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Microfossils from coastal environments as indicators of paleo-earthquakes, tsunamis and storms

Jessica E. Pilarczyk [a,b,*], Tina Dura [c], Benjamin P. Horton [a,b], Simon E. Engelhart [d], Andrew C. Kemp [e], Yuki Sawai [f]

[a] *Sea Level Research, Institute of Marine and Coastal Science, Rutgers University, New Brunswick, NJ, USA*
[b] *Earth Observatory of Singapore, Nanyang Technological University, Singapore*
[c] *Department of Earth and Environmental Science, University of Pennsylvania, Philadelphia, PA, USA*
[d] *Department of Geosciences, University of Rhode Island, Kingston, RI, USA*
[e] *Department of Earth and Ocean Sciences, Tufts University, Medford, MA 02155, USA*
[f] *Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba Central 7, 1-1-1 Higashi, Tsukuba, Ibaraki 305-8567, Japan*

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ABSTRACT

Coastal risk assessment and hazard mitigation require datasets on centennial and millennial temporal scales to capture natural variability and multiple occurrences of the largest, but least frequent, events. Coastal sediments from low-energy depositional environments archive geologic evidence of paleo-earthquakes, tsunamis, and storms. Many of the best reconstructions of these events are derived from changes in microfossil (diatoms, foraminifera, and pollen) assemblages. In this review we explain how microfossils are used to reconstruct records of paleoearthquakes by quantifying the amount of coseismic and interseismic vertical land movements along tectonically active coastlines. Examples from the United States (Alaska and the Pacific Northwest), Japan, and Chile show that microfossil-based transfer functions may provide continuous records of vertical land movement during earthquake deformation cycles. We discuss how microfossil habitat preferences and taphonomic character are used to constrain sediment provenance (e.g., beach, nearshore, or offshore sources) and identify overwash deposits, and how this information can be used to reconstruct the recurrence of tsunamis and storms. Analysis of overwash deposits from Thailand and Malaysia indicates the ability of microfossils to resolve individual waves within tsunami sediments, and an example from the Sendai coastal plain in Japan uses foraminifera to ascribe a beach to nearshore provenance for the 2011 Tohoku tsunami deposit. Finally, we present recent examples from the Gulf of Mexico on the use of foraminifera to estimate the volume and distance of transport of storm overwash from hurricanes.

1. Introduction

More than half of the world's population resides within 60 km of a coastline, including 60% of the world's most populated cities (Nicholls et al., 2007). Earthquakes, tsunamis and storms present a hazard to these intense concentrations of population, economic production and static infrastructure. Projected (annual) global losses from coastal flooding are expected to rise from US$6 billion in 2005 to US$52 billion by 2050 (Hallegatte et al., 2013). Accurate and realistic estimates of coastal hazards are hindered, however, by instrumental measurements and observational accounts that are too short to identify the potential magnitude and recurrence of rare events.

To properly assess the risk of future great earthquakes along subduction zone coastlines, it is essential that the magnitude and recurrence interval of prehistoric earthquakes are well understood (e.g., Satake and Atwater, 2007). Subduction zone earthquakes often involve vertical land-level changes (uplift or subsidence) of the coastline. Such deformation has been measured in the field for a number of large earthquakes, including southern Chile in 1960 (Barrientos and Ward, 1990; Khazaradze et al., 2002; Wang et al., 2007); Alaska in 1964 (Plafker, 1969; Savage et al., 1998; Zweck et al., 2002); Sumatra in 2004 (Banerjee et al., 2007; Chlieh et al., 2007; Paul et al., 2007); and Japan in 2011 (Iinuma et al., 2011; Simons et al., 2011; Ozawa et al., 2012). Land-level changes of this type are archived and recognized in coastal stratigraphic sequences as abrupt changes in relative sea-level (e.g., Atwater, 1987; Bourgeois and Reinhart, 1989; Nelson et al., 1996b; Shennan et al., 1999; Sawai, 2001; Cisternas et al., 2005; Grand Pre et al., 2012). In the wake of the 2004 Indian Ocean and 2011 Tohoku tsunamis, increased attention was paid to identify their predecessors. Examinations of coastal sedimentary records identified paleotsunami deposits that provided insight into the potential scale and impact of the events in 2004 in the Indian Ocean (e.g., Jankaew et al., 2008; Monecke et al., 2008; Malik et al., 2011; Grand Pre et al., 2012; Brill

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* Corresponding author at: Sea Level Research, Institute of Marine and Coastal Science, Rutgers University, 71 Dudley Road, New Brunswick, NJ 08901-8525, USA. Tel.: +1 848 932 3482.
E-mail address: jpilar@marine.rutgers.edu (J.E. Pilarczyk).

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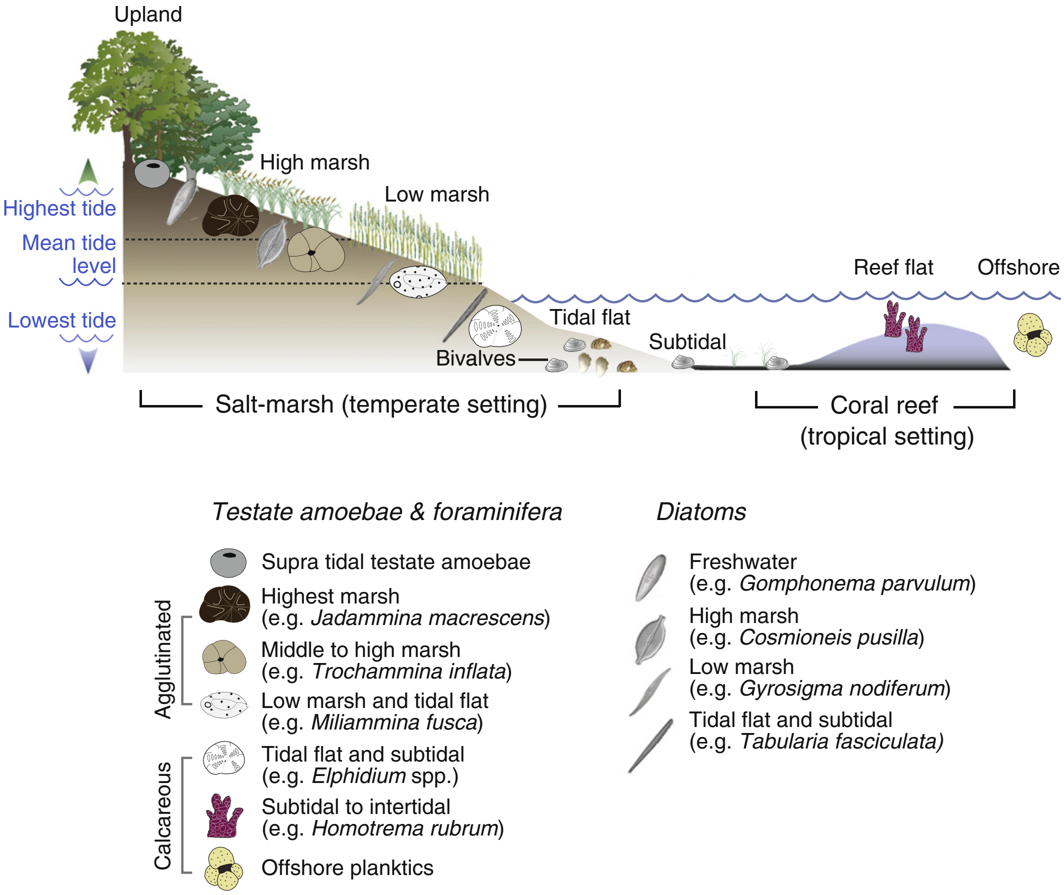

Fig. 1. Generalized cross-section of a coastline indicating habitat preference and life modes of microfossils discussed in this review. Left: a temperate salt-marsh indicating vertical zones of plants (upland, high marsh, low marsh), foraminifera, diatoms and testate amoebae. Right: a coral reef is depicted with the foraminifer *Homotrema rubra* growing attached to the reef (see Fig. 5) and planktics living suspended in the water column.

et al., 2014) and in 2011 in Japan (e.g., Minoura et al., 2001; Sawai et al., 2012). Reconstruction of the history of tsunami inundation is often based on identifying anomalous beds of overwash sand in low-energy environments where they would not normally occur, such as salt- and freshwater marshes, coastal lakes, and swales (e.g., Dawson et al., 1996; Hemphill-Haley, 1996; Bourgeois et al., 1999; Bondevik, 2003; Gelfenbaum and Jaffe, 2003; Kelsey et al., 2005; Garrett et al., 2013).

Recent storms in the Philippines (Haiyan in 2013), Australia (Yasi in 2011), Taiwan (Morakot in 2009), and the United States (Katrina in 2005, Sandy in 2012) highlighted the socio-economic and environmental repercussions of the largest events. The study of past storm activity, by means of geological proxies (known as paleotempestology), seeks to reconstruct and explain the geographical and temporal variability in frequency and intensity of storms during past centuries to millennia (e.g., Liu and Fearn, 1993, 2000; Nott, 2003; van de Plassche et al., 2006; Donnelly and Woodruff, 2007; Toomey et al., 2013). Similar to tsunami deposits, sediments deposited by storm surge are most commonly recognized as anomalous sand layers washed over into low-energy environments where “normal” conditions between storms are characterized by deposition of organic and fine-grained sediments (e.g., Liu and Fearn, 1993). At locations along the U.S. Atlantic coast (Connecticut and New Jersey), repeated sequences of erosion and rapid infilling of the resulting accommodation space have been interpreted as a record of landfalling storm surges (e.g., van de Plassche et al., 2006; Nikitina et al., 2014).

Some of the best reconstructions of land-level movements related to earthquakes and coastal inundation from tsunamis and storms are derived from diatoms, foraminifera, and pollen. Microfossils are used as a proxy, because their assemblages reflect subtle changes in environmental conditions (e.g., Murray, 2006). Species of diatoms and foraminifera show distributions that correlate with tidal elevation (e.g., Scott and Medioli, 1978, 1980; Zong and Horton, 1999; Horton and Edwards, 2006) and, thus, are strong proxies of relative sea-level change. Allochthonous marine assemblages within a terrestrial setting are indicative of a short-lived, abrupt marine incursion from a tsunami or storm. The species and taphonomic (e.g., surface condition) composition can be used to qualitatively estimate the origin of overwash sediment, depth of scour, and distance of transport (e.g., Hawkes et al., 2007; Pilarczyk and Reinhardt, 2012a; Tanaka et al., 2012). Here, we summarize the growing body of information obtained from diatoms, foraminifera and pollen as they apply to coastal environments. We provide examples of reconstructions from marshes and intertidal flats, salt ponds, nearshore and subtidal environments, lagoons and sinkholes. We discuss the application of quantitative microfossil-based techniques in producing records of earthquakes, and highlight advancements and challenges in using microfossils as proxies for overwash from tsunamis and storms.

2. Microfossils and coastal environments

Microfossils commonly occur in large numbers in coastal deposits, and because of their small size (silt- to sand-size particles), make it possible to acquire statistically significant populations with core samples (Birks, 1995). High preservation potential in coastal sediments enables reconstructions that span several thousands of years (e.g., Shennan et al., 2000). The use of microfossils as a proxy for marine inundation in coastal sequences is particularly effective because of their diverse ecological niches, which span the entire environmental gradient