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Palaeotsunami in the East China Sea for the past two millennia: A perspective from the sedimentary characteristics of mud deposit on the continental shelf

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ABSTRACT

Palaeotsunami studies have revealed that a great tsunami occurred in the South China Sea (SCS) and hit Xisha Archipelago a thousand years ago, suggesting the risk of tsunami hazard in this region. However, knowledge about palaeotsunamis in the East China Sea (ECS) is still limited. In this study, the grain size sequence of a marine sediment core was analyzed and the history of tsunamis in the East China Sea for the past two millennia is presented. We first conducted a numerical simulation of the SCS tsunami to see its impact on the ECS. The results suggest that the impact of an M_w 8.0 earthquake-induced tsunami is small. For the sediment core, according to its mean grain size distribution, the sediments were formed by two components, the <57.8 μm fraction and the >57.8 μm fraction, consisting about 90% and 10% of the core. The most significant change in the grain size sequence of the <57.8 μm fraction is consistent with the SCS tsunami temporally and this might be the result of the westward transportation of coarse grains by the tsunami. For other abrupt changes in the grain size sequence, they have not exhibited greater amplitudes than the tsunami-affected layer, indicating that the impact of the SCS tsunami was the most significant during this period. Thus, the East China Sea has not been struck by great tsunamis in the past two millennia. For palaeotsunamis occurring before the late-Holocene, more studies based on various proxies are required to reveal their history.

1. Introduction

The great tsunamis triggered by the 2004 M_w 9.0 Sumatra-Andaman earthquake and 2011 M_w 9.1 Tohoku-oki earthquake led to severe damage and casualties in Indonesia (Satake et al., 2006) and Japan (Mori et al., 2011). The coasts of China were also slightly impacted by the Japan tsunami. A blue tsunami warning was issued by the National Marine Environmental Forecasting Center 20 min after the earthquake. The initial tsunami wave arrived at the southeast coast of China about 6–8 h after the earthquake and tidal gauges along the coasts of Zhejiang, Fujian and Guangdong recorded sea surface elevations ranging from 10 to 55 cm (Wang et al., 2012). Although the global frequency of magnitude 9 or larger earthquakes was estimated merely to be one to three per century (McCaffrey, 2008) and not all giant earthquakes can generate devastating tsunamis (Gusiakov, 2011), the frequent occurrence of such disasters during the past decade and their destructive impacts over the disaster areas urged that more attention should be paid towards such events to gain clear insights into their process and influence and to mitigate their disastrous impacts.

The study of palaeotsunamis can help to understand their frequency, intensity and influence on coastlines (Scheffers and Kelletat, 2003). Onshore tsunami deposits have revealed mid-to late-Holocene records of tsunamis occurring along the west coast of North America (Graehl et al., 2015; Nelson et al., 2008), the Kuril trench (Nanayama et al., 2003), east coasts of Japan (Fujiwara et al., 2000; Kitamura et al., 2013; Sawai et al., 2008) and New Zealand (Clark et al., 2011; Cochran et al., 2005; Goff et al., 2001; Wallace et al., 2014) as well as the Asian section of the Indian Ocean Rim (Jackson et al., 2014; Monecke et al., 2008). Although their damage could not be depicted clearly due to the limitation of the sedimentary records, these studies have warned us of the risk of tsunami hazard along the Pacific coast (Satake and Atwater, 2007).

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Despite the negligible impacts from the recent 2010 Chilean tsunami (triggered by an M_w 8.8 earthquake, the third largest in this century) and 2011 Japan Tsunami (Wang et al., 2012; Yu et al., 2011; Zhang et al., 2011), China is also vulnerable to tsunami hazard (Jing et al., 2013; Liu et al., 2007b; Suppasri et al., 2012) as the Ryukyu and Manila subduction zones lie along the eastern edges of the East and South China Seas. Studies based on tsunami deposits (Sun et al., 2013; Yu et al., 2009) and historical documents (Lau et al., 2010; Liu et al., 2009b; Mak and Chan, 2007) indicated that the South China Sea and its surrounding coasts have been struck by tsunamis in the past. Based on the coarse-fraction (>1 mm in mean grain size) content and sedimentation rate in a lagoon core from Yongshu Reef, Nansha Islands, Yu et al. (2009) proposed that strong storm or tsunami events occurred at 1872 ± 15, 1685–1680 ± 8, 1443 ± 9, 1336 ± 9, 1210–1201 ± 3 and 1064 ± 30 AD in the southern South China Sea. However, they did not distinguish tsunami deposits from storm deposits. Sun et al. (2013) studied a sediment core derived from Dongdao Island, Xisha Archipelago. A 10-cm-thick layer of coral sand was found in the core and the radiocarbon ages of caryopsis in the upper and lower boundaries of this event layer, ranging from 1017 AD to 1034 AD, were almost identical. Besides, heavy coral and fossil shells were transported more than 200 m inland. They proposed that these were the results of a high-energy event such as a tsunami. Intriguingly, a strong event recorded in Chinese historical literature caused damage to the coast of Guangdong in 1076 AD and was suspected to be a tsunami (Lau et al., 2010). All these evidences support the risk of tsunami hazard in the South China Sea.

The tsunami history in the East China Sea, however, is not well understood. Onshore deposits indicative of palaeotsunamis in the South China Sea were mainly discovered on uninhabited small islands, where preservation potential of the deposit is higher. The human activity in the coastal regions of East China Sea has introduced disturbance to the preservation of sediments, making the reconstruction of the tsunami history difficult. Offshore deposits are proved capable of providing information on tsunamis (Arai et al., 2013; Feldens et al., 2012; Ikehara et al., 2014; Sakuna et al., 2012), offering us an opportunity to extend our knowledge about tsunamis. In this paper, we seek to uncover the history of palaeotsunamis in the East China Sea during the past two millennia by using a marine sediment core. As the 1024 AD South China Sea tsunami has been previously documented (Sun et al., 2013), we conducted a numerical simulation of this event to evaluate its impact on the East China Sea. An offshore sediment core, in which the record of this event was identified, was used to reconstruct the palaeotsunami history of the East China Sea.

2. Material and methods

2.1. Sample collection

Muddy sediment core T08-A was collected at site T08 (Fig. 1) with a gravity corer in 2011 on the research vessel *Dongfanghong II* (Ocean University of China). The coring site (28° 30.2′ N, 122° 28.3′ E) was on the mud belt depositing over the inner continental shelf of the East China Sea and the water depth was 64.6 m. The 2.2-m-long core was grey and mainly consisted of clayey silt. We sliced the core at 1 cm interval on the ship and obtained 220 samples. Samples were preserved at −10 to −6 °C and air-dried before analysis. Due to the disturbance of the gravity corer, analysis results of the upper 30 cm section will not be discussed in this study.

2.2. Radiocarbon dating and grain-size tests

Benthic foraminifera of various species were picked for radiocarbon dating. Calib 6.1.1 and the Marine04 calibration curve (Hughen et al., 2004) were used for the radiocarbon age calibration. A regional difference from the average global marine reservoir correction (ΔR) of −128 ± 35 yr was obtained from the online ^{14}CHRONO Marine Reservoir Database (http://www.calib.qub.ac.uk/marine/). The calculation of the ΔR was based on reference points No. 416 (36.1° N, 120.3° E, $\Delta R = -81 \pm 60$), 417 (36° N, 126.3° E, $\Delta R = -111 \pm 45$) and 418 (34.7° N, 128.2° E, $\Delta R = -154 \pm 35$) (Kong and Lee, 2005; Southon et al., 2002). Picking of the foraminifera was conducted in South China Sea Institute of Oceanology, Chinese Academy of Sciences and radiocarbon tests in Peking University.

For grain-size analysis, a mixture of 0.1–0.15 g of air-dried sample and 15 mL of H_2O_2 (30%, v/v) was heated at 150 °C for 45 min to remove organic contents. Then 10 mL of HCl (10%, v/v) was added to remove calcareous content. Before measurement, 10 mL of $(NaPO_3)_6$ solution (10%, wt%) was added to the sample and ultrasonic treatment for 1 min was applied to the mixture for an improved dispersion of the grains. The analysis was performed with an LS 13 320 laser diffraction particle size analyzer (Beckman Coulter, Inc.). The analytical range of the analyzer was 0.4–2000 μm and the size resolution was 0.125 ϕ.

2.3. Numerical simulation of the SCS tsunami

Numerical simulation is an effective method for studying tsunami propagation and its inundation in coastal areas. Models such as FUNWAVE (Fully Nonlinear Wave Model; Wei and Kirby, 1995), COMCOT (Cornell Multigrid Coupled Tsunami Model; Liu et al., 1998), MOST (Method of Splitting Tsunami; Titov and González, 1997) and TUNAMI (Tohoku University's Numerical Analysis Model for Investigation; Imamura et al., 1995) have been used in many studies and their validity and reliability are recognized. COMCOT has been used for modeling the impact of the 2011 Japan tsunami upon China (Wang et al., 2012), the tsunami hazards from Manila trench to Taiwan (Wu and Huang, 2009) and assessing the tsunami early warning system in the South China Sea (Liu et al., 2009a). Moreover, this model was treated as a standard for the comparison between the simulation results of various numerical models (Koh et al., 2009). Taking these reasons into consideration, we chose COMCOT to simulate the propagation of the South China Sea tsunami and its impact on the coastal seas of China.

The simulation domain ranged from 100° E to 130° E and 0°–40° N. Bathymetry data covering this domain were extracted from the NOAA ETOPO1 dataset (Amante and Eakins, 2009). Cell size for ETOPO1 was 1 arc-minute and no interpolation was conducted to produce finer bathymetry grids. Hypothesized M_w 8.0 earthquakes on six fault segments along the Manila subduction zone (Fig. 1) were set as tsunami sources. Locations of the epicenters and fault plane parameters were from Liu et al. (2009a). Four tidal gauges were placed at T08 site, Nan'ao Island, Guangdong Province and Dongdao Island, Xisha Archipelago to identify the impact of the South China Sea tsunami. Coordinates of the tidal gauges and water depths are listed in Table 1.

3. Results

3.1. Chronology

The age model of core T08-A (Fig. 2) was constructed using the calibrated radiocarbon dates (Table 2). The calibrated ^{14}C age of the foraminifera picked from the top 4 cm of the sediments was 580 ± 68 yr BP, much older than the age of the section at core depth of 38 cm. This outlier was not used in the construction of the age model and the age of the top was fixed at 2011 AD (−61 yr BP), the

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