THE IMPACT OF TSUNAMI ON THE COASTLINE OF JERVIS BAY, SOUTHEASTERN AUSTRALIA

Edward A. Bryant
School of Geosciences
University of Wollongong
Northfields Avenue
Wollongong, New South Wales, 2522
Australia

Robert W. Young
4 Roxborough Avenue
Thirroul, New South Wales, 2515
Australia

David M. Price and *David J. Wheeler*
School of Geosciences
University of Wollongong
Northfields Avenue
Wollongong, New South Wales, 2522
Australia

Mark I. Pease
Queensland Department of Environment
Brisbane, Queensland, 4000
Australia

Abstract: The Jervis Bay area offers a diversity of landforms that do not fit within contemporary views of coastal evolution. Field evidence indicates that catastrophic tsunami have had a significant impact on the coast and its hinterland both within and outside the embayment. Runup has overtopped cliffs 80 m above sea level and deposited chevron-shaped ridges to elevations of 130 m on the southern headland. Boulders, up to 6 m in diameter, have been deposited in an imbricated fashion against cliffs, on clifftops, and along shoreline ramps. Bed-form features and the size of transported material indicate flow depths up to 10 m and velocities around 8 m s^{-1}. While significant Pleistocene material has been swept onto the coastline, mainly in the form of barriers, radiocarbon dating indicates that tsunami have occurred repetitively throughout the Holocene. The most recent event occurred just before European settlement over 200 years ago. [Key words: barrier beaches, coastal geomorphology, tsunami, Jervis Bay, Australia.]

INTRODUCTION

Although 30 years have passed since Coleman (1968) pleaded for the consideration of tsunami in the study of coastal evolution, only in the last decade or so has much attention been given to their effects. There is detailed evidence now for major impacts on many coasts, including those of Hawaii (e.g., Moore and Moore, 1984, 1988), North America (e.g., Clague and Bobrowsky, 1994), and southeastern Australia (Young and Bryant, 1992; Bryant, Young, and Price, 1992; Bryant et al., 1996). Nevertheless, the impact of tsunami is still widely regarded as being limited to tectonically active coasts, and of no great significance to coastal studies in general. Indeed, several major coastal textbooks do not even mention tsunami. Coastal studies are still dominated by gradualism, and have as yet no counterpart to the catastrophic events identified in fluvial studies following Baker's vindication of Bretz's pioneering work on the Lake Missoula superfloods (Baker, 1973, 1981).

In recent publications, we have presented evidence showing that the east coast of Australia, south of Sydney, has been repeatedly affected by catastrophic tsunami throughout the late Holocene. We use the term tsunami in the broadest sense to refer to any repetitive and suddenly generated wave having a period greater than 60 s and a height at shore in excess of 2 m. Extensive thermoluminescence (TL) and radiocarbon dating of tsunami deposits have shown that there have been at least five, and probably six, tsunami-related catastrophic events along this coastline in the late Holocene (Young et al., 1997). The most recent large event occurred about 800 radiocarbon years BP and was followed by a smaller event just before European settlement more than 200 years ago.

A suite of depositional and erosional geomorphic signatures generated by tsunami has been identified along this coastline (Bryant et al., 1996). Depositional evidence consists of boulder masses either chaotically tossed onto the back of rock platforms, or imbricated and aligned in the direction of tsunami flow (Bryant, Young, and Price, 1992; Young, Bryant, and Price, 1996). Tsunami can also lay down highly bimodal mixtures of sand and boulders, or "dump" deposits of well-sorted coarse debris. In unusual cases, chenier ridges consisting of marine sand and shell have been emplaced in estuaries beyond the reach of contemporary storm waves, under either present or higher sea levels. Many of the smaller Holocene barriers that make up the coast south of Sydney also consist of a significant component of Pleistocene sand transported from the inner shelf by tsunami and deposited over Holocene estuarine deposits (Young et al., 1995; Bryant et al., 1996).

Erosional evidence is more dominant. Last Interglacial barriers have been eroded so that only scattered remnants are preserved in sheltered locations along the coast (Young, Bryant, and Price, 1993; Bryant et al., 1997). Tsunami have had a major impact on the 70% of this coast that is made up cliffs and rocky headlands. They have planed the faces off cliffs, removed talus debris from raised platforms, eroded ramps that rise to elevations of 16 to 34 m above sea level, and in many cases are responsible for successive tiers of planed surfaces rising more than 20 m above sea level (Young and Bryant, 1993). Most dramatic has been the ability of tsunami to sculpture bedrock terrain at two scales (Bryant and Young, 1996). At the smaller scale, *s-forms* analogous to features carved by fast-flowing water in subglacial environments (Kor et al., 1991) have been eroded in a spatially well organized fashion on many headlands of varying lithology. At the larger scale, potholes up to 10 m deep and containing a central bedrock plug have been bored into the sides of resistant headlands by flow akin to that generated within tornadoes. These erosional signatures are so widespread that tsunami must be considered a major process in the evolution of this coast (Bryant et al., 1996).

To demonstrate just how important tsunami can be in shaping a coastline, we now describe a wide array of features formed by them near Jervis Bay, an area that is representative of the range of physiographic environments—such as coastal barriers, rocky cliffs and platforms, and dunes—found along the coast of southeastern Australia.

JERVIS BAY ENVIRONMENT

Jervis Bay is a 15 km long by 10 km wide bay located 100 km south of Sydney (Fig. 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 steep inshore slopes that terminate at the shoreline in spectacular cliffs that rise up to 135 m above sea level. Bedrock consists mainly of the Snapper Point Formation sandstones and conglomerates overlain by Wandrawandian siltstones deposited during the early Permian (Abell, 1995; Taylor et al., 1995). During the late Permian and early Triassic, these were subsequently folded with minor faulting into a series of north-trending anticlines and synclines that control the shape of the bay and the form of the coastline. High cliffs occur near the crests of the anticlines, whereas dip-controlled bedrock ramps occur along the arms of the anticlines. The occurrence of Oligocene basalt, within 90 m of present sea level, and of late Cretaceous–early Tertiary weathering profiles (Young, Cope, et al., 1996) in the vicinity of Jervis Bay demonstrate that the last significant uplift of this region took place no later than the early Cenozoic.

Large bodies of sand, interpreted as transgressive dunes (Taylor et al., 1995), onlap the southern shoreline. Where the cliffs diminish in height southward, a large transgressive sand barrier, Bherwerre Beach, encloses an extensive coastal lagoon, St. George's Basin. On the northern side of the bay, the headlands have been blanketed with "cliff-top" dunes whose origin is problematic. Otherwise, the ocean shoreline for the most part is dominated by cliffs, raised platforms, and boulder deposits. The cliffs are remarkable for the absence of talus, and it would be easy to infer that active coastal erosion has removed such debris. However, closer examination reveals that remnant pockets of talus are in fact preserved along cliff faces above a platform surface that lies 7 to 8 m above sea level. Not only does this surface lie beyond the reach of most storm waves, but it also lies at a regional level that has been identified as late Pleistocene in age (Young and Bryant, 1993). Inside the bay, extensive barriers of clean white sand have formed. These sands originate from the leached A2 horizon of podsolized dunes, formed at lower sea levels on the floor of the bay during the Last Glacial. With the Holocene marine transgression, this sand presumably was swept by swell waves shoreward, forming 1 to 2 km wide barriers and barrier plains. The evolution of this coastline has been explained in terms of high frequency–low magnitude marine and eolian processes superimposed on the effects of changing sea level during the late Quaternary (Thom, 1983; Taylor et

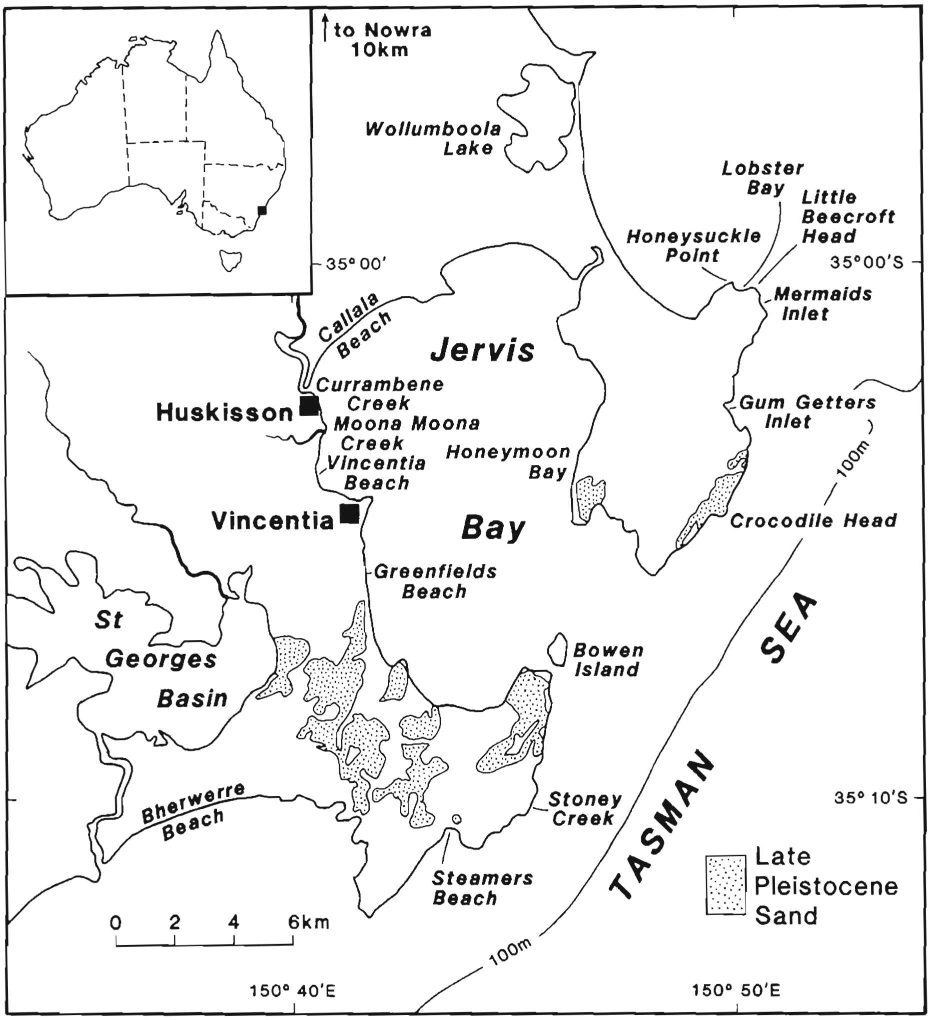

Fig. 1. Location of Jervis Bay, southeastern Australia. Late Pleistocene sand deposits are modified from Abell (1995) and Taylor et al. (1995).

al.,1995). But there is much evidence that points to the repeated catastrophic impact of tsunami.

TSUNAMI IMPACT

Boulder Fabric

The most compelling evidence of tsunami impact is manifested in the various boulder deposits along the foreshores of the open coastline and within the bay. General characteristics of these deposits are indicative of high flow velocities and runups, which are beyond the capability of storm waves along this coast. We

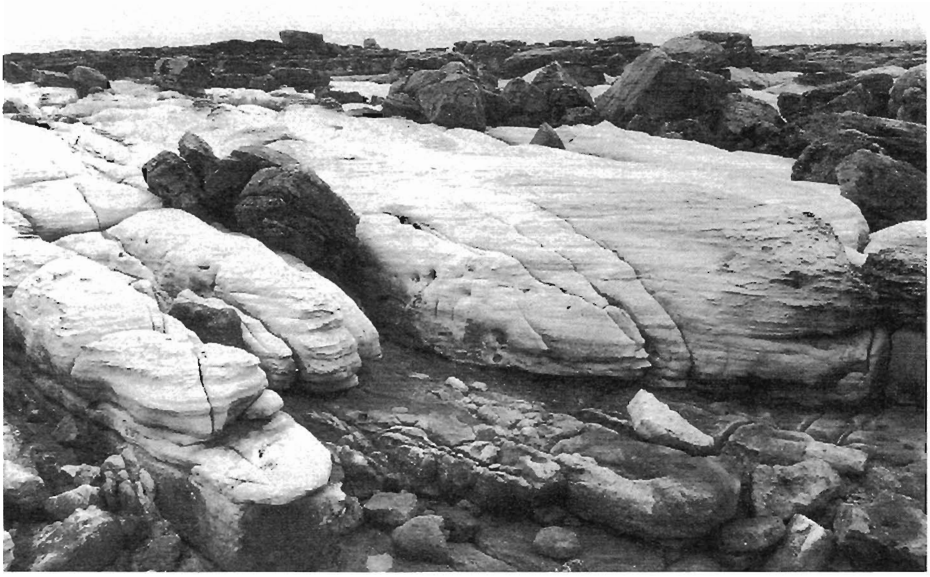

Fig. 2. Tsunami boulder train on a stripped and fluted shore platform near the mouth of Stoney Creek; the largest boulders are >2 m in diameter. Flow was from right to left.

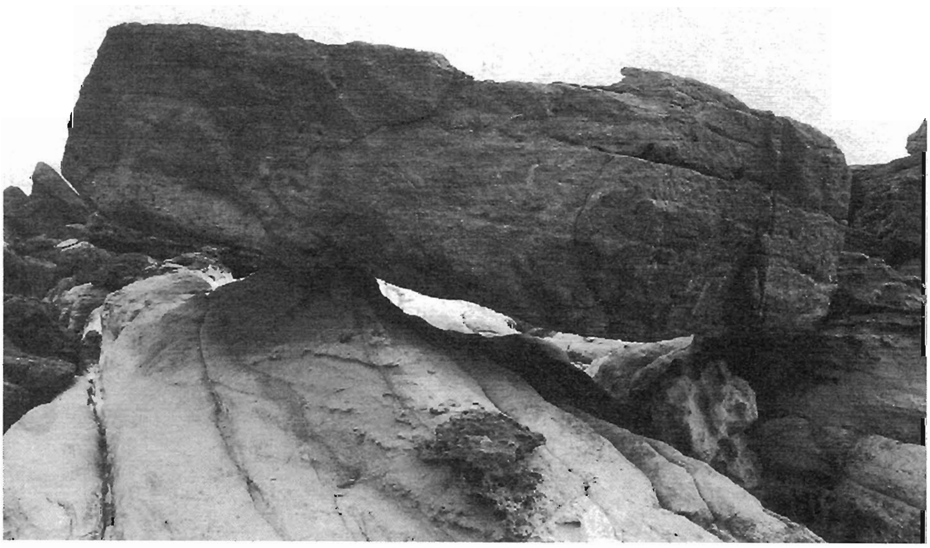

Fig. 3. A boulder ~4 m long resting on fluted sandstones near Stoney Creek. As the fragile pinnacle shows no sign of damage, the boulder apparently was dropped from suspended flow. Depth of flow was ~8 m.

believe that these can only be generated by tsunami. The evidence includes the size of boulders, the elevation above sea level to which they have been transported, and their degree of imbrication. In addition, their consistent alignment to the south, especially within the bay, agrees with the direction of tsunami approach in the region determined from a variety of other geomorphic signatures (Bryant and Young, 1996).

The distribution and heights of the bouldery deposits vary markedly with the structurally controlled changes in cliff and ramp morphology. A particularly impressive array of large boulders, which have been swept onshore from a southerly direction, lies on the stripped surface of the shore platform, standing at an elevation of about 5 m immediately south of Stoney Creek (Fig. 2). The boulders, which extend to sea level, appear to be eroded from joint-controlled sandstone bedrock, but their origin is problematic. The orientation of the flutes and the imbrication of some boulders points to a southerly wave approach; however, there is no other exposure of bedrock this far seaward of the coastline. We can only conclude that tsunami erosion of the bedrock coast occurred at some depth seaward of the headland. The boulders, many of which exceed 2 m in intermediate diameter, were deposited without abrading the deeply fluted surface of the platform (Fig. 3). They must have been carried in suspension, rather than as a tractive bedload. Sand mounds containing rounded cobbles, on top of the adjacent cliffs, indicate runup heights of 25 to 30 m elevation. Northwards, boulder deposits terminate where the ramps and benches again give way to high cliffs, although boulders 6 to 7 m in diameter have been transported and imbricated on a low platform at the foot of the cliffs. The occurrence of ramps on the southern side of the entrance to Jervis Bay, and on the adjacent Bowen Island, is again matched by extensive and elevated boulder deposits. Boulder deposition indicates that tsunami here surged at least 32 m above present sea level (Young and Bryant, 1993).

On the northern headland, an impressive array of boulders occurs near Gum Getters Inlet (Fig. 1), where sandstone slabs up to 6 to 7 m in diameter have been rammed up to 25 m above sea level into a small indent in the cliffs (Fig. 4). The blocks are crudely imbricated and aligned to the east. It would be tempting to attribute the debris to cliff collapse but for the fact that the imbricated blocks rise to the top of the cliffs. The deposit is all the more unusual in that the indent is virtually protected from the dominant southeast storm swell. Imbricated blocks of similar size choke the entrances of two narrow and deep gulches at Mermaids Inlet (Fig. 5). Some of the largest blocks, which are over 5 m in length, have not simply dropped from the cliff faces, but rotated 180° and shifted laterally as they settled from suspension flow. On the cliff tops north of Mermaids Inlet, well-imbricated slabs of sandstone have been deposited at an elevation of 32 m (Young, Bryant, and Price, 1996). Even at Honeysuckle Point (Fig. 1), where only the refracted component of a tsunami surged along ramps dipping to the northeast and northwest, tractive forces were sufficient to detach, lift, and transport sandstone slabs measuring 7.5 to 9.8 m on the a-axis and 2.2 to 2.9 m on the b-axis. Upper limits of boulder deposition decrease westward from 13 m above mean sea level at Little Beecroft Head to 8 m at Honeysuckle Point.

Fig. 4. Boulders stacked against the cliff face on the south side of Gum Getters Inlet. Note person for scale.

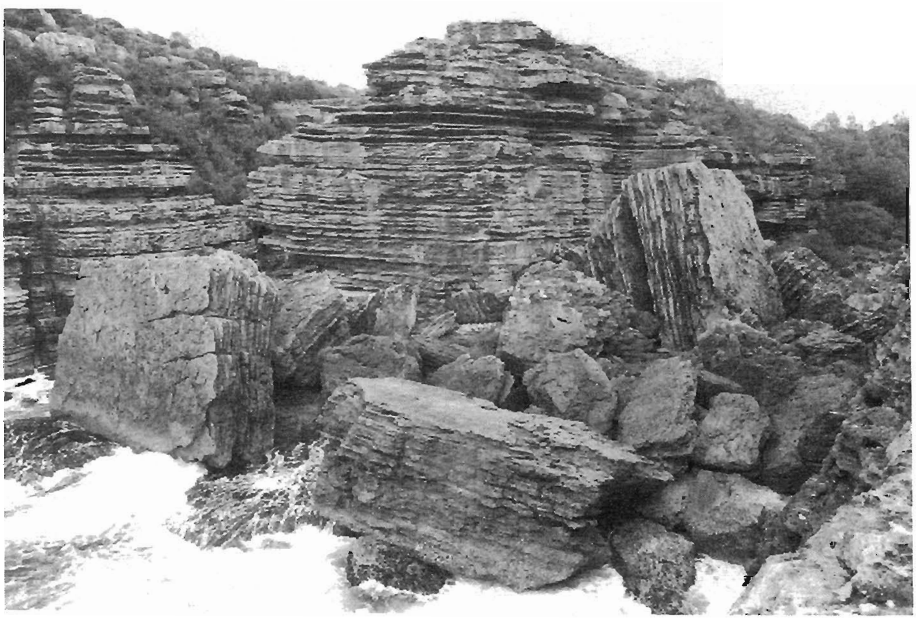

Fig. 5. Boulder pile blocking the mouth of gulches at Mermaids Inlet. The largest blocks are >5 m in length. The gulch on the right contains a postulated "interglacial" beach that gives a TL determination of only 18.8 ± 1.7 ka, and a stranded "recent" beach giving an age of 23.1 ± 3.3 ka. The slackwater deposit in Figure 11 is located 50 m up the gulch to the left.

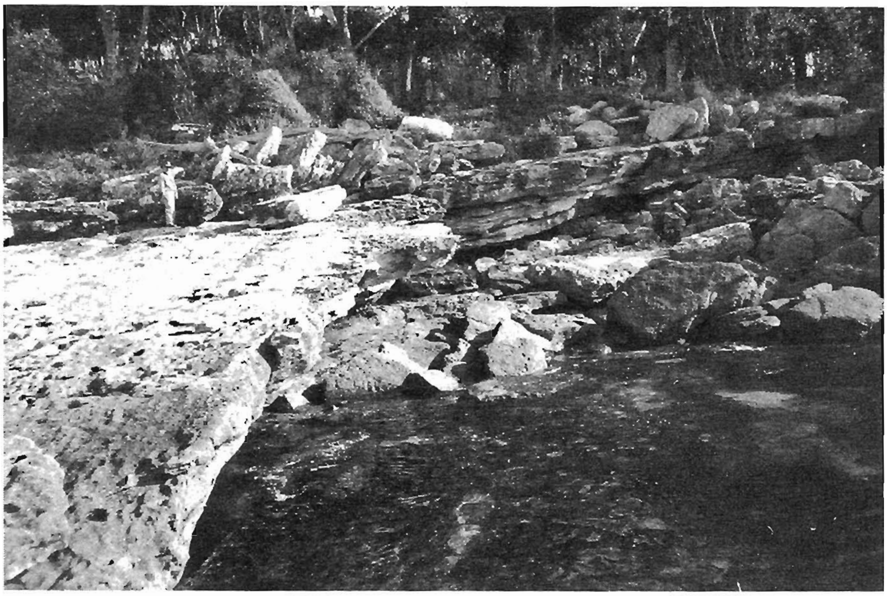

Fig. 6. An imbricated boulder pile deposited at Greenfields Beach inside Jervis Bay. Flow moved along the ramped bedrock surface from left to right .

Boulder deposits that rise well above the limits of storm waves also occur inside Jervis Bay. The most impressive of these is located at Greenfields Beach, where large imbricated slabs of sandstone rise from the shoreline to heights of 8 m (Fig. 6). Virtually continuous deposits of boulders, at elevations of 5 m above sea level, also occur along the west-facing shore of the northern headland, south of Honeymoon Bay. These deposits are now well vegetated and lie above the limits of storm waves. Furthermore, the angular and unweathered nature of the boulders indicates that they are not remnants of interglacial high sea levels, but the result of recent catastrophic processes.

The velocity of the flows necessary to transport bouldery material in tsunami runup can be estimated using Costa's equation $v = 0.18\ d_l^{0.487}$, where d_l is the average b-axis of the five largest boulders in a deposit (Costa, 1983). Tsunami flow velocities range from 10.3 m s^{-1} at Little Beecroft Head and 8.6 m s^{-1} at Honeysuckle Point to 7.8 m s^{-1} at Mermaids Inlet (Young et al., 1996). At Greenfields Beach, where boulders were carried northward alongshore over the edge of a ramp (Fig. 6), the estimated flow velocity is 7.9 m s^{-1}, remarkably similar to those listed above. However, as boulders >2 m in diameter were carried as suspended load, localized velocities may have been considerably greater.

At some locations, the piles of boulders assume certain bed-form characteristics. At Honeysuckle Point, four defined ridges of boulders, spaced less than 60 m apart, are aligned normal to shore and separated by large areas of bare rock. A similar spatial arrangement in boulders exists at Stoney Creek. At both locations the landward limit of boulders terminates abruptly in a 3 to 4 m wide, 1.5 m high continuous ridge of boulders that resembles a low swash line. At Little Beecroft Head, imbrication of individual boulders lying in a 4 to 5 m high, asymmetric pile of boulders, at an elevation of 16 m above sea level, is similar to foreset and topset bedding in a ripple. Comparison of the dimensions of these features with data for megaripples formed by catastrophic floods (Baker, 1973) suggests flow depths of 15 to 20 m and velocities up to 10 m s^{-1}.

Erosional Bedrock Sculpturing

On the small scale, tsunami jetting and overwashing of bedrock surfaces can generate vortices that sculpture bedrock, producing a suite of s-forms including muschelbrüche, sichelwannen, cavettos, flutes, and cavitation marks (Bryant et al., 1996). These features are spatially organized (Fig. 7) and are often orientated in the same direction as associated tsunamigenic boulder deposits along the adjacent coastline. At the larger scale, extreme velocities can be generated as runup flows over cliffed headlands. Tornadic flow can erode potholes 10 m deep into bedrock along cliffs (Bryant and Young, 1996). This process may be restricted to headlands less than 20 m high. In the Jervis Bay region, many of the cliffs rise to elevations of 30 m or more. Deposits of mixed sand, gravel, and shell indicate that tsunami overrode these cliffs, but potholes are missing. Instead, high-velocity vortices appear to have bored large broad caves into the base of massive sandstone cliff faces, like those south of Stoney Creek (Fig. 8). This process appears similar to the undercutting of entablature rims of basalt by kolks generated in the Lake Missoula floods (Baker, 1981).

The coast near Stoney Creek also displays the best coherent imprint of bedrock erosion by tsunami. Here, at least one tsunami event and probably more have swept over a headland rising 7 to 8 above mean sea level. Flow has carved an impressive set of flutes with a relief exceeding 2 to 3 m (Fig. 2). Profuse faceting caused by hydraulic hammering is imprinted on the flanks of these flutes. The impact of tsunami is made more dramatic by the deposition of boulder blocks across the fluted terrain. The contrast in erosion and deposition indicates the occurrence of at least two tsunami waves in a single wave train, if not two separate events.

Sand Deposits

The extensive sand deposits around Jervis Bay have been attributed to normal beach and eolian processes (Taylor et al., 1995). However, recognition that tsunami may have transported large boulders to heights greater than 30 m above sea level prompts a careful reassessment of the origin of sand and other fine-grained sediments.

Although sandy marine barrier deposits dating from the Last Interglacial are well preserved on the coast of northern New South Wales, they are, paradoxically, extremely rare along the coast south of Sydney (Young, Bryant, and Price, 1993). We have identified only one remnant of a Last Interglacial barrier along 75 km of coastline in the vicinity of Jervis Bay. This deposit, which is situated in a highly sheltered position at the back of Lobster Bay on Little Beecroft Head, consists of boul-

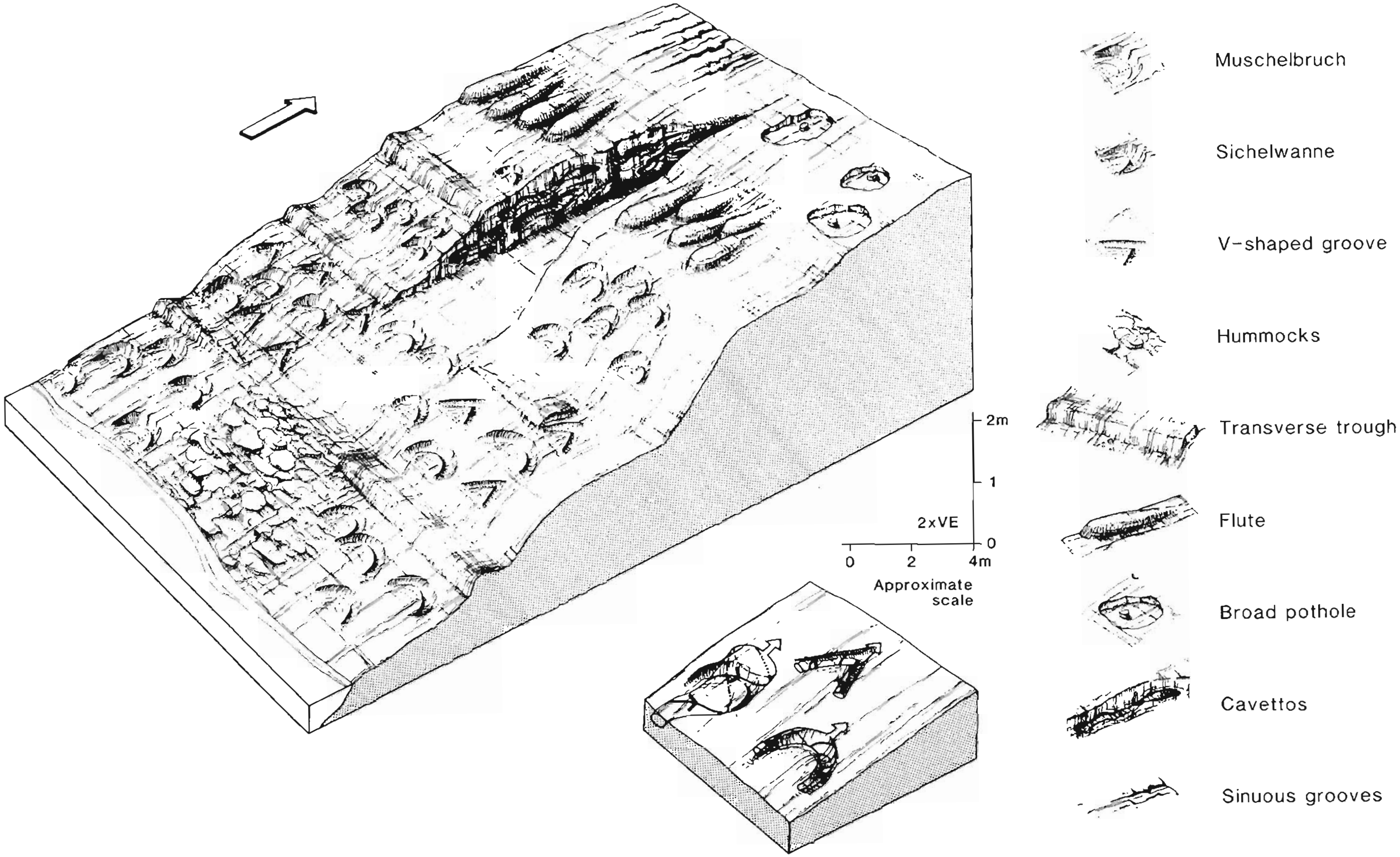

Fig. 7. Model for smooth, small-scale, bedrock sculptured terrain created by tsunami (Bryant and Young, 1996).

Fig. 8. Cave bored into the base of the cliffs south of Stoney Creek on the outer cliffs of Jervis Bay. Note that the cave lies above the limit of significant, modern storm wave attack and is mostly free of debris. Deposits above the cliffs indicate that runup exceeded 25 m elevation.

ders and cobbles that grade upward into gravels and coarse sands. The entire deposit, which rises from about 2 m to 6.5 m above present high tide, is well indurated by humate. Sand near the top of the deposit yielded a TL age of 115 ± 22 ka (W1572, Table 1), which overlaps with the Last Interglacial age of sand complexes determined from 16 locations elsewhere along the New South Wales coast (Bryant et al., 1997). Fragments of alluvial deposits, which yielded Interglacial TL ages ranging in age from 162 ± 27 ka (W1724) to 118 ± 17 ka (W1721), occur along the shore south of Vincentia inside the bay, where their cliffed seaward margin is bounded by boulders extending northwards from the tsunami deposit at Greenfields Beach (Young, Cope, et al., 1996). Erosion of older materials is also evident at Steamers Beach, where Holocene tsunamigenic material overlies truncated humate-rich sands that yielded a TL age of 55.9 ± 14.7 (W1884). We have previously attributed the scarcity of Pleistocene sediment, and especially of interglacial marine barriers, to the destructive impact of tsunami elsewhere along the coast (Young and Bryant, 1992; Young, Bryant, and Price, 1993). This conjecture is confirmed both by the evidence of tsunami impact preserved by the elevated trains of boulders and by the sedimentary and morphological characteristics of some key sandy deposits in the vicinity of Jervis Bay.

The fact that materials of all sizes were moved by tsunami along this coast is demonstrated beyond doubt at Steamers Beach, on the southern headland of Jervis Bay (Fig. 1). At this site, a sedimentary mass that was previously mapped as an eolian dune (Abell, 1995; Taylor et al., 1995) consists of sand interbedded with

Table 1. Thermoluminescence Dates Used in Determining the Age of Coastal Deposits in the Jervis Region[a]

Sample no.	Location	Type of deposit	Palaeodose (grays)	K (%)	Th and U chains specific activity (Bq/kg)	Annual dose (μgrays)	TL age × ka
W1367	Currumbene Cr.	"Inner" beach ridge	8.0 ± 1.0	0.22	4.60 ± 0.22	478 ± 49	16.7 ± 3.1
W1368	Currumbene Cr.	"Inner" beach ridge	9.8 ± 1.0	0.51	7.72 ± 0.34	799 ± 47	12.3 ± 1.4
W1369	Moona Moona	"Holocene" lagoon	47.9 ± 4.4	0.54	48.2 ± 1.4	1464 ± 46	32.7 ± 3.2
W1370	Vincentia	"Holocene" barrier	11.4 ± 0.8	0.26	5.2 ± 0.2	519 ± 49	21.9 ± 2.6
W1394	Callala	"Holocene" beach ridge	8.5 ± 0.8	0.36	7.84 ± 0.28	677 ± 49	12.6 ± 1.4
W1572	Little Beecroft	Raised barrier	130 ± 24	0.02	48.6 ± 4.0	1132 ± 74	115 ± 22
W1721	Nelsons Beach	Alluvium	134 ± 19	0.12	45.7 ± 1.3	1136 ± 50	118 ± 17
W1724	Nelsons Beach	Alluvium	175 ± 28	0.12	45.6 ± 1.4	1075 ± 48	162 ± 27
W1882	Steamers Beach	"Chevron" ridge	8.7 ± 0.8	0.55	11.2 ± 0.4	952 ± 49	9.2 ± 0.9
W1883	Steamers Beach	"Chevron" ridge	10.9 ± 1.3	0.41	13.2 ± 0.4	829 ± 49	13.2 ± 1.7
W1884	Steamers Beach	Basal humate	65.8 ± 17.1	0.65	20.2 ± 0.5	1176 ± 47	55.9 ± 14.7
W1885	Steamers Beach	Tsunami deposit	24.3 ± 2.4	0.50	12.3 ± 0.4	898 ± 48	27.1 ± 3.0
W1934	Little Mermaid Inlet	Slackwater deposit	38.2 ± 4.2	2.70	67.6 ± 2.1	3989 ± 53	9.6 ± 1.1
W1935	Little Mermaid Inlet	Raised talus matrix	34.6 ± 3.2	0.29	40.4 ± 1.3	1142 ± 47	30.3 ± 3.1
W1936	Mermaid Inlet	Stranded beach	17.3 ± 2.2	0.28	15.4 ± 0.5	747 ± 49	23.1 ± 3.3
W1937	Mermaid Inlet	Raised humate	26.2 ± 2.2	0.25	56.0 ± 1.5	1394 ± 48	18.8 ± 1.7

[a]Cosmic contribution to annual radiation dose assumed to be 150 μgrays. Specific activity levels measured by calibrated thick source alpha counting over a 42 mm scintillation screen assuming secular equilibrium. K and Rb levels determined by XRF. All TL determinations are carried out on 90–120 microns quartz sand fraction except where indicated.

Fig. 9. Fabric of sand and gravel deposited by a tsunami at Steamers Beach. Car keys for scale. The rounded ball to the left of the keys consists of humate eroded elsewhere from the B horizon of a podsolic soil profile. This deposit rises from the modern beach to 30 m elevation.

coarser clasts that grade upward from boulders to cobbles and gravels (Fig. 9). The sizes of the inclusive clasts, together with some distinctive crossbedding, leave no doubt that this deposit, which rises from the modern beach to a height of 30 m, was emplaced by waves rather than wind. The lack of any pedogenetic development, other than minor organic accumulation in the top few centimeters, attests to a late Holocene age. The stratigraphy at Steamers Beach also demonstrates that this coast was struck by more than one major tsunami. On its eastern margin, the deposit described above overlaps a distinctly different body of sediment that consists of sand and fine shell hash. Although this second deposit has been mapped as eolianite (Abell, 1995), it too is of marine origin because it contains muddy lenses and quartz pebbles and is characterized by numerous sequences of flat bedding up to >2 m thick. Moreover, the shell hash is similar to that found in shallow water offshore. While Holocene sea levels rose no more than about 2 m above their present level along this coast (Young, Bryant, Price, Wirth, and Pease, 1993), in situ outcrops of this deposit can be traced to elevations of at least 70 m.

Estimates of the maximum height to which this wave train rose are dependent upon the interpretation of large parabolic sand mounds, which rise to 130 m elevation on the headland behind Steamers Beach. These mounds have been repeatedly interpreted as parabolic dunes formed by eolian processes (Walker, 1967; Abell, 1995; Taylor et al., 1995). The possibility of some eolian reworking is not denied, but detailed analysis showed no significant difference between the sand in the parabolic mounds and the sand in the adjacent tsunami deposits. We therefore suggest that the mounds may be runup features, similar to the "chevron" ridges described from the Bahama Islands (Hearty et al., in press). Although the chevron ridges of the Bahamas have been attributed to megastorms, the great elevation of the features behind Steamers Beach precludes any marine process other than tsunami runup. This 130 m elevation is greater than the height of the divide along this peninsula. It is conceivable that some of this runup washed into Jervis Bay. This could account for the northward transport of boulders along Greenfields Beach described above.

Further evidence of catastrophic washover occurs near Crocodile Head, north of the entrance to Jervis Bay (Fig. 1). Sandy ridges atop 80 m cliffs have also been mapped as eolian dunes, but likewise contain numerous pebbles and gravel that apparently preclude emplacement by wind. Indeed, how wind might have swept sand to the brink of these very high cliffs, and even onto narrow promontories separated from the headland by deep cliff-bounded gulches, has always been problematic. The only likely mechanism seemed to be that sand was blown from the floor of Jervis Bay, lying to the southwest, during lower sea levels (Jennings, 1967). We contend that the presence of numerous coarse clasts mixed with the sand and also the morphology of the sand bodies point to emplacement by tsunami.

The sand hills at Crocodile Head extend as a series of well-defined, undulatory-to-lingoidal giant ripples from the top of 80 m high cliffs, northwards over a distance of at least 1.5 km. The best defined of these megaripples have a relief of 6.0 to 7.5 m, are asymmetric in shape, and are spaced 160 m apart (Fig. 10). Their length-to-height ratio varies between 21–27, typical of giant ripples or sand waves developed by tidal currents (Reineck and Singh, 1980; Allen, 1984). While evidence of layering exists, exposures are too limited to identify any large scale cross-bedding. Smaller eolian cross-bedding is not evident. The megaripple field is restricted to a 0.5 to 0.7 km wide zone along the cliffs, and is bounded landward by a linear ridge of sand, several meters high, paralleling the coastline. This ridge is flanked by small depressions. Farther inland, deposits grade rapidly into hummocky topography, and then a 1 to 2 m thick sandsheet. The latter contains broad, shallow, oversized drainage swales. Several leached sandy layers are evident in exposures. The megaripple field itself shows evidence of post-depositional reshaping by water draining off the features. We believe that the megaripples were produced by overwashing of the cliffs by sediment-laden tsunami runup, with subsequent deposition of sediment as megaripple bedforms along the cliff top, and then as an overwash splay as water drained downslope across the headland towards the northwest.

If the interpretation of these features as megaripples is correct, their emplacement hydraulics should be commensurate with those estimated for tsunami elsewhere in the region. These hydraulics can be determined from general relationships for sand waves (Allen, 1984). As a first approximation water flow over the hills was 7.5 to 12.0 m deep. The height-to-length ratio of the megaripples can also be related graphically to the Froude number ($F = V \times [gh]^{-2}$, where V = velocity, g = gravitational acceleration and h = flow depth). The flow had Froude numbers of 0.90 to 0.95, yielding maximum flow velocities of 6.9 to 8.1 m s^{1}. These hydraulic characteristics are similar to those calculated for the transport of boulders at the top of the cliffs nearby at Mermaids Inlet and inside the bay at Greenfields Beach. Their

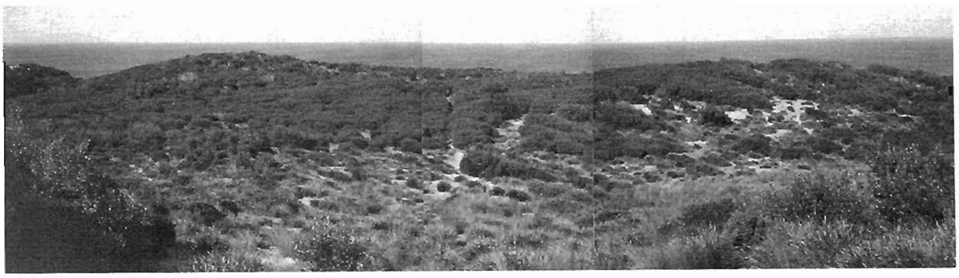

Fig. 10. The megaripple bedforms at the top of the cliffs at Crocodile Head.

agreement with those determined for the boulder ripple field at Honeysuckle Point suggests a common catastrophic mechanism of formation for all features.

Tsunami and TL Signatures

We have recently demonstrated that anomalous TL ages of the 90 to 125 mm quartz fraction of marine sands seems indicative of rapid emplacement of sediments by tsunami (Young et al., 1995, 1997). The TL dating follows the procedures used at Wollongong University for dating coastal sand bodies (Bryant et al., 1990). It is important to note that a TL age indicates the last time that sand was bleached of residual energy by exposure to sunlight, and not necessarily the time that the sand was deposited in its present position. As such, bleaching occurs rapidly, most residual energy is removed when sand is exposed to sunlight by winnowing on a beach or dune face (Bryant, Young, Price, and Short, 1992); but little is lost if the sand is dumped and buried in a large mass of sediment carried by a tsunami.

The clear evidence of tsunami deposition at Steamers Beach again provides a valuable test of this hypothesis. The older deposit was apparently carried on to Steamers Beach during the early Holocene because the shell hash yielded a ^{14}C age of 8.74 ± 0.7 ka (Beta82245, Table 2), and the sand gave TL ages of 9.2 ± 0.9 ka (W1882) and 13.2 ± 1.7 ka (W1883). However, the second, stratigraphically younger tsunami deposit at Steamers Beach gave a much older TL age of 27.1 ± 3.0 ka (W1885), that is to say a Last Glacial age when sea level along this coast was far below its modern counterpart. This latter body of sand was apparently last bleached at low sea level, but then transported shoreward, and subsequently dumped rapidly onshore more recently by tsunami.

Similar lack of bleaching owing to rapid deposition by tsunami is the most likely explanation for anomalous TL ages derived from marine sands elsewhere in the vicinity of Jervis Bay. The earliest Holocene marine deposition along the present coastline of southern New South Wales occurred around 7 ka (Young, Bryant, Price, Wirth, and Pease, 1993). Sand from the most landward point of Holocene marine sedimentation within Jervis Bay, 1.6 km from the ocean in an infilled lagoon attached to Moona Moona Creek, gave a TL age of 32.7 ± 3.2 ka (W1369). The well-defined, apparently Holocene barrier at the north end of Vincentia beach gave a TL age of 21.9 ± 2.6 ka (W1370). Much younger TL determinations of 16.7 ± 3.1

Table 2. Radiocarbon Ages from Tsunami Deposits in the Jervis Bay Region

Laboratory no.	Site	Environment	Measured[a,b] ^{14}C Age x ka	$^{13}C/^{12}C$ ratio	Conventional[b] ^{14}C Age x ka
Beta76596	Mermaids Inlet	stranded beach	0.11 ± 0.06	1.4‰	0.55 ± 0.07
Beta78895	Greenfields	tossed boulder	103.3 ± 0.7	0.6‰	0.16 ± 0.06
Beta78896	Stoney Creek	tossed boulder	1.3 ± 0.06	3.0‰	1.76 ± 0.06
Beta82245	Steamers Beach	tsunami runup	8.4 ± 0.6	–5.3‰	8.74 ± 0.07

[a]Ages are adjusted for a global ocean reservoir effect i.
[b]Error terms are reported to 1 standard deviation.

ka (W1367) and 12.3 ± 1.4 ka (W1368) were obtained from sand ridges near the mouth of Currumbene Creek. These ridges have previously been interpreted as part of an "inner" Pleistocene barrier, probably of Last Interglacial age (Walker, 1967). An age of 12.6 ± 1.4 ka (W1394) was also obtained from the inner ridge of the "Holocene" barrier system behind Callala Beach. If the ages of these sands were indicative of the time of deposition, paradoxically, sea levels were anywhere from 50 to 130 m lower than present.

Three more ages indicative of bleaching during the Last Glacial were obtained from the narrow gulches at Mermaids Inlet (Fig. 5). Sand between imbricated boulders 10 m above sea level at the rear of one gulch gave an age of 30.3 ± 3.1 ka (W1935). The other gulch, which is now completely blocked from storm wave attack, contains what could be interpreted as remnants of a Last Interglacial beach positioned 6 to 7 m above sea level, and of a Holocene beach consisting of shell and sand left stranded on the floor of the gulch. The postulated "interglacial" beach gave a TL determination 18.8 ± 1.7 ka (W1937) while the stranded "recent" beach gave an age of 23.1 ± 3.3 ka (W1936). Shoreward transport of sands within the gulch, without significant bleaching, is also demonstrated by the ^{14}C age of 0.55 ± 0.07 ka (Beta76596) obtained from shell trapped under a boulder at the back of the stranded "recent" beach. Moreover, a silty sand tucked into a crevice 7.5 m above the floor of the little gulch (Fig. 11) seems to be a slackwater deposit laid down when the gulch was filled by tsunami surge. This deposit gave an age of 9.6 ± 1.1 ka (W1934). We have little doubt that all these features in the gulches at Mermaids Inlet were deposited by tsunami, especially given the emplacement of huge boulders at the mouth of the inlet and 32 m above sea level on the adjacent cliff tops. Moreover, these results, and in particular the TL ages of the Vincentia barrier and stranded beach at Mermaids Inlet, are supported by similar anomalous TL ages from other Holocene barrier deposits along the New South Wales coast (Young et al., 1995; Bryant et al., 1997).

Of course, the chronological data considered here not only point to a useful method for identifying tsunamigenic deposits, but also highlight the difficulties of determining an accurate age of deposition. The stratigraphic evidence shows that the impact of several tsunami is recorded in the Jervis Bay area. The best indications of their ages are the ^{14}C date of 8.7 ± 0.07 ka and corresponding TL date of 9.2 ±

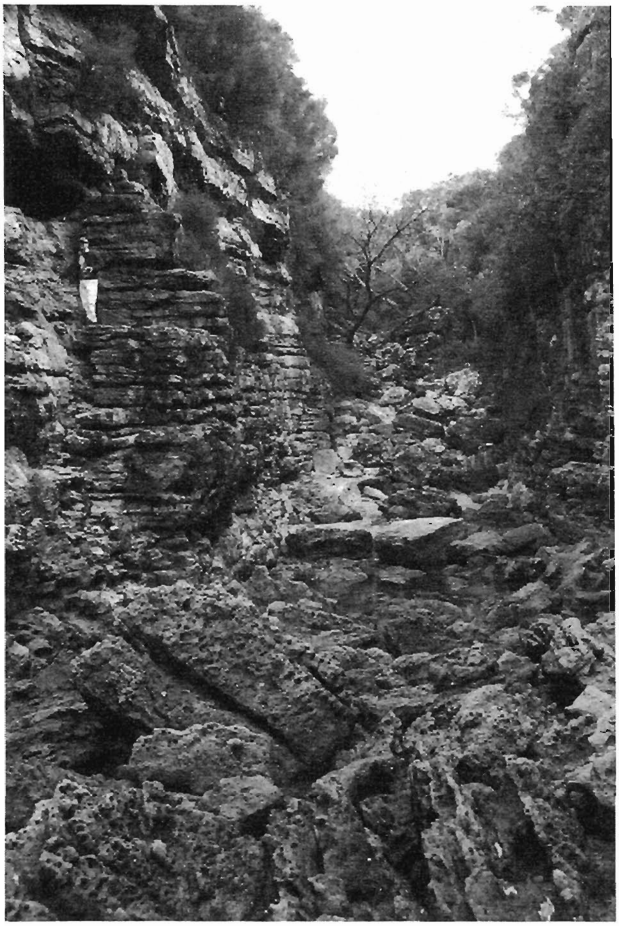

Fig. 11. The little gulch at Mermaids Inlet. The tsunami slackwater deposit is positioned in the cavity above the person. It yielded a TL age of 9.6 ± 1.1. The ramp of boulders that fills in the back of the gulch yielded a TL age of 30.3 ± 3.1 ka (W1935) from its sandy matrix.

0.9 ka from Steamers Beach, the ^{14}C age of 1.76 ± 0.06 ka (Beta78896) for in situ worm tubes (Galeolaria caespitosa) attached to the base of a boulder at Stoney Creek, the ^{14}C age of 0.55 ± 0.07 ka for shell at Mermaids Inlet, and a modern ^{14}C determination of 0.16 ± 0.06 ka (Beta78895) for worm tubes attached to one of the lowest boulders at Greenfields Beach. These dates correspond well to the timing of events we have determined along the coastline in general (Young et al., 1997).

CONCLUDING COMMENTS

It is not difficult to see why the features described above have been misinterpreted or simply ignored in the literature. Their characteristics and juxtaposition relative to modern sea level are often so different from what coastal researchers expect to see that geomorphologists have either side-stepped their presence or described them in terms of contemporary concepts of coastal evolution and processes. However, the ubiquitous nature of anomalous geomorphic 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. The imbricated boulders stacked on top of 32 m high cliffs, the >6 m long blocks barricading the gulches at Mermaids Inlet, the stony cliff-top dunes, the anomalous ages of sands, and a half dozen other disparate aspects of the coastal landscape of Jervis Bay are explained best by tsunami. The fact that such events have not appeared in the historic record, only highlights the shortness of that record. It does not necessarily invalidate the possible occurrence of such phenomena.

The presence of coastal landforms that can be linked to tsunami hydrodynamics has wider significance for other commonly recognized, but little studied, features in the coastal zone. For example, what are sea caves? The literature frequently refers to such features, but sheds little light as to their formation, especially in resistant and massively bedded bedrock. Many other aspects of cliffed and rocky coasts are treated in a similar cursory fashion (e.g., Trenhaile, 1997). If sea caves, bedrock ramped surfaces, sheered cliffs, imbricated boulder piles, and chevron ridges are the signatures of tsunami then how common are tsunami in shaping coastline in other parts of the world?

Unless coastal geomorphologists recognize the possibility of catastrophic phenomena such as tsunami in the coastal zone, then we will continue to interpret chevron ridges as parabolic eolian dunes, even where such deposits obviously contain large clasts that could not possibly be transported by wind. To avoid embarrassment, coastal geomorphologists should be more thorough in their field investigations and less willing to fit cursory observations into popular views or acceptable models. Most of the coastal landscape of Jervis Bay cannot be explained by reading any textbook because it shows the pervasive imprint of catastrophic tsunami, which have unwittingly been ignored to date as a significant coastal process.

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BIBLIOGRAPHY

Abell, R. S. (1995) *Geosciences and Environment of Jervis Bay Territory and Beecroft Peninsula*. Canberra, Australia: Australian Geological Survey Organisation (1:25,000 scale map).

Allen, J. R. L. (1984) *Sedimentary Structures: Their Character and Physical Basis* (Vol. 1). Amsterdam, The Netherlands: Elsevier.

Baker, V. R. (1973) Paleohydrology and sedimentology of Lake Missoula flooding in eastern Washington. *Geological Society of America Special Paper*, No. 144.

______ (ed.) (1981) *Catastrophic Flooding: The Origin of the Channeled Scabland*. Stroudsburg, PA: Dowden, Hutchinson, and Ross.

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

______, ______, and Price, D. M. (1992) Evidence of tsunami sedimentation on the southeastern coast of Australia. *Journal of Geology,* Vol. 100, 753–765.

______, ______, and ______ (1996) Tsunami as a major control on coastal evolution, Southeastern Australia. *Journal of Coastal Research*, Vol. 12, 831–840.

______, ______, and ______ (1997) Late Pleistocene marine deposition and TL chronology of the New South Wales, Australian coastline. *Zeitschrift für Geomorphologie N.F.*, Vol. 41, 205–227.

______, ______, ______, and Short, S. A. (1990) Thermoluminescence and uranium-thorium chronologies of Pleistocene coastal landforms of the Illawarra region, New South Wales. *Australian Geographer,* Vol. 21, 101–112.

______, ______, ______, and ______ (1992) Evidence for Pleistocene and Holocene raised marine deposits, Sandon Point, New South Wales. *Australian Journal of Earth Science*, Vol. 39, 484–493.

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,* Vol. 41, 176–184.

Coleman, P. J. (1968) Tsunamis as geological agents. *Journal Geological Society Australia*, Vol. 15, 267–273.

Costa, J. E. (1983) Paleohydraulic reconstruction of flash-flood peaks from boulder deposits in the Colorado Front Range. *Geological Society of America Bulletin*, Vol. 94, 986–1004.

Hearty, P. J., Neumann, A. C., and Kaufman, D. S. (1998) Chevron-shaped beach ridges record disrupted end of Substage 5e in the Bahamas. *Palaeogeography, Palaeoclimatology, Palaeoecology* (in press).

Jennings, J. N. (1967) Cliff-top dunes. *Australian Geographical Studies*, Vol. 5, 40–59.

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*, Vol. 28, 623–642.

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,* No. 229, 101–110.

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

Reineck, H.-E. and Singh, I. B. (1980) *Depositional sedimentary environments* (2nd ed.). Berlin, Germany: Springer-Verlag.

Taylor, G., Abell, R., and Paterson, I. (1995) Geology, geomorphology, soils and earth resources. In C. Cho, A. Georges, and R. Stoutjesdijk, eds., *Jervis Bay: A Place of Cultural, Scientific and Educational Value. Kowari 5*. Canberra, Australia: Australian Nature Conservation Agency.

Thom, B. G. (1983) Transgressive and regressive stratigraphies of coastal sand barriers in southeast Australia. *Marine Geology,* Vol. 56, 137–158.

Trenhaile, A. S. (1997) *Coastal Dynamics and Landforms*. Oxford, UK: Clarendon.

Walker, G. T. (1967) *The Coastal Geomorphology of the Jervis Bay Area.* Unpublished master's thesis, Australian National University, Canberra.

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

______ and ______ (1993) Coastal rock platforms and ramps of Pleistocene and Tertiary age in southern New South Wales, Australia. *Zeitschrift für Geomorphologie N.F.*, Vol. 37, 257–272.

______, ______, and Price, D. M. (1993) Last Interglacial sea levels on the South Coast of New South Wales. *Australian Geographer*, Vol. 24, 72–75.

______, ______, and ______ (1995) The imprint of tsunami in Quaternary coastal sediments of southeastern Australia. *Bulgarian Geophysical Journal*, Vol. 21, 24–31.

______, ______, and ______ (1996) Catastrophic wave (tsunami?) transport of boulders in southern New South Wales, Australia. *Zeitschrift für Geomorphologie N.F.*, Vol. 40, 191-207.

______, ______, ______, Dilek, S. Y., and Wheeler, D. J. (1997) Chronology of Holocene tsunamis on the southeastern coast of Australia. *Transactions Japanese Geomorphological Union*, Vol. 18, 1–19.

______, ______, ______, Wirth, L. M., and Pease, L. M. (1993b) Theoretical constraints and chronological evidence of Holocene coastal development in central and southern New South Wales, Australia. *Geomorphology*, Vol. 7, 317–329.

______, Cope, S., Price, D. M., Chivas, A. R., and Chenhall, B. E. (1996) Character and age of lateritic weathering at Jervis Bay, New South Wales. *Australian Geographical Studies*, Vol. 34, 237–246.