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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 andwave 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. Nonerosional 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 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 andWoodruff, 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 swales (Hopley, 1970). Sections of the sand ridges give way inland to salt pans and erosion cut-outs that are flooded with saline waters on the highest tides while seasonal runoff from Mt Elliott drains into extensive sedge swamps. These areas are comprised of Quaternary muds and silts that, further inland, are replaced by the soils and sediments of the coastal plain. Tidal range is approximately 3.84 m at Cape Ferguson, with the very highest tides reaching 2.15 m above Australian Height Datum (AHD) (DERM, 2010).

Mountainous outcrops comprising Cape Cleveland, The Cone and Feltham Cone are distinct in the predominantly low relief area around Cungulla (Fig. 1). These outcrops are largely composed of adamellite and granite of Permian to Mesozoic age with small areas of older intermediate lavas and pyroclastics (Gregory, 1969). The area is drained seaward into Bowling Green Bay by the Haughton River, which runs for 5–6 months of the year, and a number of minor creeks. In addition, seasonal floodwaters from the Burdekin River overflow northward to discharge into Bowling Green Bay (Hopley, 1970).

Cungulla, at latitude 19.35°S, is situated centrally in the seasonally wet tropics (Dalla Pozza, 2005) and experiences pronounced wet and dry (b60mm/month) seasons. The ridge plain is located in a rain shadow between substantially higher rainfall areas to both the north and the south. Annual average precipitation is 1249mmat Giru and 1165mmat Cape Cleveland (BOM, 2011). The rainfall occurs predominantly in summer and 80% of that falls in the months December to April (BOM, 2011). A high proportion of this rainfall is generated by convergence of the southeasterly trade winds into the monsoon trough. Tropical cyclones also bring substantial amounts of rain.

The region around Cungulla experiences a relatively low energy wave climate. Observations indicate that southeasterly trade winds averaging 5–16 knots (9–30 km h^{-1}) predominate along the northeast Queensland coast and these winds are the chief source of wave energy at shore (Nott et al., 2009). The Great Barrier Reef (GBR) limits the wave fetch in this region and the longest fetch at Cungulla is approximately 75 km to the northeast. The coast rarely experiences waves in excess of 0.5min heightwith wave periods of 2–4 s even during strong trade wind conditions. Significant wave height (Hsig) records for 15 m water depth near Cape Cleveland indicate that Hsig ranges between 0.2 m and 0.6 m for 50% of the time with a wave period of 3 to 5 s (Fig. 2) (DERM, 2011). The type of waves recorded can be generally categorised as either sea waves generated inside the GBR with a peak period (Tp) of 2.5 to 5.0 s; or swell waves generated outside of the GBR with a Tp of 5.0 to 9.0 s. Maximum recorded average Hsig between 1975 and 2011was 5.46mon February 3, 2011 during the passage of TC Yasi (peak intensity 929 hPa) (DERM, 2011). Significantwave heights of 2 to 6moccur less than 0.5% of the time, predominantly during summer months coinciding with the passage of TCs. Tropical cyclones can generate significant wave heights of up to 10m and wave periods of 12 s between the GBR and the mainland (Nott et al., 2009). Such storms can also generate storm surges several metres above the normal tidal range.

4. Methodology

Numerous sedimentary coasts are backed by plains composed of shore parallel/sub-parallel ridges (beach ridge plains). The processes responsible for ridge formation vary between locations. Consequently there are several interpretations for the term 'beach ridge'. Recent reviews have sought to clarify the origin of beach ridges (e.g. Hesp, 1999, 2006; Tanner, 1995; Taylor and Stone, 1996). Some authors have suggested that beach ridges consist exclusively of wave built features (Johnson, 1919; Hesp, 1999) whereas others such as Tanner (2000) suggest that both waves and wind can be responsible. Here we refer to beach ridges sensu Hesp (1999, 2006) who defined beach ridges as principally or purely marine deposits of triangular to convex form located in the backshore at or above the normal spring high tide level. They are swash aligned and deposited by waves (Hesp, 1999). Relict foredune on the other hand is the name given to the ridge-like features formed principally by wind (Hesp, 1999). series of methodologies were engaged to determine the origin of chronological gaps and whether the sand ridges at Cungulla were deposited by aeolian or wave processes. These methods included textural analysis of ridge sands, OSL dating, processing LIDAR imagery, topographic surveying and numerical modelling of wave and storm surge conditions necessary to inundate ridges of varying heights.

4.1. OSL analysis

Forty ridges from within the Holocene outer barrier complex at Cungulla were dated using the optically stimulated luminescence (OSL) technique. A total of forty-five sediment samples were collected for OSL age determinations from the forty ridges on a traverse across the Cungulla ridge sequence (Fig. 3a). Forty samples were collected from 85 to 100 cm below ridge crests by hammering lightproof PVC tubes into the side of 1.3mdeep pits and then sealing the tubes — samples were carefully protected from solar radiation and precautions were made to ensure that the sample tubes were well packed to eliminate subsequent mixing of sediments. Five of the samples were collected at different depths of a vertical profile to provide an indication of the rate of ridge emplacement; three sediment samples from 2 m depth were taken from ridges 5, 10 and 15 and two further sediment samples from 3 m depth were taken from ridges 10 and 15.

Each sample was measured for luminescence using twelve multigrain single aliquots of 180–212 mm quartz grains, adopting a single aliquot regenerative-dose (SAR) protocol (Murray and Wintle, 2003). The samples were assessed initially using a preliminary procedure to determine infrared stimulated luminescence (IRSL) contamination, signal sensitivity, approximate equivalent dose (De), and an indication of the degree of inter-aliquot variability. Low IRSL values were observed for all samples, suggesting that good quartz separation had been achieved. Preheat conditions adopted for these samples were 220 °C for 10 s for preheat 1 and 200 °C for 10 s for preheat 2. The samples displayed high OSL signal sensitivities and also excellent recycling behaviour; the mean value for all samples was within 3% of unity. Generally low thermal transfer values were observed, though some aliquots of younger samples had values up to 10% of the natural signal. Dose rates were calculated from determinations of U, Th and K concentrations based on fusion–dissolution inductively coupled plasma mass spectrometry and optical emission spectrometry. These dose rate values were corrected for grain-size attenuation and past water content, using 5% ± 5%. The cosmic dose rate estimation and a soft component were included for shallower samples.

4.2. Textural analysis

Hopley (1970) carried out textural characteristic analyses of Cungulla ridge plain sands in an attempt to detail sea level changes and ridge plain sand provenance. Sand was collected by using a posthole auger along the transect shown in Fig. 1. Data describing a total of 241 samples collected from 26 ridges and from along the beach are presented below. Samples were taken 0.3 m from the crest of every third or fourth ridge along the sequence down to a depth of 2.4 m. Sieve sizes used for analysis were related to the phi (ϕ) scale and sieves ranged in size between −4.5 ϕ and 0 ϕ (63 μm to 1000 μm) at half ϕ intervals. Analysis of sample statistics was calculated according to the method described by Friedman (1961).

4.3. LiDAR

LiDAR data were used to assist in mapping of the Cungulla ridge plain (Figs. 3 and 4). The LiDAR data were acquired by the Queensland Government Department of Environment and Resource Management as part of a larger North Queensland-wide LiDAR acquisition project and supplied under an agreement with the Townsville City Council as 1 m-resolution xyz (easting, northing, elevation) ASCII files. The source data horizontal datum used the Geocentric Datum of Australia 1994 (GDA94) with a UTM Zone 55 South projection. The vertical datum is AHD (or approximate MSL).

The data were imported into GRASS GIS. Horizontal resolution was maintained at 1m, avoiding the need for interpolation. The resultant individual tiles were then mosaicked into a single digital elevation model (DEM) covering the entire region of interest. Sample site coordinates were used as transects from which vertical profiles were generated at full 1 m spatial resolution. The vertical profiles were then rendered in Scalable Vector Graphics (SVG) format (Fig. 3b). Expected error using this approach is ±0.15 m at the 1σ uncertainty margin according to metadata associated with the original LiDAR dataset.

4.4. Numerical modelling

Numerical storm tide (GCOM2D tropical cyclone storm tide model) and shallow water wave models (SWAN model) (Hubbert and McInnes, 1999) were used to determine the conditions necessary to generate a marine inundation (including wave run-up) equal to or greater than the height of the ridges. The procedure used in this study followed the methodology described in detail by Nott (2003), Nott et al. (2009) and Forsyth et al. (2010). Wave run-up was assumed to play a substantial role in the formation of the beach ridges at Cungulla and it was assumed that the marine inundation including wave runup was equal to the height of the ridges. The total marine inundation estimated to be able to reach the crest of a given ridge was assumed to consist of storm surge, a mean tide level, wave set-up = 12% Hs and wave run-up = 30% Hs. This approach follows the methodology used by Nott et al. (2009).

A series ofmodel runswere undertaken to determine the sensitivity of storm surge height to changes in TC translational velocity, radius of maximum winds (Rm), angle of TC approach and TC central pressure. Bathymetry and coastal configuration data were fixed for the model runs and incorporated within the model as a 250 m resolution DEM. A nested grid approach was used whereby a 100 m resolution fine grid was superimposed upon a 1000 m resolution coarse grid. Sensitivity tests carried out on this basis suggested that the storm surge and shallow water wave model runs generating the largest possible surge for this site included storm parameters of radius of maximum winds (Rm) = 30 km, TC translational velocity = 30 km and a northeast to southwesterly TC track direction. The Rm and TC translational velocity of 30 km and 30 km/h respectively are the historical means for TCs in this region (McInnes et al., 2003).

The sensitivity testswere undertaken to determine the variability of storm surge heights with varying TC parameters such as forward speed of TC, radius of maximum winds (Rm), TC central pressure, angle of TC approach towards the coast and distance of landfall of the TC from the study site. In the modelling a TC scenario is chosen where the TC crossing location, angle of approach and radius of maximum winds will generate maximum surge for a given central pressure at the study site. The technique estimates the central pressure of the TC responsible for generating an inundation of certain height. Hence the central pressure of a TC generating an inundation equal to the height of a given ridge can be determined. By maximizing the other variables (TC crossing location, Rm, forward speed) the maximum central pressure (hence the weakest storm possible) necessary to achieve this can be determined. This provides the most conservative estimate of the storm intensity required to generate this level of inundation. This central pressure therefore is likely to be an underestimate. If for example a scenario is chosen where the other variables were changed to reduce the size of the surge/inundation at the study site it would be necessary to have a more intense storm (lower central pressure) to achieve an equivalent inundation level.

The estimated central pressures have uncertainty margins, which are associated with not knowing the height of the tide during the prehistoric TC event. The 2σ probability tidal range of the frequency distribution of the nodal tide curve forms the 2σ uncertainty margin and likewise for the 1σ uncertainty margin (Nott, 2003). The 1σ tidal range at Cungulla is−0.38 to 0.35 m AHD and the 2σ tidal range is−1.12 to 1.19 m AHD. Sea-level changes are considered in association with the modelling of past TC intensities. In this region relative sea level has fallen by about 1 m since the mid-Holocene (Chappell et al., 1983; Lewis et al., 2008). To account for a sea-level variation over time it is possible to subtract the amount of sea-level fall fromthe ridge height and compare this to the TC intensity required to deposit a ridge of that height. For example if a 5 kya ridge of 5mAHDwas deposited at a 1mhigher relative sea level then this would equate to a current day TC inundation of approximately 4mAHD. The central pressure for a TC generating an inundation of this height can then be determined from our results. It should be noted however, that if sea level has influenced the resulting heights of the ridges it could be expected that there would be a progressive decrease in the height of the ridges towards the seaward side of the ridge plain. Also the uncertainty margins associatedwith the central pressure estimates for the TCs responsible for depositing a sedimentary unit of certain height (Nott, 2003) are considerably larger than the late Holocene fall in sea level. Hence if the sea level has influenced the resulting heights of the ridges then itwill be masked by the variability in inundation heights responsible for depositing the sedimentary units. This is assuming of course that TCs have played a role in the formation of these ridges and this will be discussed later.

5. Results

The Cungulla plain contains over 100 shore-parallel ridges ranging in elevation between 2.8 and 8.4 m AHD. Most ridges in the sequence are curvilinear in planform and have sharply re-curved terminations (Fig. 1).

5.1. Ridge plain morphology

LiDAR imagery shows the occurrence of two distinct ridge types within the Cungulla ridge plain. Type 1 ridges have shore-parallel crests, are arranged in sets that are unconformable (Fig. 4a) and are fairly uniform in height, width and orientation. Type 2 ridges contain modern and relic blowouts and parabolic forms, they are relatively wide and tall and these ridges generallymark the most seaward ridge of each unconformable set of Type 1 ridges (Fig. 4). The contrastingmorphology of these ridge types suggests that different processes may be responsible for their respective development.

The 40 sampled ridges located along the OSL transect (Fig. 3b) are numbered starting with ridge 1 being located adjacent to the beach and ridge 40 as the most landward ridge (Fig. 3). LiDAR imagery suggests that blowouts and parabolic forms are widespread along ridge 1 and in places spill over on to ridge 2 forming non-linear ridge crests (Fig. 4). Ridges 1 and 2 therefore form Type 2 ridges and their morphology is reminiscent of coastal aeolian dunes. Also, a group of Type 1 ridges terminate along the landward flank of ridge 2. This unconformable relationship suggests that the shore-parallel ridges have been truncated by one or more erosion events and that ridges 1 and 2 have developed through re-working of eroded Type 1 ridge sediments. The imagery suggests that Type 2 ridges separate the unconformable sets of Type 1 ridges. The Type 2 ridges appear to be a reworked Type 1 ridge on the seaward side of the set. These truncations appear to be generally restricted to the southern part of Cungulla ridge plain sequence.

Elsewhere, Hopley (1970) suggested that the saline flats composed of black clay soils and saltpan with sticky black muds shown in Fig. 1 indicates the location of eroded areas around and within the ridge sequence.

5.2. Ridge sediments

The 26 ridges sampled by Hopley (1970) (Fig. 1) are named in alphabetical order. The ridge located adjacent to the beach is referred to as ridge A and the most landward ridge along this transect as ridge Z (Fig. 3a).

5.2.1. Mean grain size

The overall mean size of all samples analysed was 2.6 ϕ, which means that Cungulla beach ridge sediments lie within the fine-grained sand category according to the Udden–Wentworth scale. Mean grain sizes of Cungulla beach and ridge plain sediment samples ranged between 1.8 ϕ and 3.3 ϕ (105 μm and 294 μm), an overall range of 189 μm. The mean size of all samples was 2.6 ϕ (162 μm). Mean grain size within individual ridges showed remarkable conformity with a maximum intra-ridge standard deviation of 38 μm from ridge G (Fig. 3a). Mean grain size along the beach was 2.4 ϕ (185 μm), of ridge A 2.8 ϕ (143 μm) and of ridge B 2.5 ϕ (181 μm).

5.2.2. Sorting

The standard deviation of all ridge samples ranged between 0.3 ϕ and 0.9 ϕ, which suggests that the Cungulla sediments are moderately sorted according to the verbal Inclusive Graphic Standard Deviation scale (Folk andWard, 1957). Therewas a remarkable conformitywithin individual ridges with amaximumintra-ridge standard deviation of 0.1 ϕ from ridge T (Fig. 3a). The beach had a standard deviation of 0.6 ϕ, ridge A 0.4 ϕ and ridge B 0.5 ϕ. No correlation was apparent between ridge sets and degree of sorting.

5.2.3. Skewness

Skewness has been used to attempt to differentiate between dune and beach sands (e.g. Chappell, 1967; Friedman, 1961; King, 1966; Pye, 1982; Sevon, 1966). Skewness values for ridge samples ranged between −0.7 (ridge H) and 0.4 (ridge N) and a comparison of stratified sampling shows considerable intra-ridge variability (Fig. 5). Values for the modern beach, ridge 1 and ridge 2 were −0.4, −0.9 and −0.8 respectively. These results suggest that skewness values of the modern beach sand falls within the range of the majority of ridge sediment skewness values.

5.2.4. Kurtosis

Kurtosis values of ridge samples were generally high ranging between 2.4 and 12.6. Though values varied within each ridge, mean values for each ridge varied little (ranging between 3.7 and 5.9) with the exception of ridge H (7.0). Mean kurtosis values for the beach, ridge 1 and ridge 2 were 2.7, 6.4 and 6.6 respectively.

5.2.5. Local area sediment analysis

Hopley (1970) attempted to differentiate between possible aeolian dune sands and beach sands within the ridges. He analysed eighteen beach samples and ten dune samples from Townsville (broader Cungulla) region. The results of that study are presented here.

Mean sediment size values of dune and beach samples from the Townsville region fell within the range of Cungulla ridge samples (1.2965 ϕ to 3.2470 ϕ). The mean skewness value of beach sand was −1.0943 and dune sand 0.0449. Some overlap occurred in the dataset suggesting that these values were not prescriptive of the depositional process. Therefore, the standard deviation for beach sand (0.7599) and for dune sand (0.5667) was calculated. These values were used to designate the probable depositional processes of ridge samples. Interpretation was carried out as follows:

- Skewness values beyond 2 standard deviations of the mean dune sand value (lower than −1.0885) were defined as 'almost certainly beach sand';
- Skewness values between 1 standard deviation and 2 standard deviations of the mean dune sand value (from−1.0884 to−0.5218) were defined as 'probably beach sand';
- Skewness values between 1 standard deviation and 2 standard deviations of the mean beach sand value (from −1.5217 to 0.3344) were defined as of 'indeterminate' origin; and
- Skewness values beyond 2 standard deviations of the mean beach sand value (greater than 0.3344) were defined as 'almost certainly dune sand'.

Hopley's (1970) interpretations of Cungulla ridge sands are presented in Fig. 5. These results suggest that marine processes are responsible, at least in part, for deposition of the 26 sampled ridges in this sequence. Most notable of these are a number of ridges that include well-elevated sedimentary units composed of 'likely beach sands'. These include ridges C, D, E, F, J, L, P, Q, U, V,W, X, Y and Z. Otherwise, the data suggest that sediments comprising the upper 2.4mof two ridges (M and N) are composed entirely of aeolian sand and that aeolian processes have occasionally contributed to the elevation of all ridges in this sequence. Although these results suggest that ridge samples with skewness values greater than 0.3344 are aeolian in origin, Dalla Pozza (2005) showed that beach and nearshore sediments (i.e. sands forming the sediment source for ridge development) at Cungulla commonly display similar skewness values to those in the supposed aeolian units within the ridges. Indeed Dalla Pozza (2005) data suggests that 79% of beach and nearshore (collected within 1 km of shore) sediments at Cungulla display skewness values that would be classified as 'almost certainly dune' or 'indeterminate' under the scheme illustrated in Fig. 5. Dalla Pozza (2005) results suggest that the apparent aeolian units within the beach ridges at Cungulla may simply reflect the characteristics of the sediment source at the time. Hence a wave origin for these units cannot be ruled out.

5.3. Numerical modelling

The results of the storm surge and shallow water wave modelling are presented in Figs. 3b and 5. The data suggest that inundations generated by Category 4 or 5 TCs are required to reach elevations equivalent to the upper sedimentary units within most of the Cungulla ridges. For example, the highest interpreted beach sand layer occurs at 6.4 m in ridge F. Modelling suggests that this level may be reached by combined waves and surge during a TC with a central pressure of between 883 and 897 hPa within the 1 σ tidal range and between 870 and 912 hPa within the 2 σ tidal range. As a result, even if a TC crossed at close to the highest possible tide during a full nodal tidal cycle (= 95th tidal quintile) the TC would have central pressure of 912 hPa.

5.4. Chronology

The chronology (Table 1) indicates that the forty dated ridges range in age from 0.02 to 8.10 kya. The ridges generally increase in age with distance inland. However, a number of age reversals (from ridges 11, 17, 20, 22, 25, 26, 27, 29 36 and 37) are indicated where the uncertainty margins do not overlap and they are likely a result of mechanical or biological disturbance. If these age reversals are disregarded, development of the Cungulla ridge plain commenced between approximately 6.00 and 6.50 kya which is in agreement with dated sequences elsewhere in this region (Rhodes, 1982; Rhodes et al., 1980; Nott and Hayne, 2001; Nott et al., 2009; Forsyth et al., 2010, 2012; Hayne and Chappell, 2001). The overall progradation rate across the 5 km of ridge plain is calculated at between 0.83 and 0.77m yr^{-1} when age reversals and any ages >6.5 kya are disregarded.

6. Discussion

The ridges forming the Cungulla ridge plain are unlike ridges in other ridge plains studied so far in this region. The ridges here are composed of moderately sorted, fine-grained sands, whereas the beach ridges studied at the relatively nearby Cowley Beach (Nott et al., 2009), Rockingham Bay (Forsyth et al., 2010) and Wonga Beach (Forsyth et al., 2012) are all composed of coarse-grained sands. Furthermore, the Cungulla ridge plain displays numerous different sets of ridges with unconformable boundaries and saline flats and saltpans located around and within the ridge sequence. These characteristics are not present in the other ridge plains at Cowley Beach, Rockingham Bay and Wonga Beach.

6.1. Origins of ridges at Cungulla

6.1.1. Type 1 ridges — beach ridges

Most ridges in the Cungulla sequence display smooth, regular, curvilinear crest lines and incorporate recurved terminations (Fig. 1). Similar curvilinear ridge morphologies elsewhere have been suggested to develop through swash processes (e.g. Bristow et al., 2000; Curray et al., 1969; Donoghue et al., 1998; Missimer, 1973; Stapor et al., 1991; Tanner and Stapor, 1971). Coastal plains with some recurved ridges have been ascribed an aeolian origin elsewhere (eg Thom and Hall, 1991) but these could have developed from an aeolian capping of a wave deposited recurved berm. The 'beach' type sediments in the upper stratigraphy of many of the ridges at Cungulla, however, suggest that this is unlikely to be the origin of these ridges. The origin of the fine grained sand in the ridges at Cungulla may simply be a reflection of the texture of the beach sand being the source material for the ridges rather than being an indicator of the depositional process. The question could also be asked as to why storm waves will deposit ridges composed of coral shingle or coarse-grained sand or marine shells in this region but not deposit ridges of fine-grained sand when that is the only source material available. It is likely therefore that texture alone may not be a reliable indicator of the processes responsible for deposition of the ridge sand (Nott, 2014).

The data suggests widespread distribution of beach sand within the upper sedimentary units of Cungulla ridges (Fig. 5). The results of the numerical modelling suggest that storm surge and wave action produced by intense (category 4 and above) TCs are required for water levels to reach an elevation of at least 4 m AHD at Cungulla (Fig. 3b). Nott et al. (2009) came to a similar conclusion for the Cowley Beach beach ridge plain, as did Forsyth et al. (2010) for Rockingham Bay. Marine inundations generated by lower intensity TCs may have deposited the sedimentary units composed of beach sand now preserved at lower elevations within the ridges and initial formation of the beach ridge could have occurred as a result of inundations generated during non-TC events. Subsequent beach-ridge growth likely corresponded with higher magnitude marine inundations. These beach ridges have increased their elevation to a level where low magnitude events can no longer generate marine inundations capable of reaching the ridge crest. Only extreme intensity TCs generating relatively large marine inundations have been capable of depositing sediments onto the ridge crest once it reaches a critical height. We suggest that these marine inundations are responsible for deposition of beach sand layers in the upper sedimentary units of the Cungulla ridge plain.

Variations in sea-level may have had a role in the development of the ridge plain. Sea level has fallen by approximately 1 m in this region since the mid-Holocene (Chappell et al., 1983; Lewis et al., 2008).If falling relative sea level throughout the late Holocene has been a major influence then it could be expected that ridge heights would decrease in height towards the present day which would be expressed as a decrease in ridge height towards the seaward side of the ridge plain. This isn't the case at Cungulla and the same is true of other beach ridge plains studied throughout the region (Nott et al., 2009; Forsyth et al., 2010).

6.1.2. Type 2 ridges — dunes

Type 2 ridges display a hummocky topography that has the appearance of a series of dune blowouts and parabolic forms. This topography suggests that aeolian processes have shaped these ridges. Hopley (1970) suggested that these features were originally beach ridges that had been subsequently disturbed by aeolian processes. Their common occurrence as the first ridge on the seaward side of a set of Type 1 ridges suggests that the unconformable nature of the Type 1 ridge sets and the origin of the Type 2 ridges may be linked.

Hopley (1970) suggested that the former distributaries of the Haughton River located between Mount Elliott and Feltham Cone and along the seaward side of The Cone (Fig. 1) are responsible for occasionally diverting floodwaters to the north of its normal course. The expanse of saltpan and salt marsh in Fig. 1 infers that such flows have removed large sections of ridges once located near the rear of the present sequence. Also the ridge truncations separating the sets of Type 1 ridges appear to be largely confined to the southern part of the plain, close to the Haughton River, suggesting that here floodwaters may have occasionally eroded through the ridge sequence to the sea. The oblique orientation of ridge truncations infers the paths that fluvial incursions have followed through the ridge sequence. Hence flooding of the Haughton River has likely destroyed parts or all of some ridges resulting in gaps in the ridge chronology.

The occurrence of parabolic forms on the Type 2 ridges suggests that these features may have developed after fluvial erosion has scarped the toe of former Type 1 ridges exposing the sediments to aeolian activity. Such scarping leads to undermining of vegetation and ridge wall collapse (Hesp, 2002). Onshore wind velocities sufficient to entrain exposed ridge sediments may then initiate blowout development, subsequent blowout enlargement and downwind deposition of eroded sediments in parabolic-shaped depositional lobes (Carter et al., 1990). Over time a new beach ridge is deposited seaward of the disturbed (Type 2) ridge and a new set of Type 1 ridges develops often with a different orientation to the previous Type 1 set. Type 2 ridges then are former beach ridges that have experienced aeolian reworking following fluvial erosion of part of a set of Type 1 ridges. The Type 2 ridges often mark the unconformable boundary between sets of Type 1 ridges. Reworking may also be responsible for the coincidence of dunes in this sequence with several reversals in the OSL chronology.

It is also possible that wave action may have caused the erosion of the ridges. This cannot be ruled out. However, as mentioned earlier, observations of the impact of recent TC inundations on beach ridges in the region (Nott, 2010) revealed that beach profile flattening (hurricane beach) and scarping of the first seaward ridge occurred and there was an absence of ridge plain breaching. This is unlike the impact of TC inundations observed along the Western Australian coast (Nott andHubbert, 2005) and by others along the shores of the Gulf of Mexico (Morton and Sallenger, 2003; Fritz et al, 2007). The reasons behind these differences are not clear however the answer may lie in the morphological characteristics of the different environments. The beach ridge plains in north Queensland extend inland for kilometres whereas the dunes in Western Australia and along the shores of the Gulf of Mexico form relatively Narrow barriers (hundreds of metres) backed by lower elevation coastal plains. It may be that when an inundation overtops these narrow barriers the hydraulic jump associated with the change in elevation from the dunes to the backing coastal plain assists substantially with eroding the dunes to cause a barrier breach. This change in topography assisting in the development of a hydraulic jump in the onshore marine inundation (flow) is absent in the beach ridge plains of north Queensland. In fact in many cases the topography here often gradually increases in elevation with distance inland. The topography therefore may assist in the preservation of the ridges from wave attack apart from scarping and partial removal of a ridge along sections of an embayment.

Post-event surveys of the impacts of recent TC inundations on the beach ridge plains in north Queensland, the proximity of the Haughton River and its distributaries and the observation that most of the unconformable sets of Type 1 ridges occur at the southern end of the plain close to the river suggest that fluvial erosion is more likely responsible for truncation of the ridges here at various times in the past. Such events probably occurred during major floods, which often, but not always, are a result of the passage of TCs. Hence periods of severe wave attack and river floods may have coincided but it appears that fluvial action is the most likely process for erosion of the ridges and as a consequence the development of the Type 2 ridges by subsequent aeolian activity. The fine-grained texture of the sand comprising the ridges makes these ridges more amenable to aeolian disturbance compared to the coarse grained ridge sequences elsewhere in this broader region. Interestingly, these coarse-grained ridge sequences do not display Type 2 ridges and unconformable sets of ridges with different orientations (Nott and Hayne, 2001; Nott et al., 2009; Forsyth et al., 2010, 2012).

6.2. Chronological gaps in the record

The beach ridge record at Cungulla displays two substantial chronological gaps. An 870-year gap occurs between ridges 14 and 15 and a 1600-year gap occurs between ridges 30 and 31. The 870-year gap coincides with tall, hummocky Type 2 ridge morphology displayed by ridge 15. However, the 1600-year gap does not coincide with a Type 2 ridge. Nor does it coincide with a Type 1 set unconformity. Hence, there appears to be two types of chronological gaps here. The first is characterised by a coincidence with an unconformable ridge set boundary, blowouts and parabolic forms that suggest past erosion. The second type is not characterised by these morphological features and may be the result of a cessation or slowing down in beach ridge development.

6.2.1. Gap due to erosion

Floodwaters exploiting the former distributary along the seaward side of The Cone are likely responsible for the unconformity that occurs between ridges 14 and 15 (Fig. 3). Fig. 1 shows the extent of salt marsh and saltpan that form erosion surfaces likely remnant from one or possibly several flood events stretching along the front of ridge 15 to the northern end of the sequence. The chronology suggests that this erosion occurred between approximately 1.53 to 2.40 kya. The widespread nature of other similarly oriented unconformities here also suggests that the depositional record contained in the Cungulla beach ridge plain includes evidence of numerous past fluvial erosion events.

6.2.2. Gap due to cessation of severe TC activity

There is no morphological evidence to suggest that erosion is responsible for the approximately 1600-year gap between ridges 30 and 31. A detailed examination of ridges either side of this gap suggests that these two ridges are conformable and that no ridge truncations, parabolic forms or other evidence of past erosion occur either at a single site or along the length of these ridges. The lack of any sign of an unconformity associated with this gap suggests a decrease or cessation in the incidence of beach ridge-building processes occurring during the period approximately 6.29 to 4.67 kya. The modelling, as shown in Fig. 5, suggests that inundations associated with TCs are responsible for depositing the upper sedimentary units of beach ridges in this sequence. Low elevation ridges and chronological gaps in the sequence are therefore likely to be periods when a decrease or cessation in the incidence of extreme intensity TCs occurred.

The Cungulla ridge plain is not the only ridge plain in the region to display non-erosional gaps. Indeed, every ridge plain examined so far throughout this region displays one or more of these types of gaps. Nott and Forsyth (2012) compared TC deposited beach ridge plains from around Australia (northeast Queensland, Gulf of Carpentaria and Western Australia) with hurricane overwash sequences in the Gulf of Mexico, US Atlantic and Japan and found that all of these long-term TC sedimentary sequences display chronological gaps between one and many centuries to a millennium in length. Nott and Forsyth (2012) concluded that these gaps appear to be an inherent characteristic of the long-term TC sedimentary records globally and that they are most likely caused by periods of relative quiescence in intense TC or hurricane activity. The chronological gap between 6.29 and 4.67 kya at Cungulla appears to be another of these types of gaps associated with a period of less intense TC activity.

Periods of reduced sediment supply could be a cause for the nonerosional chronological gaps in the ridge plain. The Haughton River controls sediment supply locally here. Indeed every major beach ridge plain in this region has a substantial stream draining into their embayment, which appears to be one of the necessary conditions for beach ridge development in this region. Sediment delivery to the coast is dependent upon river flow/flood activity which in turn is dependent upon climate. Many of the major floods here occur as a result of TCs or 'wet' wet seasons (years with active monsoon). So sediment supply and TC activity are typically associated. Low TC activity would often be associated with a reduction in sediment supply and the opposite is true. Hence if the non-erosional gaps are due to a reduction in sediment supply then this is most likely associated with low TC activity.

6.3. TC-records

Shore-parallel ridges composed of fine-grained sand in this region have been routinely ascribed aeolian origins (e.g. BPA, 1979). The recurved ends of ridges, sediment characteristics and different orientations of Type 1 ridge sets suggest that waves are responsible for their deposition. The numerical modelling further suggests that only TCs of severe intensity are able to generate inundations capable of depositing sediments on the crests of most of these ridges. Observations of ridge stratigraphy elsewhere have suggested that each ridge in a plain develops through inundation processes exploiting an abundant sediment source, probably at the beach or nearshore, and re-depositing those sediments at the rear of the beach (Nott et al., 2009, 2013; Nott, 2010).

Ridges increase in elevation over time with successive TC-generated marine inundation events. Tropical cyclones are thought responsible for depositing numerous beach ridge plains in this way, including those composed of coral shingle (Hayne and Chappell, 2001; Nott and Hayne, 2001), sand and shell (Rhodes et al., 1980) and coarse-grained sand (Nott et al, 2009, 2013; Nott, 2010; Forsyth et al, 2010; Forsyth et al., 2012). There is nothing to indicate that extremely energetic sediment transport processes associated with TC inundations will discriminate between fine-grained sand and coarser-grained sediments. To the contrary, and as mentioned earlier data presented by Dalla Pozza (2005) suggests that 79% of beach and nearshore (collected within 1 km of shore) sediments at Cungulla display skewness values that would be classified as 'almost certainly dune' or 'indeterminate' under the scheme illustrated in Fig. 5. These data infer that the sedimentary characteristics of ridges forming this plain are not necessarily the result of sorting processes incurred during transport from the beach or nearshore to their present position. Instead, beach ridge sediment characteristics may simply reflect the characteristics of the sediment source. Accordingly, it is likely that inundations associated with TCs are the principle process responsible for depositing beach ridges within the Cungulla ridge plain. This doesn't mean that wind cannot play a part in constructing the ridges at times but rather the elevated 'beach' and 'indeterminate' type sand units within many of the ridges suggests that waves and inundations likely play the major role in depositing these features. It further suggests that other beach ridge plains composed of fine-grained sand elsewhere along the coast of this broader region may also contain palaeo-TC records.

7. Conclusion

Numerical modelling and sedimentary analysis suggest that marine inundations associated with TCs are principally responsible for depositing beach ridges composed of fine-grained sand at Cungulla although wind at times may play a part. Comparative studies of local barrier and nearshore sediments suggest that marine processes, not wind, are responsible for depositing beach ridges within this sequence. The numerical modelling suggests that the upper sedimentary units of most beach ridges in this sequence were deposited by inundations associated with the nearby passage of extreme intensity (category 3 to 5) TCs. These findings suggest that detailed studies are required to determine the origin of shore-parallel fine-grained sand coastal barriers and that the texture of these landforms may not necessarily be diagnostic of their origin.

The beach ridge plain at Cungulla also contains two types of chronological gaps. Angular unconformities in ridge orientation and variations in ridge morphology between smooth and convex to hummocky probably signals past erosion. Other chronological gaps where these morphological characteristics are absent are likely due to periods of quiescence in terms of ridge development due to less intense TC activity. These morphological characteristics may be used as diagnostic indicators of the origin of chronological gaps in other beach ridge plains (particularly fine-grained ones) constructed by TC inundations globally.

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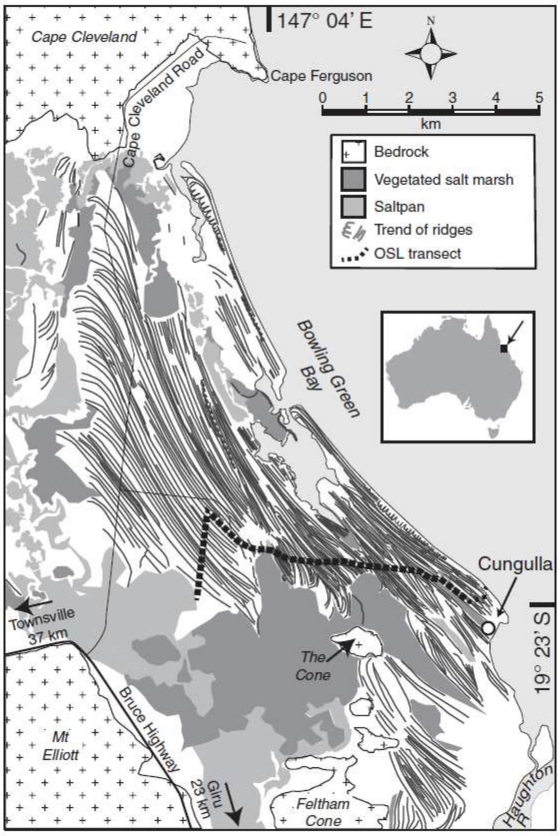

Fig. 1. Location map of the Cungulla ridge plain including delineation of mapped ridge crests.

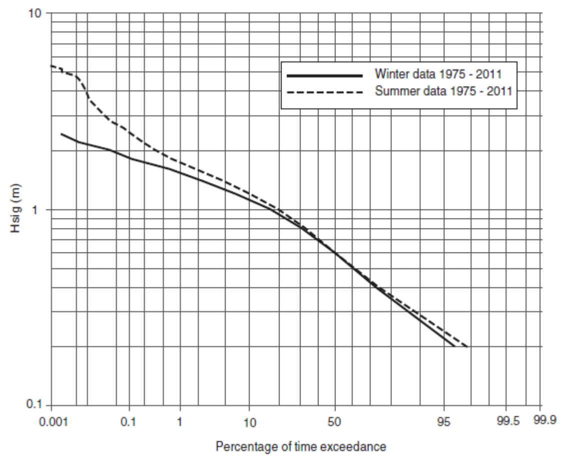

Fig. 2. Significant wave height (Hs) from wave rider buoy in 15 m depth water, Cape Cleveland, Townsville from 1975 to 2011.Winter refers to months June, July, August and summer refers to December, January, February.

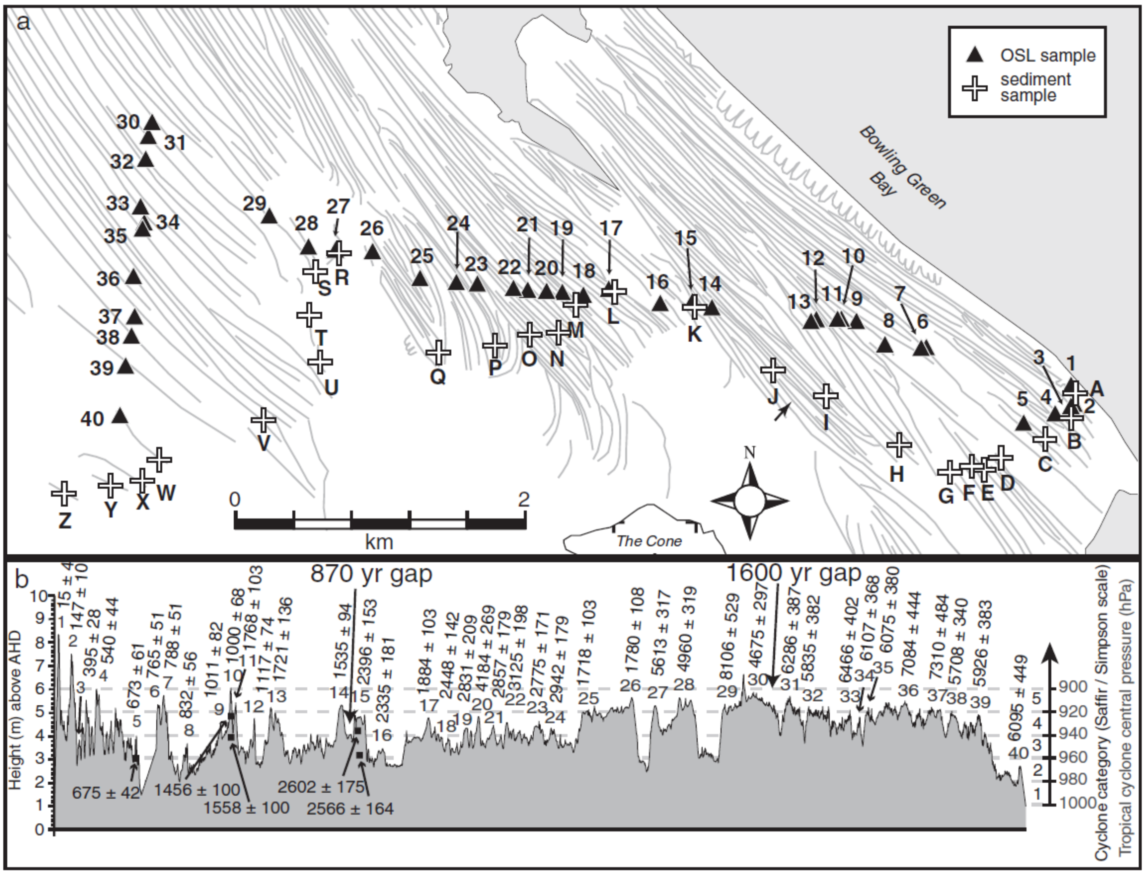

Fig. 3. Graphic representation of Cungulla ridge plain elevation data overlain by: (a) OSL and sediment sampling sites; and (b) cross-section of Cungulla ridge plain showing height of ridges above AHD, OSL dates with error margins and modelled TC intensity required to produce inundation level equal to ridge height based upon mean tide level. Note seaward side of cross-section is to left of figure.

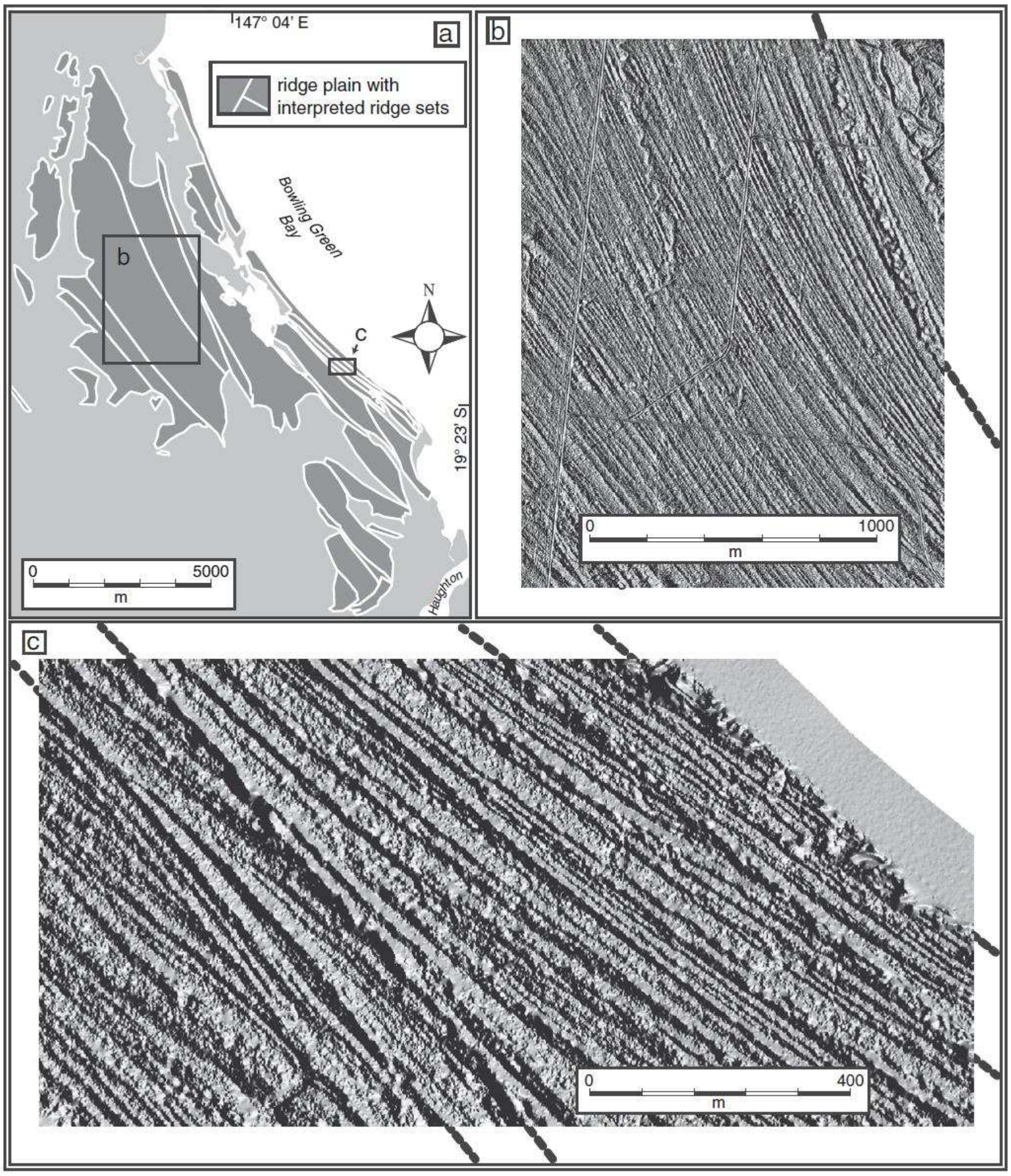

Fig. 4. (a) Map showing the location of ASPECT analysis results and (b and c) sample images of ASPECT analysis data. Dotted lines indicate the orientation of Type 2 ridges and all other ridges in the sequence are likely Type 1 ridges. Solid lines indicate truncations in Type 1 ridges.

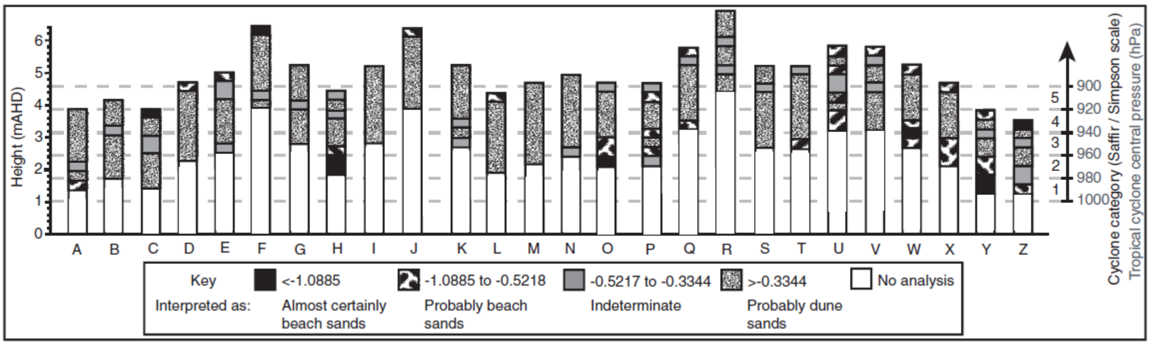

Fig. 5. Cross-section of Cungulla ridge plain sediment data (after Hopley, 1970) showing height of ridges above AHD, skewness with interpretation and modelled TC intensity required to produce inundation level equal to ridge height based upon mean tide level.

Table 1
OSL age determinations and associated data from Cungulla. Note De is dose equivalent.

Field Code	Ridge	Depth (m)	De (Gy)	Age (years before 2006)
CB-01	K1535	0.85	0.032	15 ± 4
CB-02	K1536	0.85	0.305	147 ± 10
CB-03	K1537	0.85	0.988	395 ± 28
CB-04	K1538	0.85	1.204	540 ± 44
CB-05	K1539	0.85	1.469	673 ± 61
CB-06	K1540	0.85	1.719	765 ± 51
CB-07	K1541	0.85	1.634	788 ± 51
CB-08	K1542	0.85	1.598	832 ± 56
CB-09	K1543	0.85	2.575	1011 ± 82
CB-10	K1544	0.85	3.224	1000 ± 68
CB-11	K1545	0.85	5.574	1768 ± 103
CB-12	K1546	0.85	3.170	1117 ± 74
CB-13	K1547	0.85	4.307	1721 ± 136
CB-14	K1548	0.85	4.004	1535 ± 153
CB-15	K1549	0.85	5.850	2396 ± 153
CB-16	K1550	0.85	5.327	2335 ± 181
CB-17	K1551	0.85	6.100	1884 ± 103
CB-18	K1552	0.85	6.016	2448 ± 142
CB-19	K1553	0.85	5.585	2831 ± 142
CB-20	K1554	0.85	8.392	4184 ± 269
CB-21	K1555	0.85	6.677	2857 ± 179
CB-22	K1556	0.85	6.992	3125 ± 198
CB-23	K1557	0.85	7.591	2775 ± 171
CB-24	K1558	0.85	7.556	2942 ± 179
CB-25	K1559	0.85	3.438	1718 ± 103
CB-26	K1560	0.85	3.565	1780 ± 108
CB-27	K1561	0.85	14.143	5613 ± 317
CB-28	K1562	0.85	12.414	4960 ± 319
CB-29	K1563	0.85	16.362	8106 ± 529
CB-30	K1564	0.85	11.408	4675 ± 297
CB-31	K1565	0.85	13.418	6286 ± 387
CB-32	K1566	0.85	13.174	5835 ± 382
CB-33	K1567	0.85	11.454	6466 ± 402
CB-34	K1568	0.85	12.006	6107 ± 368
CB-35	K1569	0.85	13.453	6075 ± 380
CB-36	K1570	0.85	13.513	7084 ± 444
CB-37	K1571	0.85	14.260	7310 ± 484
CB-38	K1572	0.85	12.257	5708 ± 340
CB-39	K1573	0.85	22.901	5926 ± 383
CB-40	K1574	0.85	11.938	6095 ± 449
CB-05	K1575	2.00	1.320	675 ± 42
CB-10	K1576	2.00	2.884	1456 ± 100
CB-10	K1577	3.00	2.627	1558 ± 100
CB-15	K1578	2.00	5.246	2602 ± 175
CB-15	K1579	3.00	4.934	2566 ± 164