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Recurrent slope failure enhancing source rock burial depth and seal unit competence in the Pearl River Mouth Basin, offshore South China Sea

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ABSTRACT

High-quality 3-D seismic data are used to assess the significance of mass-transport deposits (MTDs) to the evolution of the Pearl River Mouth Basin (South China Sea). Basal shear surfaces and lateral margins of seven recurrent MTDs are mapped to reveal a general NE-SW transport direction throughout the Late Miocene-Quaternary. A key result of our analysis is the perceived relationship between the recurrence of slope instability in the study area and the Dongsha Tectonic Event. Using borehole data to constrain the ages of interpreted MTDs, we show that tectonic uplift in the northern South China Sea led to slope oversteepening in the Late Miocene (between 10.5 Ma and 5.5 Ma), preconditioning it to fail recurrently for more than 10 Ma. Interpreted MTDs are shown to enhance burial depths of source and reservoir units, and improve seal competence in lower-slope areas. Conversely, upper slope regions record important erosion and reduced sealing capacity in Late Cenozoic strata. As a result, we postulate that the thickness variations imposed by MTDs on Late Miocene-Quaternary strata have important implications to petroleum plays in the South China Sea.

1. Introduction

Mass-transport deposits (MTDs) are ubiquitous on continental margins and play a vital role in redistributing vast amounts of sediment into deep-water areas (Masson et al., 2006; Bull et al., 2009). Recent data have also demonstrated that MTDs provide an important contribution to slope architecture and infill on both passive and tectonically active continental margins (Bache et al., 2011; Strasser et al., 2011). In these settings, MTDs can comprise reliable stratigraphic markers of tectonic activity. For instance, MTDs appear to be reliable markers of breakup events on continental margins (Soares et al., 2014). They are also competent markers of seafloor uplift and deformation in any tectonic setting (Alves et al., 2014). Significantly, MTDs comprising mud prone successions or homogeneous debris flows can act as seal units for underlying petroleum reservoirs (Moscardelli et al., 2006).

The northern South China Sea is a key area in SE Asia where MTDs are known to accumulate on the outer shelf and continental slope areas (Li et al., 2014). Possible triggers of mass-wasting include high sedimentation rates, abrupt sea level variations and, as argued in this paper, slope oversteepening and enhanced seismic activity during the Dongsha Tectonic Event. As one of the most effective methods to recognise both buried and modern mass-waste deposits (e.g.,Gong et al., 2014), 3-D seismic data are used in this paper to investigate a series of MTDs located in the southwest part of the Dongsha Uplift (Fig. 1b). We use a high-quality 3-D seismic data, tied to borehole stratigraphic information, to demonstrate that the Pearl River Mouth Basin experienced three main episodes of tectonic uplift during the Cenozoic; the Nanhai, the Baiyun and the Dongsha Events (Dong et al., 2009). While the Nanhai and Baiyun tectonic events are well documented in the literature, little is known about the Dongsha Event and its impact on offshore basins of South China Sea. The aims of this study are thus (1) to briefly describe the recurrent MTDs observed in the Pearl River Mouth Basin; (2) to estimate the age of these recurrent MTDs; (3) to tentatively correlate these MTDs with a major tectonic event in the South China Sea, i.e., the Dongsha Event; and (4) to discuss the influence of these MTDs (and associated tectonic event) on petroleum systems of the Pearl River Mouth Basin.

2. Data and methods

The interpreted 3-D seismic volume was acquired and processed by China National Offshore Oil Corporation. The volume is located southwest of the Dongsha Islands (Fig. 1a), in water depths between 1400 m and 1800 m (Fig. 1b). It covers an area of approximately 600 km^2 with a bin size of 12.5 m × 12.5 m. Its frequency bandwidth

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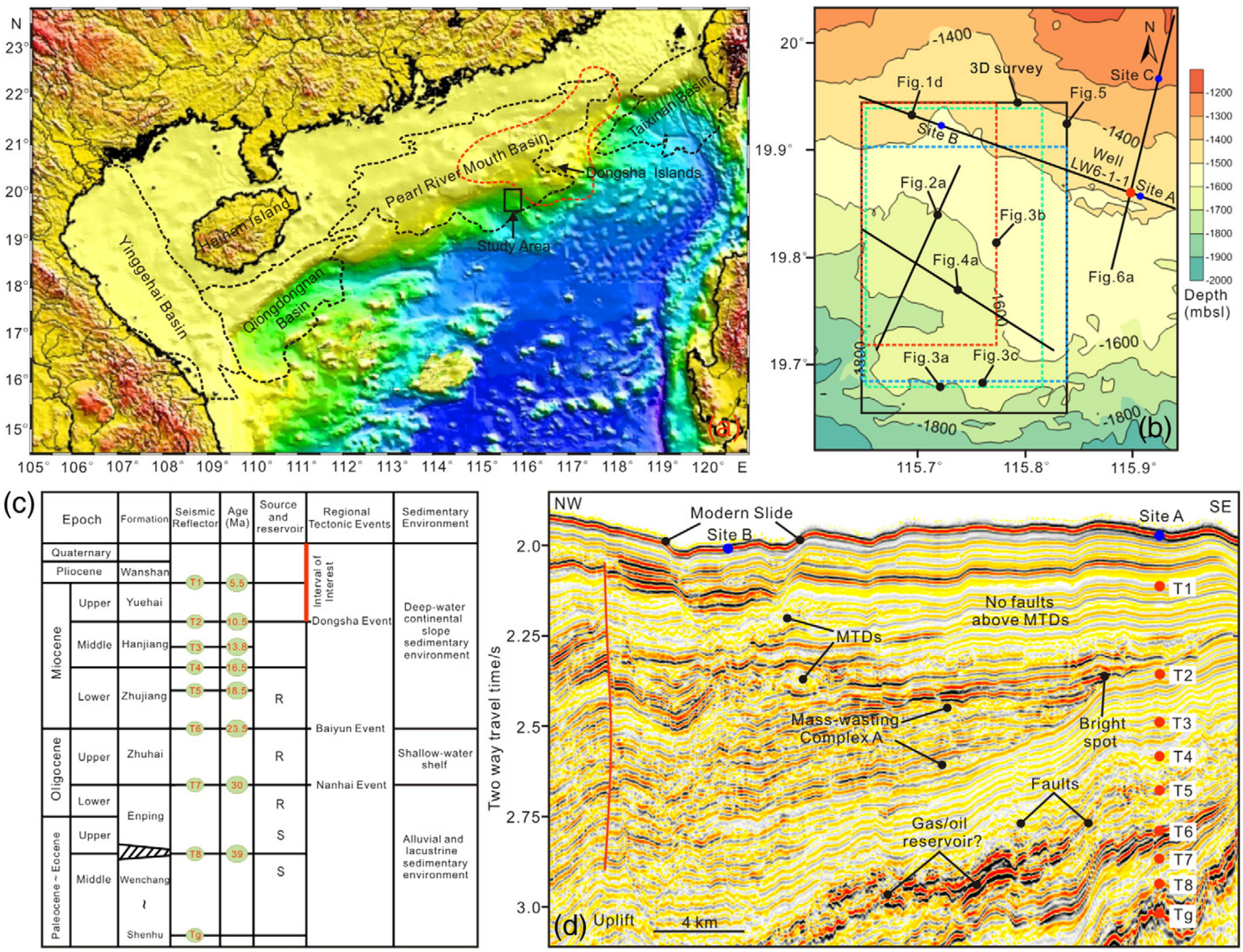

Fig. 1. (a) Combined bathymetric and topographic map showing the locations of major Cenozoic basins in the northern South China Sea. The black box indicates the study area. The red dotted line represents the region affected by Dongsha Event (modified after Sun et al., 2013; Wu et al., 2014; Zhao et al., 2012). (b) Depth contour map of the study area (see location in Fig. 1a). The black box marks the location of the interpreted 3-D seismic volume. Black solid lines highlight the 2D profiles shown in this paper. The location of well LW6-1-1 used to constrain the seismic stratigraphy in the study area is also shown. (c) Schematic stratigraphic columns of the Pearl River Mouth Basin showing source rock, reservoir, tectonic event and sedimentary environments (modified after Li, 1993).(d) 2-D seismic profile across MTD-prone regions in the Pearl River Mouth Basin showing eight main seismic sequences. The ages of the seismic surfaces are determined from Well LW6-1-1 and data from Sun et al. (2013) and Wu et al. (2014). Note the presence of a Mass-Wasting Complex A within Late Miocene strata (between T1 and T2) deposited above a brightened interval, likely to comprising hydrocarbon accumulations.

ranges from 45 to 100 Hz, with a dominant frequency of 75 Hz. Average vertical resolution for the studied interval is 8-10 m.

Borehole LW 6-1-1 and data from four other industry wells were used to tie nine stratigraphic unconformities to the seismic data (Fig. 1c and d; Sun et al., 2013; Wu et al., 2014). In parallel, three key horizons (Horizon 1 to 3) were mapped in detail. Time structure maps of basal shear surfaces were extracted from the 3-D seismic dataset to characterize the source areas and geometries of MTDs.

Different fault families were identified on coherence data and manually mapped. In parallel, throw-depth (t–z) techniques were used to analyze the propagation histories of Late Cenozoic faults in the study area (e.g., Baudon and Cartwright, 2008).

3. Geological setting

As one of the largest and deepest marginal seas in the SE Asia, the South China Sea records complex tectonic events that reflect its location between the Eurasian, Pacific and Australia-India plates (Briais et al., 1993). The Pearl River Mouth Basin lies on the northeastern continental margin of the South China Sea and spans an area larger than 40,000 km^2 (Fig. 1a). The Pearl River Mouth Basin is one of the most prolific hydrocarbon-rich basins of the South China Sea (Dong et al., 2009; Zhu et al., 2009). Its geological evolution can be divided into three main phases (Gong et al., 1989): (1) early continental rifting and onset of subsidence (Late Cretaceous–Early Oligocene); (2) syn-rift faulting, subsidence and deposition within distinct sub-basins (Late Oligocene–Early Miocene); and (3) post-rift subsidence and infill of the entire basin, occurring from the Mid Miocene onwards. Rifting in the South China Sea began during the Nanhai Event, which occurred ~32 Ma ago (Dong et al., 2009). The Baiyun episode took place at ~23 Ma and separates syn-rift from post-rift sequences (Dong et al., 2009). After seafloor spreading ceased at ~16.5 Ma, shallow marine deposits dominated the subsequent deposition of the Hanjiang Formation. In such a setting, the Dongsha Event occurred in the Late Miocene (10.5-5.5 Ma) and ceased around the Miocene/Pliocene boundary (5.5 Ma) (Wu et al., 2014; Zhao et al., 2012). The Dongsha Event resulted in generalised uplift of the northern slopes of the South China Sea, upper crust faulting, erosion and in widespread magmatism. These