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Tsunami sediments and their foraminiferal assemblages

Briony Mamo [a,*], Luke Strotz [a,b], Dale Dominey-Howes [b]

[a] Department of Biological Sciences, Macquarie University, Sydney, NSW 2109, Australia
[b] Australian Tsunami Research Centre and Natural Hazards Research Laboratory, School of Biological, Earth and Environmental Sciences, University of New South Wales, Sydney, NSW 2052, Australia

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ABSTRACT

Tsunami hazard assessment begins with a compilation of past events that have affected a specific location. Given the inherent limitations of historical archives, the geological record has the potential to provide an independent dataset useful for establishing a richer, chronologically deeper time series of past events. Recent geological studies of tsunami are helping to improve our understanding of the nature and character of tsunami sediments. Wherever possible, geologists should be working to improve the research 'tool kit' available to identify past tsunami events. Marine foraminifera (single celled heterotrophic protists) have often been reported as present within tsunami-deposited sediments but in reality, little information about environmental conditions, and by analogy, the tsunami that deposited them, has been reported even though foraminifera have an enormous capacity to provide meaningful palaeo-environmental data. Here, we review what foraminifera are, describe their basic form and significance, summarise where they have been reported in tsunami sediments and identify what can be learnt from them. We review the gaps in our understanding and make recommendations to assist researchers who examine foraminiferal assemblages in order to enhance their use within tsunami geology.

Contents

1. Introduction and aims

The December 2004 Indian Ocean Tsunami (2004 IOT) (Lay et al., 2005) demonstrated that tsunami have the capacity to cause enormous loss of life, damage to property, lifelines, assets and infrastructure and represent a major hazard process capable of affecting geographically widespread and distant locations simultaneously. Further, tsunami can also initiate widespread modification and reorganisation of coastal geomorphic systems acting as a trigger process tipping the system across a critical threshold into a new dynamic state (Andrade, 1992; Goff, 2008). The 2004 IOT, together with recognition that tsunami have occurred many times in historical and geological periods (Cisternas et al., 2005; Jankaew et al., 2008; Monecke et al., 2008), has prompted international efforts to better understand this hazard and to implement tsunami disaster management strategies at the regional and global level (Dominey-Howes, 2007; Satake and Atwater, 2007).

Hazard assessment (including past frequency and magnitude) is the foundation stone upon which tsunami risk management is based. To this end, historical records are important but are limited by the length of the record, its accuracy, coverage and completeness (Dominey-Howes, 2002; Satake and Atwater, 2007). Fortunately however, geological, sedimentological and geomorphological evidence of tsunami are (where available and amenable to dating) potentially useful for extending the length of the record well beyond that of the historical period providing a richer, chronologically deep time series (Satake and Atwater, 2007).

* Corresponding author.
E-mail address: bmamo@els.mq.edu.au (B. Mamo).

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Table 1
Modern and palaeotsunami signature types reported in the geological literature.

Signature type	Description of the signature	Site locations for signature type	References
Basal unconformity	Contact between base of tsunami-deposit and underlying sediment may be sharp, unconformable or erosional	(1) Scotland; (2) Hawaii; (3) Japan	(1) Dawson et al. (1988); (2) Moore and Moore (1988); (3) Fujiwara et al. (2000)
Intraclasts	Lower/basal unit of tsunami-deposit may contain 'rip-up' or intraclasts or reworked underlying material	(1) Scotland; (2) Hawaii; (3) New Zealand	(1) Dawson (1994); (2) Moore et al. (1994); (3) Goff et al. (2001)
Basal load structures	Lower/basal unit of tsunami-deposit may contain loading structures	(1) SW England; (2) Japan	(1) Foster et al. (1991); (2) Minoura and Nakaya (1991)
Fining upward sequence	Particle size of tsunami-deposit fines upward	(1) SW England; (2) Scotland; (3) Flores, Indonesia; (4) New Zealand; (5) Japan; (6) Papua New Guinea	(1) Foster et al. (1991); (2) Dawson (1994); Dawson and Smith (2000); (3) Shi (1995); Shi et al. (1995); (4) Chague-Goff et al. (2002); Goff et al. (2001); (5) Fujiwara et al. (2000); Nanayama et al. (2000); (6) McSaveney et al. (2000)
Landward fining sequence	Particle size of tsunami sediment unit fines landward from the coast	(1) SW England; (2) Scotland; (3) Flores, Indonesia; (4) Russia; (5) Japan	(1) Foster et al. (1991); (2) Dawson (1994); (3) Shi (1995); Shi et al. (1995); (4) Minoura et al. (1996); (5) Sawai (2002)
Distinctive layering	Separate waves in the tsunami wave train may deposit individual layers and / or individual layers may contain distinctive sub-units associated with deposition during run-up	(1) Hawaii; (2) Scotland; (3) Indonesia; (4) Japan; (5) Portugal	(1) Moore and Moore (1988); (2) Smith et al. (2004); (3) Dawson et al. (1996); (4) Nanayama et al. (2000); (5) Hindson and Andrade (1999)
Cross bedding	Landward and seaward currents shown by imbrication of shells and / or low angled wedged shaped lamination and / or cross bedding	(1) Japan; (2) Italy; (3) Argentina; (4) Tanzania	(1) Fujiwara et al. (2000); (2) Massari and D'Alessandro (2000); (3) Scasso et al. (2005); (4) Bussert and Aberhan (2004)
Imbricated boulders	Stacks or lines or accumulations of imbricated boulders at the coast	(1) Australia; (2) Caribbean; (3) Italy; (4) Cyprus	(1) Nott (1997); (2) Scheffers (2004); (3) Mastronuzzi and Sanso (2004); (4) Kelletat and Schellmann (2002)
Biostratigraphy	Microfossil assemblages of diatoms and foraminifera. May be pelagic and/or benthic species in shallow water or coastal environments. Frustules/tests may be crushed or broken in significant percentages	(1) Greece; (2) United States; (3) Scotland	(1) Dominey-Howes et al. (1998); (2) Hemphill-Haley (1995, 1996); Williams and Hutchinson (2000); (3) Smith et al. (2004)

In recent years, 'tsunami geologists' have significantly enhanced our knowledge about the deposits left by tsunami and the signatures they may imprint upon the coastal landscape. This has been achieved in two ways. First, and of particular value, by conducting rapid post-tsunami surveys after modern events (for example: 1992 Nicaragua (Satake et al., 1993); 1992 Flores Island (Shi et al., 1993); 1994 Java (Dawson et al., 1996); 1998 Papua New Guinea (Goldsmith et al., 1999; Kawata et al., 1999); 2004 Indian Ocean (Hawkes et al., 2007); 2006 Java (Fritz et al., 2007; Kato et al., 2007) and 2007 Solomon Islands (Fritz and Kalligeris, 2008). Second, many teams have reported geological studies of known historic, and inferred palaeo tsunami. This has led to the identification of a suite of tsunami sediment features or characteristics (Table 1 and references therein). Debate exists as to whether these features may be termed 'diagnostic' but this is less significant than the reliability of these characteristics for the identification of tsunami deposits.

There have recently been some important systematic attempts to draw together what is known about tsunami sediments that have resulted in the publication of special issues of international journals (see *Sedimentary Geology*, 200 (3/4), 151–388, 2007 and *Pure and Applied Geophysics*, 164 (2/3), 249–631, 2007) and an edited book entitled "*Tsunamiites*" by Shiki et al. (2008). Readers interested in descriptions of tsunami sediment features are referred to (amongst others) Dawson and Stewart (2007); de Lange and Moon (2007); Fujiwara and Kamataki (2007); Hawkes et al. (2007); Hori et al. (2007); Jaffe and Gelfenbuam (2007); Kortekaas and Dawson (2007); McFadgen and Goff (2007); McMurty et al. (2007); Moore et al. (2007); Morton et al. (2007); Nanayama et al. (2007); Nichol et al. (2007); Peters et al. (2007); Smith et al. (2007) and Tappin (2007). The value of this work lies in its capacity to identify palaeotsunami deposits which, when clearly dated, provides an extended chronology of past events — exactly the sort of data required to undertake robust risk assessment. For example, in the NE Pacific, Kelsey et al. (2005); Losey (2005); Nelson et al. (2006); Nelson et al. (2008) and Peters et al. (2007) show a series of tsunami generated by the Cascadia subduction zone over the last few thousand years within coastal sediments of Washington and Oregon, USA and British Columbia, Canada. And, in the NW Pacific, Bourgeois et al. (2006) and Pinegina et al. (2003) identified a series of Holocene palaeotsunami affecting the east coast of Kamchatka, Russia.

An additional and important contribution of this work relates to its value in helping to distinguish between sediments deposited by storms and those deposited by tsunami. Whilst this paper does not focus on the differences between these two 'high energy' deposit types, we acknowledge that there remains a need to examine in some detail the foraminiferal assemblages associated with storm deposits and to compare and contrast them with tsunami foraminiferal assemblages (see discussion below). Readers interested in studies that specifically compare and contrasts storm and tsunami deposits should see Goff et al. (2004); Kortekaas and Dawson (2007); Morton et al. (2007) and Nanayama et al. (2000).

Increasingly, in studies concerning tsunami sediments, analysis of the marine micro assemblage has been included in the suite of investigative techniques. In particular, many have focused on the foraminiferal assemblages present. However, there has been, to our knowledge, no systematic compilation, review and assessment of the contribution, or potential value of foraminifera to the field of tsunami geology. Interestingly, Dawson (1999) noted that, "studies of foraminifera contained within tsunami deposits are very much in their infancy and the value of this particular technique remains to be discovered" (Dawson, 1999; p124). Work focusing on other microfossil groups — in particular, diatoms (Hemphill-Haley, 1996; Dawson and Stewart, 2007; Nichol et al., 2007; Sawai et al., 2008) and ostracods (Ruiz et al., 2005; Alvarez-Zarikian et al., 2008) have provided useful information about tsunami, particularly in regards to indicating marine conditions pre and post tsunami and defining the upper and lower boundaries of the deposit. As such, we believe, detailed analysis of 'tsunami foraminiferal assemblages' may prove to be equally useful.

In light of the introduction and the fact that a decade has passed since Dawson (1999) questioned the potential value of foraminifera to tsunami geology, the aims of this paper are to:

- outline what foraminifera are and provide a short summary of their use as palaeoenvironmental indicators;
- summarise the tsunami geology literature that describes foraminiferal assemblage composition and variation;
- review the gaps in our understanding about foraminifera within tsunami sediments; and
- to make recommendations to assist tsunami geologists to utilise foraminifera in the most effective way and to propose a series of research questions to enhance the use of foraminifera within tsunami and palaeotsunami studies so that they may be confidently added as a technique to the 'tool kit' of the tsunami geologist.

2. Foraminifera — what are they and their use as palaeoenvironmental indicators

Foraminifera (Figs. 1 and 2) are single celled, heterotrophic protists possessing a mineralised test (shell) and granular pseudopodia, which extend through apertures of the test wall (Fig. 1a).

Classification of foraminifera is largely based upon the composition and morphology of the test. Four main compositions are currently recognised: agglutinated (test composed of cemented detrital material – Fig. 1b left) (Lee and Anderson, 1991); calcareous (test composed of secreted calcium carbonate – Fig. 1b centre and right) (Haynes, 1981); proteinaceous (organic-walled test) and siliceous (test composed of silica) (Sen Gupta, 1999). The first two however, are the most commonly encountered. Both the proteinaceous and siliceous forms are relatively rare and are confined to very specific environments (low salinity shallow water and deep sea settings respectively) (Sen Gupta, 1999). This makes their use in palaeoenvironmental studies somewhat limited, as only in very specific situations will they be present.

Agglutinated foraminifera are those that construct their test from foreign particles, cementing them together using either proteinaceous, carbonate or ferric oxide cements (Lee and Anderson, 1991) (Fig. 1b-left). Calcareous foraminifera secrete a test composed of calcium carbonate. Traditionally, they have been divided into two groups; the porcelanous forms and the hyaline forms. An extinct group of calcareous foraminifera, the microgranular forms, is also recognised. Porcelanous foraminifera have imperforate tests consisting of randomly oriented rods of calcite with an ordered inner and outer layer. This structure gives the test a porcelain-like appearance (Haynes, 1981) (Fig. 1b-centre). Hyaline forms possess perforate tests where the framework of calcite rods that compose the test have a preferred orientation, usually radial, giving the test a glassy appearance (Haynes, 1981) (Fig. 1b-right). More recent classification schemes (Loeblich and Tappan, 1987, 1992; Sen Gupta, 1999) have further subdivided the calcareous foraminifera into a number of suborders based upon chemical composition and the structure of the test (see Sen Gupta (1999) for an overview).

Due to their small size (between ~100 μm–2 cm), abundant incidence, high preservation potential within the sediment record after death and distinctly diagnostic test shape, they are unsurpassed stratigraphic, palaeoecologic and palaeoenvironmental tools for statistical and systematic analysis and environmental reconstruction (Loeblich and Tappan, 1987; Hayward et al., 1999; Sen Gupta, 1999). Assemblage composition is influenced by both abiotic (temperature, salinity, dissolved oxygen availability, nutrient flux, sedimentology, current flow, etc) and biotic (food, predation, inter- and intra-specific competition) conditions of an area (Murray, 1991). 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, eludes to a shift in marine environmental conditions at the location where the tests are subsequently preserved.

Foraminifera, as a group, have a cosmopolitan distribution, found throughout the entire marine realm. However, individual taxa are extremely restricted to specific environmental niches (for instance, marsh and brackish environments), and it is this characteristic that makes foraminifera instrumental in palaeogeographic analysis and palaeoenvironmental reconstruction. For example, as demonstrated by Bernhard and Sen Gupta (1999), the presence of the species *Bolivina seminuda* Cushman (1911) (Fig. 2) can be indicative of hypersaline and eutrophic conditions, since this taxon is regarded as a 'stress tolerant' species, able to withstand these types of extreme conditions.

Changes in the composition of a foraminiferal assemblage can reflect migrations (Murray, 1991), extinctions (Groves et al., 2007), glaciation events (Herguera and Berger, 1991; Wells et al., 1994), marine transgression/regression (Narayan et al., 2005), the effects of biotic competition and environmental adaptation (Linke and Lutze, 1993), changes in primary productivity, seasonality (Sun et al., 2006) and even, extreme events (such as earthquake subsidence (Alvarez-Zarikian et al., 2008), storms (Palma et al., 2007) and tsunami (Hawkes et al., 2007)).

Analysis of foraminiferal assemblage composition has the capacity to enable inferences about palaeo-sea levels and environmental conditions if appropriate indicative species are identified. For example, marsh assemblages are defined by low diversity assemblages containing an abundance of agglutinated taxa (Scott et al., 2001), whereas hypersaline settings are dominated by assemblages consisting of mainly porcellanous forms (Lynts, 1971).

In addition to examining 'gross' assemblage composition, the use of systematics (the classification of organisms with the aim of reconstructing evolutionary relationships) for individual foraminifera found within a deposit, can also provide significant information about local environmental conditions (Hayward et al., 1999; Strotz, 2003). For example, species such as *Cibicidoides pseudoungerianus* (Cushman, 1922a) (Fig. 2) typically indicate shallow water depths (Murgese and DeDeckker, 2005) and *Uvigerina hispida* Schwager (1866) (Fig. 2) commonly represents mid bathyal to abyssal depths (Bornmalm, 1997). Similarly, palaeotemperatures and other palaeogeographic characteristics can be inferred from foraminiferal assemblages. For example, a species such as *Melonis pompilioides* (Fichtel and Moll, 1798) (Fig. 2), tends to be particularly abundant during glacial periods (Miao and Thunell, 1993).

The value and application of foraminifera coupled with palaeoenvironmental analysis, assuming that they can be recovered from the deposit, should be of relevance to tsunami geologists seeking to resolve questions about the nature, character and origin of tsunami sediments. For example, information about the composition of foraminiferal assemblage within the tsunami deposit might 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 (Uchida et al., 2004, 2007a,b).

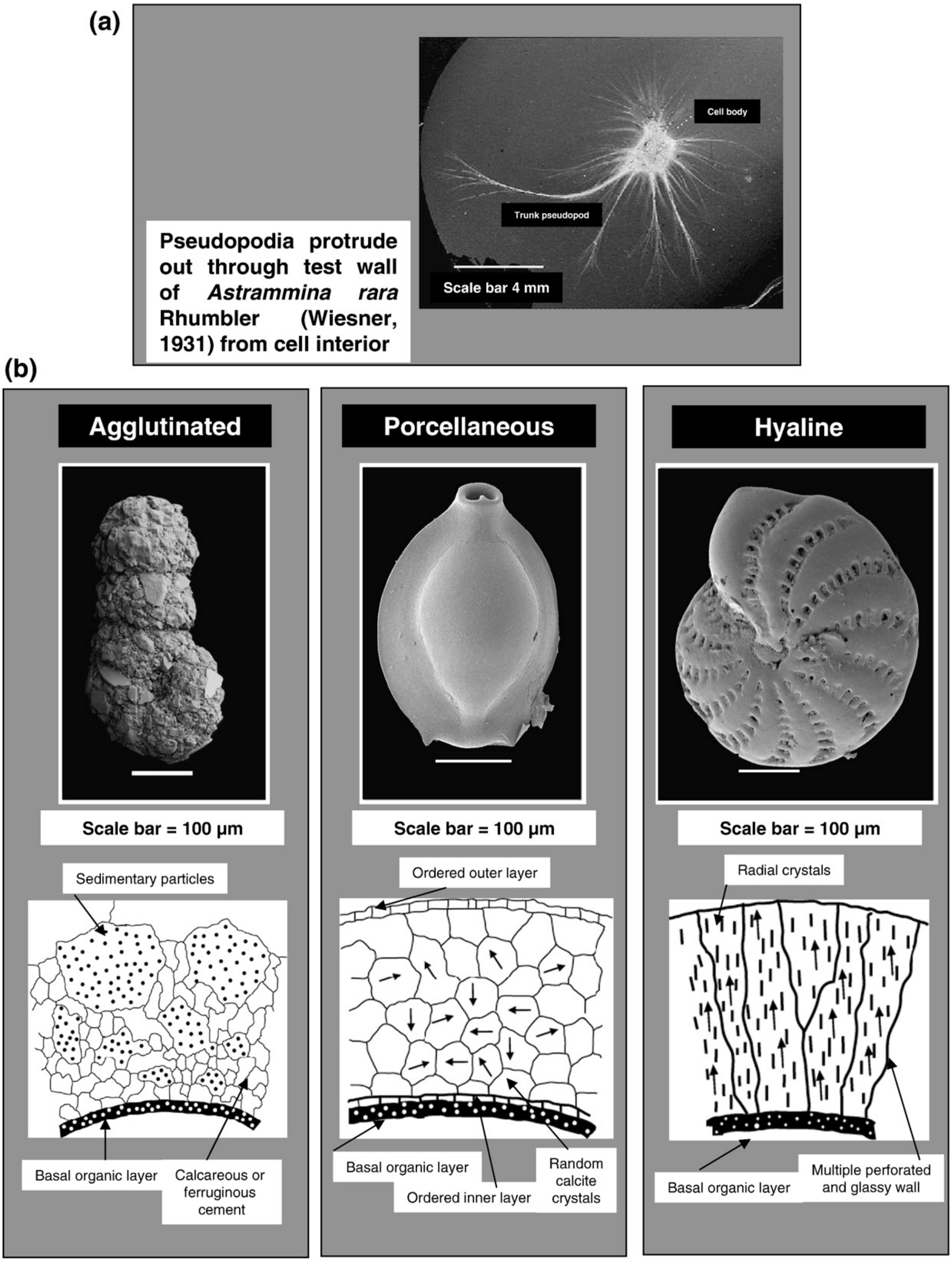

Fig. 1. (a) Photograph of living Foraminifera *Astrammina rara* Rhumbler (Wiesner, 1931) showing pseudopodia protruding through test wall (Sen Gupta, 1999). (b) Left: the agglutinated Foraminifera *Ammobaculites exiguus* Cushman and Brönniman (1948) specimen CL3, July from Tuross Estuary, Australia (Strotz, 2003). (b) Centre: the porcelaneous Foraminifera *Pyrgo oblonga* (d'Orbigny, 1839) specimen MU60809 from New Caledonia. (b) Right: the hyaline Foraminifera *Elphidium advenum* (Cushman, 1922c) specimen MU 62145 from Heron Island, Great Barrier Reef, Australia.

Preservation and the taphonomic character (post-depositional factors that directly affect the preservation of fossilised remains) of individual tests may reveal something of the flow velocity, turbidity, abrasion and post depositional environmental processes of a tsunami in terms of the nature and the severity of abrasion and disarticulation a test has undergone (Dawson et al., 1995; Hindson et al., 1996; Andrade et al.,

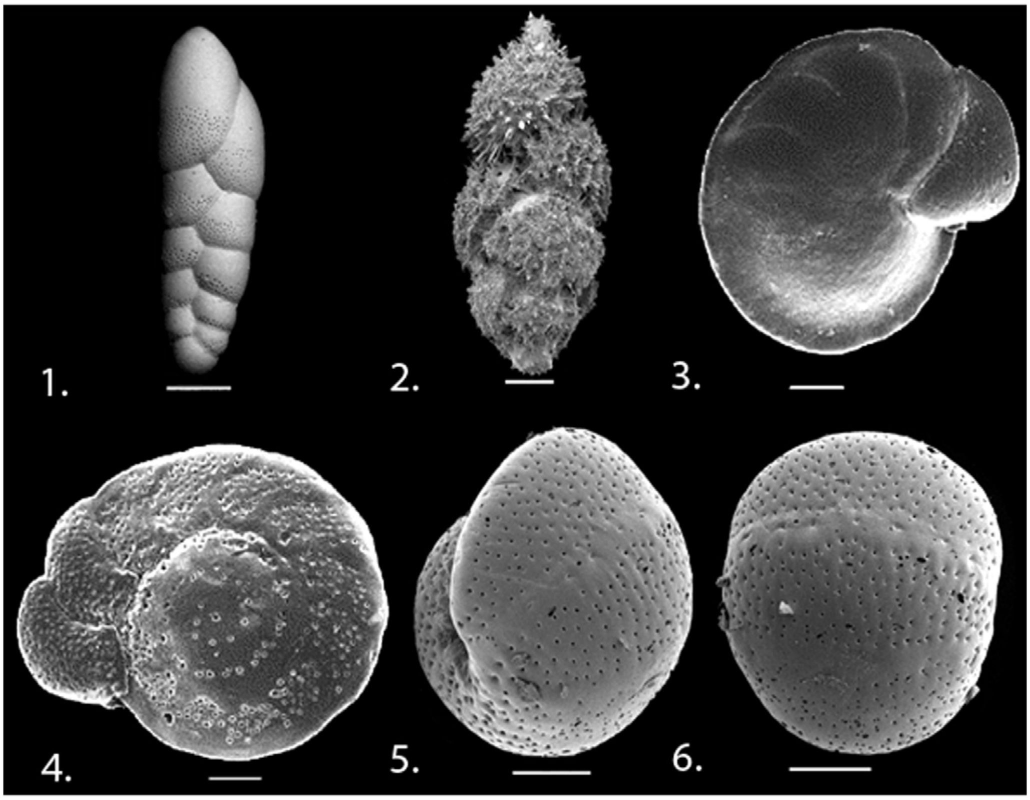

Fig. 2. Plate of Foraminifera mentioned in the text. Unless otherwise specified all scale bars = 100 μm. 1. *Bolivina seminuda* Cushman (1911), MU 60888, (Scale bar = 50 μm); 2. *Uvigerina hispida* Schwager (1866), MU 60909; 3–4. *Cibicidoides pseudoungerianus* (Cushman, 1922a), specimen FR2-4 (Murgese and DeDeckker, 2005 Fig. 4); 5–6. *Melonis pompilioides* (Fichtel and Moll, 1798), MU60943.

1997; Dominey-Howes et al., 1998; Hindson and Andrade, 1999; Hindson et al., 1999; Hawkes et al., 2007; Kortekaas and Dawson, 2007; McMurty et al., 2007; Satyanarayana et al., 2007; Alvarez-Zarikian et al., 2008). Lastly, dating foraminiferal tests contained within the tsunami deposit has the potential (depending on test wall composition and the dating methods used) to provide robust and very well constrained dates (and chronologies) for tsunami sediments where other techniques may prove problematic or are limited by available datable material. However, care must be taken, as tsunami deposits consist of sediments that often represent a chaotic mix derived from several sources and stratigraphic layers.

3. Studies of tsunami deposits that report foraminifera

As the field of tsunami geology has developed, there has been an explosion in the number of published and unpublished reports that identify, describe and analyse tsunami deposited sediments from around the world (see our list of references).

Those studies that specifically examine, report and analyse foraminifera may be grouped into two subsets. The first simply mentions that '*Foraminifera were identified and recovered from within the tsunami sediment…*'. These studies come from diverse locations such as Greece (Cundy et al., 2006), the United Kingdom (Smith et al., 2004), Norway (Bondevik et al., 1997), the Americas (Mathewes and Clague, 1994; Jacobs et al., 2001; Le Roux et al., 2008), Japan (Uchida et al., 2007b), New Zealand (Goff et al., 2001) and southern Asia (Davies et al., 2003; Kumar and Achyuthan, 2006; Hawkes, 2007; Jonathan et al., 2007; Pilarczyk and Reinhardt, 2007). Whilst these studies all mention the presence of foraminifera within tsunami deposits, for varying reasons (for instance, insufficient abundance, poor preservation, a lack of expertise etc), they do not provide any detailed analysis of the assemblage composition, variation and taphonomic character of individual tests. Because no detailed information is provided, little can be interpreted from the foraminifera presented in these studies, other than the fact that the investigated sites were marine influenced at some period of time.

One study of note is that by Hawkes et al. (2005), which used variations in foraminiferal assemblages in coastal sediment sequences of the NW United States margin adjacent to the Cascadia Subduction Zone, to reconstruct patterns of pre-seismic movement and post-seismic recovery associated with Cascadia earthquake-tsunami events. Interestingly though, the tsunami deposits left by the Cascadia events contained little in the way of foraminifera themselves and as such, revealed no information regarding the tsunami.

The second and more significant subset, provide a more detailed analysis of foraminiferal assemblage composition, variation, taphonomy and systematics. Table 2 provides a comprehensive list of those locations and studies (that we have been able to find) and Fig. 3 shows their global distribution.

Table 2 shows that:

- there is no consistency in the type of data reported by authors;
- there is little consistency in terms of what is actually found in different tsunami deposits in relation to the recovered foraminiferal assemblage, their degree of sorting, levels of abrasion and other diagnostic factors. Given the varied means by which tsunami are generated, this is not necessarily surprising;
- studies almost exclusively concentrate on benthic taxa. Reports of planktonic taxa in tsunami deposits are rare. This could either be due to the rarity of planktonic forms in tsunami deposits or because authors have focused on benthic taxa as they consistently yield much more detailed information about sedimentary environments and their origins;
- sometimes authors only identify individual foraminiferal tests to the level of genera or higher taxonomic levels and do not identify specimens to species level;

- authors almost never provide full taxonomic diagnoses, and rarely do they provide plates (photographs) of foraminiferal species identified or specify where the examined material is stored. This makes it very hard for subsequent researchers to re-examine the original specimens, confirm taxonomic assignations, or to make comparisons with their own findings;
- foraminifera are preserved within a wide range of sediment types from silts and clays, through to gravels and coarse cobble/boulder deposits;
- there is a tendency to note the transport of open water or deeper water foraminiferal assemblages into shallow water, coastal, lagoonal or marsh environments;
- it seems to be easier to distinguish displaced 'open' or 'fully marine' assemblages within a marsh setting than it is to distinguish a displaced marine assemblage in an estuarine or lagoonal setting;
- the size and shape of a foraminiferal test may influence the degree of sorting and breakage during transport and deposition by tsunami;
- post-depositional processes (taphonomy) can influence the preservation of individual tests; and lastly
- foraminifera have never been used to date the deposition of tsunami deposited sediments.

In addition to the research mentioned in Table 2, we are aware that a number of further papers (Okahashi et al., 2002; Abe et al., 2004; Nanayama and Shigeno, 2004; Uchida et al., 2004, 2007a) have been published by Japanese teams in Japanese language journals, which at present, we are unable to access. However, Uchida et al. (2005, 2007b) presented posters at the American Geophysical Union Congresses in 2005 and 2007 that examined foraminifera contained within Holocene tsunami sediments from Japan and we have included details from these posters in Table 2. Specifically, Uchida et al. (ibid) showed that the foraminiferal assemblages from 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 either side of 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).

4. Discussion, gaps in our understanding and recommendations for further research

In thinking about the potential value of foraminifera, it seems appropriate to start by making a necessarily obvious point. In rare cases where no foraminifera are present in coastal or shelfal waters, then none will be available for a tsunami to deposit and a significant amount of laboratory preparation and analysis time will be lost (Andrade et al., 1997; Kortekaas and Dawson, 2007; Ramirez-Herrera et al., 2007). However, a lack of foraminifera in tsunami deposited sediments is more likely due to taphonomic effects, given the ubiquitous distribution of foraminifera in the marine realm. Therefore, tsunami geologists should use multiple techniques and palaeoenvironmental indicators such as foraminifera, diatoms and ostracods and not rely on just one group.

Micropalaeontology is a distinct branch of geology and requires significant skill, expertise and experience. Misidentification of specimens, even at a generic level, let alone species level, can have major implications for environmental and palaeoenvironmental interpretations, and given the considerable intraspecific variation in foraminiferal tests, it is often difficult to assign specimens to a species based purely upon 'picture matching'. Therefore, in order to maximise the value of information that can be derived from an analyses of foraminifera, we recommend that tsunami geologists should work with a well qualified and experienced micropalaeontologist who is competent and capable with taxonomy and systematics.

Where tsunami geologists have investigated foraminifera, a wide range of characteristics have been advocated to demonstrate tsunami provenance. These characteristics include; changes in assemblage composition (Hindson and Andrade, 1999; Hindson et al., 1999; Hawkes, 2007) for example, marine shelf species within a lagoon or brackish environment; changes in test size or juvenile to adult ratios (Guilbault et al., 1996); a shift in population numbers (Cundy et al., 2000; Hawkes et al., 2007; Kortekaas and Dawson, 2007); or a change in the taphonomic character of the tests (Hindson et al., 1999; Hawkes et al., 2007). This diversity (or lack of consistency) of viewpoints makes it difficult to identify a specific characteristic that might be diagnostic. In reality, it may be that a combination of characteristics (taken together with other 'diagnostic' criteria for tsunami) will be needed to positively attribute a sedimentary sequence to deposition by a tsunami. Further, given that the exact composition of an assemblage 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.

Our review of the available literature suggests that at best, tsunami geologists might expect to see displaced assemblages and/or deeper water species being transported and deposited into shallow water, lagoonal and marsh settings. Additionally, displaced assemblages might only be readily identified when there is a sudden rather than gradual change in assemblage. For instance, a deep water assemblage sitting within a high marsh environment should be extremely obvious.

The capacity of a tsunami to transport deep water foraminiferal assemblages in particular, may be governed by several specific factors including proximity of deep water to the locations where the tsunami sediments are deposited; or the near-shore current flow and its potential to bring fossilised foraminiferal tests into shallow water for the tsunami to redeposit. This possibility would have to be carefully examined and discounted to avoid giving a false impression of the distance of sediment transport and depth from which tsunami sediments had been derived. Either way, it is clear from empirical work (Dominey-Howes et al., 1998; Nanayama and Shigeno, 2006; Uchida et al., 2007b) that tsunami *have* deposited deeper water species that would not otherwise be expected from the shallow water, coastal settings where the tsunami deposits are now found. Consequently, the occurrence of deep water assemblages may be one of the key diagnostic characteristics for tsunami-deposited sediments, given the ideal conditions. This is a hypothesis that should be tested by future research.

The maximum possible ocean depth from which landward transport of sediments and foraminiferal assemblages might occur is currently unknown. Uchida et al. (2007b) report that assemblages indicative of water depths between −90 and −130 m were moved and deposited on land by tsunami and Dominey-Howes et al. (1998) noted the deposition of species associated with outer shelfal to upper bathyal waters to a depth of −200 (or more) metres were deposited by a tsunami. In an interesting numerical study however, Weiss (2008) used linear wave theory and a parameterized Shields curve to demonstrate that the 2004 IOT was capable of entraining fine sand particles in water as deep as −985 m in the Bay of Bengal and −335 m in the Indian and Pacific Oceans. Whilst Weiss (2008) does not actually examine the issue of the transport of foraminiferal tests, given that their size is similar to the fine sand particles he examined, this work represents a theoretical lower limit for the possible entrainment and transport of foraminiferal tests by tsunami (at least of the magnitude of the 2004 IOT). The work of Uchida et al. (2005, 2007b) and Weiss (2008) indicates that wave amplitude and wave period are likely important parameters in determining what range of particle sizes (and by analogy, foraminifera) may be entrained and transported

Table 2
Tsunami sediment studies that report the presence of Foraminifera.

Geographic location of deposits (region, country, site location)	Reference	Reported age of tsunami deposit	Foraminiferal content	Comments and notes
Europe				
Greece, Astypalaea Island	Dominey-Howes (1996); Dominey-Howes et al., (2000)	AD1956	• 4 species identified from 3 genera • No counts provided • No plates provided • No mention of test condition ie; level or preservation • Information provided about environmental conditions inferred by reported species – Open marine / shelfal foraminiferal species present in deposit • Noted that low numbers of individual tests and assemblage diversity makes it difficult to make reliable environmental interpretations	• Inferred tsunami sediment contained marine sands and cobbles deposited on to a terrestrial colluvial sediment fan
Greece, Crete Island, Falasarna	Dominey-Howes et al., (1998)	AD63 – 75 ± 90 radiocarbon years BP	• 28 species identified from 14 genera • Counts provided • No plates provided • Inferred tsunami sediment layer bracketed by shallow water lagoonal sediments. Foraminiferal assemblage within tsunami layer contains increased numbers of *Cibicides advenum* (d'Orbigny, 1839) ** and *Eponides repanda* (Fichtel and Moll, 1798) - both outer shelf to deeper water species • Foraminiferal assemblage of non-tsunami sediments dominated by *Ammonia, Elphidium* and *Quinqueloculina* species • Within inferred tsunami sediment layer, breakage of tests (all species) jumps from a background average of 21% to 55%. Further, pennate specimens specifically jump from a background breakage average of 26% to 83% in the tsunami sediment layer • Inferred that pennate forms more susceptible to breakage in high energy deposition environment of a tsunami	• Tsunami sediments consist of numerous large subrounded limestone blocks • Sudden change of red silty clay sand to significantly large limestone blocks along with an abrupt change in sedimentation from marine to terrestrial sediments indicates deposition related to high energy event and sea/land level changes occurred due to vertical co-seismic deformation
Greece, Gulf of Atalanti	Cundy *et al.*, (2000)	AD1894	• At least 11 species from at least 8 genera • No counts provided but relative abundance is illustrative of dominant species • No plates provided • Sediments contain shallow marine taxa including *Elphidium spp., Ammonia beccarii var. batavus* Hofker (1951). • Overlying marsh sequence contains brackish foraminiferal species such as *Trochamina inflata* (Montagu, 1808) • Abrupt and rapid change in taxa from marsh to shallow marine types used to establish action of tsunami • The planktonic foraminifera *Rosalina globularis* d'Orbigny (1826) without presence of float chamber used to 'restrict' time of year of event and infer rapid deposition	• Inferred sandy tsunami sediment layer overlies supratidal soil. Tsunami occurred in association with coseismic subsidence • Subsided area (including tsunami deposited) then overlain by developing marsh sequence
Greece, Gulf of Corinth	Alvarez-Zarikian et al. (2008)	Two events: 373 BC; 2500-2300 BC	• 17 species identified from 15 genera • No counts provided • 2 plates provided but only 4 species shown • Taxonomic identification completed and focused on salinity tolerances of included species to interpret palaeoenvironmental changes. Noted that both assemblage diversity and abundance is low • Tsunami sediments not only bear increased numbers of marine species but also contain more abraded specimens	• Tsunami deposited sands overlying marsh sediments/ interbedded into colluvial sediments • Samples analysed consisted of siliceous clays, silts and sands with intermittent pockets of gravel and pebbles • Study coupled with ostracod analysis
Portugal, Boca do Rio	Dawson *et al.*, (1995); Hindson and Andrade (1999); Hindson et al., (1996; 1999)	AD1755	• 32 species identified from 20 genera • No counts provided • No plates provided • Assemblage change used to infer tsunami deposit. Estuarine/marsh sediments contain low species diversity and number of specimens including indicative marsh forms such as *Trochamina inflata* and *Jadammina macrescens* (Brady, 1870). Tsunami sediment layer contains higher number of foraminiferal species in a more mixed assemblage • Assemblage includes fully marine species such as *Elphidium crispum* (Linné, 1767), *Quinqueloculina seminulum* (Linné, 1758) and *Cibicides lobatulus* (Walker and Jacob, 1798) – inner shelf species	• Inferred tsunami deposit bracketed by estuarine/marsh sediments • Study coupled with ostracod analysis

(continued on next page)

Table 2 (*continued*)

Geographic location of deposits (region, country, site location)	Reference	Reported age of tsunami deposit	Foraminiferal content	Comments and notes
Europe				
Portugal, Boca do Rio	Dawson et al., (1995); Hindson and Andrade (1999); Hindson et al., (1996; 1999)	AD1755	• Tests poorly preserved, many broken and show signs of abrasion • Porcelanous forms may be more susceptible to damage and abrasion • Level of test disarticulation and degree of abrasion is also taken into account. For instance, exotic milioline (porcelanous foraminifera with distinct longitudinally coiled chambers) species tended to be more severely abraded than agglutinated species • Authors interpret environmental conditions of sediment deposition based on foraminiferal assemblage and they identify exotic species at site of deposition used to infer sediment transport (during tsunami)	
Portugal, Martinhal	Andrade et al. (1997); Kortekaas and Dawson (2007)	AD1755	• 13 species identified from 10 genera • No counts provided but relative abundance down core displayed • No plates provided • Inferred tsunami sediment layer contains fully marine species such as *Ammonia becarii var. batavus, Elphidium crispum, Elphidium Macellum* (Fichtel and Moll, 1798), *Cibicides refulgens* de Montfort, (1808), *Eponides repandus* (Fichtel and Moll, 1798) and *Quinqueloculina seminulum* • Tsunami deposits have 'slightly' higher absolute number of foraminifera and greater diversity of marine species over the storm deposit. However, number of specimens relatively low in both deposits • Both storm and tsunami deposits had high numbers of broken foraminiferal tests	• This study sought to determine whether it is possible to distinguish between tsunami and storm deposited sediments • Fluvial sand and freshwater clay to silty sediments interrupted by coarse to medium grained fining upwards gritty shelly sand containing significant amounts of limestone boulders and cobbles, large shell fragments, pebbles and bioclasts
UK, Northumberland	Boomer et al. (2007)	~8350 BP – hypothesized link to the Storegga Slide tsunami	• 5 species identified from 4 genera • Counts provided • No plates provided • Little significance given to specific species attributes, more interest in environmental preference of species ie-marine and brackish species • Lack of foraminifera within sedimentary record overlain by a large, unconsolidated, coarse gravel layer, then overlain by sediments with a significant number of marine foraminifera • Sediments above marine foraminifera layer contained higher numbers but nearshore brackish and saltmarsh species, eluding to a drop in salinity levels and a shift in tidal frame positioning	• Ostracod and pollen analysis completed as well. One particular nearshore marine ostracod species found ONLY in sediments directly above pebble/gravel layer, suggesting the occurrence of a marine-sourced event • Initial sedimentary layers contained no microfossils • Sediments directly above gravel layer contained abundant microfossils • 3000 year age gap in the sediments between the underlying fine sediments and the coarse pebble/ gravel layer
USA and Canada				
Canada, Vancouver Island, British Columbia	Clague and Bobrowsky (1994); Guilbault et al., (1996)	100 – 400 years ago with a possible deposit from the 1964 Alaska event.	• 24 species identified from 15 genera. 13 species specifically associated with tsunami deposit (on Meares Island) • Counts provided • No plates provided • Assemblages focus on the abundance of the three marsh species *Trochammina macrescens* Brady (1870), *Trochammina inflata* and *Miliammina fusca* (Brady, 1870). Their shift in dominance and abundance is used to infer subsidence and deposition via tsunami • Foraminiferal assemblages used more to infer a shift in environmental conditions that was coincident with a tsunami as opposed to establishing tsunami foraminiferal assemblages • Presence of foraminiferal species that live only at elevations lower than the tidal marshes is strong evidence of a landward movement of sediments as opposed to fluvial processes • Unusually high percentages of adult *Miliammina fusca* at one locale on Meares Island used to locate unusual reworked sediments possibly deposited by tsunami • Meares Island, the tsunami sand contains subtidal species believed to have been transported from more open marine conditions into a high marsh environment. Specifically, five species are identified in this tsunami sand deposit – e.g., *Trochammina nana* (Brady, 1881) and *Eggerella advena* (Cushman, 1922b); *Cribrostomoides jeffreysii* (Williamson, 1858); *Trochammina ochracea* (Williamson, 1858); *Miliammina fusca*	• Peaty marsh soil is overlain by a sand sheet and intertidal muds during an earthquake subsidence/ tsunami event. The new assemblage dominated by middle marsh species • One locality on Meares Island bears a silt layer with a paleoelevation 25 cm lower than the sediments directly above and below. With no known sea level fluctuations from that time the reworking is interpreted to be due to the 1964 Alaska tsunami. • Thecamoebians[#] also included in microfossil analysis.

Table 2 (*continued*)

Geographic location of deposits (region, country, site location)	Reference	Reported age of tsunami deposit	Foraminiferal content	Comments and notes
USA and Canada				
USA, Swanton Marsh, Whidbey Island, Washington	Williams and Hutchinson (2000)	Four tsunami events at: AD600-790; 250-550AD; 110BC-140AD; 170BC-120AD	• Only low numbers of foraminiferal species found, 2 species identified from 2 genera • No counts provided • No plates provided • No foraminifera found within sand sheets. However, peat layers contained common marsh species from the area *Jadammina macrescens* and *Haplophragmoides wilberti* Andersen (1953) • Hypothesised that perhaps the sediments offshore to this locale contained no foraminifera to be transported due to the fact that marine diatoms were deposited in much greater abundance	• Distinctive sand sheets deposited over tidal marsh and peat sediments • Diatom study completed on sediments as they proved far more abundant within deposited sand sheets
Western Pacific				
Japan, eastern Hokkaido Island (various locations)	Noda et al., (2007)	2003 Tokachi-Oki earthquake-tsunami	• No species identified (despite stating they were in methods) • No counts provided • No plates provided • Only information given regarding foraminifera within the deposit is that agglutinated and hyaline forms were the most abundant and that the ratio of agglutinated versus hyaline forms varied considerably between pre- and post- tsunami samples	• Deposit from the sea floor – very fine sands overlain by coarser sands and in some localities a shelly gravel with a muddy matrix • Diatom analysis completed
Japan, Tateyama, southern Boso Peninsula	Uchida et al. (2005)	Several events between ~8,000-8,100 BP	• 13 species identified from 12 genera • No counts provided • Plates provided dividing species into environmental preferences • Found percentage of planktonic foraminifera in total foraminifera, and benthic foraminiferal numbers in the sand layer were as high as those found in open oceanic depths of -90 to -130 m deep • Underlying mud sediments contained inner bay species which became inner sublittoral and bathyal species up the stratigraphic sequence • Bathyal specimens were small and well-sorted, suggesting long distance transportation	• Uchida et al. (2005) is a poster from AGU 2005 • Several expansive sand sedimentary sequences largely regarded as tsunami deposits • Each tsunami deposit subdivided into four units: dark medium to coarse grained sand; fine to coarse sand; very fine sand; sandy silt layer with plant fragments
Japan, Taisei, southwest Hokkaido Island	Nanayama and Shigeno (2006)	1993 Hokkaido-Nansei-oki earthquake	• 22 species identified from 17 genera • No counts provided • No plates provided • Species abundance dominated by *Cibicides refulgens, Ammonia beccarii* (Linné, 1758) and *Elphidium crispum* • Some difficulty with species identification due to dissolution of tests by rain and flood waters • Discovery of rare deep water species *Hoeglundina elegans* (d'Orbigny, 1826), a species that inhabits depths from 80-240 m in the outer sublittoral zone, is known to be too deep to have been deposited by typhoon or extreme storm events, further confirming the cause of the deposit was a tsunami • Many species found within the tsunami deposit were found further inland than the modern beach sediments • Numerical analysis also conducted of tsunami velocity along the seafloor and entrainment threshold velocities for particles of varying sizes in order to demonstrate that foraminiferal tests of deep water had the ability to be entrained by the tsunami and then transported landward	• 2 tsunami deposits investigated each with a run-up and backwash unit • Both deposits consisted of sand derived from the seabed at depths below 5.5 m in the offshore area
Australasia				
New Zealand, Okupe Lagoon	Goff et al., (2000)	Six events at: 4780 +/- 100 BP ; 3360 +/- 40 BP; ~AD1290/1220 AD; ~1450AD; ~500AD/190AD and AD1855	• 22 species identified from 16 genera • Counts provided • No plate provided • Abundance and diversity fluctuations within units is noted along with environmental preferences of dominant species, particularly *Ammonia beccarii, Elphidium advenum limbatum* (Chapman, 1907), *Haynesina depressula* (Walker and Jacob, 1798) and *Trochamina inflate* • Uses assemblage change to infer palaeo environments and shifts in environmental processes operating in the area including the occurrence of earthquake and subsequent catastrophic saltwater inundation	• Fining upward silt laminated sediments containing shell fragments and organic matter overlain and continually interrupted by further mud units but containing large shell debris and fining upward sequences with shell, reed and wood fragments. All units bear distinct often erosional contacts • Pollen analysis also completed

(*continued on next page*)

Table 2 (*continued*)

Geographic location of deposits (region, country, site location)	Reference	Reported age of tsunami deposit	Foraminiferal content	Comments and notes
Australasia				
New Zealand, Okarito Lagoon, Westland	Nichol et al., (2007)	1320 – 1495 AD	• 10 species identified from 9 genera • Counts provided • No plates provided • Uses foraminifera for palaeoenvironmental reconstructions. Notes changes in the depositional environment over time • Also used to note abrupt changes in salinity during the accumulation of sediments in Okarito Lagoon	• Organic rich mud or silts overlain by massive beds of fine to medium grained sands and silts with local shell and wood fragments • Sharp contacts between units
Caribbean				
Bermuda, Castle Harbour, Bermuda Island	McMurty et al., (2007)	Sometime earlier than 310 – 360 ka (marine isotopic stages 9 – 11)	• 27 species identified from 18 genus. However, only 13 species were identified within tsunami deposit • No counts provided • No plates provided however there is one picture as assortment of the featured foraminifera • Sediments contained a mixture of foraminifera from several environmental settings including reef, back lagoon, marine and outer shelf with a depth range of -5 to -60 m • Some of the smaller and fragile species of foraminifera were likely preserved due to the cementation of the tsunami sediments within the cave. By coating the tests in calcite. Therefore, the original tsunami sediments may have been more diverse than what has been preserved	• Large tsunami rolled across coastal zone depositing sediments in karst caves. In these sediments are clasts of algae and foraminifera. Sediments have now formed conglomerates • Cave geometry influenced both the manner of deposition of tsunami sediments and preservation of sediments, particularly foraminiferal tests • Preservation potential of sediments limited by local conditions and manner of deposition
Indian Ocean region				
Sri Lanka, Peraliya and Galle	Dahanayake and Kulasena (2008)	2004 Indian Ocean event	• 25 species identified from 14 genera • No counts provided • 1 plate provided displaying selected species • These authors looked at tsunami, palaeotsunami and storm deposits (and near shore modern sediments) to make comparisons between foraminiferal assemblages • Storm surge and near shore samples - foraminifera only constitute c. 3% by volume of sediment • Tsunami sediments contained almost 50% total volume of foraminiferal tests • High foraminiferal content of sediments resulted in distinct colour difference between tsunami sediments and near shore sediments • Tsunami foraminifera derived from shallow neritic zone	• Authors were extremely careful to retrieve samples that were untouched, not reworked – protected samples to ensure absolute certainty for analysis • Radiolarians and sponge spicules also investigated • Storm surge and near shore sediments better sorted than tsunami sediments
* Malaysia – Thailand Peninsula (various sites)	Hawkes et al., (2007)	2004 Indian Ocean event	• 16 species identified from 8 genera • No counts provided but abundance displayed • 2 comprehensive plates provided displaying all significant taxa • Noted test size could be associated with sediment deposition during run-up. Found larger tests appear in lower, coarser sediments, then fining upwards • At each location, foraminiferal species distribution, and abundance is displayed alongside test size, cluster analysis, grain size distribution and core sedimentology. This facilitates rapid comparison of sedimentary units and the correlation of features that identify significant stratigraphic points in the core. • Tsunami and pre-tsunami sediments can be recognized through foraminiferal assemblage content, diversity and test size. For instance, uncommon species found within pre-tsunami sediments allow the categorization of environmental niches (eg, inter-tidal or inner shelf zone), whereas tsunami sediments bear a turbulent mix of assemblages including marine and mangrove species from backwash sedimentation • Tsunami foraminiferal assemblages can provide information regarding wave characteristics and sedimentary provenance • In some instances total foraminiferal abundance increased towards upper tsunami sediments. However, when this occurred, underlying pre-tsunami sediments bore little to no foraminifera • Turbulent high energy conditions appear to destroy smaller, more fragile test types resulting in the selective preservation of only more robust foraminiferal species	• Samples taken from 6 sites, within each site both stratigraphic units and foraminiferal zones were established • Tsunami sediments marked by sharp contacts, fining upwards sequences and coarser sand sediments overlying medium to fine grained sands

Table 2 (*continued*)

Geographic location of deposits (region, country, site location)	Reference	Reported age of tsunami deposit	Foraminiferal content	Comments and notes
Indian Ocean region				
India, Karaikal-Nagore-Nagapattinam	Satyanarayana et al. (2007)	2004 Indian Ocean event	• 23 species identified within 15 genera • Counts not provided • One plate provided with 12 significant species • Preserved nature of particularly delicate species for instance, *Asterorotalia trispinosa* (Thalmann, 1933) is argued to indicate assemblage was scooped up and held in suspension before deposition, causing minimal breakage • Species identified are inner shelfal from depths of 30 m or less • No evidence of faunal mixing even though tsunami travelled more than 2000 km to reach destination	• Deposit consisted of thin layer of silt and clay deposited over beach sand sediments • Clay nature of tsunami sediments was foreign, indicating origin was offshore
India, Kachchh	Nigam and Chaturvedi (2006)	2 events: ~8,000 BP; later than ~7,000 BP	• 151 species identified within 35 genera • Counts not provided • No plate provided • Both inverted ages of sediments and foraminiferal assemblage change were used to infer tsunami/extreme storm event. • Extreme event assemblages contain smaller foraminifera and different species to normally deposited sediments with common modern beach and shallow water fauna associated with the area	• Coastal detrital sediments interbedded with fine grained deeper sea sediments • Inverted age sequence – 8,000 year old sediments overlain by 11,000 year old, overlain by 7,000 year old, overlain by 10,000 year old sediments

Thecamoebians are singled-celled, benthic testate amoebae that, like foraminifera, belong to the Kingdom, Protista. Similarly, they are microscopic organisms utilised in palaeoenvironmental reconstructions.
This case study has been high-lighted because in our view, it is the most comprehensive and represents a model of 'better' practice.
** Species classifications listed within this table have been reported from the above listed publications and were not completed by the authors of this paper.

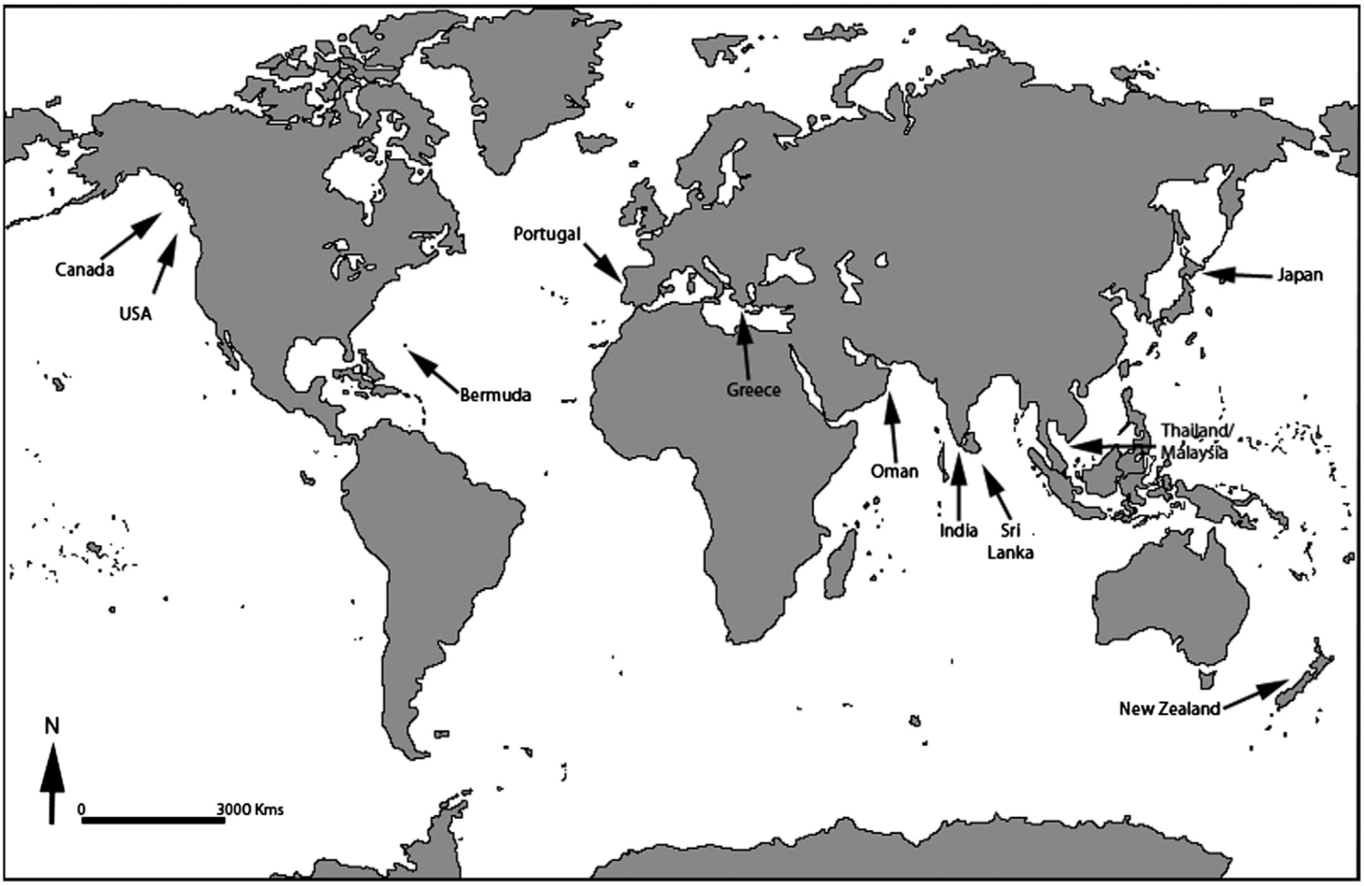

Fig. 3. Global map of locations where studies report the deposition of tsunami sediments containing Foraminifera.

landward during a tsunami (keeping in mind that this also depends on the sediment size available to be entrained). Therefore, future research could seek to explore these issues.

Uchida et al. (2007a) suggest that the horizontal distance sediments can be moved by a tsunami is proportionate to the wave period and amplitude. The weight of individual sediment grains (including foraminifera) and water depth where sediments are deposited, may provide information regarding possible critical thresholds of wave amplitude and wave period. Presently, we are not certain which is more important. Therefore, future research should test the hypothesis that only very large tsunami (such as the 2004 Indian Ocean event) are likely to have the capacity to cross a critical threshold (of wave length and amplitude) to transfer deeper water sediments and microfossil assemblages to shallow water, coastal settings or inland.

We do not know much about the source zones of tsunami-deposited sediments. Therefore, when geologists examine tsunami-deposited sediments, attempts could be made to determine the most likely source region of the sediments, noting probable depth or origin and distance from position where deposited. This relies heavily on the availability of baseline data for the region and is therefore, like many of these suggestions, subject to context and location.

The studies that we have examined present mixed findings in regard to test size, shape and breakage. Some suggest that smaller tests are preferentially preserved, whereas, others suggest larger (but physically more robust) species are preserved during tsunami transport and deposition. Hawkes et al. (2007) infers that assemblages may be skewed to the preservation of more robust species with a higher preservation potential. However, we suspect that in most descriptions of tsunami foraminifera, the sample relates to specimens recovered from a specific geographic point. We can imagine that the test size preserved might relate to the size of the sediments in which they are entrained and these are known to fine landward within tsunami deposits. Therefore, to address this possibility, we recommend foraminiferal analysis within tsunami sediments along a landward transect to examine lateral (landward) assemblage composition and variation. We might expect test size to decrease landward 'mirroring' landward particle size fining. This hypothesis however, remains to be tested.

No studies have looked at the hydrodynamic forces that would be expected to affect an individual foraminiferal test during tsunami flow. However, work by Wetmore (1987) did look at force to strength ratios in high energy turbulent wave environments and showed that spherical rather than pennate morphologies were more robust and resistant to damage. Dominey-Howes et al. (1998) observed in sediments believed to have been laid down by a tsunami in 66 AD at Falasarna Harbour, western Crete, Greece, that pennate rather than spherical foraminifera were much more fragile. Work by Hindson et al. (1999) however, found no significant variation between breakage and test morphology. Therefore, we recommend future research explore relationships between test morphology and wave energy with and without the inclusion of turbulent sediment mixtures of different particle sizes that may affect abrasion of tests by devising and running wave tank, particle size and turbulance experiments. This is because any relationship between test morphology and breakage might have less to do with force and more to do with the sediment that foraminifera are entrained within during tsunami flow. Work by Jaffe and Gelfenbuam (2007) and Morton et al. (2007) has indicated that tsunami flow is laden with a turbulent mix of sediment. It may be that where sediment of mixed (rather than uniform) size is transported, the capacity for damage to individual tests is higher. This could be readily resolved from the experimental work recommended above.

We also recommend the need for research that explores the effects of buoyancy and how individual foraminiferal tests are entrained in tsunami sediment (if at all). Such work might be undertaken through the development of particle entrainment and transport models that examine the effects of shape, size, test density and buoyancy. Clearly such models would need testing in the laboratory and verification via field analysis from post-tsunami field surveys.

It appears that the nature and character of tsunami sediments in which foraminiferal tests are embedded, as well as the local environment (including geomorphology) (McMurty et al., 2007) appear to play a role in determining the size of tests deposited, how well abraded they are (or are not) and how well they have resisted post-depositional weathering processes (Nanayama and Shigeno, 2006). Therefore, it is clear that tsunami geologists should always be careful to clearly describe the geomorphic and sedimentary environment of the locations where their tsunami sediments are located.

Some work has been undertaken that examines the foraminiferal assemblages deposited by storms of various magnitudes (Collins et al., 1999; Hippensteel and Martin, 1999; Scott et al., 2003; Hippensteel et al., 2005; Horton et al., 2009). How these storm deposited assemblages compare and contrast to those of tsunami sediments has not been extensively explored. In fact, the work is rather contradictory (Hawkes et al., 2005). Therefore, we recommend that further research should be undertaken on the foraminiferal records of storm and tsunami-deposited sediments. This would be especially useful in places that are known to have been impacted by *both* storm and tsunami such as the Caribbean, Indonesia and Japan.

We believe that a standardised sampling methodology should be adopted for analysis of foraminiferal assemblages from potential and known tsunami deposits. A good discussion on sampling methodology for modern foraminiferal assemblages is provided by Scott et al. (2001) and Murray (2006) and we suggest that both of these should be consulted prior to undertaking sampling, particularly the sections on sample processing. Importantly, given that the foraminifera found within a tsunami deposit will be sourced from the surrounding area, and the type of foraminiferal assemblage present in a tsunami deposit can vary markedly because of this, it is vital to sample the full gamut of available modern habitats (for example: high marsh, inner shelf, outer shelf etc) in order to establish a 'baseline fauna' for comparison. Ideally, an intensive sampling program should be conducted, to account for possible variability and provide enough data for valid statistical analysis, unless a previous study has documented the fauna in detail. This should then provide a good baseline for comparison with tsunami deposits.

Comparison between baseline and tsunami deposit faunas should always be conducted using statistical analysis. Whilst a simple comparison of faunal composition (presence/absence of taxa) is useful, by itself it is not enough to definitively establish relationships. Using a heuristic index that incorporates both diversity and abundance data, such as the Bray–Curtis distance measure (Bray and Curtis, 1957), and incorporating the results into a cluster analysis, should provide good quantitative comparison. Comparison of diversity indices, such as the Shannon index (Shannon, 1948) or Fisher's alpha index (Fisher et al., 1943) may also help better elucidate possible relationships between baseline and tsunami deposit faunas. Analysis of this kind can be performed using a number of different commercially available programs. We recommend using PAST (Hammer et al., 2001) as it can perform all necessary analysis and is easily accessible.

One area that deserves discussion, particularly in relation to establishing modern baseline faunas, is the use of total assemblages versus dividing the fauna into living and dead assemblages for environmental and ecological analysis. The debate about these two approaches is found throughout the literature (see Scott et al. (2001) and Murray (2006) for synopsis of each view). We propose that tsunami geologists use total assemblages (the entirety of the fauna, both living and dead combined) when comparing baseline faunas to tsunami deposit faunas. Tsunami are rapid, catastrophic events that transport sediment in bulk. As such, the tests of both living and dead foraminifera will be incorporated into a tsunami deposit and rapid burial will ensure that many of the post-mortem processes that would normally change the composition of the foraminiferal assemblage prior to burial (such as disaggregation and transport) will not apply. This therefore means that the foraminiferal assemblage present in a tsunami deposit will most closely resemble the combined living/dead assemblage (the total assemblage) present at the source location, after accounting for taphonomic processes associated with the tsunami.

Given the opportunity, an additional rarely addressed aspect of tsunami analysis that should be included in the suite of methodologies mentioned in this paper is to explore the adaptation and recolonisation by foraminifera after a tsunami. Depending on the tsunami magnitude and impact, a coastal environment can completely change character (Goff et al., 2000). Studies (Alve, 1995, 1999; Alve and Goldstein, 2003) of the dispersal and recolonisation of benthic foraminifera post catastrophic disturbance, represent what we believe to be a good model for the study of pre- and post-tsunami sediments to see if there is a difference in assemblage composition and abundance. Such analysis would provide valuable data with which to 'isolate' the boundaries of a tsunami deposit within the sedimentological record.

We still have no idea about the potential value of dating individual foraminiferal tests contained within tsunami-deposited sediments for establishing robust chronologies. However, great care must be taken to ensure meaningful dates are obtained because of the nature of a tsunami deposit. It is likely that tests of varying age and source will be found within one deposit. Possible solutions for overcoming these challenges include dating closely spaced pairs of samples to assess the reliability of results (Cearreta and Murray, 2000) and the dating of multiple tests of the same taxon from within a single horizon, which may help to minimise error. As with any program of chronological analysis, samples for dating should be recovered from both within the 'catastrophic' event deposit but also from the sediments above and below the event deposit to enable the development of a robust chronological framework.

Previous analyses of tsunami foraminiferal assemblages have rarely taken a systematic approach to the taxonomy of the tests identified. Consequently, a great deal of potential information has been overlooked by researchers. A good example however, is Hindson et al. (1999) who identified tests to species level and examined and described what these species indicated in relation to the depositional environment. Further, Nanayama and Shigeno (2006) used taxonomy to infer information about tsunami wave velocity at the locations where their assemblages were first entrained by the tsunami.

It is our view that the work by Hawkes et al. (2007) in relation to the foraminiferal assemblage composition of sediments deposited by the 2004 IOT represents the most comprehensive work to date (Table 2). This study contains a very good level of detail including identification of tests to species level, the provision of plates to facilitate appropriate taxonomic assignment, data about relative abundance down core, test size and cluster analysis. Further, foraminiferal species are not only analysed in regard to their environmental preferences (and by analogy, the location from where they were derived prior to deposition), but the implications of their test size and level of disarticulation is considered. Finally, all the information derived by Hawkes et al. (2007) is presented in a single diagram that includes the down core lithostratigraphy, grain size, loss on ignition, foraminiferal results and so forth. This enables careful correlation between results down core through the tsunami deposits, providing unparalleled detail about the tsunami sediments. The work of Hawkes et al. (2007) can therefore, be considered a model of 'better' practice.

However, in order to improve the usefulness of foraminifera in future studies, we recommend that authors provide proper taxonomy and identify specimens, when possible, to species level (obviously test disarticulation and abrasion in tsunami sediments often prevents this). Typically only generic level identifications are provided. This is frustrating, given the additional information that can be gained, but is understandable, given that many previous tsunami studies were not conducted by foraminiferal workers. This requirement is overcome when a micropalaeontologist is included as a member of the research team or is consulted as part of the study. We also recommend that when proportions of foraminifera in tsunami sediments are discussed, exact counts should be provided. For example, to simply list that '60% of the specimens present belong to the genus *Elphidium*' when only 10 individual specimens are actually present is not particularly useful for analysis and palaeoenvironmental reconstruction (Murray, 2006).

It would also be helpful if authors separate out their benthic and planktonic species. Planktonic foraminifera are limited in species diversity, are ubiquitous through the ocean water column and are not especially diagnostic of environmental conditions and do not appear to be diagnostic of tsunami deposited sediments. Therefore, when authors have stated that foraminifera are present (but have not distinguished between benthic and planktonic) much information has been overlooked.

It would also be of great assistance if authors provided quality scanning electron microscope images as plates of their principle species to enable later authors to verify and utilise the initial descriptions. It is also important that all examined material is lodged with a reputable institution as part of a curated collection, so future workers can re-examine where necessary. Inaccessibility of examined material is a problem that plagues ecological and palaeoecological studies (Bortolus, 2008) and one that needs to be avoided by tsunami workers from the beginning.

We do not have sufficient geographic spread of studies that examine the foraminiferal assemblages contained within tsunami-deposited sediments. We do not know if what has already been observed and reported in the literature is representative or not. There are many places around the world where we know that a detailed and rich geological record of palaeotsunami exists — such as alongside the Cascadia Subduction Zone of the NW United States and Canada, along the coast of Chile and Peru, along the coasts of Kamchatka and along the NE Atlantic coasts adjacent to the Storegga submarine slides. However, to date, these locations have not had the foraminiferal assemblages of their palaeotsunami deposits investigated. Therefore, since these locations provide valuable natural laboratories, we recommend that the foraminiferal assemblages of their tsunami-deposited sediments be examined in detail. Such analyses will enable us to gain a better geographic spread of tsunami foraminifera.

Notwithstanding all the uncertainties and issues described in the preceding paragraphs and the incompleteness and variability of past studies, the global distribution of studies of tsunami foraminifera are clearly helpful in relation to examining tsunami sediments. Furthermore, as tsunami sediment analysis has been developed and foraminifera have been examined in greater detail, we have seen that a reasonable degree of palaeoenvironmental data can be extracted from the foraminifera. Should foraminifera not prove suitable for analysis, the methodologies outlined here are also applicable for analysis of other macro and microfossil assemblages such as ostracods, diatoms and bivalves. Therefore, foraminifera *do* have the capacity to be a powerful tool for the tsunami geologist.

So, when Dawson (1999) noted that "studies of foraminifera contained within tsunami deposits are very much in their infancy and the value of this particular technique remains to be discovered" (ibid; p124), we argue that the value of foraminiferal analysis is now slowly being realised. However, as research in tsunami geology grows, so there is a need to address gaps in our analytical methodology to fully realise the potential contribution foraminiferal analysis within tsunami geology may make.

5. Conclusions

Investigations of the geological deposits left by tsunami have enormous capacity to deliver meaningful information about past events and to contribute to robust assessments of risk. As this field of geology has developed, significant numbers of papers have been published describing the characteristics of tsunami deposits. Wherever possible, tsunami geologists must work towards increasing the research toolkit available to us. Foraminifera are ubiquitous in the marine realm and many tsunami geologists have examined – with varying degrees of complexity – the foraminiferal assemblages contained within individual tsunami deposits. Foraminifera have the potential to provide meaningful information about tsunami including (amongst others) depth of water from which sediments are entrained, distance of sediment transport, hydrodynamics, flow velocity and turbidity and post-depositional environmental processes.

We have reviewed the available literature that describes the foraminiferal assemblages of tsunami deposits from around the world. The recent work of Hawkes et al. (2007) provides a model of 'better' practice in terms of how foraminifera may be utilised by tsunami geologists. However, improvements in the use of this technique are recommended and we propose a series of research questions to be addressed by tsunami geologists.

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