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Deep-water sedimentary systems and their relationship with bottom currents at the intersection of Xisha Trough and Northwest Sub-Basin, South China Sea

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ABSTRACT

Based upon 2D reflection seismic data and numerical modelling, this study confirms the presence of a complex deep-water sedimentary system on the present-day seafloor at the intersection of the Xisha Trough and the Northwest Sub-Basin (South China Sea) and investigates their relationship with bottom currents. The deep-water sedimentary system consists of submarine canyons, slides and slumps, wave-like successions, mounded drifts and two groups of marginal depressions (those with erosional features and those appearing as morphological sediment sinks). Three-dimensional process-based modelling is applied to investigate sediment dynamics induced by a combined effect of tidal currents and a quasi-steady geostrophic current (South China Sea Deep Water Circulation). Simulation results show that the South China Sea Deep Water Circulation at the southeastern flank of the seamount plateau could reach velocities of 15 cm/s during flood tides, enabling erosion and transport processes. In contrast, the rest of the plateau area is favoured for deposition, since current velocities in this region are persistently lower than 10 cm/s. The current velocities at the feet of the obstacles (where the morphological depressions are located) are strengthened and are several cm/s higher than that in adjacent flat areas (e.g. where the mounded drifts are located). The flow is constricted and accelerated after being deflected by the obstacles, resulting in contrasting higher sedimentation rates within the mounded sediments and lower rates at the morphological depressions. A comparison between the seismic stratigraphy and the simulated fluid dynamics enables a decoding of the pathway, identifying the current regime as well as unravelling the relationship between depositional processes and the deep-sea water circulation. This study provides new insights and exposes new challenges in understanding the dynamics of deep-sea sedimentation processes in South China Sea.

1. Introduction

Due to recent technological advances, the knowledge of deep-sea sediments and their processes is rapidly improving (Mulder et al., 2011). Within the deep-sea, contourites, turbidites and pelagites represent end-members in a continuum of deep-sea sedimentary facies (Rebesco et al., 2014). An intensive collaboration between geologists and physical oceanographers is highly encouraged to investigate alongslope and downslope sedimentary systems from a combined perspective of sedimentology and fluid dynamics (Rebesco et al., 2014). Although numerical or sand-box modelling has been applied to simulate turbidite processes (e.g., Salles et al., 2008; McHargue et al., 2011), modelling of depositional and erosional processes is still in a maturing stage. It requires more detailed, high-resolution in-situ observations as well as interpretations of 3D seismics, multibeam and backscatter data to compare the modelling results to (Palomino et al., 2011; Campbell and Deptuck, 2012; Sweeney et al., 2012; Van Haren et al., 2013). Integrated acoustic and oceanographic data have been used to analyse and simulate the specific hydrodynamic conditions of contouritic activities (Preu et al., 2011, 2012; Hernández-Molina et al., 2014; Hanebuth et al., 2015). It yields significant advances to (1) understand contourite depositional system evolution, (2) identify oceanographic processes

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affecting contouritic transport, and (3) correlate these processes with seafloor morphological features.

The northern South China Sea (SCS) provides an ideal laboratory to investigate deep-water depositional processes and their relationship with deep-sea circulations. On one hand, modern physical oceanographic observations have confirmed the existence of a complex system of deep-sea currents in the northern SCS (e.g., Metzger and Hurlburt, 1996; Chao et al., 1996; Chu et al., 1999; Liu et al., 2001; Su, 2004; Gan et al., 2006; Wang and Li, 2009; Wang et al., 2011; Lan et al., 2013; Xiao et al., 2013; Xie et al., 2013). On the other hand, various types of deep-water sedimentary systems, e.g., canyons, mass wasting transport deposits (MTDs), turbidites and contourites, have been discovered in this region (Lüdmann et al., 2005; Pang et al., 2006, 2007; Shao et al., 2007; Wang, 2007; Liu et al., 2009; Su et al., 2011, 2014; Ding et al., 2013; Li et al., 2013; Chen et al., 2014; H. Chen et al., 2015). Although it is conceptually clear that seafloor topographies and bottom currents have a significant control on each other, quantitative investigations on the development and evolution of deep-water sedimentary systems and their relationship with alongslope bottom current circulation in this region are still missing.

By focusing on the intersection of the Xisha Trough and the Northwest Sub-Basin in the northern SCS, this study aims to unravel the relationship between deep-water depositional processes and bottom current activities in the northern SCS. The study consists of summarizing the depositional characteristics and distribution of recent deep-water sedimentary systems through 2D reflection seismic data, and analysing the effects of specific hydrodynamic conditions and bottom-current activities on sediment dynamics by means of 3D process-based numerical simulations. The verification of the simulated fluid dynamics by comparing them to the seismic stratigraphy could provide new insights into deep-sea sediment dynamics within the SCS.

2. Regional setting

2.1. Geological background

The northern SCS consists of the northern part of the Central Sub-Basin, the Northwest Sub-Basin, the Xisha Trough and a series of Cenozoic rift basins on the SCS northern margins (e.g., the Qiongdongnan Basin containing the Central Canyon System as well as the Pearl River Mouth Basin containing the Outer Pearl River Canyon System) as major components (Fig. 1A). The key study area (about 17.5° N to 18.5° N and 113° E to 114° E) is located on a seamount plateau with water depths ranging from 200 m to over 3000 m (Fig. 1B, C). It is bounded by the Northwest Sub-Basin in the east, the Xisha Trough in the north, the Pearl River Mouth Basin in the northeast and the Xisha Uplift in the southwest (Fig. 1A).

The Northwest Sub-Basin opened from 32 Ma to 30 Ma (Sun et al., 2006) (Fig. 1A). The northern SCS experienced a rifting stage (from about 65 Ma until 30 Ma in the Pearl River Mouth Basin and until 23 Ma in the Qiongdongnan Basin) and then a post-rift subsiding stage (Ru and Pigott, 1986; Chen et al., 1994; Li et al., 2009; Wang and Li, 2009; Zhu et al., 2009). During the SCS regional transgression, a deep-water sedimentary environment was gradually introduced in the northern SCS from the Early Miocene onwards. In the study area, a deep-water setting was present no later than the Late Miocene (Chen et al., 1994; Wang et al., 2003; Shao et al., 2004; Li et al., 2009; Su et al., 2009, 2014; Xie et al., 2011; He et al., 2013). Seamounts of mafic volcanic rocks are scattered around the Northwest Sub-Basin (Fig. 1A). They formed mostly during the post-spreading stage and have been active since the Late Miocene, reaching a peak during the Late Pliocene–Pleistocene (Mao et al., 2015). During the Pliocene and Quaternary, gravity flow deposits (e.g., MTDs and turbidites) with sources in the northern slopes dominantly developed within the Xisha Trough as well as in the Outer Pearl River Canyon System (He et al., 2011; Su et al., 2011; Ding et al., 2013).

2.2. Oceanographic framework

The present-day SCS oceanography is composed of three major water masses, specifically, the SCS Surface Water, SCS Intermediate Water and SCS Deep Water (SDW) (Wyrtki, 1961; Faughn, 1974; Wang and Li, 2009). The range of the SCS Intermediate Water mass (which generally moves anti-cyclonic in the northern SCS) has not been well constrained (Chen, 2005; Lüdmann et al., 2005; Zhao et al., 2009; Zhu et al., 2010; Li et al., 2013; Wang et al., 2013; Xie et al., 2013). But it is widely accepted that the SCS Surface Water mass (moving cyclonic in winter and anti-cyclonic in summer) generally occurs above 350 m depth, and that the SDW (cyclonically circulating) occurs below 1500 m depth (Chen and Wang, 1998; Yuan, 2002; Qu and Lindstrom, 2004; Wang and Li, 2009; Xie et al., 2009a; Xu et al., 2014).

Influenced by the southwestward intrusion of the Northern Pacific Deep Water through the Luzon Strait, the average bottom current velocity exceeds 0.15 m/s at water depths of 2500 m to 2600 m in the Bashi Channel, with maximum velocities reaching 0.3 m/s (Xie, 2009; Xie et al., 2009a, 2009b) (Fig. 1A). About 100 km west of the Luzon Strait, a stream of southwestward flowing currents with velocities of 0.02 m/s to 0.05 m/s has been recently observed in the vicinity of ODP Site 1144, at water-depths of 1800 m to 1900 m (Z.F. Liu, personal communication). During its westwards flow, the SDW bottom currents sweep the SCS northern margins until they encounter the Xisha Trough.

3. Material and methods

3.1. Seismic data acquisition

A dataset, provided by the China National Offshore Oil Corporation, of over 450 km multichannel 2D airgun reflection seismic profiles, covering an area of about 6000 km^2 at the intersection of the Xisha Trough and the Northwest Sub-Basin was analysed. All the seismic profiles (Fig. 1C) are oriented either NNW–SSE (about 3 km to 6 km spacing) or ENE–WSW (about 2 km to 8 km spacing). Using a P-wave velocity of 1500 m/s for the water column, the vertical scale of these profiles was converted from two-way travel time (s) to depth (m) for quantifying seabed morphologies. The seismic signals were generated using a Bolt Longlife Airgun (3850 cubic inches) by means of compressed air (2000 psi). The record length and sampling rate were set at 11,996 s TWT and 2 ms, respectively. The acquired signals were recorded within 396 channels using a fold of 99, and lied in the frequency range of about 60 Hz, allowing a vertical resolution of up to 3 m. The data was processed through the Omega V1.8.1 software, applying a band-pass filter (ranging from 6 Hz of low-cut frequency and 12 dB/s of low-cut slope to 136 Hz of high-cut frequency and 276 dB/s of high-cut slope), a de-noising and amplitude compensation and a Kirchhoff post-stack time migration. After processing, the seismic data was loaded into a Geoframe (V4.5, 64-bit) project for horizon picking, seismic stratigraphy and sediment dynamic interpretations.

3.2. Model simulations

The world ocean temperature and salinity profiles from 1990 to 2012, obtained from the Coriolis Ocean Database for ReAnalysis (Cabanes et al., 2013), were used to constrain the local water mass stratification at the intersection of the Xisha Trough and the Northwest Sub-Basin. These data were visualized using the Ocean Data View software (V4.6.5, 64-bit). A first understanding of the general deep-water flow patterns (at 2000 m and 3000 m water depth, respectively) in the study area was derived from the Hybrid Coordinate Ocean Model and Navy Coupled Ocean Data Assimilation global 1/12° Analysis (GLBa0.08, http://hycom.org/dataserver/glb-analysis) developed by the Naval Research Laboratory of U.S. Navy. The Hybrid Coordinate Ocean Model is designed as a generalized (hybrid of isopycnal) coordinate ocean model (Bleck, 2002). The K-Profile Parameterization mixing