Competing mechanisms for boulder deposition on the southeast Australian coast

Adam D. Switzer a,⁎, Joanna M. Burston b

a Department of Earth Sciences, The University of Hong Kong, Hong Kong SAR, China
b School of Geosciences, Madsen F09, University of Sydney, Sydney, Australia

Abstract

This study investigates the role of late Holocene sea-level change, large storms and possible pre-historic tsunami in the deposition of boulder features on an exposed headland and sheltered rock ramp. Large accumulations of boulders are found on coastal rock platforms, cliff tops and ramps in the Jervis Bay region of southeastern Australia. These deposits are elevated above sea-level and in places exhibit obvious signs of imbrication as a response to flow in a landward direction. The event history of these features is controversial and Holocene sea-level change, storms and tsunami can be considered as possible, non-mutually exclusive mechanisms of deposition. It is apparent that even if the detachment site, transport distance, elevation and final orientation of a boulder can be identified, deciphering the event history remains a difficult task.

© 2009 Elsevier B.V. All rights reserved.

1. Introduction

Despite recent advances in the study of the sedimentology and geomorphology of cliffed and rocky coasts (Scoffin, 1993; Nott, 1997; Hansom, 2001; Felton and Crook, 2003; Sommerville et al., 2003; Noormets et al., 2004; Williams and Hall, 2004; Stephenson and Thornton, 2005; Felton et al., 2006; Hall et al., 2006; Kennedy et al., 2007; Hall et al., 2008; Hansom and Hall, 2009), the action of coastal processes on rocky and cliffed coastlines remains understudied and complicated (Stephenson, 2000; Felton 2002; Felton and Crook, 2003; Stephenson and Thornton, 2005; Dominy-Howes et al., 2006). One aspect that has received recent attention is the detachment, transport and deposition of boulders and large clasts (Nott, 1997; Scheffers, 2002; Nott, 2003; Scheffers and Kelletat, 2003; Noormets et al., 2004; Morton et al., 2006; Goto et al., 2007; Imamura et al., 2008), Boulder deposition on the southeast Australian coast has been subject to considerable research dating back to the early 1900s (Sussmilch, 1912; Young and Bryant, 1992; Bryant et al., 1996; Young et al., 1996; Bryant, 2001; Felton and Crook, 2003; Switzer, 2005; Saintilan and Rogers, 2005; Dominy-Howes et al., 2006; Dominy-Howes, 2007).

The southeast Australian coast (Fig. 1A) is a microtidal (<2 m), temperate continental margin that experiences a dominance of high-energy ocean waves often exceeding 2 m in amplitude offshore. Superimposed on this wave-dominated environment are periodic storm events that cause swells in excess of 5 m high with offshore waves often in excess of 10 m (Roy and Boyd, 1996; Switzer and Jones, 2008a). The coast is best described as wave-dominated due to a persistent background swell (Short and Trenaman, 1992). Dominant low-pressure systems from the south produce frequent high-energy pulses of swell to the coast. Periodic cyclones and locally produced east-coast lows can also generate swell from the north to east but are generally much less frequent (Short, 1993). In particular low pressure systems in the Tasman Sea have the demonstrated ability to produce waves capable of transporting boulders on rocky shorelines (Saintilan and Rogers, 2005). One storm in 1912 is reported to have quarried and moved a boulder in excess of 200 tonnes a considerable distance (possibly up to 50 m (see discussion of Felton and Crook, 2003)) across coastal rock platforms just above the high water mark (Sussmilch, 1912).

1.1. Tsunami deposited boulders?

Initial evidence for tsunami activity on the southeast coast of Australia came from two papers. Young and Bryant (1992) focused on boulder deposits from rock ramps on the south coast of New South Wales at Tura Point, where the authors attributed several large rock accumulations on coastal ramps to a tsunami, possibly the Pleistocene tsunami of 105 ka identified by Moore and Moore (1984) in Lanai, Hawaii. This hypothesis was challenged by Jones (1992) who showed that such an event in the Hawaiian Islands would reach the Australian east coast with little possibility of catastrophic effects. Bryant (2001) re-examined the age of the event, using radiocarbon dating of encrusting shells and suggesting the deposits are much younger. A second paper, by Bryant et al. (1992), furthered the tsunami hypothesis with more boulder evidence from a number of sites on the southeast coast of Australia including Batemans Bay, Gum Getters inlet on Beecroft Head and Bass Point (Fig. 1).
Three subsequent publications by Bryant and Young (1996), Bryant et al. (1996) and Young et al. (1996) described a broad spectrum of evidence which they attributed to late Quaternary tsunami activity along the southeast coast of Australia. Much of this published evidence was recently reviewed in a paper by Bryant and Nott (2001) and a monograph by Bryant (2001). Recent work on large scale overwash into estuaries including Dunmore embayment and Killalea Lagoon (Fig. 1) has focussed on sandsheet deposits and dune modification, and has furthered the tsunami hypothesis suggesting a tsunami struck the coast between 800–200 yrs BP (Switzer et al., 2005, 2006; Switzer and Jones, 2008b).

2. Regional setting: tsunami evidence from Jervis Bay

The area around Jervis Bay in southeast Australia (Fig. 2) received particular attention from Bryant et al. (1997), who attributed numerous boulder accumulations on Beecroft Head, Gum Getters Inlet and at Greenfields Beach to tsunami deposition in a range of environments from cliff tops to gently sloping sheltered rock shelves. This paper revisits two of these sites and shows that although detachment sites, landward transport routes, boulder orientation and final deposition can be identified the definitive chronology, event history and depositional mechanism of the boulder accumulations remains difficult to determine.

2.1. Study site

Large accumulations of boulders are found at several sites on coastal rock platforms and ramps in the Jervis Bay region of southeastern Australia. These deposits are elevated above sea level and in many places show signs of imbrication. Two sites are presented here: the first at Little Beecroft Peninsula occurs on the more exposed parts of the coast and the second at Greenfields Beach within the relative shelter of Jervis Bay (Fig. 2). The Greenfields Beach site is a small shallow-dipping rock ramp with elevated boulders some 7 m above contemporary sea level. Twenty boulders are found in two imbricated piles of fourteen and six respectively at the northern end of the platform. The imbricated group start at approximately 4.5 m above sea level and rises to 5.8 m. This deposit contrasts directly with boulders on top of Little Beecroft Peninsula that exist up to 30 m above sea level. The high-energy shoreline of the Little Beecroft Head is characterised by steep cliffs and rock falls that topple periodically to the rock platforms or sea below (Fig. 3A). In both cases the boulders are erosional remnants of the local pebbly sandstone stratigraphy. Some boulders at both sites exhibit obvious signs of inversion or imbrication as a response to flow in a landward direction whilst other larger clasts appear characteristic of fallen blocks with no hydraulic reworking.
2.2. Modern erosion at Little Beecroft Head and Greenfields Beach

Modern erosion at both Little Beecroft Head and Greenfields Beach is best described as blocky erosion along two sets of near perpendicular joints in the shallow dipping strata (Fig. 3). The blocky nature of the erosion results in blocky boulders that are found along the shoreline around Little Beecroft Head and Greenfields Beach. Erosion is ongoing and modern rockfalls are common. Observations from local residents indicate that boulders that fall into the ocean are often reworked and transported either offshore or landward during storms. It should also be noted that in October 1999 at Whale Point approximately 1.5 km to the north of Little Beecroft Head the onshore transport and breaking of a boulder estimated at 15.7 tonnes was recorded on a rock platform. The boulder split into two smaller boulders and the largest clast had moved more than 40 m laterally and 2 m vertically during a large storm (Saintilan and Rogers, 2005).

3. Methods

Boulders at both sites were measured for dimension, orientation and lithology and compared to the local stratigraphy. Supplementary notes were also taken on grain size, imbrication, dip direction, jointing, cross-bedding, bioturbation and relative size and abundance of lichens. These features were used as indicators of boulder source and for signs of transport and direction.

At Greenfields Beach, boulder elevation and transport distance were also recorded. The boulder transport equations for subaerial and joint bounded boulders proposed by Nott (2003) were applied to eight measured boulders from four sites at Greenfields Beach. The two largest transported boulders at each of four sites were selected for analysis. Of the eight boulders, seven were of the fine-grained cross-beded lithology of the lower platform and the remaining one was of the pebbly lithology of the upper platform. This analysis was not conducted on the boulders at Little Beecroft Head as this environment is elevated at 30+ m above sea level and the equations were deemed not applicable.

4. Results

The two contrasting sites allowed direct comparison of the boulder accumulations on an exposed cliffed coastline and a sheltered embayment. At both sites, transported boulder accumulations were identified by their lithology, orientation and sedimentary features (Tables 1 and 2).

4.1. Little Beecroft Head

Although many boulder piles and individual boulders exist on top of Little Beecroft Head (Fig. 4), only three main sites are presented here. Examination of the stratigraphy interpreted by Tye (1995) suggests that many of the boulders are likely to be remnants of a formerly overlying gravelly sand lithology as no such unit exists in the

---

**Fig. 2.** A) Location of Little Beecroft Head and Greenfields Beach in the Jervis Bay region. Little Beecroft Head (B) is a dramatic cliffed coastline that is open to consistent high-energy waves and contrasts directly with the Greenfields Beach site that has the morphology of a shallow dipping shore platform (C) and lies within the shelter of Jervis Bay. (Photos by Charlie Bristow).
underlying stratigraphy (Fig. 4C). Two lithologies of boulder were found on top of Little Beecroft Head. One of these lithologies is found in both the immediately underlying unit and overlying stratigraphy, the other lithology is quartz rich sand with larger gravel clasts is not found in the units below. Reconnaissance of the larger headlands that are more than 50 m above present mean sea level (PMSL) to the south of Little Beecroft Head show many randomly orientated boulders exist as eroded remnants of the formerly overlying stratigraphy.

The first boulder site presented here lies at an elevation of approximately 30 m above PMSL on the southeastern end of the headland. Here are two small detached boulders that exhibit clear signs of that they are not in situ because they rest on other small cobble and boulders (Fig. 5A). One boulder weighing just over 1 tonne rests on a smaller boulder and the detachment site is interpreted as being approximately 3 m to the southeast.

The second site on Little Beecroft Head consists of one large boulder that rests across a large prominent joint in the platform (Fig. 5B). This boulder is the largest on the platform and weighs more than 22 tonnes. The heavily bioturbated sandstone block appears to have been transported because to rest across a prominent joint and analysis of jointing through the block shows that it is currently rotated approximately 55° to the jointing in the surface below.

The third site occurs approximately 15 m to the northwest of the large boulder, and consists of five boulders of different lithology and up to 3 tonnes, in an imbricated stack stretching over approximately 8 m (Fig. 6). These boulders are found at an elevation ~33 m above PMSL and are orientated facing southeast suggesting flow from the southeast across the platform.

4.2. Greenfields Beach

Within the shelter of Jervis Bay, another site on a rock platform south of Greenfields Beach contrasts with the high energy shoreline of Little Beecroft Head. (Figs. 2B, 3B, and 7A). The Greenfields Beach
site is a small shallow dipping rock ramp with boulders elevated
some 7 m above contemporary sea-level, much lower than the Little
Beecroft Head site. The boulders in this area are also considerably
more block-shaped than those found on Little Beecroft Head. The
lower rock ramp appears cleared of boulders although large boulder
accumulations appear on the upper ramp and at the northern end
but not at the southern end, possibly indicating wave approach from
the south.

Table 1
The dimensions and mass of the boulders identified at five sites along the top of Little Beecroft headland.

<table>
<thead>
<tr>
<th>Site</th>
<th>Boulder #</th>
<th>Rock unit</th>
<th>a-axis</th>
<th>b-axis</th>
<th>c-axis</th>
<th>Vol.</th>
<th>Mass (tonne)</th>
<th>Inv.</th>
<th>Imb.</th>
<th>Moved (horiz)</th>
<th>Moved (vert)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LBH 1</td>
<td>1.1</td>
<td>1</td>
<td>2.30</td>
<td>2.20</td>
<td>0.35</td>
<td>1.77</td>
<td>4.25</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>LBH 1</td>
<td>1.2</td>
<td>1 (J)</td>
<td>2.50</td>
<td>2.30</td>
<td>0.35</td>
<td>2.01</td>
<td>4.83</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>LBH 1</td>
<td>1.3</td>
<td>1</td>
<td>1.30</td>
<td>1.10</td>
<td>0.30</td>
<td>0.43</td>
<td>1.03</td>
<td>Y</td>
<td>2</td>
<td>?</td>
<td></td>
</tr>
<tr>
<td>LBH 1</td>
<td>1.4</td>
<td>1</td>
<td>1.20</td>
<td>1.00</td>
<td>0.30</td>
<td>0.36</td>
<td>0.86</td>
<td>?</td>
<td>Y</td>
<td>2</td>
<td>?</td>
</tr>
<tr>
<td>LBH 1</td>
<td>1.5</td>
<td>1</td>
<td>1.05</td>
<td>0.90</td>
<td>0.30</td>
<td>0.28</td>
<td>0.58</td>
<td>N</td>
<td>Y</td>
<td>8</td>
<td>?</td>
</tr>
<tr>
<td>LBH 1</td>
<td>1.6</td>
<td>1</td>
<td>1.15</td>
<td>0.90</td>
<td>0.30</td>
<td>0.18</td>
<td>0.50</td>
<td>N</td>
<td>Y</td>
<td>8</td>
<td>?</td>
</tr>
<tr>
<td>LBH 2</td>
<td>3.1</td>
<td>1</td>
<td>3.50</td>
<td>2.10</td>
<td>1.30</td>
<td>9.56</td>
<td>22.93</td>
<td>N</td>
<td>N</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>LBH 3</td>
<td>4.1</td>
<td>1</td>
<td>2.40</td>
<td>2.40</td>
<td>0.25</td>
<td>1.44</td>
<td>3.46</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>LBH 3</td>
<td>4.2</td>
<td>2</td>
<td>2.10</td>
<td>1.90</td>
<td>0.30</td>
<td>1.20</td>
<td>2.87</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>?</td>
</tr>
<tr>
<td>LBH 3</td>
<td>4.3</td>
<td>1</td>
<td>3.00</td>
<td>3.50</td>
<td>0.55</td>
<td>5.78</td>
<td>13.86</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>?</td>
</tr>
<tr>
<td>LBH 3</td>
<td>4.4</td>
<td>2</td>
<td>2.00</td>
<td>2.00</td>
<td>0.40</td>
<td>1.60</td>
<td>3.84</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>?</td>
</tr>
</tbody>
</table>

Notes are also presented on whether the boulder appears inverted (Inv.), imbricated (Imb.) or has moved horizontally (horiz) or vertically (vert) are also presented.

Boulder lithologies.
1 — medium quartz sandstone with pebbly storm lags and mild bioturbation (J=jointed).
2 — medium-coarse quartz sandstone with pebbly storm lags, larger clasts and mild bioturbation.

Table 2
The dimensions and mass of the boulders identified at four sites on the rock platform south of Greenfields beach.

<table>
<thead>
<tr>
<th>Site</th>
<th>Boulder #</th>
<th>Rock unit</th>
<th>a-axis</th>
<th>b-axis</th>
<th>c-axis</th>
<th>Vol.</th>
<th>Mass (tonne)</th>
<th>Inv.</th>
<th>Imb.</th>
<th>Moved (horiz)</th>
<th>Moved (vert)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GF 1</td>
<td>1.1</td>
<td>3</td>
<td>1.80</td>
<td>2.00</td>
<td>0.50</td>
<td>1.80</td>
<td>4.32</td>
<td>N</td>
<td>N</td>
<td>12</td>
<td>2</td>
</tr>
<tr>
<td>GF 1</td>
<td>1.2</td>
<td>3</td>
<td>1.10</td>
<td>1.70</td>
<td>0.55</td>
<td>1.03</td>
<td>2.47</td>
<td>N</td>
<td>N</td>
<td>8</td>
<td>2</td>
</tr>
<tr>
<td>GF 1</td>
<td>1.3</td>
<td>3</td>
<td>2.50</td>
<td>1.2</td>
<td>0.35</td>
<td>1.05</td>
<td>2.52</td>
<td>Y</td>
<td>N</td>
<td>8</td>
<td>2</td>
</tr>
<tr>
<td>GF 1</td>
<td>1.4</td>
<td>3</td>
<td>2.20</td>
<td>2.30</td>
<td>0.65</td>
<td>3.29</td>
<td>7.89</td>
<td>N</td>
<td>N</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>GF 2</td>
<td>2.1</td>
<td>3</td>
<td>1.70</td>
<td>1.30</td>
<td>0.60</td>
<td>1.33</td>
<td>3.18</td>
<td>N</td>
<td>N</td>
<td>21</td>
<td>5</td>
</tr>
<tr>
<td>GF 2</td>
<td>2.2</td>
<td>3</td>
<td>1.40</td>
<td>0.90</td>
<td>0.50</td>
<td>0.63</td>
<td>1.51</td>
<td>Y</td>
<td>N</td>
<td>25</td>
<td>5</td>
</tr>
<tr>
<td>GF 2</td>
<td>2.3</td>
<td>3</td>
<td>1.20</td>
<td>1.80</td>
<td>0.35</td>
<td>0.76</td>
<td>1.81</td>
<td>Y</td>
<td>Y</td>
<td>26</td>
<td>5</td>
</tr>
<tr>
<td>GF 2</td>
<td>2.4</td>
<td>3</td>
<td>0.90</td>
<td>1.00</td>
<td>0.20</td>
<td>0.18</td>
<td>0.43</td>
<td>N</td>
<td>Y</td>
<td>28</td>
<td>6</td>
</tr>
<tr>
<td>GF 2</td>
<td>2.5</td>
<td>3</td>
<td>1.50</td>
<td>0.90</td>
<td>0.45</td>
<td>0.61</td>
<td>1.46</td>
<td>Y</td>
<td>N</td>
<td>26</td>
<td>5</td>
</tr>
<tr>
<td>GF 3</td>
<td>3.1</td>
<td>3</td>
<td>2.80</td>
<td>1.60</td>
<td>0.70</td>
<td>3.14</td>
<td>7.53</td>
<td>N</td>
<td>Y</td>
<td>20</td>
<td>2</td>
</tr>
<tr>
<td>GF 3</td>
<td>3.2</td>
<td>3</td>
<td>2.50</td>
<td>2.60</td>
<td>1.00</td>
<td>6.50</td>
<td>15.60</td>
<td>N</td>
<td>Y</td>
<td>30</td>
<td>2</td>
</tr>
<tr>
<td>GF 3</td>
<td>3.3</td>
<td>3</td>
<td>2.90</td>
<td>2.10</td>
<td>0.90</td>
<td>5.48</td>
<td>13.15</td>
<td>N</td>
<td>Y</td>
<td>28</td>
<td>2</td>
</tr>
<tr>
<td>GF 3</td>
<td>3.4</td>
<td>3</td>
<td>1.70</td>
<td>1.40</td>
<td>0.90</td>
<td>2.14</td>
<td>5.14</td>
<td>Y</td>
<td>Y</td>
<td>35</td>
<td>3</td>
</tr>
<tr>
<td>GF 4</td>
<td>4.1</td>
<td>1</td>
<td>2.10</td>
<td>1.50</td>
<td>0.70</td>
<td>2.21</td>
<td>5.29</td>
<td>?</td>
<td>Y</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>GF 4</td>
<td>4.2</td>
<td>1</td>
<td>2.00</td>
<td>1.90</td>
<td>0.55</td>
<td>2.09</td>
<td>5.02</td>
<td>?</td>
<td>Y</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>GF 4</td>
<td>4.3</td>
<td>1</td>
<td>1.70</td>
<td>1.40</td>
<td>0.55</td>
<td>1.31</td>
<td>3.14</td>
<td>Y</td>
<td>Y</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>GF 4</td>
<td>4.4</td>
<td>1</td>
<td>1.60</td>
<td>0.90</td>
<td>0.25</td>
<td>0.36</td>
<td>0.86</td>
<td>?</td>
<td>Y</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>GF 4</td>
<td>4.5</td>
<td>1</td>
<td>1.90</td>
<td>1.40</td>
<td>0.60</td>
<td>1.60</td>
<td>3.83</td>
<td>?</td>
<td>Y</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>GF 4</td>
<td>4.6</td>
<td>1</td>
<td>1.50</td>
<td>1.00</td>
<td>0.40</td>
<td>0.60</td>
<td>1.44</td>
<td>?</td>
<td>Y</td>
<td>26</td>
<td>5</td>
</tr>
<tr>
<td>GF 4</td>
<td>4.7</td>
<td>1</td>
<td>1.40</td>
<td>0.90</td>
<td>0.20</td>
<td>0.25</td>
<td>0.60</td>
<td>?</td>
<td>Y</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>GF 4</td>
<td>4.8</td>
<td>3</td>
<td>2.00</td>
<td>1.90</td>
<td>0.40</td>
<td>1.52</td>
<td>3.65</td>
<td>Y</td>
<td>Y</td>
<td>4</td>
<td>15</td>
</tr>
<tr>
<td>GF 4</td>
<td>4.9</td>
<td>1</td>
<td>3.00</td>
<td>2.10</td>
<td>0.50</td>
<td>3.15</td>
<td>7.56</td>
<td>?</td>
<td>Y</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>GF 4</td>
<td>4.10</td>
<td>1</td>
<td>2.00</td>
<td>1.30</td>
<td>0.30</td>
<td>0.78</td>
<td>1.87</td>
<td>?</td>
<td>Y</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>GF 4</td>
<td>4.11</td>
<td>1</td>
<td>1.60</td>
<td>1.60</td>
<td>0.35</td>
<td>0.90</td>
<td>2.15</td>
<td>?</td>
<td>Y</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>GF 4</td>
<td>4.12</td>
<td>1</td>
<td>1.00</td>
<td>0.80</td>
<td>0.25</td>
<td>0.20</td>
<td>0.48</td>
<td>?</td>
<td>Y</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>GF 4</td>
<td>4.13</td>
<td>1</td>
<td>1.50</td>
<td>1.00</td>
<td>0.30</td>
<td>0.45</td>
<td>1.08</td>
<td>?</td>
<td>Y</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>GF 4</td>
<td>4.14</td>
<td>1</td>
<td>1.05</td>
<td>0.90</td>
<td>0.20</td>
<td>0.00</td>
<td>0.24</td>
<td>?</td>
<td>Y</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>GF 4</td>
<td>4.15</td>
<td>1</td>
<td>1.40</td>
<td>1.40</td>
<td>0.60</td>
<td>1.18</td>
<td>2.82</td>
<td>?</td>
<td>Y</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>GF 4</td>
<td>4.16</td>
<td>3</td>
<td>1.80</td>
<td>1.50</td>
<td>0.50</td>
<td>1.35</td>
<td>3.24</td>
<td>Y</td>
<td>Y</td>
<td>4</td>
<td>16</td>
</tr>
<tr>
<td>GF 4</td>
<td>4.17</td>
<td>1</td>
<td>1.40</td>
<td>1.10</td>
<td>0.60</td>
<td>0.92</td>
<td>2.22</td>
<td>?</td>
<td>Y</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>GF 4</td>
<td>4.18</td>
<td>1</td>
<td>0.80</td>
<td>0.70</td>
<td>0.25</td>
<td>0.14</td>
<td>0.34</td>
<td>?</td>
<td>Y</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>GF 4</td>
<td>4.19</td>
<td>1</td>
<td>1.20</td>
<td>1.50</td>
<td>0.80</td>
<td>1.44</td>
<td>3.46</td>
<td>Y</td>
<td>Y</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>GF 4</td>
<td>4.20</td>
<td>1</td>
<td>2.10</td>
<td>1.20</td>
<td>0.40</td>
<td>1.01</td>
<td>2.42</td>
<td>?</td>
<td>Y</td>
<td>?</td>
<td>?</td>
</tr>
</tbody>
</table>

Notes are also presented on whether the boulder appears inverted (Inv.), imbricated (Imb.) or has moved horizontally (horiz) or vertically (vert) are also presented.

Boulder lithologies.
1 — medium quartz sandstone with pebbly storm lags and mild bioturbation (J=jointed).
2 — medium-coarse quartz sandstone with pebbly storm lags, larger clasts and mild bioturbation.
3 — fine- to medium-grained cross-bedded sandstone.
The upper ramp is composed of bioturbated pebbly sandstone which erodes to form joint bounded blocks (Fig. 3C). This lithology provides little structural and lithological information making it difficult to decipher whether a rock has been transported or not. In contrast a finer cross-bedded sandstone unit is found in two large wave-cut notches on the lower part of the ramp which exposes the stratigraphy of the underlying sequence. The overlying stratigraphy is composed of pebbly, bioturbated medium-grained sandstone indicating that any boulders that contain cross-bedding must have originated from this lower unit (Fig. 7B).

Numerous cross-bedded boulders are found at Sites 1 and 2 on the southern and central part of the platform (Fig. 6A and B). Many of these boulders lie at least 8 m away from the notch and weigh between 2 and 8 tonnes (Fig. 8A). The boulders are often found mixed with boulders of the pebbly sandstone lithology and many are found imbricated against other boulders. At Site 3 to the north, several large cross-bedded boulders are also identified with the largest weighing more than 15 tonnes. This boulder (Boulder 3.2) must have come from the seaward wave-cut notch (Fig. 6B and C) and moved at least 30 m horizontally and more than 2 m vertically (Table 2). This suggests that an event of significant magnitude detached and transported the boulders up the ramp and deposited them up to 30 m from their original position. In addition to transporting the boulders, such an event also plucked the boulders from the notch and lifted them over the lip of the notch.

Of these boulders, 16 were of the fine-grained cross-bedded lithology of the lower platform and the remaining 14 were of the pebbly lithology of the upper platform. Of the twenty boulders found in two imbricated piles at the northern end of the platform (Fig. 9) two boulders were deemed to be transported because one was of the fine grained crossed bedded lithology (Boulder GF-4.4) and the other (Boulder GF-4.9) was clearly imbricated and dipping seaward at a high angle (Fig. 9B).


Recently a considerable number of studies have relied heavily on equations published by Nott (1997, 2003) when attempting to determine if tsunami or storm waves are the most likely mechanism for boulder detachment and transport in a variety of locations. Application of the boulder transport equations (see Appendix A) for subaerial and joint bounded boulders proposed by Nott (2003) were applied to the two largest measured boulders from four sites at Greenfields Beach (Table 3). The Nott equations suggest that the largest wave heights are required for boulder 4.4 which would require a tsunami wave height of 5.70 m or a storm wave height of 22.80 m if joint bounded, or a tsunami wave height of 2.19 m or a storm wave height of 8.78 m if subaerially exposed and wave heights only slightly higher if submerged (refer to Table 3). Note that the heaviest boulder at Greenfields Beach (Boulder 2.3) did not require the greatest wave height to move it as the shape of the boulder is the primary determinant in the Nott equations.

To provide a modern analogue and test the validity of the method, the boulder called ‘Mermaid Rock’ at Ben Buckler Head north of Bondi Beach in Sydney (Fig. 1B) was also analysed using the equations of Nott (2003). This sandstone block measures 6.1 x 4.9 x 3.0 m and weighs approximately 235 tonnes (Sussmilch, 1912). The block appears inverted relative to its original orientation in the bed and was deposited by a large storm on or in the days preceding July 15, 1912 (Sussmilch, 1912; Felton and Crook, 2003). Assuming that the boulder at Ben Buckler Head was joint bounded, then Nott’s equations...
indicate that detachment and transport of this boulder would require a tsunami wave in excess of 11.5 m in height or a storm wave in excess of 46 m in height (Table 3). Records of the 1912 storm indicate storm wave heights of less than 10 m (Sussmilch, 1912), indicating that Nott’s equations overestimate the required wave height. Although the pioneering work of Nott is admirable, the applicability of these equations appears limited and suggests the equations need to be tested against other clasts from known events and reworked and extended to include other variables (see discussion of Kelletat, 2008).

A recent study by Morton et al. (2006) also highlighted problems with the Nott equations, stating that the simple mathematical assumptions lead to the conclusion that storm waves must be approximately four times higher than tsunami waves to transport the same size particle. The mode of transport assumed by Nott (1997,

![Image](image_url)

**Fig. 5.** A) Small scale sketch map of the boulders at Site 1 on Little Beecroft Head showing the present positions of the boulders and the likely detachment site. Photographs shown in B and C show the cliff top setting and boulders 1.1–1.4. Boulders 1.3 and 1.4 appear to have been transported in a landward direction and rotated. Photograph C shows boulder 1.4 resting on a smaller boulder of the same lithology. D) A sketch map of site 2 is provided, a large boulder weighing almost 23 tonnes (boulder 3.1) rest across a prominent joint. The boulder also contains joints and appears rotated ~55° to the joint orientation of the underlying bedrock. The boulder is of a pebbly lithology similar to the material directly below in the stratigraphy. Photograph (E) shows boulder 3.1 and the head land at Little Beecroft Head. Site 1 is at the end of the headland. Larger cliffs (50 m+) can be observed in the top right of the photograph.
2003) involves overturning and the wave height required is determined by the square of the velocity, which is proportional to the height of storm waves and to one-quarter the height of tsunami waves. The assumption of particle overturning may not be correct because there is growing evidence from high wave energy coasts that movement of blocks that are not fully submerged is dominated by sliding rather than overturning or suspension (Noormets et al., 2004; Williams and Hall, 2004; Morton et al., 2006; Goto et al., 2007) or rolling or saltation (Imamura et al., 2008).

5. Event history: storm waves vs tsunami

It is often not possible to work out the prehistoric event history for a boulder, given that it may have been transported by several storm and/or tsunami events. Even if it is assumed that a single event transported the boulder, and the boulder dimensions, detachment position and final position are known, it is still difficult to determine the type and size of the wave that emplaced it. The problem is an inverse one, and given the chaotic nature of turbulence and the associated non-linearity of the hydrodynamics at the shoreline, there may be non-unique solutions. With a numerical model of wave dynamics and boulder transport, it may be possible to find the solution space (i.e., the range of possible waves) by using reverse Monte-Carlo simulations. However, the possibility of non-unique solutions means that such an approach may provide little constructive meaning.

The dynamics of quarrying and transport were also studied by Noormets et al. (2004) who suggested that both tsunami and storm waves are capable of quarrying mega clasts from cliff edges. They concluded that a higher quarrying capacity is expected from short period storm waves when combined with super elevation of sea level associated with storm surge. Such events may flood the rock platform, thus moving the potential zone of wave impact and possibly promoting block transport. Noormets et al. (2004) also noted that tsunami waves are of considerably longer period, and may have higher transporting capacities because each wave has the potential to transport blocks for a longer time than a storm wave. Recently the work of Goto et al. (2007) has examined the transport of boulders in Thailand by the 2005 Indian Ocean tsunami. Here they examined the boulder fields on a reef flat and using the equations of Noji et al. (1993) and assuming the boulder is a sliding block (not overturned or rolling) found that the inferred velocity to move the largest clasts ($2\text{−}3 \text{ m s}^{-1}$) is far below that likely to be experienced during tsunami inundation.

Recent work by Imamura et al. (2008) may also show promise in assisting the hindcasting of wave heights and possible mechanisms for palaeoevents. In hydraulic experiments conducted in an open channel, blocks of cubic and rectangular shape were observed to be mainly transported by rolling or saltation rather than by sliding. This observation differs significantly from previous models of boulders on rocky coasts that have assumed sliding as a mode of transport for the boulder (Goto et al., 2007). Imamura et al. (2008) concluded that the sliding assumption in tsunami transport models may underestimate the distance a boulder moved when it was transported. Furthermore they developed a practical model for the transport of a boulder by tsunami, introducing an empirical variable coefficient of friction and assuming that the coefficient decreases with decrease in ground contact time when the block was transported by rolling or saltation. Thus this model can explain various modes of transport, i.e., sliding, rolling, and saltation. Importantly, Imamura et al. (2008) tested their model against a tsunami deposited boulder transported by the 1771 Meiwa tsunami on Ishigaki Island, Japan, and found transport distances consistent with the descriptions in historical documents.

Morton et al. (2006) also suggested that applying the equations of Lorang (2000) may aid the prediction of boulder size transport considering wave height, wave period, runup elevations, and swash velocities. The recent studies summarised above suggest that the wave mechanics and hydrodynamics of both storm waves and tsunami require more detailed investigation and modelling. Modern examples have shown that single extreme-wave event (storm or tsunami) have the ability to move and transport large boulders on rocky coasts. However, despite significant advances in numerical modelling over the last decade the current numerical and empirical models available for the analysis of boulders do not allow the differentiation of storm or tsunami transport based solely on the size boulders and their position in the landscape.

5.1. Boulders accumulations at Jervis Bay: can they be attributed to an event type?

The boulders on top of Little Beecroft Head and at Greenfields Beach provide evidence of landward transport. Although the evidence for landward movement is fairly compelling there are a number of unresolved issues that require attention before attributing these deposits to either toppling of eroded remnants of overlying stratigraphy, deposition during higher sea level, storm, tsunami or a combination of factors. The first problem lies with the age of the deposits and the history of the events. Radiocarbon dating of encrusting shells on transported boulders by Young and Bryant (1992) suggested that many of the boulders in the Jervis Bay region are late-Holocene in age. If this is a true indication of the age then sea level change cannot reasonably invoked as a mechanism for deposition. Even if the deposits are much older (eg. OIS5e) there is no evidence that sea level on this tectonically stable coast has exceeded 2 m above present levels for the last 200 ka (Murray Wallace and Belperio, 1991). If the deposits are mid-Holocene in age then higher sea level (up to 2 m) may be a possibility (Flood and Frankel, 1989). However, the reliability of the use of fixed biological indicators to
provide accurate spatial and temporal controls on prior sea level has recently been challenged by Sloss et al. (2006, 2007). Higher sea levels may be invoked to be partially responsible for at least the Greenfields boulders but the affect of 2 m sea level rise on the boulders at Little Beecroft Head would be minimal.

The second and major problem lies in defining the event history. It is impossible to know if the boulders were emplaced by single or multiple events. One fundamental and unanswered question limits analysis of these types of deposit: Is it possible that multiple or single tsunami, a series of high-energy storms or combination of both processes can deposit a boulder accumulation that exhibits imbrication?

Young et al. (1996) and Bryant (2001) suggested that the largest boulder (Boulder LBH2-3.1) found on top of Little Beecroft Head was

![Fig. 7. A) Aerial photograph of study sites at Greenfields Beach B) Topographic map with key geomorphic features. The two large wave cut notches can be observed in the lower platform. This is the site of wave quarrying before transport for the cross-bedded boulders. C) The wave cut notch at the southern end of the platform. The lower rock ramp is composed of cross-bedded sandstone and is overlain by pebbly bioturbated sandstone. Site GF1 lies to the northwest of the notch and contains boulders of both lithologies.](image)
emplaced by a Holocene tsunami where they cited its different lithology, elevation and irregular contact as evidence for transport from much lower in the cliff sequence. Analysis of the stratigraphy of Tye (1995) shows that the pebbly lithology of the boulder suggests that it is more likely to be an erosional remnant of the coarser overlying stratigraphy (now eroded) than the slightly gravelly sequences immediately below (Fig. 4C). Although the boulder has obviously been transported it is impossible to say whether its present position is the result of washover of the headland and plucking from the underlying unit or deposition as an eroded remnant produced by rock fall during earlier erosion. It is possible that both scenarios have occurred.

The identification of imbricated, reworked and transported boulders from coastal rock platforms and cliff tops shows vivid evidence of large washover events (Noormets et al., 2002; Sommerville et al., 2003; Noormets et al., 2004; Williams and Hall, 2004; Hall et al., 2006, 2008; Hansom and Hall, 2009). Some boulders at both sites exhibit obvious signs of imbrication as a response to flow in a
landward direction whilst other larger clasts appear characteristic of blocks with no hydraulic reworking. Interestingly, the imbrication of these deposits appears to only occur in boulders up to a threshold size, thus providing a possible constraint on wave power for the depositional event or events.

Both of the sites in this study were studied by Bryant et al. (1992, 1996, 1997) and Young et al. (1996) who attributed the boulder deposition to tsunami. Although striking, these deposits present significant analytical problems in dating and depositional history some of which have been discussed controversially (Felton and Crook, 2003; Dominey-Howes et al., 2006). It is also important to note that recent research on Northern Atlantic coasts by Hansom (2001), Sommerville et al. (2003), Williams and Hall (2004), Hall et al. (2006, 2008), Hansom and Hall (2009) have convincingly related the frequent removal and movement of very large boulders into organised imbricated ridges to wave activity during large storms over the last century or so. Much of this activity occurs at heights of around 20 m above sea level, but more chaotic piles and smaller individual boulders also occur at up to 50 m above sea level. Hansom and Hall (2009) demonstrate that these processes have been ongoing for at least 1400 years. Other recent work by Morton et al. (2006) suggests that reinterpretation of boulders and other deposits attributed to tsunami in the Caribbean are also now overdue.

6. Conclusions

The imbrication, mixed lithology and sedimentary characteristics of boulder deposits at Little Beecroft Head and Greenfields Beach provide compelling evidence for large-scale movement attributed to washover by single or multiple events. However, it is impossible to attribute these deposits to a unique event. It cannot definitively stated that the boulders are purely the result of tsunami washover. If the deposits are late-Holocene in age then a hypothesis of higher Holocene sea level can be discarded and it is likely that storms and tsunami may have both played a role in the development of the high elevation boulder deposits. However, for the sites reported here, it remains that the mechanism of emplacement, and the number of steps in boulder movement, is not yet definable, and may never be.

Acknowledgments

This project was supported by Dunmore Sand and Soil Pty Ltd. Kerry Steggles, Managing Director of Dunmore Sand and Soil, is thanked for his enthusiasm for this research. Funding for the project came from ARC SPIRT grant C00107062 (now ARC Linkage grants). The Landscape Research Centre (now GeoQuEST) at the University of Wollongong also supported this study. Field visits and discussions...
with Ted Bryant, Simon Haslett, Anne Felton, Keith Crook, Charlie Bristow, David Fink and Wayne Stephenson provided stimulus for much of the material in this paper. An informal review from Craig Sloss and the reviews of two anonymous reviewers greatly assisted the drafting of this paper.

Appendix A. Boulder transport equations from Nott, 2003

For a submerged boulder
Tsunami: \( H = 0.50(\rho_f - \rho_b)/\rho_w \times [(a/b)^2]C_d + C_l \)
Storm wave: \( H \geq 20(\rho_f - \rho_b)/\rho_w \times [(a/b)^2]C_d + C_l \)

For a boulder-destroying boulder
Tsunami: \( H \geq 0.25 \times [(\rho_f - \rho_b)/\rho_w] (2a - C_m(a/b) \times (\bar{u} - \bar{g})) \times [(a/b)^2]C_d + C_l \)
Storm wave: \( H \geq 0.25 \times [(\rho_f - \rho_b)/\rho_w] (2a - 4C_m(a/b) \times (\bar{u} + \bar{g})) \times [(a/b)^2]C_d + C_l \)

For a jointed boulder
Tsunami: \( H = 0.25(\rho_f - \rho_b)/\rho_w \times C_l / C_0 \)
Storm: \( H \geq 0.25(\rho_f - \rho_b)/\rho_w \times C_l / C_0 \)

Where \( H \) is the wave height at breaking point, \( \rho_b \) is density of the boulder (2.7 g/cm\(^3\)), \( \rho_w \) is density of water (1.02 g/ml), \( a \) is -axis of boulder, \( b = B \)-axis of boulder, \( c = C \)-axis of boulder, \( C_m = \) coefficient of drag (1.5) and \( C_l = \) coefficient of lift (0.178), \( C_0 = \) coefficient of mass, \( \bar{u} = \) instantaneous flow acceleration, \( g = \) acceleration due to gravity (9.8 m/s\(^2\)). Equations derived from Nott (2003).

References
