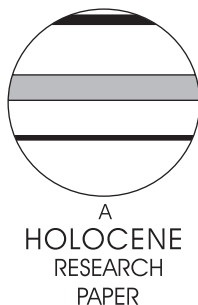


Tsunami and palaeotsunami depositional signatures and their potential value in understanding the late-Holocene tsunami record

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Received 20 April 2005; revised manuscript accepted 16 May 2006



Abstract: In recent years, much research on modern and palaeotsunami deposits has been published. From these studies, a range of signature types has been identified. Identifying and dating such deposits is an important element in understanding late-Holocene tsunami hazard and risk. However, important questions such as, ‘do modern and palaeotsunami leave similar or dissimilar traces?’; ‘do tsunami leave the same signatures all around the world or are there significant variations?’; and ‘what is the actual record of tsunami in different parts of the world?’ still remain. Answering these questions is not an easy task but examining megatsunami flood deposits should shed some light on these questions because such high-magnitude events should leave very clear and detailed traces within the coastal landscape. The coast of SE Australia is reported to have been affected by numerous palaeomegatsunami in the late Holocene. As such, the coast of New South Wales offers an important natural laboratory to examine in detail deposits associated with such events. Here, we summarize the published characteristics of modern and palaeotsunami deposits globally and within Australia. We briefly outline the tsunami risk to Australia before examining a site called Minnamurra Point on the coastline of SE Australia (south of Sydney) that has previously been described as containing evidence for a palaeomegatsunami of an unknown age. We describe the results of a detailed coastal survey, field stratigraphic investigation and various standard laboratory analyses. Surprisingly, we are unable to replicate the previously reported findings of tsunami deposits. Whilst we prefer the interpretation that the sequence is an *in situ* soil (the sediment sequence examined contains none of the usually reported lines of evidence to demonstrate tsunami provenance), we recognize and discuss the significance and difficulty of identifying tsunami deposits in the field and consider the implications of our findings to the wider debate about the preservation of tsunami-deposited sediments.

Key words: Tsunami, palaeotsunami, signatures, evidence, tsunami risk, Australia, Holocene.

Introduction and aims

The Great Sumatra-Andaman Indian Ocean tsunami of December 2004 (Lay *et al.*, 2005) was significant for several reasons: (1) it is the most catastrophic event known to have occurred in terms of the number of lives lost, and people made homeless and displaced (Geist *et al.*, 2006); (2) it has raised public awareness of tsunami, a hazard type not previously fully appreciated (Bryant, 2001); (3) it was an extremely large teletsunami affecting many countries around the Indian

Ocean – one of the largest such events in the last 100 years; and (4) for such a large event, the tsunami has only left a small ‘imprint’ in the coastal landscape (Keating *et al.*, 2005). That is, its geomorphological and sedimentological record is limited and is likely to be rapidly lost as normal marine processes modify and erode these imprints (Keating *et al.*, 2005). The last point is very significant because tsunami scientists argue that the preservation, identification and dating of ‘palaeotsunami’ deposits is an important component in assessing long-term (late Holocene) tsunami risk (Dawson and Shi, 2000; Dominey-Howes, 2002) especially when the historic record is short. Obviously, such assessments are only possible where tsunami leave distinctive and datable deposits. Therefore,

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studies must identify a detailed set of distinguishing tsunami features (hereafter referred to as 'signatures') that researchers may use as a diagnostic tool. There are two important tasks to such work. First, post-tsunami surveys following contemporary events should identify and describe all erosional and depositional signatures. Second, palaeotsunami deposits should be investigated and their signatures identified and described. It will then be possible to determine to what degree modern and palaeotsunami leave similar or dissimilar signatures. Of particular value in the second task is to examine sites thought to record evidence for megatsunami because such sites should contain clear and unambiguous signatures that may become 'type signatures' for palaeotsunami studies.

Palaeotsunami investigations from southeast Australia suggest that the New South Wales (NSW) coast has been repeatedly impacted by megatsunami. Unfortunately, it is not clear to what sources these palaeomegatsunami events might be linked – an important component of understanding risk (Dawson, 1999). As such, the NSW coastline offers a natural laboratory for examining palaeotsunami records.

In light of the introduction, the aims of this paper are to:

- (1) summarize the reported 'signatures' of modern and palaeotsunami globally and in Australia, and to provide an outline of the previously reported tsunami risk to Australia;
- (2) examine in detail a site from southeast Australia reported to have been affected by a palaeomegatsunami flood; and
- (3) consider the importance of the findings of this study to the wider debate about tsunami depositional signatures and their identification and preservation.

Tsunami signatures

Modern and palaeotsunami signatures worldwide

The geological investigation of tsunami is a new research area (Dominey-Howes, 2002; Scheffers and Kelletat, 2003) and there have been no direct observations of tsunami sediment erosion, transport and deposition (Dawson, 1996; Dawson and Shi, 2000). There have however, been numerous post-tsunami field surveys following recent events (eg, 1992 Nicaragua, Satake *et al.*, 1993; 1992 Flores Island, Shi *et al.*, 1995; 1994 Java, Dawson *et al.*, 1996; 1998 Papua New Guinea, Goldsmith *et al.*, 1999 and Kawata *et al.*, 1999; and 2004 Maldives, Keating *et al.*, 2005). From these surveys, a variety of signatures have been recorded. Similarly, investigations indicate that palaeotsunami may be identified within the geological record. Table 1 summarizes the signatures identified for modern and palaeotsunami sediments.

Tsunami sediments are frequently deposited as continuous and discontinuous 'sediment sheets', which may comprise silts, clays, sands and boulders; these sheets mantle the underlying surface, which may have been affected by wave erosion (though not always); rise in altitude and taper landward; are often sharply bounded at the top and bottom; are moderately to well sorted; are fine to massively bedded; have particle size distributions that fine upward and landward; include rip-up intraclasts within the body of the tsunami sediment unit and have microfossil assemblages that suggest landward transport of species from different water environments (or from the marine environment into a terrestrial environmental setting) and the shells of which may be crushed or broken (see references cited in Table 1). Recently, boulder and megaclast deposits together with their imbrication and orientation have

been presented as evidence of tsunami (Bryant, 2001; Bryant and Nott, 2001; Scheffers, 2004; Mastronuzzi and Sansò, 2004). However, some authors contest this claim (Williams and Hall, 2004) whilst others remain to be convinced (Saintilan and Rogers, 2005). Deposition and preservation of tsunami sediments is dependent upon an adequate sediment supply, processes of reworking during backwash and subsequent tsunami inundation and post-depositional environmental processes (Dawson and Shi, 2000; Dominey-Howes, 2002).

In summary, modern and palaeotsunami studies demonstrate that a range of sediments are deposited, that these deposits are distinctive within the stratigraphic record and are often characterized by unusual micro- and macrofossil assemblages (Dominey-Howes *et al.*, 1998; Goff *et al.*, 1998; Dawson and Shi, 2000). Authors usually present a 'suite' of these signatures in their analyses to argue the tsunami provenance of specific units. Consequently, the signature types in Table 1 are becoming used as an 'unofficial check-list' in identifying evidence for tsunami.

Australian tsunami

Since the 1980s, published research suggests that the coasts of Australia have been repeatedly impacted by (palaeo-)tsunami (Young and Bryant, 1992; Bryant *et al.*, 1992a,b; Young *et al.*, 1995, 1996; Bryant and Young, 1996; Nott, 1997, 2003a,b, 2004; Bryant, 2001; Bryant and Nott, 2001; Kelletat and Scheffers, 2003; Switzer *et al.*, 2005). Given the huge distances of inundation (up to 30 km from the coast, Bryant and Nott, 2001: 242) and enormous flood run-ups (up to +130 m a.s.l. at Steamers Beach, Bryant *et al.*, 1997) described, at least two (if not more) of the reported palaeotsunami events fall within the category of being classified as 'megatsunami'. Consequently, some of this work has led to what has been referred to as the 'Australian mega-tsunami hypothesis' (Goff *et al.*, 2003). If it transpires that this hypothesis can be independently validated, it has profound implications for investigating long-term tsunami frequency everywhere, for understanding Australian coastal evolutionary processes and for determining coastal vulnerability in Australia. However, some authors have begun to question the evidence reported for Australian palaeotsunami (Felton and Crook, 2003; Goff and McFadgen, 2003; Goff *et al.*, 2003; Noormets *et al.*, 2004). Given the very short historic record of Australian tsunami (which only dates back to AD1858; Sydney Morning Herald, 1858), careful analysis and validation of the reported palaeotsunami record of Australia is important for (1) contributing to the global debate about tsunami and palaeotsunami signatures preserved within the geological record and (2) for resolving any controversies within the Australasian geological community.

Australian palaeotsunami signatures

Part of the controversy about the Australian megatsunami debate relates to the type of signatures used to identify tsunami. Bryant (2001) and his co-workers have identified a variety of signatures of tsunami impact in Australia (Table 2), which they divide into two major classes: (1) depositional, and (2) erosional. For both of these major classes, examples of either 'sedimentary deposits' and 'geomorphic forms' or just 'geomorphic forms' are provided. Depositional signatures are divided into small-scale individual sedimentary deposits such as 'sand laminae' or 'dump deposits' and large-scale geomorphological forms such as 'carseland' or 'coastal barriers'. The erosional signatures are divided into small scale features such as 'drill holes' or 'cavettos' eroded into rock surfaces and large scale features that are individual geomorphological forms such as 'truncated cliffs' or 'arches'. For a fuller account of these

Table 1 Modern and palaeotsunami signature types

Signature type	Description of the signature	Site locations for signature type	References
Basal unconformity	Lower contact between base of tsunami-deposit unit and underlying sediment may be unconformable or erosional	(1) Scotland; (2) Hawaii; (3) Japan	(1) Dawson <i>et al.</i> (1988); (2) Moore and Moore (1988); (3) Fujiwara <i>et al.</i> (2000)
Intraclasts	Lower/basal tsunami unit may contain 'rip-up' or intraclasts or reworked or underlying material	(1) Scotland; (2) Hawaii; (3) New Zealand	(1) Dawson (1994); (2) Moore <i>et al.</i> (1994); (3) Goff <i>et al.</i> (2001)
Basal load structures	Lower/basal tsunami unit contains loading structures	(1) SW England; (2) Japan	(1) Foster <i>et al.</i> (1991); (2) Minoura and Nakaya (1991)
Fining upward sequence	Tsunami sediment horizons fine upwards	(1) SW England; (2) Scotland; (3) Flores Indonesia; (4) New Zealand; (5) Japan; (6) Papua New Guinea	(1) Foster <i>et al.</i> (1991); (2) Dawson (1994) and Dawson and Smith (2000); (3) Shi (1995) and Shi <i>et al.</i> (1995); (4) Chagué-Goff <i>et al.</i> (2002) and Goff <i>et al.</i> (2001); (5) Fujiwara <i>et al.</i> (2000); Nanayama <i>et al.</i> (2000); (6) McSaveney <i>et al.</i> (2000)
Landward fining sequence	Particle size of tsunami sediments fine landward from the shore	(1) SW England; (2) Scotland; (3) Flores Indonesia; (4) Russia; (5) Japan	(1) Foster <i>et al.</i> (1991); (2) Dawson (1994); (3) Shi (1995) and Shi <i>et al.</i> (1993); (4) Minoura <i>et al.</i> (1996); (5) Sawai (2002)
Distinctive layering	Separate waves in the tsunami wave train may deposit individual layers that contain distinctive subunits associated with deposition during run-up	(1) Hawaii; (2) Scotland; (3) Indonesia; (4) Japan; (5) Portugal	(1) Moore and Moore (1988); (2) Smith <i>et al.</i> (2004); (3) Dawson <i>et al.</i> (1996); (4) Nanayama <i>et al.</i> (2000); (5) Hindson and Andrade (1999)
Cross-bedding	Landward and seaward currents shown by imbrication of shells and/or low-angle wedged shaped lamination and/or cross-bedding	(1) Japan; (2) Italy; (3) Argentina; (4) Tanzania	(1) Fujiwara <i>et al.</i> (2000); (2) Massari and D'Alessandro (2000); (3) Scasso <i>et al.</i> (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 Sansò (2004); Kelletat and Schellmann (2002)
Biostratigraphy	Microfossil assemblages of diatoms and foraminifera. May be pelagic and/or benthic species in shallow water environments. Tests/frustules may be crushed and broken in significant percentages	(1) Greece; (2) USA; (3) Scotland	(1) Dominey-Howes <i>et al.</i> (1998); (2) Hemphill-Haley (1995, 1996); Williams and Hutchinson (2000); (3) Smith <i>et al.</i> (2004)

Table 2 Australian palaeotsunami signature types (from Bryant, 2001: 60)

Depositional		Erosional	
<i>Sedimentary deposits</i>	Sand laminae	<i>Cavitation features</i>	Impact marks
	Landward tapering splays		Drill holes
	Foraminifera and diatoms		Sinuuous grooves
	Boulder floaters in sand	<i>S-forms</i>	Muschelbrüche, sichelwannen, V-shaped grooves
	Dump deposits		Flutes and rock drumlins
	Disturbed middens		Facets and cavettos
	Ridges, mounds and dunes		Potholes and hummocky topography
	Smear deposits		Transverse troughs
	Imbricated boulder stacks		
	Turbidites		
<i>Geomorphic forms</i>	Carseland	<i>Geomorphic forms</i>	Ramps
	Coastal barriers		Canyon drainage channels
			Sculptured headlands features
			Pools and cascades
			Fluted promontories
		Inverted keel like stacks	
		Sea caves, arches	
		Whirlpools and plugs	
		Landscape features	Truncated cliffs
			Raised platforms
			Toothbrush shaped headlands
			Eroded barrier remnants

palaeotsunami signature types, see Bryant (2001) and the references contained therein. We will return to the importance of these reported signature forms in the discussion.

In the remainder of this paper, we examine a field site at Minnamurra Point, south of Sydney on the New South Wales (NSW) coast of southeastern Australia. We investigate this site for several reasons. It has previously been reported to preserve evidence for palaeotsunami sediment deposition at a height of +40 m a.s.l. Such an elevation implies evidence for a megatsunami event. The site is very accessible, making it amenable to study. Finally, it is reported to preserve evidence for what has been termed 'tsunami dump deposits' – a signature form not reported outside of Australia. However, the previously published description for this site is somewhat limited even though the site is potentially rather important. Therefore, we investigate this site in order to provide the wider tsunami geological community with detailed palaeotsunami information.

Minnamurra Point study site

Minnamurra Point is a coastal headland located at 150° 51' 55" E, 34° 37' 80" S, 2.5 km north of Kiama (800 m to the east of the Pacific Highway) (Figure 1). The headland is approximately 100 m wide at its narrowest point (the seaward end) and the axis of the ridge crest is aligned in a NE–SW direction. The eastern edge of the headland is bounded by vertical cliffs that are highest (c. 55 m a.s.l.) to the south and decline in altitude northward. The headland slopes down to the Minnamurra River to the west at an average angle of 18°. The bedrock geology is composed of Permian age latite (specifically, the Bumbo Latite) of the Gerringong Volcanics sequence (a component of the Shoalhaven Group) (Bowman, 1974). The study site (Figure 2a), approximately 100 m south of the northern headland tip, is located at the rear of an amphitheatre-shaped bedrock bench, the base of which is approximately 3 m below the top of the cliff. The bench is largely devoid of soil and loose rock. The cliff displays prominent columnar jointing, a characteristic feature of the Bumbo Latite (Bowman, 1974) (Figure 2b). The site currently supports

buffalo grass (*Stenotaphrum secundatum*), a widespread exotic pasture species in the region. The headland is now part of a recreation reserve but it appears to have supported dairying in the immediate past. Prior to European settlement the site would have supported coastal shrubs (eg, *Westringia fruticosa*) on very exposed positions grading to rainforest in more protected areas.

Bryant (2001) states that at this location a chaotically sorted tsunami dump deposit (a signature type reported only in Australia) rests upon the underlying bedrock. Bryant defines 'dump deposits' as:

chaotic sediment mixtures emplaced in coherent piles ... often possessing large volumes with limited sorting ... may contain cobbles and boulders ... are often found plastered against headlands ... may contain mud lumps ... have an internal fabric that suggests hydrodynamic flow ... contain alternating layers of fine to coarse sand and may contain chipped gravels and shells. (Bryant, 2001: 67–71)

Only a generalized description of the Minnamurra site and deposit was provided by Bryant (2001). As such, we reproduce *in full*, this description, which states that the deposit is:

set in a matrix of mud overlying the volcanic bedrock, contains rounded metamorphic pebbles (transported by tsunami flow from elsewhere) and shell bits plastered on top of the headland. The deposit rests at an elevation of +40 m a.s.l. (Bryant, 2001: 69).

Bryant (2001) attributes the deposition of this facies to a tsunami flood across the headland although this event remains undated.

Given this site overview, we seek to determine: (1) what is the nature of the marine evidence for the megatsunami deposit at this location; (2) how does the sedimentary material of the reported 'tsunami dump deposit' compare to the local lithology, and (3) what are the implications of our findings for the wider geological community when considering the identification and preservation of palaeotsunami deposits?

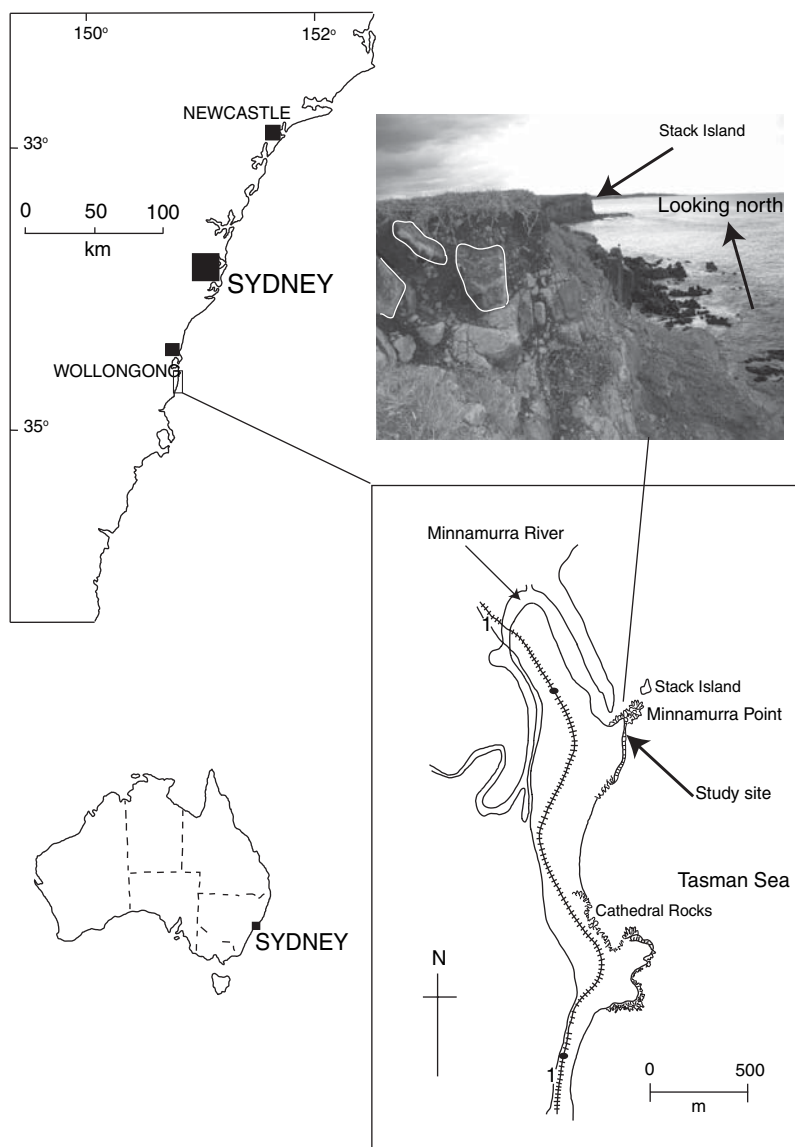


Figure 1 Location map of the coastline of New South Wales and sketch of the Minnamurra Point field site (inset). –1– indicates the path of the Pacific Highway. (Upper) photo of the cliff top including our exposure looking north towards Stack Island. This photo was taken from the same angle as the location photo that appears in Bryant (2001: 69). The three boulders highlighted in white are the specific boulders used for cross-referencing between our study and that of Bryant (2001)

Methods

The exact same site (Figure 1, photo inset) at $150^{\circ} 51' 55''$ E, $34^{\circ} 37' 80''$ S described by Bryant (2001) was located using the photograph and description in Bryant (2001: Figure 3.6; 69) and especially from distinctive individual boulders evident in the photograph (Figure 1, photo). (Note: a request to obtain a copy of Figure 3.6 in Bryant (2001) to use for comparative purposes was denied so we provide the photograph in Figure 1 of exactly the same section to enable readers to be confident we have worked at the same site.) A systematic field inspection was undertaken 150 m north and south of the site section. The survey sought to determine the geological and geomorphological setting of the site and to identify any boulders, sand, middens, other archaeological materials and so forth that may be present on the cliff top and which might be relevant to understanding the late Quaternary evolution of Minnamurra Point. The site section (Figure 3), *c.* 4 m in length, was subdivided into layers (Layers I to IV) based primarily on composition (predominantly clast content) and stratigraphic relationships using standard approaches (Gardiner and

Dackombe, 1983). The layers were described as a sediment (as per Folk, 1974). The section was surveyed using an autaset level and nine bulk samples were collected from profile A–B (Figure 3). Major elements, standard sediment chemistry, particle characterization, and micro- and macrofossil analyses were undertaken on the samples. Thin sections were also made of the uppermost Layer I and the fine clast component of Layer II to assist with determining clast lithology. Details of these techniques are given below.

Clast analysis

Over 400g of Layer I and over 1000 g of Layer II material was processed for clast content, composition and roundness. The sample, previously dried to determine moisture content, was dispersed in calgon overnight and the material wet sieved to remove the < 2 mm fraction and oven dried. The dry sample > 2 mm size was placed in a nest of sieves and shaken gently for 5 min to avoid destroying highly weathered clasts. The size classes are standard sieve sizes, which approximates to B_{max} , at half phi intervals. Composition was determined by visual inspection using a $10\times$ magnifying glass and supplemented by

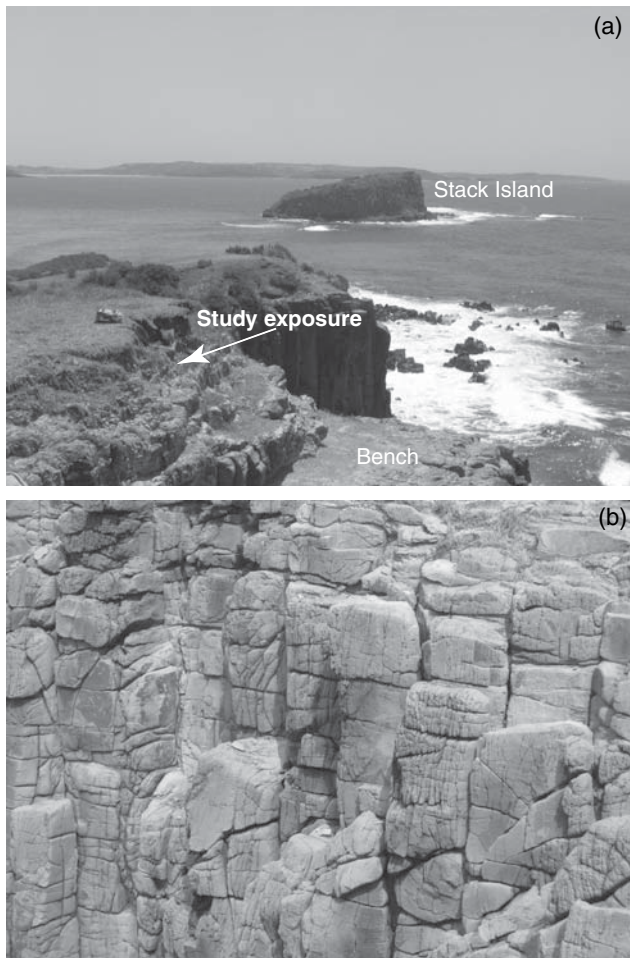


Figure 2 (a) View looking north towards Stack Island. The study exposure is indicated by the arrow. (b) Section of the vertical cliff beneath our exposure. This is bedrock that is composed of the Bumbo Latite. Note the significant jointing of the rock

thin section analysis. Powers roundness classes (Folk, 1974) were used to characterize each half phi sample.

Thin sections

Samples were placed in a mould and impregnated with araldite under vacuum from which standard petrological sections were produced. Two samples were examined: aggregates of Layer I and the 2–8 mm clast fraction of Layer II.

Particle sizing of the fine earth fraction

In order to determine the particle size of the fine earth fractions (eg, sand (63–2000 μm) and mud (< 63 μm)) of Layers I and II, 10–25 g of sediment was air dried and gently ground through a 2 mm mesh. The residue in each sieve nest was collected and the volume of that fraction was calculated as a percentage of the original mass. Samples were treated with hydrogen peroxide to remove organic matter and dispersed in calgon before wet sieving through a 63 μm mesh. The gravimetric moisture content was determined from an additional 10 g sample after oven drying at 105°C for 24 h and the result used to determine the oven-dried equivalent mass of the dispersed sample. The loss on ignition (LOI) was determined from the same oven-dried samples after heating to 500°C in a muffle furnace for 24 h.

Major elements

Bulk samples of the < 2 mm fraction from Layers I and II as well as three separate clast size fractions from Layer II, and a

whole rock sample from Layer IV, were analysed by Energy-Dispersive Polarised X-Ray Fluorescence (EDPXRF) on a SPECTRO X-Lab 2000 X-Ray Spectrometer. This analysis was undertaken on crushed (TEMA tungsten carbide mill) samples (0.3–0.4 g) fused with lithium tetraborate/metaborate flux at 1050°C and set in a carbon die to form glass discs. Loss on ignition involved heating samples in a muffle furnace at 1000°C for 4 h.

Sediment chemistry

Bulk samples from Layers I and II were air dried at 35–40°C overnight and crushed to pass through a 2 mm sieve. Soil pH was obtained from a 1:2 (v/v) soil–water mix with a potentiometric determination. Exchangeable K, Ca, Mg and Na were obtained from a 1M neutral ammonium acetate extraction and measured by ICP-OES. CEC is the summation of extractable cations (K, Ca, Mg, Na) plus extractable acidity. Total carbon and total N were obtained by a Dumas combustion. Available P was obtained using an Olsen extraction followed by Molybdenum Blue colorimetry. Total P was obtained from a nitric/hydrochloric digestion and measured by ICP-OES. Analysis was undertaken At Hill Laboratories, New Zealand, an internationally accredited facility.

Micro- and macrofossil analysis

All bulk samples were soaked in distilled water for 2 h and wet sieved through a stack sieve to 63 μm . Sieved samples were oven dried at 20°C for at least 24 h and the residue was examined under the microscope. Any micro- and macrofossil specimens were recovered and identified.

Results

The cliff top field survey

During the cliff top inspection we observed no boulders, sand sheets or middens (disturbed or intact) and the cliff top is devoid of any unusual features or deposits. However, living gastropods were observed and, in several locations, small amounts of shell hash and broken mollusc fragments were present in discrete patches on the ground surface along the headland (but not landward of the site section). Table 3 lists the species observed.

The exposure – lithostratigraphy

The target section consists of a thin mantle of unconsolidated material, < 1 m thick, overlying bedrock (Figure 3). The top of the section is located at +20.26 m a.s.l. and the base is at +19.25 m a.s.l. The unconsolidated material was divided into three layers (I to III). Layer IV is the underlying bedrock – the Bumbo Latite.

Layer I consists of a very dark (10YR3/1) (dry) to black (7.5YR2.5/1) (moist), pedal clay loam grading to light clay with fine clasts interspersed throughout (ie, a slightly gravelly clay *cf* Folk, 1974). Layer I also contains fine to very fine (3–10 mm) subangular blocky peds, is rough faced, is very friable and slightly hard with many very fine and a few fine roots. Layer I is non-calcareous and varies in thickness between 10 and 30 cm and its base is at +20.05 m a.s.l. The lower boundary between Layer I and the underlying Layer II is gradational. A stone artefact of Aboriginal style was located at the boundary between Layers I and II.

Layer II consists of a very dark greyish brown (10YR3/2) (dry) to black (10YR2/1) (moist) pedal light to medium clay. In comparison with Layer I, Layer II has a much greater proportion of coarse clasts (ie, a clayey pebbly gravel *cf*. Folk, 1974). Varying degrees of weathering of the gravel clasts

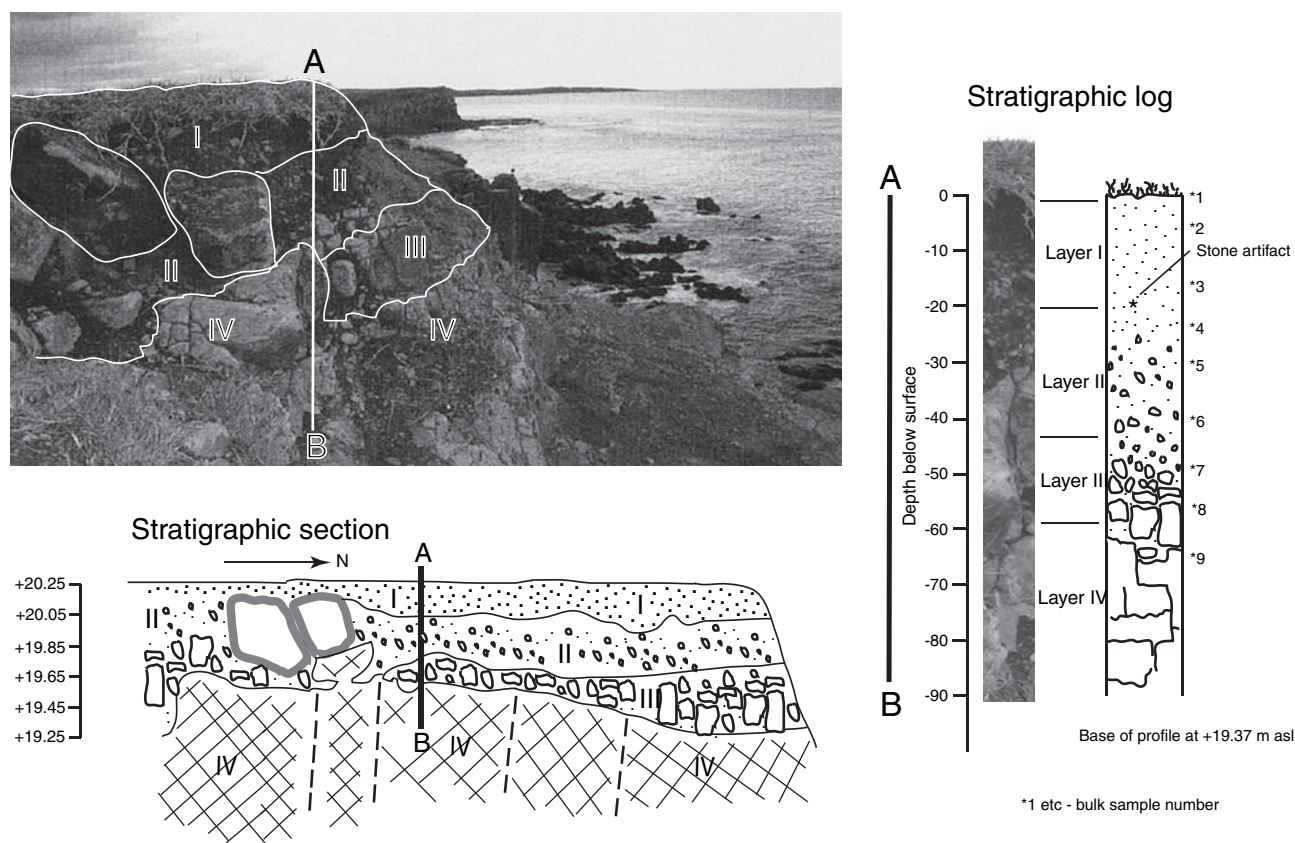


Figure 3 Photograph and lithostratigraphic log and section of the site exposure at Minnamurra Point, New South Wales. See text for explanation of facies layers

is indicated by a colour change from light grey to reddish brown and a weathering rind of up to 0.5–1 mm is present on many clasts. Layer II also contains medium to coarse subangular blocky peds, is rough faced, friable and slightly to moderately hard. There are many very fine and a few fine roots and Layer II is non-calcareous. Layer II has an average thickness of about 35 cm and the base of Layer II is at approximately +19.70 m a.s.l. The lower boundary between Layer II and the underlying Layer III is gradational.

Layer III is dominated by pebble to cobble size clasts (ie, a cobbly gravel *cf.* Folk, 1974) in which pockets of clay loam occur along joint partings. Layer III has an average depth of 15 cm. The base of Layer III is at +19.55 m a.s.l. The lower boundary between Layer III and Layer IV is sharp.

Layer IV is intact latite bedrock and is bounded by prominent joints to define intact boulder blocks (Figure 2b). In the field it appears that the joints can be traced from the latite into Layer III.

Particle size and shape data

Particle size was determined for Layers I to IV (Table 4). The coarsest fraction (> 2 mm) decreases up through the profile indicating that, as a percentage of volume, particle size fines upwards. A similar trend is replicated in all size class categories. There is a tendency towards increased clast roundness with decreasing clast size in Layers II and III but much less so in Layer I (Table 4).

Thin section results

A thin section of Layer I aggregates revealed crumb ped structure and the presence of non-quartz silicate minerals and plant tissue but no carbonate minerals. A thin section of the 2–8 mm clast fraction from Layer II shows that the clast lithology is latite. With the exception of the stone artefact of Aboriginal style at the boundary between Layers I and II (see Figure 3 for location) no exotic clast material was recognized in any layer.

Table 3 Mollusc species observed at Minnamurra Point

Species	Habitat	Comments
Living specimens on exposed rock	Exposed rocky shores, high intertidal	'Most abundant mollusc. Living high on Australian shores. Clusters of this pale blue species occur in slight depressions on the rock, with the largest individuals recorded as far as 10 metres above high tide level. The species feeds predominantly on lichens scraped from the rock surface'. (Edgar, 2000: 245)
<i>Nodilittorina unifasciata</i> (Gray, 1826)		
<i>Nodilittorina australis</i> (Quoy and Gaimard, 1826)	Exposed rocky shores, high intertidal	'Tends to be solitary rather than gregarious'. (Edgar, 2000: 245)
Shell debris from discrete patches		
?????	?????	Shell hash too badly fragmented and weathered to permit identification

Table 4 Summary of gravel (clast) and particle size data and gravel characteristics

Particle size class	Layer I % volume	Layer II % volume	Layer III % volume	Layer IV ^a % volume
Gravel (> 2 mm) content	2.6	57	70	na
Sand (63–2000 µm) content	14.0	6.9	24.2	na
Mud (< 63 µm) content	83.4	36.1	5.8	na

Clast size	Roundness ^b of gravel sized clasts			
	Layer I	Layer II	Layer III	Layer IV ^a
32–64 mm	no material	a – sa	sa – sr	na
16–32 mm	no material	a – sa	sa – sr	na
8–16 mm	a – sa	a – sr	sa – sr	na
4–8 mm	a – sa	a – sr	sr	na
2–4 mm	sa – sr	sa – sr	sr	na

^aLayer IV is composed of solid bedrock – there are no clasts or fine sediment available for analysis.

^ba, angular; sa, subangular; sr, subrounded.

Major elements

Table 5 presents results of major element analysis. Eleven major elements were analysed in the following samples: (1) Layer I; (2) Layer II; (3) Layer II gravel in the 2–4 mm fraction; (4) Layer II gravel in the 4–8 mm fraction; (5) Layer II gravel in the 8–16 mm fraction and (6) Layer IV latite bedrock. Analysis of the results contained within Table 6 reveals the following trends: (1) there is an increase in the value of S up profile; (2) there is a decrease in the value of Si, Al, Mg, Ca, NA and P up profile; (3) there are no trends in the values of Ti, Fe and Mn up profile. The common soluble cations decrease in concentration in a consistent manner in order of potassium, sodium, calcium and magnesium, with the exception of the Layer IV (latite) sample where calcium replaces potassium. Sample 6 from Layer IV (the Bumbo Latite) has a composition that generally rests between basalt and andesite.

Sediment chemistry

Table 6 summarizes results of chemical analyses of the fine earth fraction (< 2 mm) of the samples taken from Layers I and II. There is little difference between Layers I and II in

terms of chemistry. In terms of Australian standards (McDonald *et al.*, 1984; Isbell, 1996) these materials have high levels of base saturation, and cation exchange capacity and exchangeable potassium, very high levels of exchangeable magnesium and sodium but low to moderate levels of exchangeable calcium and low available phosphorous, which contrasts with the high total P. Organic matter and LOI are also high.

Palaeontology

Samples were examined for the presence of foraminiferids and ostracoda. None were present in any of the samples. No macrofossil material such as marine molluscs (bivalves and gastropods), brachiopods, echinoderms (sea urchins, brittle stars and star fish) and fish remains were recovered either.

Discussion

Our discussion is divided in to three parts. First, we revisit the published global and Australian tsunami signature types and

Table 5 Major elements in the unconsolidated sediment, clasts and rock

	Unconsolidated sediment at Minnamurra Point					Rock samples		
	Layer I	Layer II	Layer II clasts 2–4 mm	Layer II clasts 4–8 mm	Layer II clasts 8–16 mm	Layer IV Bumbo Latite	Andesite ^a	Basalt ^a
<i>Increasing trend</i>								
S	0.08	0.07	0.02	0.02	0.02	0.01		
<i>Decreasing trend</i>								
SiO ₂	43.97	43.31	49.34	50.72	52.08	54.69	58.17	50.83
Al ₂ O ₃	14.39	16.50	16.13	17.15	17.62	17.85	17.26	14.07
MgO	0.89	0.92	1.64	1.75	1.86	1.80	3.23	6.34
CaO	1.17	0.85	1.78	2.39	3.26	5.67	6.93	10.42
Na ₂ O	2.42	2.25	2.86	3.38	3.50	4.22	3.21	2.23
P ₂ O ₅	0.34	0.32	0.36	0.44	0.60	0.78	0.2	0.23
<i>No obvious trend</i>								
TiO ₂	1.07	1.14	1.21	1.26	1.25	1.07	0.8	2.03
Fe ₂ O ₃	8.14	9.33	14.28	11.57	9.38	6.49	7.24	11.94
MnO	0.16	0.18	0.20	0.19	0.15	0.11		0.18
K ₂ O	3.33	3.24	4.30	4.84	4.87	4.40	1.61	0.82
LOI	23.71	21.63	7.43	6.10	5.18	2.52		
TOTAL	99.66	99.72	99.57	99.79	99.78	99.60		

^aAverage composition from Krauskopf and Bird (1995).

Table 6 Sediment chemistry

Measure	Layer I	Layer II
pH (1:2 soil–water)	6.1	6.3
Extractable P (Olsen) (mg/L)	2	2
Extractable K (me/100 g)	1.64	2.01
Extractable Ca (me/100 g)	6.0	4.7
Extractable Mg (me/100 g)	10.8	10.4
Extractable Na (me/100 g)	8.65	7.88
Cation Exchange Capacity (me/100 g)	35	32
Base saturation (%)	78	79
Organic carbon (%)	10.2	6.6
Total N (%)	0.46	0.32
Total P (mg/kg)	971	879
Loss on Ignition – 500°C (%)	15.0	11.2

consider their significance. Second, we discuss the results of our analysis of Minnamurra Point and consider what light this work sheds on the record of palaeotsunami flooding at this location. Third, we consider the importance of our work to the broader debate about the preservation and identification of palaeotsunami deposits everywhere.

Global and Australian tsunami signatures

As more and more geological studies of modern and palaeo-tsunami are published, we are learning much about the nature of their deposits. From these studies a suite of distinguishing or ‘diagnostic’ signatures have become apparent. It is also becoming clear that tsunami and palaeotsunami leave similar signatures imprinted within the coastal landscape. However, it is also obvious from a careful analysis of the studies listed in Table 1 that not all tsunami result in the deposition of all of the reported signature forms. In fact, at best, only a selection of these signature forms may be present in any specific tsunami facies. This is potentially rather problematic. Consequently, whilst it is inappropriate to refute a tsunami origin for an individual sediment facies simply because it does not contain any (or all) of the reported signature types, it is in our opinion the reporting authors responsibility to unequivocally demonstrate that a particular sedimentary facies owes its origins to a tsunami, based upon other lines of evidence such as geomorphological data, eye witness accounts and so forth. Furthermore, they should present a sustained argument based on evidence that cannot be accounted for in less dramatic ways – ie, the application of Occam’s Razor.

Notwithstanding the previous comment, one of the most significant lessons of the 2004 Indian Ocean tsunami to the Australasian geological community is that Australia *is* at risk from tsunami flooding. This event did inundate coastal areas of Western Australia, although no systematic field surveys have been reported that quantify the extent, nature and record of this flooding (Cummings, personal communication, 2005). Consequently, to dismiss entirely the reported palaeotsunami evidence in Australia as some authors have, is both unwise and unfair. However, it is also apparent that the reported Australian tsunami signature forms (see Table 2) differ from those described elsewhere (see Table 1) and that many of the Australian types are seemingly unique. Several possibilities exist to explain these observations, including that tsunami impacting on the Australian coastline are somehow different, or that researchers in Australia have evolved different explanations for the same evidence. There is no quick or ready solution to this paradox other than to acknowledge that such a difference exists and to seek ways of identifying the different signatures as well as re-examining the published evidence. It is this latter approach that has been followed in our study of Minnamurra Point.

Interpretation of the Minnamurra Point site and stratigraphy

In our cliff top survey we found no unusual geomorphological forms or sedimentary deposits that might reasonably be interpreted as the product of catastrophic marine inundation (of any form). No boulders, sand sheets, coral blocks or other features of marine origin are present. The small isolated patches of shell hash (Table 3) are thought to relate to sea birds eating living molluscs at a specific feeding spot (behaviour observed by us). The live molluscs are in living position attached to cliff top rocks at +20 m a.s.l. Therefore, dead specimens probably relate to death at that location and should not be inferred to represent evidence of marine inundation and deposition (Williamson, personal communication, 2006).

Bryant (2001) reported that the site section is at an altitude of +40 m a.s.l. In fact, we levelled the site at an elevation of just +20 m a.s.l. Our study section consists of a thin mantle of unconsolidated material (< 1 m thick) divided in to three layers overlying bedrock. The pebble clasts within Layers I to III have the *same* lithology (Bumbo Latite) as the underlying bedrock. The volume of pebble clasts (as a percentage of the entire sediment) present in each layer is highest in Layer III directly above the bedrock and decreases up profile towards the ground surface. Maximum clast size is also greatest in Layer III and decreases up profile. There is also a tendency for increasing clast roundness up profile. Taken together, these three pieces of evidence indicate that the pebble clasts within this unconsolidated sediment owe their origins to *in situ* weathering of the underlying bedrock. We recognize that the fining up of the clasts towards the top of the sequence could be indicative of tsunami sediment deposition but the fining up can equally be explained by natural weathering of the clasts. The major elements (XRF analysis, Table 5) seem to indicate a consistent weathering pattern from rock to coarse gravel to fine gravel (Table 6). The slight reversal in trend between Layers II and I most likely reflects the influence of the higher organic matter and hence LOI (Table 6) in the latter. Such a weathering pattern is consistent with the presence of weathering rinds and, presumably, neoformation to common clay minerals. With the exception of a single stone artefact, all of our observations and results indicate that the entire gravel fraction is derived from the local latite.

The Bumbo Latite sample (Layer IV) has a composition between average basalt and andesite (Krauskopf and Bird, 1995) in terms of its oxides of Si and Ti. Several other elements are similar to the andesite including Al, Fe, Ca and Na, but Mg is much lower and K and P are much higher (Table 6). These observations support the regional geological mapping (Bowman, 1974).

If a tsunami had dumped marine sediments at this location, they might be expected to contain shell hash or microfossils as well as sand. The analytical results do not indicate this. First, no shell or microfossils were recovered. Second, the results of the sediment chemical analysis demonstrate that the samples have chemical compositions similar to the latite (indicating local provenance) and do not contain any elevated exchangeable Ca and higher pH values that might be expected from the shell material that would be deposited by a tsunami and which has been reported elsewhere (see Table 7). Bryant (2001: 69) describes the deposit as ‘set in a matrix of mud overlying the volcanic bedrock, contains rounded metamorphic pebbles ... and shell bits. The material (our Layers I and II) certainly consists of gravel set in a mud matrix and it does overlie volcanic rock (latite), but we could not confirm the presence of either shell or rounded metamorphic pebbles.

Table 7 Results from our study section compared with published tsunami-deposited sediment sequences

Known/reported characteristics	References	Results from our study section
<i>Geochemistry</i> : increases in concentrations of sodium, sulphur, chlorine, calcium and magnesium (relative) to underlying and overlying sediments – indicates salt-water inundation or/and high marine shell content. Variations in other elements may occur depending on nature of mineralogy of sediments and any bedrock	Goff <i>et al.</i> (2001); Chagüe-Goff and Goff (1999); Chagüe-Goff <i>et al.</i> (2002)	There is a slight increase in the oxides of Ca, Na, K and P in Layer I over Layer II but these are all much lower than in the gravel-size fraction and the latite bedrock. Geochemically it appears as a normal weathering sequence with the slight relative increase in Layer I attributed to organic matter
<i>Marine microfossils</i> : (eg, diatoms and foraminiferids) – increases in abundance of marine and brackish water diatom species; increases in planktonic diatoms; increases in the percentage of broken diatom frustules. Marked changes in marine foraminiferal assemblages; increases in the percentage of deeper water species; increases in the percentage of broken foraminiferal tests; increases in abundance of planktonic foraminifera; introduction of marine and brackish assemblages in to otherwise non-marine (terrestrial) sediment sequences	Goff <i>et al.</i> (2000, 2001); Hemphill-Haley (1995); Minoura <i>et al.</i> (1994); Shennan <i>et al.</i> (1996); Dominey-Howes <i>et al.</i> (1998); Dawson and Shi (2000)	We recovered no marine microfossils of any type
<i>Marine macrofossils</i> : (eg, molluscs) – individual shells and shell-rich units often present (shells frequently articulated)	Goff <i>et al.</i> (1998, 2000, 2001); Fujiwara <i>et al.</i> (2000); Nanayama <i>et al.</i> (2000)	We recovered no marine macrofossils of any type
<i>Wood and organic debris</i> : wood, woody material, vascular plant material and other organics often found within or 'rafted' on top of tsunami sediment layer	Goff <i>et al.</i> (2001); Dominey-Howes <i>et al.</i> (1998); Imamura <i>et al.</i> (1997)	We recovered no such material from our samples other than living roots from grass species and minor amounts of charcoal. NB, charcoal is common in Australian sediments/soils
<i>Particle size fines upward</i> : tsunami sediment layers fine upward through sequence	Foster <i>et al.</i> (1991); Dawson (1994); Shi (1995); Minoura <i>et al.</i> (1996); Sawai (2002)	There is a slight coarsening in the fine earth fraction (63–2000 µm) to the surface but there is a decrease in gravel content that could be interpreted as fining upward or alternatively, as a normal weathering pattern in soil
<i>Erosional or unconformable lower boundary</i> : Lower contact between base of tsunami-deposited unit and underlying sediment may be unconformable or erosional	Dawson <i>et al.</i> (1988); Fujiwara <i>et al.</i> (2000)	We observe no unconformities within our sediment sequence

All of the information presented above is consistent with the stratigraphy being an *in situ* soil derived from the underlying latite bedrock. Our sediment description correlates with other descriptions of soils obtained during regional mapping in this area (Parbery, 1947; Hazelton, 1992). The section is very easily classified as a *Eutric Andosol* (WRB, 1998). In the Australian soil classification system this is a *Chocolate Soil* using the great soil group system of Stace *et al.* (1968) or a *Black Dermosol* (Isbell, 1996). In order to assist readers in making an independent judgement of our interpretation, we summarize our data and compare our findings with published examples of tsunami deposits (see Table 7). It is clear that our results bear no resemblance to published tsunami deposit characteristics.

The results of our work at Minnamurra Point and various standard laboratory analyses conducted on samples returned to the laboratory indicate that the field site preserves no features that demonstrate the effect of a tsunami or other catastrophic marine inundation. We prefer the alternative explanation that the stratigraphic sequence located at Minnamurra Point owes its origins to the development of an *in situ* soil derived from the underlying latite bedrock.

The absence of any unequivocal evidence for a tsunami is not proof that a megatsunami has not impacted this part of the NSW coastline. However, we suggest that there is no compelling evidence for such an event. We are very surprised at being unable to replicate the previously reported findings at Minnamurra Point. An obvious implication from this study is that careful and systematic re-examination of other sites reported to contain evidence for palaeotsunami flooding in Australia should take place so a better determination of the evidence may be made and that controversies surrounding the Australian palaeotsunami record may be resolved.

The wider debate about the preservation of tsunami deposits

Our work at Minnamurra Point highlights two important issues relevant to the wider tsunami community beyond Australasia. First, there exists the possibility that when Bryant (2001) conducted his analysis, the field evidence really was present but, between his work and ours, that evidence has been lost to natural environmental processes. Since we are able to relocate specific individual clasts (see the outlined clasts in Figure 1 photo inset) at the study site (and which are displayed in the field photo of Bryant (2001: Figure 3.6, 69)) we doubt this is the case but such a possibility would mean that the preservation potential of tsunami-deposited sediments is fickle and not guaranteed and is highly variable and site specific. This would be enormously problematic. Second, the loss or absence of evidence for past tsunami would mean it is impossible to examine longer-term records of tsunami in any given area. The implications for understanding environmental processes, coastal landscape evolution and late-Holocene tsunami hazard and risk cannot be understated.

Conclusion

The identification and dating of tsunami and palaeotsunami deposits is a vital element in understanding late-Holocene tsunami hazard and risk. To this end, much work has been published detailing the signatures of modern and ancient tsunami deposits. Our review of the published literature indicates that there is some variation in the types of signatures recognized around the world. There is no easy way to address this difference except to acknowledge its existence and to examine in detail sites reported to preserve evidence for

modern and palaeotsunami. In our analysis of such a site at Minnamurra Point on the New South Wales coast of Australia, we have been unable to identify the previously reported evidence for a palaeomegatsunami flood. Several possibilities exist to explain the discrepancy between the original report of this site and the results of our investigation. The most significant issue to arise from our study, and which is relevant to the wider tsunami geological community, is that the preservation potential of tsunami-deposited sediments may be rather limited (except under very favourable conditions). Consequently, determination of the late-Holocene tsunami record may be rather problematic and the implications for understanding long-term tsunami risk can not be understated.

Acknowledgements

This research was supported by Macquarie University Research Grant number 9802 0222. We thank Carol Lawson of GEMOC at Macquarie University for the XRF analyses, Hannah Nair for examination of the shell fragments and Jane Williamson (department of Biological Sciences, Macquarie University) for assisting in the identification of the whole mollusc specimens. Maurizio Labbate is thanked for providing assistance in the field. We thank Alastair Dawson, Sue Dawson, Iain Stewart and an anonymous referee for valuable comments on an earlier draft of this paper.

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