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# Evidence of Tsunami Sedimentation on the Southeastern Coast of Australia

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## Abstract

In the coastal region, the highest magnitude storms cannot always be invoked to account for large-scale, anomalous sediment features. Any coastline in the Pacific Ocean region can be affected by tsunamis, including Australia which historically lacks evidence of such events. Geologically, tsunamis along the New South Wales coast have deposited a suite of Holocene features that consist of anomalous boulder masses, either chaotically tossed onto rock platforms and backshores or jammed into crevices; highly bimodal mixtures of sand and boulders; and dump deposits consisting of well sorted coarse debris. In addition many coastal aboriginal middens were disturbed by such events. Within estuaries, tsunamis have left a record of stranded run-up ridges which have been interrupted mistakenly as cheniers. Dating of such deposits indicates that several events have affected this coastline since 3000 BP. In contrast to storm waves, tsunamis can leave a depositional imprint of their passage that is characterized by chaotic sorting and mixing of sediments either from different coastal environments or of different sediment sizes. The preservation potential of these deposits is high where sediments have been deposited above present sea-level or stranded inland.



## Keywords

tsunami, New South Wales, deposits, GeoQUEST


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# GEOLOGICAL NOTES

# Evidence of Tsunami Sedimentation on the Southeastern Coast of Australia[1]

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## ABSTRACT

In coastal regions, the highest magnitude storms cannot always be invoked to account for large-scale, anomalous sediment features. Any coastline in the Pacific Ocean region can be affected by tsunamis, including Australia, which historically lacks evidence of such events. Geologically, tsunamis along the New South Wales coast have deposited a suite of Holocene features that consist of anomalous boulder masses, either chaotically tossed onto rock platforms and backshores or jammed into crevices; highly bimodal mixtures of sand and boulders; and dump deposits consisting of well-sorted coarse debris. In addition, many coastal aboriginal middens were distributed by such events. Within estuaries, tsunamis have left a record of stranded run-up ridges that have been interpreted mistakenly as cheniers. Dating of such deposits indicates that several events have affected this coastline since 3000 BP. In contrast to storm waves, tsunamis can leave a depositional imprint of their passage characterized by chaotic sorting and mixing of sediments either from different coastal environments or of different sediment sizes. The preservation potential of these deposits is high where sediments have been deposited above present sea level or stranded inland.

## Introduction

There has been an increased awareness that convulsive events are important geological processes. Scientific procedure dictates that in the absence of convincing proof, the evidence for convulsive events must be explained by more common events of lesser magnitude (Clifton 1988). For example, storms are often invoked, albeit with few supporting observations, to explain most convulsive coastal morphology and sedimentation (Morton 1988: Bryant 1991). However the alternate phenomenon of tsunamis certainly has the potential for moving sediment and moulding coastal landscapes to the same degree. Tsunamis have for the most part been ignored in the geologic and geomorphologic literature. Notwithstanding accounts of the impact of individual tsunamis (Houtz 1963; Moore and Moore 1984; Myles 1985; Dawson et al. 1988; Talandier and Bourrouilh-Le-Jan 1988), only Coleman (1968) pleads convincingly for their consideration in shaping the continental shelf profile and sculpturing coastal morphology. This neglect is unusual considering that tsunamis are common, high-magnitude phenomena producing an on-surge with velocities up to 15 m $sec^{-1}$ (Coleman 1968). In the Pacific Ocean region, 38 tsunamis have generated wave run-up heights in excess of 6 m since 1900 (Lockridge and Smith 1984), while five events since 1600 have produced run-up heights 51–115 m (Ilda 1983).

The New South Wales south coast is supposedly far removed from zones of high tsunami risk (figure 1). Historical tsunamis have generated vertical sea-level displacements of only 0.8–1.0 m within Sydney harbor (Bryant 1991). Coastal sedimentation here is ascribed to the interplay between accretional and erosional swell and wind waves (Wright et al. 1979). Storm waves of 7–10 m height, as measured recently at wave rider buoys (Youll 1981), are an important factor in accounting for dramatic, if temporary erosion of modern beaches (Bryant 1988). The geological record along this coast, however, indicates that tsunami wave erosion has been active and that its importance in shaping coastal landscapes has been neglected. This evidence is most striking at Tura Point, where erosional streamline bedforms, plucked joint-controlled block depressions and sickle troughs, all in resistant bedrock, indicate the occurrence of a tsunami train with a minimum height of 16–25 m around

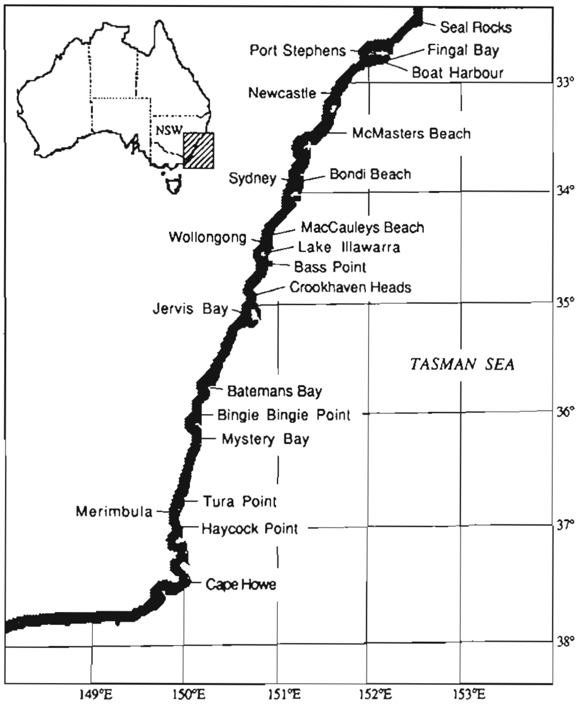


**Figure 1.** Location map of the central-south coast of New South Wales.

105,000 BP (Young and Bryant 1992). We suggest that this tsunami train slammed against the coastline, modifying most headlands and destroying much of the evidence of Late Quarternary barriers between Newcastle and the Victorian border.

We argue in this paper that much smaller events, but still with considerable potential for altering coastal deposits, also have occurred on this coast during the Holocene. While many of the apparent sedimentary signatures of these postulated tsunamis by themselves may appear equivocal, we describe a suite of features which, when taken together, suggest that smaller tsunamis should not be ignored as a major process of modern coastal sedimentation.

## Anomalous Boulder Masses

Most of the evidence indicative of tsunamis is drawn from deposits that are seemingly incompatible with the existing wind and wave regimes. Despite the presence of 7–10 m high storm waves, open coast rock platforms display little movement of boulder material measuring up to 5 m in diameter. An exception is the description by Sussmilch (1912) of the movement over a distance of 50 m of a 200 ton boulder measuring 6.1 × 4.9 × 3.0 m on a platform at Bondi Beach, Sydney. This block has not shifted since then. Detailed observations during the 25 May 1974 storm, which produced waves of 7 m and was assessed as the most extreme event experienced in 70 years along the Sydney and the Central coast of New South Wales (Bryant and Kidd 1975), revealed minimal evidence even of small boulders being moved across platforms.

While much higher storm events can and have been invoked for the movement of the boulders now piled up in embayments behind many platforms, tsunamis offer a simpler mechanism for the sweeping of debris from platforms and the emplacement of such debris either shoreward or further upslope. Isolated boulders, many of which have fresh and angular faces, can be found tossed up onto raised platforms or into Holocene dunes, and thrown in a scattered fashion well above the run-up limit of storm waves. In many cases these boulders grade up the backshore with large, isolated rounded boulders up to 2 m in diameter sitting further inland than angular blocks of 0.2–0.4 m diameter. These deposits are numerous, but the best examples are located at Boat Harbor, Bass Point, Bingie Bingie Point, and Mystery Bay. At Boat Harbor, Port Stephens, blocks measuring 4 × 3 × 3 m not only have been moved shoreward more than 100 m but also lifted 10–12 m above existing sea-level. Houtz (1963), Moore and Moore (1988), and Talandier and Bourrouilh-Le-Jan (1988) describe similar movement of blocks either in prodigious numbers, or of colossal size, which have been ascribed to tsunamis on Pacific Islands.

Tsunamis rather than ordinary storm waves are the only viable mechanism for one unusual rock deposit sitting 2–3 m above present sea level at Haycock Point, south of Merimbula (figure 1). Haycock Point is dominted by a series of platform ramps facing NE and developed on the dip slopes of folds in the red beds and sandstones of the Late Devonian Worange Point Formation. Along one such low dip ramp a rockfall has collapsed onto the platform no more than 3 m above existing sea level. The rockfall consists of sandstone blocks up to 5 m in length that have dropped onto the platform and then been shoved chaotically into the cliff face (figure 2). A substantial portion of the rockfall has been swept into a crevice that penetrates 3–5 m into the base of the cliff face at the contact between red beds and the overlying sandstones. Angular blocks up to 2 m in length and 0.5 m in width have been jammed tightly into the crevice, often in an interlocking series 3 or 4 blocks deep. As the blocks have only fallen a few metres down the cliff face, elastic rebound of the debris after striking the surface of the platform cannot account for the extremely tight jamming of this

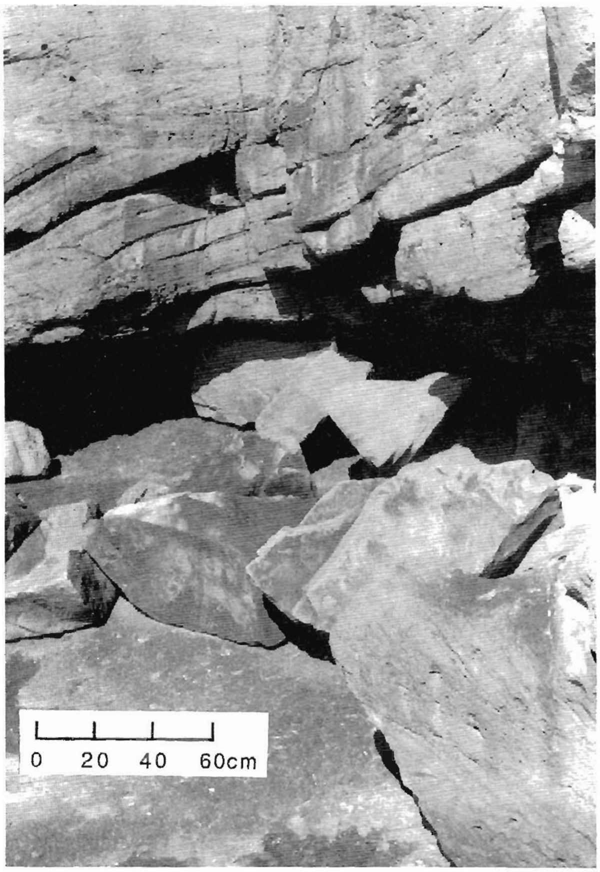


**Figure 2.** The rockfall which has been subsequently jammed into a crevice at Haycock Point. Note the angularity and size of blocks and their chaotic packing.

material into the crevice. If storm waves had produced the packing then, given the proximity of the debris to the ocean, more recent storms would surely have reworked the deposit, sorting and rounding what are still unweathered and angular blocks. What is more unusual about the deposit is the presence along the adjacent cliff face of isolated blocks 0.4–0.5 m long perched in crevices 4–5 m up the cliff face. These blocks could not have dropped into such positions but must have been tossed up from the platform surface below.

Above 50 m west of this rockfall, the sandstone forms a ramp that dips westward parallel to shore from the crest of a 7m vertical rock face (figure 3). At the base of this ramp, rounded and angular blocks, some with volumes of 30 $m^3$ and weighing 75 tons have been piled into a jumbled mass. This rock face and the immediately adjacent shoreline outcrops show evidence of plucking of joint-bounded blocks at elevations of up to 5 m above sea-level. Impact marks over the complete ramp surface indicate that many of the boulders must have been thrown onto the ramp and then rolled in saltation or suspension down its inclined surface before coming to rest in the pile of boulders.

We suggest that a tsunami slammed into the cliff face at this site, triggering the rockfall, and that subsequent waves in the tsunami wave train then pushed the debris back toward the cliff, jamming blocks into the crevice and tossing smaller blocks into the air where they lodged on ledges on the cliff face. Seventy-five ton blocks were also tossed over the 7 m high edge of the upper ramp and bounced down this ramp, coming to rest individually or on top of each other at the base. Evidence that the tsunami responsible for the transport of these blocks may be recent comes from

**Figure 3.** The jumbled pile of boulders rolled down the ramp at Haycock Point.

**Table 1.** Thermoluminescence Age Determinations

| Laboratory No. | Palaeodose (Grays) | K[b] (%) | Specific Activity[c] Th and U chains (Bq/kg) | Annual Dose[d] ($\mu$Grays) | TL Age (yr) |
|---|---|---|---|---|---|
| *Mystery Bay* | | | | | |
| W1201 | 6.4 | .430 | 29.5 | 1188 | 5400±900 |
| *Bellambi Beach* | | | | | |
| W1296 | 24.4 | .180 | 40.9 | 1108 | 22000±3400 |
| *Cullendulla Creek*[a] | | | | | |
| W977 | 5.9 | 1.280 | 17.2 | 1374 | 4300±500 |
| W978 | 5.6 | 1.060 | 26.6 | 1599 | 3500±400 |
| W979 | 9.1 | 1.130 | 29.1 | 1776 | 5100±400 |
| W980 | 9.8 | .945 | 23.1 | 1231 | 7900±700 |
| W981 | 8.3 | .875 | 23.6 | 1240 | 6700±600 |
| W982 | 6.0 | 1.085 | 48.4 | 1374 | 4400±400 |
| W983 | 4.2 | 1.915 | 69.1 | 2473 | 1700±300 |

Notes. Error terms representing the summation of all environmental and laboratory errors are reported to 1 $\sigma$.
[a] The palaeodose values shown for Cullendulla Creek represent the mean taken over the temperature plateaux at 25°C intervals, typically n = 5 (300–400°C).
[b] K levels are measured by means of AES and Rb values were assumed to be 100 ppm.
[c] Specific activity levels measured by calibrated thick source alpha counting over a 42 mm scintillation screen and assuming secular equilibrium.
[d] Cosmic contribution to the annual radiation assumed to be 150 $\mu$Grays.

a $^{14}C$ determination (Beta-43950) on *Galeolaria* worm tubes on one block tossed at the edge of the mass (106.4 ± 0.8% modern). Nonetheless, the tsunami must have occurred more than 200 yr ago because it does not appear in historical records since European settlement.

## Highly Bimodal Beach Deposits

Highly bimodal sediment in sandy beach deposits along this coastline also are suggestive of tsunami. Bryant et al. (1992) describe one of these deposits at MacCauleys Beach in northern Wollongong (figure 1). This deposit forms part of an elevated sandy beach, 50–60 m in length lying 3.2–3.9 m above Australian Height Datum (approximately 0.8 above LLW in this region). It contains isolated oblate pebbles lying parallel to the bedding plane and weathered boulders 0.2–0.4 m in diameter floating throughout the sand matrix. These boulders are more prevalent at the upper and lower contacts of the unit. Thermoluminescence dating (table 1) provided an age of 5200 BP for this highly bimodal unit. The sequence terminates northward in a disturbed quartz sand beach unit that contains isolated midden shells, Aboriginal stone flakes, some oblate pebbles and profuse amounts of pumice. Thermoluminescence and $^{14}C$ analyses (table 2) gave identical dates of 1520 BP for this deposit.

The irregular distribution of boulders throughout the elevated beach is unusual. While there are many descriptions of boulder or mixed gravel and sand beaches (McLean and Kirk 1969; Kirk 1980; Oak 1984), we can find no evidence in the literature for an assemblage of sand and boulders deposited contemporaneously by wind waves. The boulders originate from an adjacent rock platform, and they may have been moved alongshore and thrown up to their present position by storm waves. However, the shoreward movement of boulders this size is usually accompanied along this coast by storm waves with a deep water wave height of 4 m (Oak 1981). Such waves would erode the sands in which the boulders are now found (Bryant 1988).

**Table 2.** $^{14}C$ Age Determinations new to this study

| Laboratory No. | Elevation AHD (m) | Sample Type | $^{13}C$ Adjusted Age (BP) |
|---|---|---|---|
| *Mystery Bay* | | | |
| Beta-43948 | 4.85 | whole shell seaward ridge | 106.2±.8% modern |
| Beta-43949 | 2.0 | whole shell landward ridge | 1580±60 |
| *Haycock Point* | | | |
| Beta-43950 | 1.7 | *Galeolaria* worm tubes | 106.4±.8% modern |
| *Cullendulla Creek* | | | |
| SUA 2900 | 1.5 | whole shells | 3200±60 |
| SUA 2901 | 1.2 | whole shells | 2950±70 |
| Beta-36434 | 1.2 | whole shell | 1850±75 |
| Beta 36435 | 1.0 | whole shell | 1420±75 |

Note. Error terms representing only the counting error are reported to 1 $\sigma$. Note that no oceanic reservoir correction has been applied to the dates.

The deposition of the boulders by overwashing, which also would have preserved the sands, can be ruled out as an alternative hypothesis. Not only does a very steep backshore slope prohibit significant overwashing, but the overwashing process sorts sediment spatially (Leatherman 1981), and this deposit most certainly is not sorted. Erosion of boulders from a backing deposit onto an existing beach, while seen on adjacent beaches, is also not feasible here. The raised deposit abuts a bedrock surface that neither contains boulder deposits nor produces rounded boulders through weathering. Additionally, the storm wave run-up of the May-June 1974 storms, considered to be the worst storms to affect this coastline in the past 50 yr, failed to reach this elevated beach.

The deposit is not unique. It also appears 5 km further south at Bellambi, where boulders can be found floating within an indurated sand deposit 1.0–1.5 m thick and dating using TL at 22,000 BP. As sea level was nowhere near the present level in this region at this time (Chappell and Veeh 1978), we believe that a tsunami overrode Last Glacial aeolian sand near the present shoreline and rapidly mixed this sand with marine boulders before dumping both as a single unit. The sands were not exposed to sunlight long enough to bleach away the remnant TL signature. Since this unit is near present sea level, the timing of this event must have occurred in the mid-Holocene, concomitantly with the marine transgression reaching the coast.

Other bimodal sand and boulder deposits lie along this coast. A cobble and beach sand deposit rising up to 5 m above the modern beach is located on the southern side of Bass Point, south of Wollongong (figure 1); a larger deposit, consisting of boulders up to 0.5 m in diameter mixed with cobble and sand, is situated at Crookhaven Heads south of the Shoalhaven River. These latter two deposits are chaotically sorted and have the appearance of being rapidly dumped. In addition, elevated remnants of similar deposits of mixed sand and gravel can be found between Seal Rocks and Cape Howe on the Victorian state border (figure 1).

There is little doubt that these deposits represent tsunami deposition. There is substantial evidence from Hawaii of tsunamis depositing layers of mixed sand and boulder material (Moore and Moore 1988; Lander and Lockridge 1989). Additionally, tsunamis, because of their low height relative to a long wavelength, also form constructional waves on the type of nearshore slopes fronting much of the New South Wales coastline, especially at Wollongong. Such waves would be strong enough to move boulders off platforms or the seabed near headlands, and transport and mix them with sand at these locations. Finally, the Bellambi deposit evidences at least two cycles in sorting with depth similar to those found in known tsunami sand deposits in Scotland and on the Scilly Islands (Dawson pers. comm. 1991). Each cycle is hypothesized as representing an individual wave in the tsunami wave train.

## Dump Deposits

While some of the bimodal beach deposits described above appear dumped, we reserve this term for more prominent coastal features composed of either boulders or mixtures of well-sorted cobble and shell stacked into isolated ridges, terraces, or mounds. These deposits often rise to heights of 3 m or more above the limits of modern storm wave activity. None of these deposits can be explained satisfactorily by existing wave processes.

At the largest scale are boulder beaches that do not fit the contemporary model for boulder beach formation described so systematically by Oak (1981) for the New South Wales coastline. Contemporary storm-worked boulder beaches consist of material averaging .36–.51 m in size, which is being reworked landward along platforms into shallow embayments. The anomalous boulder deposits are very much relict and sit on the most exposed parts of headlands. Bishop and Hughes (1989) have described one such deposit at McMasters Beach dating at 4780 yr BP. The deposit lies only 1.5 m above AHD and is so tightly packed that it has resisted all storm wave attack over a period of 5000 yr. Of particular note is an unusual boulder beach at Boat Harbor, Port Stephens. This beach consists of two levels of boulder material averaging between 0.29–0.56 m in length and reaching a height of 6 m above AHD. While the lower tier of the beach is certainly reached by modern storm waves, the upper part is inactive. The boulders throughout both tiers are loosely packed and unstable to walk on. Furthermore, along the sides of the embayment, angular and rounded boulders are profusely scattered to the same heights as on the beach. Finally, even though the complete width of the 250 m wide embayment is exposed to the open ocean, the boulder beach does not obtain the arcuate planform typical of swell wave deposits. The boulder beach is higher in the center and drops in elevation toward the north corner, where boulders grade into cobble-sized material.

The cobble and shell deposits are present as ridges, benches, or mounds. The best example of ridges is developed at Mystery Bay and consists of

**Figure 4.** The cobble-gravel-shell dump ridge at the back of the sand beach at Mystery Bay.

rounded cobbles and gravel poorly sorted and mixed with weathered but unbroken shell (figure 4). The deposit forms an unvegetated ridge 5.75 m (AHD) in elevation with a convex seaward slope of 20° rising abruptly behind a sand beach that lies at an elevation of 2.5 m. The largest cobbles measure 5 cm in width, with the most common clasts being pea-sized. While no cobbles or gravel occur on the modern beach, no sand occurs in the ridge. Landward of the ridge, and also at an elevation of 5.75 m, is the eroded remnant of a similar cobble and shell deposit, but in this case mixed with sand. This second ridge is vegetated and laps onto a steep bedrock slope where scattered cobble debris has been tossed up to heights of 9.1 m. Cobbles in this second ridge are coarser, with the largest clasts measuring 10 cm in width. Behind the remnant of the second ridge, at an elevation of 5.85 m, is a relict sandy beach deposit which fills the mouth of a small gully.

Late Holocene origins for all three units are demonstrated by the thermoluminescence age of 5400 ± 900 yr BP obtained for the relict beach sand at the back of the sequence. However shell from the seaward ridge is modern (Beta-43948, 106.2 ± 0.8% modern), while that from the landward ridge is 1580 ± 60 yr old (Beta 43949). We are hesitant to correct the latter age for the oceanic reservoir effect of 450 yr for this coast given the fact that shell yielding an age less than this correction exists in the seaward ridge. Nonetheless, the comparability of the approximate age of the rear ridge with the age of the tsunami deposit at MacCauleys Beach, and the age of the seaward ridge with that of the *Galeolaria* covered block at Haycock Point is intriguing.

Mound features of cobble and shell material, similar in composition to the ridges at Mystery Bay, occur on the north side of Bass Point, forming some of the most unusual deposits along the coast. The mounds front one of the largest midden deposits in New South Wales (Hughes and Djohadze 1980). These middens, which consist of organically rich, thinly bedded shell, lie in a position on the north side of Bass Point protected from the dominant storm wave direction. Nonetheless, they have been scarped to a height of 2–3 m. The mounds consist of chaotically sorted shell hash with rounded cobble and boulder sized debris mixed throughout but are devoid of any of the organic or sandy material found in the middens. The mounds extend 100 m alongshore some 5–10 m seaward of the midden scarp, are up to 3 m high, and are punctured landward by lobate breaches (figure 5). Westward the mounds merge into a 10–20 m wide bench of the same material rising steeply to a height of 4 m above the present storm wave limit. The mounds are not unlike the shell mounds formed by tsunamis in Japan; however they are an order of magnitude larger (Minoura and Nakaya 1991). Slopes on both sides of the mounds exceed 20°, a value much steeper than the 7–9° found on equilibrium profiles formed by storm waves in similar-sized material (Oak 1984). The mounds are fronted by a chaotic sheet of cobble and boulder material protruding through a shell hash matrix. This sheet rests on a seaward sloping bedrock platform. The fact that this debris is partially vegetated suggests that it has not been affected by present storm wave run-up, although at the eastern end of the section, the mounds are slowly being reworked by the present storm wave regime into a much

Figure 5. The boulder-shell hash mounds at Bass Point.

lower angled beach deposit. The chronology of the middens (Hughes and Djohadze 1980) indicates that the mounds formed since 740 BP.

At both Mystery Bay and Bass Point, tsunami wave trains apparently eroded sediment from the backing raised beach or midden deposits and mixed it with cobble from offshore. The first waves in the tsunami train, being steeper, eroded the material, while the last waves in the train dumped this debris as a bank in front of the eroded section. At Mystery Bay an elevated ridge was formed, but at Bass Point the mobilized material was dumped either in irregular mounds or as a ridge that was subsequently breached. This process was repeated at a later date at Mystery Bay, but in this case, only cobble mixed with shell material was dumped at the back of the beach. At Boat Harbor the tsunami-dump material is much larger in size. The tsunami wave train moved boulder debris from steeply sloping bedrock ramps, tossing them up along the coastline, and concentrating them into the Boat Harbor embayment. The deposits at this site were dumped suddenly and by a wave train able to move blocks up to 4 m in length on the open coast, but was too short-lived to distribute material along the back of the embayment to form a coherent beach. Neither at Boat Harbor nor Mystery Bay have subsequent storm waves been able to rework any of the deposits. Only at Bass Point is the material being reworked to any degree, and there it is being moved seaward to form a cobble beach of lower gradient.

## Disturbed Midden Deposits

Many of the tsunami deposits such as those at MacCauleys Beach, Crookhaven Head, and Bass Point are associated with disturbed middens. Hughes and Sullivan (1974) describe 16 such deposits along this coast and conclude that they were evidence of reworking by storm waves. All the disturbed sites include marine shell grit, water-worn shells, rounded pebbles or pumice mixed with the usual characteristic midden material. In some cases the pumice is 5–10 cm in diameter, a size that is impossible to be moved by wind, the more so if mixed with heavier debris. In many cases, the reworked deposits are overlain by undisturbed midden devoid of pumice.

We have reinvestigated most of these deposits over the past two decades and believe that Hughes and Sullivan's (1974) interpretation must be revised because the deposits can be found elevated above the limits of storm wave action and are uncharacteristic of storm wave processes. Two deposits lie at an elevation of >10 m above the existing swash limit, while nine others lie >3 m. Again, storm waves tend to erode shell- and sand-sized sediment seaward and do not deposit bodies of mixed debris several meters thick at the point of run-up on steep backshores at these high elevations. When storm waves do deposit this size of sediment, it is in situations conducive to overwashing, where sorting by particle shape and size is inevitable. The only process that can deposit sediment in these situations is tsunami run-up.

## Estuarine Run-up Deposits

Tsunamis operate best within semi-closed embayments where their long periods of between nine and 30 minutes can resonate at frequencies approximating the resonance frequency of the bays. These types of embayments characterize the New South

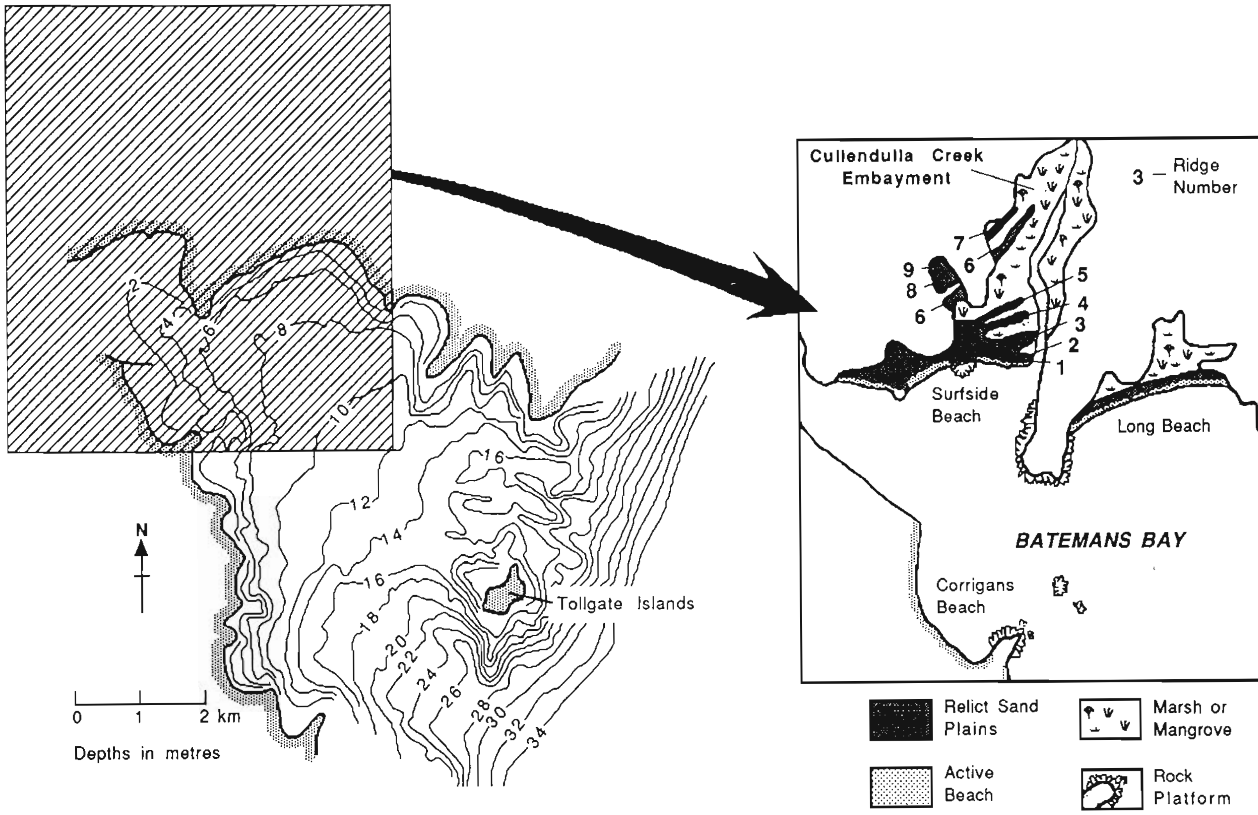


**Figure 6.** Location map of the Cullendulla Creek, Batemans Bay sand deposits.

Wales coast; we believe that tsunami resonance has operated within several of these. At Batemans Bay, a series of run-up ridges mistakenly interpreted as cheniers has been formed. Batemans Bay is a 14.4 km long funnel-shaped embayment, averaging 11 m in depth and semi-compartmentalized by N-S structurally controlled headlands (figure 6). This shape is conducive to resonance and enhancement of tsunamis entering from the open ocean. The basin resonance periods are 4.5, 13.4, 22.5, and 31.0 minutes, values that fall within the range of typical tsunami periods measured in harbors (Bryant 1991).

At the back of the embayment on its north side, a series of six isolated ridges and one bench has developed along Cullendulla Creek. The ridges rise 1.0–1.5 m above the surrounding estuarine flats and increase in width and volume toward the bay, where they merge into a barrier complex consisting of at least eight ridges behind Surfside Beach. The isolated ridges appear to overlie estuarine muds and are asymmetric in shape, rising steeply to a height of 0.5–0.6 m and then dropping landward over a 30–40 m distance to the estuarine surface. The most landward ridge is situated behind a high tide platform remarkably free of any debris, even though it fronts a cliff consisting of vertically bedded Ordovician metamorphic rock. Various authors (Donner and Junger 1981; Thom et al. 1981) have labeled the ridges as cheniers. Donner and Junger (1981) and Thom et al. (1986) summarize $^{14}C$ dates on shell within the ridges and underlying estuarine fill (figure 7). Both sets of $^{14}C$ dates display a curiously irregular pattern instead of the expected clear-cut shoreward decrease in ages. Consequently a complex evolution after 3000 yr BP has been proposed for the embayment, involving a progressive shallowing of the inner part of Batemans Bay and subsequent reduction of wave energy (Donner and Junger 1981; Thom et al. 1986). Sediment was also brought into the embayment by tides, and younger shells invaded the estuarine flats as the embayment filled in.

We have re-investigated this embayment, obtained additional $^{14}C$ dates from the main ridge sequence, and used thermoluminescence to date the quartz sands. In addition, we found sand deposits that have not previously been described, forming raised banks deposited 1 km up a creek entering the SW corner of the Cullendulla Creek embayment and 1.6 km inland of the present bay shoreline (figure 6). The banks are 30–40 m wide and

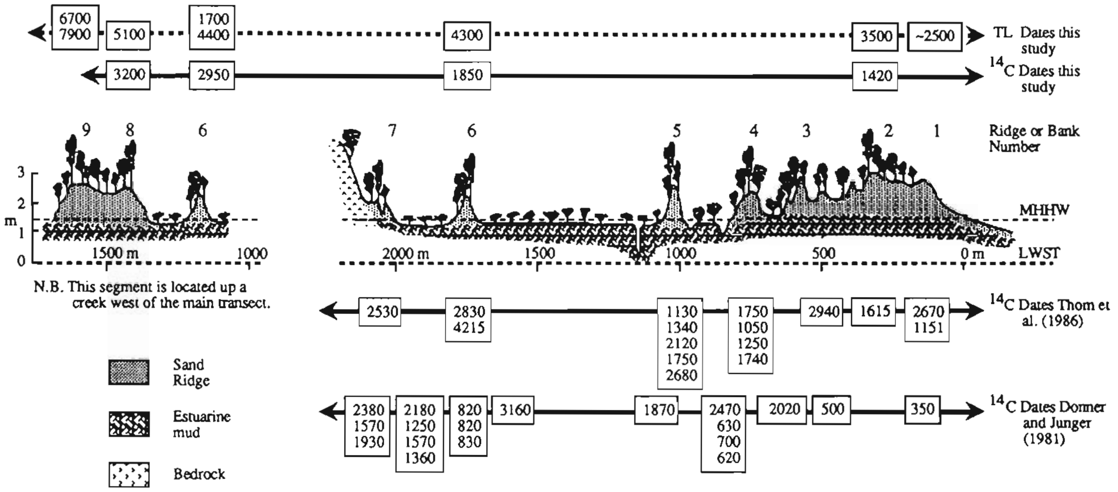


**Figure 7.** Schematic cross-section of the chronology of the Cullendulla estuarine plain.

0.75–1.0 m above the high tide limit. The innermost shoal consists of clean sand for a depth of 1.0–1.5 m overlying lenses of shell. The shoals are fronted by a ridge that is located from the main embayment sequence and overlies a mottled estuarine clay, with both rounded and angular cobble-sized material located at the contact. Evidence along this coast suggests that this estuarine fill most likely was deposited under sea levels up to 2 m higher than present (Bryant et al. 1992).

Emplaced within the estuarine fill is at least one shell-rich sand layer analogous to the type of tsunami sand deposits described in estuarine environments in Scotland (Dawson et al. 1988) and the Columbia River estuary (Atwater 1987). A similar horizon is also described by Macphail (1974) at Fingal Bay, Port Stephens, where we have described various anomalous boulder deposits attributable to tsunamis. Five TL dates were obtained from the sands within the estuarine muds and sand bodies. The shell assemblage is unusual in that it consists of six species characteristic of estuarine mudflats, four species characteristic of sheltered rocky shores, six species found on open ocean sandy beaches, seven species located on exposed rock platforms and one species found on the inner continental shelf. These observations are in agreement with those of Donner and Junger (1981) for the main embayment except that all our shell was virtually unbroken. This degree of shell mixing has also been noted for other tsunami deposits, namely the Lanai boulder gravels in Hawaii (Moore and Moore 1988).

No ocean reservoir correction was applied to the $^{14}$C dates. The dates were ranked relative to each other by stratigraphic positioning, and the landward trends in $^{14}$C ages assessed using Spearman's rank correlation analysis (figure 8). The $^{14}$C dates from the sand ridges show a general increase in age landward (Spearman's rank r = .53, n = 20, significance level 0.01); however the majority of ages span a restricted period between 1000–3000 yr BP and within that range show considerable spatial scattering across the embayment (figures 7 and 8). The trend in $^{14}$C dates from the estuarine fill, while appearing to parallel the trend apparent in the ridges, is not significant at the .05 level (Spearman's rank r = .37, n = 16, significance level = .063). In addition, average shell ages from the fill are younger than the shell material from the ridges. The $^{14}$C dates from the sand ridges are parallelled

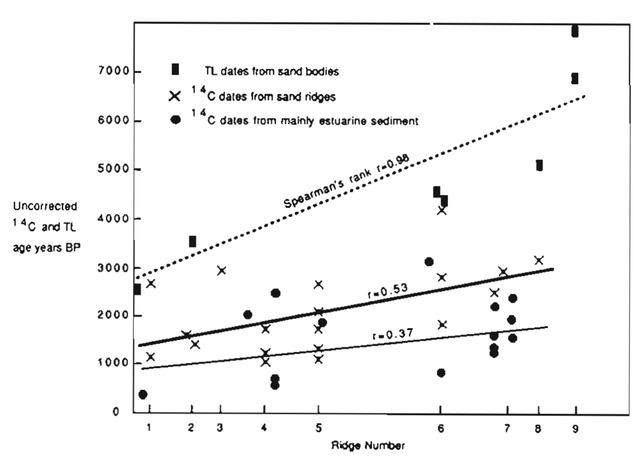


**Figure 8.** $^{14}$C and TL dating trend lines across the Cullendulla embayment. Note that only TL dates for sand units or lenses have been plotted. This excludes sample W983 dating at 1700 BP from the levee of the tidal creek near unit 6.

by the TL age of quartz sand (Spearman's rank r = .98, n = 7, significance level <.01) from the same sites; however, in most cases the TL ages of the sands are 1500–1900 yr older than the $^{14}C$ dates. The sand material in the main ridge sequence dates between 3500 and 4400 BP, and that from the banks at the head of the small creek range in age from 5100 to 7900 BP. This latter age is older than the earliest date for the arrival of the Holocene marine transgression along this coast (Jones et al. 1979). Also unusual is the fact that the surface sand on the innermost bank is apparently older than that at depth.

As thermoluminescence does not necessarily date a deposit, but rather the time that the sand within that deposit was last bleached by sunlight, it might be argued that the sand in this sequence has not been thoroughly bleached and is therefore giving too great an age for the ridges. However, the experimental evidence indicates that all of the Batemans Bay sand samples are well bleached. Moreover, there is good agreement for ridges 1 and 6 between TL ages and some of the $^{14}C$ ages reported by Thom and his colleagues (Thom et al. 1986).

The accepted origin of this supposed chenier plain is that the ridges formed under a swell and wind regime similar to the present (Donner and Junger 1981; Thom et al. 1986). This regime consists of deep water storm waves in excess of 7 m, a value that can recur every 3–5 yr on top of a surge that may exceed 2.0–2.2 m above AHD within the bay. We do not believe that this hypothesis is realistic because waves undergo substantial refraction into the inner bay with wave heights being reduced by more than 50% along Surfside beach. To deposit sediment up the re-entrant within Cullendulla Creek, waves would have to travel in the most convoluted pathway possible through a 600 m gap at the most sheltered part of Surfside Beach where wave refraction has reduced wave energy by 90%, bend 500 m west behind a large rock promontory, and then bend northward up the re-entrant for a distance of 600 m, at all times shoaling across a shallow embayment that our evidence suggests was already partially infilled with estuarine sediment before the emplacement of the landward ridges (figure 6). We believe that tsunamis are the only viable mechanism to have sufficient energy to deposit the ridges and sand banks throughout Cullendulla embayment as run-up deposits. The chaotic mixing of sand and shell, the varied assemblage of shell species spanning the spectrum of marine environments, and the irregular arrangement of $^{14}C$ and TL dates shown in figures 6 and 7 support this conclusion. Furthermore, examination of anomalous ridges in other embayments along this coast is suggestive of a similar tsunami origin.

The TL dates and the concomitant high level of bleaching implies that the sands in the ridges probably originated from dunes constructed at the back of a barrier within Batemans Bay. One or more tsunami events affected Batemans Bay and swept this older sand, together with shell dating around the time of each event, into the Cullendulla Creek embayment. Sand lenses within the estuarine fill support this hypothesis. The suggestion that there was more than one event is based upon three observations. First, the TL age of sand in the re-entrant dating older than 6700 BP is substantially older than material in the main body of the embayment. This sand also contains shell having the oldest $^{14}C$ age of around 3000 BP. We believe that the first tsunami event occurred around this time. At least one event occurred shortly afterward, laying down the inner series of ridges, and was followed by the completion of estuarine infilling. The presence of shell species characteristic of more open marine environments in sand lenses within this estuarine fill and the tendency for younger shell ages and their random dispersal in the seaward ridges, indicates that this estuarine infilling was influenced by later tsunami events. Moreover the TL age from sand in the tidal creek dating at 1700 BP is younger than any other sand in this embayment, including the present beach, but corresponds to the $^{14}C$ ages of many of the shells. These dates are remarkably similar to a modal age of 1500–1700 BP, being obtained from sand and shell from modern reworked deposits along the New South Wales coast (Young et al. 1992). A similar age also appears in the MacCauleys Beach tsunami sediments described in this paper. We believe that this age represents a significant event in coastal sedimentation along the New South Wales coastline. Many environmentally corrected $^{14}C$ shell dates in this embayment are younger than the 1700 BP age of the estuarine sand lens. Given that these young shells are mixed with much older shells and sand, we suggest that they were deposited by, and indicate the date of a yet more recent tsunami occurring within the last 500–700 yr. This is in line with the evidence from Mystery Bay and Haycock Point presented above.

## Concluding Remarks

This paper has not been an attempt to play down the role of storms in influencing existing coastal sedimentation. On the contrary, storms are important in moulding coastal landforms along the New South Wales coast (Bryant and Kidd 1975; Bryant

1988, 1991). Nonetheless, tsunamis are an alternative mechanism for reworking coastal sediment (Lander and Lockridge 1989) and ultimately for imprinting upon the landscape a signature of convulsive events that in some areas has not been removed over thousands of years (Young and Bryant 1992). The difficulty in invoking storms for all coastal deposition lies not just in the insufficient magnitude of observed events but also in the inapplicability of storm wave processes to account for a suite of anomalous deposits. For instance, the mixed sand and boulder deposits at MacCauleys and Bellambi Beaches, the bouldery shell mounds at Bass Point and the highly unsorted sand-to-boulder deposits found along the coast, cannot be explained by storm waves because such waves erode sand from the shoreline, transport coarse sediment shoreward as a body, and sort debris in a shore normal direction. Furthermore, there is minimal description in the literature for sand movement shoreward under storm waves, except for overwash deposits on barriers (Leatherman 1981), and shoreline morphology at the sites described here is not conducive to overwash. Tsunamis can move and deposit highly bimodal sediment mixtures (Lander and Lockridge 1989). If tsunamis have been present along this coast, such effects should be nowhere more evident than inside Batemans Bay, where they would be enhanced by resonance. The presence of saw-toothed sand ridges in the main embayment, of sand banks tucked in the most sheltered location in the embayment, of the chaotic mixture of shells ranging from open marine to estuarine environments, and of the broad timespans covered by $^{14}C$ and TL dates from individual deposits is evidence that such events did indeed occur.

Unfortunately it is difficult to date with high resolution the occurrence of tsunami events. We have elsewhere argued that a truly enormous convulsive event occurred about 105,000 BP (Young and Bryant 1992). The Batemans Bay evidence suggests several events occurred in the Holocene, beginning possibly around 3000 BP. The clustering in the age of shells and sands along this coast around 1500–1700 yr BP is baffling and may represent another hiatus in sedimentation that was produced by a tsunami event. Certainly the dating results from shell in the dump ridge at Mystery Bay and on the *Galeolaria* worm tubes at Haycock Point are surprisingly young. These dates came out as modern. It may therefore be fortuitous that European settlement missed by a very short time the most recent of what has been a succession of tsunami events affecting this coast throughout the Late Holocene.

Several triggering mechanisms for tsunamis can be invoked for eastern Australia. While Pacific Ocean tsunamis in historical times have not registered as significant events along this coast, they cannot be ruled out as a source over geological time (Young and Bryant 1992). Alternatively a regional source in the Tasman Sea including the chain of seamounts about 300 km offshore, or the Alpine Fault on the west coast of New Zealand, might be considered. While the Australian east coast is widely regarded as tectonically quiescent, the recent severe damage to the city of Newcastle by an earthquake of 5.6 magnitude on the Richter scale forcibly demonstrates that the region is seismically active. Finally, tsunamis could be triggered by earthquakes under the continental shelf or by slumps at the shelf edge (Moore and Moore 1988). The continental shelf edge along the New South Wales south coast has been a preferred location of seismicity in recent times (Doyle et al. 1968). Whatever the source of tsunamis, the observations presented in this paper indicate that tsunamis can no longer be ignored as a significant agent in sediment reworking and landform evolution along this coast. The recent literature detailing tsunami sedimentation in Washington State (Atwater 1987) and the British Isles (Dawson et al. 1988), where seismicity is perceived as rare, broadens the implications of this study. The observations of a convulsive tsunami along the southern New South Wales coast apparently linked to Hawaii during the Last Intergalcial (Young and Bryant 1992) implies that such events on geological timescales must be considered in any scenario of coastal evolution in the Pacific Ocean region.

The preservation potential of the types of tsunami events described in this paper is good. Both of the sandy bimodal tsunami deposits in northern Wollongong are mid-Holocene in age and have survived significant periods of coastal erosion. They are being buried by modern aeolian sediments, lie stranded above storm wave limits or are being preserved inland from the zone of present wave activity. Other counterparts recorded along this coast have similarities to Holocene sandy tsunami deposits found in Washington State (Atwater 1987) and the British Isles (Dawson et al. 1988). Cobble and boulder deposits that protrude above the landscape are less likely to be preserved because they are either subject to weathering or subsequent erosion. Because of their exposure on the open coast on headlands, dump and disturbed deposits are very vulnerable to reworking especially under oscillating sea levels. Such coarse deposits can only be preserved if they are pushed inland on wide coastal plains or thrown substantially above the

zone of storm wave activity. Such tsunami deposits with a high preservation potential have been found elevated on both the islands of Crete in the Mediterranean Sea (Myles 1985) and Lanai in Hawaii (Moore and Moore 1984) dating at 3600 and 105,000 BP, respectively. In light of the observations presented in this study, a tsunami origin should be considered for any highly bimodal, chaotically sorted, or coarse sized sediments of marine origin, lying unconformably within the rock record.


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