The Baiyun Slide Complex, South China Sea: A modern example of slope instability controlling submarine-channel incision on continental slopes

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Abstract

The Baiyun Slide Complex is one of the largest known submarine landslides on the northern margin of the South China Sea. Newly acquired high-resolution bathymetric data, 2D and 3D seismic data permitted the systematic investigation of the Baiyun Slide Complex in terms of its seafloor morphology and associated sedimentary processes. The headwall region of the Baiyun Slide Complex, located at a water depth between 1000 m and 1700 m, is U-shaped and opens towards the east. It was efficiently and almost completely evacuated, generating pronounced headwall and sidewall scarps. Submarine channels, sediment waves, migrating channels, sediment drifts and moats can be observed within and around the headwall region, illustrating the effects of both downslope and along-slope sedimentary processes. Submarine channels are 16-37 km-long 800-1500 m-wide, and 20 to 50 m-deep. As a modern example of the interplay between slope instability and subsequent incision, submarine channels were generated after the formation of the Baiyun Slide scar to suggest intensified downslope sedimentary processes after the slope collapsed. The initiation and formation of these submarine channels are suggested to result from the evacuation of the Baiyun Slide scar, which provided accommodation space for subsequent turbidity currents and mass wasting. Our results are an important example of how submarine landslides can influence erosional and depositional processes on continental margins.

Keywords: South China Sea; Submarine landslide; submarine channels; bottom currents; turbidity currents.

1. Introduction

Submarine landslides, turbidity currents and bottom currents are dominant sedimentary processes occurring along both passive and active continental margins (Vorren et al., 1998; Rebesco et al., 2014; Mosher et al., 2017). Downslope processes such as landslides and turbidity currents are driven by gravity and lead to the deposition of broad mass-transport deposits or turbidite systems within erosive channels (Moscardelli et al., 2006; Casalbore et al 2010; Bourget et al., 2011; Li et al., 2015b). They can transport large volumes (>100 km^3) of sediment sourced from the continental shelf and upper slope areas into the deep ocean (Georgiopoulou et al., 2010; Li et al., 2018), re-shaping the sea floor to influence subsequent sedimentary processes (Casalbore et al 2018). They can also control the distribution of sand in deep-water environments (Haflidason et al., 2004; Mosher et al., 2017). Along-slope bottom currents result in extensive depositional (e.g. sediment drifts) and erosional (e.g. contourite channels) features on outer continental shelves and upper continental slopes (Hernández-Molina et al., 2006; García et al., 2009; Rebesco et al., 2013). A close interplay between downslope turbidity currents and alongslope contour currents is therefore expected when both processes occur on continental margins (Rebesco et al., 2002; Caburlotto et al., 2006; Brackenridge et al., 2013; Martorelli et al 2016).

The continental margin offshore the Pearl River Mouth Basin (PRMB) is incised by deep-water submarine canyons and channels (Zhu et al., 2010). The most striking feature in the PRMB is the Baiyun Slide Complex, which has a large spatial coverage (~10,000 km^2) and is composed of several intersecting slide scars and overlapping deposits (Li et al., 2014; Sun et al., 2018b) (Fig. 1). The total volume of sediment removed by the Baiyun Slide Complex is ~1035 km^3 and comprises four major mass-transport deposits (MTDs) separated by basal erosional surfaces (Sun et al., 2018b). These MTDs retrograded upslope to reveal a decreasing time interval between events (Wang et al., 2017; Sun et al., 2018b). Two main instability events occurred in the headwall region of the Baiyun Slide Complex during the Quaternary (Li et al., 2014; Wang et al., 2017; Sun et al., 2018b), at ~0.79 Ma and ~0.54 Ma (Sun et al., 2018b). The older MTD (1570 km^2) covers most of the headwall region, while the younger MTD is mainly limited to the northern area of the headwall region to reveal a relatively smaller area of ~ 840 km^2 (Wang et al., 2017).

The study area is chiefly located in the headwall region of the Baiyun Slide Complex, at a water depth of 900 m to 1800 m (Figs. 2a and b). This region is affected by alongslope bottom currents associated with a clockwise flow of intermediate water at a depth of 350 m to 1350 m, and an anticlockwise flow of deep water at depths beyond 1350 m (Gong et al., 2013; Chen et al., 2014) (Fig. 1). Thus, it provides a key opportunity to characterise how bottom currents, turbidity currents and submarine landslides influence the morphological and sedimentary evolution of the northern South China Sea margin.

High-resolution bathymetric, 2D/3D seismic and borehole data are used to provide a detailed analysis of erosional and depositional features in and around the headwall region of Baiyun Slide Complex. The specific aims of this research are to:

a) investigate the seafloor morphology in and around the headwall region of the Baiyun Slide;

b) describe the internal seismic characters of the Baiyun Slide, and determine what are the main sedimentary processes in this area;

c) discuss the role of the Baiyun Slide Complex on the incision and development of submarine channels.

2. Geological and oceanographic background

2.1 Geological setting

The South China Sea is one of the largest (and deepest) marginal seas in the western Pacific Ocean (Fig. 1). The formation of the South China Sea as observed at present involved the formation of a proto-South China Sea, likely floored by oceanic crust, that was subducted during the Mesozoic (Pubellier et al., 2003). The earliest phase of rifting in South China Sea started in the latest Cretaceous to Early Paleocene and, after ~30 Ma of rifting, continental breakup occurred first in its Eastern Sub-basin in the Early Oligocene before ~32 Ma (Barckhausen et al., 2013; Briais et al., 1993). Continued continental rifting led to breakup of the Southwest Sub-basin in the Late Oligocene at ~25 Ma. In parallel to continental breakup, seafloor spreading in the South China Sea started during the Early Oligocene before terminating in the Late Oligocene (Li et al., 2015a). Seafloor spreading in the South China Sea thus spans from 33 Ma to 15 Ma in the Northeast Sub-basin, and from 23.6 Ma to 16 Ma in the Southwest Sub-basin, respectively, based on the new results at IODP Site U1435 (Li et al., 2015a).

The northern South China Sea margin has been influenced by seasonal alternations of the East Asian summer monsoon and the East Asian winter monsoon sub-regimes since, at least, the Late Miocene (Steinke et al., 2010). The rate and composition of terrigenous sediment supplied to continental shelves, continental slopes and deep-sea basins has been largely influenced by changing monsoon conditions (Steinke et al., 2003; Steinke et al., 2006). Intensified winter monsoon winds can increase wave heights in coastal zones, further amplifying sediment reworking processes. In such a setting, fine-grained fluvial sediment can be suspended in the water column to bypass the outer shelf and settle on the continental slope (Steinke et al., 2003; Steinke et al., 2010).

The PRMB lies in the central part of the northern South China Sea and it is one of the most important hydrocarbon-rich basins in the region (Fig. 1). The geological evolution of the PRMB comprised three main stages: (1) a first rifting stage in the Late Cretaceous-Early Oligocene, essentially marked by continental rifting; (2) a transitional stage (Late Oligocene-Early Miocene) recording syn-rift faulting, subsidence and deposition within distinct sub-basins; (3) a post-rift stage from the Middle Miocene to Holocene dominated by post-rift subsidence and filling of syn-rift basins (Gong et al., 1989). In the PRMB, regional tectonic uplift, faulting, erosion and magmatism are recorded in association with major tectonic events (Wu et al., 2014; Zhao et al., 2016). The most prominent tectonic event in the study area, the Dongsha Event, started in the Late Miocene (T2:

10.5 Ma; Fig. 3) and ceased around the Miocene/Pliocene boundary, at around 5.5 Ma (T1; Fig. 3; Wu et al., 2014). As a result, a deep-water depositional setting was gradually developed after the Early Miocene, originating multiple submarine canyons, submarine channels on the continental slope and associated deep-water sediment fans (Fig. 3; Xie et al., 2006).

2.2 Oceanographic setting

Water masses in the South China Sea include a seasonally-influenced surface water and permanent intermediate- and deep-water masses (Tian et al., 2006; Chen et al., 2014) (Fig. 1). Surface water is controlled by the East Asia monsoon system and occurs at a water depth less than 350 m (Lüdmann et al., 2005; Contreras-Rosales et al., 2019). Surface water is clockwise during the summer and counterclockwise during the winter (Zhu et al., 2010). Intermediate water (350 m-1350 m) follows a permanent clockwise movement and corresponds to the western boundary current in the South China Sea (Tian et al., 2006). It was established in the Late Miocene, resulting in: 1) the development of unidirectionally migrating deep-water channels in the Pearl River Mouth Basin (Zhu et al., 2010; Gong et al., 2013), 2) the subsequent formation of depositional and erosional patterns around the South Shenhu Seamount (Chen et al., 2014) (Fig. 1). Deep water originates from the incursion of the southward flowing North Pacific Deep Water into the South China Sea via the Luzon Strait (Lüdmann et al., 2005). Widespread and thick sediment drifts occur to the southeast of the Dongsha Islands in association with deep-water currents, in places recording a maximum velocity of ~30 cm/s (Zhao et al., 2014).

3. Data and methods

High-resolution multibeam bathymetric data, 2D seismic profiles and 3D seismic volumes are used in this work. The bathymetric data was acquired at water depths ranging from 230 m to 2600 m using differential GPS positioning. It was processed using the software CARIS HIPS®. Its horizontal and vertical resolutions are ~100 m and ~1-3.3 m, respectively, enabling the identification and analysis of seafloor features generated by downslope and alongslope currents.

The interpreted seismic dataset was acquired and processed by China National Offshore Oil Corporation (CNOOC) and covers the headwall region of the Baiyun Slide Complex. It consists of one long (~100 km) 2D seismic profile crossing submarine canyons and channels on the continental slope, and ~4000 km^2 of 3D seismic data. The dominant frequency of the 2D seismic data is ~30 Hz, and its vertical resolution ranges from 15 to 20 m. The 3D seismic data has a dominant frequency of 40-60 Hz in the interval of interest, providing a vertical resolution of about 10-15 m. This relatively high resolution of the seismic data enabled the detailed investigation of sedimentary features in the headwall region of Baiyun Slide Complex (Fig. 4a).

Exploration Well L-13 was drilled in the central part of the study area and provided age constrains for the interpreted seismic horizons (Fig. 2a). Main seismic reflections were identified and traced using Schlumberger's Geoframe® 4.5 so that a regional seismic-stratigraphic framework could be built for the study area. Three important seismic horizons (T0, T1 and T2) were recognised and dated as 1.9 Ma, 5.5 Ma and 10.5 Ma in age (Fig. 4a).

4. Seismic stratigraphy

The seismic stratigraphy of the study area was interpreted and tied to borehole data from Exploration Well L-13. Three main seismic units, named as Units A, B and C from top to bottom, were identified based on the differences in their internal reflection configurations (Figs. 4a and b).

Unit A is bounded by T0 at its base and its top coincides with the sea floor (Fig. 4a). Unit A is suggested to be Quaternary in age. On the upper continental slope, moderate- to high-amplitude reflections predominate (Fig. 4a). Downslope, widespread chaotic seismic reflections suggest the presence of MTDs (Fig. 4d). The most prominent feature in Unit A is the slide scar from the Baiyun Slide Complex, herein named Baiyun Slide scar, and MTDs resulting this latter instability feature (Fig. 4b).

Unit B is Pliocene in age and bounded by seismic horizons T1 and T0 (Figs. 4a and b). Seismic facies in Unit B change in different parts of the study area (Fig. 4a). In the upper slope region, several submarine canyons can be identified (Figs. 4a and c). In the middle sector of the slope, Unit B shows continuous and moderate-amplitude reflections (Fig. 4a). Strata downslope from this latter region shows chaotic seismic reflections bounded by irregular top and bottom surfaces (Figs. 4a and d), likely comprising MTDs. Unit B shows variable thickness in the E-W seismic profile in Fig. 4a.

Unit C is bounded by seismic horizon T2 at its bottom and T1 at its top. Unit C is Late Miocene in age and shows low- to moderate-amplitude reflections (Figs. 4a and b). A main valley and several buried submarine canyons are observed in the middle part of Unit C (Fig. 4a). The thickness of Unit C is variable on the E-W seismic profile in Fig. 4a, but shows a constant thickness on the SW-NE oriented seismic profile in Fig. 4b. Several large-scale faults can be observed cutting through Unit C.

5. Seafloor morphology

Seafloor morphology is uneven in the study area (Figs. 2a and 5a). Different kinds of morphological features can be identified, with the most prominent feature being the Baiyun Slide scar (Fig. 2a).

5.1 Baiyun Slide scar

The headwall region of the Baiyun Slide Complex displays a U-shaped slide scar that opens towards the east with a length of ~50 km and an average width of 14 km (Figs. 2a and 5a). This scar is located at a water depth between 1100 m and 1600 m, and covers ~700 km^2 in area (Figs. 2a and b). The northern escarpment of the scar is ~45 km in length and consists of several smaller-scale scars (Fig. 5a). In the south, the escarpment shows a length of ~50 km and appears to be disrupted by several ridges. The headwall scarp has an average height of ~90 m and a slope gradient of up to 19° (Figs. 2a and 4a). The escarpment of the slide scar is much steeper in the north (up to 22°) than in the south (~5°), as shown on the bathymetric profiles crossing the slide scar (Figs. 5b and c). The undeformed seafloor has a gradient of ~1° (Fig. 5a).

5.2 Submarine canyons and channels

Submarine canyons are usually not connected to a modern river, and have nearly vertical and steep walls that extend well onto the continental shelf. Submarine channels are smaller, usually meandering, and comprise a thalweg and confining levees (Shepard, 1936; Shepard, 1981; Amblas et al., 2018). They are much less steep than canyons and are commonly within canyons themselves - it is not uncommon to record channel systems at the bottom of canyons. To the north of the headwall area of the Baiyun Slide Complex occur seventeen (17) submarine canyons, as already documented by Zhu et al. (2010), Gong et al. (2013) and Ma et al. (2015). In this study, only seven of these canyons are fully imaged on the newly–acquired bathymetric data, towards the western part of the complex (Fig. 2a). The orientation of these submarine canyons is NNW-SSE, and is perpendicular to the continental slope. These submarine canyons are sub-linear and sub-parallel in plan view, displaying a regular spacing of 8 to 10 km. They are located at water depths ranging from 500 m to 1500 m (Fig. 2b). As observed on the contour map in Fig. 2b, these submarine canyons are confined on the continental slope and do not erode the shelf edge, which occurs at a water depth of ~200 m. These submarine canyons are about 20-40 km-long, 3-5 km-wide and incise the slope to a depth of 100-300 m. The bathymetric profile crossing the submarine canyons shows that canyon flanks are steep and display V-shaped geometries (Fig. 6a). Compared to the large-scale submarine canyons, several small-scale submarine channels (A1 to A6) can be clearly distinguished on the upper continental slope above the headwall region (Figs. 2a, 6b and 6c; Table 1). These submarine channels are 16-37 km-long, 800-1500 m-wide and 20 to 50 m-deep (. 6b). Some of these channels (A2-A3 and A4-A5) incise the headwall scarp to extend into the upper part of the Baiyun Slide Complex (Figs. 2a and 5a).

6. Morphology and internal character of the Baiyun Slide scar

6.1 Slide scarps and mass-transport deposits (MTDs)

The headwall and sidewall scarps of the Baiyun Slide Complex can be readily identified on the bathymetric map and seismic profiles (Figs. 2a, 4a and 7a). The slide scarps are steep and adjacent intact strata show obvious erosional truncations (Figs. 4b and 7b). Most MTDs are located in Units A and B, especially downslope from the slide headwall where recurrent MTDs are observed (Figs. 4a and c). The uppermost MTD shows a thickness of ~75 m (Figs. 4c and d). Beneath this MTD, several smaller-scale MTDs are vertically stacked and naturally increase the total thickness of mass-wasting deposits on the continental slope (Fig. 4c). Compared to the seismic profiles imaging the lower continental slope, relatively thin MTDs can be identified within the headwall area of the Baiyun Slide Complex (Figs. 7a and c).

6.2 Erosive channels and moats

Six submarine channels are observed on the bathymetric map and on seismic data (Figs. 4b, 6b, 7 and 8). A submarine channel (A2-3 generated by the confluence of channels A2 and A3) is incising the seafloor of the uppermost (westward) part of the Baiyun Slide Complex (Figs. 5a and b). This channel has a width of approximately 2 km and a depth of about 50 m (Figs. 5b and 8a). It cuts the headwall scarp of the Baiyun Slide Complex and extends farther towards the east. Seismic reflections crossing the submarine channel are not continuous, and erosional truncations can be observed on both flanks of the channel (Figs. 8c and d). Another two erosive channels are located in the southern part of its headwall region (Fig. 5a). They both have an E-W orientation, parallel to the southern escarpment of the slide scar.

Elongated depressions can be observed on the bathymetric map and seismic profiles located in the vicinity of the slide scarps (Figs. 8a, b and c). Strata close to these depressions typically exhibit a mounded shape (Fig. 8c). Such features can be interpreted as moats, i.e. localised erosional features with little effect other than forming channeled paths for sediment that is redistributed along the slope (Rebesco et al., 2007; García et al., 2009). Mounded strata comprise sediment drifts (Figs. 7b and 8c), as their most distinctive feature is the termination of internal reflections towards the moat (Rebesco et al., 2016).

6.3 Sediment waves

Sediment waves are observed at different locations within and around the Baiyun Slide Complex, such as those within the slide scar (Fig. 7c) and south of the slide scar (Figs. 9a, b and 10b). Internal seismic reflections within the sediment waves are continuous, showing moderate to low amplitude (Figs. 10a and b). Continuous internal reflections can be traced across adjacent waves. Sediment waves show a variety of dimensions, wavelengths ranging from 2 km to 4 km, and wave heights between 30 m and 70 m. The crests of sediment waves within the slide scar typically show upslope migration trends (Fig. 10a). Also, these sediment waves have asymmetric geometries. The sediment waves in the south of the slide scar are dominated by vertical aggradation, rather than upslope migration (Fig. 10b). Deposition occurs both on their upslope and the downslope flanks. Individual sediment waves are usually symmetric.

6.4 Migrating channels

Buried channels are widely observed and some show typical unidirectional migration (Figs. 7b and 11). Buried migrating channels are located in the southern part of the headwall region. The channels are marked at their base by a basal erosional unconformity, which is marked by a continuous and high-amplitude concave upwards reflection (Fig. 11). The thalweg of a buried channel in the shallower area (water depth <1500 m) is progressively offset towards the north and the unidirectional migration distance of its thalweg reaches 3 km (Fig. 11). In parallel, MTDs are observed within the channel and are likely the main depositional elements of the channel fills (Fig. 11).

7. Discussion

7.1 Importance of combined downslope and alongslope processes on a sediment-fed continental slope

We propose that the headwall region of the Baiyun Slide Complex was affected by both downslope and alongslope sedimentary processes since its inception as: (a) it is located at a water depth influenced by bottom currents associated with intermediate (350 m-1350 m) and deep-water circulation (>1350 m); and (b) it is close to submarine canyons incising the continental slope at the same place where submarine slides and turbidity currents occurred frequently in the past. In this work, several types of depositional and erosional features are identified, demonstrating the influence of turbidity currents, contour currents and sediment mass-wasting on the geomorphology of the headwall of the Baiyun Slide Complex, and around it.

MTDs are mainly identified in Unit A and B, indicating that downslope sedimentary processes have been active since the end of the Late Miocene. The uppermost two MTDs have been interpreted as the slide deposits of the last stages of instability in the Baiyun Slide Complex (Li et al., 2014; Wang et al., 2017; Sun et al., 2018b), and were respectively dated as 0.54 Ma and 0.79 Ma based on seismic-stratigraphy correlations with ODP Site 1146 (Sun et al., 2017). The other MTDs are noticeably smaller and might have been sourced from adjacent submarine canyons. Multiple scars of submarine landslides associated with submarine canyons have been mapped in this region, being bounded by headscarps and basal shear surfaces (He et al., 2014; Chen et al., 2016). These submarine landslides are mostly distributed around the canyon heads and flanks, with some having been able to further disintegrate and evolve into turbidity currents flowing along the submarine canyons (Chen et al., 2016).

Buried sediment waves observed within the slide scar display asymmetric morphologies with gentle upslope flanks and steep downslope flanks (Figs. 6c and 9a). These sediment waves have thicker beds on their upcurrent face and their crests exhibit an upslope migration trend (Fig. 10a). The internal seismic reflections within these sediment waves are continuous and can be traced from one wave to the next. In addition, they are very close to the submarine canyons in the upper continental slope where turbidity currents occur more frequently. Therefore, based on the criteria of Wynn and Stow (2002), these sediment waves can be interpreted to have been formed by turbidity currents flowing through submarine canyons on the upper continental slope. Once the initial sediment wave topography is established, the process leading to wave migration and growth is self-perpetuating (Normark et al., 2002). Sediment waves with similar internal seismic characters have also been documented in the Magdalena turbidite system (Ercilla et al., 2002), on the South Iberian Margin (Perez-Hernandez et al., 2014) and on the South China Sea slope offshore SW Taiwan (Gong et al., 2012; Gong et al., 2015), where the genesis of sediment waves is considered to result from turbidity currents. Additionally, erosive channels on the upper continental slope may also be formed by the erosion of turbidity currents, which were probably initiated by the transformation of slumps or storm-generated flows near the shelf edge (Figs. 2a and 7d).

Two moats and associated sediment drifts have been identified close to the slide scarps in the headwall region of the Baiyun Slide (Figs. 4a and 7c), indicating enhanced activity of bottom currents after the formation of the observed slide scar, as uneven seafloor bathymetry may locally intensify and focus bottom-current activity (García et al., 2009; Vandorpe et al., 2016; Martorelli et al 2016). The moats can also be used to reconstruct the path of the inferred bottom current flow that controlled the development of sediment drifts (Surlyk and Lykke-Andersen, 2007; Rebesco et al., 2016). The two erosive channels in the south of the slide scar are interpreted as contourite channels as they are far away from the influence of turbidity currents (Figs. 2a, 6b, 8a and b). In comparison, the sediment waves observed in the southern part of the slide scar are relatively more symmetric with continuous, parallel to sub-parallel internal reflections, indicative of active vertical aggradation rather than upslope migration (Figs. 8a and b). This internal character is consistent with that observed from bottom-current sediment waves (Gong et al., 2015; Baldwin et al., 2017).

Of particularly interest is the identification on bathymetric data of an erosive channel to the south of the Baiyun Slide scar (Fig. 5a). This channel has no obvious levee and its base migrates progressively northwards (Figs. 7b and 11). It can be interpreted as an unidirectionally migrating channel similar to those documented on the northern South China Sea margin (He et al., 2013; Gong et al., 2013; Gong et al., 2018), on the continental rise of southeast Greenland (Rasmussen et al., 2003) and along the continental margin of Equatorial Guinea (Jobe et al., 2011). The presence of this unidirectionally migrating channel suggests a close interaction between episodic downslope gravity or turbidity flows and persistent alongslope bottom (contour) currents.

7.2 The role of slide scars on the initiation and formation of submarine channels

The bathymetric map covering the headwall of the Baiyun Slide Complex reveals the presence of several submarine channels (Figs. 4a and 5b). These submarine channels with a general NW-SE orientation incise the headwall scarp of the Baiyun Slide Complex and erode the Baiyun Slide scar farther – up to a maximum distance of 10 km from this latter (Figs. 2a, 5a and 6b). The submarine channels are close to submarine canyons and have similar orientations (Fig. 2a).

The bathymetric profile crossing the submarine canyons and channels reveals conspicuous differences in their scales and incision depths (Fig. 6a). Submarine canyons have developed, at least, since the Middle Miocene (Gong et al., 2013; Ma et al., 2015), but the timing of formation of channels has not been constrained in the literature. Truncations can be clearly observed on the seismic profiles crossing the observed submarine channels (Figs. 4b, 7a and 8c), which eroded the draped strata above the MTDs up to a depth of ~60 m (Fig. 5b). These data provide a robust proof that these submarine channels were formed after the Baiyun Slide Complex was initiated (Fig. 4b). Therefore, we propose that submarine channels identified around the Baiyun Slide scar are relatively newly-formed erosional features compared to the longer-lived submarine canyons.

Based on the detailed interpretation of bathymetry and seismic data, we propose a conceptual model to explain the morphological evolution of the study area (Fig. 12). The Baiyun Slide Complex evacuated large volumes of sediment (~1035 km^3) and greatly changed the slope morphology (Figs. 12a and b; Li et al., 2014; Sun et al., 2018a). In addition, the formation of the Baiyun Slide scar was able to enhance local accommodation space for subsequent turbidity currents and mass-wasting deposits (Figs. 12b and c). We therefore suggest that the formation of the Baiyun Slide scar has played a vital role on the initiation and formation of the submarine channels identified on the upper part of the slide scar. Qin et al. (2017) also found that slide scars can capture turbidity flows and facilitate flow channelisation, both key processes for the initiation of submarine channels in the Espírito Santo Basin, SE Brazil. In addition, Abdurrokhim and Ito (2013) have investigated the role of slump scars as initial seabed features responsible for the formation of slope channels in the Bogor Trough, West Java. Initial depressions or seafloor roughness induced by slump scars and by mass-transport deposits may develop an area of sediment-gravity flow convergence able to locally incise the slope to form submarine channels (Alves and Cartwright, 2010; Qin et al., 2017).

The submarine channels in the upslope region of Baiyun Slide scar are V-shaped in cross-section (Figs. 4b, 5a and 6b) and their upper reaches are close to the shelf edge (Figs. 2a and 6a). Several other small-scale slide scarps close to the shelf edge are imaged on high-resolution bathymetric data (Figs. 2a and 6b). They may result either from large, unconfined and erosive turbidity currents or from mass wasting. In such a setting, channels are suggested to be the first features to form on steeply dipping slopes sculpted by mass wasting (e.g. Lonergan et al., 2013; Laberg et al., 2007). Micallef and Mountjoy (2011) have also proposed gravity flows to be responsible for initiating V-shaped channels in the Cook Strait, New Zealand. The importance of interaction between turbidity current processes and seafloor roughness on channel initiation has also been stressed by Gee et al. (2007) and Covault et al. (2014). Hence, the incision of submarine channels in the study area can be considered as an indicator of intensified downslope sedimentary processes (e.g. turbidity currents and mass wasting) after the Baiyun Slide scar was formed. As for the triggering factors increasing downslope sedimentary gravity flows, Wang et al. (2018) proposed that the long-term erosion by contour currents associated with the South China Sea Branch of the Kuroshio Current caused the slope to become unstable and prone to collapse.

8. Conclusions

High-resolution bathymetry and 2D/3D seismic data enabled us to investigate the headwall region of Baiyun Slide Complex on the northern South China Sea in terms of its geomorphology, associated sedimentary processes and its role on the initiation of submarine channels. The main conclusions of this study are as follows:

(1) The headwall region of Baiyun Slide Complex has a U-shaped morphology in plan view at a water depth between 1000 m and 1700 m. Sediment was almost completely evacuated from the complex, leaving pronounced headwall and sidewall scarps.

(2) Sediment waves, moats, erosional channels and migrating channels were identified inside and around the headwall of the Biyun Slide Complex. Downslope and alongslope sedimentary processes have controlled and affected the overall geomorphology inside and around the latter headwall region.

(3) Sediment waves identified in the downslope from submarine canyons were generated by turbidity currents, while those distinguished in the southern part of the Baiyun Slide scar were

generated by bottom currents interacting with the sea floor. The presence of migrating channels reveals a close interaction between downslope and alongslope sedimentary processes.

(4) The submarine channels on the upper part of the Baiyun Slide scar were formed in the Quaternary, after the formation of this latter bathymetric feature. The submarine channels are proposed as indicating the intensification of downslope sedimentary processes (e.g. turbidity currents and mass wasting) over alongslope processes after the Baiyun Slide scar was formed.

This research is an important case study of the role of submarine landslides on regional sedimentary processes. Our results are also of importance to characterise the sedimentary processes operating on continental margins where a close interplay between downslope and alongslope currents occurred in the past.

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Figure Captions

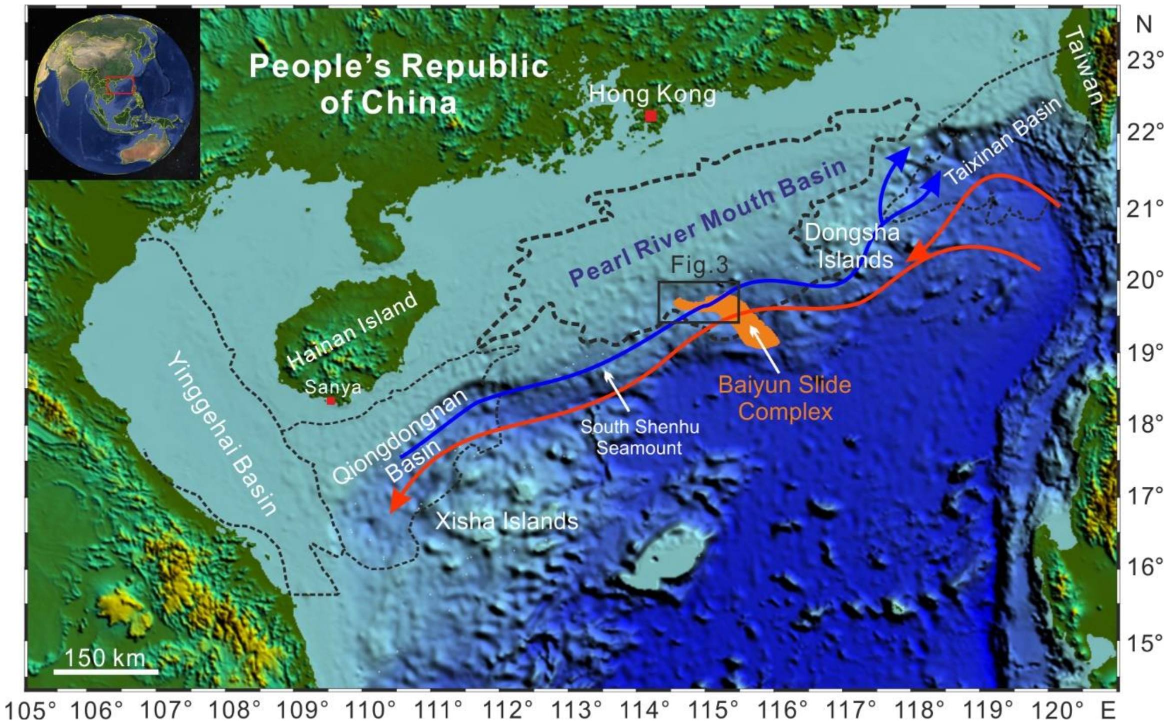

Fig.1 Seafloor physiography of the northern South China Sea margin showing the distribution of the major sedimentary basins and geomorphological features (e.g. Dongsha Islands, Xisha Islands and South Shenhu Seamount). The blue and red curves indicate the paths of intermediate and deep water offshore the northern South China Sea (Tian et al., 2006; Chen et al., 2014). The location of the Baiyun Slide Complex is marked in orange (Li et al., 2014). The black box indicates the location of the study area (see Fig. 2).

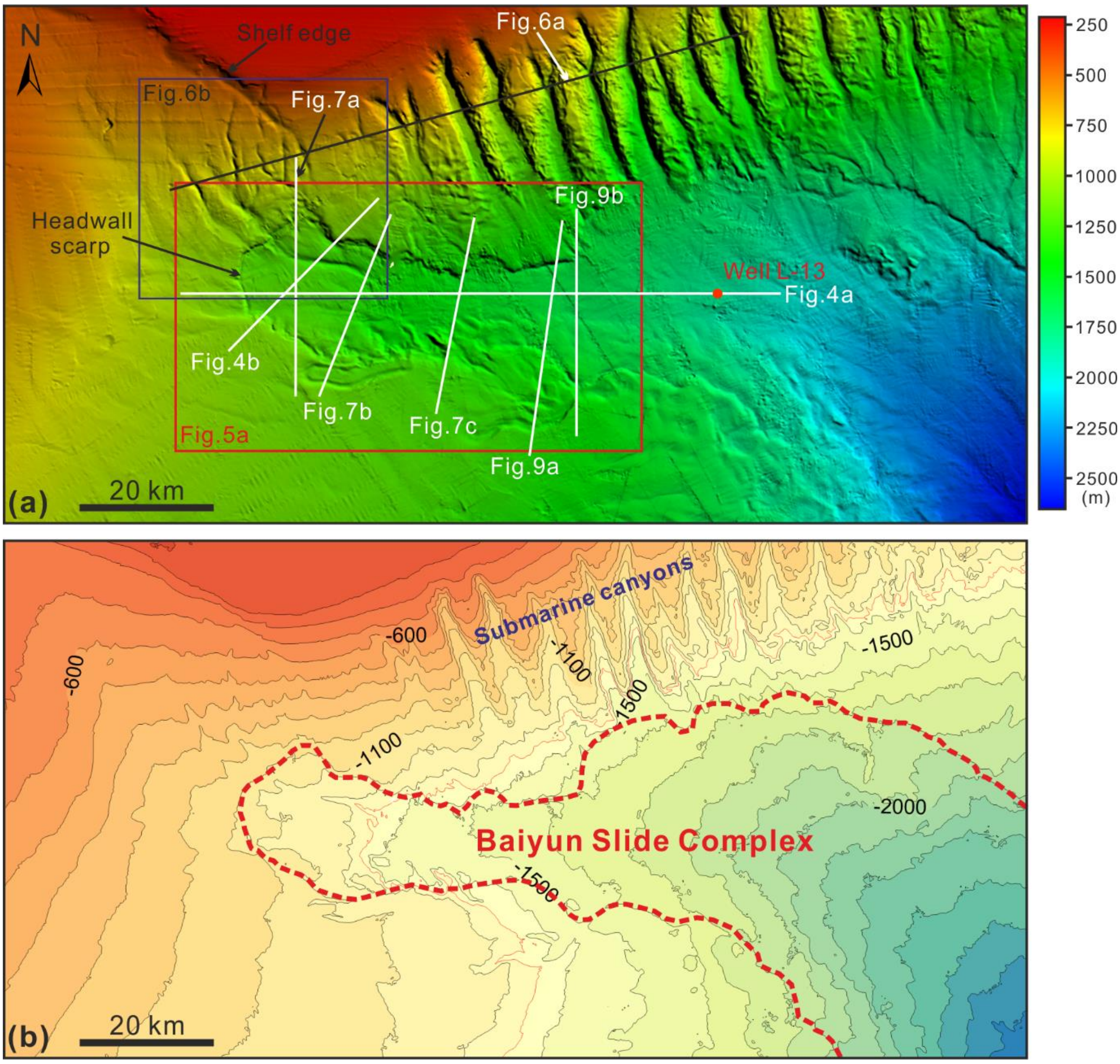

Fig. 2 (a) Multibeam bathymetry map of the study area illustrating the seafloor morphology of the headwall region of Baiyun Slide Complex, and multiple submarine canyons. The white lines reveal the location of seismic lines interpreted in this paper. The red box indicates the location of the headwall region of the Baiyun Slide Complex, which is highlighted in Fig. 5a. The location of Fig. 6b is marked by the purple box. (b) Contour map of the study area. The contour interval is 100 m. The red dashed line indicates the boundary of the Baiyun Slide Complex. Please see the location of Fig. 2 in Fig. 1.

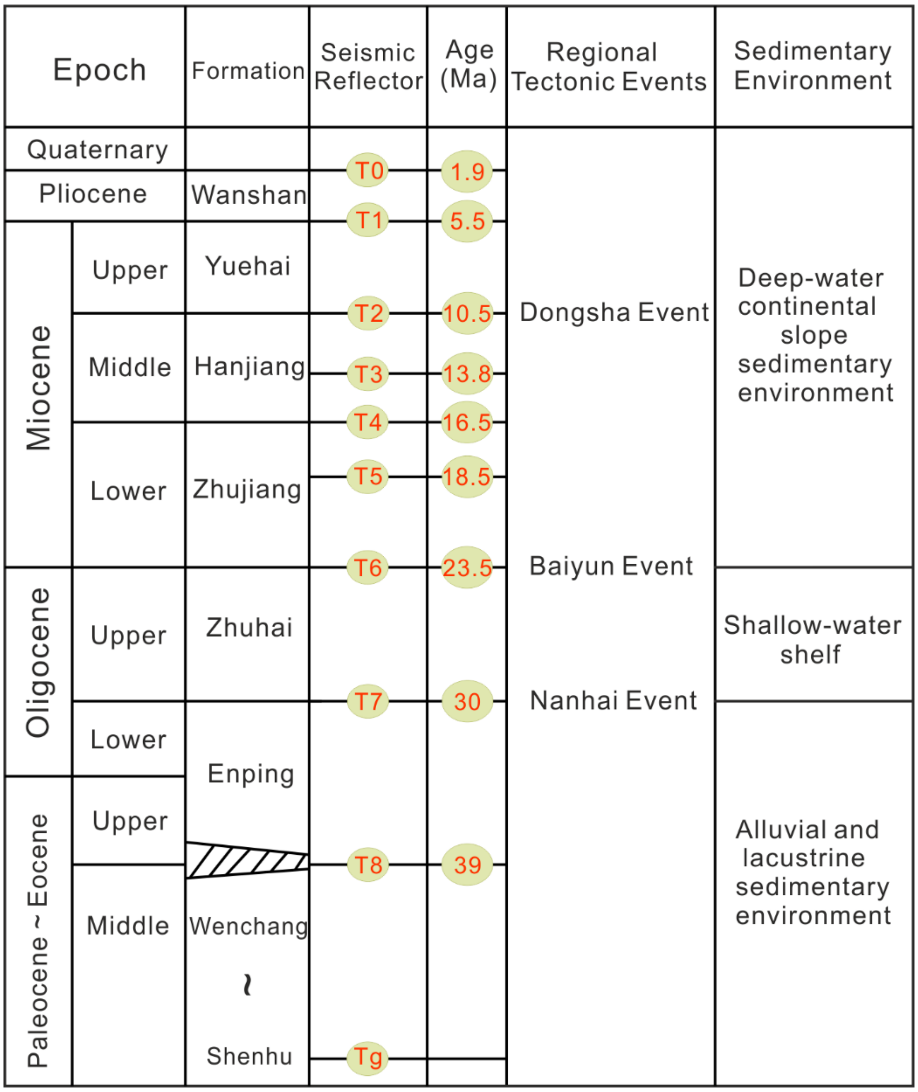

Fig. 3 Schematic stratigraphic columns of the Pearl River Mouth Basin showing the main regional tectonic events and sedimentary environments (modified after Zhao et al., 2015).

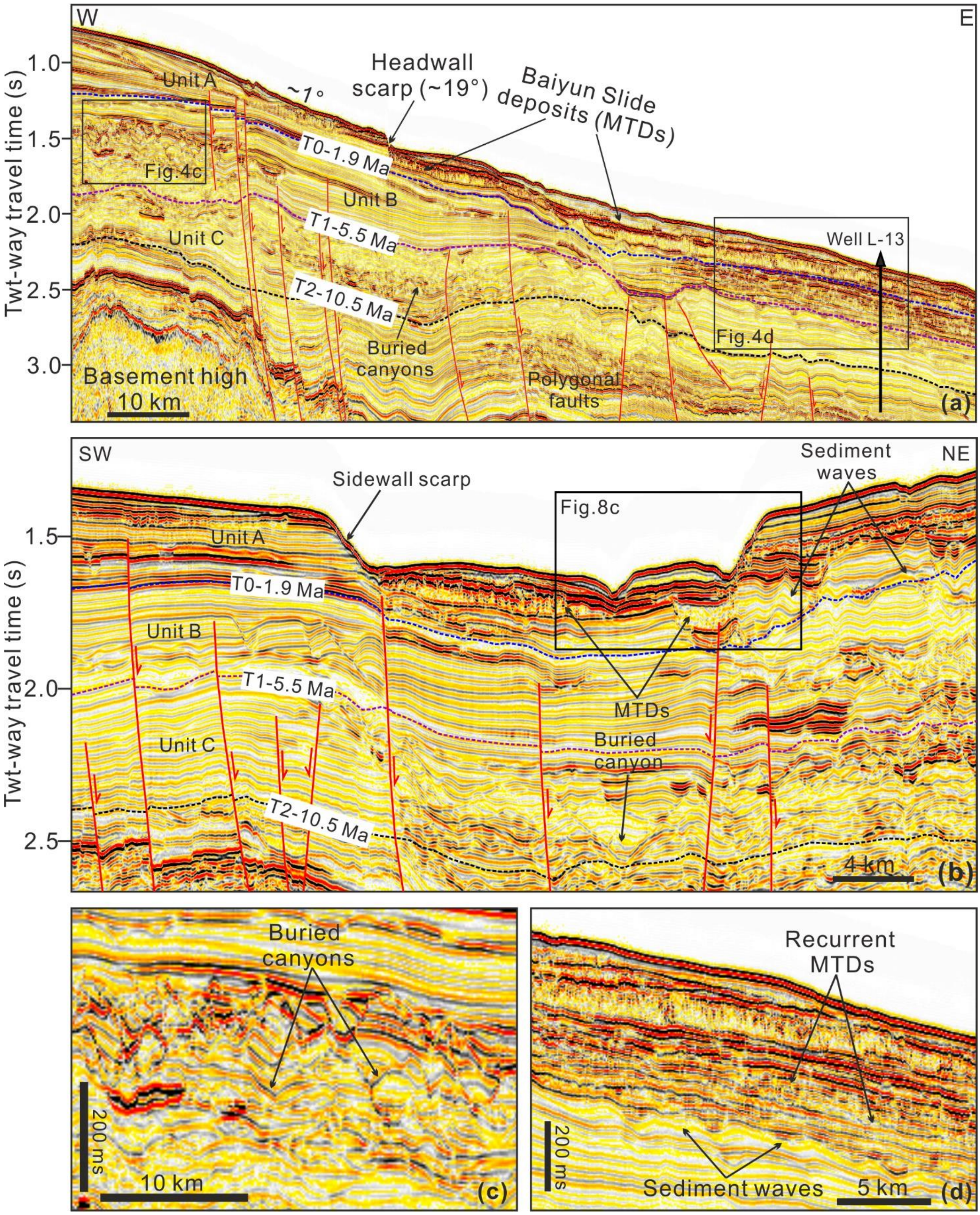

Fig. 4 (a) Three-dimensional seismic profile crossing the headwall region of Baiyun Slide Complex and showing details of the headwall scarp and corresponding mass-transport deposits (MTDs) on the lower continental slope. (b) Zoomed in seismic profile (see location in Fig. 6a) revealing the presence of sediment waves beneath MTDs. (c) Zoomed in seismic profile in the lower continental slope below the headwall region. The profile illustrates the presence of recurrent MTDs. Please see the location of Fig. 4 in Fig. 2.

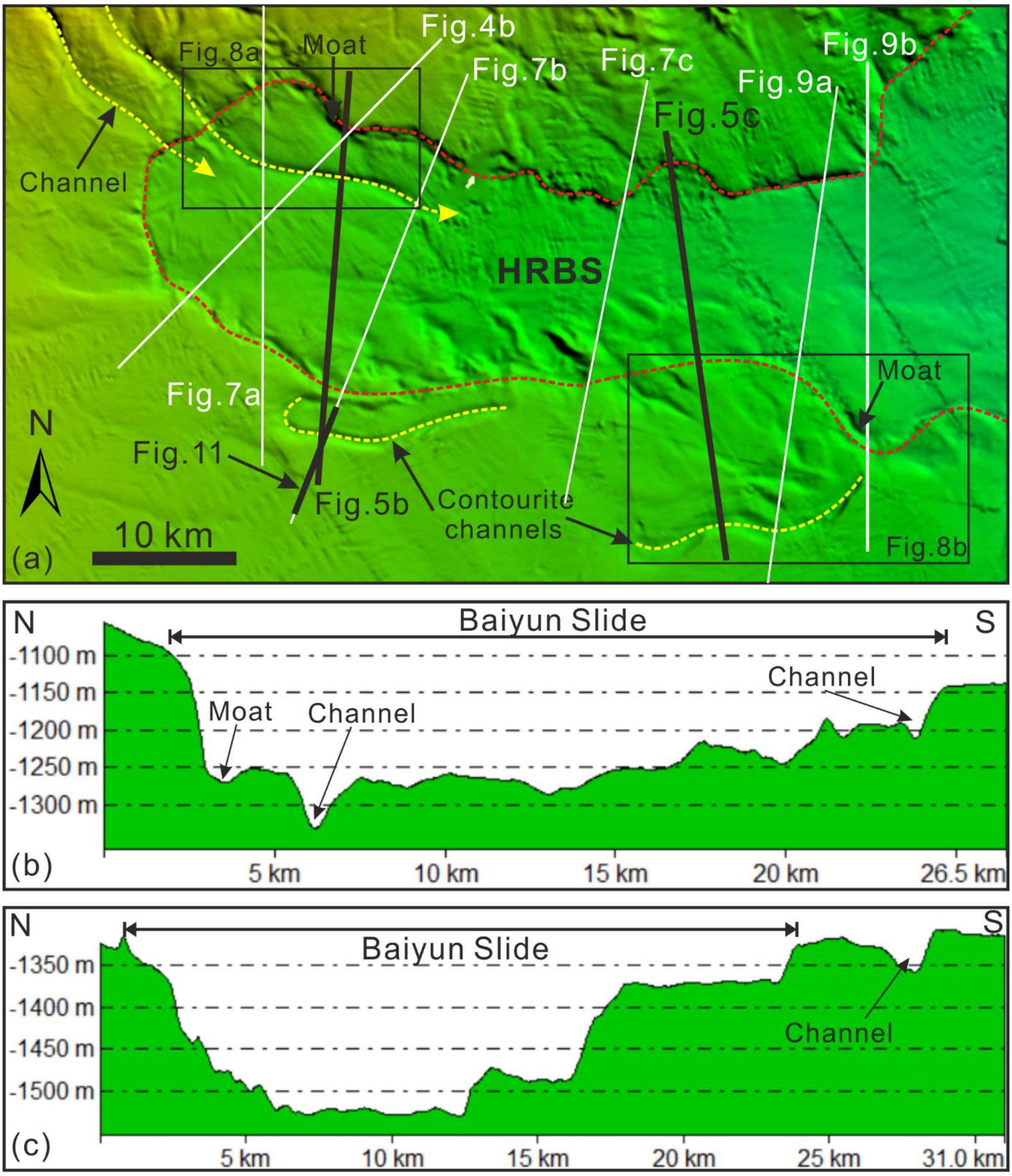

Fig.5 (a) Multibeam bathymetric map showing the detailed seafloor morphology of the headwall region of the Baiyun Slide Complex. The escarpment in the headwall region of the Baiyun Slide is marked by a red dashed line. The yellow dashed lines indicate the locations of submarine channels on the modern sea floor. The black solid lines represent the bathymetric profiles in Figs. 5b and 5c. Please see the location of Fig. 5a in Fig. 2a. (b) Bathymetric profile crossing the headwall region of the Baiyun Slide and revealing the presence of submarine channels. (c) Bathymetric profile revealing the presence of submarine channels in the headwall region. HRBS: headwall region of the Baiyun Slide.

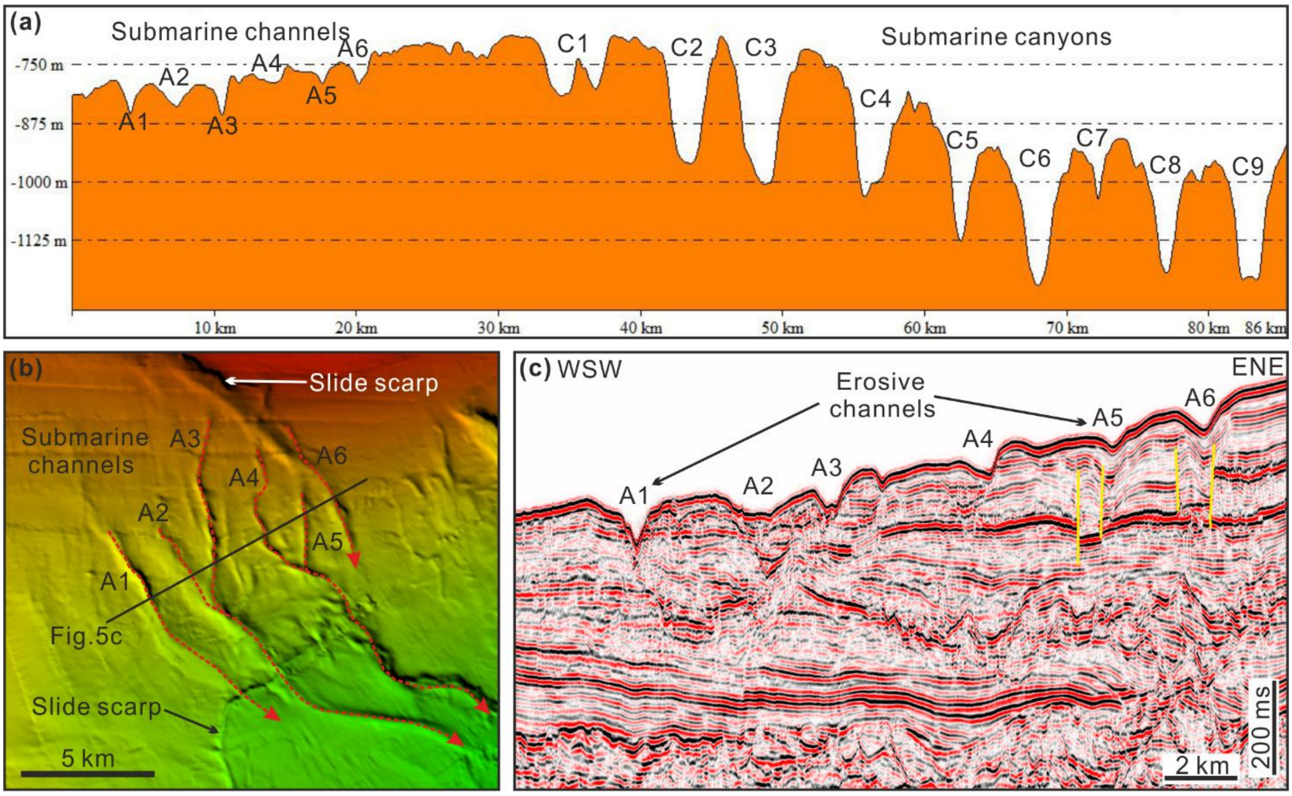

Fig. 6 (a) Bathymetric profile crossing submarine canyons C1 to C9 and submarine channels A1 to A6 in the upper continental slope region of the Baiyun Slide Complex (see location in Fig. 3). Note that submarine canyons (C1 to C9) show much larger incision depths than submarine channels A1 to A6. Please see the location of Fig. 6a in Fig. 3a. (b) Multibeam bathymetric map showing the detailed seafloor morphology of submarine channels A1 to A6. (c) Two-dimensional seismic profile revealing the internal architecture of submarine channels above the headwall region of the Baiyun Slide Complex. See location of the seismic profile in Fig. 6b.

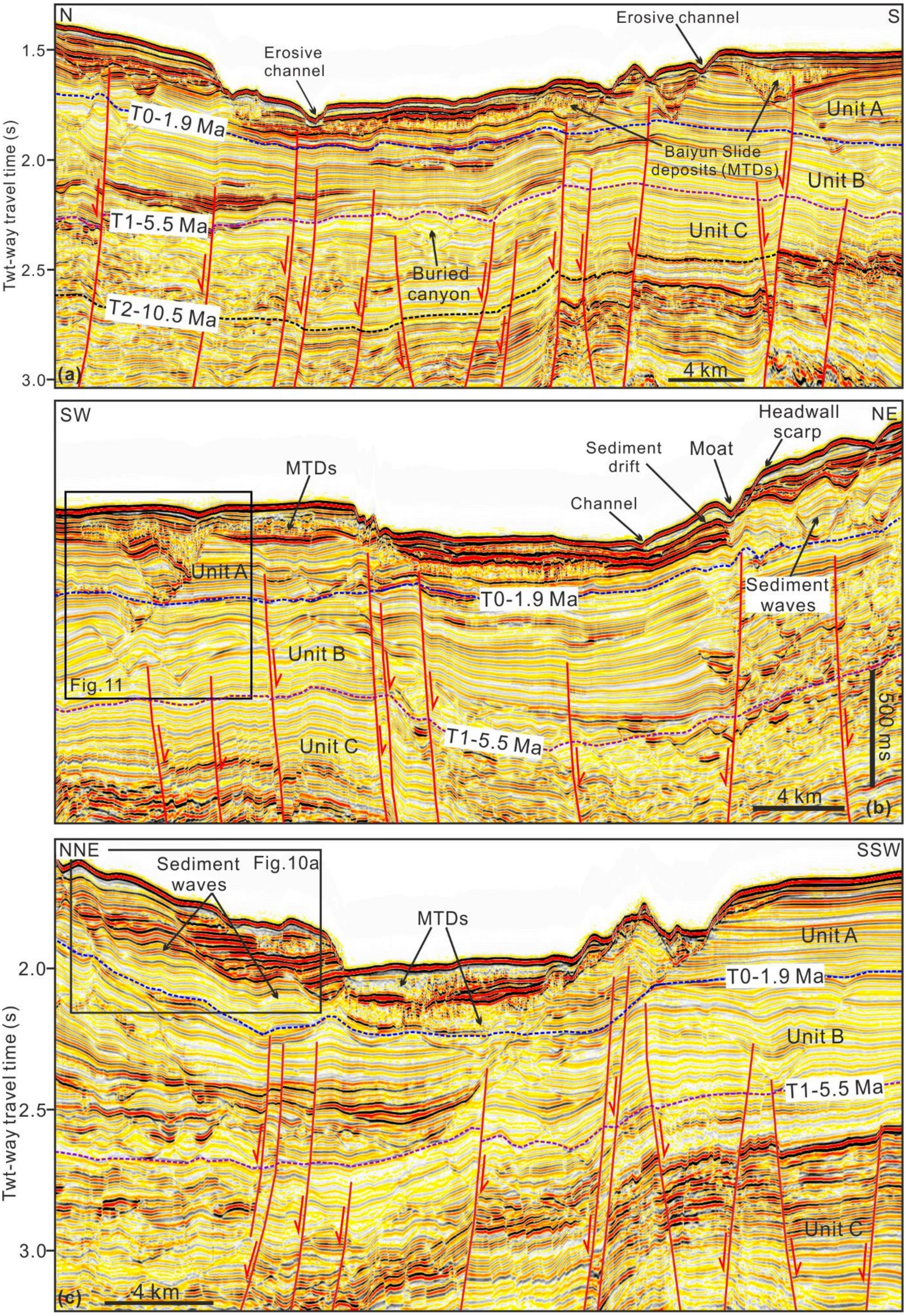

Fig. 7 Three high-resolution seismic profiles crossing different locations of the headwall region to

reveal its detailed internal architecture. (a) 3D seismic line showing the presence of buried submarine canyons, MTDs, large-scale faults and erosive channels on the modern sea floor. (b) A moat and buried sediment waves can be identified in the northern part of the headwall region. A migrating channel is located in the southern part of the headwall region, as shown in detail in Fig. 11a. (c) 3D seismic profile reveals the presence of sediment waves in the northern part of the headwall region, as shown in detail in Fig. 10a. Please see the location of Fig. 7 in Figs. 2a and 5a.

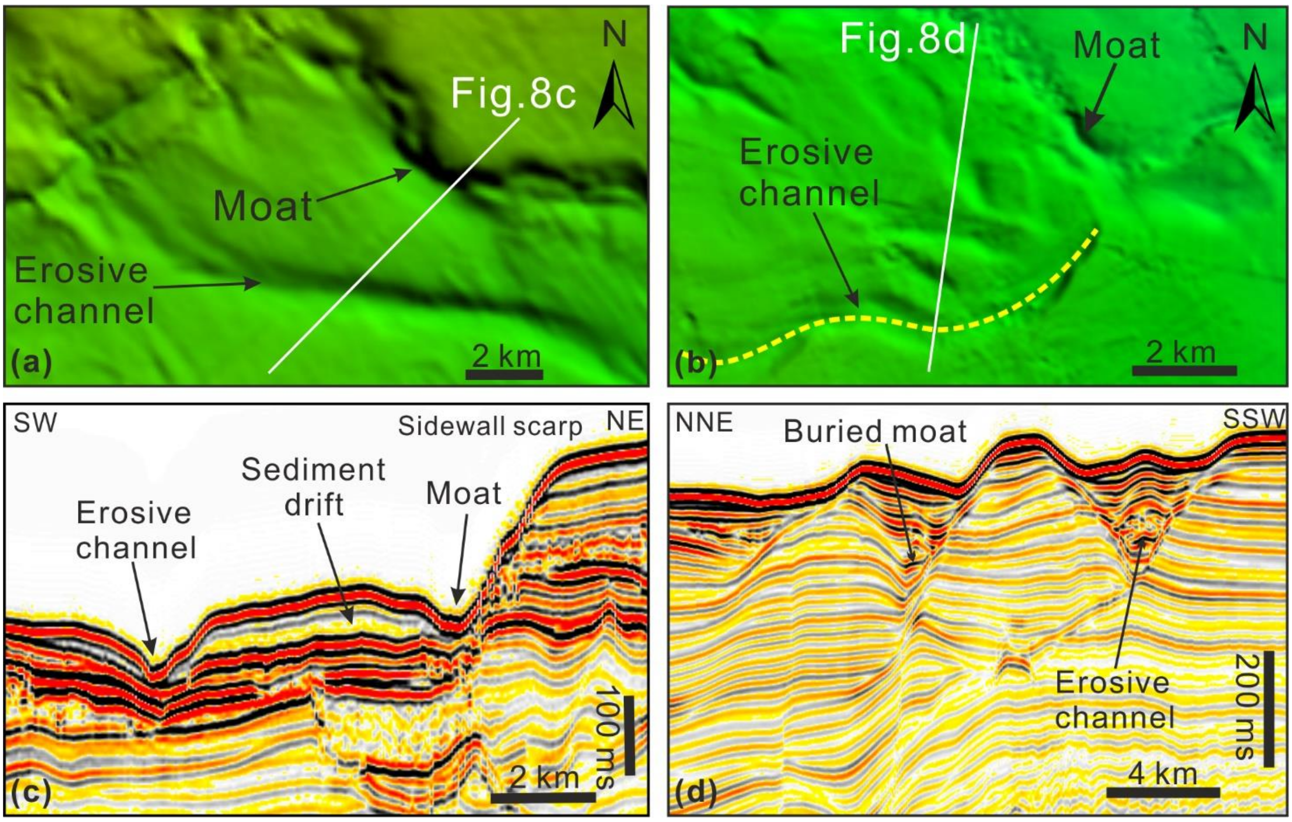

Fig. 8 Enlarged seismic sections (a-d) illustrating the moat and sediment drift developed close to the southern sidewall scarp of the Baiyun Slide Complex. Erosive channels and related truncations can be observed on the modern sea floor.

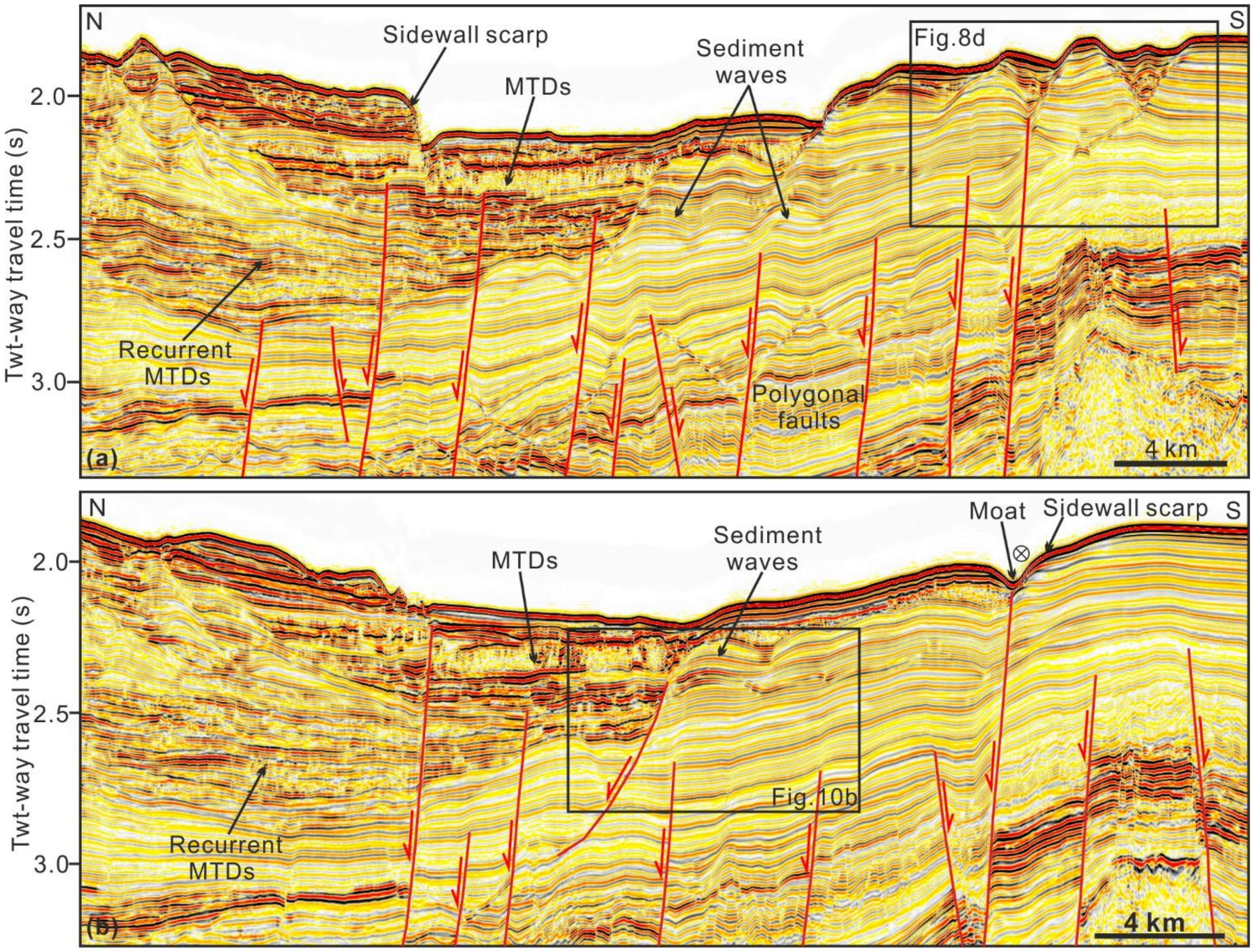

Fig. 9 (a) 3D seismic line crossing the eastern part of the headwall region showing sediment waves buried by recurrent MTDs. A buried moat and a submarine channel can be observed in the southern part of the headwall region. (b) 3D seismic line illustrating a moat close to the sidewall scarp of the Baiyun Slide. A large-scale fault nearly propagates to the sea floor. Please see the location of Fig. 9 in Figs. 2a and 5a.

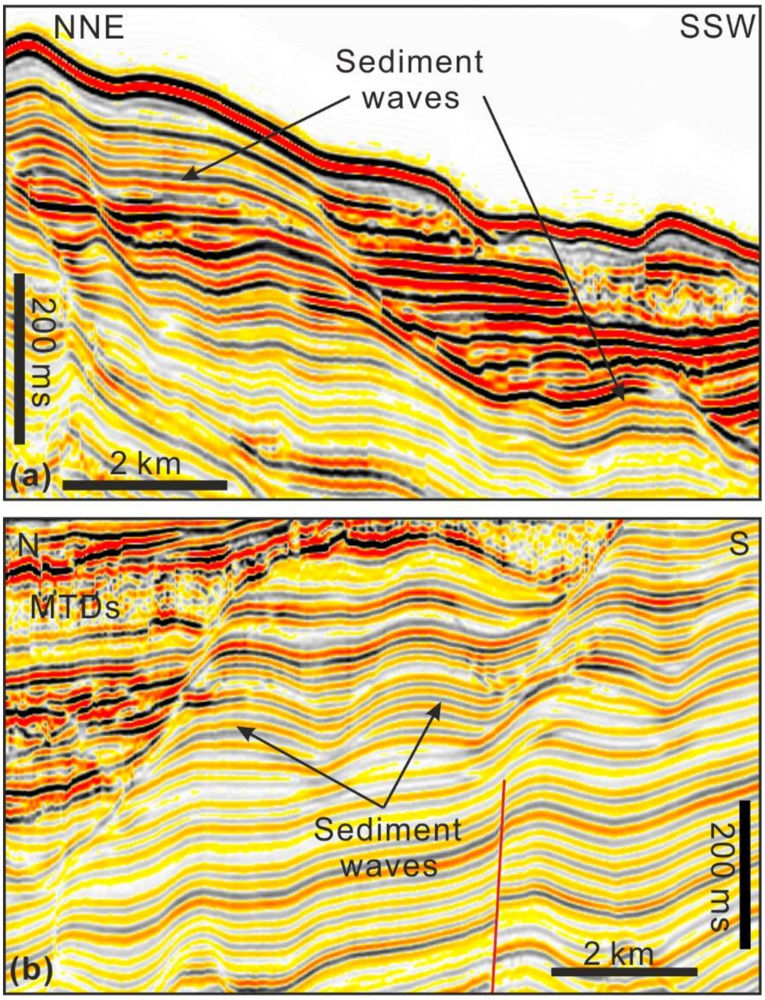

Fig. 10 (a) Zoomed-in seismic profile showing the internal architecture of sediment waves in the northern part of the headwall region, close to the submarine canyons on the upper continental slope. See location of the profile in Fig. 7. (b) Zoomed in seismic profile revealing the presence of sediment waves in the southern part of the headwall region. See location of the seismic profile in Fig. 9b.

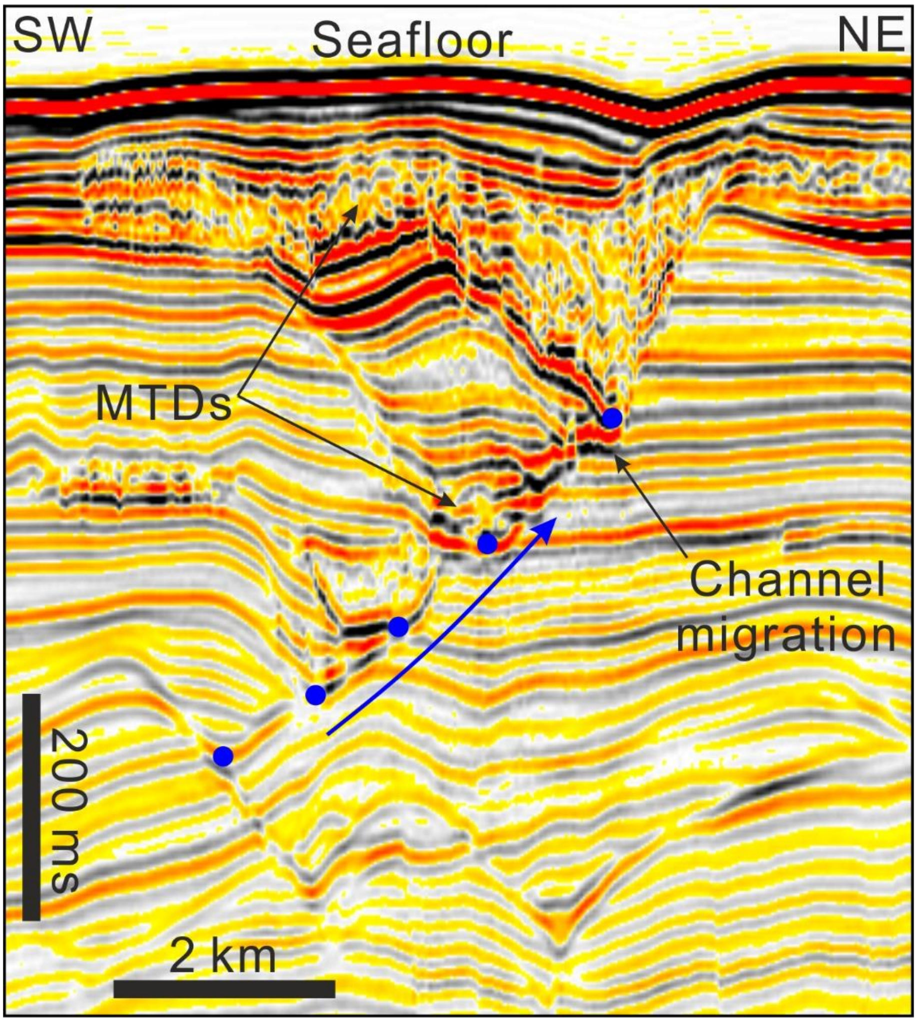

Fig. 11 Interpreted seismic profile from the southern part of the headwall region revealing a buried submarine channel. The blue dots represent the base of the buried channel, which reveal a N-S migration trend at start to then migrate towards the north. Please see the location of Fig. 11 in Fig. 5a.

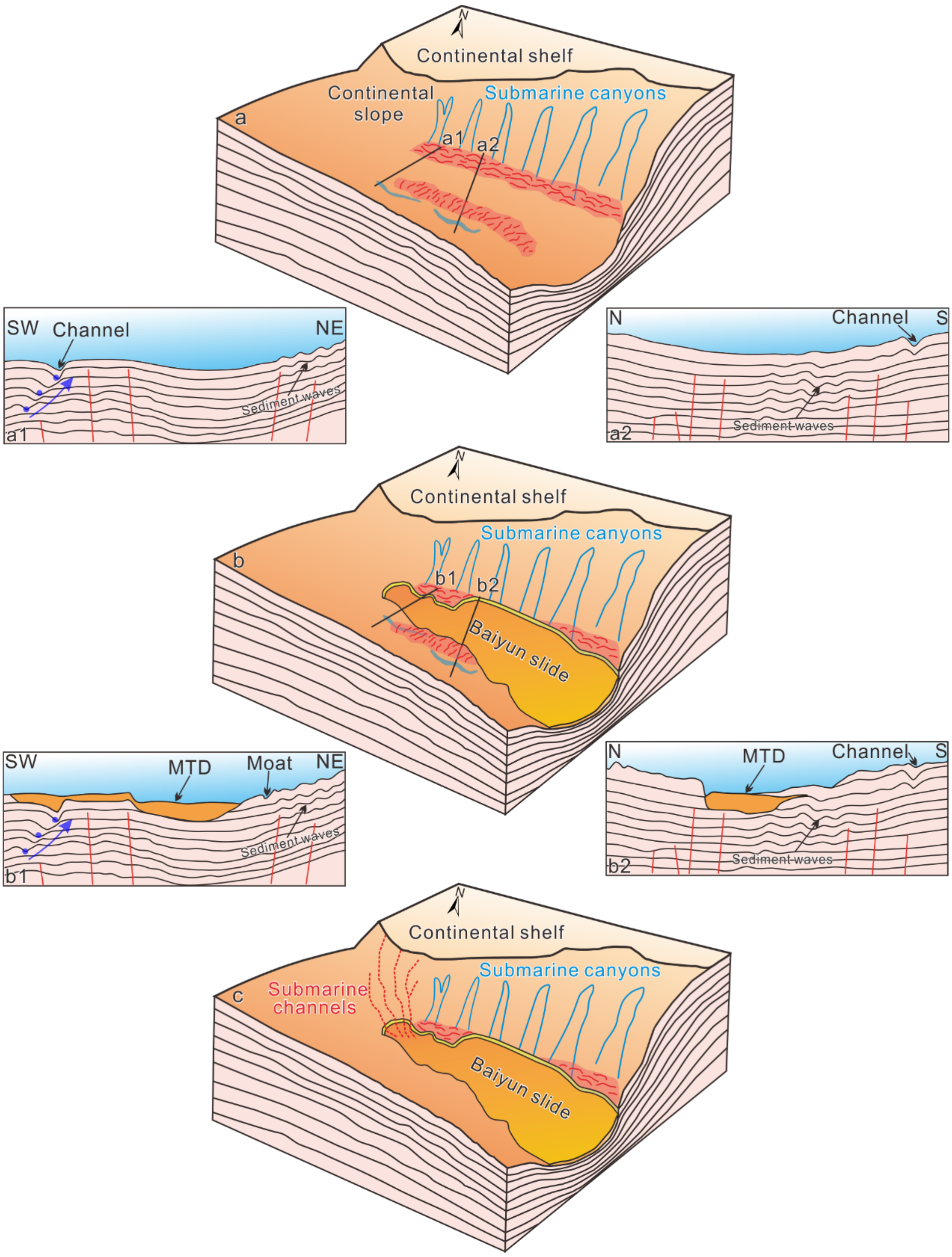

Fig. 12 Conceptual model showing the morphological evolution inside and around the Baiyun Slide scar. (a) The continental slope was incised by several submarine canyons. The sediment waves in the north were formed by turbidity currents flowing through the submarine canyons (a1), while those in the south resulted from the interaction of bottom currents with the seafloor (a2). A submarine channel shows an obvious migration pattern towards northeast (b) The Baiyun Slide

occurred downslope from the submarine canyons and it evacuated large volumes of sediment (~1035 km^3) on the sea floor. The Baiyun Slide eroded the sediment wave fields and the resulted MTDs filled the migrating channel in the south (b1 and b2). (c) Several submarine channels were formed after the Baiyun Slide Complex to erode the headwall scarps of the Baiyun Slide Complex.

Channels	A1	A2	A3	A4	A5	A6
Width (m)	~900	~1500	~800	~1000	~900	~1400
Length (km)	~24	~33	~37	~32	~26	~16
Incised Depth (m)	~73	~22	~52	~34	~42	41
SW Flank (°)	~10	~3	~7	~4	~7	~3
NE Flank (°)	~11	~5	~16	~7	~8	~4

Table 1 Morphological parameters, including widths, lengths, incised depths, dipping angles of the southwestern (SW) and northeastern (NE) flanks, of the submarine channels identified in the upslope region of Baiyun Slide scar.