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The origin of centennial- to millennial-scale chronological gaps in storm emplaced beach ridge plains

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ABSTRACT

Recent studies of tropical cyclone surge and wave emplaced beach ridge plains have shown that these sequences often contain centennial to millennial scale gaps in their chronologies. Two explanations for the gaps exist — they are due to erosion, or alternatively a cessation or substantial slowing of depositional processes suggestive of a quieter phase in intense storm activity. Differentiating between the two is important for uncovering reliable long-term storm histories from these sequences. We use landform morphology, sediment texture and luminescence chronology to determine the origin of substantial chronological gaps in a plain containing more than 100 shore-parallel ridges composed of fine-grained sand located in northeast Australia. We identify and describe the characteristics associated with both erosional and non-erosional gaps. The erosional gaps are associated with changes in orientation between ridge sets and often a high ridge with hummocky topography that appears to have been disturbed by aeolian activity. River floods likely caused the partial erosion of ridge sets. Non-erosional gaps do not display these morphological characteristics and are likely associated with quiescence in severe tropical cyclone activity. These geomorphic and chronological signatures can be used to identify different sorts of gaps in other ridge plains and are an important tool in the reconstruction of long-term storm histories from these coastal landforms. The data also suggests that fine-grained ridges can, like their coarse-grained counterparts, be predominantly deposited by storm waves and surge and their texture need not necessarily be indicative of the processes responsible for ridge development.

1. Introduction

One of the striking characteristics of long-term sedimentary records of tropical cyclones (TCs) globally is they display centennial to millennial scale chronological gaps (Nott and Forsyth, 2012). In the case of hurricane overwash deposits (Liu and Fearn, 2000; Donnelly and Woodruff, 2007; Woodruff et al, 2009) it is difficult to ascribe erosional processes to the gaps for the records are composed of sand layers sandwiched within fine-grained sedimentary units in back barrier lagoons. Chronological gaps within beach ridge plains that record long-term TC histories (Nott, 2003; Nott et al., 2009; Forsyth et al., 2010) are possible via two causes; erosion and removal of ridges or periods of slower or no ridge building possibly associated with a quiescence in intense TC activity.

Beach ridge plains are extensive globally and especially within many regions that are impacted by TCs, hence their potential for obtaining long-term records of TCs is high. Differentiating between chronological gaps caused by erosion versus those due to periods of less intense TC activity is critical for uncovering accurate records of these storms. To this end we present a brief review of studies examining the impact of TCs on sand coasts and in particular their impact on beach ridge and dune systems.

Following this review we present details of our study of an extensive sand beach ridge plain at Cungulla, approximately 30 km southeast of Townsville in NE Queensland, Australia. This sand beach ridge plain offers an opportunity to differentiate between chronological gaps caused by erosion, and the nature of the erosional processes, and those possibly due to less intense TC activity. This is because the Cungulla sequence includes ridges arranged into distinctly unconformable sets with some ridges displaying smooth convex-up shaped profiles while others display hummocky profiles. Unlike other beach ridge plains studied in this region (Nott and Hayne, 2001; Hayne and Chappell, 2001; Nott, 2003, 2010; Nott et al., 2009; Forsyth et al., 2010, 2012) the plain here appears to contain evidence of gaps associated with erosion along with non-erosional chronological gaps. We present high-resolution LiDAR data to highlight the ridge morphologies, a statistical analysis of ridge sediments, a detailed Optically Stimulated Luminescence (OSL) chronology and results of numerical wind and wave modelling to help

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identify the characteristics useful for differentiating between erosional and non-erosional chronological gaps in these beach ridge plains.

2. Impact of tropical cyclones on sand coasts

Unlike temperate storms TCs generate a substantial storm surge and inundation (surge, tide, wave set up, wave action and wave run up combined) depending upon a range of meteorological, bathymetric and topographic characteristics (Nott, 2006). In general, storm surge varies with TC intensity (decreasing TC central pressure), speed of forward TC movement, radius of maximum winds, bathymetry, and coastal configuration. Temperate storms too can generate surges but they are usually substantially lower in magnitude than those generated by TCs although, like TCs, temperate storms can generate substantial wave run-up heights (Nott, 2006). The most obvious difference between the two is that TCs sometimes generate inundations where the flow depth is higher than the beach ridges and coastal dunes. While this can also occur with temperate storms their inundations appear to result more often in the scarping of the ridges/dunes because the storm surge is typically lower (Thom and Hall, 1991; Nott, 2006, 2010; McLean and Shen, 2006).

Like temperate storms, beach erosion is common following the impact of a tropical cyclone. Often the beaches regrade into gently seaward sloping almost planar surfaces which extend into foredunes. Such features have been termed 'hurricane beaches' (Hayes, 1967). Hopley (1974) observed this form of beach erosion following TC Althea in North Queensland 1971. Here, at beaches close to the location of TC coastal crossing, the distinction between the upper and the lower beach was lost and the foredunes were scalloped by wave swash (Hopley, 1974). In places the entire foredune was eroded but elsewhere it was scarped and eroded horizontally but not completely removed. At the site of maximum surge the beach ridges were submerged and scarped on the seaward edge but not entirely removed. Washover fans were also deposited in some places into back barrier mangroves (Hopley, 1974).

Eroded beaches and washover fans are common features following TCs. They have been observed extensively along the shores of the United States of America (Morton, 1978; Horton et al., 2009) and Australia (Hopley, 1974; Nott et al., 2013) and the washover fans have been used for studies of palaeotempests (Liu and Fearn, 1993, 2000; Donnelly and Woodruff, 2007; Woodruff et al., 2009).

The extent and type of beach/dune/ridge erosion and washover fan deposition are dependent upon a range of factors including the existing coastal topography and configuration, sediment texture, storm approach angle, storm forward speed, storm intensity and size, fetch and bathymetry (Morton and Sallenger, 2003). The resulting height of the storm inundation relative to the coastal topography is also critical. As Morton (2002) notes, waves erode scarps when the inundation is below the level of the back beach and dunes. When the inundation is about equal in height to the dunes minor washover fans are produced and these become substantial when the inundation is above the level of the dunes. This can involve washover fans being deposited onto an existing topography so the elevation of the coastal landscape inland of the beach is elevated locally. Vertical dune erosion can also occur, resulting in a lowering of the coastal topography; these dune sediments also become a substantial source of sediment for fan development. Nott and Hubbert (2005) observed such a phenomenon following TC Vance in Western Australia, 1999. Here three parallel rows of 6 to 7 m high dunes were eroded to the level of the back beach. The sand was transported inland as a tapering wedge that contained cross-bedded foresets and which terminated abruptly approximately 300 m inland of the position of the former dunes. This vertical dune erosion only occurred along a stretch of beach approximately 750 m in length corresponding to the zone of maximum inundation; elsewhere the inundation didn't overtop the dunes and they were extensively scarped.

Dune and barrier breaching is common during severe TC inundation and wave attack. This is particularly the case when the inundation is constricted by pre-existing topography causing flow depth and erosive potential to increase. Deposition of the eroded sand in these situations usually extends further inland compared to those areas of the coast where the inundation moves across the barrier as sheet flow (Morton and Sallenger, 2003). Other forms of erosion due to TC inundations include channel incisions and washouts, the latter occurring when there is a seaward flow of water from a water body normally separated from the sea by the barrier (Morton and Sallenger, 2003). Wetlands too on the landward side of dunes can experience substantial erosion resulting in the formation of linear and amorphous ponds and braided channels (Morton and Barras, 2011).

Tropical cyclone inundations can have a substantial impact on sandy coasts with shoreline retreat sometimes over 100 m as was the case during Hurricane Katrina in 2005 along the Gulf of Mexico coast (Fritz et al., 2007; Horton et al., 2009). Breaching of barriers often occurs with some breaches attaining widths up to 1.9 km as occurred on Dauphin Island, a barrier island offshore from Louisiana, during Hurricane Katrina (Fritz et al., 2007). Substantial sand deposition can also occur in the coastal landscape resulting in the raising of existing barrier topography in places (Fritz et al., 2007; Morton and Barras, 2011; Morton and Sallenger, 2003; Horton et al., 2009; Hopley, 1974; Nott, 2010; Nott et al., 2009; Hawkes and Horton, 2012).

Most of the above cited studies have examined the impacts of TC inundations on barrier islands and aeolian dune fronted mainland coasts as opposed to coasts dominated by beach ridges. Whilst Hopley's (1974) reconnaissance of the North Queensland coast impacted by TC Althea in 1971 did reveal that some sections of the beach ridge backed coast had foredune/frontal ridge scarping, there were no kilometre scale breaches and extensive removal of ridges from a beach ridge plain. Nott (2010) reported post-event surveys of several TCs in North Queensland and noted that erosion was limited to the flattening of beach profiles and the scarping of the first ridge fronting beach ridge plains. Nott et al (2009) noted the same for the coast impacted by TC Larry in North Queensland, 2006. A survey (by the authors) of the impact of TC Yasi in North Queensland in 2011 (929 hPa central pressure) found no major breaching of ridge plains but flattening of beach profiles, scarping of the first ridge and extensive deposition of sand on top of the most seaward ridge (Nott et al., 2013). This lack of extensive erosion during inundations that substantially overtop the coastal topography, unlike the total removal of three rows of 6 m high aeolian dunes in Western Australia during TC Vance (Nott and Hubbert, 2005), suggests that beach ridge plains may be somewhat more resistant to extensive breaching and erosion during a single event. The beach ridge plain at Cungulla, however, does show evidence of removal of multiple beach ridges in the past. The results of a detailed examination of this ridge plain, as presented here, helps to explain the nature of the processes responsible for these phases of extensive erosion and beach ridge removal.

3. Setting

The ridge plain at Cungulla is fronted by a 13 km long fine- to medium-grained sand beach stretching between the Haughton River and Cape Ferguson (Fig. 1). The barrier complex is a asymmetrical cuspate foreland tying Cape Cleveland and several isolated outcrops to the mainland. Ridges are generally oriented northwest, arranged subparallel to the modern shore and the majority have sharply recurved terminations. The ridge plain is approximately 5 km wide at its widest point and the ridges are, as shown later, Holocene in age. The weathered appearance of sediments comprising several ridges at the very rear of the sequence suggests that they are Pleistocene in age.

Ridge soils vary in degree and kind of profile development. Most are freely drained fine-textured sandy soils with uniform texture profiles, although some weakly developed podzols (spodosols) occur in the