity generated cliffs, which constrained sediment transport and resulted in deposition differentiation. The active faults changed the sedimentation accumulation area by adjusting the fault-fall. From 10.5 to 5.5 Ma, the fault cliffs were small and had little effect on the turbidity currents. After 5.5 Ma, peak fault activity produced large cliffs, which limited the sediment input to the northeastern Baiyun Sag, and abyssal deposits replaced channel deposits. As a result, the DCS IV narrowed to the southwest.

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