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Controls of contour currents on intra-canyon mixed sedimentary processes: Insights from the Pearl River Canyon, northern South China Sea

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ABSTRACTS

Contour currents are ubiquitous in global oceans, the role of which in shaping submarine morphology and controlling deep-water sedimentary processes has long been underestimated. This study uses 3D seismic and piston-core data to investigate the seismic geomorphology and lithofacies within the upper segment of the Pearl River Canyon (PRC), northern South China Sea, to better understand the mixed sedimentary processes within the submarine canyons. Within the upper segment of the PRC, various morphosedimentary features are recognized according to their seismic expressions in map and section views, including gravity flow-dominated (slope failures, turbidity channels and gullies) and contour current-dominated features (contourite drifts, contourite channels, contourite terrace, and sediment waves). The piston cores contain abundant shelf-derived coarse sediments within several contourite intervals, implying that the contourites were very likely sourced from pre-existing gravity-flow deposits. AMS 14C dating results further indicate that the contourites were mostly deposited during and after the last glacial maximum (LGM), suggesting active gravity flows during the same period. Silt-free sandy contourites are preferentially observed at the canyon thalweg, which may be related to intense contour currents. All the above evidence implies that the study area was influenced by mixed sedimentary processes, including gravity flows and vigorous contour currents. Further analyses suggest that the South China Sea Branch of Kuroshio (SCSBK) and Intermediate Water Current (IWC) greatly influenced the late Quaternary sedimentary processes within the PRC. Specifically, the SCSBK was responsible for the formation of the upper-slope contourites and associated contourite channels near the shelf edge. The SCSBK also promoted the occurrence of upper slope failures and gravity flows when the sea level was much higher than the shelf edge, and contributed to the LGM and post-LGM gravity-flow deposits. In contrast, the IWC was responsible for the formation of contourite drifts along the southwestern flank of the PRC. The IWC intensified when flowing along the canyon thalweg and fault scar, contributing to the formation of contourite channel. Under the influence of winnowing processes from the intense IWC, silt-free medium sands are exposed at the canyon thalweg. The mixed sedimentary processes that are highlighted in this study may have been a potentially underestimated mechanism in explaining the formation of high-quality deep-water sands within submarine canyons.

1. Introduction

Two major sedimentary processes dominate deep-sea settings, including gravitational (e.g., turbidity currents and sediment mass failures) and contourite processes (e.g., contour currents, internal waves/tides, deep-sea storms) (Cacchione et al., 2002; Pomar et al., 2012; Stow et al., 2013; Talling, 2014; Kneller et al., 2016; Rebesco et al., 2017). These processes could occur concurrently or alternately

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under various external conditions, such as climate, sea level, and tectonic activities (Mulder et al., 2006; Mosher et al., 2017). Although many previous studies have emphasized the role of turbidity currents and sediment mass failures in shaping deep-sea topography and sedimentation (Mutti and Normark, 1987; Piper and Normark, 2009; Talling, 2014; Kneller et al., 2016), recent publications indicated that various types of bottom currents can be equally important (Cacchione et al., 2002; Gaudin et al., 2006; Viana et al., 2007; Rebesco et al., 2014 and 2017). Unlike gravity flows, which are catastrophic in nature, contour currents are persistent and can chronically affect other deep-water sedimentary processes, which should not be neglected when assessing submarine hazards, predicting deep-water reservoirs, and decoding the Earth's evolutionary history (Rebesco et al., 2017).

Three major aspects regarding the influences of contour currents on deep-water sedimentary processes have been documented. First, contour currents can remove previously deposited fine-grained sediments when the shear stresses of the contour currents are greater than the critical shear stresses of seafloor sediments, which is called “winnowing” (McCave et al., 1995 and McCave and Hall, 2006; Mulder et al., 2006, 2013; Brackenridge et al., 2018). Second, intense contour currents can erode continental slopes by destabilizing the slope stability and increasing the likelihood of submarine landslides. This phenomenon can be achieved by the exposure of underlying aquifers and the inducement of water sapping (Hampton and Lee, 1996; Viana et al., 2007; Prieto et al., 2016). Third, contourites with high sedimentation rates are prone to collapse and generate gravity flows under certain triggering events, such as tectonic activities, gas-hydrate dissociation or vertical fluid flows (Bryn et al., 2005; Mulder et al., 2009; Martorelli et al., 2016; Elger et al., 2017; Wang et al., 2017). Despite advancements in the understanding of bottom currents and gravity flows, the mixed effects of these phenomena are still poorly known, especially the specific contribution from each process on the final deposits. Previously, researchers mostly focused on individual interactive processes (Mulder et al., 2006; Preu et al., 2013; Brackenridge et al., 2013, 2018; Martorelli et al., 2016; Elger et al., 2017). However, systematical studies that focus on the controls of contour currents on the aforementioned mixed sedimentary processes in the same area are still missing, which hampers our understanding of the occurrences of submarine geohazards and the distribution of deep-water reservoirs.

The Pearl River Canyon (PRC) is one of the most prominent features with negative relief on the northern South China Sea (SCS), transferring a large number of sediments from the shelf to the deep sea (Fig. 1) (Ding et al., 2013). The PRC lies against the late Quaternary shelf-edge delta to the north, and multiple late Quaternary shelf channels have supplied sufficient sediment to the PRC (Lüdmann et al., 2001; Zhuo et al., 2015). Previous studies proved the role of the Intermediate Water Current (IWC) in the sedimentary evolution of the northern SCS margin since the Middle Miocene (Li et al., 2007; Li et al., 2013; Wang et al., 2013; Chen et al., 2014; Sun et al., 2016). A group of regularly spaced slope canyons formed on the northern flank of the PRC under the interaction of downslope gravity currents (mainly fed by shelf-edge delta-front failures) and along-slope contour currents (IWC) (Fig. 1) (Zhu et al., 2010; Li et al., 2013; Zhou et al., 2015; Ma et al., 2015; Jiang et al., 2017; Lin et al., 2017). Thus, the morphologically complicated PRC is potentially an ideal natural field to gain knowledge of mixed sedimentary processes among gravitational and contourites sedimentary processes.

By using newly acquired 3D seismic data and piston cores, this study aims to 1) show the seismic geomorphologies and sediment facies in the upper segment of the PRC, 2) reveal the distribution of different sedimentary processes in the study area, and 3) highlight the controls of contour currents on the mixed sedimentary processes within the PRC.

2. Regional setting

2.1. Geological background

The SCS is a typical semi-closed marginal sea, the evolution of which has been jointly influenced by the Eurasian, Pacific and Australia-India plates. The seafloor spreading of the SCS initially started at ca. 33 Ma in the northeastern SCS, and the spreading center jumped ca. 20 km southwards and triggered a second phase of spreading in the Southwest Subbasin at ca. 23.6 Ma (Li et al., 2014). The seafloor spreading stopped at ca. 15 Ma in the East Subbasin and ca. 16 Ma in the Southwest Subbasin (Li et al., 2014). A ridge jump at ca. 23.8 Ma resulted in a rapid subsidence stage for the Baiyun Sag, which is the deepest sag along the northern margin of the SCS (Fig. 1) (Zhang et al., 2014). Thus, the shelf edge jumped from Baiyun Sag's south margin to its northern margin after ca. 23.8 Ma (Pang et al., 2007), and the persistent and rapid subsidence changed the Baiyun Sag to a constant negative topography with a relatively steeper and unstable upper slope. Multiple phases of lowstand slides, slumps, and downslope gravity currents flowed into the Baiyun Sag and eroded the slope, resulting in the initiation of PRC since ca. 21 Ma (Ding et al., 2013; Sun et al. 2017a and 2018). The continental slope, which has been influenced by neotectonic activities (i.e., Dongsha Movement) in the northern SCS since the late Miocene, is unstable, and some deep-seated faults have penetrated the seafloor during the late Quaternary (Lüdmann and Wong, 1999; Lu et al., 2017; Wang et al., 2017).

The PRC has been dominated by a deep-water slope sedimentary environment since the Miocene (Pang et al., 2007). Multiple stages of shelf-edge deltas developed when the sea level dropped near or below the shelf edges at ca. 23.8 Ma, ca. 21 Ma, ca. 13.8 Ma and the late Quaternary (Lüdmann et al., 2001; Lin et al., 2017; Jiang et al., 2017). These shelf-edge delta fronts were prone to collapse and trigger downslope gravity currents to erode the slope, forming slope channels, canyons and fans (Zhu et al., 2010; Zhou et al., 2015; Jiang et al., 2017; Wang et al., 2017). During the late Quaternary, at least four major phases of lowstand deltas developed to the north of the PRC. The second-to-last lowstand delta was a shelf-edge delta that formed from Marine Isotope Stage (MIS) 7 to MIS 6, and its shoreline is the present shelf edge (Lüdmann et al., 2001). However, the last lowstand delta was limited in the inner-middle shelf during the last glacial maximum (LGM), at the end of which the sea level was ca. 120 m below the present sea level and ca. 100 m above the paleo-shelf edge and the paleo-shoreline was ca. 100 km from the paleo-shelf edge (Lambeck and Chappell, 2001; Lüdmann et al., 2001; Liu et al., 2016a).

2.2. Oceanographic settings

As a semi-enclosed basin, the SCS develops basin-scale deep-water clockwise circulation (Deep Water Current, DWC) and anti-clockwise intermediate water circulation (Intermediate Water Current, IWC) (Fig. 1) (Tian et al., 2006; Qu et al., 2006). The surface circulation of the northern SCS has been largely influenced by the seasonal East Asian Monsoon and Kuroshio intrusion during the Quaternary (Wang and Li, 2009; Liu et al., 2016a, 2016b). The southwestward winter monsoon is always stronger than the northeasterly summer monsoon (Wang and Li, 2009). One branch of the Kuroshio, the South China Sea Branch of Kuroshio (SCSBK), intrudes into the SCS through the Luzon strait, and its maximum speed can reach 30 to 50 cm/s when flowing westwards along the northern margin of the SCS (Hu et al., 2000; Luan et al., 2012). In-situ measurements (E114°, N20°) showed that the average westward velocity of the SCSBK is ca. 23 cm/s at a water depth of 200 m in the upper segment of the PRC, and the velocity decreases with increasing water depth (Fig. 1) (Qiu et al., 1984). The SCSBK weakens the summer northeastward surface circulation but strengthens the southwestward surface circulation during winter (Fig. 1) (Luan et al., 2012; Zhuo et al., 2014). Previous studies showed that the interfaces between