ARTICLE IN PRESS

Marine Geology xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Marine Geology

journal homepage: www.elsevier.com/locate/margo

Elemental and mineralogical analysis of marine and coastal sediments from Phra Thong Island, Thailand: Insights into the provenance of coastal hazard deposits☆

Dat T. Pham[a,b], Chris Gouramanis[c,*], Adam D. Switzer[a,b], Charles M. Rubin[a,b], Brian G. Jones[d], Kruawun Jankaew[e], Paul F. Carr[d]

[a] Asian School of the Environment, Nanyang Technological University, 639798, Singapore
[b] Earth Observatory of Singapore, 639798, Singapore
[c] Department of Geography, Faculty of Arts and Social Sciences, National University of Singapore, 117570, Singapore
[d] School of Earth and Environmental Sciences, University of Wollongong, NSW 2522, Australia
[e] Department of Geology, Faculty of Science, Chulalongkorn University, Bangkok 10330, Thailand

ARTICLE INFO

Keywords:
Tsunami deposit
Storm deposit
Provenance
Trace elements
Mineral compositions
Grain size parameters
Cluster analysis
Principal component analysis
Bootstrap analysis
Discriminant function analysis

ABSTRACT

Sediment records left by coastal hazards (e.g. tsunami and/or storms) may shed light on the sedimentary and hydrodynamic processes happening during such events. Modern onshore and offshore sediment samples were compared with the 2004 Indian Ocean Tsunami, three palaeotsunami and a 2007 storm deposit from Phra Thong Island, Thailand, to determine provenance relationships between these coastal overwash deposits. Sedimentological and stratigraphic characteristics are generally inadequate to discriminate tsunami and storm deposits so a statistical approach (including cluster analysis, principal component analysis and discriminant function analysis) was used based on grain size, mineralogy and trace element geochemistry. The mineral content and trace element geochemistry are statistically inadequate to distinguish the provenance of the modern storm and tsunami deposits at this site, but the mean grain size can potentially discriminate these overwash deposits. The 2007 storm surge deposits were most likely sourced from the onshore sediment environment whereas all four tsunami units statistically differ from each other indicating diverse sediment sources. Our statistical analyses suggest that the 2004 tsunami deposit was mainly derived from nearshore marine sediments. The uppermost palaeotsunami deposit was possibly derived from both onshore and nearshore materials while the lower palaeotsunami deposits showed no clear evidence of their sediment sources. Such complexity raises questions about the origin of the sediments in the tsunami and storm deposits and strongly suggests that local context and palaeogeography are important aspects that cannot be ignored in tsunami provenance studies.

1. Introduction

Coastal areas offer favourable conditions to support dense human populations and critical infrastructure (Syvitski et al., 2009). These areas, however, are also vulnerable to coastal hazards, of which tsunamis and storms are the most disastrous (e.g. Switzer et al., 2014). A series of such disasters have occurred in the last decade, including the 2004 Indian Ocean Tsunami (IOT), Hurricane Katrina (2005), Cyclone Nargis (2008), the Tohoku-oki earthquake-induced tsunami (2011), Hurricane Sandy (2012), Typhoon Haiyan (2013) and Hurricane Patricia (2015). These disasters highlight the need for accurate coastal vulnerability assessments including the examination of the recurrence interval of such events. Understanding the recurrence interval of these events is crucial for future risk assessment (e.g., Switzer et al., 2014). Due to the inadequate and short historical records (i.e. frequently < 100 years) in many affected areas, the geological record preserved along coasts may capture a much longer timeframe and provide evidence for historical occurrences and allow the determination of the recurrence intervals of tsunamis (e.g. Minoura et al., 2001; Jankaew et al., 2008; Monecke et al., 2008) and storms (e.g. Liu and Fearn, 2000; Nott, 2011).

Both tsunami and storm deposits are the result of overwash processes caused by high-energy events, and in many cases they exhibit very similar sedimentary signatures (e.g. Kortekaas and Dawson, 2007;

DOI of original article: http://dx.doi.org/10.1016/j.margeo.2017.01.004
☆ This article is a reprint of a previously published article. For citation purposes, please use the original publication details; Marine Geology 385 (2017) 274–292.
* Corresponding author at: Department of Geography, Faculty of Arts and Social Sciences, National University of Singapore, AS2-04-02, 1 Arts Link, Kent Ridge, 117570, Singapore.
E-mail address: geogc@nus.edu.sg (C. Gouramanis).

https://doi.org/10.1016/j.margeo.2018.01.006
Received 27 August 2016; Received in revised form 12 December 2016; Accepted 13 January 2017

Switzer and Jones, 2008). Thus, in order to accurately assess how frequently catastrophic events affect coastal regions, it is necessary to know whether the identified coastal washover deposit was caused by a tsunami or a storm event (e.g. Switzer et al., 2014).

Tsunami and storm deposits have been compared in numerous studies with an expectation of developing a suite of diagnostic criteria to distinguish deposits formed by different coastal overwash processes (e.g. Nanayama et al., 2000; Goff et al., 2004; Tuttle et al., 2004; Kortekaas and Dawson, 2007; Morton et al., 2007; Switzer and Jones, 2008; Phantuwongraj and Choowong, 2012). Nonetheless, criteria that have been used are still problematic and site specific or only valid for known events (Gouramanis et al., 2014b). Many of these studies have relied on sedimentological and stratigraphic signatures that can be found in both tsunamigenic and cyclonic deposits. For example, Shanmugam (2012) reviewed 15 sedimentological criteria that had been found in both tsunami and storm deposits and drew the conclusion that "there are no reliable sedimentological criteria for distinguishing paleo-tsunami deposits in various environments" (p. 23). Gouramanis et al. (2014b) used a multi-proxy approach (granulometric, loss on ignition, heavy minerals and microfossils) to statistically compare the 2004 IOT deposit and 2011 Cyclone Thane deposit superimposed at the same location along the southern coast of India. The Gouramanis et al. (2014b) study indicated that tsunami and storm deposits from the same site could not be distinguished using the standard sedimentological parameters typically used to identify coastal hazard deposits.

Thus, the difficulty of using conventional diagnostic criteria in differentiating coastal washover deposits requires the development of new and novel proxies.

In this study, we seek to test two hypotheses:

1. that the mineral composition, element geochemistry and grain size parameters of modern onshore, nearshore and offshore environments can be used to determine the provenance of the 2004 IOT and paleo-tsunami deposits, and the 2007 storm surge deposit preserved on Phra Thong Island, Thailand (Fig. 1); and
2. that the 2004 IOT, paleo-tsunami and the 2007 storm surge deposits can be distinguished using mineral composition, element geochemistry and grain size parameters.

To investigate these hypotheses, we apply several novel and seldom-used (for coastal hazard deposits) statistical techniques to gain insight into the provenance of the washover deposits and compare the deposits from different events and causal mechanisms (i.e. storm, recent and paleo-tsunami).

To date, little attention has focused on the mineralogy and geochemistry of overwash deposits (Chagué-Goff, 2010 and references therein). It is believed that the geochemical signature and mineral composition of tsunami sediments are source-dependent (Chagué-Goff et al., 2011; Goff et al., 2012), and are expected to reflect the origin of coastal overwash deposits (Font et al., 2013; Chagué-Goff et al., 2015). Addressing these issues will contribute a greater understanding of the sedimentation and hydrodynamic processes (i.e. erosion and deposition) occurring during coastal overwash sediment deposition (e.g. Switzer et al., 2012; Goff and Dominey-Howes, 2013; Sugawara et al., 2014).

2. Site description

Phra Thong Island is approximately 125 km north of Phuket on the west coast of southern Thailand in the Andaman Sea (Fig. 1). Phra Thong Island is characterized by a series of north-south trending, sandy Holocene beach ridges and marshy swales on the western side, and dense tidal mangroves on Pleistocene sand dunes on the eastern side (Jankaew et al., 2008; Brill et al., 2012a; Scheffers et al., 2012; Brill et al., 2015).

The offshore area is characterized by a shallow-gradient shelf dominated by quartz, and minor carbonates (aragonite and calcite), feldspars (microcline, orthoclase, labradorite), heavy minerals (cassiterite, zircon, garnet), muscovite, monazite and kaolinite (Fig. 2 and Supp. Info. Figs. S1–S2). The grainsize varies from medium- to fine-sand in the nearshore and medium- to coarse-sand in water deeper than 15 m (Fig. 2). This grain size distribution is similar to the offshore sediment grain size described from offshore Pakarang Cape approximately 40 km south of Phra Thong Island (Feldens et al., 2012). From the early 1900s to the 1970s and sporadically since, tin and other heavy metals were mined both from the onshore and offshore environments of Phra Thong Island (Jankaew et al., 2011). This activity would have influenced the mineral phases transported onshore in the last 120 years.

During the 2004 IOT event, the maximum observed tsunami wave height was 20 m - the highest recorded wave height along the Thai coast (Tsuji et al., 2006). More importantly, on Phra Thong Island, the sedimentary signatures of the 2004 IOT and at least three different past tsunami events (preserved as 5 to 20 cm thick sand sheets in coastal swales) were identified by Jankaew et al. (2008).

Since Jankaew et al. (2008)'s study, the 2004 IOT tsunami and paleo-tsunami deposits on Phra Thong Island have been extensively studied to determine the chronology and potential tsunami recurrence interval (Fujino et al., 2009; Brill et al., 2012a; Prendergast et al., 2012), micropaleontology (Sawai et al., 2009), sedimentology and stratigraphy (Fujino et al., 2008; Fujino et al., 2009; Brill et al., 2012a; Brill et al., 2012b; Brill et al., 2015), flow conditions (Choowong et al., 2008; Sawai et al., 2009; Brill et al., 2014) and a ground penetrating radar survey to image the thin tsunami beds (Gouramanis et al., 2014a; Gouramanis et al., 2015).

Phra Thong Island is rarely impacted by storms (Jankaew et al., 2008; Brill et al., 2014) but in early May 2007 an unusual tropical depression that formed in the upper part of Gulf of Thailand moved across southern Thailand (Thai Meteorological Department, 2007). As the tropical depression moved into the Andaman Sea, the depression interacted with the southwest monsoon resulting in heavy rain (200 to 400 mm) and intense onshore waves along the north-western coast of Thailand (Thai Meteorological Department, 2007). The resultant storm surge deposited sands upon the youngest berm of Phra Thong Island.

Although the shallow marine environment is considered to be the source of the sediments comprising the 2004 IOT deposit on Phra Thong Island based on evidence from diatom assemblages (Sawai et al., 2009) and grain size distribution (Fujino et al., 2008; Fujino et al., 2010), the provenance of the older deposits has not been identified. Thus, we aim to identify the provenance and compare the granulometry, mineralogy and geochemistry of the 2004 IOT tsunami, paleo-tsunami and 2007 storm deposits.

3. Methods

3.1. Sample collection

Sediment samples were collected in March 2012 and May 2013 from the offshore and nearshore marine environment, the modern beach and beach ridges inland, pits that contained the 2004 IOT and three palaeotsunami deposits (e.g., Jankaew et al., 2008), and pits through the 2007 storm deposit. Fourteen offshore samples were collected using a Van Veen grab from water depths ranging from 3 to 25 m and up to 10 km away from the modern shoreline. Eight onshore samples were collected from the modern beach and from 5 to 12 cm deep pits in locations where the 2004 IOT capped the ridges and swales. Four samples each of the 2004 IOT (Sand A) and the most recent prehistoric tsunami (Sand B) deposits were collected from a trench Swale Y (Jankaew et al., 2008). Three sediment samples of the third oldest palaeotsunami sandsheet (Sand C) was sampled from a pit 8.5 m south of the trench and two samples of the oldest palaeotsunami sandsheet (Sand D) from auger 10 (Fig. 1; Gouramanis et al., 2015).