Natural Hazards **24:** 231–249, 2001.

Geological Indicators of Large Tsunami in Australia

E. A. BRYANT[1] and J. NOTT[2]
[1]*School of Geosciences, University of Wollongong, Wollongong, New South Wales, 2522, Australia;*
[2]*Department of Tropical Environment Studies and Geography, James Cook University, P.O. Box 6811, Cairns, Queensland, Australia, 4870*

(Accepted in final form: 31 May 2000)

Abstract. Tsunami waves can produce four general categories of depositional and erosional signatures that differentiate them from storm waves. Combinations of items from these categories uniquely define the impact of palaeo-tsunami on the coastal landscape. The largest palaeo-tsunami waves in Australia swept sediment across the continental shelf and obtained flow depths of 15–20 m at the coastline with velocities in excess of 10 m s^{-1}. In New South Wales, along the cliffs of Jervis Bay, waves reached elevations of more than 80 m above sea-level with evidence of flow depths in excess of 10 m. These waves swept 10 km inland over the Shoalhaven delta. In northern Queensland, boulders more than 6 m in diameter and weighing 286 tonnes were tossed alongshore above cyclone storm wave limits inside the Great Barrier Reef. In Western Australia waves overrode and breached 60 m high hills up to 5 km inland. Shell debris and cobbles can be found within deposits mapped as dunes, 30 km inland. The array of signatures provide directional information about the origin of the tsunami and, when combined with radiocarbon dating, indicate that at least one and maybe two catastrophic events have occurred during the last 1000 years along these three coasts. Only the West Australian coast has historically been affected by notable tsunami with maximum run-up elevations of 4–6 m. Palaeo-tsunami have been an order of magnitude greater than this. These palaeo-tsunami are produced most likely by large submarine slides on the continental slope or the impact of meteorites with the adjacent ocean.

Key words: depositional and erosional signatures, Australian coastline, 'dump' deposits

1. Introduction

The coastline of Australia is perceived as a coast little affected by tsunami. At least the historic record of the last two centuries for this continent is bereft of the large events that have affected other countries in the West Pacific such as Japan, New Zealand and Indonesia. Even events affecting the whole west Pacific region have impacted on the Australian coastline less severely. For instance, the Chilean earthquake of 1960 generated a tsunami wave train that caused damage and the loss of 2,500 lives around the Pacific Ocean (Bryant, 1991). However its effects along the east coast of Australia were minor. Whereas wave heights reached 3.5–6.0 m along the east coast of Japan, they did not exceed 0.8 m on tide gauges along the Australian east coast. This quiescence has been explained by the protection

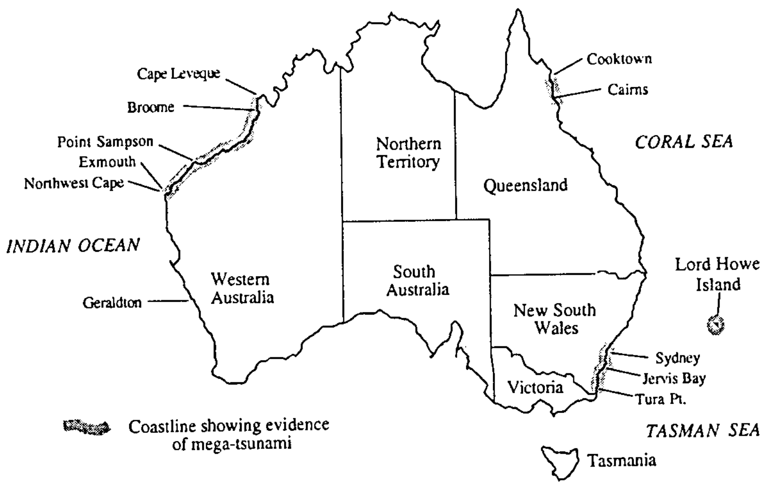

Figure 1. Locations of coastline around Australia showing the most prominent evidence of palaeo-tsunami.

afforded by south Pacific Islands, and by the 2000 km length of the Great Barrier Reef. Only events in Indonesia have impacted significantly on Australia along its west coast; but here the sparse nature of European settlement has precluded detailed observation of historical events. The Krakatoa eruption of 1883 generated tsunami runup in Geraldton, 1500 km away, that obtained a height of 2.5 m. In recent times tsunami, with run-up approximately 4–6 m high, occurred in 1977 and 1994 as the result of earthquakes in Indonesia. These waves impinged upon Cape Leveque, and moved boulders 2 m in diameter 100 m inland opposite gaps in the Ningaloo Reef protecting the Northwest Cape (Nott, 1997).

Yet, recently discovered geomorphic evidence indicates that extensive stretches of the Australian coastline – southeastern New South Wales, Lord Howe Island, northeastern Queensland and northwestern West Australia (Figure 1) – have been affected by tsunami at least an order of magnitude greater than anything recorded historically along the Australian coast. The purpose of this paper is threefold: (1) to present the catalogue of geomorphic signatures that have been compiled for palaeo-tsunami along the Australian coast, (2) to describe briefly some of the impressive field evidence for large tsunami around Australia, and (3) to present the chronology for these events.

2. Geomorphic Signatures of Tsunami

Most of the geomorphic signatures for palaeo-tsunami (Figure 2) were identified from a 400 km stretch of the South Coast of New South Wales. This evidence has been widely published (Bryant *et al.*, 1992, 1996; Young and Bryant, 1992; Young *et al.*, 1995, 1996; Bryant and Young, 1996) and only the most dramatic aspects will be repeated here. The signatures can be classified as either depositional or

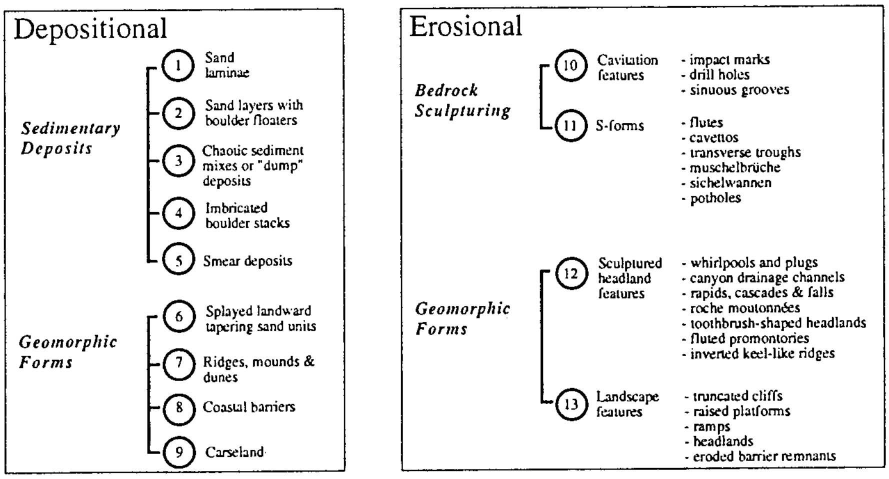

Figure 2. The depositional and erosional signatures of large tsunami identified for the Australian coast.

erosional. Singly or in combination, they allude to the presence of large tsunami. The depositional signatures can be subdivided into sedimentary deposits and geomorphic forms. The sedimentary deposits, except for imbricated boulders, are less dramatic because they do not form prominent features in the landscape. Without detailed examination, they also could be attributed to other processes. Both sand laminae and sand layers containing boulders are buried beneath the surface. Sand laminae appear as 20–30 cm thick layers sandwiched within deltaic or lagoonal muds. They are a commonly recognised signature of tsunami, for example in western North America and Scotland (Dawson *et al.*, 1988; Atwater, 1987; Clague and Bobrowsky, 1994). However, unless these deposits are exposed in trenches or cored, they are difficult to find. The detection of boulders of tsunami origin within sand deposits is also a difficult task, because the boulders may make up less than 0.1% by volume.

Chaotic sediment mixtures or ‘dump’ deposits can also be problematic. Elsewhere, they can be formed by solifluction, ice push, human disturbance or slope wash. Only because these processes can be ruled out on a coast where there is no ice or ground freezing, and at sites without any evidence of human disturbance, can deposits be linked to a process such as catastrophic tsunami capable of transporting and depositing large volumes of sediment with minimal sorting in a very short period of time. Coarser ‘dump’ deposits, containing an added component of cobble and boulders, often are plastered against the sides or on the tops of headlands. It would be tempting to assign these deposits to storms but for three facts. First, storm waves tend to separate sand and boulder material. Storms comb sand from beaches and transport it into the nearshore zone in backwash and rips. Storm swash, however, moves cobbles and boulders landward and deposits them in storm berms (Bryant *et al.*, 1992). Secondly, while it may be possible for exceptional storms to toss sediment of varying sizes onto cliff tops more than 15 m above sea-level, these cliffs are usually exposed to the full brunt of storm waves. Tsunami 'dump' deposits can be found along the New South Wales coast on cliffs not only much higher above sea-level, 20–30 m, but also in sheltered positions. Finally, tsunami generated by submarine landslides have been shown to deposit mixed sand and boulder material to considerable elevations. For instance on the island of Lanai in Hawaii layers of mixed sand and boulder material have been deposited several hundred metres above sea-level (Moore and Moore, 1988).

More enigmatic are deposits on headlands containing mud, labelled 'smear' deposits, spread in a layer less than 30 cm thick over the steep sides and flatter tops of headlands, also to elevations 20–30 m above sea-level. These deposits can contain 5–20% sand, shell and gravel. Such deposits are not the product of in situ weathering because some contain quartz sand where the underlying bedrock is made up of volcanic sandstone or basalt which lacks this mineral. These 'smear' deposits form the traction carpet at the base of a sediment-rich flow overwashing headlands.

Perhaps the most dramatic deposits laid down by mega-tsunami are large boulders piled above the level of storm waves. These piles take many forms, but include boulders up to 106 m^3 in volume and weighing as much as 286 tonnes. These boulders are imbricated and stacked on top of each other in parallel lines at various locations along the east coast of Australia (Young *et al.*, 1996; Nott, 1997). At Jervis Bay, New South Wales, blocks weighing almost 100 tonnes have clearly been moved in suspension above the limits of storm waves to the tops of cliffs 33 m above present sea-level, on a coastline that has not had sea-level exceed present levels by more than 2 m over the past 7,000 years (Bryant *et al.*, 1997). These boulders are not orientated at right angles to the cliffline, but to the direction of tsunami wave approach to the coast. It is difficult to envisage how boulders randomly tossed onto cliffs by storm waves could form such features. Moreover, Nott (1997) calculated the hydrological forces required to move boulders of this size and showed that only tsunami overwash, not storm waves, had the necessary power required to transport such large blocks onto cliffs. We believe that these parallel, imbricated boulder piles are the unmistakable signature of tsunami overwash. Unfortunately this signature has not been reported outside Australia.

Except for carseland, which represents the planing or smoothing of raised estuarine surfaces by tsunami run-up, the depositional forms built by tsunami could be interpreted as swell or storm wave-built features. However their internal fabric and chronostratigraphy are different to that produced by storm waves. For example, ridges and mounds built above the high tide line at Bass Point contain a chaotic mixture of boulders, gravel, sand and shell (Bryant *et al.*, 1992). The steep sides of these landforms are presently being combed down by storm waves. Features with such a wide range of grain sizes bear no relationship to anything described in the sedimentological literature as being storm or swell wave-deposited. Their closest analogue is an ice-push ridge; however the New South Wales coast is unaffected by sea-ice. Similar features have been attributed to tsunami in Japan (Minoura and Nakaya, 1991). We believe that the mounds were deposited in vortices, by large tsunami overwash, in the lee of headlands.

Inconsistencies in chronology have been found at over 8 sites along the south-east coast (Bryant *et al*., 1996). One of the better examples occurs on a Holocene barrier at Bellambi, 60 km south of Sydney (Young *et al.*, 1995). What would appear to be a typical example of a barrier formed by the Holocene marine transgression within the last 6,000 years turns out to contain sand dated at +22,000 BP based on thermoluminescence (TL) dating. Pumice within the deposit dates at the same age. These old sands however overlie estuarine sediments radiocarbon dated at 6,560 BP (Beta 43951). The sands originated as wind-blown material, deposited on the shelf when sea-levels were lower during the Last Glacial. They have been recently swept from the shelf by tsunami and deposited at shore as a barrier feature without rezeroing of their TL clock.

Mega-tsunami can also be identified by its erosional signatures sculptured into bedrock at two scales (Young and Bryant, 1992; Bryant and Young, 1996; Bryant *et al.*, 1996). First are the large-scale features that dominate headlands. Under the effects of gravity, flow concentration or jetting, erosive channelisation can produce linear canyon features 2–7 m deep, and pool-and-cascade features incised into resistant bedrock on the lee side of steep headlands (Figure 3). Wave breaking may also leave a raised ramp or butte-like structure at the seaward edge of a headland, separated from the shoreline by an eroded depression. These features look like an inverted toothbrush. Large scale fluting of a headland can also occur, and on smaller rock promontories where the baseline for erosion terminates near mean sea-level, the resulting form looks like the inverted keel of a sailboat (Figure 4). Perhaps the most impressive feature are whirlpools formed in bedrock on the sides of headlands. These often contain a central plug of rock and show evidence of smaller vortices around their rim. The hydrodynamics producing such features are analogous to flow in tornadoes. Under extreme conditions, the complete coastal landscape can bear the imprint of catastrophic flow. Talus and jagged bedrock may be stripped from cliff faces, platforms planed smooth to heights of 20 m above sea-level, sloping bedrock ramps carved into the front of cliffs 30 m high, and whole headlands sculptured into a fluted or ‘drumlin’ shape (Bryant *et al.*, 1996). Such features appear to be beyond the capability of earthquake-induced tsunami. They require higher run-up velocities that can only be induced by the higher or longer waves generated by large submarine landslides or meteorite impacts in the ocean. Such events only appear in the geological record and are just now receiving wide attention. Similar forms have been observed in Scotland along the coast affected by the Storegga submarine slide over 7,000 years ago and in New Zealand. However these latter observations are yet to be published.

At the second scale are small features induced by cavitation or small vortices. These create bedrock sculpturing features analogous to those generated by high velocity flows associated with sub-glacial environments or mega-floods origin-

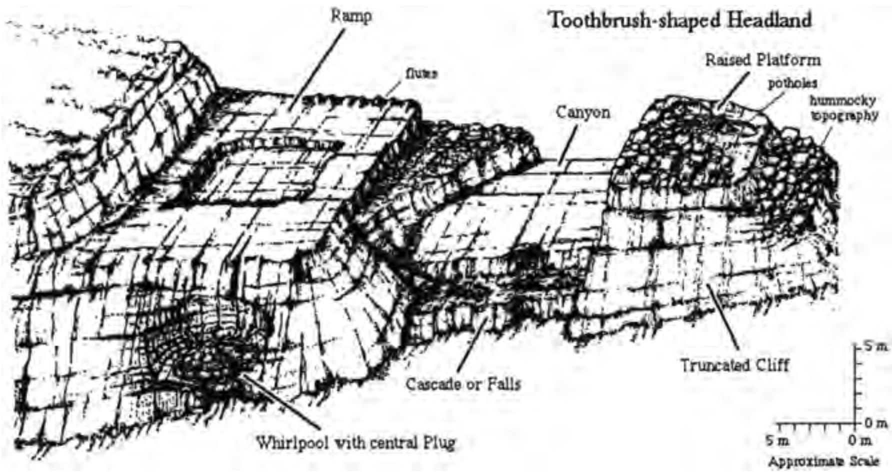

Figure 3. Schematic diagram of large-scale bedrock sculpturing with some smaller-scaled features superimposed. The headland represents those in the Wollongong area of New South Wales that have been swept repetitively by mega-tsunami from different directions.

Figure 4. Inverted keel-like forms at Cathedral Rocks 80 km south of Sydney. Flow came from the right over the top of a 30 m high headland. The stacks are either the plugs of bedrock left in the centre of vortices formed as the wave went up the cliffs, or remnants of promontories streamlined by the flow.

ating from glacial icesheets (Baker, 1981; Kor *et al.*, 1991). Glaciation has not been present at any of the sites shown in Figure 1 since the Permian. Nor can erosional features be attributed to the exhumation of this older glaciated landscape, because the forms occur on much younger bedrock. Such sculptured forms have been labelled ‘s-forms’ and include features such as muschelbrüche, sichelwannen,

Figure 5. Examples of some of the sculptured ‘s-forms’ produced by the tsunami event at Tura Point, South Coast of New South Wales. The flutes are situated on the north face of a 14 m high cliff facing the tsunami which came in from the northeast. Superimposed on the sides of the flutes are cavettos.

cavettos, and flutes (Figure 5). Those moulded by tsunami overwash are spatially organised across headlands or rock platforms (Bryant and Young, 1996).

3. Description of Sites around Australia

The geomorphic signatures of large tsunami have been compiled from numerous locations around Australia. Only four stretches of coast: southeastern New South Wales, Lord Howe Island, northeastern Queensland and northwestern West Australia, are described in detail here (Figure 1).

3.1. SOUTHEAST COAST OF NEW SOUTH WALES

The New South Wales coast evinces most of the signatures of tsunami summarised in Figure 2. To show the dominance of this process along the coast, the features found along one small stretch of coastline at Jervis Bay – an area which is representative of the range of physiographic environments such as dunes, coastal barriers, rocky cliffs and platforms found along the coast of southeastern Australia – will be summarised here (Bryant *et al.*, 1997). Jervis Bay is a 15 km long by 10 km wide bay located 100 km south of Sydney (Figure 1). The shape of the bay is structurally controlled by headlands that protrude 15 km seaward of the regional trend of the coastline. The adjacent continental shelf is restricted to a width of 10 km with

Figure 6. Boulders stacked against the cliff face on the south side of Gum Getters Inlet, Jervis Bay. The boulders reach to the top of the 25 m high cliff behind. Note person for scale.

steep inshore slopes that terminate at the shoreline in spectacular cliffs that rise up to 135 m above sea-level.

The most compelling evidence of tsunami impact is manifested in the various boulder deposits. The boulders, many of which exceed 2 m in intermediate diameter, are deposited in an imbricated fashion along clifftops, on deeply fluted rock platform surfaces, within the sheltered confines of the bay, and mixed within sandy deposits dumped on clifftops. In all cases, including within the bay, their imbrication implies a southeast source for the waves. All evidence suggests that the boulders were carried in suspension even to the tops of cliffs 30 m high. The most impressive evidence occurs near Gum Getters Inlet (Figure 6), where sandstone slabs up to 6–7 m in diameter have been rammed up to 25 m above sea-level into a small indent in the cliffs. The deposit is unusual in that the boulders rise to the top of the cliffs, ruling out cliff collapse, and lie in a small embayment protected from storm waves. The velocity necessary to transport this bouldery material is estimated to range from 7.8 to 10.3 m s^{-1} (Young *et al.*, 1996). At some locations along the coast, the piles of boulders show bedform characteristics either as evenly spaced ridges, or as foreset and topset ripple bedding.

Perhaps the more striking evidence of bedforms occurs in dunes at the top of 80 m high cliffs at Crocodile Head (Bryant *et al.*, 1997). These features are not aeolian dunes because they contain numerous pebbles and gravel. The sand hills extend over a distance of at least 1.5 km as a series of well-defined, undulatory-to-lingoidal giant asymmetric ripples, having a relief of 6.0–7.5 m and spaced 160 m apart. The dune field shows evidence of post-depositional reshaping by water draining off the features. The mega-ripples were produced by sediment-laden tsunami runup overwashing the cliffs. Hydraulic interpretations based upon large mega-ripples in tidal and fluvial environments indicate that the flow was 7.5–12.0 m deep. Maximum flow velocities ranged between 6.9–8.1 m s^{-1}, similar to those calculated for the transport of boulders in the region.

Undoubtedly the most impressive evidence of tsunami occurs at Steamers Beach on the southern headland of Jervis Bay (Bryant *et al.*, 1997). Here parabolic-shaped dunes consisting of sand mixed with cobbles, rise from the modern beach to a height of 30 m. A second deposit of sand and fine shell hash containing muddy lenses and quartz pebbles rises as a series of parabolic dunes to a height of 130 m behind the beach. The bottom section of the dunes shows cross-bedding with foreset beds present at the base and topset beds 40 m higher up. The sequence can be interpreted as climbing mega-ripples produced by tsunami run-up. We have labelled the overall features ‘chevron’ ridges. The 130 m run-up elevation is greater than the height of the divide along much of this peninsula, and a substantial amount of water must have washed into Jervis Bay. Interestingly, the orientation of boulders deposited within the bay project back to Steamers Beach.

The above descriptions form only a part of the evidence for tsunami in the Jervis Bay region. There is also substantial evidence of older sands washed onto barriers within the bay, and sea caves formed at heights above storm wave attack. The ubiquitous nature of these anomalous features in the Jervis Bay region, and for that manner along a substantial portion of the New South Wales coast, begs recognition and correct interpretation. Such forms cannot be explained by contemporary wave processes perceived as the major factor forming coastal landscapes.

3.2. LORD HOWE ISLAND

The anomalous features summarised above are widespread within the Australian coastal environment. Lord Howe Island provides evidence that tsunami did not originate locally along the South Coast of New South Wales, but were ubiquitous in the Tasman Sea. The island is the remnant of a Late Miocene shield volcano formed on the Lord Howe Rise between Australia and New Zealand (Woodroffe *et al.*, 1995). The island rises from depths of 1800 m to a platform at 20–60 m water depth. It is 11 km long, 2.8 km wide and covered on its northern half by Late Pleistocene calcarenites. The island is dominated by numerous sculptured bedrock features at varying scales and orientations – the latter without apparent structural control. Streamlined inverted keel-like features are prominent on the eastern side of the island indicating a tsunami wave approach from the Kermadec trench north of New Zealand. Perhaps the most unusual feature is a 150 m wide blade-like structure, Balls Pyramid, lying 23 km southeast of the main island, and rising in cliffs to a point 552 m above sea-level. The cliffs are devoid of talus and the feature has an aerodynamic shape aligned to other smaller, sculptured forms on the main island.

Figure 7. Blocks of calcarenite forming foreset beds on a 4 m high mega-ripple, 20 m above sea-level on the east side of Lord Howe Island. Trapped amongst the blocks are basalt gravels derived from sea cliffs 200 m away.

Depositional evidence for tsunami exists at several locations. Most notable is the occurrence of a series of three ridges having a maximum relief of 6 m, lying at the top of a terrace 20 m above sea-level on the eastern side of the island. The ridges consist of 1–2 m wide calcarenite blocks which have been deposited as foreset and topset beds (Figure 7). Interspersed amongst the calcarenite blocks are basaltic gravels which have come from the cliffs fronting the ridges. The amplitude, spacing and the internal fabric of the ridges indicates that they are mega-ripples, analogous to features described for Jervis Bay. Flow depth would have been in the range of 7.5–12.0 m with flow velocities near 8.0 m s^{-1}. At three locations, blocks of coral or shell have been transported beyond the limits of storm waves. One site at Searle Point on the eastern side of the island provides strong evidence that the material was deposited from tsunami overwash rather than tossed up by storm waves. Here the headland stands 6–8 m above sea-level and consists of calcarenite beds dipping towards the ocean. The beds have been differentially eroded into a saw-toothed surface with a relief of 1.0–1.5 m. This provides an impassable surface to storm run-up and bedload transport of sediment. Trapped in the depressions, across the complete surface, are fragile pieces of branching coral and oyster shells. Storm waves could not wash over the rough surface of this elevated headland and deposit fragile pieces of coral without breaking them. However tsunami would have no problem doing this. The coral and shells have been picked up in bulk, carried in suspension and have settled into the pockets without being fractured.

3.3. NORTHEAST QUEENSLAND

The presence of large boulders near the coast is not necessarily a unique signature for tsunami. However the height to which boulders can be found along the New South Wales coast and the fact that these boulders were found in imbricated piles, led Young *et al.* (1996) to conclude that tsunami was the most likely mechanism for their transportation and deposition. Boulder piles also exist inside the Great Barrier Reef between Cairns and Cooktown along the northern Queensland coast (Nott, 1997). At many locations boulders weighing over 100 tonnes can be found at elevations of 8–10 m above sea-level. One of the largest boulders found, at Cow Bay, has a volume of 106 m^3 and weighs 286 tonnes. At Oak Beach, boulders weighing up to 156 tonnes and measuring over 8 m in length can be found in imbricated piles. Tsunami would appear to be an unlikely mechanism for the transport of these boulders because the region is subject to intense tropical cyclones. Even if tsunami have occurred in this part of the Coral Sea, the mainland coast should have been protected by the Great Barrier Reef.

Evidence now suggests that tsunami have indeed reached the mainland coast with enough force, not only to transport boulders, but also to begin sculpturing bedrock. Nott (1997) showed that flow velocity is the critical variable determining whether or not a wave can transport boulders as bedload, and that boulder thickness is the crucial variable determining whether or not it can be moved. The theoretical velocities critical to boulder movement in water by wind-generated and tsunami waves are as follows:

$$\text{wind wave:} u = 0.5\sqrt{gh}, \tag{1}$$

$$\text{tsunami wave:} u = \sqrt{gh}, \tag{2}$$

where u is velocity, g is the gravitational constant and h is wave height. Velocities under a tsunami wave are double those for a wind wave as the wave approaches shore. On dry land this difference may double again. A wind wave 56 m in height would be needed to overturn the size of boulders typical of the Cairns coast. However a wind wave breaks in water depths 1.2 greater than its height. Even with reported surges in excess of 12 m, it is virtually impossible to find sufficient depth of water inside the Great Barrier Reef to permit a wind wave of this magnitude to reach shore without breaking. In contrast, a tsunami wave 3.5 m in height is required to move the same sized boulder. All of the boulders found along this coast can be transported by tsunami 1.4–11.2 m in height. The heaviest block can be moved by a tsunami wave 7.2 m high; however the same block would require a wind wave more than 110 m in height. The velocities produced by these tsunami waves range from 3.7–10.4 m s^{-1}, with a mean value of 5.8 m s^{-1}. The upper range of these values is well within the scope of those required to generate cavitation and bedrock sculpturing (Bryant *et al.*, 1996). Indeed many of the boulder piles are emplaced on undulatory, smooth surfaces. At Oak Beach the platform surface shows evidence of s-forms, while the northern headland has been dissected into a tooth-brush shape and is covered with sinuous grooves and cavitation drill holes.

The source of tsunami in the Cairns region must be from outside the Great Barrier Reef. It appears that palaeo-tsunami have penetrated the reef through openings such as Trinity Opening and Grafton Passage which are more than 10 km wide and between 60–70 m deep. The alignment of boulders north of Cairns points directly towards Trinity Opening. At other locations, where the alignment of boulders is more alongshore, it is possible that tsunami waves were trapped through diffraction and refraction by the reef, the mainland and major headlands jutting from the coast at Cape Tribulation and Cairns.

3.4. NORTHWEST WEST AUSTRALIA

If the geomorphic evidence for palaeo-tsunami defined along the east coast of Australia is correct, then some of these signatures should exist for known tsunami events that have impinged on the northwest coast of West Australia. This is indeed the case. Nott (1997) found that the June 1994 tsunami originating in Indonesia struck the mainland coast through gaps in the Ningaloo Reef, resulting in the deposition of marine fauna, sand and isolated coral boulders up to 2 m in width. Some of the largest boulders have been swept through gaps in the coastal dunes almost 1 km inland across a flat, elevated plain. No cyclone storm surge has occurred to account for this transport. These deposits can only be described as ephemeral 'dump' deposits according to the classification presented in Figure 2. None of the coral boulders are formed into piles or aligned to any degree with the direction of tsunami approach from Indonesia.

This contemporary evidence is dwarfed by the signature of older mega-tsunami along 1000 km of coastline between Cape Leveque and Northwest Cape. The magnitude of some of this evidence is the greatest yet found in Australia. At Cape Leveque, at least 4 waves from a palaeo-tsunami dumped gravelly sands mixed with shell in sheets and mounds along the coast. In some places headlands 60 m above sea-level were overridden. The sandstone platform in front of Cape Leveque was sculptured smoothly with the clear signature of large sicklewannen, fluting and transverse troughs. Repetitive waves oscillated large slabs of bedrock 1–2 m thick until they broke into blocks 4–5 m wide. These were then entrained by the flow and dumped alongshore into imbricated piles. A similar process is clearly present at Broome. The angle of approach of waves at both locations appears to have been slightly from the southwest, a direction not matching the modelled approach of tsunami from Indonesia. In the Great Sandy Desert, aeolian ridges originating from the interior of the continent were truncated more than 30 km from the coast, with the deposition of marine shell and lateritic clasts mixed with these aeolian sands to form large 'chevron'-shaped ridges. The distance that tsunami penetrated inland is more than three times further than documented for the South Coast of New South Wales. Seven hundred kilometres further south, at Exmouth on Northwest Cape, transverse dune ridges have been overridden from the east by large waves. Coral, shell and cobble have been mixed with aeolian sand and spread more than 2 km inland across the upper surface of at least seven dune ridges paralleling the coast.

By far the most dramatic evidence occurs at Point Sampson. Here waves have impinged upon the coast from 35° east of north. A hill more than 500 m inland and over 60 m high has been overwashed with the deposition of three layers of sand 30 m thick on its lee side. The sands contain boulder floaters, coral pieces and shell. In a valley leading back from the coast, large mega-ripples with a wavelength approaching 1000 m, and consisting of cross-bedded gravels, have been deposited up to 5 km inland. The gravels contain well rounded boulders over 1 m in diameter (Figure 8). Tsunami waves then overrode hills 60 m high, another 1 km inland, carving wind gaps 20 m deep through the ridges. Deposition of sand and gravel continued inland for at least another 2 km. Hills 15 m high, were sculptured into hull-shaped forms with evidence of plucking of bedrock along their flanks and crest. On the crest of one ridge, extreme plucking left a cockscomb-like protuberance above the overall smoothed hydrodynamic shape of the feature (Figure 9).

4. Chronology of Events around Australia

The chronology of tsunami events has been determined for the New South Wales coastline (Young *et al.*, 1997) and for northern Queensland (Nott, 1997). Here we update this chronology by including more dates from the New South Wales coast and reporting dates for Lord Howe Island and West Australia. The details of these latter dates will be presented elsewhere. Histograms of these dates are presented in Figure 10 for each region, and for Australia as a whole. Each of the ninety-two dates represents the conventional (uncalibrated) radiocarbon age of shell or coral from a deposit strongly linked to one of the depositional signatures summarised in Figure 2. A C^{13}/C^{12} correction has been applied to all dates; however a local reservoir correction has not been used. Because older material can be incorporated into a deposit, the ages may not represent the actual age of an event. In order to minimise this aspect, whole, unweathered, unchipped shell was dated wherever feasible. A substantial number of dates are younger than the 450 year reservoir correction usually applied to shell and coral from Australian waters. While contamination with post-1950 C^{14} cannot be ruled out, there is ample evidence to suggest that marine organisms close to the coast are absorbing radiocarbon in equilibrium with the atmosphere at the time of growth, rather than radiocarbon from older upwelled ocean water. Discussion of these aspects is beyond the scope of this paper.

Young *et al.* (1997) also supplemented the dating of tsunami events in New South Wales with thermoluminescence dates from marine sands swept onto the coast from the shelf. A more detailed description of TL and its relevance to tsunami can be found in their paper and in Bryant and Price (1997). TL dating also does not provide the exact time for a tsunami event because the TL clock is zeroed by

Figure 8. Chiselled boulders deposited in bedded gravels in a mega-ripple about 5 km inland of the coast at Point Sampson. The dip in bedding aligns with bedrock sculptured features in the area (Figure 9) and shows flow from the northeast, from the Indian Ocean.

exposure to sunlight. Sands have often been rapidly transported, without further bleaching, by these long waves from the shelf where they were last exposed to sunlight during the Last Glacial when sea-levels were up to 130 m lower than present. The chronology characterises three aspects of tsunami events in Australia: (1) tsunami events have occurred repetitively over time, (2) events have taken place as recently as those appearing in historical records elsewhere, and (3) some events may have occurred contemporaneously around Australia. The first aspect is substantiated by the chronology for the South Coast of New South Wales. Tsunami have occurred here at the following times: ∼6,500 BP, ∼2,900 BP, 1,500 BP, 900 BP and 220–250 BP. The biggest events in terms of size and extent occurred at ∼6,500 BP and 900 BP. Both events had a significant impact on coastal evolution along over 400 km of coast. Runup from the more recent event overran cliffs at least 16 m above sea-level as evidenced by shell deposited at this level (Beta 107032, 770ñ ± 0 BP). The event around 2,900 years ago appears only in the Batemans Bay region. A recent radiocarbon date from a layered, shelly sand deposit raised along the shoreline of the estuary confirms this age (Beta 107033, 2,810 ± 70 BP).

Figure 9. Inverted hull-shaped ridge with a keel- or cockscomb-like proturbance. Wave travelled left-to-right. Blocks of bedrock were plucked from the sides of the ridge by lift forces in the flow. Ridge is located at Point Sampson and is aligned 35° east of north. Person circled for scale.

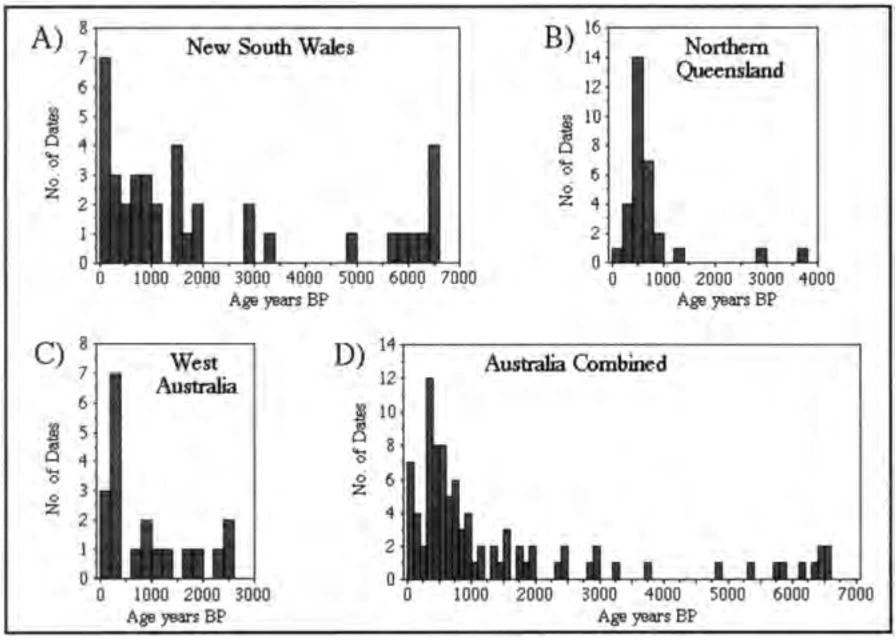

Figure 10. Histogram of dates of tsunami deposits: (a) New South Wales including Lord Howe Island, (b) northern Queensland (Nott, 1997), northwest West Australia, (d) combined results.

In recent years, events appear to be occurring every 600 years. Considerable effort has been made to determine the age of the youngest event. Many of the dates for this event show up as modern in Figure 10(a). These dates are contaminated; but, because large tsunami have not been noted since European settlement, the event must have occurred before 1788 AD. While the dates of events inside the barrier reef of northern Queensland appear to cluster around a single peak at 490 BP, Nott (1997) believed that there may have been more than one event. Reinterpretation of these data suggests that events occurred 400 and 550 years ago, with a third event around 700–900 BP. The data for West Australia presented in Figure 10(c) are preliminary; however there is strong evidence that two events have occurred around 350 and 900 years ago.

The fact that tsunami events may be contemporaneous around the Australian coast is based on the fact that similar ages appear in all three regions. The combined data indicate that a significant event occurred 350–400 years ago in each region. In Western Australia and northern Queensland this is the largest event. The event does not appear prominently in the list of tsunami along the South Coast of New South Wales; but this may be due to the scarcity of datable material. Only two dates in New South Wales coincide with this interval. While all other dates from New South Wales are associated with tsunami approaching from the southeast, both of these dates are from sites showing evidence for a large tsunami from the northeast. This may be the ‘Tura’ event that so dramatically sculptured bedrock along the coast, especially towards the south of the region. The first date of 390 $\pm$ 60 BP (Beta 93326) comes from whole shell (Cabestana spengleri) found in a craig-and-tail ‘dump’ deposit on the southwest side of Green Island, 200 km south of Sydney. A second age of 350 $\pm$ 60 BP (Beta 87100) comes from oyster shells collected from the highly irregular calcarenite surface of Searle Point, on Lord Howe Island. Because of the problem with radiocarbon dating raised above, the age of this prominent event cannot be expressed as a calendar year. However it probably occurred in the 18th century. If so, it could have been noticeable to Portuguese or Dutch explorers periodically travelling in the region, or to coastal Aborigines. Certainly modern Aborigines in all three regions can recount stories describing aspects of tsunami from their oral traditions.

The second event that may be common to all regions occurred 750–1050 years ago. This event appears as a broad peak in the age histograms. In New South Wales, dates can be linked to a large wave from the southeast that overrode a headland 20–25 m high at Atcheson Rock (Beta 78894, 770 $\pm$ 60 BP), and deposited boulders on a terrace 4 m above mean sea-level within the sheltered confines of Port Hacking, Sydney at Gogerlys Point (Beta 107034, 1020 $\pm$ 50 BP). Similar evidence for a large wave at this time has been obtained from coral wedged within imbricated boulders at Cape Tribulation in northern Queensland (for example Beta 93226, 940 $\pm$ 60 BP) and from oyster in a craig-and-tail ‘dump’ deposit in the lee of a 60 m high headland at Cape Leveque in West Australia (Beta 98473, 890 $\pm$ 60 BP). The corrected calendar age for this event centres on 1500 AD.

This synchroneity in dates, if correct, alludes to the source of these mega-tsunami. Only three mechanisms can generate waves big enough to create the features found around the Australian coastline. These are submarine landslides similar to those documented geologically for Hawaii (Moore and Moore, 1984; Moore *et al.*, 1994) and Scotland (Dawson *et al.*, 1988); meteorites crashing into, or exploding over, an ocean (Huggett, 1989); or large submarine volcanic eruptions. While all three factors are feasible in each locality, especially for the South Coast of New South Wales (Bryant *et al.*, 1996), the fragmentation of a large meteorite smashing into the oceans around Australia is the only mechanism that can explain the coincidence in dates. Huggett (1989) has calculated that an object as small as 0.2 km in diameter crashing into the ocean can produce tsunami with a run-up height of 10–100 m. Meteorites of this size have a theoretical recurrence interval for the Pacific Ocean of 24,000–43,000 years. Smaller objects are just as capable of generating tsunami, but with greater frequency. Aborigines also have stories describing the impact of meteorites. From the point of view of risk, the occurrence of cosmogenic mega-tsunami is ambiguous; however without such a mechanism, one is left with the conclusion that mega-tsunami may be a natural and regular geologically induced feature of the Australian coastline. Whether or not this conclusion applies to coastlines elsewhere-ones also lacking historic records-remains to be investigated.

5. Conclusions

Palaeo-tsunami events in Australia have been truly catastrophic. Cliff tops 80 m above sea-level were overtopped along the New South Wales coast, boulders more than 6 m in diameter and weighing 286 tonnes were tossed alongshore above cyclone storm wave limits inside the Great Barrier Reef of northern Queensland, and marine shell and lateritic cobbles were transported and deposited in ‘dunes’ 30 km inland in the Great Sandy Desert of northwestern West Australia. This field evidence for mega-tsunami can be grouped into thirteen sets of geomorphic signatures that uniquely or in combination allude to the hydrodynamics of unidirectional flow produced by these waves. Radiocarbon dating of shell material contained within the deposits indicates that not only have events occurred repetitively, but also that some of these events have occurred contemporaneously in disparate regions. The latter aspect is suggestive of a cosmogenic origin for these tsunamigenic events. Indeed, many of these palaeo-tsunami, had they affected a country such as Japan, would be considered to be recent, having occurred within the last 1000 years and as recently as 250–400 years ago. If mega-tsunami have a more localised cause, such as submarine landslides, then their frequency of occurrence certainly poses problems in risk assessment for these sections of the Australian coast.

Acknowledgements

This research was supported by the University of Wollongong through the Quaternary Research Programme and by James Cook University of Northern Queensland through its special and small Australian Research Council grants schemes. Figure 3 is taken from a drawing by Susan Fyfe of the School of Geosciences, Wollongong University.

References

Atwater, B. F.: 1987, Evidence for great earthquakes along the outer coast of Washington state, *Science* **236**, 942–944.

Baker, V. R. (ed.): 1981, *Catastrophic Flooding: The Origin of the Channelled Scabland*, Dowden, Hutchinson and Ross, Stroudsburg.

Bryant, E. A.: 1991, *Natural Hazards*, Cambridge University Press, Melbourne.

Bryant, E. A. and Price, D. M.: 1997, Late Pleistocene marine chronology of the Gippsland Lakes region, Victoria, *Physical Geography* **18**, 318–334.

Bryant, E. A. and Young, R. W.: 1996, Bedrock-sculpturing by tsunami, South Coast New South Wales, Australia, *Journal Geology* **104**, 565–582.

Bryant, E. A., Young, R. W., and Price, D. M.: 1992, Evidence of tsunami sedimentation on the southeastern coast of Australia, *Journal Geology* **100**, 753–765.

Bryant, E. A., Young, R. W., and Price, D. M.: 1996, Tsunami as a major control on coastal evolution, Southeastern Australia, *Journal of Coastal Research* **12**, 831–840.

Bryant, E. A., Young, R. W., Price, D. M., Pease, M. I., and Wheeler, D. J.: 1997, The impact of tsunami on the coastline of Jervis Bay, southeastern Australia, *Physical Geography* **18**, 441–460.

Clague, J. J. and Bobrowsky, P. T.: 1994, Evidence for a large earthquake and tsunami 100–400 years ago on western Vancouver Island, British Columbia, *Quaternary Research* **41**, 176–184.

Dawson, A. G., Long, D., and Smith, D. E.: 1988, The Storegga slides: Evidence from Eastern Scotland for a possible tsunami, *Marine Geology* **82**, 271–276.

Huggett, R.: 1989, *Cataclysms and Earth History*, Clarendon, Oxford.

Kor, P. S. G., Shaw, J., and Sharpe, D. R.: 1991, Erosion of bedrock by subglacial meltwater, Georgian Bay, Ontario: a regional view, *Canadian Journal of Earth Science* **28**, 623–642.

Minoura, K. and Nakaya, S.: 1991, Traces of tsunami preserved in inter-tidal lacustrine and marsh deposits: some examples from northeast Japan, *Journal of Geology* **99**, 265–287.

Moore, G. W. and Moore, J. G.: 1988, Large-scale bedforms in boulder gravel produced by giant waves in Hawaii, *Geological Society of America Special Paper* **229**, 101–110.

Moore, J. G. and Moore, G. W.: 1984, Deposit from a giant wave on the island of Lanai, Hawaii, *Science* **226**, 1312–1315.

Moore, J. G., Bryan, W. B., and Ludwig, K. R.: 1994, Chaotic deposition by a giant wave, Molokai, Hawaii, *Geological Society of America Bulletin* **106**, 962–967.

Nott, J.: 1997, Extremely high-energy wave deposits inside the Great Barrier Reef, Australia: Determining the cause-tsunami or tropical cyclone, *Marine Geology* **141**, 193–207.

Woodroffe, C. D., Murray-Wallace, C. V., Bryant, E. A., Brooke, B., Heijnis, H., and Price, D. M.: 1995, Late Quaternary sea-level highstands in the Tasman Sea: Evidence from Lord Howe Island, *Marine Geology* **125**, 61–72.

Young, R. and Bryant, E.: 1992, Catastrophic wave erosion on the southeastern coast of Australia: Impact of the Lanai tsunami ca. 105 ka? *Geology* **20**, 199–202.

Young, R. W., Bryant, E. A., and Price, D. M.: 1996, Catastrophic wave (tsunami?) transport of boulders in southern New South Wales, Australia, *Zeitschrift für Geomorphologie N.F.* **40**, 191–207.

Young, R. W., Bryant, E. A., Price, D. M., Dilek, S.Y., and Wheeler, D. J.: 1997, Chronology of Holocene tsunamis on the southeastern coast of Australia, *Transactions Japanese Geomorphological Union* **18**, 1–19.

Young, R. W., Bryant, E. A., Price, D. M., and Spassov, E.: 1995, The imprint of tsunami in Quaternary coastal sediments of southeastern Australia, *Bulgarian Geophysical Journal* **21**, 24–32.