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

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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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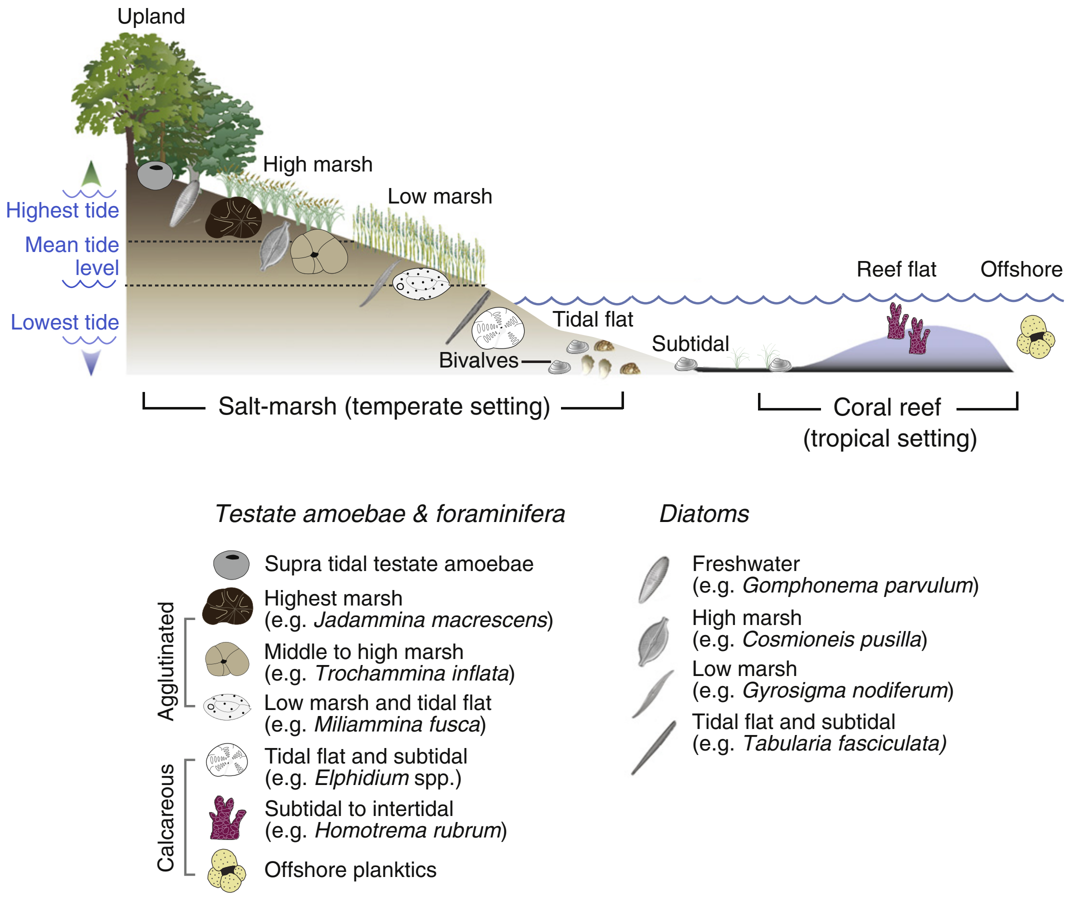

Fig. 1. Generalized cross-section of a coastline indicating habitat preference and life modes of microfossils discussed in this review. Left: a temperate salt-marsh indicating vertical zones of plants (upland, high marsh, low marsh), foraminifera, diatoms and testate amoebae. Right: a coral reef is depicted 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

Table 1
Summary of the studies discussed in Sections 3 and 4 that use microfossils to document paleo-earthquakes, tsunamis, and storms.

Environment/region	Site	Earthquake studies	Tsunami studies	Storm studies
Temperate				
North Pacific	Alaska	(1) Hamilton and Shennan (2005, 2006); Hawkes et al. (2005); Shennan et al. (1999, 2014); Zong et al. (2003) (2) Shennan et al. (1999); Hawkes et al. (2005) (1, 2) Briggs et al. (2014) (3) Shennan et al. (1999); Zong et al. (2003)	(1, 2) Briggs et al. (2014)	
	Cascadia	(1) Hemphill-Haley (1995); Shennan et al. (1996, 1998) (2) Guilbault et al. (1995, 1996); Shennan et al. (1996); Hawkes et al. (2010, 2011) Engelhart et al. (2013)	(1) Hemphill-Haley (1996); Clague et al. (1999); Kelsey et al. (2005) (2) Clague et al. (1999);	
	Japan	(1) Sawai et al. (2004a, b); Sawai et al. (2012)	(1) Minoura et al. (2001); Nanayama et al. (2003, 2007); Szczuciński et al. (2012); Takashimizu et al. (2012) (2) Pilarczyk et al. (2012) (3) Nanayama et al. (2007)	
South Pacific	Chile	(1) Nelson et al. (2009); Garrett et al. (2013)	(1, 2) Horton et al. (2011)	
North Atlantic	USA			(2) Collins et al. (1999); Hippensteel and Martin (1999); Scott et al. (2003); Hippensteel et al. (2005)
Gulf of Mexico	USA			(1) Parsons (1998) (2) Horton et al. (2009); Lane et al. (2011); Hawkes and Horton (2012)
Tropical				
Oceania	Papua New Guinea		(1) Dawson (2007)	
	Wallis & Futuna		(1, 2) Goff et al. (2011)	
Indian Ocean	Sumatra	(1, 3) Grand Pre et al. (2012)	(1) Monecke et al. (2008) (2) Grand Pre et al. (2012)	
	Thailand		(1) Jankaew et al. (2008); Sawai et al. (2009a) (2) Hawkes et al. (2007); Sugawara et al. (2009)	
	India		(1) Malik et al. (2011)	
Caribbean Sea	British Virgin Islands		(2) Pilarczyk and Reinhardt (2012a)	(2) Pilarczyk and Reinhardt (2012a)
Arid				
Arabian Sea	Oman		(2) Pilarczyk et al. (2011); Pilarczyk and Reinhardt (2012b)	

(1) diatoms; (2) foraminifera; (3) pollen.

presented by the coastal zone from marine to freshwater conditions. Diatoms and foraminifera are indicators of environmental variables, including inundation frequency, water depth, salinity, and nutrient level, because of the varied ecological optima and tolerances of species and assemblages (e.g., Hallock, 1984; Murray, 2006).

Diatoms are unicellular, photosynthetic algae with a siliceous cell wall composed in part of two connected, distinctly ornamented sections, called valves. It is estimated that there are more than 1000 genera (Fourtanier and Kociolek, 1999) and 100,000 species found worldwide (Round et al., 1990), including numerous species with valves that are resistant enough to taphonomic degradation to be preserved well in the sedimentary record, particularly in temperate to cold climates (Jones, 2007). Systematic and taxonomic investigations of contemporary and fossil diatoms began to be supplemented by studies of distributional ecology in the late 1890s (e.g., Cleve, 1894, 1895). Subsequently, diatoms were recognized as a valuable tool in reconstructing paleoenvironmental changes (e.g., Cleve-Euler, 1922) and comprehensive ecological classifications conducted by Hustedt (1953, 1957), Juggins (1992), Patrick and Williams (1990), and Vos and de Wolf (1993) identified indicator species that respond to subtle environmental variations within the intertidal zone (e.g., tidal exposure, nutrient level, substrate, salinity). Diatoms are often the dominant microphyte in estuarine and marine littoral environments (Admiraal, 1984; Palmer and Abbott, 1986; Cooper et al., 2010) and become incorporated in coastal sediments through time, resulting in buried assemblages that constitute an environmental history. Diatoms are found in freshwater, as well as brackish and marine environments and can document changes in marine influence (e.g., Zong and Tooley, 1996).

Foraminifera are single-celled protozoans with a test that is either secreted (carbonate, organic, siliceous) or agglutinated. Foraminifera span brackish to marine environments, living freely in sediment (benthic forms), on rocks, shells and corals (attached benthic forms), and within the water column (planktic forms). Testate amoeba (thecamoebians) may be combined with salt-marsh foraminifera to provide information on freshwater sources within the coastal zone (e.g., Charman, 2001; Hawkes et al., 2010). Early studies of foraminifera focused on taxonomy (e.g., Montagu, 1808; Parker and Jones, 1859; Brady, 1884). Although this focus of research continues (e.g., Loeblich and Tappan, 1986; Brönnimann and Whittaker, 1988; Scott and Vilks, 1991; Javaux and Scott, 2003; Milker and Schmiedl, 2012), ecological studies of foraminifera have gained prominence. Most ecological studies of living or surface assemblages are carried out with the aim of providing a contemporary database against which fossil foraminifera can be compared and interpreted (Murray, 1991). A characteristic of benthic foraminifera in the intertidal zone is a predictable distribution of agglutinated assemblages restricted to vegetated marshes and calcareous assemblages dominantly found on mudflats and sandflats (Fig. 1).

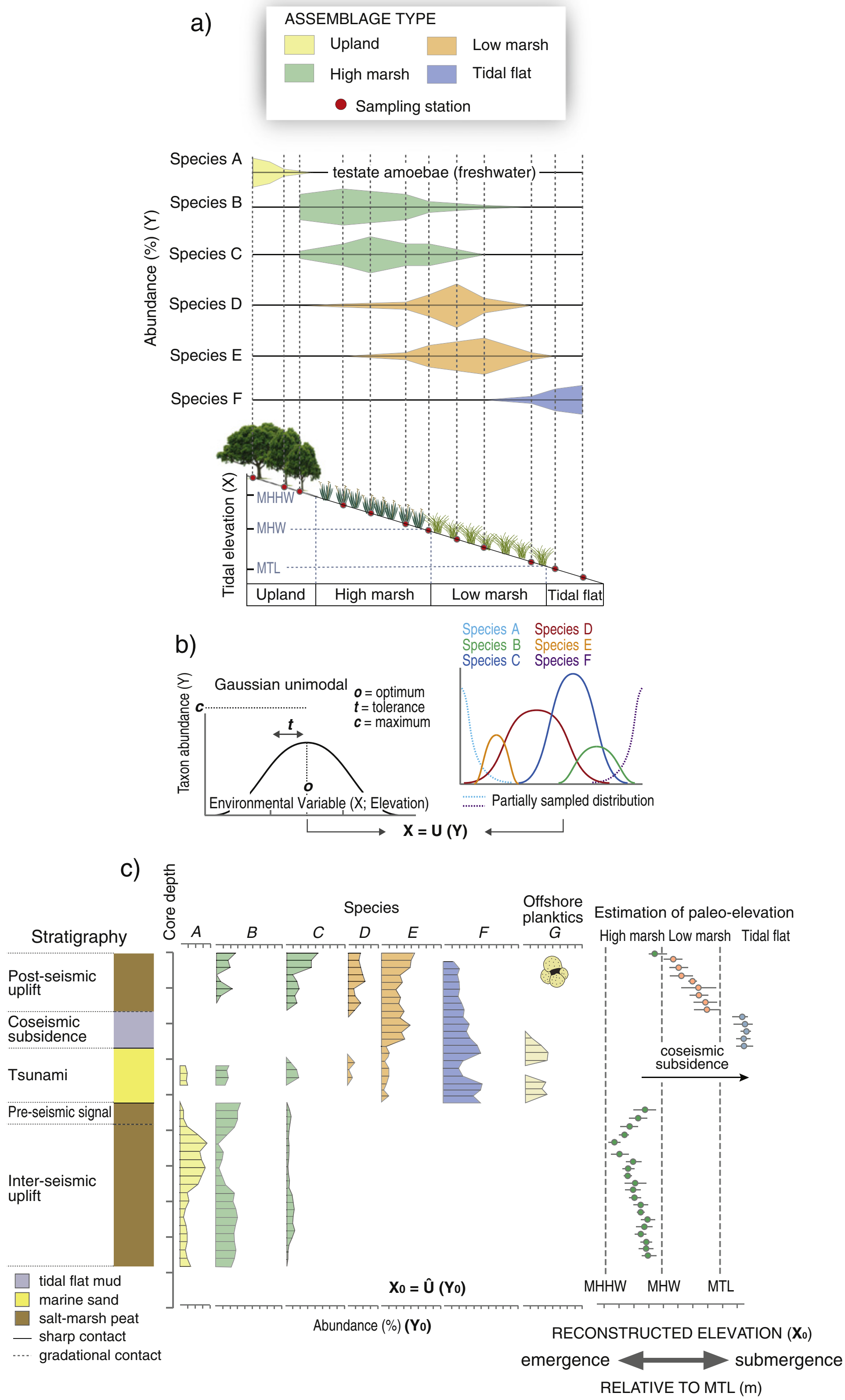

Fig. 2. Schematic of the development and application of a transfer function for assessing vertical land movements caused by subduction zone earthquakes. a) Distribution of microfossils is described using samples collected (red circles) from transects across the full environmental (tidal elevation) gradient. Modern microfossils (*Y*) and modern sea level (*X*) are observable. b) Elevation (*X*) is quantitatively expressed as an empirically derived function (*U*) of microfossil assemblages (*Y*). c) Fossil microfossils (Y_0) are observed by documenting assemblages preserved in sedimentary deposits. The transfer function estimates the elevation with respect to sea level at which each core sample accumulated (X_0). The amount of coseismic subsidence (black arrow) is estimated by comparing the pre- and post-earthquake palaeomarsh surface elevations. MHHW = mean higher high water; MHW = mean high water; and MTL = mean tide level.
Modified from Horton et al. (2013).

Pollen, produced by all flowering plants, is encased in cell walls composed of sporopollenin, a decay-resistant material that aids in preservation over timescales that span thousands of years (e.g., Grindrod, 1985; Ellison, 1989). Pollen assemblages in coastal environments indicate changes in vegetation type, diversity, and stability resulting from environmental factors such as climatic and land-use changes (Ellison, 1996; Zong et al., 2007; Brush, 2009; Willard and Bernhardt, 2011). Pollen-based paleoenvironmental interpretations can be complicated by the fact that assemblages include contributions from local and regional (e.g., wind, water, or animal transported) flora as well as variations in pollen production by plants over time and among species (e.g., Godwin, 1934; Freund et al., 2004; Moss et al., 2005). In tropical mangrove settings, pollen is often the only microfossil preserved (e.g., Berkeley et al., 2007), because it is the most resistant to decay (Ellison, 2008); although subsequent sedimentary sequences are prone to bioturbation (e.g., Chappell and Grindrod, 1985). Nevertheless, Grand Pre et al. (2012) used pollen, in the absence of both diatoms and foraminifera, to identify evidence of early Holocene paleoseismic subsidence preserved as buried mangrove soils in Aceh Province, Indonesia.

3. Microfossils and paleoearthquakes

The earthquake-deformation cycle includes a long (centuries to millennia) period of interseismic strain accumulation, where the subduction zone coastline is gradually displaced vertically due to locking of the plate interface and compression of the overriding tectonic plate (Yeats et al., 1997). During this interseismic period, the rate of vertical deformation of a coastline can exceed eustatic sea-level change, resulting in net relative sea-level fall (e.g., Nelson et al., 1995) or rise (e.g., Sawai et al., 2004b). In the stratigraphic record this interseismic phase is preserved as a gradual change in relative sea-level (Leonard et al., 2010). During megathrust earthquakes, abrupt, co-seismic land-level change results from the sudden release of accumulated strain (Yeats et al., 1997). In the stratigraphic record this is manifested as a dramatic change in depositional environment, such as a buried peat or soil that is sharply overlain by tidal-flat mud in the case of coseismic subsidence, or a tidal-flat mud that is overlain by a salt-marsh peat in instances of coseismic uplift. The direction of interseismic and coseismic land-level changes is a result of site location with respect to subduction zone geometry.

Reconstructing and quantifying land-level change hinges on the well-established relationship between microfossil assemblages and tidal elevation (Fig. 1) that has been documented for numerous coastal sites (e.g., Jennings et al., 1995; Shennan et al., 1996; Hayward et al., 1999; Zong and Horton, 1999; Sawai et al., 2004a; Patterson et al., 2005; Horton and Edwards, 2006; Table 1). For example, Hawkes et al. (2010) showed that modern, intertidal foraminifera in the U.S. Pacific Northwest form distinctive assemblages from upland (freshwater testate amoebae), high/middle salt-marsh (e.g., *Balticammina pseudomacrescens*, *Haplophragmoides wilberti*, and *Trochammina inflata*) and low salt-marsh/tidal flat (e.g., *Miliammina fusca*) environments.

Early studies in Cascadia that used microfossils to estimate the amount of coseismic subsidence/uplift accompanying great earthquakes were either semi-quantitative and/or relied on differences between intertidal elevational zones with broad ranges (e.g., Nelson and Kashima, 1993; Hemphill-Haley, 1995; Hawkes et al., 2005). When combined with lithostratigraphic data, semi-quantitative land-level reconstructions from Cascadia, for example, may be as precise as $\pm$~0.5 m (Nelson et al., 1996a). The development of statistically based microfossil analyses began with the application to deep sea marine sediments to reconstruct paleoclimate change (Imbrie and Kipp, 1971; CLIMAP Project Members, 1976). In the late 1990s, Guilbault et al. (1995, 1996) and Shennan et al. (1996, 1998) pioneered the use of similar techniques to estimate coseismic subsidence in Cascadia sedimentary sequences. Transfer functions formalize the relationship between the relative abundance of microfossil species and an environmental variable, such as elevation (e.g., Horton and Edwards, 2006). Calibration is the reconstruction of the same paleoenvironmental variable from microfossil assemblages preserved in (and enumerated from) cores or outcrops (Fig. 2). The most precise of these reconstructions are derived from microfossils associated with the uppermost part of the intertidal zone (Kemp et al., 2009). The transfer function provides a continuous record of relative sea-level change during interseismic and postseismic parts of the earthquake cycle (Sawai et al., 2004b), which provides essential information for understanding the mechanics of plate-boundary ruptures in subduction zones. For example, Hawkes et al. (2011) showed that employing a transfer function to estimate the amount of coastal subsidence in Oregon (USA) during the A.D. 1700 earthquake produced estimates with errors that were more precise (within $\pm$0.18–0.32 m) than those obtained from semi-quantitative methods. Engelhart et al. (2013) further tested the application of the transfer function technique for calculating the amount of subsidence along the Cascadia subduction zone by experimentally simulating a great earthquake. The authors transplanted modern high-marsh sediment into a tidal flat, simulating 0.64 m of co-seismic subsidence. Comparison of the simulated (0.64 m) and reconstructed (0.61 $\pm$ 0.24 m) elevation changes showed excellent agreement.

Detailed diatom studies of Zong et al. (2003), Hamilton and Shennan (2005) and Shennan and Hamilton (2006) on a series of peat-mud couplets from southern Alaska produced a precise record of relative sea-level changes during parts of six earthquake deformation cycles. Intriguingly, not only did diatoms record abrupt subsidence during great earthquakes, but they also left a pre-seismic signal in the years prior to some of the events. Sequences of peat contained mainly brackish (e.g., *Pinnularia lagerstedtii*) and freshwater species (e.g., *Eunotia exigua*), whereas the muds contained dominantly marine species (e.g., *Delphineis surirella*). Shennan et al. (1999) explained the occurrence of marine diatoms in the upper few centimeters of peat layers as a component of the earthquake deformation model, where subtle subsidence preserved in the peat was a precursor to abrupt coseismic subsidence (i.e., a pre-seismic signal).

Coastal stratigraphy from eastern Hokkaido, Japan contains evidence for cycles of coastal deformation (Sawai et al., 2004a) associated with multi-segment earthquakes on the Kuril trench (Nanayama et al., 2003). Sawai et al. (2004a) used a diatom-based transfer function to document pre-seismic, co-seismic and post-seismic land-level changes associated with a great 17th century earthquake. The diatom assemblages suggest that tidal flats gradually changed into freshwater upland in decades after the 17th century tsunami. The amount of land-level change was estimated to be up to 1.5 m. In Chile, Cisternas et al. (2005) and Nelson et al. (2009) qualitatively estimated the recurrence of coastal subsidence associated with giant earthquakes along the Peru–Chile Trench. Following the work of Cisternas et al. (2005) and Nelson et al. (2009), Garrett et al. (2013) investigated stratigraphic sections containing both the 1960 M_w 9.5 and the 2010 M_w 8.8 earthquakes (Fig. 3). Estimates of land-level change were limited by lack of modern analogues for the fossil diatom assemblages, indicating the need for larger, more comprehensive training sets that include local as well as regional samples (Horton and Edwards, 2005; Watcham et al., 2013). Where there was sufficient similarity between fossil and modern assemblages, Garrett et al. (2013) calculated 1.12 $\pm$ 0.53 m of coseismic subsidence (Fig. 3d).

4. Microfossils and paleo-tsunamis and storms

4.1. Paleotsunamis

Paleotsunami deposits are commonly recognized as anomalous sand sheets that were washed into marsh or lake sediments (e.g., Hemphill-

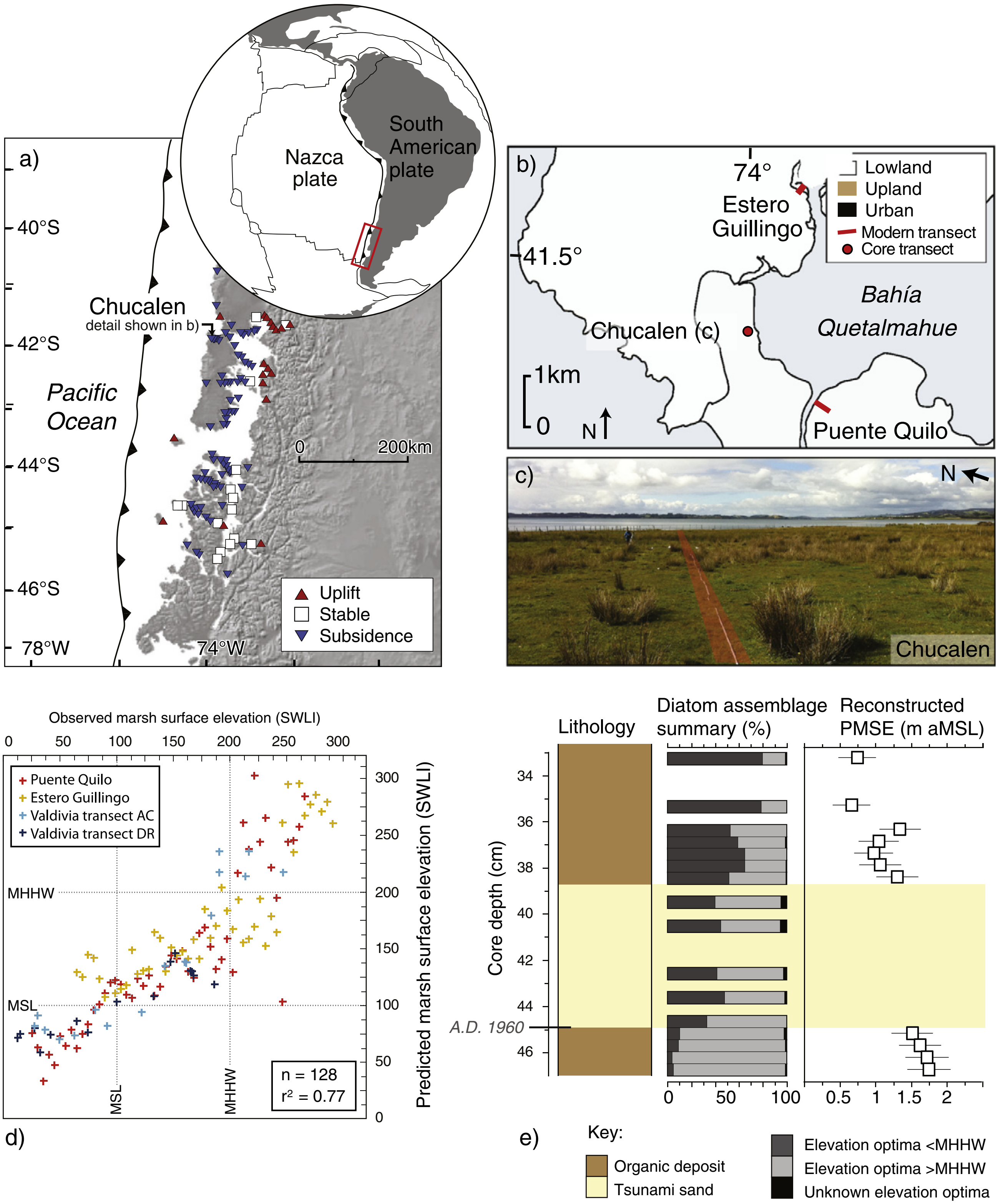

Fig. 3. Summary of findings by Garrett et al., 2013. a) Tectonic setting of the Chilean subduction zone and Chucalen field site location (detail in (b)). Symbols show vertical land surface deformation resulting from the 1960 M 9.5 earthquake (Plafker and Savage, 1970). b) Northern Isla de Chiloé, including the Chucalen coring locality and modern transects at Estero Guillingo and Puente Quilo. c) View of the salt marsh at Chucalen and location of the coring transect (red line). d) Observed versus predicted elevation values for four transects included in the weighted averaging partial least squares regression (WA-PLS) component 3 transfer function model. The data are from the two transects shown in (b) plus two transects collected by Nelson et al. (2009): Valdivia AC from a fan bordering Río Angachilla; and Valdivia DR from Isla del Rey. The elevation of each modern sample was converted to a standardized water level index (SWLI) to account for variations in tidal ranges between sites. e) Analysis of the stratigraphy, diatom assemblages, and paleomarsh surface elevation reconstructions (PMSE) for the 1960 M 9.5 earthquake at Chucalen. Diatom assemblage summary based on modern species coefficients derived from the WA-PLS transfer function model, defined by elevation optima above and below mean higher high water (MHHW). Estimates of coseismic deformation compare pre- and post-earthquake paleomarsh surface elevations as estimated by the transfer function model, accounting for the thickness of any tsunami deposit. Reconstructions are based on the highest and lowest PMSE values and indicate land subsidence of 1.12 ± 0.53 m. Modified from Garrett et al. (2013).

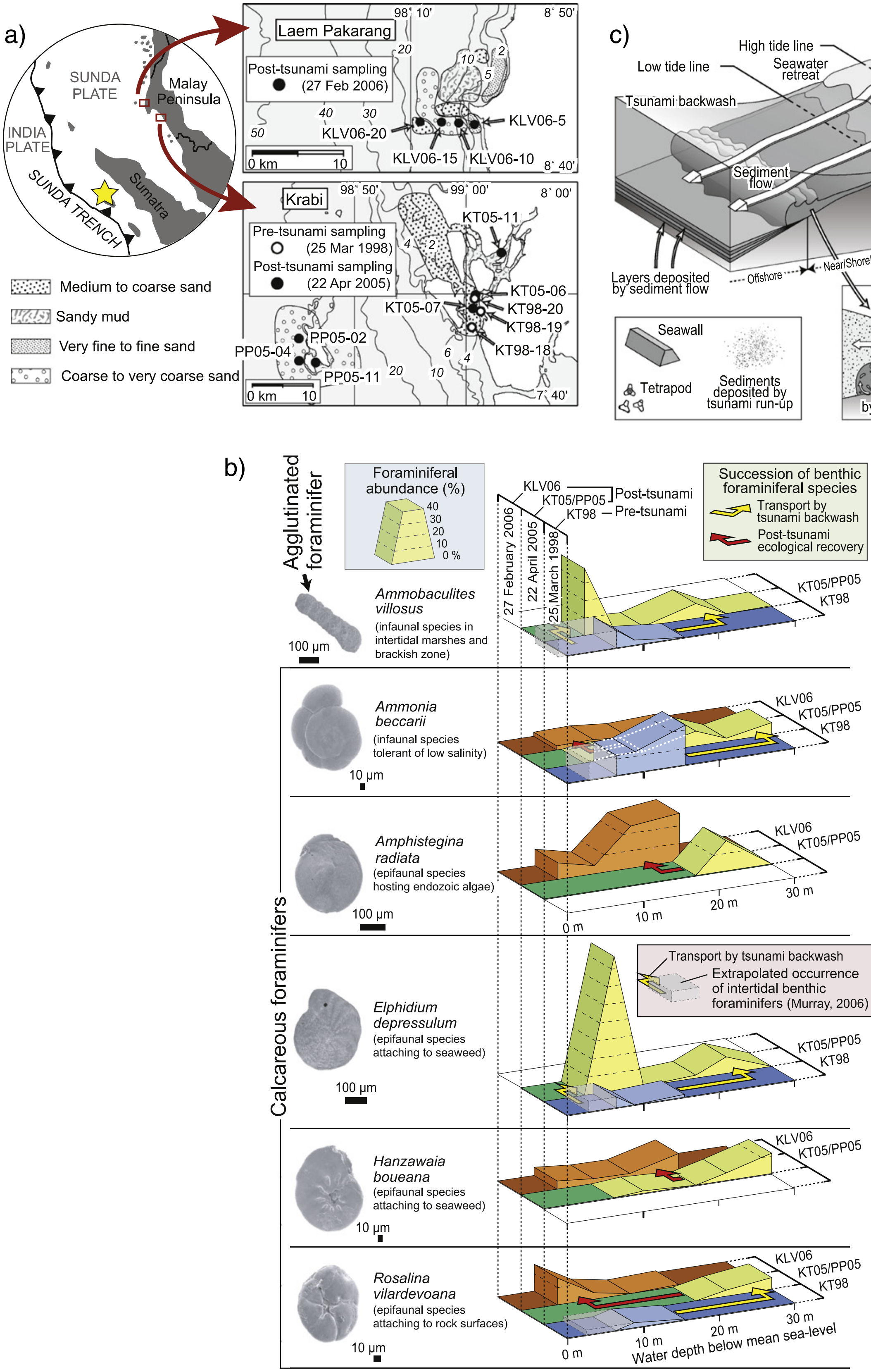

Fig. 4. A study of foraminifera by Sugawara et al. (2009) showing the effects of transport by tsunami backwash. a) Regional map showing the epicenter of the 2004 Sumatra–Andaman earthquake (star) and broadscale tectonics, and sampling sites at Laem Pakarang and Krabi Thailand. b) Schematic diagram showing pre- (e.g., KT98) and post-tsunami (KLV06 and KT05/PP05) distributions of the six most dominant nearshore foraminifers. The data show net seaward transport (tsunami backwash) of foraminifera during the tsunami, followed by biological recovery in their optimum shallow-water environment following the event. c) Generalized cross-section of the nearshore–offshore zone showing seaward redistribution of sediment during tsunami backwash. Sediment load and speed of bottom currents from seawater retreat increase downslope causing sediment flow in the offshore direction. The decrease in slope at the base of the nearshore zone reduces the kinetic energy of the flow, depositing a layer of allochthonous sediment offshore.
Modified from Sugawara et al. (2009).

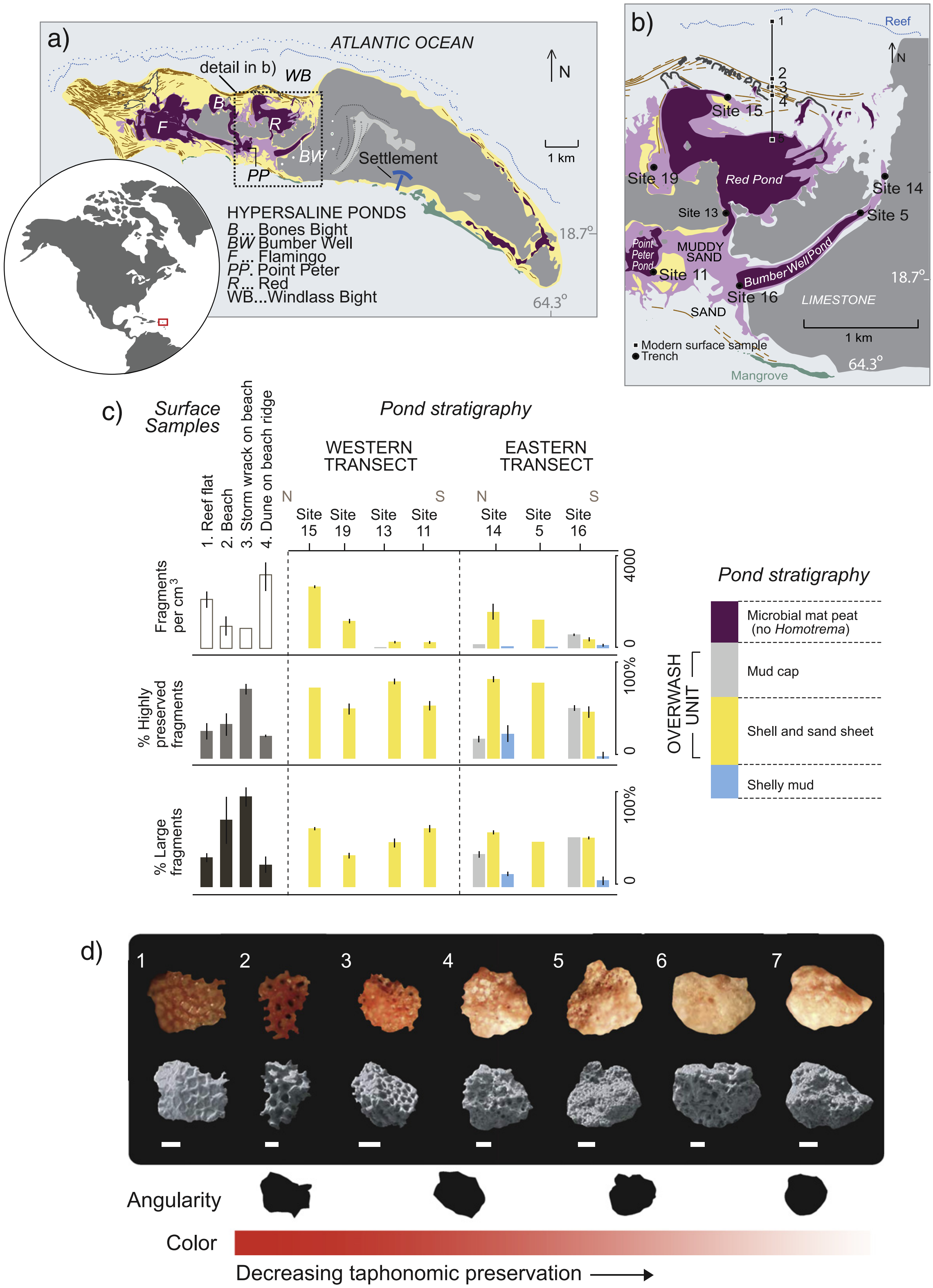

Fig. 5. A study of microfossils in overwash deposits in the British Virgin Islands by Pilarczyk and Reinhardt (2012a). a) Map of Anegada showing locations of hypersaline ponds. b) Enlarged map of study area showing location of trenches (sites 5, 11, 13, 14, 15, 16, 19) and surface samples (1–5) depicted in (c). c) *Homotrema* taphonomic data from surface samples and major stratigraphic units in the ponds. Two transects (western and eastern) are compared. The western transect runs through Red and Point Peter Ponds, while the eastern transect crosses Bumber Well Pond. d) *Homotrema* individuals taphonomically degrade in color and angularity resulting from increased exposure time after death. 1 — Exceptionally-preserved specimen with a red color, well defined test and angular edges. 2–3 — Well-preserved individuals with pink tests, hollowed chambers and angular edges. 4–5 — Moderately-preserved *Homotrema* that are pink, rounded and have hollowed chambers. 6–7 — Highly-altered individuals that are light pink to white in color and are highly rounded (Pilarczyk et al., 2014). White bars represent 100 μm.
Modified from Pilarczyk and Reinhardt (2012a).

Haley, 1996; Clague et al., 1999; Bondevik, 2003; Kelsey et al., 2005). Marine microfossils often dominate tsunami overwash deposits because of the landward transport and deposition of scoured marine sediment (e.g., Dominey-Howes et al., 2000; Mamo et al., 2009; Goff et al., 2012; Tanaka et al., 2012). However, assessing the provenance of tsunami deposits may be complicated because diatoms and foraminifera are often composed of mixed assemblages due to the fact that tsunamis erode, transport, and deposit marine, brackish, and freshwater sediments (with associated taxa) as they inundate coastal and inland areas (e.g., Dawson et al., 1996; Grand Pre et al., 2012; Briggs et al., 2014).

Microfossil analysis of recent tsunami deposits provides a basis against which paleo-deposits can be compared. Diatoms and foraminifera were used to analyze the 2004 Indian Ocean tsunami. In Thailand, the 2004 Indian Ocean tsunami deposited a sand unit that graded into a thin mud layer and contained a mixed diatom assemblage, indicating differences in flow condition (i.e., current velocity and/or settling velocity of the entrained sediments; Sawai et al., 2009a). The lower section of the deposit was dominated by benthic marine diatoms that live attached to sand grains, the middle section contained abundant marine planktic species, and the mud cap was dominated by a mixture of freshwater, brackish, and marine species. In their analysis of 2004 tsunami sediments from Thailand and Malaysia, Hawkes et al. (2007) were able to identify both tsunami uprush (i.e., landward flow) characterized by transport of offshore radiolarians, as well as backwash (e.g., seaward flow) resulting in concentrations of relocated mangrove foraminifera. These results showed that microfossils can be used to elucidate individual tsunami waves. Similarly, Sugawara et al. (2009) used foraminifera from the southwestern coast of Thailand as a sediment tracer and showed that large volumes of coastal material were transported seaward during the tsunami (Fig. 4). In this example, foraminiferal assemblages constrained sediment provenance more effectively than grain size analysis on the sand. Pre- and post-2004 tsunami sampling from water depths down to 30 m showed that nearshore benthic foraminifera (e.g., *Ammobaculites* spp., *Ammonia* spp., *Elphidium* spp., *Rosalina* spp.) were entrained by tsunami run-up and subsequently transported seaward by backwash where they are now archived as allochthonous assemblages in low-energy submarine sediments, highlighting the potential in using offshore environments to identify paleotsunami deposits.

Recently, several studies used microfossils to assess the provenance of tsunami sediments deposited by the 2011 Tohoku tsunami. Independent studies using microfossil analysis on diatoms, foraminifera, and nannoliths (marine calcareous nanofossils) indicated a dominant beach/dune origin for the overwash sand on the Sendai coastal plain from the 2011 Tohoku tsunami (Pilarczyk et al., 2012; Szczuciński et al., 2012; Takashimizu et al., 2012). In contrast, in Rikuzentakata City, ~100 km north of Sendai Bay, subtidal ostracods were found in 2011 Tohoku deposits and suggest that the deposited sediment was sourced from the sea floor in areas where water depth exceeded 9 m (Tanaka et al., 2012).

Notable examples of paleotsunami deposits that have been identified in part, using microfossil analysis, include those from the U.K. (Smith et al., 2004), Cascadia (e.g., Hemphill-Haley, 1995, 1996), Sumatra (e.g., Grand Pre et al., 2012), and Japan (e.g., Nanayama et al., 2003, 2007; Sawai et al., 2008, 2012). Hemphill-Haley (1995) used diatom distributions to show that the inundation area of a tsunami in Cascadia ~300 years ago was larger than the distribution inferred from overwash sediments alone. Along the Kuril subduction zone in Japan, Nanayama et al. (2007) used diatoms to identify nine sandy tsunami deposits intercalated with peat. The diatom assemblage of the peat units contained freshwater species (e.g., *Eunotia* spp., *Pinnularia* spp.); whereas, sand units were dominated by marine taxa including: *Delphineis surirella* and *Odontella aurita*. Based on the record of tsunami deposits, the average recurrence intervals of large subduction zone earthquakes on the Kuril Trench were estimated to be nearly 400 years, but ranging from 100 to 800 years over the last 6000 years (Sawai et al., 2009b).

The taphonomic (or surface) condition of individual microfossils is useful when the distinction between species assemblages of recent and paleotsunami deposits from the under and overlying material is subtle (e.g., Hemphill-Haley, 1996; Goff et al., 2011; Pilarczyk and Reinhardt, 2012b). Furthermore, the individual's size, shape, and patterns of fragmentation, abrasion, and corrosion assist to understand the size of the event, depth of scour, and origin of sediment. For example, Murray (1993), Dawson et al. (1996), and Kortekaas and Dawson (2007) reported high occurrences of fragmented microfossils within modern tsunami sediments as a result of high-energy transport. In the case of the 1998 Papua New Guinea tsunami deposit, Dawson (2007) found that linear, sigmoid and clavate diatoms were more readily fragmented due to their relatively fragile valve structure. In contrast, high abundances of taphonomically unaltered (i.e., pristine) diatom valves were found in tsunami deposits from Cascadia (Hemphill-Haley, 1996), Thailand (Sawai et al., 2009a), and Chile (Horton et al., 2011). Pilarczyk and Reinhardt (2012a) used the concentration and taphonomic character of fragments of the foraminifera *Homotrema rubra* (e.g., color, angularity, chamber structure and size) to gauge the directionality (from north to south) of an overwash deposit within coastal ponds on Anegada, British Virgin Islands (Fig. 5). Overwash sands within coastal ponds on Anegada contained relatively high concentrations of large (>250 μm), highly-preserved *Homotrema* that originated from reef sediments to the north of the island. A major problem in applying a taphonomic method to foraminiferal assemblages is discerning between taphonomic characters inherited from the original environment and those that are overprinted by an event (Pilarczyk et al., 2011).

4.2. Paleostorms

Landfalling storms (e.g., cyclones, hurricanes, typhoons, nor'easters) are recognized by the presence of a storm surge overwash deposit in low-energy depositional settings. These deposits extend the event record back in time, permitting the assessment of long-term ecological impacts, spatial and temporal variability of storm activity, and the relationship between storm surge frequency, magnitude, track and climate change (e.g., Donnelly and Woodruff, 2007; Mann et al., 2009). Detecting and characterizing storm deposits involves the recognition of allochthonous marine sand layers (e.g., Liu and Fearn, 1993) and marine-indicative microfossils deposited in low energy, marginal-marine environments such as lakes (e.g., Liu and Fearn, 2000), marshes (e.g., Parsons, 1998; Scott et al., 2003; Hippensteel et al., 2005; Horton et al., 2009), coastal ponds (e.g., Collins et al., 1999; Woodruff et al., 2009), lagoons/bays (e.g., Lane et al., 2013), and coastal sinkholes (Lane et al., 2011).

The microfossil signature of storms relies on the identification of abrupt switches to allochthonous assemblages. In salt-marsh cores from South Carolina, Hippensteel and Martin (1999) found influxes of recent offshore and Oligo-Miocene foraminifera within modern storm deposits. Microfossil assemblages have also been used to infer the provenance of storm-surge sediments. For example, Lane et al. (2011) inferred a storm origin for microfossil-bearing sands within a coastal sinkhole in Florida based on unusually high abundances of radiolarians and calcareous foraminifera (e.g., *Brizalina spathulata*) that originated from at least 5 km offshore. Successive overwash sands within the sinkhole provided a record of storms with decadal resolution for the northeastern Gulf of Mexico that spans the late Holocene. Hypersaline coastal ponds and sinkholes are useful for reconstructing storm records from tropical environments because they are not influenced by bioturbation. Hawkes and Horton (2012) also inferred a nearshore to inner shelf provenance for the overwash sand deposited on the coast of Texas by Hurricane Ike in 2008. Their conclusions were based on the presence of *Ammonia* spp. and *Elphidium* spp. (typical of bay and nearshore environments), as well as *Bolivina subaenariensis*, *Quinqueloculina*

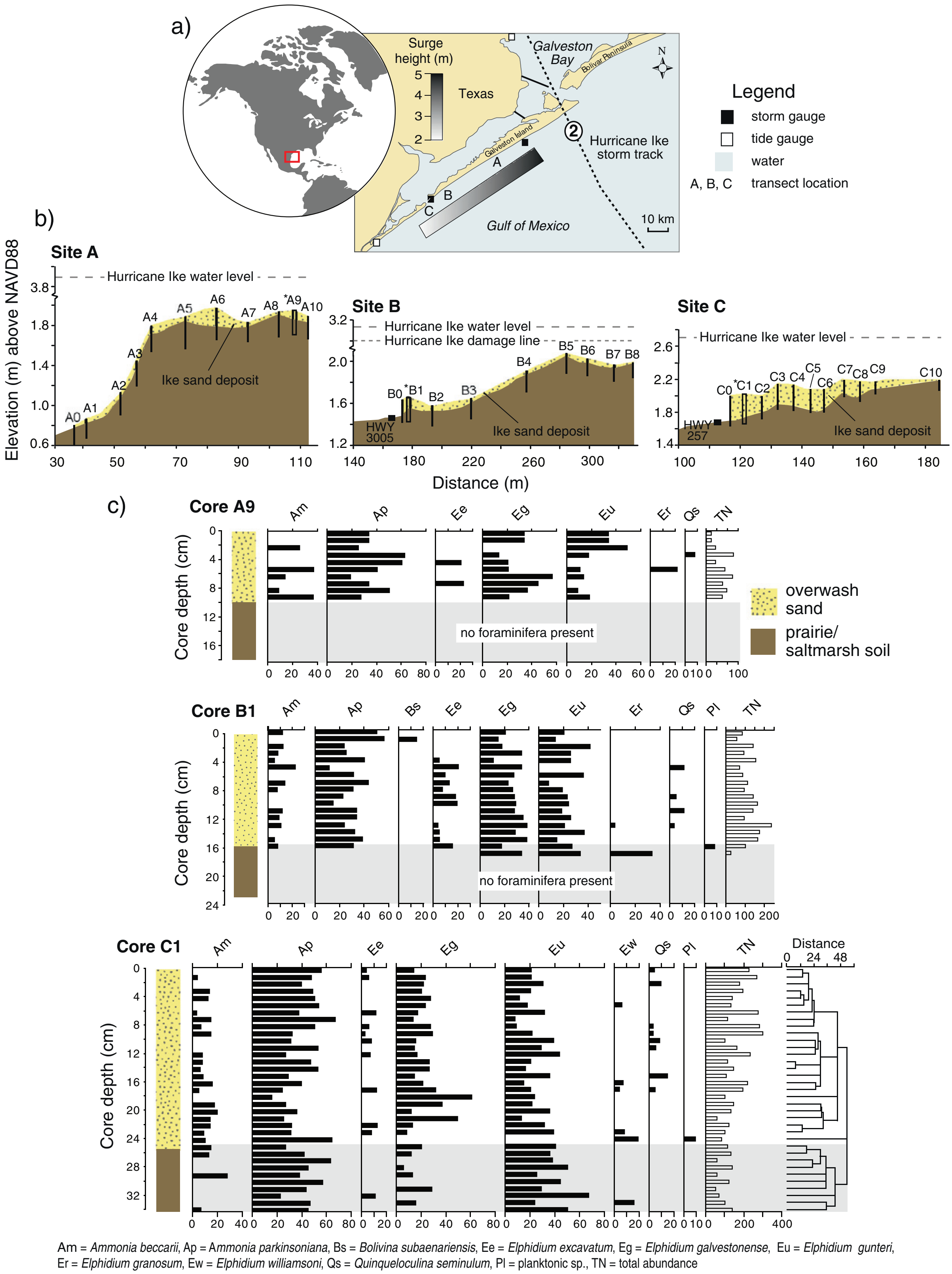

Fig. 6. Summary of findings by Hawkes and Horton (2012). a) Site map showing Hurricane Ike landfall in Galveston, Texas (dashed line) as a Category 2 storm. Gray shading off Galveston Island is the measured storm surge height in meters (NOAA probabilistic storm surge forecast at landfall; Plant et al., 2010). Core sites A, B, and C are identified as well as USGS storm gauges (black squares) and NOAA tide gauges that withstood the storm (black outlined squares). b) Core sites A, B, and C show shore-perpendicular measured transect renderings of the elevation of the pre-storm sediment (gray) and storm induced overwash deposit (stippled) above NAVD88. Core locations are identified with vertical lines and the rectangle locates the sampled core at each site. Hurricane Ike water levels are noted as dashed lines. The finer dashed line at core site B reflects the identified hurricane damage line. Zigzags (hiatus) in the y-axes at core sites A and B represent gaps in the elevation scale (x and y scales do not begin at zero). c) A log for each core (A9, B1, and C1) along with the percent of foraminifera by species (listed by two letter code, see legend for code explanation), the total number of foraminifera in each 5 cm^3 sample and for core C1 the constrained Euclidean distance cluster results for the foraminiferal assemblages. The clusters separate the pre-storm assemblages from the overwash assemblages.
Modified from Hawkes and Horton (2012).

seminulum and planktics, which inhabit inner shelf environments (Fig. 6). Hawkes and Horton (2012) further noted that only 10–30% of eroded beach material was deposited as overwash during the hurricane and that 70–90% of the eroded sediment was redeposited in the nearshore environment.

Diatom-based studies of storm washover include Parsons (1998), who reported a multi-source origin for sediments deposited by Hurricane Andrew when it made landfall in Louisiana in 1992. Assemblages within the deposit were diverse and consisted of a mixture of diatoms from marine, brackish, and freshwater settings and were easily distinguished from underlying autochthonous salt-marsh taxa. However, not all storm deposits contain microfossils. Horton et al. (2009) described a paucity of foraminifera in sediments deposited by Hurricanes Katrina and Rita in 2005 along the U.S. Gulf Coast. The absence of foraminifera within the storm deposits could be related to environmental stressors (e.g., seasonal hypoxia in the Louisiana shelf), reproductive factors (e.g., initial size of standing crop, reproductive frequency of the population), destruction of tests during transport, or post-depositional change (e.g., carbonate dissolution).

5. Concluding remarks

Microfossil analysis of coastal sediment sequences in conjunction with lithostratigraphic evidence enables recognition and characterization of paleo-earthquakes, tsunamis, and storms. The use of microfossils as land-level indicators is based on the strong association between microfossils and tidal elevation. Examples from Cascadia, Alaska, Japan and Chile document the precision of foraminiferal- and diatom-based transfer functions in quantifying the amount of interseismic and coseismic land-level changes during repeated earthquake deformation cycles. These examples illustrate how capturing centennial- to millennial-scale event records through microfossil analysis can provide important information regarding the magnitude and frequency of prehistoric earthquakes.

Numerous studies have employed microfossil analysis on overwash sediment from recent large magnitude tsunamis and storms to enable preceding events to be identified in the fossil record. Information regarding assemblages and the taphonomic condition of individual tests or valves can be used to assess provenance and transport history. Properly constraining sediment provenance provides insight into the distance of sediment transport and depth of scour (i.e., paleo-water depth). The differentiation between tsunami and storm surge deposits in the fossil record is extremely difficult, since most of their characteristics only indicate marine inundation. But storm surge sediments are mainly composed of nearshore material dominated by beach and nearshore sand, whereas tsunami deposits have a wide range of material from inner shelf to terrestrial debris (Switzer and Jones, 2008). Therefore, when placed into geomorphological, sedimentological, and historical contexts, microfossils can be useful in helping to ascribe depositional origin to overwash layers.

The utility of microfossils in documenting event records is dependent on their availability for transport and/or suitable preservation. The best microfossil-based reconstructions are from favorable coastal environments that are both quiescent and contain sufficient accommodation space for sediment to accumulate and preserve (Brill et al., 2014). For example, salt-marshes in Cascadia are excellent recorders of earthquakes and tsunamis because of the subsiding coastline that provides the necessary accommodation space. In contrast, net emergent coastlines (e.g., Chile and Sumatra) do preserve relative sea-level changes representative of the earthquake deformation cycle and tsunami deposits, but the lack of accommodation space makes preservation more difficult (Grand Pre et al., 2012). Records of localized coseismic subsidence and accompanying tsunamis on emergent coastlines are scarce, and where discovered, fragmentary (e.g., Dura et al., 2011; Grand Pre et al., 2012; Szczuciński, 2012; Brill et al., 2014).

Microfossils remain at the center of new developments seeking to improve our understanding of earthquakes, tsunamis, and storms, how these processes influence coastal evolution, and how they are recorded within coastal sedimentary sequences. It is also clear from the examples presented here that the use of microfossils from coastal environments as indicators of paleo-earthquakes, tsunamis, and storms remains a work in progress. Ample scope exists for improving the reliability, accuracy and precision of the reconstructions. This may come through the development of new statistical tools (Salonen et al., 2014) or the novel combination of microfossil data with other quantitative environmental proxies (e.g., Khan et al., 2013). However, a firm understanding of the ecology and taphonomy of microfossils must remain central to any future development. Furthermore, the quality and reliability of resulting reconstructions are dependent upon an understanding of the geological and geomorphological contexts of the sampling location, and the processes operating within it.

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