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The tsunami geomorphology of coastal dunes

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Abstract. An examination of the coastal geomorphology of bays along the Otago coastline, SE New Zealand, has identified a geomorphology consistent with tsunami inundation. A tsunami geomorphology consisting of a number of elements including dune pedestals, hummocky topography, parabolic dune systems, and post-tsunami features resulting from changes to the nearshore sediment budget is discussed. The most prominent features at Blueskin Bay are eroded pedestals although it is speculated that hummocky topography may be present in the bay. Tsunami geomorphology at Long Beach is more comprehensive with a marked association between pedestals and a hummocky topography. A full suite of potential geomorphological features however, is not present at either site. The type of features formed by a tsunami, and the ability to detect and interpret a tsunami geomorphology, hinges on the interaction between five key variables; sand availability, embayment type, nature of the coast, accumulation space, and landward environmental conditions. An appreciation of the geomorphic setting and history of a coast is therefore of fundamental importance when identifying what to look for and where to look for tsunami evidence. It is also important to realise that these features can also be formed by other processes.

1 Introduction

Prior to the Indian Ocean Tsunami (2004 IOT) of 26 December 2004, there had been a moderate amount of data collected concerning historically-documented events and the geological evidence of palaeotsunamis in Australia (e.g. Rynn, 1994; Bryant, 2001) and New Zealand (e.g. de Lange and Healy, 1986; Goff et al., 2001). In the aftermath of the 2004 IOT however, there has been a significant push to improve and add value to both sets of data (Berryman, 2005; Dominey-Howes, 2007; Goff, 2008). The added-value component discussed in this paper concerns tsunami geomorphology. It is important to distinguish here between tsunami geomorphology and tsunami geology in the context of the Holocene sand dune environments discussed in this paper. Geomorphology looks at landforms and the processes that created them; geology investigates the material that comprises these forms and the processes that led to their deposition.

Geomorphologically, as opposed to geologically, the most common signature of a tsunami consists of a hummocky, onshore landform; geological – this is normally a sand sheet (e.g. Goff et al, 2004; Jaffe and Gelfenbaum, 2007). Few though, have considered a comprehensive study of possible geomorphological features related to tsunami inundation. A previously reported, but little-used, geomorphic tsunami signature is called a "tsunami-scour fan" (Kitamura et al., 1961; Yulianto et al., 2007). It forms where a tsunami cuts a breach, or cleans out an existing one, through a dune ridge. Using scoured material, the tsunami builds a fan as it emerges from the breach. The fan may build on the landward side during inflow, on the seaward side during outflow, or both (Kitamura et al., 1961). Tsunami-scour fans were previously noted, on opposite sides of the Pacific Ocean, as products of the tsunami associated with the giant Chilean earthquake of 22 May 1960. They formed abundantly in northeast Japan by inflow and outflow where the 1960 tsunami cut breaches through roads and levees (Kitamura et al., 1961). They have also been reported from the tsunami's source region. Near the city of Valdivia, Chile, a fan built by tsunami inflow approaches 1 m in thickness behind an open-coast beach ridge (Bourgeois and Reinhart, 1989). In addition, to the south near Maullín, fans (comprised of sand) are evident on aerial photos taken in January 1961 (Atwater et al., 1999). Still other examples of tsunami scours have been reported from Kamchatka (MacInnes et al., 2005).

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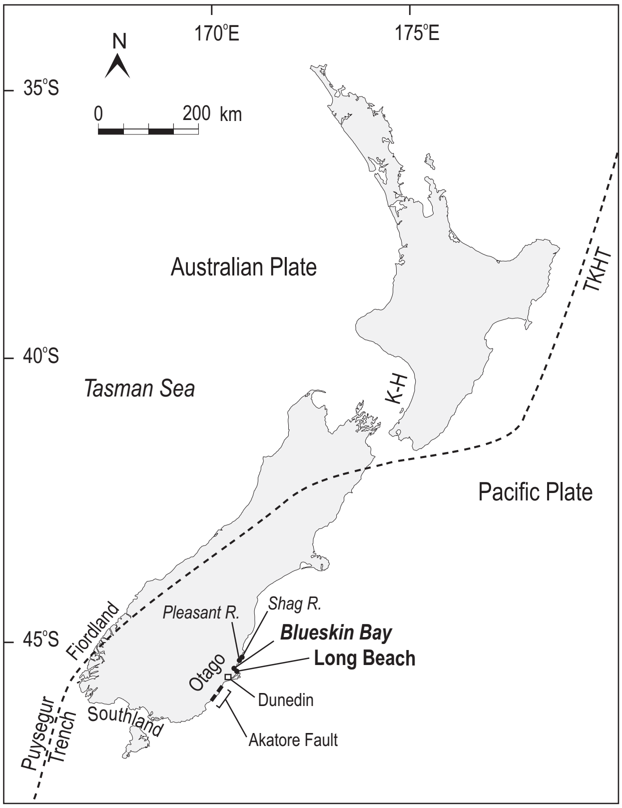

Fig. 1. Map of New Zealand showing key tectonic associations and names mentioned in the text (dashed line represents approx. boundary between the Pacific and Australian Plates).

This paper reports on work carried out on coastal geomorphology in New Zealand, where similar scour fan and breach features have been noted. Unlike those reported by researchers in Chile, Japan, and the US however, the New Zealand features are considered as components of a more extensive coastal geomorphological association. The main goal of this work was to determine whether or not we could define a suite of features that could be termed a tsunami geomorphology, and if so, what criteria might control their presence or absence in the landscape.

2 Study area

New Zealand sits astride the boundary between the Pacific and Australian Plates (Fig. 1). To the north at the Tonga-Kermadec-Hikurangi trench, the Pacific Plate is subducting from the east at a rate of 40 mm/yr. To the south at the Puysegur trench subduction zone, the Australian Plate is subducting from the west with a convergence rate of 35 mm/yr. In the centre of New Zealand, the plates are locked. This unique tectonic setting provides a wide range of potential tsunamigenic sources (Walters et al., 2006a, b).

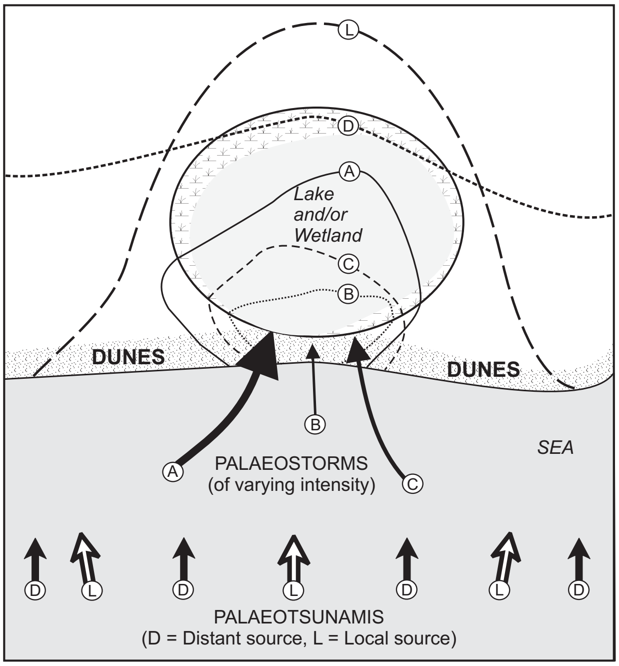

Fig. 2. General landward and alongshore characteristics of storm and tsunami inundation (after Liu and Fearn, 2000; Goff et al., 2006a). Thicker arrows for palaeostorms indicate higher intensity events (intensity varies from high to low, A-C-B), filled and unfilled arrows for palaeotsunamis indicate directional flows for Locally (L) or Distantly (D) generated tsunamis.

The Australian-Pacific plate boundary is at its widest in the coastal Otago region. No recognised uplift or subsidence has been noted in the immediate study areas of Blueskin Bay and Long Beach. The relative tectonic stability of Blueskin Bay actually made it one of the keys sites for the reconstruction of New Zealand's Holocene sea level curve (Gibb, 1986). To the south of Dunedin however, three Holocene ruptures of the Akatore Fault (Fig. 1) have been identified (Hayward et al., 2007). These are believed to have occurred around 1000 cal yrs BP (0.4 m subsidence), 3600 cal yrs BP (1.2 m uplift), and 4500–5000 cal yrs BP (1.0 m subsidence).

Aside from tectonic activity, predicted maximum storm surges in the Blueskin Bay to Long Beach area range from 1.55–1.80 m above mean sea level in a 20–500 year return period with a tidal range of about 1.5 m (Hayward et al., 2007).

3 Features of a tsunami geomorphology

This paper does not aim to present a detailed discussion of the differences between storm and tsunami geomorphologies. Conceptually however, it is important to consider storm and tsunami features since theoretically either could be responsible for sudden marked changes in coastal geomorphology. General observations of the potential longshore and inland extent of these two processes are shown in Fig. 2 which is sourced from the conceptual diagram of Liu and Fearn (2000). They showed the relative longshore and inland extent of deposits from different intensity hurricanes in and around a coastal lake or wetland in Florida. For this paper however, the coastal assemblage is generic and merely serves to show that the longshore and inland inundation from a tsunami (D, L) would, on average, be expected to be greater than that of storms of different intensity (A, B, C). In addition, locally generated tsunamis (L) are generally more likely to inundate further inland but less along shore than their distantly generated counterparts. A detailed discussion of the differences between storm and tsunami geomorphologies is presented in Goff et al. (2006a).

Event magnitude is likely to be an important control on tsunami geomorphology. In general terms, and based upon field evidence from 2004 IOT sites, inundation by large, region-wide events is likely to cause multiple breachings of dune systems (Higman et al., 2005; Goff et al., 2006b). In other words, multiple "tsunami-scour fan" assemblages can be formed during one inundation. The assemblages could include remnant dune ridges, or "pedestals", between each breach, and individual overwash fans that could coalesce to form landward "sand sheets" that may or may not be mobile depending upon aeolian and dune swale conditions (Goff et al., 2008). If landward sand sheets infill or overlay a wetland they can stabilise and weather in situ to form a low profile "hummocky topography". If they remain dry and are exposed to aeolian onshore processes they can form an extensive, region-wide parabolic dune system (Goff et al., 2008). The overall geomorphological assemblage of dune pedestals and multiple breaches is not new, and was modelled through morphological descriptions by Minoura and Nakaya (1991). However, the fate of landward material has rarely been considered (Goff et al., 2008).

Bryant (2001) makes the point that storms tend to only surge through gaps in dunes, sporadically depositing lobate fans that rarely coalesce or penetrate far inland. This can be the key difference between storm and tsunami geomorphology but there is room for confusion in areas of low accumulation space (e.g. in a small pocket beach, there may be insufficient longshore and landward accumulation space for more than one lobate fan and two pedestals) (Goff et al., 2008).

The 2004 IOT provided clear evidence that the topographic extent of a tsunami geomorphology is generally governed by antecedent sand supply (Paris et al., 2009; Goff et al, 2006a, b). Once formed, the long-term preservation of these geomorphological features is affected by subsequent sand supply. Assuming similar post-tsunami conditions, in sand-rich areas there would be rapid rebuilding of coastal dunes and loss of pedestal topography, with possibly only the largest pedestals remaining exposed. There are however, several variables to be taken into account.

Firstly, post-tsunami sand supply may be severely reduced if the tsunami entrains all available nearshore sand (above and often considerably below storm wave base) and transports it inland. Subject to sub-aerial processes on land, this probably removes sand from the coastal sediment transport system for some considerable time. Evidence of sand removed from the system would be preserved landward in deposits.

Secondly, post-tsunami sand supply may be severely reduced if the tsunami transports large quantities of sand from the shore and nearshore seaward beyond normal storm wave base. This effectively removes sediment from the nearshore transport system. Onland, there may be erosional evidence of the sand removed from the system.

Thirdly, post-tsunami sand supply may increase markedly if the tsunami was generated by a large, local earthquake that led to considerable quantities of new sediment being routed into the coastal zone from rivers (Goff and McFadgen, 2002). A delayed pulse can also occur in arid areas where years may pass between the earthquake and the next major rain event (Moseley et al., 1991).

Fourthly, other factors unrelated to tsunamis may affect sand supply conditions, such as extreme climatic events or anthropogenic land clearance.

4 A New Zealand tsunami geomorphology

If the proposed geomorphological features are preferentially preserved in the coastal landscape it should be possible to identify them initially by remote sensing. The ability to remotely sense these features could potentially provide a rapid survey technique to assess the likelihood of past tsunami inundation for long stretches of coastline. The relatively recent development of airborne Light Detection and Ranging (LiDAR) as a remote-sensing tool offers the kind of detail necessary for such a survey technique. LiDAR data are expensive to acquire and as such have not yet become a widespread tool for aiding geomorphological interpretation, but recent research has recognised its important for tsunami hazard studies (Teeuw et al., 2009). With its high spatial density of data points (typically ∼1–2 m) and accurate ground elevation fixes (typically to within a standard error of 0.15 m), LiDAR delivers topographic information that should theoretically be adequate to identify hummocky topography, pedestals, and scour-fan features if they have been preserved within the landscape.

The Otago region coastline (Fig. 1) of SE New Zealand has extensive LiDAR coverage. Based upon the existing historical tsunami database, it has been inferred that there is little significant tsunami hazard for the region's coast. A recent Ministry of Civil Defence & Emergency Management (MCDEM) report states that the expected "mean estimate wave" for a tsunami with a return period of 2500 years is 3.8 m for Dunedin and between 4–8 m for the Otago region open coast (Berryman, 2005). This estimate was largely based upon statistical extrapolation from the short historical

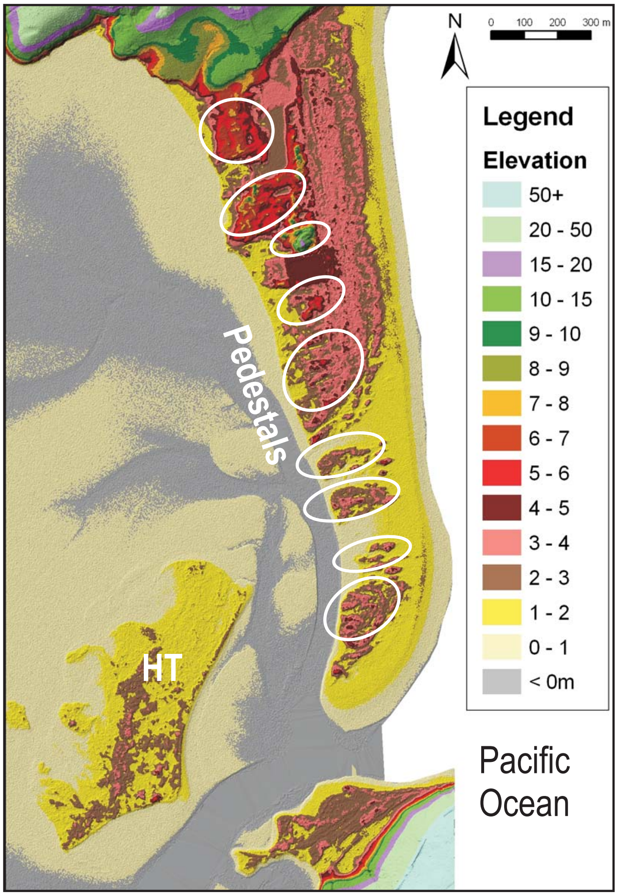

Fig. 3. LiDAR image of Blueskin Bay showing remnant pedestals (white circles) on the spit and hummocky topography (HT) inside the bay.

tsunami database. A recent review of existing geological and archaeological information for the Otago coastline however, suggests that tsunami inundation may have occurred since human occupation in the 13th century (Goff, 2008). If inundation did occur, it would seem likely that this was a relatively rare event because there are no obvious active local or regional earthquake sources thought to be significant enough to generate a large tsunami (Berryman, 2005). Sections of Otago coast could therefore preserve a marked tsunami geomorphology if only rare large inundations (one?) have occurred over the last 7000 years or so since sea level reached close to its present height. Examples for Blueskin Bay and Long Beach (Fig. 1) are discussed below.

4.1 Blueskin Bay

A LiDAR image of Blueskin Bay reveals a series of possible pedestal features along the spit (Fig. 3). A ground survey subsequently confirmed their presence. All were topped with trees and relatively mature vegetation. Pedestals had a core of compact weathered sand and soil markedly older than the overlying unconsolidated, fresh sand (Goff et al., 2006a). At the low-lying southern end of the spit, scours separating the pedestals are actively maintained by tidal flows at or near high spring tides.

Comparison between 1958 and 1990 aerial photographs indicates that the pedestals have largely remained stable over the last 40 years. Minor variations in pedestal volumes are visible, probably as a result of scour in storm events. The locations of pedestal cores however, have not changed. During the ground survey, evidence for Archaic (early) Maori occupation was noted in the upper soil horizon of inactive, relict pedestals towards the northern end of the spit. Given that Maori settlement dates to the 13th century (Anderson et al., 1996), and the Archaic Maori period ends around the 15th century (McFadgen, 2007), this places an upper limited on on the age of any event. It is likely that pedestal core material and formation dates to no later than the 15th century, although no specific fieldwork has been undertaken. Evidence from the estuary landward of the spit is more equivocal. The preservation of a sand sheet would seem unlikely in this active environment since it would be subject to ongoing fluvial and tidal processes. While speculative, it is possible that the rapid deposition of a large volume of sand by tsunami inundation could have exceeded the ability of these processes to remove all the material. The large, severely eroded island assemblage landward of the spit has a morphology consistent with a proposed hummocky topography that would eventuate following long-term sub-aerial weathering. In the absence of a more detailed study, however, this interpretation must be considered tentative.

4.2 Long Beach

The LiDAR image for Long Beach reveals a small embayment with two distinct sets of dunes (Fig. 4a). A fragmented landward set of higher elevation dunes, and an intact seaward group of lower elevation dunes. These are separated by a wide, low-profile plain sequence. The seaward dune system started to form around 1863 (Anderson, 1981). A section of well-defined hummocky topography is shown landward of the set of higher elevation dunes. The fan of hummocky topography splays into a small wetland formed where a stream ponded behind the dunes. This pedestal-hummocky topography association is interpreted as tsunami geomorphology.

If the tentative interpretation of the chronology of Blueskin Bay is correct, and inundation was more regional than local, this event would most likely have been contemporaneous, occurring around the 13th–15th centuries. Long Beach contains an important Archaic Maori site that shows evidence of having been "washed by the sea" (Leach and Hamel, 1981). Numerous stone and bone artefacts were reworked by the sea and redeposited within a layer of pebbles and sand. Occupation at this time was radiocarbon dated to about AD 1460+/-58 years. There was a temporary hiatus following inundation with subsequent re-occupation moving

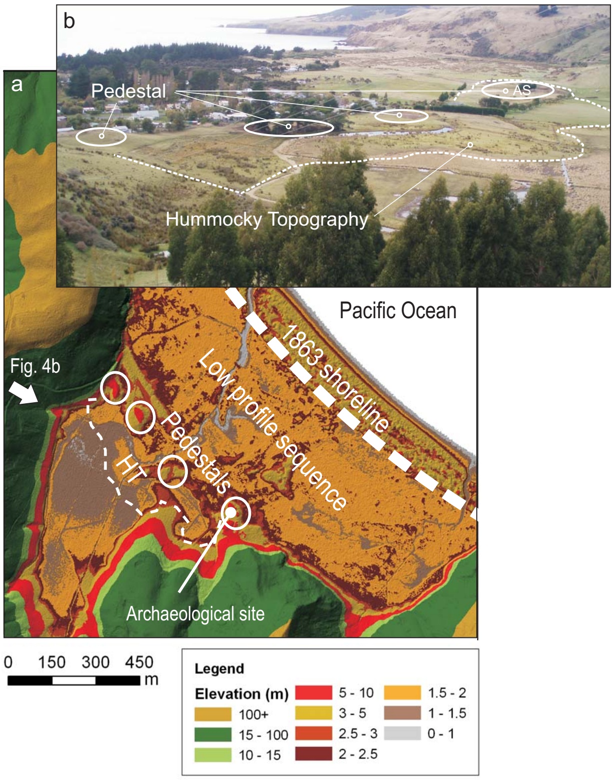

Fig. 4. **(a)** LiDAR image of Long Beach showing remnant pedestals (white circles) and hummocky topography (HT) in the landward wetland. The location of the archaeological site is shown – this point also marks the location of the photo shown in Fig. 5. The white arrow marks the photo site for Fig. 4b. **(b)** Low angle photo of Long Beach with key features shown. AS=Archaeological Site, the dashed line delimits the known extent of the tsunami deposit.

to the recently-deposited, and poorly vegetated, fan of hummocky topography (Leach and Hamel, 1981). A ground survey found the dune system overlain by a unit of pebbles and sand approximately 20 cm thick with a marked erosional contact at the base (Fig. 5). The unit fines upwards and landward into a fine-medium sand composed mainly of aeolian material. The unit was traced across almost the entire width of the valley floor, seaward to the base of the pedestal adjacent to the archaeological site, and landward about 150 m (Fig. 4a, b). In similar geomorphological associations elsewhere in the country, this type of sedimentary unit has been defined as a tsunami deposit (e.g. Nichol et al., 2004). Perhaps the important point to make here is that there is no other process capable of depositing such a sedimentary sequence – it is not diagnostic of a storm deposit (e.g. Goff et al., 2004). Since this layer overlies the early Maori site, and extends inland as a coherent unit into the sand sheet/hummocky topography (Fig. 4a, b), it seems reasonable to conclude that this relates to a tsunami inundation that occurred around the late 14th to 15th centuries. The tsunami geomorphology reflects scour between, and the overtopping of, the dune system.

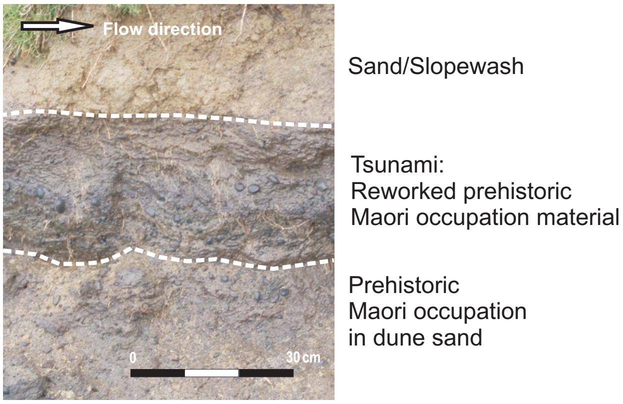

Fig. 5. Photo and description of overlying tsunami deposit at Long Beach. Photo taken looking southeast with tsunami flow from left (seaward) to right (landward).

5 Regional tsunami source for the Otago coast

The data discussed above provides a valuable extension to our current knowledge about tsunami inundation along the Otago coast. However, this has not explicitly addressed the issues of tsunami source, timing, and hazard for the region.

There has been no extensive geological study of tsunami deposits along the Otago coast. Most of the limited chronological evidence for tsunami inundation along this stretch of coast comes from archaeological studies. Chronological control is poor, but we infer that one large event probably occurred around the 14th to early 15th centuries. Based upon the data from Long Beach, it appears that this may have been the only large tsunami to have inundated the coastline since sea level rose to the approximate point we experience today about 7000 years or so ago (Goff et al., 2006a). So the hazard would appear to be low. The most significant problem with interpreting a large, regional tsunami around the 14th to early 15th centuries is that there do not appear to be any obvious sources (Berryman, 2005). A possible source is the Akatore fault, about 50 km south of the study sites (Fig. 1). The most recent rupture has been dated to between AD 1330 and AD 1410, which closely approximates the estimated age for tsunami inundation. This source however, can be discounted because while it caused fairly extensive regional groundshaking and compaction of estuarine sediments (McFadgen, 2007) the fault length is too short to generate a large enough tsunami. Submarine landsliding off the adjacent continental shelf has also been proposed as a possible source, but only small volume slides appear to have occurred during the Holocene, and these are not capable of generating large tsunamis (Berryman, 2005).

Berryman (2005) recently observed that in the offshore Fiordland region (Fig. 1), plate boundary structures including the Puysegur trench subduction zone are capable of producing large-to-great earthquakes of >Magnitude 8. There are early historical records of a possible tsunami in southern New Zealand around the 1820s, and recently a numerical modelling study was carried out for the Southland region (Fig. 1) adjacent to the Otago coast (Downes et al., 2005). This was later extended across the Tasman Sea to include tsunami wave heights of about 1.5 m off the east coast of Tasmania (e.g. Greenslade et al., 2007). Interestingly, it was felt that the bathymetry off the southern South Island appeared to offer some degree of natural protection to the southern shores of New Zealand because the water shallows at a substantial distance from the coast (Berryman, 2005). The northeastern extent of a tsunami generated by a large Puysegur trench subduction zone earthquake has therefore only recently been modelled (Lane et al., 2007). Waves refract around the southeastern continental shelf of New Zealand and focus in on the Otago coast (Greenslade et al., 2007; Lane et al., 2007). Tsunami inundation at Blueskin Bay has water over 2.0 m deep overtopping and scouring the spit (Lane et al., 2007). This modelling was based upon contemporary coastal geomorphology at Blueskin Bay which appears to have remained relatively stable since Maori settlement about 700 years ago (Goff et al., 2006a). Unfortunately, at Long Beach there has been over 500 m of progradation over the same time period and as such model results cannot be related to past tsunami geomorphology (Fig. 4a).

A regionwide tsunami generated by a Puysegur trench subduction earthquake seems to be the most realistic source for the 14th–15th century event. Independent dating of inundation (e.g. Long Beach) from the Puysegur trench subduction earthquake, and compaction of estuarine sediments following the associated groundshaking (e.g. Shag River, Pleasant River: McFadgen, 2007) (Fig. 1) from the Akatore fault event produce overlapping ages. Some association with the Akatore fault event cannot therefore be ruled out.

6 What to look for and where to look

Assuming that a coast has been subject to inundation by a large tsunami in the recent geological past, the ability to detect and interpret their geomorphic signature from LiDAR data, and also in the field, hinges on the interaction between five key criteria.

6.1 Sand availability

The spectrum of sediment availability ranges from sediment-rich to sediment-poor. In sediment-rich environments, tsunami geomorphology is more likely to be rapidly buried by incoming post-event material (tens of years). This is particularly pertinent for pedestals. In a sediment-poor system, geomorphology is more likely to be preserved for a much longer period (hundreds to thousands of years). Blueskin Bay shows the effects of a moderate sediment regime, where there have been substantial volumetric changes in pedestal morphology and sand has periodically accumulated and eroded over time. At Long Beach, an extended period of reduced sediment supply and poor positive sediment budget led to the progradation of a low profile plain sequence. There were no large pulses of sediment delivery to the coast capable of forming marked dune ridges (e.g. Wells and Goff, 2007). A recent human-induced increase in sand supply has formed a new, lower dune sequence from 1863 onwards (Fig. 4a).

6.2 Embayment type

Embayment types vary in a range from enclosed/semi-enclosed embayments through to pocket beaches. In this study, the closest to the former end member was Blueskin Bay. This semi-enclosed embayment has possible hummocky topography that has been subject to erosion by tidal and fluvial processes. Small pocket beach type embayments, such as Long Beach, which often have small streams and/or wetlands ponded behind coastal dunes, are more likely to preserve the features of tsunami geomorphology. This is because neither their coastal nor fluvial processes are sufficiently energetic to rework tsunami-emplaced geomorphology.

6.3 Nature of the coast

An eroding coast is unlikely to preserve a complete geomorphological record of past tsunamis. Over time, the record will become degraded or lost. A prograding coast, such as Long Beach, is more likely to preserve a tsunami geomorphology.

6.4 Accumulation space

A restricted landward accumulation space limits the development of tsunami geomorphology. On the other hand, there is less likelihood of post-tsunami remobilisation of the sand sheet, for example by wind and estuarine currents, thus hummocky topography is more likely to develop and be preserved (e.g. Long Beach). Differentiation of hummocky topography from conventional dune ridge formation will be complicated if multiple tsunami inundations add further scour fan material. Large accumulation spaces provide the potential for the development of a more complex tsunami geomorphology with the creation of remobilised sand dune phases as landward parabolic dune systems (e.g. Kapiti-Horowhenua coast; Goff et al., 2008).

6.5 Landward environmental conditions

In a wet landward environment (e.g. backshore swamp/pond) inwashed sand is more likely to stabilise and weather (in situ) over time to form a hummocky topography. Dune systems are often associated with some form of ponded landward drainage system. Low profile hummocky topography closely linked to a pedestal landscape is therefore the most likely geomorphological association to be found in relation to tsunami inundation. This is not always the case however, and dry landward environments would enable remobilisation of sand with the possible formation of a parabolic dune field.

7 Conclusions

A survey of sites on the Otago coast of New Zealand has provided evidence of a tsunami geomorphology. The assemblage of geomorphological features includes dune pedestals, hummocky topography, and post-inundation adjustments to the coastline. Chronological data are inconclusive, but the evidence points towards a regionwide tsunami generated by a Puysegur trench subduction earthquake around the 14th–15th century.

All elements of the proposed tsunami geomorphology are common on sandy coasts and are often formed by other coastal processes. There are several variables that determine the exact nature of the geomorphological assemblage, and indeed whether or not the evidence is preferentially preserved at all. A tsunami geomorphology can consist of dune pedestals, hummocky topography, parabolic dune systems, and post-tsunami features resulting from changes to the nearshore sediment budget. When viewed as an assemblage however, their process of formation is compelling. It is important to note however, that simply because all or some of the component parts of a proposed tsunami geomorphology can be identified does not mean that inundation has occurred. It does mean however, that the process of tsunami inundation needs to be considered when interpreting process-form relationships in sandy coast environments, especially if these are located in tectonically active areas.

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