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## **Catastrophic wave (tsunami?) transport of boulders in southern New South Wales, Australia**

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### Abstract

Deposits of large boulders above modern limits of storm waves along the coast of southern New South Wales record catastrophic wave action. The largest boulders that were moved weigh 80-90 tonnes, and the maximum height of wave action was 32 m. Hydraulic reconstruction indicates flow depths of 3.4 and perhaps > 4 m and velocities of 5.5 m/s to 10.3 m/s. Cavitation features on some rock surfaces support the estimates of maximum velocities. A remarkably limited range in the orientation of imbricated boulders along 150 km indicates that the deposits record a single event that approached from the SE. to SSE. The fabric and size of the deposits point to a tsunami wave train rather than to exceptional storm waves. The most probable source of the wave train is the Macquarie Ridge in the south Tasman Sea. An earliest Holocene age for the event is indicated by a thermoluminescence determination of 9.5ka from sand associated with one boulder deposit, and by the transport of some boulders from below present sea level.

### Keywords

boulder transport, tsunami, New South Wales

### Disciplines

Life Sciences | Physical Sciences and Mathematics | Social and Behavioral Sciences

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# Catastrophic wave (tsunami?) transport of boulders in southern New South Wales, Australia

by

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with 8 figures and 2 tables

**Summary.** Deposits of large boulders above modern limits of storm waves along the coast of southern New South Wales record catastrophic wave action. The largest boulders that were moved weigh 80–90 tonnes, and the maximum height of wave action was 32 m. Hydraulic reconstruction indicates flow depths of 3.4 and perhaps > 4 m and velocities of 5.5 m/s to 10.3 m/s. Cavitation features on some rock surfaces support the estimates of maximum velocities. A remarkably limited range in the orientation of imbricated boulders along 150 km indicates that the deposits record a single event that approached from the SE. to SSE. The fabric and size of the deposits point to a tsunami wave train rather than to exceptional storm waves. The most probable source of the wave train is the Macquarie Ridge in the south Tasman Sea. An earliest Holocene age for the event is indicated by a thermoluminescence determination of 9.5 ka from sand associated with one boulder deposit, and by the transport of some boulders from below present sea level.

**Zusammenfassung.** Gerölltransport durch Wellen katastrophaler Stärke (Tsunami?) im südlichen Neusüdwaales, Australien. – Ablagerungen großer Gerölle oberhalb des Niveaus heutiger Sturmwellen entlang der südlichen Küsten von Neusüdwaales dokumentieren die Wirkung von Wellen katastrophalen Ausmaßes. Die größten Gerölle, die hierbei bewegt wurden, wiegen 80–90 Tonnen, wobei die maximale Wirkungshöhe der Wellen 32 m betrug. Die hydraulische Rekonstruktion deutet auf Wassertiefen von 3,4 bis eventuell 4 m und Geschwindigkeiten von 5,5 m/s bis 10,3 m/s. Die Schätzungen der maximalen Geschwindigkeiten werden durch Kavitationsmarken auf einigen Gesteinsoberflächen unterstützt. Die Orientierung der Gerölle in Dachziegellagerung zeigt eine erstaunlich begrenzte Spannweite entlang einer Strecke von 150 km. Hierdurch wird angedeutet, daß die Ablagerungen auf ein einziges, von SE bis SSE kommendes Ereignis zurückzuführen sind. Das Gefüge und die Größe der Ablagerungen deuten eher auf einen Tsunami-Wellenzug als auf außergewöhnliche Sturmwellen als Ursache hin. Die wahrscheinlichste Quelle des Wellenzuges ist der Macquarie Rücken in der südlichen Tasmansee. Durch die Datierung von mit der Geröllablagung in Zusammenhang stehendem Sand mittels Thermolumineszenz auf 9,5 ka, sowie durch den Transport einiger Gerölle aus Bereichen unterhalb des heutigen Meeresspiegels, wird ein frühestholozänes Alter für das Ereignis angedeutet.

**Résumé.** Transport de gros blocs par des vagues catastrophiques (tsunami) en Nouvelle Galles du Sud, Australie. – Des accumulations de gros blocs au-dessus de la limite actuelle des vagues de tempête sur la côte de Nouvelle Galles du Sud attestent l'intervention de vagues catastrophiques. Les plus gros blocs qui

ont été portés en altitude pèsent 80 à 90 tonnes et la limite supérieure d'action des vagues est de 32 mètres. Une reconstitution des conditions hydrauliques indique des profondeurs de flot de 3,4 m et peut-être même de plus de 4 m, et des vitesses correspondantes de l'eau de 5,5 à 10,3 m/sec. Ces estimations sont attestées par des traces d'érosion sur quelques surfaces. Une étude de l'orientation de blocs imbriqués sur 150 km de longueur indiquent qu'ils se sont mis en place en une seule phase et que le flot venait d'un secteur étroit compris entre le SE et le SSE. La structure et la taille des dépôts est en faveur d'un tsunami plutôt que de vagues de tempête exceptionnelle. L'origine la plus probable du train de vagues est le Macquarie Ridge dans le sud de la Mer de Tasmanie. Un âge de 9.500 ans a été obtenu par la thermoluminescence appliquée à du sable associé à un dépôt de blocs.

### *Introduction*

Although the role of catastrophic events is clearly recognised in fluvial geomorphology (e. g. BAKER 1978, ELFSTROM 1987), it has received remarkably little attention in coastal geomorphology. This is especially true of tsunamis. Twenty five years have passed since COLEMAN (1968) pleaded for their consideration in studies of erosion on coasts and continental shelves, but there are as yet relatively few accounts of the geomorphological impact of tsunami (e. g. MOORE & MOORE 1984, MYLES 1985, DAWSON et al. 1988), and most of these are concerned with the impact of tsunami near their source. We have argued recently (YOUNG & BRYANT 1992, 1993, BRYANT et al. 1992, YOUNG et al. 1993) from evidence in southern New South Wales that their impact can be seen on coasts that are far from the source of tsunami. Recognition of tsunami impact on coasts thought to be free from this hazard has important implications not only for historical studies of shorelines, but also for coastal zone management. In this paper we extend our earlier work by reporting evidence for catastrophic wave transport recorded in massive boulder accumulations at several sites on the coast south of Wollongong (fig. 1).

Considerable caution is, of course, needed in the interpretation of individual boulders or small accumulations of them. This is especially so in sandstone and granitic terrain, from which our examples are drawn, where weathering or toppling of blocks is common. Caution is also needed where boulders have been transported seaward in debris flows, as is the case along the shoreline north of Wollongong. Consequently we report only accumulations of boulders where erosion and transportation by waves is beyond doubt.

### *Jervis Bay*

We reported previously that a ramp on the coastal cliffs on the southern side of the entrance to Jervis Bay has been swept by waves to a height of 34 m above mean sea level (A.S.L.), and that a boulder had been thrown landward by wave action from the flanking cliff into a pool at the top of this ramp (YOUNG & BRYANT 1993). Similar, but much more impressive evidence of wave action can be seen at the top of the cliffs near Mermaid's Inlet, 10 km north of the entrance to Jervis Bay (fig. 1). At this site boulders, measuring up to  $4.0 \times 2.3 \times 0.4$  m, have been ripped from the cliff face and thrown upwards onto the sandstone summit platform. The source of the boulders is clearly defined by fracture faces on the cliff, and the slight weathering on the fractured rock faces shows that this is not an ancient deposit formed at higher sea levels,

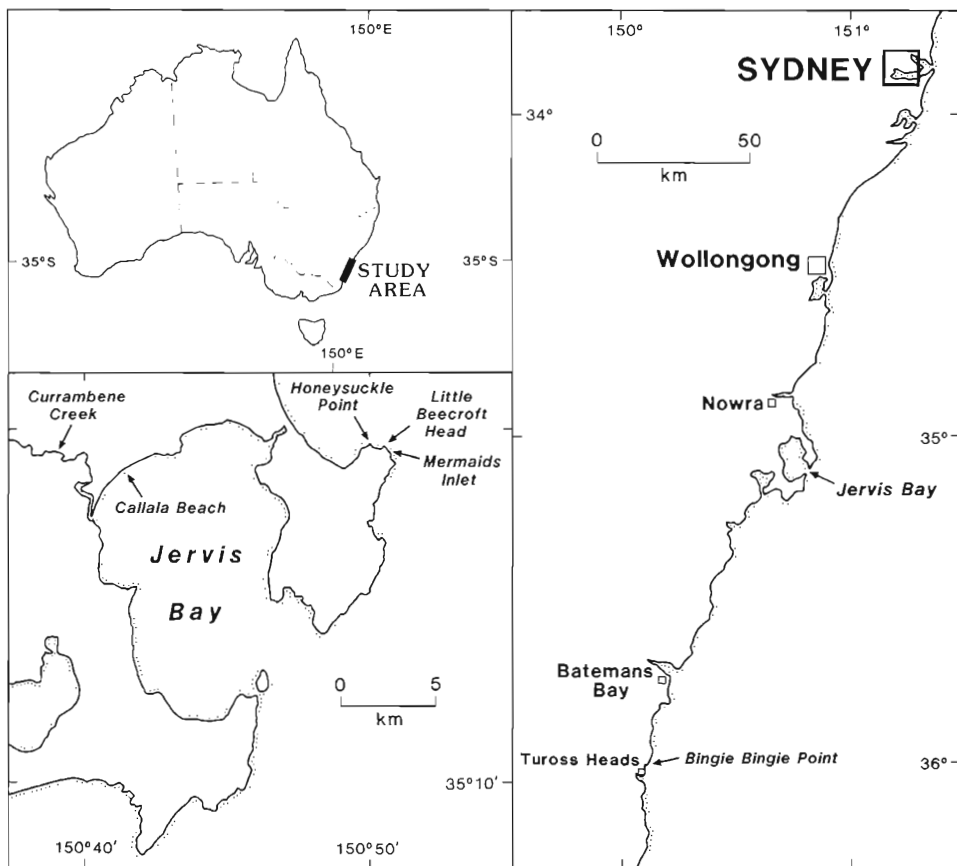


Fig. 1. Location of field sites.

but that erosion occurred during the late Holocene with the waves sweeping up the entire 32 m of the cliff. Indeed, the waves must have substantially overtopped the cliff because the distinctive iron-stained summit beds were eroded to a depth of 0.5 m as slabs up to 2 m long were ripped off and thrown into an imbricated pile (fig. 2). In front of the pile of displaced boulders, which stands about 2 m high, the sandstone surface has been stripped bare. As the imbrication of the measured boulders has a mean bearing relative to True North of  $110^\circ$ , with a Standard Deviation of only  $18^\circ$ , the wave train apparently approached the shore from E.S.E.

About 1 km further north the shoreline swings around to the west. Beyond Little Beecroft Head (fig. 1), the shoreline takes the form of a ramp which closely follows the  $8^\circ$  dip of the sandstone towards E.N.E. down the arm of an anticline. The southeastern part of the ramp is backed by cliffs reaching a height of 20 m, but the northwestern part rises as an inclined plane to a height of about 13 m. On the south-



Fig. 2. Imbricated sandstone boulders 32 m ASL above the cliffs at Mermaids Inlet, Jervis Bay. The boulders have been thrust over the remnant of the upmost bed from which they have detached. Note the intensely eroded surface across which waves flowed from left to right.



Fig. 3. Imbricated boulders on the sandstone ramp at Little Beecroft Head, Jervis Bay. Waves which moved the boulders ran up the ramp which dips seaward (left to right) at 8°.

eastern part of the ramp catastrophic wave action, clearly recorded by displaced boulders, can be traced over the top of the backing cliffs, and on the northwestern part to the very top of the ramp from whence the wave train apparently plunged into the adjacent bay (fig. 1).

The main source of the transported boulders is not the ramp itself, but a large depression, about 20 m wide, cut in the base of the southeastern end of the ramp. Boulders, up to 5 m across, were swept from this source across the now bare surface of the ramp and thrown in an imbricated pile against the backing cliff (fig. 3). Slabs of sandstone, > 2 m across, at the top of the cliff were pushed landward 0.5 m to 1 m from their original location, and the crevasses opened by this displacement were then partly filled with debris. Boulders were also carried > 10 m inland from the cliff edge and now form a distinct mound under a thick cover of scrub. The northwestern part of the ramp also is swept free of debris up to a height of approximately 7 m, where there are several large isolated boulders, but the main mass of debris extends from a height of approximately 9 m to the top of the ramp (fig. 4). This deposit includes boulders ranging in size from 4.5 m to 7 m on the a axis, 2.4 m to 5.4 m on the b axis and 1.1 m to 1.8 m on the c axis. Comparable dimensions for boulders now covered by scrub behind the top of the ramp are 3.2 m to 0.8 m, 1.8 m to 0.45 m and 0.8 m to 0.3 m. The boulders under the scrub and on the ramp are well imbricated with a mean direction of 78°, and a standard deviation of 28°. The differences in mean and standard deviation of direction of imbrication between Mermaid's Inlet and the ramp at Little Beecroft Head indicate that they are drawn from distinct populations ( $p < 0.001$ ), but we believe that the difference is due to the constraints placed on wave approach by the configuration of the ramp, and that both masses of boulders were therefore emplaced by the same event. The abrupt westward swing of the shoreline and the cliffs bounding the southern side of the ramp preclude the approach of waves from a bearing of > 115°; the effect of refraction would be further increased as waves surged up ramp surface which dips at a bearing of 75°. Wave approach from E.S.E. is certainly indicated by the displacement W.N.W. of blocks at the top of the cliff.

At Honeysuckle Point, 0.5 km further west, another ramp, in this case dipping 6° to the N.W., has been formed on the folded sandstone (fig. 1). The eastern edge of this ramp is bounded by a cliff which rises to a height of about 8 m. Boulders 3 m to 4 m in diameter are imbricated against the base of the cliff, and although some of these have toppled from the cliff face, many have apparently been carried up from the platform below. Moreover, the sandstone above the cliff has been stripped bare over distances of up to 20 m, beyond which lie complex deposits of boulders. The southern limit of boulders transported as the wave train passed obliquely over Honeysuckle Point is still clearly recorded by distinctive, and well-defined mounds of debris, now covered by dense scrub. These mounds, which run approximately E.S.E.-W.N.W. and descend from an elevation of about 8 m to about 5 m, are up to 10 m wide, rise to about 2 m above the sandstone surface, and contain boulders > 2 m on the a axis, 1.3 m on the b axis and 0.5 on the c axis. By far the greatest quantity of the bouldery debris is piled in a series of four mounds, which are aligned approximately N-S and run obliquely down the sloping surface of the ramp. These mounds are thus aligned at roughly 90° to the general direction of the passage of the wave train. Furthermore, the general direction of movement is clearly recorded by the imbrication directions which were measured on boulders in three of the largest mounds. In the mound clos-



Fig. 4. Boulder pile 9–13 m ASL at the top of the sandstone ramp at Little Beecroft Head, Jervis Bay. The boulders can be traced under a thick vegetative cover to the left of the photo.



Fig. 5. Boulders on the sandstone ramp dipping left to right at  $6^\circ$  at Honeysuckle Point, Jervis Bay. Note the boulders thrust against the 2 m scarp cut into the ramp. The large boulder weighing about 80 tonnes, shown in the centre of the photo, was lifted vertically from the space immediately below it and rotated  $50^\circ$ .



est to the east-facing cliffs the mean is  $86^\circ$  and standard deviation is  $28^\circ$ ; in the second of the large mounds the mean is  $86^\circ$  and the standard deviation is  $20^\circ$ ; and in the third mound the mean is  $80^\circ$  and the standard deviation is  $24^\circ$ . Comparison of the imbrication from all three mounds and from the ramp on Little Beecroft Head shows that they are drawn from the same population ( $p > 0.90$ ) and were apparently formed by the same event. The mounds rise 2 to 3 m above the surface of the ramp, vary in width from about 7 to 15 m, and are separated by generally bare rock surfaces which are about 10 to 15 m wide, although one is about 40 m wide. This sequence of mounds, separated by generally bare spaces, and aligned obliquely to the direction of flow, seems similar to the boulder ripples described from catastrophic stream floods (BAKER 1978) and is similar to a category of sediment deposits linked in previous work to tsunami along this coast (BRYANT *et al.* 1992).

Much of the debris on the ramp was ripped from the seacliffs on the eastern side. The other main source, and certainly the source of the biggest blocks, was a 1 to 2 m scarp, aligned approximately N.-S. 15 to 20 m behind those cliffs. The remainder of the ramp seems to have suffered very little erosion other than the stripping of soil and a few centimetres of weathered rock, for not only does most of the surface lack joint-bounded plucking scars, but what seems to be the lower mottled zone of a lateritic profile is partly preserved. As most of the boulders that were plucked from the cliffs and the low scarp are joint-bounded, their size depends much on local variations in fracture spacing in the sandstone. Boulders 2 m to 5 m on the a-axis, 2 m to 3 m on the b-axis and 0.5 m to 1.5 m on the c-axis are common. The two largest measure  $7.6 \times 2.2 \times 1.4$  m and  $9.8 \times 2.9 \times 1.3$  m; the first of these was lifted vertically 1.8 m up the low scarp and swung  $50^\circ$  westward on its a-axis (fig. 5), while the second was transported 40 m across, rather than down, the platform from its source at the low scarp.

### *Tuross Head*

Tuross Head lies approximately 140 km south of Jervis Bay. The headland, which is cut in tonalite, rises to an elevation of only about 10 m. As at Jervis Bay, trains of boulders can be traced up from at least present sea level into scrub and grass cover above the limits of contemporary wave action. In this case, however, the boulders reach elevations of only about 5 to 8 m. Furthermore, because of the relatively close spacing of joints in the tonalite, the boulders are generally 1–2 m on the a-axis, 1–1.7 m on the b-axis and 1.4–0.5 on the c-axis. These very angular boulders, which have pitted surfaces, contrast to the highly rounded, unweathered and smaller clasts of the modern boulder beaches. The impact of waves on an adjacent low cliffline has rotated a block of tonalite, measuring  $6 \times 5.5 \times 3$  m, about 1 m from its original position, so that, although it is still vertical, it now lies on top of rounded clasts of the boulder beach.

As at Jervis Bay, the wave train which shifted the boulders approached from E.S.E. and S.E. This is demonstrated by the dominant imbrication, and the movement of boulders from their source, as indicated by the location of major quartz veins and textural and mineralogical variations in the tonalite. In contrast to most of the Jervis Bay deposits, however, the boulders at Tuross Head form two roughly parallel trains occupying bedrock troughs which are aligned parallel to the direction of movement (fig. 6). The troughs are similar to rat-tail forms sculptured in bedrock by horseshoe vortices around obstacles and attributed to sub-glacial waterflow (SHARPE & SHAW



Fig. 6. Elongated train of imbricated boulders at Tuross Heads. Transport was enhanced by the concentration of flow (left to right) through an elongated trough, similar to the "rat-tail" forms of sub-glacial flows, cut in the tonalite.

1989, TINKLER & STENSON 1992). These bedrock sculptured features will be described in more detail in a subsequent paper. The largest of the two boulder trains extends about 200 m downstream. In places the train is only one boulder thick, but the general height above bedrock is 2 to 3 m. Undulations superimposed on this elongated deposit seem to be boulder ripples, for at one location the dominant direction of imbrication is reversed on the lee slope over a distance of about 50 m.

### *Bingie Bingie Point*

Bingie Bingie Point lies 5 km north of Tuross Head, but, whereas the latter juts out to the S.E., this promontory is aligned to the E. The contrast in alignment is important, because at Bingie Bingie Point there is greater scope for substantial overwashing by tsunami waves. The headland is about 300 m long, 100 m wide, rises to an elevation of about 8 m, and is cut by a shallow depression facing S.E. Bingie Bingie Point is cut not only from tonalite, but also from gabbroic diorite, with a major aplitic dyke at the eastern extremity and basaltic dykes on the southern side. The greater petrological diversity provides added scope for determining the direction of the transport of boulders. The movement of boulders by very large waves approaching from S.E. is even more spectacularly preserved at Bingie Bingie Point than at Tuross Head. Boulders, the largest of which measures  $6 \times 3.4 \times 2.4$  m, have been piled up on the southern shore, some reaching heights of 6 m above the present limits of runup at high tide. And a major train of boulders, the largest measuring  $2 \times 1.5 \times 1$  m, has been transported through the central depression from the southern to the northern shore (fig. 7). The origin of the boulders is obvious both from the entirely stripped southern

entrance to the depression and by petrological variations between the southern and northern sides. The displaced boulders on the southern flank of the depression demonstrate that the depth of flow through it must have reached 5 m given the size of some of those boulders (fig. 7). Eastward of the depression the southern shore is almost completely bare of debris, but boulders, measuring 1 m on the a-axis and 0.5 m on the b-axis, have been carried northward 23 m from their source on basaltic dykes which strike eastward, 5 to 15 m behind the southern shore.

Considerable refraction of the wave train apparently occurred at the extremity of Bingie Bingie Point, where a shallow rock shelf extends about 200 m offshore. The change in direction of wave approach from S.E. to E.S.E. and E. is recorded in the transport of boulders from the aplite dyke at the eastern extremity of Bingie Bingie Point. Numerous large blocks have been torn from this dyke and carried landward along the northern shore. One block, measuring  $4 \times 3 \times 2$  m, was moved 13 m, another, measuring  $2 \times 1.5 \times 1$  m, was moved 30 m, and another, measuring approximately 0.5 m on all three axes, was moved about 150 m from its source. Although waves wash over the eastern section of Bingie Bingie Point during major storms, it is nonetheless evident that the larger boulders of aplite were moved by abnormally large waves, not only because of their great size, but also by the fact that they lie on bare rock surfaces above the present limit of boulder deposition (fig. 8).

The smooth, rounded surfaces cut across tonalite and gabbroic diorite at Bingie Bingie Point are impressive (fig. 8). The rock surface is smooth and polished, but this stripping of the weathered rind seems most likely due to very high water pressure rather than to abrasion, because of the almost complete absence of sand or gravel clasts. Furthermore, the dominantly convex rounded morphology is cut in solid rock,



Fig. 7. Evidence of catastrophic overwash at Bingie Bingie Point. Many of the boulders were plucked from the eroded zone on the S.E. shore, transported (right to left) through the central depression, and deposited on the N.W. shore. Boulders scattered across eroded bedrock on the sides of the trough show that the depth of flow was  $> 5$  m.



Fig. 8. On the eastern end of Bingie Bingie Point boulders of aplite (up to  $24 \text{ m}^3$ ) were transported (right to left) across an eroded bedrock surface which displays evidence of cavitation. High velocity stripping of the surface prior to entrainment of the largest boulders indicates two peaks in wave energy similar to that reported for many tsunami wave trains.

and there are definitely no sheeting structures which could account for it. The surfaces also display evidence of bedrock sculpturing. Closed spindle flutes appear on the smooth bedrock surface at the highest point of the seaward edge of the headland, carved into resistant gabbroic diorite. Many of these obviously were formed by the excavation of microfractures running parallel to xenolithic inclusions, but most are very fresh, and are apparently erosional, not weathering features. Moreover, they occur only on the polished and rounded surface of the tonalite at the eastern end of the point, and not on the more highly elevated and weathered surfaces in the centre of Bingie Bingie Point. We suggest that these were formed by extremely rapid excavation of microfractures by wave overwash which was deep enough not only to move the large aplite boulders, but also to generate the high velocities required for the onset of cavitation (BAKER 1978). We have recently reported similar features in association with catastrophic erosion at Tura Head on the far south coast of New South Wales (YOUNG & BRYANT 1992).

*Flow Dynamics*

The best estimate of the magnitude of the wave train can be derived from the elevation to which the boulders were transported, and from the size of the largest blocks moved. At Tuross Heads, a block with a volume  $> 32 \text{ m}^3$  was dislodged from a cliffed promontory and rotated onto the existing storm wave boulder beach. At Bingie Bingie and Honeysuckle Point, multiple blocks with volumes  $> 3 \text{ m}^3$  were transported and deposited forming swashline lobes with upstream normal imbrication. At Jervis Bay, after surging 32 m up the cliffs adjacent to Mermaids Inlet, waves still had sufficient power to throw a 10 tonne block over the clifftop and to rip up slabs weighing about 8 tonnes from the summit plateau. Although perhaps reduced by diffraction at Little Beecroft Head, the wave train still swept boulders up the ramp to a height of at least 13 m, and probably as high as 20 m. And, as boulders  $> 1 \text{ m}$  were among those transported to the upper limit of deposition, tractive forces  $> 100 \text{ kg/m}^2$  were needed to move them (BAKER 1978). Indeed at Honeysuckle Point there was sufficient turbulent lift to pluck a 60 tonne block and raise it almost 2 m, and to lift another block weighing about 90 tonnes and push it 40 m horizontally across the ramp. The wave train at Bingie Bingie Point must have been of similar magnitude, for it was able to transport blocks of up to 80 tonnes.

Using standard hydraulic formulae to calculate the flow depths and velocities responsible for transporting the boulders onto the headlands is difficult because of the fact that flow occurred upslope and was not constrained within discernible channels. We have therefore approached this problem by applying the extensive theoretical and observational studies that have been undertaken relating velocity of the flow to sediment diameter (COSTA 1983, WILLIAMS 1984). Diameter can be characterised by volume, the mean b-axis of boulders or the mean intermediate axis of the coarsest fraction. Velocity relationships have been defined using the bed velocity, the critical velocity initiating transport, or the mean velocity of the flow measured some distance above the bed. The velocity required to initiate boulder movement is greater than the velocity needed to sustain transport. COSTA (1983) determined that this mean flow velocity required to sustain boulder transport approximated  $0.18 d_1^{0.487}$  where  $d_1$  is the average intermediate axis of the five largest boulders; the exponential in this relationship fits closely the sixth power law defined originally by BRAHMS in the 18th century. This relationship applies to steep downhill slopes, whereas much of the observed boulder movement occurred initially on positive slopes of  $30^\circ$  or more at the front of rock platforms or headlands. To overcome this difficulty, it is useful simply to consider the lowest mean velocity capable of transporting boulder material. WILLIAMS (1984) defines this velocity as  $0.065 d^{0.5}$ . Table 1 presents the calculated velocities using these 2 equations for the five largest boulders found at each of the locations described above. The minimum theoretical flow velocity necessary to move these larger boulders ranged between 2.2–4.2 m/s. Mean flows appear to have exceeded 5 m/s with values of 7.8 and 10.3 m/s being obtained on exposed ramps or at the top of cliffs.

Calculation of flow depth is more problematic because most formulae from the hydrological literature assume a confined channel with some knowledge of either the bed slope or the surface energy gradient. Most of the boulder deposits in our study were transported and deposited on positive slopes. Boulders were transported down-

Table 1 Mean and Lowest Flow Velocities for Boulder Movement by Tsunami on headlands along the New South Wales South coast. Sediment size,  $d_i$ , refers to the mean intermediate diameter of the five largest boulders. See text for description of velocity calculations.

Location	$d_i$ (mm)	Mean velocity m/s	Lowest Velocity m/s
<i>Jervis Bay</i>			
Mermaids Inlet	2300	7.8	3.1
Little Beecroft Head			
ramp	4100	10.3	4.2
cliff-top	1150	5.6	2.2
Honeysuckle Point	2780	8.6	3.4
<i>Tuross Head</i>	1300	5.9	2.3
<i>Bingie Bingie Point</i>	2800	8.6	3.4
<i>O'Hava Headland</i>	1100	5.5	2.2

hill by tsunami washover only at Honey-suckle Point. While the dip of this platform is  $6^\circ$ , boulder transport occurred across the dip so that the effective slope angle was no greater, and probably  $< 3^\circ$ . COSTA (1983) related particle size to average flow depth using a combination of theoretical and empirical approaches. His relationship in the form of a nomogram also incorporates bed slope. For the  $3^\circ$  slope at Honey-suckle Point, the effective flow depth was at most 3.4 m for the largest boulders having a mean intermediate diameter of 2.8 m.

### *Erosion and Deposition*

Given the likely characteristics of the wavetrain and the resulting products of erosion and deposition, it is possible to describe how these catastrophic waves impacted upon this coast. The headlands in question consist of relict, raised platforms from 2 to 8 m in height (YOUNG & BRYANT 1993), that presented a wall to the approaching waves. As these waves reached the shoreline, a vortex apparently developed in front of the raised platforms and a jet of water tore away from the top of the vortex and washed across the platform. That flow did occur as a jet can be deduced from the relatively thin flow depths of 2.6–3.4 m compared to the height of the headlands over which boulders were transported. Moreover, velocities exceeding 5.5 m/s and reaching up to 10.3 m/s (Table 1) along the most exposed section of coastline at Little Beecroft Head implies jetting. Where the waves approached exposed cliffs, they surged vertically up and over cliff faces to a height of 32 m as indicated by imbricated boulder deposits at this elevation at Mermaids Inlet. Velocities here reached 7.8 m/s. The combination of these estimated flow depths and velocities approximate the criteria for generating cavitation (c. f. BAKER 1978), and the presence of s-forms at Tuross Heads and Bingie Bingie Point leaves little doubt that cavitation did occur.

We envisage that, as the waves reached the shoreline, they generated vortices at the seaward edge of the headlands. At Bingie Bingie jetting across the raised platform produced the high velocity flow required for cavitation and the production of spindle flutes at the platform edge. At Tuross Heads the initial flow ran up a ramp carving out the two parallel flutes in a similar fashion to the formation of "rats-tails" theorised by TINKLER & STENSON (1992). At Jervis Bay the first waves moved considera-

ble boulder talus slabs from the base of cliffs and deposited them as a lobate boulder swash line or scattered dusting of boulders up to 12 m to 13 m above sea-level. At Honeysuckle Point a mass of imbricated boulders was initially deposited at the top of a platform ramp with boulders dropping out of the flow as its competency decreased through frictional dissipation or spreading of the flow. Subsequent waves moved a succession of boulder material over the headland depositing them en echelon on top of this initial deposit.

As the waves decreased in height they continued to pound into the cliff faces or break over the outer edges of the raised platforms. Boulder material was broken off along joint lines and prepared for subsequent transport. Relict preparation zones adjacent to Tuross Heads and Honeysuckle Point attest to this process. Material from these preparation zones was then moved by another period of high waves along the flutes at Tuross Head or overwashed at Bingie Bingie and Honeysuckle Points. At Bingie Bingie the second period of high flow formed boulder lobes in the middle of the headland and drove a continual supply of boulder material around the seaward part of the headland. At Honeysuckle Point this flow led first to stripping of weathered parts of the platform ramp and then to deposition of boulder mounds at small clifflines eroded along bedding planes on this ramp. Individual waves are probably represented by single contact-imbricated boulders in the mounds. The lack of percussion marks or chipping on most boulders, some of which are highly fretted by chemical weathering, is suggestive of sediment-starved flows with each boulder moving in suspension without bed-contact until deposition. If this was the case, flow depths must have exceeded 4 m, the maximum intermediate diameter of the boulders.

#### *Storm waves or tsunami*

The boulder accumulations described here obviously were moved during catastrophic events, and we suggest that these were tsunami rather than storm waves. Although storm waves certainly have shifted individual blocks of this magnitude on shore platforms along this coast (SUSSMILCH 1912), it is difficult to envisage how they could have produced such large accumulations of boulders with, for example, the distinctive fabric and spacing of those at Honeysuckle Point. Moreover, published accounts of deposits formed by storm waves do not report the very marked imbrication of boulders that characterise these accumulations. There is, on the other hand, a striking similarity in fabric between these deposits and those transported by catastrophic flow from beneath glaciers which seems indicative of the repeated overwashing of the headlands by the large volumes of water produced by a tsunami wave train. The volume of water necessary for repeated overwashing certainly could be provided by the long wavelength of each tsunami wave; as a general rule the cross-sectional area of the coast being flooding equals the cross-sectional area beneath each wave approaching the shoreline (SPASSOV pers. comm.). At Tuross Heads, the contact-imbricated boulders piled en echelon with an upstream dip of 30–50° in two single files over a distance of 150 m (fig. 6) is a pattern similar to that produced in erosive fluvial environments (KESEL & LOWE 1987). The size of the imbricated boulders not only matches that produced by high-magnitude flows in streams (BAKER 1984), but also by the catastrophic flows hypothesised for meltwaters in front of, or beneath

large glaciers (ELFSTRÖM 1987, MAIZELS 1989). We do not envisage a continuous flow of water flooding over the low headlands of the south coast but rather a succession of waves of a tsunami wave train. In its depositional mode, each wave moved boulders singly or in groups.

Observation of modern tsunami wave trains provides the simplest explanation of the evidence for bimodal energy peaks during the deposition of the boulder masses. The distribution of boulders of different sizes at Honeysuckle Point shows that at least two pulses of very large boulders were transported and deposited; the common orientation of the boulders leaves little doubt that these were pulses in a single event, rather than two separate events. A double peak in wave energy is also indicated by the fact that the largest boulders transported at Bingie Bingie lie on a smooth surface which had already been stripped by flows with velocities high enough to produce cavitation features (fig. 8). The evidence of a bimodal wave energy can be readily attributed to the fact that, whereas the earliest part of a tsunami train has the highest waves, a secondary peak tends to occur sometime later (WIEGEL 1964).

#### *Probable source and age of the tsunami*

The common direction of imbrication of the boulders over a distance of 150 km of coastline suggests that a single event was responsible for deposition of these boulder deposits. The ESE imbrication of the boulder deposits and orientation of *s-forms* point to the likely source of the tsunami that generated these features being the Macquarie Ridge in the south Tasman Sea. This region has generated 12 earthquakes with magnitudes greater than or equal to Ms 7.0 between 1920–84 (JONES & McCUE 1988). Macquarie Ridge has historically produced numerous small tsunamis measured on tide gauges along the southeast coast of the continent; however rarely have wave heights exceeded 0.1 m. Wave periods of 20–30 minutes over a 36 hour timespan have been recorded (JEPSEN pers. comm. 1993). Refraction analysis has been performed for long period tsunami traversing this region, albeit with an original source in southern Chile (WIEGEL 1964). Waves of this nature appear to impinge preferentially along the southeast coast of New South Wales. Macquarie Ridge is therefore the most likely source for tsunami in the Tasman Sea and, given favourable crustal movement, has the capability of generating a wave train consisting of 70–100 individual waves which can significantly impact upon this coastline.

The timing of the catastrophic event which transported the bouldery masses reported here is uncertain. It seems younger than the event reported previously by us (YOUNG & BRYANT 1992) from Tura Head, further south along this coast, which we interpreted as the as long distance effect of the great wave train that swept up to heights of 375 m on Lanai in the Hawaiian Islands at about 105 ka (MOORE & MOORE 1984). As the latter approached from N.E., and was almost certainly larger than the event we have described here, it would have disrupted the imbrication which clearly demonstrates the approach of the second event from the S.E. The great height to which the boulders were piled leaves little doubt that this was an event which, if it were recent, would have eliminated the depositional evidence of smaller, Late Holocene tsunamis which apparently impacted along this coast after c. 3 ka (BRYANT et al. 1992). Furthermore, there is no disruption in the sedimentary record after sea level reached its present height along this coast c. 7 ka (YOUNG et al. 1993). Given that sea



Table 2 Thermoluminescence ages on sand at the mouth of Coila Lake.

Sample	Paleodose (grays)	% K	Specific Activity (Bq/kg)	Annual Radiation ( $\mu$ grays)	TL Age (ka)
W1493	$3.9 \pm 0.5$	0.105	$7.3 \pm 0.2$	$409 \pm 49$	$9.5 \pm 1.7$
W1492	$4.1 \pm 0.9$	0.145	$7.9 \pm 0.26$	$460 \pm 49$	$8.9 \pm 1.2^{**}$

\* Note that the glow curve plateau for this sample was poorly defined.

levels were substantially depressed for most of the late Pleistocene, these constraints suggest an early Holocene age.

This conjecture is supported by the thermoluminescence (TL) determinations of the age of an anomalous body of sand associated with one of the boulder trains. At Tuross the boulder train can be traced along the shoreline into the entrance to the adjacent Coila Lake where a large body of sand juts out landward abruptly from the Holocene barrier beach which now encloses the lake. This mass appears to be a sandy distal extension of the boulder train, although it is now separated from the boulders by the modern entrance to the lake, and a distinct contrast in pedogenesis indicates that this sand mass is certainly older than the main barrier beach system. TL analysis of a sample 1.5 m below the surface of this sand mass yielded an age of  $9.5 \pm 1.7$  ka (table 2). This result is supported by an age of  $8.9 \pm 2.1$  for a sample from a depth of 1 m, but it must be pointed out that the plateau region on the TL growth curve for this sample is poorly defined. As the sea did not reach its present level along this coast until about 7 ka (YOUNG et al. 1993b), this sand mass was apparently emplaced by an event predating the final stage of the Holocene transgression. Given the position of the sand mass at the distal end of the boulder train, together with the source of many of the boulders below present sea level, we suggest that it was swept onshore in the same event which moved the boulders. A tsunami reaching heights above the early Holocene level seems the most obvious mechanism for their emplacement.

TL determinations from sand ridges in Jervis Bay also provide supporting, if somewhat more tenuous evidence of the age of the event. A tsunami entering the bay from the S.E. would have had maximum impact on the N.W. shore. Sand ridges behind Callalla Beach and at the mouth of Currumbene Creek on that shore (fig. 1) yielded ages of  $12.3 \pm 1.4$  ka and  $12.6 \pm 1.4$  ka (PEASE 1992), the 1 standard deviation error range of which overlap those of the TL determinations from Coila Lake. And, as at Coila Lake, pedogenetic differences between these ridges and the adjacent Holocene barrier beach deposits add confidence to the age determinations (PEASE 1992). As the ages from Jervis Bay are significantly older than the 7 Ka estimated for the Holocene transgression reaching modern sea level along this coast, they too seem indicative of a catastrophic surge of waves well above the mean sea level at that time.

### Conclusions

Boulder deposits above the limit of modern storm waves along this coastline record truly catastrophic wave erosion, which was most probably the result of the impact of

a tsunami wave train which ran in from the Macquarie Ridge during the earliest Holocene. This was apparently not the only impact of tsunamis here, for three have struck since about 3 ka and one at about 105 ka (BRYANT et al. 1993, YOUNG & BRYANT 1992). Consequently the possible role of tsunamis needs to be investigated not only in areas of major seismic activity, but also on presumably stable coastlines like this one seemingly far removed from major seismic zones. The need is pressing not only because of the implications of tsunami erosion for longterm coastal evolution, but more so because of the implications for coastal zone management.

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