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Depositional characteristics and formation mechanisms of deep-water canyon systems along the northern South China Sea margin

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Abstract:

Submarine canyon systems are sites for coarser clastic sediment accumulations in the deep-water domains, having the most potential for hydrocarbon reservoirs. Based on the interpretation of high resolution 2D/3D seismic and drilling data, depositional characteristics of three large deep-water canyon systems over the South China Sea northern margin have been analysed. The Central Canyon System has a deep incision geomorphology extending from east to west, featured by distinct canyon segmentations, multi-provenance sediment supplies and multi-stage canyon fillings. The Pearl River Canyon System’s formation is closely related to the Pearl River Delta’s development. Its vertical stacking and migrating channel patterns have changed over time. The depositional architectures and evolution of the recent Penghu-Gaoping Canyon System responds to tectonic movements along the Taiwan-Luzon convergent continental margin. The main controlling factors of the formation and evolution of these three canyon systems include the tectonic setting, sediment supply, sea level change and paleo-geomorphology, among which the former two are dominant. The Penghu-Gaoping Canyon System formed along the subduction structural zone, directly indicating a typical tectonic origin. Numerous seismic data show that the Central Canyon and Pearl River Canyon systems are obviously affected by tectonics, associated local topography and sediment supply.

Keywords:
Deep-water canyon systems; Turbidite channels; Deep-water reservoirs; Northern margin of South China Sea
1 Introduction

Canyons are elongated, narrow (a few kilometres) and deep (frequently more than a kilometres) negative submarine topography, appearing near active and passive continental margins as well as island arcs. Harris and Whiteway (2011) counted as many as 5,849 large submarine canyons along the present global continental margins. Submarine canyon systems are widely developed on shelves, slopes and abyssal plains, as the main conduits for sediment transport from shallow continental waters to the deep ocean, and they are important recorders of paleoclimate and changes in sea level, as well as regional tectonic evolution (Baztan et al., 2005; Deptuck et al., 2003). More importantly they form the main reservoirs for deep-water oil and gas (Antobreh and Krastel, 2006; McHugh et al., 2002; Laursen and Normark, 2002; Piper and Deptuck, 1997). Thus, in recent decades, submarine canyon systems have become one of the focal points for studying deep-water sedimentary environments and processes.

Submarine canyons can generally be divided into two categories (Harris and Whiteway, 2011; Twichell and Roberts, 1982): shelf-indenting canyons (headed canyons) and slope-confined canyons (headless canyons). The former group commonly develops from continental shelves to the deep, where abundant sediment supplies, carried by large rivers, are fed to the canyon heads (Kudrass et al., 2018; Pickering and Hiscott, 2016; Mulder, 2011). Some of these canyons occur at the mouth of terrestrial rivers, and their heads may connect directly to river deltas. For the second group, the heads may start in the slope, and they are more likely to develop in areas where the sediment supply is insufficient, with no large rivers above the heads (Pickering and Hiscott, 2016; Hanebuth et al., 2015; Mulder, 2011). They undercut continental slopes as a result of sediment instability of steep slopes. In general, submarine canyons carry mass wasting deposits, debris deposits and turbidity deposits and transport them from shallow-water region to the abyssal plain (Antobreh and Krastel, 2006; Laursen and Normark, 2002; McHugh et al., 2002). Regional geological conditions (i.e., submarine topographies, sea level changes, tectonics, the sediment supply, etc.) lead to distinct depositional architectures of different deep-water canyons (Pickering and Hiscott, 2016; Mulder, 2011).

The northern continental margin of the South China Sea (SCS) presents various tectonic and sedimentary features (Zhou and Yao, 2009) (Fig. 1a). Along its northern margin, three large deep-water canyon systems have developed under different tectonic settings and depositional conditions. They are the Penghu-Gaoping (Formosa-Penghu-Gaoping) Canyon System (PGCS) within the Taixinan Basin on the north-eastern margin, the Pearl River Canyon System (PRCS) within the Pearl River Mouth Basin on the northern margin, and the Central Canyon System (CCS) within the Qiongdongnan-Xisha Trough Basin on the north-western margin (e.g., Hsiung et al., 2015a; Su et al., 2014; Ding et al., 2013; Gong et al., 2011; Hsiung and Yu, 2011) (Fig. 1b). In this study, the latest high resolution 2D/3D seismic and drilling data from oil companies (e.g., CNOOC) have been analysed. The seismic interfaces involved in this data are T0 (0 Ma), T2 (2.6 Ma), T28 (3.8 Ma), T3 (5.3 Ma), T31 (8.2 Ma), T4 (11.6 Ma), T5 (15.5 Ma) and T6 (23 Ma). Their ages are determined by biostratigraphic analysis from
Xie (2011) and others (Fig. 2). Through meticulous analysis, this paper attempts to reveal the distinctive depositional architectures of three large deep-water canyon systems along the northern margin of the SCS, and to further reveal the factors controlling their formation and evolution.

2 Depositional characteristics of the Central Canyon System (CCS)

The CCS is located on the north-western margin of the SCS and extends parallel to the northern slope of the Qiongdongnan Basin (Figs. 1b and 3a). This canyon reaches a total length of about 425 km, passes through the Central Depression within the Qiongdongnan Basin and the Xisha Trough, and terminates within the Northwest Sub-Basin, with its head tracing westwards to the south-eastern edge of the Yinggehai Basin (Feng et al., 2018; Wang et al., 2011; Su et al., 2009). The western segment became filled with sediments during the Late Miocene, while the eastern segment (from the eastern Changchang sag within the Qiongdongnan Basin to the Xisha Trough) has not yet been filled up with an incision morphology of up to 700 m (Shang et al., 2015; Su et al., 2014; Chen et al., 2013; 2016) (Fig. 3a). From the analysis of high resolution 2D/3D seismic and drilling data, the depositional architectures and evolution of the CCS were determined. These features are described in the following section.

2.1 Geomorphology and depositional characteristics of the CCS

Depositional architectures within the CCS exhibit obvious zoning from west to east, and can be divided into 3 segments: the western segment (passing through the Ledong Sag, Lingshui Sag, Songnan-Baodao Sag, Southern Uplift Zone), the middle segment (the Changchang Sag) and the eastern segment (the Xisha Trough) (Fig. 3a). The canyon-fill deposits consist of turbidity channels, channel-levee complexes, sheeted sand-mudstone complexes and mass-transport deposits (MTDs) (Fig. 3b, c, d). In the western segment of the CCS, the canyon-fill is dominated by turbidity channels and MTDs (Fig. 3b), resulting in higher sand contents and enrichment of coarser clastic deposits (Shang et al., 2015; Huang et al., 2015; Su et al., 2009). Recent hydrocarbon exploration has proved those coarser clastic turbidite deposits are most favourable for deep-water oil and gas reservoirs (Wang et al., 2015; Zhu et al., 2012). Canyon-fills within the middle segment are dominated by complexes of sheeted sands and MTDs with dramatically decreased sand contents (Fig. 3c). In the eastern segment (the Xisha Trough), the canyon-fill mainly consists of these sheeted-sand-MTD complexes in the lower layers, and MTDs in the upper layers (Fig. 3d). It has been suggested that these canyon-fill deposits have been forming since the Late Miocene (Wang et al., 2015). From west to east, the CCS was filled at different times: the western-middle segment was completely filled before 3.8 Ma (T28), while the eastern segment has yet to be completely filled (Shang et al., 2015) (Fig. 3a, b, c, d).

Differing sedimentary characteristics at different depths within the canyon-fill deposits indicate that these sediments have multiple provenances. The coarse-grained turbidity sediments are dominantly derived from Eastern Vietnam or the Red River in the west (Su et al., 2019; Chen et al., 2015). The majority of fine-grained
MTDs are derived from the northern shelf-slope of the Qiongdongnan basin, while a small amount coming from
the southern canyon wall (Su et al., 2014; 2011; 2009). During the early stage of the Late Miocene and Early
Pliocene (T4/11.6 Ma to T28/3.8 Ma), the canyon-fill was dominated by turbidity channels, and then turbidity
channels interbedded with MTDs (Fig. 3b, c, d, e), which were mostly derived from the ancient Red River and
Eastern Vietnam instead of Hainan Island (Su et al., 2019; Chen et al., 2015). During the later stage of the Late
Pliocene and Quaternary (T28/3.8 Ma to T0/0 Ma), with the dramatic decrease of coarse grained sediments from
the western source, the canyon was filled by MTDs from the northern slopes and mudstones/hemipelagic
depositions (Fig. 3b, c, d, f).

2.2 Evolution model of the CCS

Based on the interpretation of recently derived high resolution 2D/3D seismic data, the depositional filling
characteristics of different segments of the CCS were systematically studied. The evolution of the CCS was
divided into three stages. (1) The canyon-incising stage (T4/11.6 Ma to T31/8.2 Ma) is characterized by erosional
canyon processes. With the changes in the regional tectonic framework, a semi-closed horn-shaped depression
formed along the Central Depression of the Qiongdongnan basin (Fig. 3a). During that time the gravity flows
incised along the thalweg of the depression and led to the Central Canyon’s down-cutting morphology.
Correspondingly, plentiful coarse sediments were transported eastwards and deposited within the Northwest Sub-
Basin (Fig. 3b, c, d, e). (2) The canyon-filling stage (T31/8.2 Ma to T28/3.8 Ma) can be subdivided into two sub-
stages. In the early sub-stage of T31/8.2 Ma to T3/5.3 Ma, deposition in the Central Canyon was dominated by
laterally migrating and vertically-stacking turbidity channel complexes (Fig. 3b, c, d). The Red River and Eastern
Vietnam provided abundant sediment supplies for the development of turbidity channels. In the following sub-
stage of T3/5.3 Ma to T28/3.8 Ma, canyon-fill was dominated by turbidite deposits interlayered with MTDs (Fig.
3b, c, d). These canyon-fills are characterized by interbedded bidirectionally-sourced sediments (Shang et al.,
2015). MTDs were mainly derived from the northern shelf-slope system and moved southward into the Central
Canyon (Fig. 3f). Due to the shielding effect of the Southern Uplift Belt, MTDs were banded along the canyon,
moved eastwards along a secondary axis, and accumulated in the CCS (Fig. 3b, c, d, f). (3) The shrinking stage
of the CCS (from T28/3.8 Ma onwards) was dominated by MTDs (Fig. 3b, c, d). Due to the drastically reduced
supply capacity of the Red River influenced by the tectonics, turbidity deposits from the northwest were severely
limited (Fig. 3e, f). Meanwhile, influenced by the geomorphology of the Central Depression Zone of the
Qiongdongnan Basin (e.g., the shielding effect of the Southern Uplift Belt), MTDs on the northern slopes and in
the Southern Uplift zone were imported into the Central Canyon (Fig. 3f). A number of slope canyons developed
on the sliding and channelized slopes (Chen et al., 2013; He et al., 2011; Su et al., 2011), which transported
massive sediments to the abyssal plain with a part further into the Central Canyon (Fig. 3f). Blocked by the south
wall of the Central Canyon, transport of these sediments was altered from southward to eastward, moving and
depositing along the Central Canyon passage (Fig. 3f).
3 Depositional characteristics of the Pearl River Canyon System (PRCS)

The PRCS, with a total length of about 300 km, developed offshore of the Pearl River delta within the Pearl River Mouth Basin, passing through continental slopes in the Baiyun and Liwan sags and entering into the abyssal plain within the Northwest Sub-Basin (Figs. 1b and 4a). This canyon has a WNW-ESE orientation on the upper slope and changes to a NW-SE orientation on the lower slope (Fig. 4a). The present Pearl River estuary is situated more than 150 km NW of the canyon occurrence on the slope (Fig. 1b), and associated submarine fans develop on the lower slope (especially within the Liwan Sag, Fig. 1b) and the oceanic abyssal plain. Recent studies have reported a great number of deep-water fans, with favourable petroleum potentialities, developing on the Baiyun deep-water slope during the Early-Middle Miocene (Zhu et al., 2012; Pang et al., 2007). East of the main canyon course, a set of small-scale headless slope canyons have developed on the upper slopes (Zhu et al., 2010) (Fig. 4a).

3.1 Geomorphology and depositional characteristics of the PRCS

Based on analysis of geometric features, the PRCS is composed of three parts: the canyon head consists of a complex slope canyon group and a main depression in the upper slope, the middle course develops into a single canyon form within the middle slope, and the lower course develops in the lower slope as a canyon tail extending into the abyssal plain, with the development of associated submarine fan depositions (Fig. 4a, b, c, d, e). The slope canyon group in the upper slope is identified by high-amplitude and messy weak-amplitude seismic reflections, and the canyon incision presents typical lateral migrations in the seismic data, which are interpreted as composite channel complexes and MTDs (Fig. 4b). The trunk canyon in the middle slope shows a U-shaped canyon form, with shallow relief. This feature appears as medium-amplitude continuous parallel to sub-parallel seismic reflections (Fig. 4c). MTDs show chaotic, low-amplitude to transparent reflections, showing erosive surfaces at the base; the submarine fan deposits present as medium-high amplitude, continuous horizontal seismic reflectors with mounded geometries, some of which showing two-way downlapping (Fig. 4d). The PRCS, including the complex slope canyon group (head), simple canyon (trunk), and submarine fan/MTDs (tail), extends from the shelf break to the abyssal plain (Fig. 4e, f, g, h).

Architectural elements were identified in the PRCS, through facies analysis of the 2D/3D seismic data: bottom leg/thalweg sediments, turbidite channels, lateral accumulation bodies, turbidite sheeted lobes, abyssal deposits, MTDs and canyon marginal sliding/slumping deposits (Fig. 4b, c, d). There are distinct sediment compositions and depositional architectures in different segments and intervals (Fig. 4e, f, g, h). Because the Pearl River delta provides a rich supply of fine-grained sediment for canyon-filling, the cutting depth of the canyons is limited (e.g., Fig. 4b, c, d), resulting in the formation of a set of interbedded canyon deposits and muddy slope wedges. Vertically, three stages of canyon groups are identified, corresponding to the ages of 11.6 Ma, 5.3 Ma and 2.6 Ma (Fig. 2). They mostly coincided with eustatic fluctuations of the Pearl River Mouth Basin. The canyon
deposits mostly developed during the low-stand system tract period, while muddy slope wedges were deposited during the high-stand system tract period. The Quaternary canyon-fills were dominated by MTDs (Sun et al., 2018) (Fig. 4 e).

3.2 Evolution model of the PRCS

Unlike the Qiongdongnan Basin, the Pearl River Mouth Basin has experienced a deep-water setting since the Early Miocene (from 23 Ma onwards). Corresponding with the development of the paleo-deltas, the delta-canyon-submarine fan complexes of the PRCS were formed on different scales and in different positions (Fig. 4e, f, g, h). The shelf-edge delta and the seafloor fan were initially developed during the Early Miocene (Mao, 2015). With the rise in sea level, the delta moved landwards towards the shelf, and a canyon-submarine fan system then began to form in the slope area (Fig. 4c, h).

Three evolutionary stages of the PRCS have occurred since the Early Miocene. (1) Initial formation stage (23 to 15.5 Ma): the shelf-edge delta developed during the early period of this stage, and since 21 Ma the paleo-Pearl River delta began moving landwards due to the sudden northward migration of the shelf break (Shao et al., 2004). Channels began to develop but the trunk canyon did not exist on the paleo-slopes, with submarine fans depositing at the slope tail, constituting a channel-fan complex (Mao, 2015). (2) Channel-submarine fan stage (15.5 to 11.6 Ma): the U-shaped incised trunk canyon initially appeared since the Middle Miocene (T5/15.5 Ma), and the PRCS began to assume its present-day morphology (Fig. 4c, h). Sediments from the shelf were delivered directly to the ocean basin through this canyon and the channels within it, forming a massive turbidity fan system (Fig. 4c, d, h). The canyon formation was likely related to sea-level fall (Fig. 2) and sufficient sediment supplies. During this period, the PRCS constituted a pattern of complex channels in the upper course, a single trunk canyon in the middle course and fans in the lower course and the abyssal plain (Fig. 4h). (3) Canyon-fan/MTD stage (11.6 to 0 Ma): this stage featured a pattern of channel groups in the upper slope, a single canyon in the middle/lower slope and submarine fans on the abyssal plain. Since T4/11.6 Ma, a significant regional fall in sea level was present (Fig. 2), increasing the supply of sandy sediment and leading to the formation and development of the trunk canyons in the middle slope. During the Late Miocene, the shelf slope was strongly eroded by the canyon/channels (Fig. 4c, g) and sediments were transported through the canyon passage and deposited on the abyssal plain, forming a large-scale turbidity fan (Fig. 4d, g). During the early Pliocene, the sea level decreased due to climate changes, and increased sediment supplies lead to the development of new slope canyons on the top of the buried canyons, which transported large amounts of sediment to the lower slopes and formed seafloor fans/MTDs on the lower slopes (Fig. 4i). Most of the canyons were filled with turbidites and MTDs (Fig. 4b, c). During this period the slope was farther away from the Pearl River delta than the Late Miocene and before, due to the shrink of the delta, and some headless canyons developed in the upper slope (Fig. 4b). On the lower slopes and abyssal plains, submarine fans failed to be well developed. Instead, the formation of mass-transport deposits dominated during the Quaternary (Fig. 4c, d, e).
4 Depositional characteristics of the Penghu-Gaoping Canyon System (PGCS)

The PGCS, with a total length of about 240 km, developed on the northeast edge of the SCS, extending from the northeastern SCS slope and Gaoping slope to the Manila Trench along the tectonic line (Figs. 1b and 5a). The PGCS is a typical tectonics-controlled canyon system. As a result of the collision of the Eurasian plate and the Philippine plate, Taiwan’s mountain belt was formed, and a NNE-SSW aligned canyon system was formed in the foreland basin of SW Taiwan (Hsiung et al., 2015b; Hsiung and Yu, 2011).

4.1 Geomorphology and depositional characteristics of the PGCS

The PGCS is a large-scale deep-water canyon system formed along the Taiwan-Luzon convergence belt (Fig. 5a). Its northern segment is composed of three tributaries, namely the Gaoping, Penghu and Formosa canyons (Figs. 1b and 5a). They combine into a single canyon before entering the Manila Trench, along the direction of the thrust fault, as the deep-sea Penghu Canyon (Fig.5a, b, c, d). Specifically, the Gaoping Canyon developed offshore and southwest of the Taiwan Island, from the Gaoping river on Taiwan Island through the Gaoping shelf and slope (Fig. 5a). The PGCS initially formed in the Early Pleistocene, through complex scouring and filling processes (Hsiung et al., 2015a; Hsiung and Yu, 2011). The canyon morphology and filling exhibit obvious segmentation, and each segment presents different erosional/sedimentary characteristics.

The PGCS contains three segments for sediment transportation routes: the Formosa-Penghu-Gaoping canyons as the upper course, the deep-sea Penghu Canyon as the middle course and the Manila Trench as the lower course (Fig. 5). Seismic profiles in the Formosa-Penghu-Gaoping canyon segment show that the incision forms are significant along the canyon walls, and some infilling has occurred at the bottom of the canyon (Fig. 5b). In the deep-sea Penghu Canyon, depositional infillings show relatively flat and parallel reflectors, and wavy reflectors appear on an unconfined channel wall due to a wider trough (Hsiung et al., 2015a)(Fig. 5c, d). To the south, the wedge-shaped sediments developed near the lower slope are affected by the thrust fault (Fig. 5c, d, e). The position, direction and geometric features of the sediment transport system in the Manila segment are mainly controlled by the gradual transition of arc land collision in the subduction process (Hsiung et al., 2015; Hsiung and Yu, 2011; Yu and Hong, 2006). In the northern part of the Manila Trench, sediments are mainly transported through turbidity currents in the Formosa-Penghu-Gaoping canyons at the upper slope and the deep-sea Penghu Canyon at the lower slope (Fig. 5e).

4.2 Evolution model of the PGCS

Since the Pliocene, the PGCS has undergone three main evolutionary stages. (1) The infancy stage (6.5 to 1.6 Ma): Around 6.5 Ma, the incipient oblique collision between the Luzon Arc and Chinese continental margin north of the Manila Trench began (Clift et al., 2003; Lin et al., 2003). The compression resulted in a wide belt of volcano-capped ridges and troughs. During this stage the submarine Penghu Canyon began to form along the deepest trough between the SCS Basin and the westernmost edge of the North Luzon Ridge Province under the
tectonic compression. (2) The deep-water channel and small canyon stage (1.6 to 0.4 Ma): With the formation of
the foreland basin, due to an oblique arc-continent collision, a series of deep-sea troughs formed. Several small-
scale Pleistocene submarine canyons, about 5 km in width and 45 km in length, developed on the slopes of the
deep-sea troughs (Yu and Hong, 2006; Fuh et al., 1997). These deep-water slope canyons are believed to be the
precursors of the modern Penghu Canyon. (3) The present-day deep-incising canyon stage (0.4 to 0 Ma): Around
the late stage of collision in southern Taiwan, an extensive N-S aligned bathymetric trough formed along the
tectonic strike of the convergent margin, and during the same period the modern Formosa-Penghu-Gaoping
canyons were formed (Yu and Hong, 2006). Therefore, a distinctive longitudinal sediment dispersal system,
composed of tributary canyons, a single canyon and a trench, is present along the convergent margin between the
Luzon and South China Sea plates (Fig. 5a).

5 Discussion: differences in formation and evolution processes of three large-scale deep-
water canyon systems

Deep-water canyons are important conduits for sediment transportation in deep sea domains, carrying
sediments from eroding mountains to shallow water and further into the deep sea, through continuous
transportation, deposition, re-transportation and re-deposition processes. Together they constitute the complex
“source to sink” system (Pickering and Hiscott, 2016; Mulder et al., 2011). Three large deep-water canyon
systems on the northern margin of the SCS constitute an important sediment-routing architecture for transporting
sediments through the slope to the abyssal plain and even into the trench, contributing an important sediment
dispersal system for the transportation of materials to the deep sea.

5.1 Differences in tectonic backgrounds of three large-scale deep-water canyon systems

The tectonic backgrounds of the three large deep-water canyon systems on the northern margin of the SCS
were very different prior to the canyon formation (e.g., Hsiung et al., 2015; Su et al., 2014; Ding et al., 2013).
The extending direction of each canyon system was mostly controlled by the tectonics and associated
(paleo-)geomorphology (Figs. 1, 3, 4 and 5). The PGCS forms in a subduction belt at the edge of the plate, thus
it extends almost exactly along the tectonic line (i.e., the Luzon subduction zone) (Hsiung et al., 2015). The CCS
and PRCS form within the depression zones on the passive margin ( Su et al., 2009; Pang et al., 2007). The E-W
aligned CCS extends along the deepest sunken belt of the Central Depression of the Qiongdongnan Basin and the
Xisha Trough, and is clearly controlled by the tectonic framework (Yuan et al., 2009). The PRCS develops on the
slope below and SW of the Pearl River delta (Ding et al., 2013; Pang et al., 2007). Although it does not run along
a specific tectonic line as the two canyon systems mentioned above, this canyon system obviously forms along
the sediment erosional thalweg of the seafloor geomorphology (Figs. 1 and 4).

In addition, local geological conditions also affect the widths and incision depths of these canyons. For
example, within the CCS there is a diapirism developing in the Changchang depression and there are a series of small faults/uplifts developing in the Songnan-Baodao Sag (Huang et al., 2015; Mao et al., 2015) (Fig. 3a). These facts would change the local features within the CCS, but they fail to determine the overall pattern of canyon development (Mao et al., 2015; Shang et al., 2015). On the whole, tectonics and associated (paleo-)geomorphology are undoubtedly important controlling factors for the formations and extending directions of the deep-water canyon systems.

### 5.2 Differences in evolution of three large-scale deep-water canyon systems

There are distinct depositional architectures and evolutionary features in each of the three large-scale deep-water canyon systems. Major differences are summarized below.

1. Differences in down-cutting capacity of the canyon: There are different incision depths in different canyon segments. The CCS has the largest incision depth, ranging from 800 to 1200 m with a maximum of 1400 m; the PRCS has the smallest incision depth, with the most obvious down-cutting canyons developing on the upper slope (incision depths of 50 to 300 m); the most deeply-incised canyon segment of the PGCS is mainly developed on the upper slope, with incision depths of 630 to 940 m, while on the lower slope and abyssal plain it has very limited cutting depths as a smaller channel (Figs. 3, 4 and 5). Because of the strong down-cutting processes, the Central Canyon forms as the longest and deepest canyon, which took a long time (11.6 to 2.8 Ma, Fig. 6) to be filled up. In contrast, the relatively smaller canyons within the PRCS were filled up more rapidly (within 5 Ma, Fig. 7) due to their weak cutting capacity.

2. The effect of sea level change: Commonly, down-cutting processes occur in most canyons during the low-stand system tract period, while the canyon-filling processes occur during the high-stand system tract period. For example, since the Middle Miocene, the development periods of the PRCS have coincided with drops in sea level (Fig. 7). Because the incised canyon was easily/rapidly filled up, the slope progradational wedge would cover the canyon during the high-stand system tract period. In addition, during a canyon-fill period, a sediment routing system can usually be divided into the erosional, sediment-bypassing and sediment-filling segments. Their depositional processes are closely related to the turbidite flow energy and sea level changes. Changes in these parameters will lead to changes in erosional or filling processes in different canyon segments at different times, which also leads to variation in depositional architecture in different canyon segments (Figs. 6 and 7). Compared to the PRCS, the effect of sea level change to the CCS and PGCS is limited.

3. Differences in sediment supply: Changes in sediment supply not only lead to differences in lithologies of canyon-fills, but also in the depositional facies. For example, the sediment supply in the CCS include sources from the west and the north. The western source, either eastern Vietnam or the Red River, contributed mostly coarse- to fine-grained sandstones, while the northern source from the northern slope of the Qiongdongnan basin contributed mostly siltstones and mudstones. Early deposits in the CCS were dominated by the western source and are composed of sandstones. After this sediment supply suddenly decreased, the sediments in the canyon were mostly provided by the northern source, and were composed of muddy MTDs (Fig. 3e, f). The PRCS was
filled by sediments from the Pearl River delta. The early lithologies are slightly coarser due to the shorter distance to the delta, while the later sediments were finer grained, due to the longer distance from the delta (Fig. 4 e, f, g, h). Variations in sediment supply directly controlled the filling compositions of the canyons. The effect of sediment supply to the PGCS is limited.

(4) Differences in depositional architectures of canyon-fills: Different tectonic and depositional backgrounds will undoubtedly lead to changes in morphology, filling style and depositional architectures of each canyon. The tectonic background, sea level change, sediment supply, and geomorphology are the most critical elements that determine canyon-filling patterns. The pervading distribution of deep-water canyons on the periphery of the SCS fits well with sufficient sediment supplies. As a whole, the development of large deep-water canyons on the northern margin of the SCS is closely related to the tectonic background and geomorphology, and may also be closely related to the sediment supply that has been abundant since the Late Miocene. The CCS has a typical single canyon-fill sequence (Fig. 6) and the PRCS has a series of multi canyon-fill sequences (Fig. 7). The PGCS, however, has been always in an unfilled state (Fig. 4).

6 Conclusions

Three large deep-water canyon systems developed over the northern margin of the SCS: the CCS in the northwest, the PRCS in the north, and the PGCS in the northeast. Distinct depositional architectures within the three deep-water canyon systems and their extending directions reflect different tectonics and sedimentary evolutions. The main controlling factors of the formation and evolution of three deep-water canyon systems since the Late Miocene include the tectonic setting, sediment supply, sea level change and paleo-geomorphology, among which the former two are the dominant factors.

The PGCS that forms along the subduction structural zone directly refers to a typical tectonic origin, and it remains unfilled. The PRCS has a series of multi canyon-fill sequences, and its formation and evolution are significantly influenced by the external sediment supply and sea level changes. The CCS has a typical single canyon-fill sequence and its formation and evolution are dominantly controlled by the tectonic framework and the sediment supply.

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References


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**Figure Captions**

Figure 1A. The regional geography and the principal rivers (the Red River, Pearl River and rivers on Taiwan Island) around the South China Sea (SCS) (extrapolated from GEBCO gridded bathymetry data); B. Distribution of three large submarine canyon systems, i.e., the Central Canyon System, the Pearl River Canyon System and the Penghu-Gaoping (Formosa-Penghu-Gaoping) Canyon System over the northern margin of the South China Sea. PRMB = Pearl River Mouth Basin, QDNB = Qiongdongnan Basin, YGHB = Yinggehai Basin, XSTB = Xisha Trough Basin, BBWB = Beibuwan Basin, NWSB = Northwest Sub-Basin, TXNB = Taixinan Basin, BJNB = Bijianan Basin, CSB = Central Sub-Basin, BY = Baiyun Say, LW = Liwan Sag.

Figure 2 Schematic overview of the major structural and tectonic/climatic setting (including sea-level changes) in the northern South China Sea since the Middle Miocene (modified from Shang et al., 2015; Xie et al., 2011; Wei et al., 2001; Qin, 1996; Haq et al., 1987); Seismic interfaces used in this study involve from T0 (0 Ma), T2 (2.6 Ma), T28 (3.8 Ma), T3 (5.3 Ma), T4 (11.6 Ma), T5 (15.5 Ma) and T6 (23 Ma).

Figure 3 Bathymetric map(A), depositional sections (B to D), distribution and evolution since the Late Miocene (E and F) of the Central Canyon System in the northwestern margin of the South China Sea; The location of bathymetric map A is indicated within Figure 1A; LD = Ledong Sag, LS = Lingshui Sag, SN = Songliao Sag, BD = Baodao Sag, CC = Changchang Sag.

Figure 4-1 Bathymetric map (A) and depositional sections (B to D) of the Pearl River Canyon System in the north margin of the South China Sea; The location of bathymetric map A is indicated within Figure 1A; MTD = Mass-transport deposit.

Figure 4-2 Distribution and evolution since the Middle Miocene (E to H) of the Pearl River Canyon System in the north margin of the South China Sea; The location of bathymetric map is indicated within Figure 1A.

Figure 5 Bathymetric map (A) and depositional sections (B to E) of the Penghu-Gaoping (Formosa-Penghu-Gaoping) Canyon System in the northeastern margin of the South China Sea (modified from Hsiung et al., 2015a; 2011); The location of bathymetric map A is indicated within Figure 1A.

Figure 6 Depositional architecture and evolution model of the Central Canyon System (a single canyon-fill sequence); MTDs = Mass-transport deposits, Sq1/2/3/4 = Sequence 1/2/3/4, LST = Low-stand system tract, TST = Transgressive-stand system tract, HST = High-stand system tract.

Figure 7 Depositional architecture and evolution model of the Pearl River Canyon System (multi canyon-fill...
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