Catastrophic wave erosion on the southeastern coast of Australia: Impact of the Lanai tsunamis ca. 105 ka?

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Abstract

Sand barriers along the coast of southern New South Wales, dating from the last interglacial, have been almost completely destroyed, most probably by a catastrophic tsunami. Evidence for catastrophic wave erosion can also be traced to heights of at least 15 m above present sea level on coastal abrasion ramps. These erosional features lie above the range of effective erosion by contemporary storm waves, and cannot be attributed to either eustatic fluctuations or local uplift. Chronological evidence for the timing of the destruction of the last interglacial barriers suggests that tsunami generated by the submarine slide off Lanai in the Hawaiian Islands 105 ka traveled across the Pacific and eroded this coast.

Keywords

tsunami, bedrock erosion, Hawaii, New South Wales, submarine landslide

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ABSTRACT

Sand barriers along the coast of southern New South Wales, dating from the last interglacial, have been almost completely destroyed, most probably by a catastrophic tsunami. Evidence for catastrophic wave erosion can also be traced to heights of at least 15 m above present sea level on coastal abrasion ramps. These erosional features lie above the range of effective erosion by contemporary storm waves, and cannot be attributed to either eustatic fluctuations or local uplift. Chronological evidence for the timing of the destruction of the last interglacial barriers suggests that tsunamis generated by the submarine slide off Lanai in the Hawaiian Islands 105 ka traveled across the Pacific and eroded this coast.

INTRODUCTION

Notwithstanding the increasing recognition of the impact of great tsunamis on coastal landforms close to their source (Moore and Moore, 1984; Myles, 1985; Dawson et al., 1988; Talandier and Bourrouilh-Le-Jan, 1988), little is known of their long-distance effects in the geologic record. The giant wave train generated by a mega-landslide off the island of Hawaii around 105 ka is a case in point. Because this wave train swept up to an elevation of about 375 m on the island of Lanai (Moore and Moore, 1984; Moore et al., 1989), it must have had a widespread impact on Pacific shorelines. However, no evidence for its long-distance effects has been reported. We argue that such evidence can be seen along the southeastern Australian coast, more than 7000 km away from the source. We examine the destruction of last-interglacial sand barriers in southern New South Wales and present the case for catastrophic erosion of bedrock ramps up to 15 m above present sea level.

DESTRUCTION OF INTERGLACIAL SAND BARRIERS

One very problematic aspect of the coast of New South Wales is that, although substantial Holocene barriers occur along virtually its entire length, their last-interglacial counterparts do not occur south of Newcastle (Fig. 1). Last-interglacial sands preserved in sheltered sites south of Newcastle (Bryant et al., 1990), and extensive, but isolated, estuarine plains of late Pleistocene age (Bryant et al., 1991), demonstrate that these barriers were once present along almost the entire coast, but they have been selectively destroyed in the south. Roy and Thom (1981) hypothesized that the interglacial barriers in the south were eroded during times of intermediate or low sea levels and that sediment from them was swept northward along the shelf, but they did not specify the erosive mechanism. It is difficult to imagine how the barriers could have been eroded by the small streams that drain into many of the embayments now occupied by large Holocene barriers along the southern part of the coast. Many of these streams are constrained along their present courses by bedrock or Pleistocene clays and would have tended to incise rather than migrate laterally through the adjacent sand barriers as sea level fell. It is even more difficult to imagine why the smaller coastal streams in southern New South Wales should have been so much more effective in destroying the last-interglacial barriers than were the larger streams farther north. Whatever the mechanism of their destruction, it clearly operated preferentially in the south and has not been operative since the onset of Holocene barrier deposition about 7 ka (Jones et al., 1979).

We suggest that a catastrophic tsunami, probably triggered by the Lanai submarine slide in Hawaii, was responsible for this hiatus in sedimentation. The tsunami wave train overwhelmed the southern barriers, flushing the sand seaward onto the shelf from where it has subsequently been reworked. The direction of approach of such a great wave train into

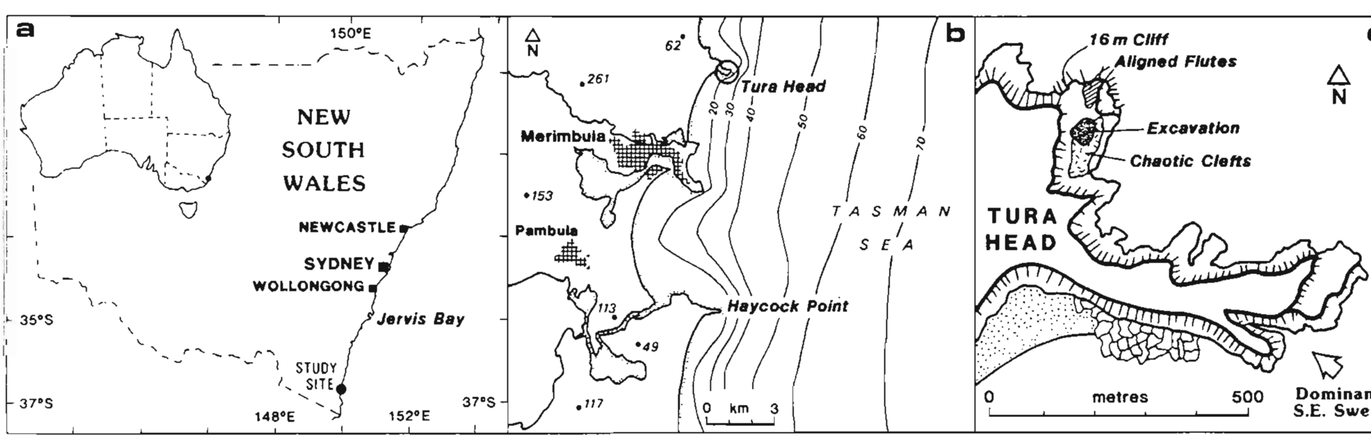

Figure 1. a: Location of study site. b: Spot heights on coastal lowland (m) and bathymetry (m) on continental shelf near Merimbula. c: Location of tsunami erosion on Tura Head; these features are sheltered from dominant southeasterly swell.

the southern Tasman Sea through the gap between New Caledonia and New Zealand would account for the decreasing erosion northward, because of the filtering effect of New Caledonia and the New Hebrides and because of the Great Barrier Reef along the Queensland coast. Catastrophic wave trains generated in the Tasman Sea, especially by movement along the active Alpine fault in New Zealand, must be ruled out because they would have affected the entire coastline of New South Wales. The 105 ka timing of the Lanai event, which coincides with the Barbados II eustatic highstand, also fits the Australian evidence. The youngest fragments of Pleistocene barriers dated along the south coast yield ages of ~120 ka (Bryant et al., 1990), while at Wollongong (Fig. 1) last-interglacial estuarine clays are notched on their seaward side and are overlapped by indurated dune sands dating from ~20 ka (Bryant et al., 1991). This apparent bracketing of the erosive event indicates that if a tsunami did overwhelm the last-interglacial barriers, it presumably occurred during the Barbados II (105 ka) or Barbados III (80 ka) highstands (Ku et al., 1990).

BEDROCK EVIDENCE

The case for destruction of the barriers by the Lanai tsunami is circumstantial and needs support from independent evidence. We suggest that this evidence is imprinted on a series of bedrock surfaces, most strikingly on an abrasion ramp on the northern side of Tura Head, 10 km north of Merimbula, ~350 km south of Sydney (Fig. 1). The ramp lies on the dip slopes of folds in the Upper Devonian Worange Point Formation, which consists of multiple upward-fining cycles of gray, coarse, quartzose sandstone and red, fine sandstone to mudstone. Most of the ramp coincides with the top of a massive sandstone from which mudstone, which now crops out at the base of the adjacent cliff, has been stripped. The ramp is 150 m wide and 300 m long, and it dips mainly to the southeast at 7° (Fig. 2). At its summit the main ramp surface flattens and then terminates in a 16 m vertical seacliff that faces northward into an embayment cut into the headland. Our concern is not with the differential stripping that formed the ramp, a process that may have extended over much of the Quaternary, but rather with the erosional detail superimposed upon the ramp that we believe is indicative of catastrophic wave action.

About one-third of the way up the ramp, a roughly rectangular depression measuring 40 × 30 m has been excavated to a depth of 1 to 1.5 m by the removal of joint-bounded blocks (Fig. 2). The perimeter and floor of this depression are bounded by joint and bedding planes and display a strikingly angular appearance with no sign of rounding by abrasion or weathering. The angularity of the faces presents compelling evidence that the depression was cut by the quarrying or plucking of joint-bounded blocks, rather than by the progressive widening of joints and attrition of blocks by weathering or persistent wave action. As further evidence against attrition, the depression is linked to the sea by a gap 2 m wide, which is situated not at the base of the depression but at an elevation nearly 2 m above its lowest point. Any storm wave reaching the upper end of the depression would have had to run up to an elevation of 8 m, gaining an entrance through this very narrow slot; therefore, it is difficult to imagine how normal wave action could have cut an embayment 40 m wide into this tough sandstone. Moreover, the geometrical constraints of the depression would have caused any debris from wave attrition to be swept down the dipping floor and to be trapped against the perimeter wall at its lower end. Remarkably, not so much as a single block or cobble is trapped against the lower wall. Indeed, the entire floor of the depression is free of debris except for several small wedge-shaped blocks that are trapped less than 0.5 m from their origin in a joint-bounded cleft. The missing blocks, some of which were 3.5 m on the long axis, had a volume of about 8 m^3, and weighed ~20 t (tonnes), were plucked clear of the depression. The joint spacing on the floor and walls of the depression indicate that even the smallest blocks removed had a volume of about 3 m^3 and weighed nearly 8 t. A total of ~1200 m^3 was removed from the depression in this manner. Not only were the blocks plucked from the depression, they were also completely removed from the ramp. Boulders are piled up at the base of the cliff in the southern corner of the ramp, but their lithology shows that they have fallen from the cliff, rather than having been plucked from the ramp.

On both sides of the excavated section, the ramp is dissected to depths of between 0.3 and 1 m by narrow, intersecting channels or clefts spaced at 0.1 to 1 m. Some of these channels follow joints but, as many show no evidence for structural guidance of any sort, the total array is highly complex and in some places almost chaotic (Fig. 2). The dissected surface initially gives the impression of having been etched by the leaching and removal of silica, enhanced by the high chloride content of coastal environments as described from elsewhere along this coast (Young, 1987). However, three facts make such an origin for these clefts unlikely. First, apart from the spalling of a layer ~1 mm thick, the sandstone is remarkably fresh, with no sign of the intense pitting generally associated with leaching of silica. Second, the floors of the clefts are remarkably free of weathered detritus. Third, the array of clefts terminates abruptly about two-thirds of the way across the platform without any change of slope or lithology. If the array of clefts were the product of weathering, it would surely be separated by a transitional zone from the undissected ramp behind it.

Numerous shallow curved depressions are superimposed on the chaotic field of clefts downstream of the quarried depression. These features appear similar to the asymmetrical "Sichelwannen" (sickle troughs) formed by cavitation in subglacial meltwater channels (Ljungner, 1930). These sickle troughs are aligned in groups in a northeast-southwest direction and are offset 10°–20° from the direction of nearest joint alignment.

Near the upper end of the ramp, between 12 and 13 m high, the erosion pattern becomes much more regular. This zone extends for ~20 m to within ~2 m of the top of the cliff terminating the ramp northward. The dominant pattern here is one of subparallel clefts or flutes cut to depths of between 0.5 and 1 m (Fig. 3). The main flutes are aligned along the strike of the sandstone rather than down the dip, which steepens locally to 10°. Moreover, the ribs of sandstone between the clefts have a distinctly streamlined morphology with a blunted proximal or upstream end and a much narrower tapered distal end toward the ramp (Fig. 3). On the edge of the

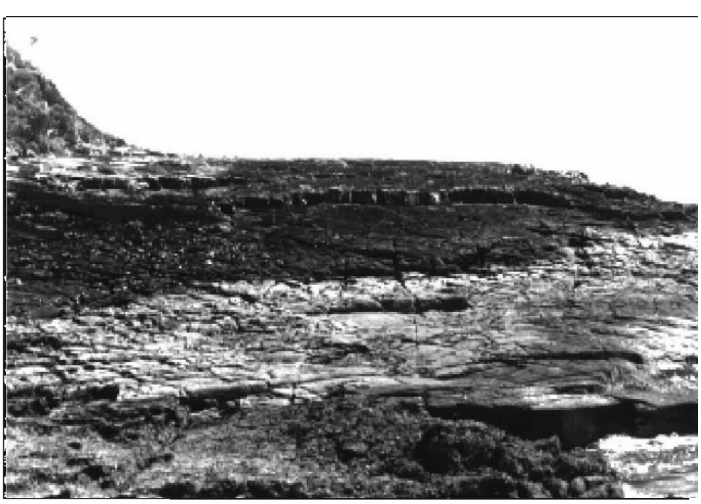

Figure 2. Main ramp on Tura headland showing depression from which blocks were excavated (A), zone of eroded clefts (B), and zone of aligned fluting near crest of ramp (C). Top of ramp is 16 m above mean sea level. View is 80 m across.

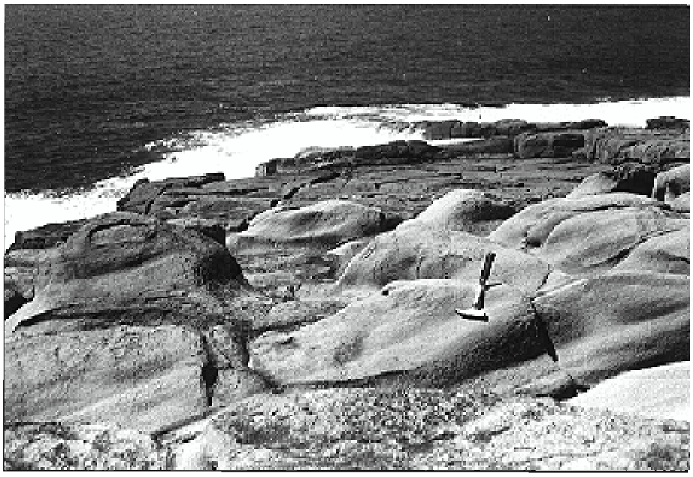

Figure 3. Wave-cut flutes near summit of ramp approximately 14 m above sea level. Hammer is 25 cm long.

cliff the fluting gives way to a zone from which joint-bounded blocks have been plucked.

We suggest that the complex arrays of clefts, flutes, and sickle troughs, so well defined and preserved on the Tura ramp, are entirely the product of erosion by water (cf. Baker, 1978). The abrupt onset of dissection seems indicative of a critical threshold, and, notwithstanding the many clefts cutting laterally across the ramp, there is a discernible pattern extending downslope. However, the highly irregular pattern of intersection and the lack of any clearly defined branching tributary system, together with the clear evidence of the plucking of blocks from some of the larger clefts, seem indicative of highly turbulent, unconfined flows of short duration.

Other ramps in the vicinity show similar, although less striking evidence for erosion by waves at high elevations. A complex assemblage of ramp segments that reflects lithological and structural variations on the front of Tura Head has been swept and eroded by waves to a height of at least 15 m. Wave action to virtually identical height can be deduced at Haycock Point, 10 km farther south, where Tertiary sediments that cap the headland have been eroded from the crest of a ramp that rises steeply to a height of 16 m. Numerous smaller ramps on both of these headlands display well-developed erosional forms above the range of contemporary storm waves. Similar instances of high-level, catastrophic erosion can be seen farther north along the coast. For example, 2–3-m-deep channels, which face northeast rather than into the dominant southeasterly swell, have been carved into and clearly postdate shore platforms dated at 347 ka (Bryant et al., 1990) near Wollongong (Fig. 1). Another notable example is a series of abrasion features and displaced blocks at elevations of over 20 m on a large ramp on the southern side of the entrance to Jervis Bay (Fig. 1).

HIGHER SEA LEVELS

The features we have described are unlikely to be ancient shorelines elevated by tectonic uplift or stranded by eustatic fall. The general tectonic stability of the south coast of New South Wales has been demonstrated by the presence of Tertiary basalts, sedimentary rocks, and weathering profiles at or near sea level (Young and McDougall, 1982). Tura Head and Haycock Point are the eroded remnants of the sides of valleys that were filled with Oligocene sedimentary strata that pass below present sea level, and both headlands are covered by a veneer of this sedimentary rock in which a late Miocene lateritic profile is preserved (Nott et al., 1991). Tectonic stability is also indicated by a 7–8 m raised platform level over a distance of 600 km between Newcastle and the Victorian border. U/Th analysis determined an age of 347 ka at Wollongong for the 7–8 m level (Bryant et al., 1990). Thus, if the sculptured features at 12–15 m were the remnant of a former sea level, they would date from at least early Pleistocene. Such a great age is difficult to reconcile with the extremely fresh appearance of the fluted rock surface on the main ramp at Tura Head and with the absence of even a veneer of sediment, either from in situ weathering or from debris shed from the cliff on the landward side of that ramp. A relatively recent stripping of weathered material from ancient features is difficult to reconcile with the complete absence of debris in the depression on the ramp which would have acted as a highly efficient trap for sediment being swept over the platform.

STORM WAVES OR TSUNAMIS

If the features cut on the main ramp at Tura Point were carved by storm waves, then, even allowing for substantial runup across the ramp, the wave regime must have been far more energetic than the present-day swell regime. Although a narrow continental shelf allows about 95% of wave power to reach the surf zone (Wright, 1976), the wave regime is dominated by swell rather than storm waves, and mean wave height is only 1.2 m. Records from deep-water wave-rider buoys of wave heights measured at Sydney, which has a higher wave-height regime than the south coast, indicate that significant wave heights exceed 4 m and 7.6 m 1% and 0.01%, respectively, of the time (Youll, 1981). The 1 in 100 yr recurrence interval of the ranked annual deep-water storm wave, based on hindcast data for the past 43 yr, is 9 m at Eden within 60 km of Tura Point and 10 m in the Sydney-Newcastle region (Blain Bremner and Williams, 1985). Assuming wave periods of 10–14 s, waves of these heights can theoretically (Coastal Engineering Research Center, 1977) run up to elevations of 14 m, given the 7° slope of the Tura ramp. In reality, however, waves of these heights and periods inevitably break before reaching the shoreline, even where headlands protrude seaward into deeper water depths.

The following criteria can be used to assess the type of wave breaking (Komar, 1976):

$$\text{breaking index} = H_b/(gsT^2), \tag{1}$$

where H_b is breaker wave height, s is slope, T is wave period, and g is the gravitational constant.

This formula gives indices of 0.01–0.06 for storm waves on the Tura ramp, values indicating plunging breakers or spilling bores (Komar, 1976). Energy dissipation is high for these types of waves, and the high theoretical runup elevations calculated above cannot be obtained. These facts are reinforced by observations of storm-wave runup along the New South Wales coast. During the May 25, 1974, storm, 7-m-high waves did not even overwash the 7-m-high raised platform at Red Point, Wollongong. Nor did these storm waves severely erode existing intertidal rock platforms. In the Sydney area, where the effects of this storm were most pronounced, observations revealed minimal chipping and boulder movement on intertidal rock platforms, let alone the plucking and erosional fluting features described above for Tura Point. Even truly catastrophic storms of very low frequency would generate plunging breakers or spilling bores along this coastline.

We believe tsunamis to be the most probable cause of the features cut on the Tura Point ramp. The quarrying of the blocks from the center of the ramp, without any rounding of joint faces by abrasion, seems indicative of a wave train of short duration. The magnitude of the vortices or degree of turbulence needed to pluck blocks of 8 to 20 t from the surface of the ramp is not known, but a considerable depth of water was undoubtedly required

for macro-turbulence of that order to develop (Baker, 1978). Furthermore, the wave had to be more than 13 m high to overtop the northeast corner of the ramp and still be at least several metres deep to cut the streamlined ribs at the ramp crest. Tsunamis, because of their much longer wave periods relative to ocean swell, are the only wave phenomenon capable of producing such flow criteria.

We suggest that a tsunami wave train hit the ramp from the northeast. The alignment of flutes and the juxtaposition of isolated boulders at the northeast corner, and the orientation of the sickle troughs further down the ramp, are evidence for this direction of approach. The tsunami ripped out part of the northeast corner of the ramp and carved the flutings at the crest as the waves swamped the ramp to an elevation of at least 16 m. The depression in the middle of the ramp was formed by boulder plucking generated either by extreme turbulence as the wave broke onto the ramp or by vortices ("kolks") developing under high-velocity flow and turbulent bursting (Baker, 1978). Flume studies indicate that a breaking tsunami generates a jet that tears off from the wave crest, followed at the point of impact by a strong splash that continues to propagate as a bore (Krivoshey, 1970). Each of these features can produce the turbulence and high velocities required for the plucking of joint-controlled blocks from the surface of the Tura ramp. The cutting of the streamlined flutes and of the complex array of clefts and sickle troughs lower on the ramp could have taken place rapidly under conditions conducive to cavitation. The sharp delineation between the smooth rear section of the ramp and the zone of chaotic clefts marks the point where the critical velocity necessary for cavitation ceased to occur. The fact that this line parallels the landward side of the ramp implies that backwash may have been important in the formation of the chaotic field of clefts on the southern part of the ramp.

These conclusions are supported by hydrodynamic estimates. For depths of flow between 2 and 10 m, mean velocities of ~10 m/s are required to produce cavitation (Baker, 1978), but few calculations of tsunami bore velocities have been made because the prediction of runup height limits has generally been perceived as more important in risk analysis. Theoretically, bore velocity in its simplest form is a function of the square root of the runup height, but this relation can be expanded to include slope and bed friction (Kirkgöz, 1983, p. 475). Given the ramp slope of 7° and the field evidence for a runup height of at least 15 m, and assuming a friction coefficient of 0.01 and a wave-trough amplitude of 1 m, this equation yields current velocities of between 17.9 and 18.4 m/s under flow depths of 2–10 m. These velocities are well in excess of the 10 m/s threshold required for cavitation. Nor would the tsunami dissipate most of its energy by breaking. Given a continental slope of 0.3° (Fig. 1), a tsunami period of 10 min and a breaker height of at least 13 m, the breaker index for the tsunami wave, if we use equation 1, is less than 7×10^{-5}. At this value, the tsunami wave will always be surging as it breaks over the inner continental slope or onto the ramp (Komar, 1976). Surge velocities across the ramp may have been locally increased by rebound from the landward cliff or by acceleration down the inclined surface of the ramp, thereby accounting for the sudden onset of cavitation features part way across the ramp.

CONCLUSIONS

A wave train with a runup as great as that recorded on Lanai must also have had a significant impact on coasts around the Pacific. Its imprint is more likely to be preserved on a stable coast such as that of southeastern Australia than on erosionally and tectonically mobile coasts such as those of New Zealand and the island arcs farther north. The extent and timing of the destruction of the last-interglacial barriers in southern New South Wales are in accord with the Lanai event, and independent evidence for catastrophic wave erosion, albeit of much less certain timing, is recorded in the erosional assemblage of the bedrock ramp at Tura Head. We suggest that these features are long-distance effects of the Lanai wave train. If so, the imprint of the Lanai event and of tsunamis of similar magnitude are probably preserved elsewhere around the Pacific rim.

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