Progress in palaeotsunami research

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Review

Progress in palaeotsunami research

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ABSTRACT

The study of palaeotsunamis preserved in the sedimentary record has developed over the past three decades to a point where the criteria used to identify these events range from well-tested and accepted to new methods yet to receive wide application. In this paper we review progress with the development of these criteria and identify opportunities for refinements and for extending their application to new settings. The emphasis here is on promoting the use of multiple proxies, selected to best match the context of the site or region of interest. Ultimately, this requires that palaeotsunami research must be a multidisciplinary endeavour and indeed, extend beyond the geological sciences of sedimentology and stratigraphy and, to include knowledge and approaches from field such as archaeology, anthropology and sociology. We also argue that in some instances, despite the use of multiple proxies, the evidence for tsunami inundation of a coast simply may not be preserved.

1. Introduction

A palaeotsunami is defined as a "tsunami occurring prior to the historical record or for which there are no written observations" (International Tsunami Information Center, 2011). Palaeotsunami research is a young discipline, but in the past 30 years or so since it effectively started, researchers have worked in all corners of the globe including the Americas (e.g. Atwater, 1987; Clague and Bobrowsky, 1994; Hartley et al., 2001; Ramírez-Herrera et al., 2009), Europe (e.g. Dawson et al., 1988; Bruins et al., 2008; De Martini et al., 2010), the Middle East (e.g. Reinhardt et al., 2006; Donato et al., 2008; Salem, 2009), Japan (e.g. Minoura and Nakaya, 1991; Nanayama et al., 2007; Goto et al., 2010; Uchida et al., 2010), China (e.g. Du et al., 2001), Russia (Pinegina et al., 2003; Bourgeois et al., 2006), Pacific Islands (e.g. Moore et al., 1994; Goff et al. 2011a, 2011b), Indian Ocean (e.g. Jankaew et al., 2008; Monecke et al., 2008), Australia (e.g. Dominey-Howes et al., 2006) and New Zealand (e.g. Goff et al., 2001; 2004b, 2010b; Chagué-Goff et al., 2002; Nichol et al., 2007). As a result there has also been a steady increase in the number of proxy data used to help identify palaeotsunamis (e.g. Goff et al., 1998, 2010c; Switzer and Jones, 2008; Chagué-Goff et al., 2011a) often after being discovered through work on their modern and historic counterparts (e.g. Cisternas et al., 2005; Kortekaas and Dawson, 2007; Morton et al., 2007, 2008a; Sawai et al., 2009).

A scan of the palaeotsunami literature reveals two interesting points. First, there is an overwhelming emphasis on the geological and palaeontological evidence for palaeotsunamis—in other words, the physical evidence in the deposits (e.g. Bourgeois, 2009). Second, the use and/or perceived relevance and importance of individual proxies indicate a strong bias towards the expertise of those involved in the research. Neither of these points is entirely surprising, but in the wider context of identifying palaeotsunamis or perhaps more to the point, differentiating them from other catastrophic saltwater inundations such as palaeostorms, this downplays the significance of other potential lines of evidence.

Researchers now have access to a wide range of proxies, including geological (e.g. grain size, anisotropy of magnetic susceptibility, heavy minerals), macro- and micropalaeontological (e.g. shells, diatoms, foraminifera, pollen, nannofossils), geochemical, geomorphological, archaeological, anthropological, and palaeo-ecological evidence with which to identify palaeotsunamis (McMillan and Hutchinson, 2002; Morton et al., 2007; Goff et al., 2008, 2010b, 2010c; Mamo et al., 2009; Ramírez-Herrera et al., 2009; Chagué-Goff, 2010; Chagué-Goff et al., 2011a). It should be noted however, that of all the sites where palaeotsunami evidence has been reported, the full list of proxies has not been explored. Equally, to our

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knowledge they have never all been found at one site. Therefore, the lack of one or more proxies (e.g. foraminifera, geomorphology, etc.) should not be taken as evidence to refute the tsunamigenic origin of an event (Goff et al., 2010c), and the presence of only a few proxies should not on their own be considered evidence for a palaeotsunami.

The ability to grow the range of palaeotsunami proxies lies in the recognition that tsunamis are a natural process that affect both the physical and human environment (Goff and Dominey-Howes, 2011).

In the physical environment, tsunamis can result in damage to both marine and freshwater ecosystems (e.g. Fernando et al., 2006; Worachananant et al., 2007). There are also locally and regionally recognisable geological outcomes associated with the generating mechanism and its after effects (Goff and McFadgen, 2002), such as uplift and subsidence (Chini et al., 2008; Farías et al., 2010), landslides (Marano et al., 2010), river channel avulsion (Kale, 2002), coastal erosion (Paris et al., 2009) and destruction of dune systems (Goff et al., 2008, 2009). Equally, tsunamis cause loss of human life, destruction of communities, shifts in settlement patterns and facilities to safer areas, and changes in the way things (culture) are done at and near the coast (Dominey-Howes and Thaman, 2009). Many of these are fundamental changes that are not “geology”, but are an equally relevant part of understanding what is and is not evidence for a palaeotsunami (e.g. King and Goff, 2010).

Modern tsunami research is starting to adopt a coupled human–environment system approach to the study of these events (Turner et al., 2003), linking the human and physical; and ultimately this is where “geology” is heading with palaeotsunami research. There is a growing realisation that there is a bigger picture that revolves around the complete palaeoenvironmental story surrounding each event, and that starts to involve numerous other disciplines (e.g. McFadgen, 2007). In essence, to examine tsunamis as a process separate from the human landscapes in which they occur means that a great deal of potential understanding and insight will be lost.

The need to *simply* identify a palaeotsunami in the geological record is by no means simple. Over the past decade or more geologists have carefully constructed a proxy toolkit for identifying palaeotsunamis and recently these have expanded to include extra-disciplinary contributions (e.g. Chagué-Goff et al., 2011a). This work is ongoing and the toolkit continues to grow even though some argue that these criteria merely serve to determine whether or not the deposit is of marine origin, not that it is a palaeotsunami as opposed to a palaeostorm (e.g. Bridge, 2008). This is unfortunate since it has been shown in several studies that palaeotsunami proxy data are valid (e.g. Goff et al., 2004a; Kortekaas and Dawson, 2007; Morton et al., 2007; Komatsubara et al., 2008).

For an assortment of reasons it is not always possible to study every possible criterion in the toolkit. What is becoming apparent however is that it is increasingly important for palaeotsunami researchers to explore a suite of multidisciplinary avenues *in conjunction with* the use of conventional geological proxies. This will inevitably take the geologist into unfamiliar territory but will provide more convincing and comprehensive evidence of palaeotsunamis. The aim of this paper is to outline the progress made in this direction in the study of Holocene palaeotsunamis.

2. Palaeotsunamis were a natural process

When studying events that occurred prior to the historical record it is easy for the scientist to forget that palaeotsunamis, just like tsunamis, could have been generated by a variety of processes including earthquakes, terrestrial and submarine landslides, volcanic eruptions and other volcanogenic processes, meteorological events, jökulhaups (glacier outburst floods), methane hydrate release and the impact of extra-terrestrial objects (Goff and Dominey-Howes, in press). In essence, the potential palaeo event must have had a source, and finding evidence for it is an important contextual argument in making a case for deposits being of a palaeotsunami origin (Goff and McFadgen, 2002).

Palaeotsunami researchers rely heavily upon studies of recent events to provide usable proxies. The sites of recent events have also tended to provide a focus for palaeotsunami research at those localities since a modern analogue provides a suite of site specific proxies that can be used to differentiate palaeotsunamis from palaeostorms and other coastal processes (e.g. Jankaew et al., 2008).

In the study of any potential palaeotsunami deposit it is also important to consider the spatial extent of palaeo-inundation. In other words, are there contemporaneous deposits elsewhere that give an indication of the local or regional extent of the palaeoevent, and by association, a potential source (Goff et al., 2010c)? This approach is starting to prove valuable for work in the Pacific Islands where contemporaneous palaeotsunamis from local, regional and distant sources are being identified by using the spatial distribution of island records throughout the Pacific Ocean in conjunction with robust event chronologies (Goff et al., 2010b, 2010d, 2011a, 2011b). Equally, in the Pacific Northwest of North America, the regional spread of contemporaneous deposits has provided convincing evidence of palaeotsunami inundation (Peters et al., 2007), and data from the recent 2011 Tohoku-oki event in Japan are casting light on the magnitude of its predecessors (Goto et al., 2011).

3. Palaeotsunami chronology

One of the most intractable issues in palaeotsunami research is establishing a robust chronology. As a catastrophic natural process, the disturbance events associated with a palaeotsunami (e.g. earthquake, cultural change) offer a range of options for establishing a chronology. In many instances vast quantities of sand are transported inland and laid down in decimetre-thick layers. This offers the opportunity for some form of Optically Stimulated Luminescence dating which may or may not prove successful depending upon the degree of exposure of the transported sediments to sunlight. For example, Murari et al. (2007) had variable success with dating of the 2004 Indian Ocean tsunami (2004 IOT) deposits obtaining ages of ~250 to <50 years, depending upon the specific technique used. In essence, this form of dating can work but is not entirely reliable for coastal sediments where partial bleaching can occur and mixed sediment sources can give variable ages. Furthermore, the harder to bleach Thermoluminescence signal previously used in many earlier studies is less consistent (Radtke et al., 2001; Yasushi, 2007). In the absence of the ability to reliably date the sediments themselves (palaeotsunami deposits are not always composed of sand) or to enhance the event chronology, the nature of the process of deposition needs careful consideration.

Coastal plants are often killed by rapid sediment deposition offering the opportunity to radiocarbon date crushed vegetation at the contact between the palaeotsunami deposit and the buried soil (e.g. Cisternas et al., 2005). This dates the actual event to within the statistical error range of the radiocarbon date (the use of a mid-point of the range gives fictitious precision). However, crushed vegetation is a rare find, and this leaves a range of less favourable options. In general, radiocarbon dating is an easy to use and popular way to establish an event chronology, but it may be misused or misinterpreted. While a full discussion of the issues is beyond the scope of this paper, there is an excellent review in McFadgen (2007). In brief, the radiocarbon method can be used to date any organic material (e.g. wood, shell and microfossils), but dating the appropriate sample is key. For example, wood in an event horizon has an in-built age which can vary greatly (species type, root, branch, trunk, outer bark, driftwood, etc.). At best it give a maximum age. A piece of wood sampled *above* the horizon is therefore of little use by itself because in-built age may produce a date prior to the event.

On balance, radiocarbon dating of shell material is often more reliable than wood simply because there is less in-built age, although marine calibration and offset need to be carefully considered since the age determination on bivalves mollusc shells can be influenced by numerous environmental factors such as diet (McFadgen, 2007; Mastronuzzi and Romaniello, 2008). For example, intact bivalves in their original growth position were most likely killed and transported by the event, as opposed to shell hash which is of indeterminate age. Equally, care must be taken with sample collection because scouring of the subtidal and intertidal zones during palaeotsunami inundation can introduce older, apparently intact shells (and microfossils), into the deposit (e.g. Nichol et al., 2007; Uchida et al., 2010).

While radiocarbon dating has become a fairly standard tool it is important to understand the stratigraphic context of the dated material. For example, archaeological studies identified “tidal wave” deposits on the island of Efate, Vanuatu, giving an estimated age of about 1400 BP (Bedford, 2006). This chronology was based upon the assumption that bracketing tephras were dated to around 2200 BP and 1452/1453 AD (Gao et al., 2006) and therefore radiocarbon dates not fitting within this date range were discounted. A subsequent re-evaluation of the tephra ages and a new radiocarbon date from an intact bivalve mollusc shell from within the palaeotsunami (defined as such by Goff et al., 2011a) deposit provided bracketing ages of between about 2200 and 2800BP, considerably older than originally proposed (Goff et al., 2011a).

There are numerous statistical filtering techniques that can be applied to fine-tune ages such as wiggle-matching (Friedrich et al., 2006), but equally there are potential problems such as calibration stochastic distortion (CSD effect i.e. the artificial clumping of calibrated dates due to radiocarbon plateaux) (McFadgen, 2007). Thus, while this is an incredibly valuable chronological technique for palaeotsunami research, it should be applied with due diligence (e.g. Goff et al., 2003).

Where possible, other chronological techniques have been applied, such as tephrochronology, biostratigraphy and dendrochronology. Tephrochronology can provide excellent bracketing ages for a palaeotsunami (e.g. Pinegina et al., 2003; Nanayama et al., 2007; De Martini et al., 2010), and can occasionally also provide the age and evidence for the volcanic palaeotsunamigenic source (e.g. Minoura et al., 2000). However, the earlier example from Vanuatu indicates that tephrochronology should be used with appropriate care.

Biostratigraphy has proven to be of particular value where distinct changes in palynological assemblages can be tied to known or dated (radiocarbon) human settlement of an area. For example, in New Zealand, a marked decline in forest taxa and the coincident appearance of abundant *Pteridium* spores, Poaceae (grasses), *Taraxacum* sp., Anthocerotae (hornworts) and microscopic charcoal reflect Polynesian deforestation which occurred after settlement c. 800 years ago (Wilmshurst et al., 2008; Goff et al., 2010b). When preserved in the sediments above, below or within a palaeotsunami horizon, these palynological markers can often be used to provide a closer age for an event than other chronological techniques (Goff et al., 2010b). Furthermore, variations in the overall pollen assemblage indicate the effects of palaeotsunami inundation on the palaeo-ecosystem (Goff et al., 2010d).

Dendrochronology or tree age dating can give a precise age for an individual tree or cohort. In the context of palaeotsunamis this is only of use if some environmental change can be identified in that tree/cohort, such as partial or complete toppling by tsunami inundation or a sudden landscape response to the tsunamigenic mechanism. In the Pacific Northwest, for example, subsidence associated with the 1700 AD Cascadia earthquake drowned a vast swath of cedar trees that were subsequently inundated by a palaeotsunami (Jacoby et al., 1997; Atwater et al., 2005). Similarly, in New Zealand, lagoon subsidence and palaeotsunami following the 1826 AD Alpine fault rupture created an unvegetated platform that was rapidly colonised by trees (Goff et al., 2004b). In both cases, tree rings provided precise ages for these landscape responses that were associated with palaeotsunami inundation.

4. Palaeotsunami proxy toolkit

Table 1 summarises the suite of potential proxies that are available to the palaeotsunami researcher. This is by no means an exhaustive list, but it does contain the most commonly used and recently applied proxies.

4.1. Geological proxies

4.1.1. Grain size

In general terms, the mean grain size (and bed thickness) of modern and palaeotsunami deposits decreases landwards (e.g. Shi et al., 1995; Minoura et al., 1996, 1997; Chagué-Goff et al., 2002; Gelfenbaum and Jaffe, 2003; Witter et al., 2003; Goff et al., 2004b). There is however, considerable divergence from this general observation. Both grain size and deposit thickness vary with local topography (e.g. Gelfenbaum et al., 2007; Hori et al., 2007) and landward coarsening deposits have also been observed (e.g. Higman and Bourgeois, 2008).

Ultimately, the grain size distribution of a potential palaeotsunami deposit is source-dependent. For example, they could be comprised of a high percentage of fine silt (Goff and Chagué-Goff, 1999) or gravel (granule to boulder) clasts (e.g. Dawson and Shi, 2000; Frohlich et al., 2009) depending upon the nature of near- and onshore sediments (Fig. 1). Further, as modern and palaeo examples indicate, post-depositional processes can reduce the grain size range through winnowing, leaving coarse lag deposits (e.g. Nichol et al., 2003a; Goff et al., 2006; Szczuciński, 2012) (Fig. 1).

During inundation of coastal areas by tsunami waves, sand and finer particles (this can also include larger clast sizes as well) are mainly transported in suspension (Jaffe and Gelfenbaum, 2007). The free settling of these particles through the water column, related to a decrease of the turbulence of the flow, forms a fining-upward sequence in a deposit. Grain size characteristics of palaeotsunami deposits therefore reflect both the origin of the displaced sediment and the hydrodynamic conditions of sedimentation. Therefore, palaeotsunami (and tsunami) deposits usually display common characteristics with normally graded sand layers related to the decrease of the hydrodynamic energy during sedimentation (e.g. Dawson et al., 1988; Shi et al., 1995; Minoura et al., 2000; Wassmer et al., 2010). Each fining-upward sequence in a deposit may therefore be recording the effects of individual surging tsunami waves.

Bed load transport also contributes to tsunami deposits. Moore et al. (2011) attributed inversely graded layers at the base of sub-units of deposits created during the 2006 West Java tsunami to forming from deposition by a traction carpet. Higman and Bourgeois (2008) also observed inversely graded intervals at the base of the 1992 Nicaragua tsunami deposits. The thickness of such coarsening-upwards (and massive) intervals in a deposit may be indicative of the duration of the tsunami waves and their source parameters (Higman and Jaffe, 2005). Tsunamis with narrower source regions and shorter duration waves are more likely to be dominated by normal grading, and those with wider sources and longer duration waves have more complex deposits with thicker inversely graded and massive intervals (Higman and Jaffe, 2005). This provides a basis for distinguishing the deposits of large subduction zone earthquakes from more local tsunamis.

While inversely graded layers have been identified in palaeotsunami deposits (Goff et al., 2011b) the cross comparisons of thickness and grading to estimate potential palaeosources is yet to be attempted although it holds great promise in assisting to better

Table 1
Proxy toolkit for palaeotsunami deposits (modified after McFadgen and Goff, 2007; Chagué-Goff et al., 2011a).

Palaeotsunami criteria

Geological

1. Particle/grain sizes range from boulders (may be 750 m^3 or larger) to fine mud. A tsunami will usually transport whatever size ranges are available—it is sediment source-dependent
2. Sediments generally fine inland and upwards within the deposit. Deposits generally rise in altitude inland and can extend for several km inland and tens or hundreds of kilometers alongshore
3. Each wave can form a distinct sedimentary unit and/or there may be laminated sub-units
4. Distinct lower and upper sub-units representing runup and backwash can sometimes be identified. This is unlike storm or anthropogenic deposits
5. Lower contact is usually unconformable or erosional
6. Can contain intraclasts (rip-up clasts) of reworked material
7. Sometimes associated with loading structures at base of deposit—and can be associated with liquifaction features on the ground surface caused by earthquake groundshaking
8. Micro-scale features can include micro-rip-up clasts, millimetre-scale banding, organic entrainment, fining-up sequences and erosive contacts that may be visible in thin section but not in field stratigraphy
9. Measurement of anisotropy magnetic susceptibility (AMS) combined with grain size analysis provides information on hydrodynamic conditions ‘typical’ during tsunami deposition. Essential when no sedimentary structures are visible. Magnetic properties of minerals (inc. magnetic susceptibility) provide information about depositional environment
10. Heavy mineral laminations often present but source-dependent. Normally near base of unit/sub-unit but not always. Composition and vertical distribution of heavy mineral assemblage may change from the bottom to top of the deposit (e.g. often more micas at the top)

Chemical

11. Increases in elemental concentrations of sodium, sulphur, chlorine (palaeosalinity indicators, including element ratios), calcium, strontium, magnesium (shell, shell hash and coral), titanium, zirconium (associated with heavy mineral laminae if present) occur in tsunami deposits relative to under- and overlying sediments. Indicates saltwater inundation, and/or high marine shell/coral content, and/or high-energy environment (heavy minerals, source-dependent). Preservation issues to be considered in particular for salt (downward leaching), but uptake and preservation in wetlands/soils
12. Possible contamination by heavy metals and metalloids (source-dependent, inc. water depth source)
13. Geochemical (saltwater signature) and microfossil evidence often extends further inland than landward maximum extent of sedimentary deposit

Biological

14. Individual shells and shell-rich units are often present (shells are often articulated and can be water-worn). Often more intact shells as opposed to shell hash. A wide range of shell ages is indicative of greater reworking by a tsunami as opposed to storm or anthropogenic deposits. Small, fragile shells and shellfish can be found at or near the upper surface of more recent palaeotsunami deposits
15. Shell, wood and less dense debris often found "rafted" at or near top of sequence (increase in organic content determined by loss on ignition, and sometimes moisture content)
16. Often associated with buried vascular plant material and/or buried soil and/or skeletal (non-human) remains
17. Generally associated with an increase in abundance of marine to brackish diatoms—often a greater percentage of reworked terrestrial diatoms near the upper part of the deposit. Large number of broken valves often observed, reflecting turbulent flows. Variations in diatom affinities often indicative of source areas and magnitude of event
18. Marked changes in foraminifera (and other marine microfossils, such as dinoflagellates, nannoliths) assemblages occur. Deeper water species are introduced—this is unlikely in storm or anthropogenic deposits, and/or increase in foraminifera abundance and breakage of tests. Composition relates to source (near shore vs. offshore). Foraminifera size tends to vary with grain size
19. Pollen concentrations are often lower (diluted) in the deposit because of the marine origin and/or include high percentage of coastal pollen (e.g. mangroves). Pollen changes above and below the deposit are often indicative of sustained environmental change, a critical ecological threshold has been crossed—e.g. infilling or shallowing of coastal wetland

Archaeological

20. Archaeological sites—a sediment layer separating, underlying or overlying anthropogenic deposits/occupation layers
21. Archaeological middens: changes in shellfish species/absence of expected species indicate sudden change in onshore and nearshore palaeoenvironmental conditions
22. Archaeological structures show structural damage by water to buildings/foundations at a site
23. Archaeological burial sites have been reworked, often recognisable as “culturally inappropriate” burials
24. Replication—coastal archaeological occupation layers and shell middens are often separated or extensively reworked at several sites along coastline giving a regional/national signal of inundation

Anthropological

25. Traditional Environmental Knowledge (oral traditions) from the locality/region

Geomorphological

26. Acquired palaeogeomorphology indicates tsunami inundation—a tsunami geomophology is present that could include evidence of: i) uplift or subsidence/compaction of site/locality, ii) scour/erosion/reworking of sediments at site/locality—altered dune morphology, iii) sand sheet or other similar deposits such as gravel deposition/gravel pavements
27. Palaeogeomorphology at the time of inundation indicates low likelihood of storm inundation

Contextual

28. Known local or distant tsunamigenic sources can be postulated or identified
29. Known local and regional palaeoenvironmental drivers indicate low likelihood of storm inundation
30. Replication—similar contemporaneous coastal deposits are found regionally giving a regional signal of inundation

understand palaeotsunami sources for island nations with 360 degrees of exposed coastline.

The majority of palaeotsunami research has focussed on the meso and macro-scale features of a deposit such as sand layers, fining-up and fining-landward sequences and so on, and there has been limited focus until recently on micromorphology. Micromorphological characteristics however, are shown to be consistent with the more traditional meso and macro-scale features but with additional details not seen in standard stratigraphies. Additional details include organic and shell fragment alignment, mechanical impact clast fragmentation and intraclast microstructures (e.g. Kilfeather et al., 2007; Vött et al., 2010; Mahaney and Dohm, 2011). Microfabric analysis can also reveal micro rip-up clasts, millimetre-scale banding, organic entrainment, fining-up sequences and erosive contacts in thin section that are not visible in field stratigraphy.

While many of the features discussed above can be formed by other processes, the key to working with these and other proxies is that in combination as opposed to individually, they provide a strong case to support palaeotsunami origin.

At the other end of the grain size spectrum there has been a growing body of research focussed on the study of boulder deposits and their potential tsunami origins (e.g. Barbano et al., 2010; Goto et al., 2010). A detailed scan of existing publications indicates that many of the more convincing examples of this work are linked with historical tsunamis, albeit in some cases many hundreds of years ago in areas such as the Mediterranean and Japan (e.g. Barbano et al., 2010; Goto et al., 2010). The ability to produce convincing evidence for palaeotsunami origin based solely upon boulder clasts however, has proven more elusive. This is not surprising given that boulders represent only one of a multitude of potential proxies for palaeotsunami inundation.

In some cases, a strong argument can be made for possible palaeotsunami emplacment of coastal boulders merely because of the sheer size of the clasts (e.g. Frohlich et al., 2009), but even these interpretations are often fraught with problems such as poor chronological control, incomplete understanding of palaeoenvironmental conditions and a lack of plausible tsunamigenic sources. This is

Fig. 1. Example of a tsunami gravel lag deposit on a foredune, Great Barrier Island, New Zealand, showing: (a) Surface gravel sheet preserving approximate extent of palaeo runup on dunes to 14 m above mean sea level; (b) Heavy mineral laminae in sand sheet deposited in dune swale (note gravel clast at contact with older sand below); (c) Poorly sorted gravel and granules that form the deposit, sourced offshore from up to 50 m water depth (Nichol et al., 2003a).

particularly evident in the Caribbean where claims of widespread palaeotsunami emplacement of boulders and associated features (e.g. Scheffers, 2002; Scheffers et al., 2005) have been tempered by later work that has highlighted the complexity of such depositional environments (e.g. Morton et al., 2008b).

The difficulties associated with attempting to distinguish between boulder deposits laid down by either large palaeotsunamis or palaeostorms are compounded when working in areas that are known to have been affected by both processes. Recently, in Anegada, British Virgin Islands, researchers were able to avoid many of the controversial aspects of past extreme-wave boulder deposit studies, since the clasts had been laid down within a sheet of sand thus allowing a greater suite of proxies to be applied to the study (Atwater et al., in press; Watt et al., in press). In this case, while much of the evidence related to an historical time period, the authors were appropriately circumspect in their conclusions, determining that the sediments could have been emplaced by one of three possible tsunami sources or a storm whose effects exceeded those of the most severe hurricane to affect the area in 1960 (Atwater et al., in press).

Further research indicated that multiple boulder deposits on Anegada may have been produced by a combination of hurricane and tsunami events spanning tens to thousands of years (Watt et al., in press). However, a combination of the rich dataset with numerous lines of proxy data, numeric hydrodynamic models and a large-clast inverse sediment-transport model, allowed researchers to discriminate between some tsunami- and storm-deposited boulders (Buckley et al., in press). Results showed that flow velocities generated by even an exceptional storm were not capable of transporting some of the largest clasts while flow velocities from a tsunami simulation could.

This work is promising and shows the value of multiple lines of evidence. Since many coastal boulders are easily identifiable in satellite images, there is an opportunity here to use sites such as those on Anegada to explore ways of discriminating between (palaeo)tsunami- and (palaeo)storm-deposited clasts. The development of techniques to rapidly assess at least some extreme events deposits may not be too far away.

4.2. Magnetic properties

Magnetic properties of minerals, including mineral composition and magnetic susceptibility, can be used not only to ascertain the origin of the deposit, but also to provide information on depositional processes (e.g. Font et al., 2010). Although this method has not yet been used in palaeotsunami research, it has successfully been applied in combination with grain size data and numerical modelling in the study of an historical event (e.g. 1755 Lisbon tsunami, Font et al., 2010). Findings from their research pointed to the strong erosional effect of the tsunami, including information about the sediment source, thereby providing another potential tool for the identification of palaeotsunami deposits.

4.3. Anisotropy of magnetic susceptibility

Anisotropy of magnetic susceptibility is a proxy of sediment fabric, which had until recently only been used on lithified deposits to provide information on the transport direction of sediments during their emplacement (e.g. Hamilton and Rees, 1970). It is yet to be used on palaeotsunami deposits, but as a tool recently developed from studies of the unconsolidated sediments deposited by the 2004 IOT it shows great potential (Wassmer et al., 2010). When used in conjunction with grain size data it provides information about the hydrodynamic conditions prevailing during tsunami inundation and the emplacement of sediments (Wassmer et al., 2010; Chagué-Goff et al., 2011a). Anisotropy of magnetic susceptibility data allowed the reconstruction of the depositional processes associated with the 2004 IOT and the distinction between early traction-dominated and later suspension-dominated deposition in each individual sequence relating to successive waves, while the characteristics of the magnetic fabric provided information about flow direction (Wassmer et al., 2010).

As with all techniques there are some frustrating limitations. A minimum sediment thickness of 2 cm is needed and results may be biased in poorly sorted sediments containing a large fraction of coarse volcanic grains because of their magnetic susceptibility. However, when used in conjunction with grain size analysis the anisotropy of magnetic susceptibility technique has great potential as a proxy for helping to identify palaeotsunami deposits, particularly if there are no visible sedimentary structures (Wassmer et al., 2010; Chagué-Goff et al., 2011a).

4.4. Heavy minerals

Heavy mineral laminae have been reported in a number of recent historical (e.g. Szczuciński et al., 2006; Babu et al., 2007; Morton et al., 2007, 2008a; Narayana et al., 2007; Higman and Bourgeois, 2008; Jagodziński et al., 2009) and palaeotsunami (e.g. Goff et al., 2004b, 2010b; Switzer et al., 2005; Nichol et al., 2007; Switzer and Jones, 2008) deposits. They are often found at the base of a (palaeo)tsunami deposit (e.g. Morton et al., 2007; Nichol et al., 2007) but have also been reported distributed throughout the sediment column (e.g. Higman and Bourgeois, 2008; Morton et al., 2008a). However, as they are source-dependent, they are not found in every deposit (Chagué-Goff et al., 2011a). A further complication is that heavy minerals are sometimes present in such small amounts (<1% of the total mineral content) that they might not be visible to the naked eye without laboratory separation, and thus they may not be reported.

Historical events have allowed researchers to carry out detailed work on the dynamics of tsunami flow, as recorded by varied heavy mineral concentrations. In the case of the 2004 IOT, Babu et al. (2007) compared the heavy mineral composition of pre- and post-2004 IOT deposits. They attributed the increase of magnetite at the expense of lighter heavy minerals in the post-2004 IOT sediments to the intensity of reworking of offshore sediments by the tsunami. Jagodziński et al. (2009) on the other hand studied the spatial distribution of heavy minerals and reported an increase in mica concentration at the expense of tourmaline, zircon, and the opaque heavy minerals, in the post 2004 IOT sediments when compared to beach sands and pre-tsunami soils. They also found an increase in mica concentration towards the upper part of the 2004 IOT deposits. The preferential distribution of mica flakes in association with the finer grain fraction was attributed to different modes of deposition during a tsunami, which occurs through bed load and suspension, as opposed to mainly bed load in beach sediments. Furthermore, the presence of micas suggested a deeper water source for the tsunami sediment than solely beach sediments (Jagodziński et al., 2009).

Detailed investigations of heavy mineral assemblages in potential palaeotsunami deposits are rare. Switzer et al. (2005) and Switzer and Jones (2008) reported on the mineralogical composition of Holocene heavy mineral laminae and used it to ascertain the origin of sand sheets and thus the possible mechanism of transport.

Heavy mineral data are often used as proxies for high-energy palaeoconditions (e.g. Nichol et al., 2007), but as recent research on the 2004 IOT indicates they can also provide information about the origin and the depth of the sediment source as well as the changes in modes of deposition during tsunami inundation (e.g. Jagodziński et al., 2009). However, as with other potential proxies, heavy mineral data are more likely to be used to provide supporting evidence in conjunction with other more commonly used proxies (Chagué-Goff et al., 2011a).

5. Chemical proxies

Chemical proxies have long been used as proven indicators of palaeosalinity (e.g. Dominik and Stanley, 1993; Chen et al., 1997; López-Buendía et al., 1999), but their value to palaeotsunami research has been met with some resistance (Chagué-Goff, 2010; Chagué-Goff et al., 2011a). The most likely reason for the slow uptake of chemical proxy data hinges on a point made earlier, that the expertise of most practising tsunami researchers centres around sedimentology. Minoura and Nakaya (1991) were the first to report chemical evidence for palaeotsunamis in Japan based largely on the analysis of interstitial water in deposits laid down by large events. They concluded that geochemical signatures could also be used to identify inundation by smaller palaeotsunamis that did not leave any sedimentary evidence at all. Furthermore, geochemical evidence from interstitial water was used in association with diatom data to infer the tsunamigenic origin of several historical anomalous sand layers (Minoura et al., 1994).

Sediment chemistry, as opposed to the chemistry of interstitial water has since been used successfully in conjunction with other proxies to help identify historical and palaeotsunami deposits (Chagué-Goff and Goff, 1999; Goff and Chagué-Goff, 1999; Chagué-Goff et al., 2002; Goff et al., 2004b, 2010b, 2010d; Schlichting and Peterson, 2006; Nichol et al., 2007, 2010; Ramírez-Herrera et al., 2007, 2009). As with other proxies, there is no simple “recipe” for using geochemical signatures as a tool to identify palaeotsunami deposits. Not all elements thought to be associated with tsunami inundation occur in all deposits, either due to lack of uptake, preservation issues resulting in leaching or dissolution, mobilisation and/or redistribution linked with post-diagenetic processes (Chagué-Goff, 2010). Therefore, like other proxies, chemical signatures should be used in conjunction with others, and the preservation potential of the depositional environment needs to be carefully considered before data can be interpreted and conclusions drawn.

The most commonly found chemical proxies in both water and sediment relate to saltwater inundation and the input of marine shell material. Minoura and Nakaya (1991) and Minoura et al. (1994) reported relative maxima in ions of chloride (Cl^-), sodium (Na^+), sulphate ($S\,O_4^{2-}$), calcium (Ca^{2+}) and magnesium (Mg^{2+}), and low Mg^{2+}/Ca^{2+} ratios associated with sandy layers of tsunamigenic origin. Increases of Ca^{2+} and Mg^{2+} were attributed to the reaction of saltwater with the carbonic acids in pond water and also to skeletal carbonate from marine shells carried in by the tsunami (Minoura et al., 1994). Cl^-, Na^+ and SO_4^{2-} were recognised as clear indicators of saltwater intrusion, because of their high concentrations compared to freshwater in the lacustrine ponds (Minoura et al., 1994).

Saltwater indicators reported in palaeotsunami sediments include bromine (Br) (Schlichting and Peterson, 2006; Goff et al. 2010b; Nichol et al., 2010), sulphur (S), chlorine (Cl), barium (Ba), strontium (Sr), sodium (Na) (Chagué-Goff and Goff, 1999; Goff and Chagué-Goff, 1999; Chagué-Goff et al., 2002; Goff et al., 2004b, 2010b, 2010d; Nichol et al., 2007, 2010; Ramírez-Herrera et al., 2007, 2009) although not all elements were found in each study (see Chagué-Goff, 2010 for a review). Elemental ratios have also been used to correct for grain size variations as the concentration of many elements is strongly dependent upon the particle size distribution (Chagué-Goff et al., 2002; Chagué-Goff, 2010). Iron (Fe), although of terrestrial origin, was reported in a number of studies in association with S, probably occurring mostly as pyrite (Chagué-Goff and Goff, 1999; Goff and Chagué-Goff, 1999; Goff et al., 2004b; Nichol et al., 2007; Goff et al., 2010b, 2010d). Relative maxima in calcium (Ca), magnesium (Mg) and Sr in tsunamigenic sediments have been attributed to the incorporation of skeletal carbonate from marine shell/hash or microfossil material, and thus are indirectly seen as signatures of palaeotsunamis (Goff et al., 2004b; Nichol et al., 2007, 2010).Titanium (Ti), zirconium (Zr) and iron (Fe) have also been reported in palaeotsunami sediments in association with heavy mineral laminae (Goff et al., 2004b, 2010b; Nichol et al., 2007), and used as indicators of high-energy deposition. They are however source-dependent and heavy mineral laminae are not reported in all historical or palaeotsunami deposits, simply because they do not occur. When heavy minerals are present in very small amounts and thus might not be visible to the naked eye, their presence might however be revealed through a change in elemental concentration, such as a relative maximum in Ti, Zr and Fe.

Two decades ago, Minoura and Nakaya (1991) suggested that geochemical signatures could be used to infer the occurrence of smaller tsunamis that did not deposit sediments and soon after Chagué-Goff and Fyfe (1996) found evidence for ancient saltwater inundation in a peat bog, in the absence of any sedimentary evidence for such an event. Recent observations of salt residues several tens of meters (or more) inland from the maximum extent of sediment deposition (Java, 2006: Fritz et al., 2007; Samoa, 2009: Chagué-Goff et al., 2011a; Japan, 2011: Chagué-Goff, 2011; Sugawara et al., 2011) indicate the potential value of geochemical proxies for determining palaeotsunami inundation limits (Fig. 2). Similarly, while it is recognised from studies of the 2004 IOT that water-soluble salts can be subject to dilution and leaching (Szczuciński et al., 2007; McLeod et al., 2010; Szczuciński, 2012), palaeotsunami research has shown that they can also be incorporated within the organic fraction of sediments in organic-rich wetlands and soils and thus retained (Chagué-Goff, 2010; Goff et al., 2010b; Nichol et al., 2010). Thus, in suitable depositional environments, the landward limit of palaeotsunami inundation can be estimated based on chemical signatures, thereby providing useful information for tsunami risk assessment (Chagué-Goff, 2010, 2011; Chagué-Goff et al., 2011a).

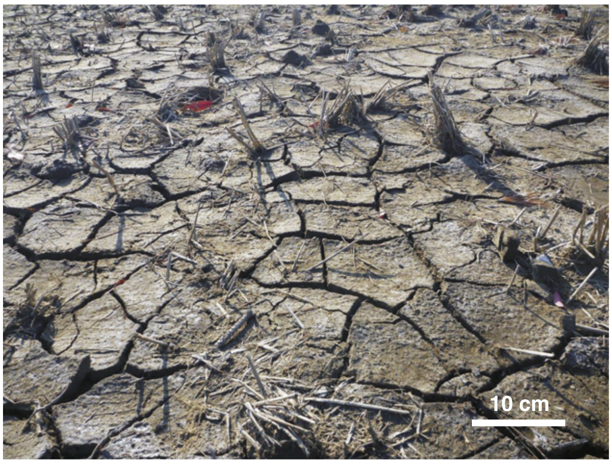

Fig. 2. Salt crust on mud-dominated tsunami deposit in rice paddy field, c. 3.2 km from shore, Sendai Plain, Japan, beyond the limit of the sandy tsunami deposit, which itself reaches c. 2.8 km inland (photo: C. Chagué-Goff, May 2011).

5.1. Biomarkers

Biomarkers are complex organic substances or compounds that can be used to identify the source of sedimentary organic matter, as they are specific to particular organisms. Recently, Alpar et al. (2012) used biomarkers (normal and branched alkanes, lipids and sterol biomarkers) in an attempt to identify the source of three anomalous sand sheets previously identified as being tsunamigenic in origin (Yalciner et al., 2005 in Alpar et al., 2012). Their study showed that marine and terrestrial biomarkers were present in at least one of the sand layers, thus inferring that it was most probably a tsunami deposit. However, not enough marine biomarkers were retrieved from the other two sand layers. Nevertheless, it appears that biomarkers may well represent an additional proxy that can be used to help identify palaeotsunami deposits. Biomarkers are specific to particular organisms, all of which have their preferred environmental niches that indicate their origins (e.g. water depth) and thus the energy of the event required to entrain them.

6. Biological proxies

6.1. Macropalaeontology

Tsunami deposits contain both marine and terrestrial material. Terrestrial material such as driftwood, trees and other coastal vegetation is often eroded from the coastal zone and transported inland. These organic inclusions, in association with other proxies, can provide useful data on flow direction, time of inundation (aiding correlation with potential palaeotsunamigenic events) and palaeoenvironmental conditions at the time of inundation (e.g. Dawson and Smith, 2000; Goff et al., 2010b).

Modern tsunamis are known to have deposited marine flora and fauna such as fish, dolphins, sea turtles, sharks, rays, coral debris, seaweed and shells onshore (Lander et al., 2003; Dominey-Howes and Thaman, 2009; Goff and Chagué-Goff, 2009; Chagué-Goff et al., 2011a; Richmond et al., 2011). These offer a wide range of potential proxy data for palaeotsunami researchers, but as far as we know the nature and extent of the marine flora and fauna deposited in modern tsunamis have not been systematically studied or reported except to note that fish and/or coral debris for example are strewn across the landscape (e.g. Lamarche et al., 2010; Chagué-Goff et al., 2011a; Richmond et al., 2011).

To be useful as proxy indicators a special set of circumstances must occur for macrofossil remains to become encapsulated/fossilised within a palaeotsunami deposit. While the soft tissue will usually decay rapidly, the taphonomy of marine mammal bones at least is highly variable, but in exposed coastal sites it rarely lasts beyond 50 years (Liebig et al., 2003). Clearly, skeletons must be rapidly covered with sand or have been incorporated within it at the time of deposition for the evidence to be preserved (Goff and Chagué-Goff, 2009). Except on rare occasions when whale or other skeletons are found at high elevations, the presence of marine fish/mammal bones within a Holocene coastal deposit does not serve as a significant palaeotsunami proxy (Goff and Chagué-Goff, 2009). However, in conjunction with other proxy indicators it can strengthen the case for the palaeotsunami origin of a deposit (e.g. Cassels, 1979; Goff, 2008). Like the presence of crushed vegetation discussed above, the discovery of marine fish/mammal bones associated with a possible Holocene palaeotsunami deposit is rare and in most cases has tended to coincide with either archaeological sites (Cassels, 1979) or inundated lacustrine environments (Dawson and Smith, 2000).

There is an increasing amount of research focussed on establishing palaeotsunami records for tropical regions. This increases the diversity of marine macrofossils that are likely to be found and extends the potential value of new proxy data. Soft and hard corals, sponges, lagoonal and other shallow water shellfish provide unique opportunities for understanding the nature of palaeo-inundation. This work is in its infancy but has already proven useful in determining the flow dynamics and relative magnitude of palaeotsunamis (e.g. Goff et al., 2011b).

In temperate areas, the most common macro organic proxies are individual shells and shell-rich units. However, there is no well-defined or expected position for individual shells and shell-rich units within a tsunami deposit. Often though, small, fragile shells and shell hash can be found near the upper surface of palaeotsunami deposits most likely rafted as less dense debris until eventual deposition (Fig. 3; e.g. Goff et al., 2000; Nichol et al., 2007). Shell beds tend to be found within a palaeotsunami deposit and, like the sediments enclosing them, can thin landward and fine upwards (Nichol et al., 2007; Donato et al., 2008; Goff et al., 2011b). The presence of many articulated offshore and estuarine bivalve species are used to indicate a rapid catastrophic palaeoevent as opposed to more prolonged inundation associated with a palaeostorm (Kortekaas and Dawson, 2007; Donato et al., 2008). Equally indicative of tsunami deposition is the mixing of articulated bivalves with abundant angular fragments. The latter are indicative of turbulent flows causing shell-to-shell contact and other impacts.

The settling out of shells on top of a palaeotsunami deposit during unidirectional flow, either as less dense rafted material on land during runup or in submarine settings during backwash can cause a coarsening-upwards unit as finer, less hydrodynamic fragments settle out first. The larger, overlying shells tend to settle in a loosely packed, convex-up orientation (Reinhardt et al., 2006). As with many of the proxy data it is not merely the presence of the shells that indicates palaeotsunami deposition, but the context in which they are found.

Fig. 3. Small, fragile articulated *Donax* shells on the surface of tsunami sediments laid down by the 17 July 2006 Western Java Tsunami (also refer to Fig. 5E, Moore et al., 2011).

6.2. Micropalaeontology

6.2.1. Diatoms.

The sub-fossil remains of microscopic diatoms, unicellular algae of the division Bacillariophyta, comprise a siliceous valve(s) termed a frustule that is identifiable to species level on the basis of its morphology and surface patterning (Werner, 1977). Diatoms are useful environmental indicators because they are ubiquitous in aquatic environments and particular assemblages are known to have affinities to specific water chemistry conditions, including salinity, pH, nitrogen and phosphorus (Battarbee, 1986). Accordingly, diatom taxa are typically classified according to their known tolerances to a range of environmental conditions, with the halobian classification scheme for salinity preference (Hustedt, 1957), a widely used system that is relevant for palaeotsunami research. In addition, the life form of diatoms is also used to associate them with particular habitats, including planktonic, epiphytic and benthic forms, and their respective sub-forms (e.g. epipsammon—attached to sand grains, epipelon—living in mud) (Admiraal, 1984; Anderson and Vos, 1992; Vos and de Wolf, 1993a, 1993b). This information is relevant for identifying likely source-environments for diatoms associated with a potential palaeotsunami deposit.

For palaeotsunami research, diatoms have traditionally been used to infer catastrophic saltwater inundations of a range of coastal depositional environments, with the key criterion being the preservation of taxa that are out of context for the particular environment in which they are preserved. For example, the preservation of open ocean planktonic diatoms in brackish to freshwater coastal wetlands has been used in several key studies to infer tsunami inundation (e.g. Hemphill-Haley, 1996; Chagué-Goff et al., 2002; Smith et al., 2004; Nichol et al., 2007). Three common characteristics of the diatom assemblages in these tsunami sediment records are: (i) preservation of diatoms from a variety of salinity groups and habitats, typically ranging from fully marine planktonic types to brackish benthic forms, and often referred to as a chaotic assemblage; (ii) poor preservation of diatom frustules, with high percentages (typically > 75%) of broken valves, indicating damage during transport, and; (iii) low concentrations of diatoms within tsunami deposits, particularly for sand-dominated deposits. These characteristics have also been noted for some modern tsunami deposits (e.g. Dawson, 2007; Kokociński et al., 2009; Sawai et al., 2009; Chagué-Goff et al., 2011a), but they are by no means exclusive to all (palaeo)tsunami deposits. In particular, several studies from the Pacific Northwest USA have reported good preservation of diatom valves and in high concentrations, interpreted as evidence for rapid transport and burial (Hemphill-Haley, 1996 and references therein). The potential exists, therefore, to use the degree of diatom preservation and concentration to make inferences about the distance of transport from source. However, this will always be limited by the varied robustness of diatoms, with many marine planktonic species characterised by robust morphologies (e.g. centric forms) with thickly silicified valves; in contrast to the delicate needle-like (pennate forms) morphology of some brackish taxa. An additional problem relates to chemical dissolution of valves, with the process occurring at a faster rate in higher temperatures such as those experienced in tropical climates (Kamatani, 1982).

Detailed studies of diatoms preserved within deposits from the 2004 IOT have illustrated the potential to use diatoms in conjunction with physical sedimentology to infer variations in the hydrodynamics of tsunami flow across a landscape. In particular, the work of Sawai et al. (2009) in Thailand has shown partitioning of a tsunami deposit into beds that formed during different stages of tsunami runup (i.e. peak flow to waning flow) resulting in preferential deposition of diatoms from different source environments, with beach and subtidal benthics deposited as part of the sand traction load and planktonic taxa deposited from suspended load as the tsunami flow waned.

For palaeotsunami research, preservation of these details can be hindered by processes such as bioturbation and physical settling of a deposit over time. In general, few palaeotsunami studies have tested this premise adequately (e.g. Goff et al., 2011b) and the opportunity exists to make use of these diatom studies from modern deposits to guide palaeotsunami research. One obvious need is for higher resolution sampling of sediment records to try and extract the type of hydrodynamic information that has been gleaned from modern deposits. Promise in doing such high resolution work has been shown from palaeotsunami studies which have used diatoms to map tsunami runup farther landward than the associated sand-silt sheet (Hemphill-Haley, 1996; Nichol et al., 2003b). Clearly, this calls for research with a sampling design that is high resolution at the spatial dimension as well as through the vertical dimension of a deposit. In summary, the use of sub-fossil diatoms in palaeotsunami research has developed to the point where we can go beyond the objective of using diatoms solely as an indicator for marine inundation to the more sophisticated aim of reconstructing flow dynamics (albeit relative) based on high resolution mapping and sampling.

6.2.2. Ostracods

Ostracods are microscopic aquatic crustacea that form a relatively robust calcareous valve that can preserve well within sediments (Frenzel and Boomer, 2004; Ruiz et al., 2005). They are responsive to a range of environmental variables, including salinity (freshwater to fully marine), temperature, water depth and sediment grain size and can regenerate (by moulting) as a colony within hours to days. It is therefore possible to use the species assemblage and population age structure of fossil ostracods to identify abrupt changes in the environmental conditions of their associated habitat.

The utility of ostracods as indicators of environmental change is well recognised (Ruiz et al., 2005), with several studies establishing clear evidence for reworking of ostracods into historical tsunami deposits (Hindson et al., 1996; Hindson and Andrade, 1999), including the 2004 IOT (Hussain et al., 2006). For palaeotsunami research, ostracods have been used to support physical sedimentary evidence for high-energy flows into brackish lagoons and shallow bays (Fujiwara et al., 2000; Vött et al., 2009), principally through the identification of allochthonous species typically associated with deeper water, open marine conditions (Ruiz et al., 2010). Ostracods have also been used to infer a temporary (decadal) change in chemistry of a freshwater lake due to tsunami overtopping (Leroy et al., 2002). In some cases, the abraded condition of ostracod valves preserved within sand sheets is also used as evidence for transport in turbulent, sediment-laden tsunami flow (e.g. Hindson et al., 1996; Alvarez-Zarikian et al., 2008). However, evidence from tsunami deposits in the Andaman Islands laid down by the 2004 IOT supports the case of good preservation of valve morphology and patterning during transport (Hussain et al., 2006). Whether these valves retain this condition over geological time will clearly depend on weathering characteristics of the depositional environment. Opportunities exist therefore to build our understanding of the taphonomic changes that may occur to ostracods remains during and after reworking by a tsunami and therefore help inform palaeotsunami studies.

6.2.3. Foraminifera

Due to their small size, abundant incidence, high preservation potential within the sediment record after death and distinctly diagnostic test shape, foraminifera are useful stratigraphic, palaeoecologic and palaeoenvironmental tools for environmental reconstruction (Loeblich and Tappan, 1987; Hayward et al., 1999; Sen Gupta, 1999). Both pelagic and benthic, they are abundant within the entire marine realm and some freshwater environments (and sediments). Any change in assemblage composition within a sedimentary sequence, whether it is the disappearance or introduction of a particularly indicative species, alludes to a shift in marine environmental conditions at the location where the tests are subsequently preserved.

Changes in foraminiferal assemblage composition can reflect extreme events (such as earthquake subsidence (Alvarez-Zarikian et al., 2008), storms (Palma et al., 2007) and tsunamis (Hawkes et al., 2007). In addition to examining 'gross' assemblage composition, the use of taxonomic systematics (the classification of organisms with the aim of reconstructing evolutionary relationships) of individual foraminifera found within a deposit, can also provide significant information about local environmental conditions (Hayward et al., 1999).

Foraminifera are therefore useful for helping in the identification of palaeotsunami deposits. For example, information about the composition of a foraminiferal assemblage within a tsunami deposit can tell us something about the depth of water from which the sediments were entrained, or their distance of transport before deposition at the location at which they are now found (e.g. Uchida et al., 2010). Equally, evidence about the preservation and taphonomy of individual tests might reveal details about the nature of flow velocity, turbidity, abrasion and post-depositional environmental processes.

As palaeotsunami research has developed, there has been a marked increase in the number of published and unpublished reports that analyse foraminifera (see Mamo et al., 2009 for a review). Recently, Uchida et al. (2010) examined foraminifera contained within tsunami sediments from Japan and showed that the foraminiferal assemblage of tsunami-deposited sands were characterised by smaller, well sorted tests associated with deeper bathyal assemblages entrained and transported by the tsunami from deeper water offshore. This contrasted with larger tests associated with shallower sub-littoral assemblages that characterised the sediments overlying and underlying the tsunami deposits. Further, the absolute number and relative abundance of planktonic versus benthic species varied between the normal marine and tsunami-deposited sediments (although it is not clear how the relative abundance changed) (Uchida et al., 2010).

In rare cases where no foraminifera are present in coastal or shelf waters, then none will be available for a tsunami to deposit. However, a lack of foraminifera in potential palaeotsunami sediments is more likely due to taphonomic effects, given the ubiquitous distribution of foraminifera in the marine realm. Yawsangratt et al. (in press) have indeed reported a rapid dissolution of carbonate foraminifera in tropical climates, with many partly or completed dissolved tests within five years of the 2004 IOT in Thailand.

6.2.4. Usefulness of microfossils

Palaeotsunami researchers should use multiple techniques and palaeoenvironmental indicators such as foraminifera, diatoms and ostracods and not rely on just one group. Given that the exact composition of microfossil assemblages varies from location to location (even at the same latitude, water temperature, etc.), it is impossible to expect to see a specific 'diagnostic' species or assemblage in association with tsunami-deposited sediments. Furthermore, taphonomic processes are known to affect the preservation of microfossils, in particular in tropical climates, and yet they can also be well preserved in such environments as well (e.g. Goff et al., 2011b). The issue of taphonomy will doubtless continue to plague the study of microfossils in potential palaeotsunami deposits, thus making it all the more important to not rely on a single group.

A comment on microfossil assemblages would not be complete without mention of a few more that sit within this general group—sponge spicules, dinoflagellates, pollen and nannofossils. Sponge spicules have been used in association with diatom and macrofossil data to assist in the interpretation of palaeotsunami deposits (e.g.

Ramírez-Herrera et al., 2009), but at our current level of understanding only serve to provide corroborative evidence that the deposit is of marine origin. Similarly, the presence of dinoflagellates was used to confirm the marine origin of anomalous layers in a coastal lagoon, as also inferred from diatom and geochemical data (Chagué-Goff et al., 2002). In the example given from Ramírez-Herrera et al. (2009), additional pollen data served to indicate a significant disturbance of the coastal environment.

Pollen data have two useful purposes as a proxy. First, pollen concentrations in marine sediments tend to be lower than in the bracketing terrestrial deposits (Goff et al., 2000) and are likely to contain a high percentage of coastal pollen (e.g. mangroves: Ramírez-Herrera et al., 2009). Second, changes in pollen assemblages immediately above a potential palaeotsunami deposit can be used as proxies for catastrophic changes in the coastal environment such as sediment infilling and a response to temporary (inundation) or permanent (inundation + subsidence) changes to salinity conditions (Hughes and Mathewes, 2003; Goff et al., 2010d).

Nannoliths, which are small (silt-clay size) heterogeneous biogenic carbonate particles, can be used as proxies of marine influence in coastal sediments (e.g. Guerreiro et al., 2005). Their distribution was recently examined in sediments deposited by the 2004 IOT in Lhok Nga, Sumatra (Paris et al., 2010a, 2010b). This study showed that nannoliths were enriched in tsunami deposits and that the assemblages could be used to identify the source of sediments. Thus, when used in conjunction with grain size data, nannoliths can provide another useful tool to identify palaeotsunami deposits. Their usefulness is, as with other microfossils, limited by taphonomic processes, which might result in carbonate dissolution.

7. Advantages of chemical and biological (microfossil) proxies

One of the most significant advantages of using a combination of chemical and/or microfossil proxies is their potential for tracing palaeotsunami inundation inland beyond the landward limit of the sedimentary evidence (Hemphill-Haley, 1996; Nichol et al., 2003b; Chagué-Goff, 2010; Chagué-Goff et al., 2011a). This potential has been shown for both historical and palaeotsunami situations with a marine geochemical signature detected in mud deposited by the 2011 Tohoku-oki tsunami in Japan to the limit of inundation about 4.5 km inland, while sandy deposits could only be traced to around 2.5–3.0 km (Chagué-Goff, 2011; Goto et al., 2011). The same technique can be used to estimate the full inundation distance of earlier historical and palaeotsunamis such as the 867 AD Jōgan event beyond any preserved or recognisable sand layer (Chagué-Goff, 2011). This means that tsunami models can use more accurate estimates of inundation and runup based upon both palaeotsunami and historical events. Tsunami risk assessments will then produce a more comprehensive understanding of the longer term hazard.

8. Archaeological proxies

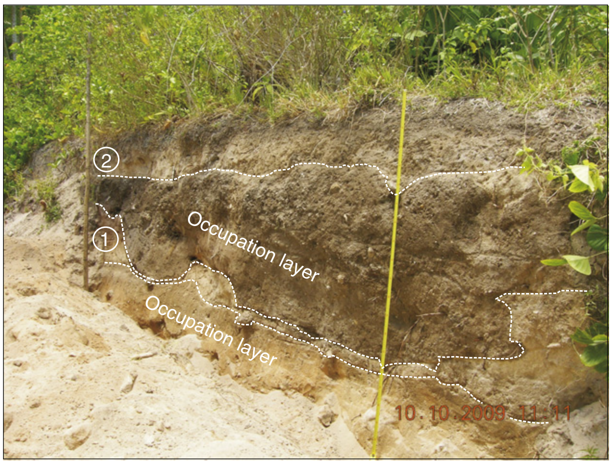

Fig. 4. Lévési, Futuna. Palaeotsunami deposits 1 and 2 overlying occupation layers (after Goff et al., 2011b). The shape of the upper contact for the lower palaeotsunami deposit has been caused by post-event anthropogenic activity similar to that noted for the Jōgan deposit, Japan (J. Goff pers. obs.).

The coupled human–environment system approach now being recognised for modern tsunami research (Goff and Dominey-Howes, 2011) is reflected in the use of proxy data outside of those more comfortably sitting in the domain of the physical scientist. Archaeological and palaeotsunami researchers have often examined the same depositional evidence but with a markedly difference focus. The former is primarily interested in the occupation layers that are occassionally separated by what is often termed 'sterile sand" (e.g. Kirch and McCoy, 2007) or "sterile storm/tidal wave sands" (e.g. Allen, 2004). The palaeotsunami researcher on the other hand tends to focus on the catastrophic saltwater inundation events represented by these apparently sterile sand units (Fig. 4). For example, in Japan, Komatsubara et al. (2008) noted that while the tsunami deposits of the 1605 AD and 1707 AD earthquakes could be identified at many key sites adjacent to the Nankai Trough, they were also known to be present in the neighbouring archaeological site of Nagaya-Motoyashiki, although detailed descriptions of the sediments were not available.

Something of this restricted approach by archaeologists to potentially catastrophic socio-cultural events is reflected by Anderson (2009) who stated that "overall, it is in the nature of rapid-onset natural hazards to be fairly localised occurrences in space and time. They have been under-researched in the Pacific, and they are an important source of additional complexity in landscape history, but they did not have the almost ubiquitous and long-term impacts of climate change and anthropogenic modification."

We tend to agree that rapid-onset natural hazards have indeed been under-researched in general, not just in the Pacific, but we find it difficult to rationalise unsupported statements such as Anderson's (2009) comment that these events are "fairly localised occurrences in space and time". On the contrary, it has been shown elsewhere around the Pacific for example that rapid-onset palaeotsunamis (and their associated generating mechanisms) can produce region-wide landscape and human settlement changes (e.g. 15th Century New Zealand: Goff and McFadgen, 2002; Pacific Northwest: McMillan and Hutchinson, 2002) and their modern counterparts provide ample evidence of the effects on human populations and communities (e.g. 2004 IOT; Liu et al., 2005).

In the past, palaeotsunami researchers have been similarly restricted in approach, as illustrated by the statement by Goff et al. (2004a) that "the tsunami penetrated far enough inland to affect archaeological material". This tells us nothing about the archaeological evidence. Fortunately, more recent work has started to recognise the importance of both the "sterile sands" and the occupation layers, and any particular admixture of the two. Perhaps the most compelling example relates to the explosive eruption at Santorini in the Aegean Sea during the second millennium BC which was the largest Holocene event of its kind in the Eastern Mediterranean region. In determining the nature and extent of the resultant tsunami in Crete, Bruins et al. (2008) were not only able to date the event using cattle bones covered by potsherds, but also to infer that these items most probably represented meal remains from one of the destroyed coastal houses. The tsunami however, did not cause the end of the Minoan civilization, but rather led to an immediate post-event building boom. This was followed by a more gradual decline that triggered the beginning of the end for the Minoans. Their tsunami-devastated coastal communities had lost any reasonable naval defences and invasion soon followed (Bruins et al., 2008).

Archaeological proxies can therefore indicate both the direct and indirect effects of a catastrophic event, often providing key contextual information to aid in the identification of a palaeotsunami. It is rare however that both expert archaeological and palaeotsunami researchers work together and this can lead to frustratingly vague interpretations, such as that for an apparently historical deposit on Norfolk Island where Macphail et al. (2001) report that “This unit has been variably interpreted as sands deposited by a tidal wave in A.D. 1834 and as a slopewash deposit accumulating on the swamp surface during levelling of the calcarenite ridge”. In this example there is no consideration given to clarifying whether this was indeed a tsunami (tidal wave) or not and yet if it was, it must have had significant implications for the fledgling colony at the time. The inferred age is poorly constrained and we therefore are unclear whether this actually relates to an earlier 1805 AD tsunami or not (we find no historical record for an 1834 AD event), one that ran up over 16 feet (~5 m) and destroyed many buildings (Anon, 1805).

Putting aside the differences in approach to the identification of potentially devastating past tsunamis, it becomes apparent that there are many useful archaeological proxies. From their New Zealand work, McFadgen and Goff (2007) list five key archaeological (and one anthropological—discussed below in the following section) proxies. First, there are often significant changes in midden composition from those found above and below a palaeotsunami deposit. Changes in shellfish species and the absence of expected ones indicate fundamental changes to the nearshore ecology potentially caused by subsidence/uplift, smothering by sediments or sediment removal (e.g. McFadgen, 2007). Second, structural damage to buildings and their foundations replicates contemporary evidence of tsunami inundation. Third, geomorphological change at the archaeological site indicates uplift, subsidence and/or compaction. This is often cross-correlated with midden changes and can be associated with scour and erosion around structures, and the deposition of sediment layers separating or overlying anthropogenic deposits. Fourth, there can be reworking of anthropogenic deposits such as occupation layers, shell middens and burials. This can lead to puzzling culturally inappropriate associations such as waste (middens) overlying burial sites. Fifth, these findings in whole or in part are replicated at more than one site along the coast and are often associated with widespread relocation of coastal settlements from exposed and/or low-lying sites to high elevation locations farther inland (e.g. Goff et al., 2011b). While such shifts in settlement pattern have been noted by numerous archaeologists (e.g. New Zealand: McFadgen, 2007; Solomon Islands: Shepard and Walter, 2006; Cook Islands: Walter, 1998; Futuna Island: Sand, 1990), few have addressed the issue of cause and effect from anything other than a sociological or ecological perspective (McFadgen, 2007). This is a similar issue faced by geologists who often fail to consider the full environmental context of physical processes be they tectonic, climatic, or both. This section on archaeological proxies is by no means an exhaustive list, but indicates that there is a wealth of data that can be used to complement other proxies.

9. Anthropological proxies

Anthropological proxies refer to the behaviour, and the physical, social, and cultural development of humans as opposed to archaeological data that deal with the examination of the physical remains. As such, Traditional Environmental Knowledge (TEK) has much to offer palaeotsunami researchers.

Few palaeotsunami researchers however, have given the evidence of past events contained in TEK much credibility, although there are exceptions (e.g. Heaton and Snavely, 1985; Clague, 1995; McMillan and Hutchinson, 2002; Goff et al., 2003; Atwater et al., 2005; King et al., 2007; King and Goff, 2010). A cause for suspicion of TEK evidence arises from the numerous stories involving great floods. Few of these events however are specifically identified as being tsunamis and many have religious overtones induced by overzealous missionary “colonisation” of vast regions such as the Pacific in the 18th and 19th centuries (McMillan and Hutchinson, 2002; King and Goff, 2010). As a result, there are many researchers who treat the gathering and interpretation of TEK with scant respect.

As an example, Bryant (2001) discussed apparent evidence gleaned from a “Maori legend” of the “Mystic Fires of Tamaatea” and later used this as part of his evidence to infer a massive comet impact to the south of New Zealand—the Mahuika comet, named after the Maori god of fire (Bryant et al., 2007). Failure to discuss, consult with and learn the interpretations of this *purakau* (oral tradition) from relevant Maori elders led to remarkably creative thinking for what were essentially real physical events associated with “The Fires of Tamatea”. They were not mystic (Goff et al., 2003). The name Mahuika does indeed relate to a Maori fire deity, variously referred to as either a male or a female (Best, 1982), not simply the Maori “god” of fire (Bryant et al., 2007). This is a small, but important point that speaks volumes about contemporary understanding of indigenous people's knowledge. In the case of the purported Mahuika comet, there is currently no evidence for this apparently catastrophic palaeotsunamigenic event (Goff et al., 2010a). We would do well to learn from this salutary lesson—as with all TEK, interpretation and meaning come from an in-depth knowledge of the culture and traditions of indigenous peoples.

Oral traditions that relate experience with extreme environmental disturbance are part of the knowledge complex of many indigenous people, assisting with the transfer of culturally important knowledge from one generation to another, and providing mechanisms through which experience can be taught, memory retained and causes explained.

It is recognised that knowledge sharing is increasingly at risk, even fragmented, as respected elders with strong links to the past are lost each year, and many people are disconnected from traditional lands, resources and social networks (Barlow, 1994).

Increasingly however, TEK is being sought as the basis for thinking more laterally about our current understanding of the world (Smith, 2001). What is apparent from TEK research of the geographical significance of stories is the relative paucity of data from some regions despite the clustering of geological and archaeological evidence for palaeotsunamis (e.g. King and Goff, 2010).

Fortunately, there are stories that show considerable geographical agreement with archaeological and geological evidence for potential palaeotsunamis. For example, the ‘Coming of the Sand’ (Smith, 1910) story centres on a place called Potiki-taua, near Cape Taranaki, New Zealand. In the story, Mango-huruhuru, the old priest, built a large house on low land near the sea while Potiki-roa (the chief) and his wife put theirs on higher ground further inland. Mango-huruhuru's house had a rocky beach in front of it that was unsuitable for landing canoes and so he decided to use his powers to bring sand from Hawaiki. After sunset he sat on his roof and recited a *karakia* (prayer/chant). On conclusion a dark cloud with its burden of sand reached the shore. The women called out “A! The sea rises; the waves and the sand will overwhelm us”. The people were buried in the sand along with the house and cultivations and all the surrounding country, and with them, the old priest and his youngest daughter (memorialised and turned into a rock which stands there today). Potiki-roa and his wife escaped the disaster because their home was farther inland and on higher ground. Geologically, the most compelling evidence from this region is the presence of extensive pebble layers extending up to at least 40 m above sea level (McFadgen, 2007). The association of these layers with other palaeotsunami proxies (e.g. archaeological, geomorphological) around much of the region indicates an event around the 14th or 15th Century (McFadgen, 2007).

Genealogical dating is commonly cited by many earth scientists as a major problem in establishing the chronology for an event, and in more general terms as the main reason why TEK has little value as a proxy tool. Care must be taken to ensure that linkages between a geologically documented palaeotsunami event and that of one retained in TEK are sound (King and Goff, 2010). This may not always be possible and in many cases there may be no link to make, simply because TEK currently provides the only evidence, thus serving as a guide to further palaeotsunami research (King and Goff, 2010). Frustratingly, TEK often 'floats in time' and as such provides no well-dated geological event, and often multiple past experiences have been merged into a single tradition making chronological interpretations impossible (McMillan and Hutchinson, 2002). Often however, chronological clues exist within traditions such as 'not very long ago, perhaps not more than three or four generations' or 'during the time of Tamatea'. While assigning a specific date to these accounts is unlikely, many cultures have a powerful understanding of their lineage and like the Maori *whakapapa* (genealogy) this defines the individual and kin group(s) and the relationships between them. A reliable chronology through the genealogy may be quite achievable. For example, the TEK of the 'Coming of the Sand' discussed above was dated through genealogical estimates to around 1500 AD (Smith, 1910), which correlates well with numerous lines of archaeological and geological evidence for palaeotsunamis in the area (King and Goff, 2010).

The use of TEK to complement the physical sciences of palaeotsunami research remains an important opportunity to help determine the timing, magnitude and character of these events. Durie (2004) argues that scientific knowledge does not have a monopoly on truth. Hence, rather than "contesting validities", there are opportunities to use the interface between scientific and indigenous knowledge as a source of inventiveness. In this way, the efforts of different approaches to knowledge can be used to enhance the other, not replace them. Indeed many researchers reject the separation of 'science' (contemporary science) and 'myth' (TEK) and point out that TEK offers a valid approach to understanding past and present phenomena in their environments (Scott, 1996). TEK should therefore be taken seriously as a legitimate perspective on prehistory (Fig. 5).

10. Geomorphological proxies

It is important to consider the geomorphological effects that (palaeo)storms and (palaeo)tsunamis might have had on the coastal landscape. General observations of the potential longshore and inland extent of these two processes have been discussed in recent literature (e.g. Goff et al., 2008, 2009). In general terms, the longshore and inland inundation from a tsunami would, on average, be expected to be greater than that of a storm.

Event magnitude is likely to be an important control on tsunami geomorphology. In general terms, and based upon field evidence from 2004 IOT sites, inundation by large, region-wide events is likely to cause multiple breaching of dune systems (Higman et al., 2005; Singarasubramanian et al., 2006). In other words, multiple breaching assemblages can be formed during one inundation. The assemblages could include remnant dune ridges, or pedestals (Fig. 6), between each breach, and individual overwash fans that could coalesce to form landward sand sheets that may or may not be mobile depending upon aeolian and dune swale conditions (Goff et al., 2008, 2009). If landward sand sheets infill or overlay a wetland they can stabilise and weather *in situ* to form a low profile hummocky topography. If they remain dry and are exposed to aeolian onshore processes they can form an extensive region-wide parabolic dune system (Goff et al., 2008). The recognition of these geomorphic tsunami signatures is not new, and was modelled through morphological descriptions by Minoura and Nakaya (1991) with large washover fans into lagoonal systems detailed from numerous European locations (e.g. Gianfreda et al., 2001; Luque et al., 2002). However, the fate of landward material has rarely been considered and is relevant to palaeotsunami research (Goff et al., 2008).

Fig. 6. Dune pedestal formed in Pleistocene dune sands, Great Barrier Island, New Zealand with tsunami gravels scattered around the base (photo: S. Nichol).

Storms tend to only surge through gaps in dunes, sporadically depositing lobate fans that rarely coalesce or penetrate far inland. This can be the key difference between storm and tsunami geomorphology but there is room for confusion in areas of low accommodation space (e.g. in a small pocket beach, there may be insufficient longshore and landward space for more than one lobate fan and two pedestals) (Goff et al., 2009).

The 2004 IOT provided clear evidence that the topographic extent of tsunami-generated geomorphic features is generally governed by antecedent sand supply (Paris et al., 2009). Once formed, their long-term preservation is affected by subsequent sand supply. Assuming similar post-tsunami conditions, in sand-rich areas there would be rapid rebuilding of coastal dunes and loss of pedestal topography, with possibly only the largest pedestals remaining exposed. The nature and extent of a possible palaeotsunami geomorphology are therefore dependent upon a series of palaeoenvironmental variables that affect sand supply to the coastal landscape (Goff et al., 2008).

There are many factors for palaeotsunami researchers to consider, not the least of which is the age of the proposed event. Notwithstanding these factors, palaeotsunami geomorphologies have been identified and used in conjunction with other proxies to produce a more comprehensive interpretation of past events (e.g. Goff et al., 2008, 2009).

Fig. 5. Ancient rock drawing of a *taniwha* (sea monster) consuming a human figure, New Zealand (after Haast, 1877).

11. Contextual proxies

Throughout the paper we have alluded to context. In its broadest sense context relates to the environmental setting or role of geological control. A better understanding of both can help to identify where tsunamis would be most likely be generated (e.g. subduction zone) or impact (e.g. low-lying coastal plain) along a coastline, and where evidence might be more likely to be found (e.g. coastal wetland). More specifically, context relates to catastrophic event-driven environmental changes in a region indicating that a palaeotsunami (as opposed to a palaeostorm) could have been generated.

A palaeotsunami needs a palaeosource. It is tempting to make a simple connection between say a source event dated to 1000 AD and a deposit of a similar age, but many factors need to be considered. For example, how good is the chronological control for each event? Can the possible palaeotsunami deposit be considered to be a reasonable outcome of the palaeosource event?

There are no hard and fast rules surrounding what does or does not constitute a contextual proxy, although a cascade of potential environmental responses has been identified for seismic events (Wells et al., 1999; Goff and McFadgen, 2002; McFadgen and Goff, 2005; Wells and Goff, 2007). These include, evidence of fault rupture (uplift/subsidence/offset), immediate after effects such as landslides and a tsunami, delayed sediment-transport process responses such as coastal dune building, river avulsion and the later formation of aggradation surfaces. Beyond this cascade of geological evidence are ecological (cohorts of disturbed vegetation ages) and human (coastal village abandonment and the abandonment of buried agricultural land) responses, some of which have been discussed separately. The key to the effective use of contextual proxies is the establishment of a robust chronology (Goff and McFadgen, 2002) that creates a strong association between the environmental driver (e.g. earthquake) and the after-effect, the palaeotsunami (Figs. 7 and 8). This becomes yet another line of evidence in making the case for a palaeotsunami as opposed to a palaeostorm origin (Goff et al., 2011b).

Fig. 7. Maullín, Chile: a series of stacked tsunami and palaeotsunami deposits topped by the 1960 AD event (photo: J. Goff). Interestingly, while there is a direct historical association between subduction zone earthquakes and tsunami inundation in the region, little proxy work has been carried out on the prehistoric sediments. One of the lower events is also believed to be an orphan tsunami from a more distant palaeosource (refer to Cisternas et al., 2005 for details about this area).

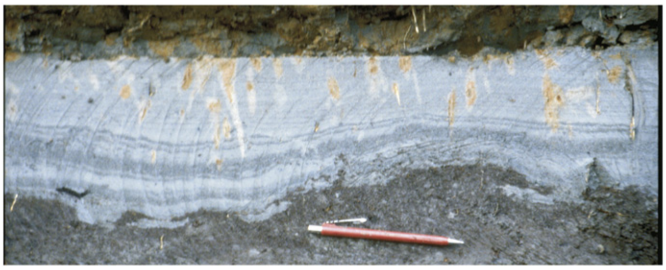

Fig. 8. 1700 AD Cascadia tsunami deposit on a cutbank exposure of the Niawaikum River, Willapa Bay, Washington (the darker bands are sand layers. Multiple sand/mud couplets are interpreted as being formed by a single uprush).

12. Extracting more information from palaeotsunami deposits - models?

Palaeotsunami deposits contain the details about the waves that put them there—we just have to work out how to read this information. Robust event chronologies and information on event magnitude will ultimately provide something akin to the holy grail of tsunami research—how big, how often, where from? Indeed, in some cases we are there already. In the recent Seaside Pilot Study, palaeotsunami deposits were used to verify inundation modelling in a Probabilistic Tsunami Hazard Analysis (Gonzalez et al., 2009) (Fig. 9). The modelled inundation for a 500 year Cascadia tsunami may therefore be considered to be a good approximation of what can be expected, but it may be prudent to re-evaluate this in light of the size of the 11 March 2011 Tohoku-oki tsunami in Japan.

There still remains the problem of “how big was the palaeotsunami?” Geochemistry and microfossils provide one solution to better approximating inundation distances, and as this technique develops so does its modelling counterpart. Sediment-transport models have focussed on estimating two parameters, tsunami height and flow speed. Four approaches have been used thus far: (1) inverse modelling of the suspension graded intervals of the deposit to calculate tsunami flow speeds necessary to suspend this sediment (Jaffe and Gelfenbaum, 2007; Jaffe et al., 2011); (2) inverse modelling of the largest grains in the deposit to estimate tsunami height at the shoreline (Moore et al., 2007); (3) forward modelling of simple settling of suspended sediment to obtain tsunami height at the shoreline (Soulsby et al., 2007), and; (4) forward modelling of flow and sediment transport using coupled hydrodynamic/sediment transport/geomorphic change models (Apotsos et al., 2009).

Of the four approaches, the inverse modelling of tsunami flow speed from grain size distribution and thickness (Jaffe and Gelfenbaum, 2007) is the only one that has been applied to palaeotsunami deposits. Witter et al. (2008, in press) estimated tsunami flow speed for the 1700 AD Cascadia tsunami at Canon Beach, Oregon. These estimates were of the same magnitude, but lower, than those from inundation modelling. The discrepancy between models can in part be attributed to the treatment of bottom roughness. Remarkably, the grading in the palaeotsunami deposits for sites close to the coast matched those predicted by sediment falling out of suspension, which is consistent with the key assumption of the model.

There is a need, however, to continue to develop and test models that relate a tsunami to the deposit it creates. The benchmark approach where models are rigorously tested against laboratory and field datasets holds promise for advancing the ability to extract information about palaeotsunami characteristics from deposits (Huntington et al., 2007).

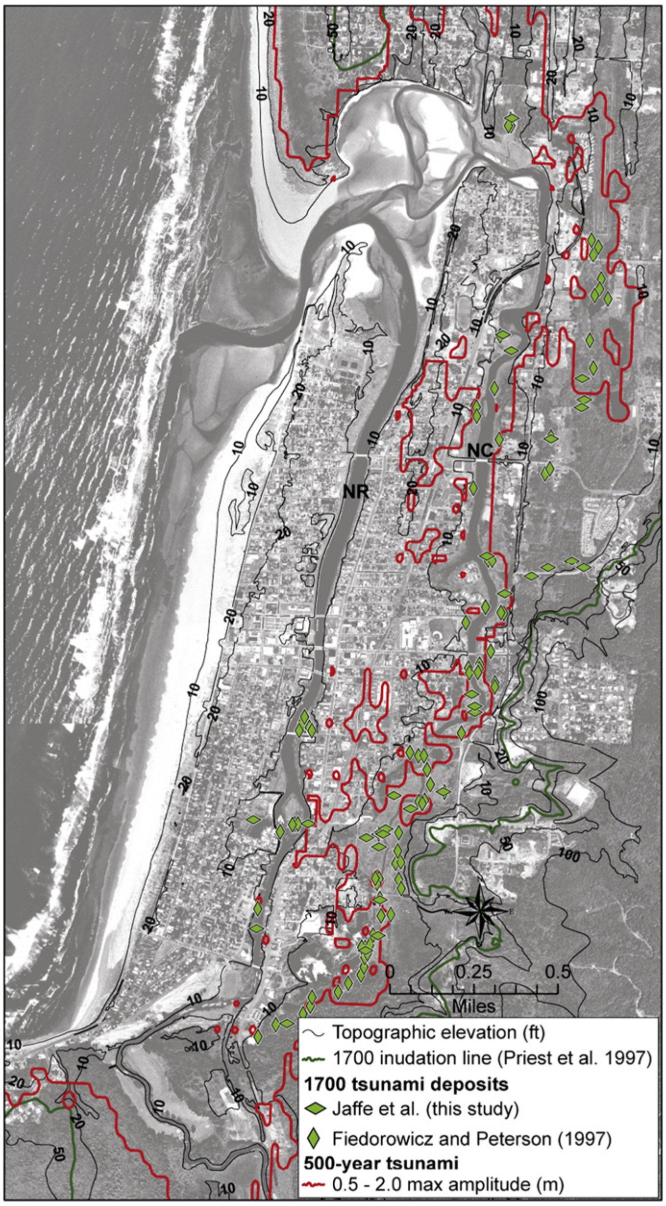

Fig. 9. Overview of 1700 AD and 500-year Cascadia tsunami data used in Probabilistic Tsunami Hazard Assessment for Seaside, Oregon showing location of deposits and respective inundation lines (Necanicum River = NR, Neawanna Creek = NC) (after Gonzalez et al., 2009—refer to Fig. 6b for full details).

13. Summary and outlook

In hindsight, we should expect there to be disagreement surrounding the ability to differentiate between palaeostorms and palaeotsunamis (e.g. Bridge, 2008). Using known, recent and historically-documented events, researchers are searching for differences between storms and tsunamis knowing that the deposits relate to different processes. As such, researchers are less likely to avail themselves of a wide range of proxy data to determine the origin of an event. However, defining whether a deposit relates to a palaeotsunami as opposed to palaeostorm is far more complex and can only be achieved convincingly through a multidisciplinary approach using a suite of proxies (Fig. 10). This suite of proxies continues to grow and while an individual proxy may indeed only indicate a marine origin, the key to determining a palaeotsunami origin lies in comparing and contrasting between many diverse lines of evidence.

The better use and integration of as many proxies as possible is the key to the identification of palaeotsunami deposits (Chagué-Goff et al., 2011a). This is a particularly important statement since palaeotsunami deposits deteriorate over time (recently termed "tsunami taphonomy") making it harder to identify them in the geological record (e.g. Goff et al., 2007). Depending upon the nature of the depositional environment—onshore or offshore, sediments can be exposed to an assortment of submarine and subaerial processes, including strong currents (Weiss and Bahlburg, 2006), bioturbation (Nichol and Kench, 2008), anthropogenic activity (McFadgen and Goff, 2007; Goff et al., 2011b), acidic soil conditions (Wang and Chappell, 2001), frequent redox transitions (Mayer et al., 1991), and aeolian winnowing of exposed sediments (Nichol et al., 2003a). Studies of recent deposits also show that the preservation potential is site specific and deterioration can be rapid (Szczuciński et al., 2007; Szczuciński, 2012).

Integration of geological proxies with biological, chemical, geomorphological, archaeological, anthropological and contextual data, as well as with numerical modelling offers greater scope for not only identifying older events, but also assessing their magnitude.

Some of the most interesting developments in palaeotsunami research are being made in multi-proxy studies of what might be termed the end members of the energy regime—from large boulders to fine sediments. Numerical (inverse) modelling of geological data gathered from boulder deposits has improved markedly with groundbreaking work by Goto et al. (2010) and Buckley et al. (in press). Equally, chemical and biological proxies associated with the fine sediment fraction and the zone landward of recognisable geological evidence, are proving invaluable in determining maximum palaeo-runup and palaeotsunami origin (Chagué-Goff, 2010; 2011; Chagué-Goff et al., 2011a). This is particularly relevant to understanding the magnitude and frequency of predecessors of events such as the 2011 Tohoku-oki tsunami (Goto et al., 2011).

We are also extending our studies into the other end members of the problem, most notably tropical climates and offshore palaeotsunami deposits. Much of the proxy toolkit has been developed through studies in temperate climates, but events such as the 2004 IOT have raised the need to better understand tsunami hazard and risk in tropical environments. This need is perhaps no more most urgent than in the Pacific islands where historical records are invariably less that 200 years, palaeotsunami sources are numerous, and Pacific Island Countries and Territories are ill-prepared for large magnitude events (Goff et al., 2011a),

Our knowledge of the offshore component of tsunami deposits is largely limited to a small dataset of historical events (van den Bergh et al., 2003, Noda et al., 2007, Paris et al., 2010a, 2010b; Sakuna et al., in press). Perhaps the best example of where research on offshore palaeotsunami deposits is heading is the work of Smedile et al. (2011). They report at least 12 anomalous submarine layers laid down over the past 4500 years off the coast of eastern Sicily. Four of these layers coincide with known historical tsunamis (1908, 1693, 1169, and 365 AD) and five with tsunami deposits found on land (De Martini et al., 2010). This research is mainly derived from geological (grain size) and biological (foraminifera) proxy data. As further offshore research is carried out it is likely that a greater range of proxies will be used and our ability to identify offshore palaeotsunami deposits will be enhanced.

We should not however, lose touch with our powers of simple observation. In a recent study carried out soon after Tropical Cyclone Yasi struck in northeast Australia (Chagué-Goff et al., 2011a; 2011b) it was noted that while superficially the sediments seemed comparable to those of a tsunami, the grass within the inundation zone was still green as opposed to the ubiquitous salt-burnt brown associated with tsunami inundation. A contemporary example of what can be expected from palaeotsunami studies—geochemical and microfossil signatures towards the landward end of inundation will be different. The equivalent offshore signal is yet to be explored.

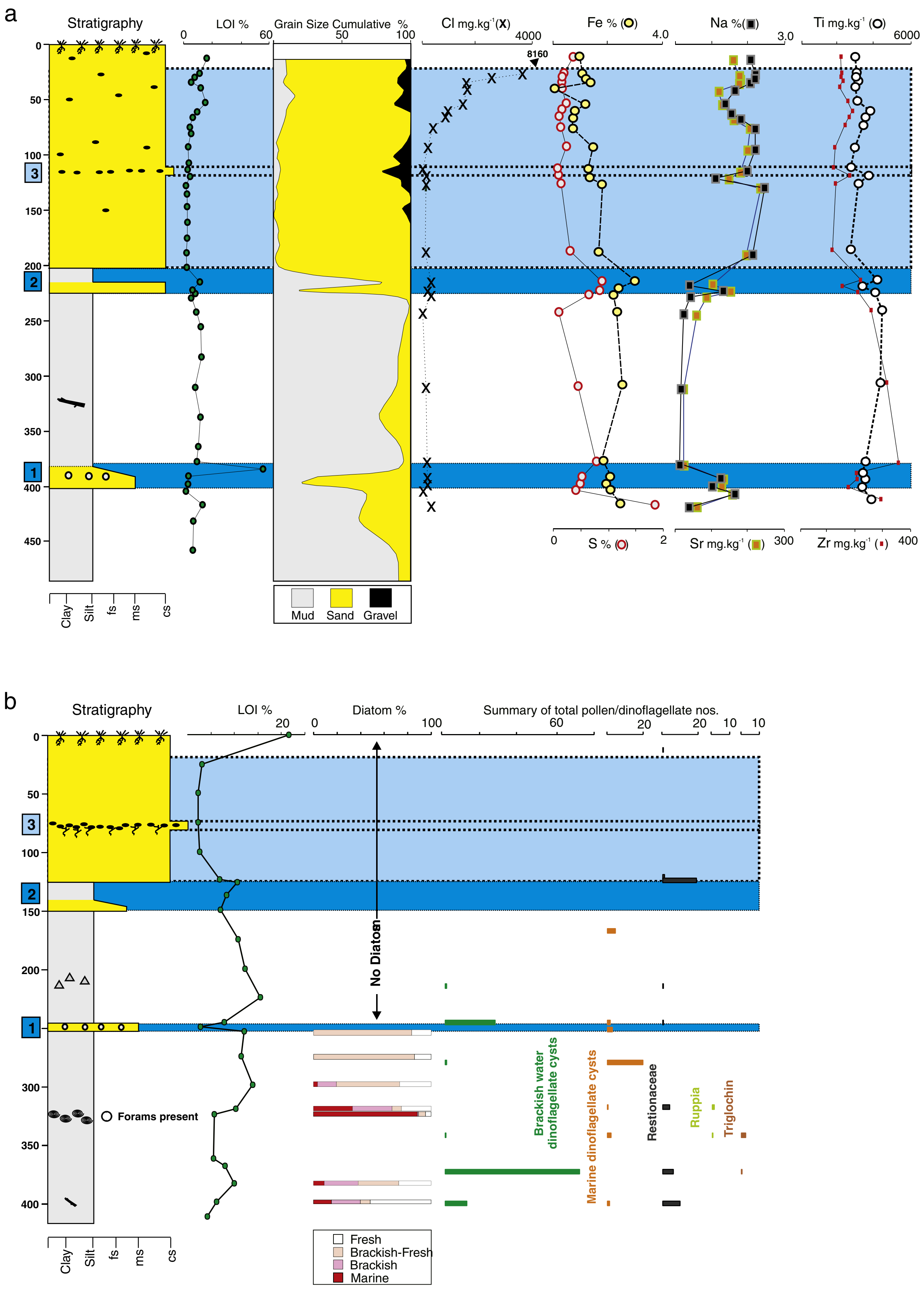

Fig. 10. Use of a suite of proxies from Mimiwhangata, New Zealand (after Goff et al., 2010d). a) Core M1 showing stratigraphy, Loss on Ignition (LOI), grain size, and elemental composition; b) Core M2 showing stratigraphy, LOI, diatom, foraminifera and key pollen data (Event 3 is bounded by two different sets of dashed lines representing two possible interpretations; fs = fine sand, ms = medium sand, cs = coarse sand).

A key advance that will greatly benefit palaeotsunami researchers will be a more effective integration of archaeological and anthropological data with the suite of more conventional proxies that sit within the earth (natural and geo-) sciences. Not all palaeotsunami researchers are from the latter group and it is not an exclusive club. This is as much about earth scientists taking on-board new lines of evidence as it is about archaeologists and anthropologists. The most significant difficulties however, are likely to be faced in attempting to merge contemporary science with TEK (King and Goff, 2010). The difficulties are not intractable but to be effective it does demand that palaeotsunami research is carried out by a truly multidisciplinary team, not just single discipline groups.

In some cases we will never be able to confidently identify the palaeotsunami origin of a potential deposit simply because, for whatever reason, there is not enough evidence. However, this does not mean that palaeotsunami research serves no purpose. Far from it, palaeotsunami research has the potential to greatly enhance our understanding of the magnitude and frequency of past events. As a future outcome, the improved reconstruction of palaeotsunamis leads to better informed modelling of future events and the reduction of hazard and risk. In some cases this potential has at least been partially realised, with an improved Probabilistic Tsunami Hazard Assessment for Seaside, Oregon (Gonzalez et al., 2009) and an enhanced Pacific Island palaeotsunami database the is providing the building blocks necessary to achieve more meaningful disaster risk reduction in the region (Goff et al., 2011a, 2012).

The current palaeotsunami proxy toolkit is extensive, but underutilised. It will undoubtedly grow, particularly as research extends into more complex environments (e.g. tropical, submarine). An exciting future outcome will be the widespread inclusion of palaeotsunami data into numerical modelling and tsunami risk assessment. This can be assisted through more robust palaeotsunami research based upon a comprehensive use of the existing toolkit and future innovations in the field.

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