Coarse-sand beach ridges at Cowley Beach, north-eastern Australia: Their formative processes and potential as records of tropical cyclone history

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ABSTRACT

Storm surges generated by tropical cyclones have been considered a primary process for building coarse-sand beach ridges along the north-eastern Queensland coast, Australia. This interpretation has led to the development of palaeotempestology based on the beach ridges. To better identify the sedimentary processes responsible for these ridges, a high-resolution chronostratigraphic analysis of a series of ridges was carried out at Cowley Beach, Queensland, a meso-tidal beach system with a >3 m tide range. Optically stimulated luminescence ages indicate that 10 ridges accreted seaward over the last 2500 to 2700 years. The ridge crests sit +3.5 to 5.1 m above Australian Height Datum (ca mean sea-level). A ground-penetrating radar profile shows two distinct radar facies, both of which are dissected by truncation surfaces. Hummocky structures in the upper facies indicate that the nucleus of the beach ridge forms as a berm at +2.5 m Australian Height Datum, equivalent to the fair-weather swash limit during high tide. The lower facies comprises a sequence of seaward-dipping reflections. Beach progradation thus occurs via fair-weather-wave accretion of sand, with erosion by storm waves resulting in a sporadic sedimentary record. The ridge deposits above the fair-weather swash limit are primarily composed of coarse and medium sands with pumice gravels and are largely emplaced during surge events. Inundation of the ridges is more likely to occur in relation to a cyclone passing during high tide. The ridges may also include an aeolian component as cyclonic winds can transport beach sand inland, especially during low tide, and some layers above +2.5 m Australian Height Datum are finer than aeolian ripples found on the backshore. Coarse-sand ridges at Cowley Beach are thus products of fair-weather swash and cyclone inundation modulated by tides. Knowledge of this composite depositional process can better inform the development of robust palaeoenvironmental reconstructions from the ridges.

Keywords Beach ridge, coast, ground-penetrating radar, north-eastern Queensland, optically stimulated luminescence, tropical cyclone.
INTRODUCTION

Beach ridges are relict sedimentary landforms developed on prograded beach shorelines; they are initially formed by a range of processes as alongshore elongate mounds that are later isolated from the present beach due to beach progradation. Individual ridges record a certain period of beach sedimentary and erosional processes. A sequence of beach ridges thus provides an archive of coastal evolution (Tamura, 2012) that has been utilized as records of sea-level, climate, catastrophic events and shoreline history (Shepherd, 1991; Mason et al., 1997; van Heteren et al., 2000; Buynevich et al., 2007; Brooke et al., 2008a,b; Tamura et al., 2008, 2012; Billy et al., 2015; Hein et al., 2016). Beach ridges occur on various wave-dominated or wave-influenced coasts globally and vary geographically (e.g. Tanner, 1995; Taylor & Stone, 1996; Otvos, 2000; Scheffers et al., 2011; Tamura, 2012), and their formation is accounted for by autogenic (Moore et al., 2016) and/or allogenic mechanisms (Tamura, 2012). Reliable palaeoenvironmental reconstructions based on beach ridges thus require a robust understanding of their formative processes, composition and chronology (Oliver et al., 2015).

There have been attempts to decode past catastrophic events based on erosional or depositional features of beach ridges and their subsurface deposits (Tamura, 2012). Imprints of beach scarps have been inferred from shore-normal ground penetrating radar (GPR) profiles of prograded barriers in a range of settings (e.g. Bristow et al., 2000; Buynevich et al., 2004; Bristow & Pucillo, 2006; Dougherty, 2014). These scarps are often associated with heavy mineral concentration and thus result in strong GPR reflections. In combination with optically stimulated luminescence (OSL) ages of sediment layers just above the scarps, Buynevich et al. (2007) concluded an intensified storminess on the northern Atlantic coast of the USA during the Little Ice Age. A series of gravel ridges composed of reworked cobble to pebble-size coral rubble on a sheltered section of coast in northeastern Queensland, Australia, were also used for reconstructing storm events (Hayne & Chappell, 2001). Hayne & Chappell (2001) recognized individual storm units divided by inter-storm soil and beach deposits from an extensive trench across the ridge system and concluded that the frequency of intense cyclones capable of transporting cobbles has been consistent over the last 5000 years. A similar idea to the coral rubble ridge study was applied to coarse-sand beach ridges several metres higher than mean sea-level on the tropical coastal plains of northern Queensland. These have been interpreted to contain records of past cyclone inundations (e.g. Nott et al., 2009). Inundation due to surge generated by tropical cyclones is considered primarily responsible for building these beach ridges. Nott et al. (2009) and Forsyth et al. (2010) estimated the magnitude of cyclones that can cause inundation up to the elevation of the beach ridges and concluded that extreme cyclones occurred more often in prehistoric times than during the last 100 years. The height and chronology of these beach ridges are regarded as long-term records of the recurrence of extreme cyclone inundations (Nott, 2012, 2015) and considered more reliable than estimates of the recurrence of these events based on numerical simulation and short-term observations (e.g. Hardy et al., 2004).

Formative processes of tropical coarse-sand beach ridges are less well-understood compared with beach ridges in temperate environments (Tamura, 2014). In Queensland, a post-cyclone survey after Category 5 tropical cyclone (TC) Yasi in 2011 reported the emplacement of overwash deposits on top of the first (most seaward) beach ridge at Tully Head, Cowley Beach, Mission Beach and Cardwell in north-eastern Queensland (Fig. 1A; Nott et al., 2013), confirming that the cyclone inundation contributed to the vertical accumulation of beach ridges. However, the stratigraphic architecture of coarse-grained sandy beach ridges and their formative processes has generally been less well-documented than fine-sand and gravel ridges (Tamura, 2012). A fine-sand beach is likely to be eroded by storm waves, while fine-sand ridges are generally formed with the welding of the longshore bar and/or building of the berm by fair-weather swash, and then by the accumulation of aeolian sand (e.g. Hein et al., 2013; Oliver et al., 2016). Gravels, in contrast, are unlikely to be transported by wind, but can be built upward as a ridge by storm waves as the storm-wave downwash loses its energy as a result of percolation of water on gravel beaches (Carter, 1988; Otvos, 2000). In mixed sand–gravel beaches, ridge formation is considered to occur through a combination of gravel and fine-grained depositional processes – gravel ridges with a coarse sand matrix can be decorated with an aeolian unit of fine sand (e.g. Orford et al., 2003; Billy et al., 2014). A beach composed primarily of coarse
sand is, however, characterized by lower mobility due to less effective aeolian processes compared to a fine-sand beach, and has less resistance to storm-wave erosion than gravels. These distinctive characteristics have not been incorporated into a comprehensive model of coarse-sand ridge formation.

There are several questions regarding the formative process of the north-eastern Queensland beach ridges. Firstly, it is not clear how the net
beach-ridge construction is influenced by the passage of tropical cyclones, as sandy beaches generally erode under energetic storm waves (Komar, 1998). Of relevance to this issue is the post-cyclone survey of the impact of TC Yasi (in 2011) that reported extensive beach erosion and scarp formation (The State of Queensland, 2012). Secondly, the role of fair-weather swash has not been constrained. Fair-weather waves and swash are normally the main agents to transport shoreface sand onshore to accrete on the beachface (e.g. Lee et al., 1998). Waves on the Queensland coast are fetch-limited as the offshore swell is attenuated by the Great Barrier Reef. The extent to which low-energy fair-weather swash may contribute to the building of beach ridges up to several metres higher than mean sea-level on this coast has not been reported. Thirdly, a key sedimentological issue to be addressed is whether one individual ridge comprises one or more overwash deposits. For example, at Cowley Beach the more inland beach ridges can be +4 to 5 m above MSL and have an age difference of around 200 years. Given that TC Yasi generated overwash deposits that are 10 to 60 cm thick on the first ridge at Cowley Beach, the elevation and age data suggest that several cyclone-generated deposits may be required to build a single ridge. The fourth question relates to the presence and extent of the aeolian contribution to ridge building. Clearly, more information on the morphodynamics of the modern beach, and the internal depositional architecture of the ridges should be integrated to better inform interpretations of the beach-ridge building process.

Further exploration of the coarse-sand beach ridges on the Queensland coast is needed to: (i) better understand the key sedimentological and morphodynamic processes that have led to the development of a distinctive variety of beach ridge; and (ii) establish a robust understanding of the utility of these beach ridges for environmental reconstructions. To address these knowledge gaps, this article identifies the formative processes of coarse-sand beach ridges at Cowley Beach by integrating ground-penetrating radar (GPR) profiles, detailed grain-size data, OSL ages, and observations of modern beach and beach-ridge pit sections.

STUDY AREA

Cowley Beach is located 90 km SSE from Cairns, in north-eastern Queensland (Fig. 1A). The embayed coastline at Cowley Beach is 15 km long and faces ESE towards the lagoon of the Great Barrier Reef and southern Pacific Ocean. A well-pronounced beach-ridge plain is developed along the coast (Fig. 1B and C). The beach-ridge plain is largely well-preserved in its natural state. It is 3 km wide at its north-eastern end, where it is bordered with the basement rock of Double Point, and narrows southward. A meandering river, Liverpool Creek, discharges at the centre of the plain, dividing the plain into the northern and southern parts. Inland of the beach-ridge plain is a coastal lowland, which is presently utilized as farmland. Generally, the elevation of the beach ridges rises landward, from +2 to 3 m Australian Height Datum (AHD) at the inner ridges to +5 to 6 m AHD at the middle ridges, and then gently lowers to +4 m AHD nearby the present coast. The beach-ridge plain is sandy overall, and mud is negligible even in the inter-ridge swales, of which elevation is generally +3 to 4 m AHD.

The present beach is tide modified, characterized by a low-tide terrace (Masselink & Short, 1993; Short, 2000, 2006), steep (ca 1/10) beachface, and narrow backshore (Fig. 2A and B). Tide range is more than 3 m, and the highest and lowest tides are +1.8 m and −1.7 m AHD, respectively, at Mourilyan Harbour, near the northern end of Cowley beach (The State of Queensland, 2014). As offshore swells are attenuated by the Great Barrier Reef, nearshore waves are fetch-limited and normally <1 m high with periods of 5 to 6 sec. The beach is classified as the ‘low-tide terrace + rip’ type in a conceptual beach model of Masselink & Short (1993). Wind is dominated by south-easterly trade winds except for the passage of cyclones and tropical lows. According to the statistics for 1941 to 2010 (Bureau of Meteorology, 2014), mean wind speed of 10 to 30 km/h exceeds 90% incidence, and 30 to 40 km/h was measured for 5% of the total duration.

The north-eastern Queensland coast has been regularly hit by tropical cyclones of various magnitudes. From 1880 to 2006, 22 cyclones impacted the region nearby Cowley Beach (Callaghan, 2004; Hitchman et al., 2006). Tropical Cyclone Yasi was the most recent Category 5 cyclone that crossed this coast in February 2011: TC Yasi was the largest and most intense cyclone in Queensland since 1918 (The State of Queensland, 2012). The estimated mean and maximum wind speeds were 185 km/h and 285 km/h, respectively, during landfall of the cyclone at...
Fig. 2. (A) Alongshore view of the modern beach at Cowley Beach during low tide. The berm defines a narrow (5 to 10 m wide) backshore. The backshore limit was marked by the beginning of the vegetation to the left. The beachface dips seaward at an angle of 1/10. The low-tide terrace occurs at the seaward end of the exposed beach. (B) Alongshore view of the modern beach just after the high tide from the same site as (A). Swash marks were left in the upper part of the beach face in relation to the ebb tide. (C) Wind ripples developed on the backshore along transect CB-6 on 16 May 2015, when the wind speed of 30 km/h and gusts of 50 km/h were recorded at Cardwell. These ripples are composed of medium to very coarse sands, indicating the possibility of beach sand transport even by the non-cyclonic winds at the Cowley Beach. (D) Vegetation, plant debris and pebble to cobble sized pumice grains on the first beach-ridge inland from the modern beach. (E) and (F) Photograph and sketch of a 3 m long trench exposing the beach sedimentary structure associated with a scarp at the backshore limit of site CB-13. An erosional surface is marked by a laminated layer of heavy mineral concentration, and extends from the foot of the scarp. Three OSL ages indicate that the scarp formed in the last 10 years. The sea is to the left.
Mission Beach. At Cardwell, the tide gauge recorded a peak storm surge of 5-3 m, ranking this as the third highest Queensland storm surge historically. Significant waves of 4-7 m and 2-4 m high were observed by wave-rider buoys offshore Townsville and Cairns, respectively. The maximum wave height at Townsville was recorded as 9-6 m before the wave gauge had a technical problem during the peak of the event. Tropical Cyclone Yasi caused an inundation higher than the highest astronomical tide level over the coast between Cairns and Townsville. The maximum inundation level during TC Yasi was +6-9 m AHD at Cardwell. Inundation levels at Bingil Bay and Etty Bay, which are 15 km south and north from the centre of Cowley Beach, were +4-9 m and +3-2 m AHD, respectively (The State of Queensland, 2012). Tropical Cyclone Larry was a Category 4 cyclone that made landfall near Etty Bay. Inundation levels during TC Larry were +5-2 m and +4-5 m AHD at Bingil Bay and Etty Bay, respectively (The State of Queensland, 2012). Nott et al. (2013) reported that TCs Larry and Yasi caused a run-up of +3-4 m and +2-8 m AHD, respectively, at Cowley Beach. Significantly, during TCs Yasi and Larry, peak surge coincided with low tides (Hitchman et al., 2006; The State of Queensland, 2012). These cyclones thus would have caused a few metres higher inundations if they had made landfall during high tides.

The sea-level in Queensland reached the modern level around 8000 to 6200 cal BP after the post-glacial sea-level rise (Woodroffe 2009). Although there are various views on the duration and level of the mid-Holocene sea-level highstand, the recent compilation by Lewis et al. (2013) suggested that a sustained highstand up to +3-0 m was followed by a pronounced fall to lower than +1-5 m after 2000 cal BP. Cyclone activity in northern Queensland has been considered constant (Hayne & Chappel, 2001) or variable (Nott & Hayne, 2001) over time. Although there exists a concern about the reliability of historical observations (Harper et al., 2008), oxygen isotope records of stalagmites suggested that multi-centennial scale cycles of cyclone activity occur in Australia, and lower activity in Queensland over the recent decades compared to the last 550 to 1500 years (Haig et al., 2014). However, this area lacks back-barrier mash environments where overwash deposits are preserved well, and thus direct evidence of coastal storm-surge events have relied on coarse-sand beach ridges (e.g. Nott et al., 2009).

METHODS

Survey periods and locations

Field surveys were carried out in February (17 to 23) and May (16 to 21) 2015 on the northern part of Cowley Beach. Three shore-normal beach transects, CB-1, CB-4 and CB-6 (Fig. 1C), were chosen for topographic survey and grain-size analysis of the surface sediment. A 3 m long trench was also dug at site CB-13 (Fig. 1C) for stratigraphic observation and sediment sampling. Ground-penetrating radar was employed along transects CB-6 and CB-7. These transects have a 30 m offset and define a single shore-normal profile that extends 675 m inland from the crest of the berm on the modern beach. Pits and auger boreholes were also dug at 24 sites along transects CB-6 and CB-7 for characterization of sedimentary structures and sediment sampling. All topography measurements were referenced to benchmark PM29637, and shown relative to Australian Height Datum (AHD). The mean tide level of this region is approximately equivalent to 0 m AHD.

Ground penetrating radar survey

The GPR survey was undertaken using a PulseEkko PRO GPR system (Sensors & Software Inc., Mississauga, ON, Canada) with bistatic, shielded 250 MHz antennae and a 165 V transmitter. The antennae were attached to a sleigh for travel along the transects, with a separation of 37 cm. Pulsed radar waves were automatically generated at a step size of 0-05 m following the odometer of the sleigh, and their reflections were recorded. The collected GPR data were processed with Reflexw software (Sandmeier Scientific Software, Karlsruhe, Germany). Data processing included dewow filtering, zero-time correction, time–depth conversion and static correction. The radar wave velocity was calculated at several points along the transect by the common mid-point method, and was consistently 0-13 m and 0-07 m/ns above and below the groundwater table, respectively. The estimated vertical radar resolution, one-quarter to one-half of the radar wavelength (Reynolds, 1997), was 15 to 30 cm and ca 10 cm above and below the groundwater table, respectively. The radar wave velocity for unsaturated sand was also confirmed with the depth to the groundwater table in an auger hole.

Sediment sampling was carried out for OSL dating and grain-size analysis. Pits were ca
Optically stimulated luminescence dating

Sample preparation and measurements for OSL dating were done at the luminescence laboratory of the Geological Survey of Japan. Samples were prepared under controlled red light to avoid affecting the quartz OSL signals. Sediment within 20 to 25 mm of the ends of the tube was removed and used for measurements of moisture content and dosimetry. Quartz grains were extracted from bulk samples following the method of Bateman & Catt (1996). Monolayers of quartz were mounted on 9-mm diameter discs to form large aliquots, which were then measured with a TL-DA-20 automated Risø TL/OSL reader (DTU Nutech, Risø Campus, Roskilde, Denmark) equipped with blue LEDs for stimulation and a $^{80}$Sr/$^{90}$Y beta source for laboratory irradiation. Emitted OSL through a Hoya U-340 filter (Hoya Corporation, Tokyo, Japan) was measured with a photomultiplier.

The single-aliquot regenerative-dose (SAR) protocol was used to determine the equivalent dose ($D_e$) using the OSL response to a test dose to monitor and correct for sensitivity changes (Murray & Wintle, 2000). The OSL measurements were made at 125°C with a stimulation time of 20 sec. Preheat dose recovery test and preheat plateau test were carried out on sample gsj15047 and samples gsj15028, 15037 and 15047, respectively, by changing the preheat temperature from 140 to 300°C in 20°C increments. Almost identical results were obtained for preheats of 180 to 240°C, and an increase in the $D_e$ at preheat above 260°C in relation to an increase of recuperation. Thus a preheat temperature of 220°C was chosen. A 160°C cutheat for the OSL response to the test dose was used for all samples. To determine $D_e$, five regeneration points were measured including 0 Gy and a replicate of the first regeneration point, which was used to check whether the sensitivity correction procedure was performing adequately. Data from aliquots were rejected if recycling ratios were beyond 1.0 ± 0.1. Feldspar contamination was also checked for three aliquots per sample by using the IR test. While most samples showed <5% depletion of post-IR blue OSL compared to blue OSL, samples showing >10% depletion were re-etched with 10% HF. The first 0.5 sec interval of the signal was integrated, and the background subtraction over an interval of 15 to 20 sec after the onset of stimulation was applied. Twenty-four replicates per sample were measured except for samples gsj15030, 15032, 15041 and 15042, from which an insufficient amount of the 180 to 250 μm fraction was obtained because of their coarse grain size; 10 to 12 replicates were measured for these coarser samples.

The contributions of both natural radioisotopes and cosmic radiation were considered for determination of the environmental dose rate. Concentrations of potassium, uranium, thorium and rubidium were quantified by inductively coupled plasma mass spectrometry and were converted to dose rate based on data from Adamiec & Aitken (1998) and Marsh et al. (2002). Past changes of moisture content are unknown, so an uncertainty margin of 5% was applied to the measured moisture content values. Cosmic dose rate was estimated based on Prescott & Hutton (1994). The final $D_e$ value was determined by applying the Central Age Model (Galbraith et al., 1999) for individual sample and further divided by an environmental dose rate to obtain OSL ages. All ages are expressed relative to AD 2015.

Grain-size analysis

The sediment samples for grain-size analysis were first sieved through a 63 mm mesh sieve to remove the very minor component of mud. Samples were then treated with 10% hydrochloric acid and hydrogen peroxide to remove carbonates and organic material, respectively. Finally, samples were visually inspected and pumice grains, if any, were removed manually. The grain-size distribution of the extracted sand fraction was determined with a Camsizer (Retsch Technology GmbH, Haan, Germany). The obtained distribution was represented by the coarsest 10th percentile, median and 90th percentile in phi scale. The presence and size of pumice gravel in the pits and auger samples were noted in the field.
RESULTS

Modern beach topography and grain size

Almost identical beach profiles were observed along transects CB-1, CB-4 and CB-6 (Fig. 3A to C). Transects CB-4 and CB-6 extend inland over two beach ridges as well as the active berm crest, while along transect CB-1 the second ridge was not accessible due to the dense vegetation. The level of the berm crest is constantly +2.5 m AHD, marking the limit of the fair-weather swash. The grain size of the surface sediment changes abruptly at the backshore limit; gravels and very coarse sand are present on the modern beach while the majority of the beach-ridge surface is medium sand. The sea is to the right and horizontal distance is shown relative to the berm crest.

Fig. 3. Shore-normal modern beach profiles observed along transects CB-1 (A), CB-4 (B) and CB-6 (C). These three profiles are almost identical to each other. The berm crest is developed at +2.5 m AHD, marking the limit of the fair-weather swash. The grain size of the surface sediment changes abruptly at the backshore limit; gravels and very coarse sand are present on the modern beach while the majority of the beach-ridge surface is medium sand. The sea is to the right and horizontal distance is shown relative to the berm crest.

Fig. 4. Ground penetrating radar (GPR) profile, OSL ages and columnar sections of pits along transect CB-7 between 440 m and 675 m (A) and 205 to 440 m (B) from the modern beach. Results of the grain-size analysis are shown on the right side of the columnar section. The highest ridge (Ridge 8) is +5.1 m AHD at 486 m. Levels of Ridges 9 and 10 at 620 m and 655 m are +4.0 to 4.2 m AHD, while other ridges are +3.5 to 4.0 m AHD. The strong reflection that occurs at +2 m AHD at the landward end and dips seaward slightly represents the groundwater table. Two GPR facies are roughly bounded by the groundwater table. The upper facies is characterized by horizontal to hummocky or gently dipping reflections that are dissected by truncation surfaces. These reflections form hummocky structure evident at 245 m, 255 m, 355 m, 430 m and 490 m. The lower facies shows a series of clear reflections that dip seaward. Some of the truncation surfaces in the upper facies appear to extend further to the lower facies beneath the groundwater table. The dipping reflections are sigmoidal or in places form two sets of cross-bedding concave upward; the upper set occurs between +2 and 0 m AHD. Their shapes are considered to reflect the topography characterized by the steep beach face, low-tide terrace and barless, steep shoreface. The OSL ages indicate the seaward accretion of the beach ridges since 2500 to 2700 years. Pit sections show the massive sand with no identifiable sedimentary structures and podsol development on the surface of the beach ridges. Rootlets are present in the sections. Initial sedimentary structure of the upper beach ridges, if any, was disturbed by plant roots. Grain-size distributions are also not effective for defining sedimentary units.
Fig. 4. (continued).
an angle of ca 1/10. The beach face is gentler below 0 m AHD, from which the low-tide terrace is developed. The berm defines a narrow (5 to 10 m wide) backshore area that dips slightly landward. On 16 May 2015, wind ripples were found on the backshore along transect CB-6 (Fig. 2C), when mean wind speed of 30 km/h and gusts of 50 km/h were recorded at Cardwell (Fig. 1A). The present beach is not vegetated and has fresh plant debris and pumice gravels up to the backshore limit (Fig. 2E and F). The first beach ridge is +3-2 to 3.5 m AHD high, has a patchy cover of shrubs and trees, and accumulations of pumice pebbles and cobbles (Fig. 2D). A 1 m deep swale is located between the first and second beach ridges. The second ridge is ca 50 cm higher than the first ridge and characterized by denser vegetation and much less pumice gravel.

Similar grain-size trends in sand are identified along the three transects, defining a sharp change at the backshore limit (Fig. 3A to C). The present beach sand is coarser and variable, while the sand on the beach ridge and swale is consistently finer than the beach sand. The median grain size is medium sand (1-0 to 1-5 phi) inland of the backshore limit, while it is medium sand to granule (−2-0 to 1-5 phi) on the beach. The coarsest 10th percentile is consistently finer than 0 phi on the ridge and swale, and shows the presence of granules and pebbles on the beach. The trend of the 90th percentile is consistently 1-5 to 2-5 phi except for samples dominated by gravels and very coarse sands. Two surface samples of wind-rippled sand were obtained at 5 m and 7 m along transect CB-6 and are dominated by coarse sands (Fig. 3C). The sample at 5 m is coarser; its 10th percentile, median grain size, and 90th percentile are 0-0, 0-6 and 1-1 phi, respectively.

**Ground penetrating radar profile and beach-ridge topography**

Ten beach ridges occur from the present beach to 675 m inland and are numbered Ridges 1 to 10 (Figs 4 and 5). Ridge 8 is the highest beach ridge (+5-1 m AHD) and occurs at 486 m from the present beach. Elevations of Ridges 9 and 10 at 620 m and 655 m are +4-0 to 4-2 m AHD. The rest of the beach ridges are +3-5 to 4-0 m AHD, except for Ridge 1, which is +3-5 m AHD (Fig. 3).

Well-defined GPR profiles were obtained along transects CB-6 and CB-7 (Figs 4 and 5) to a maximum penetration of ca 8 m. A continuous, nearly horizontal strong reflection dips seaward gently from +2-0 m AHD at the landward edge of transect CB-7 to +1-0 m AHD near the beach. This strong reflection was confirmed as representing the groundwater table at the auger borehole at 486 m, as widely recognized in other areas (e.g. Bristow & Pucillo, 2006). Reflections above 50 cm deep are from ground waves. The groundwater table roughly marks the boundary between the upper and lower facies of the GPR profile. The upper facies is characterized by horizontal to hummocky or gently dipping reflections that are in places dissected by truncation surfaces dipping seaward. The horizontal to curved reflections form hummocky structures in the cores of the beach ridges that are well-defined at 25 m, 70 m, 135 m, 245 m, 255 m, 355 m, 430 m and 490 m. This structure is similar to the modern berm crest in elevation and shape. The lower facies is dominated by a series of reflections steeply dipping seaward. These dipping reflections appear to be sigmoidal or in places to show two sets of cross-bedding concave upward, with the upper set occurring between +2 m and 0 m AHD. Typical dipping angles of the reflections are 1/10 at +2 to 0 m AHD and 1/10 to 2/0 around 0 m, 1/5 to 1/20 at −2 to 0 m, and then <1/20 below −2 m; they also show onlap and/or downlap. Some of the truncation surfaces extend from the upper facies into the lower facies, beneath the groundwater table.

**Pit and trench sections**

The 3 m long trench at site CB-13 exposed the beach sedimentary structure associated with a well-defined scarp at the backshore landward margin (Figs 1, 2E and 2F). An erosional surface marked by a laminated layer of heavy mineral concentration extends seaward from the foot of the scarp and dips seaward at an angle of 1/5 to 1/10.

Pit sections at 24 sites along GPR transects reveal the dominance of massive medium and coarse sands in the upper part of beach ridges (Figs 4 to 6). The most seaward pit section, at the berm crest, shows the well-defined parallel lamination and beds of coarser sediment (Figs 5 and 6H). The lamination of the berm deposits is sub-parallel to the berm surface. Except for Ridge 1, the surface of the beach ridge is characterized by the development of a dark-grey podsol 10 to 35 cm thick (Fig. 6A to E). The beach-ridge sand shows a gradual colour change seaward from reddish yellow through yellow to light yellow. At 35 m, light yellow sand erosionally overlies yellow sand at 55 cm deep (Figs 5...
Table 1. Optically stimulated luminescence (OSL) samples and dating results: the distance from the modern berm, depth, contents of radionuclides, moisture, dose rate, equivalent dose, overdispersion and OSL age. The OSL ages with standard error exceeding 10 and 100 years are rounded to the nearest decade and century, respectively.

| Laboratory code | Distance (m) | Depth (cm) | K (%) | U (ppm) | Th (ppm) | Rb (ppm) | Moisture (%) | Dose rate (mGy/a) | D_e (mGy) | OD (%) | Age (yr) |
|-----------------|--------------|------------|-------|---------|----------|----------|--------------|------------------|-----------|--------|----------|
| CB-6            |              |            |       |         |          |          |              |                  |           |        |          |
| gsj15042        | 0            | 20         | 1.01  | 0.84    | 6.26     | 49.8     | 4            | 1762 ± 79        | 3 ± 1     | 184    | 2 ± 1    |
| gsj15041        | 0            | 80         | 1.7   | 0.64    | 2.51     | 80.2     | 4            | 1901 ± 115       | 0 ± 274   | 0      | 0        |
| gsj15040        | 7            | 60         | 0.79  | 0.76    | 3.7      | 40.9     | 4            | 1355 ± 60        | 7 ± 1     | 110    | 5 ± 1    |
| gsj15039        | 20           | 20         | 0.79  | 0.86    | 5.8      | 39.7     | 3            | 1546 ± 62        | 9 ± 0     | 123    | 6 ± 0    |
| gsj15038        | 20           | 60         | 0.84  | 0.6     | 3.31     | 42.4     | 3            | 1349 ± 59        | 122 ± 2   | 7      | 91 ± 4   |
| gsj15037        | 20           | 80         | 1.1   | 0.56    | 2.41     | 52.4     | 4            | 1502 ± 77        | 143 ± 3   | 9      | 95 ± 5   |
| gsj15036        | 20           | 150–165    | 1.26  | 0.64    | 3.09     | 60.3     | 6            | 1657 ± 91        | 164 ± 2   | 6      | 99 ± 6   |
| gsj15035        | 25           | 30         | 0.78  | 0.65    | 3.74     | 39.7     | 2            | 1362 ± 55        | 14 ± 1    | 23     | 10 ± 1   |
| gsj15034        | 25           | 70         | 0.93  | 0.65    | 3.06     | 46.9     | 3            | 1432 ± 65        | 155 ± 4   | 12     | 108 ± 6  |
| gsj15033        | 35           | 25         | 0.79  | 0.96    | 2.8      | 40.9     | 2            | 1377 ± 56        | 15 ± 1    | 21     | 11 ± 1   |
| gsj15032        | 35           | 45         | 0.75  | 0.82    | 4.37     | 39.8     | 1            | 1423 ± 53        | 111 ± 2   | 15     | 78 ± 3   |
| gsj15031        | 35           | 70         | 0.98  | 0.54    | 2.88     | 46.7     | 2            | 1451 ± 65        | 309 ± 3   | 11     | 210 ± 10 |
| gsj15030        | 45           | 70         | 0.84  | 1.03    | 8.05     | 42.9     | 2            | 1790 ± 67        | 317 ± 3   | 6      | 180 ± 10 |
| gsj15029        | 55           | 60         | 0.84  | 1.03    | 8.38     | 42.9     | 4            | 1785 ± 75        | 350 ± 5   | 8      | 200 ± 10 |
| gsj15028        | 65           | 70         | 0.91  | 0.57    | 3.21     | 44.5     | 3            | 1400 ± 63        | 384 ± 6   | 7      | 270 ± 10 |
| gsj15027        | 65           | 180–195    | 1.08  | 1.02    | 5.45     | 47.6     | 3            | 1790 ± 79        | 447 ± 6   | 8      | 250 ± 10 |
| gsj15026        | 70           | 40         | 0.92  | 0.62    | 4.32     | 46.9     | 3            | 1508 ± 66        | 355 ± 6   | 8      | 240 ± 10 |
| gsj15025        | 70           | 80         | 0.72  | 0.82    | 7.08     | 36.1     | 2            | 1562 ± 57        | 401 ± 4   | 7      | 260 ± 10 |
| gsj15024        | 75           | 70         | 1.17  | 0.86    | 3.81     | 54.7     | 4            | 1753 ± 81        | 688 ± 11  | 9      | 390 ± 20 |
| gsj15023        | 105          | 70         | 0.9   | 1.39    | 3.19     | 44.7     | 4            | 1559 ± 70        | 630 ± 8   | 9      | 400 ± 20 |
| gsj15022        | 105          | 140–150    | 0.88  | 0.97    | 5.71     | 43.5     | 12           | 1463 ± 69        | 766 ± 13  | 18     | 530 ± 30 |
| gsj15021        | 125          | 50         | 0.77  | 0.89    | 6.81     | 40.1     | 3            | 1601 ± 63        | 688 ± 11  | 9      | 430 ± 20 |
| gsj15020        | 155          | 70         | 0.78  | 0.91    | 3.47     | 39.2     | 3            | 1375 ± 57        | 699 ± 9   | 6      | 510 ± 20 |
| gsj15019        | 155          | 190–205    | 1.93  | 0.93    | 3.11     | 87.9     | 4            | 2374 ± 132       | 1382 ± 19 | 10     | 580 ± 30 |

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and 6E). Pumice gravels up to 5 cm in diameter are scattered in sand or present in weakly defined layers. Lamination and stratification are generally not pronounced in pit sections of the inland beach ridges, while the minor presence of parallel lamination is recognized at an inter-ridge swale site at 560 m inland (Fig. 4A). Only Ridge 1 shows well-defined stratification. The pit section at 35 m reveals that a layer at 55 to 35 cm deep has a basal erosional surface with a concentration of pumice gravels, corresponding to the abrupt colour change (Fig. 5). This layer is then overlain by another layer 35 cm thick, and the boundary between these two layers is also marked by pumice. At 25 m, a weak podsol occurs at a depth of 35 to 55 cm and is overlain by a light-yellow sand layer. An abrupt boundary is present 25 cm below the surface at 20 m, between the overlying massive layer and the underlying disturbed sand with rootlets. Rootlets are generally present above 50 cm deep in the pit sections, but they are also found deeper at some sites closer to the shore (Fig. 5).

Results of grain-size analysis for samples taken from auger boreholes and pit sections show that the vertical succession of beach-ridge sediments is generally characterized by variable trends (Figs 4, 5 and 7). The median grain size is 1 to +1/4 phi above +4.0 m AHD, 1-4 to -0.2 phi in +3.0 to 4.0 m AHD, and 1-6 to -1.6 phi below +3.0 m AHD. The 10th percentile is 0 to 0.6 phi above +4.0 m AHD, 0-6 to -1.6 phi in +3.0 to 4.0 m AHD except for one outlier at 242 m, and 1 to -2.4 phi below +3.0 m AHD. The gravelly layer between 70 cm and 80 cm deep at 240 m corresponds to the truncation surface in the corresponding GPR profile.

Optically stimulated luminescence ages

Optically stimulated luminescence ages younger than 2700 years were obtained from the ridge samples and indicate the successive formation of the beach ridges in relation to the seaward progradation of the shoreline (Table 1). All samples showed unimodal distributions of $D_m$. The overdispersion value was generally less than 20% but very high for very young samples taken from or very close to the modern beach, indicating the general validity of the application of the Central Age Model. Most samples showed recuperation lower than 5%, except for samples with final ages younger than 100 years, which may thus have been slightly overestimated (Madsen & Murray, 2009). The OSL ages are generally younger upward.
Fig. 5. Ground penetrating radar (GPR) profile, OSL ages and columnar sections of pits along transect CB-6, seaward extension of CB-7 (Fig. 4). Results of the grain-size analysis are shown on the right side of the columnar section. Ridge levels are +3.5 to 4.0 m AHD. This profile also shows a strong reflection representing the groundwater table around +1.0 m AHD. Two GPR facies are recognized as in transect CB-7 (Fig. 4). Hummocky structures are well-pronounced at 25 m, 70 m and 135 m. The OSL ages define the high-resolution chronology, especially of Ridges 1 and 2, suggesting the successive formation of ridges separated by a hiatus. A contrast in sand colour occurs between Ridge 1 and inland ridges. At 35 m, an erosion surface at 55 cm deep corresponds to a gap in OSL age and sand colour. Pit sections in Ridge 1 reveal some sedimentary units because they are not disturbed by podsolization. Grain-size distributions do not define sedimentary units.
at individual sites and seaward, being concordant
with the morpho-stratigraphic order of the beach
ridges, while slight age reversals are observed at
655 m, 486 m and 225 m of the GPR profile. There
are several ages for each beach ridge in the sea-
ward part of the GPR profile, but almost no age
overlap is seen between ridges, indicating that the
beach ridges have formed during discrete periods.

At 35 m, a gap in the OSL age succession occurs
between gsj15031 (210 ± 10 years) and gsj15032
(78 ± 3 years), corresponding to an erosional sur-
face and change in sand colour. The landward part
of Ridge 2 was dated as 240 to 270 years, while its
seaward part is slightly younger (180 to 210 years),
concordant with the internal structure showing
the seaward accretion of the beach ridge. The OSL
ages show that the initial deposition of Ridge 1
was ca 110 years ago, clearly younger than Ridge
2. The majority of Ridge 1 was dated as 108 to
91 years. However, OSL ages younger than
10 years were determined for samples near the
surface, indicating very recent sedimentation on
top of Ridge 1. Samples taken from the beach pit
sections at 0 m and 7 m were very young and
regarded as modern, concordant with the pre-
sently active beach sedimentation. Three samples
were dated along the beach trench section at site
CB-13 (Fig. 2F). Ages of two samples beneath the
erosional surface were 30 ± 2 years and 37 ± 2 years, while a sample above the surface
was dated as 8 ± 1 years, recording recent erosion
of the beach.

Fig. 6. Photographs of pit sections at: (A) 486 m, (B) 255 m and (C) 240 m of transect CB-7; and (D) 70 m, (E)
45 m, (F) 35 m, (G) 20 m and (H) 0 m of transect CB-6. Except for sites in Ridge 1, (F) to (H), the dark-grey podsol
characterizes the surface of the beach ridge. The colour of the beach ridge sand gradually changes seaward from
reddish yellow (A) through to yellow (B) to (F) to light yellow (F) to (H); at 35 m, light-yellow sand abruptly over-
lies yellow sand 55 cm deep (F), and this boundary defines an erosion surface associated with a gap in OSL age
(Fig. 5). Sedimentary units are only recognizable in Ridge 1 (F) to (H). Black dots show locations of the OSL sam-
ples with ages expressed relative to AD 2015.
DISCUSSION

Formative processes of beach ridges

Beach sedimentation

Integrating newly obtained data of the beach topography, GPR and pit stratigraphy, grain size, and OSL ages enables a robust assessment of the formative processes of beach ridges at Cowley Beach (Fig. 8). The sequence of seaward-dipping reflections in the lower part of the GPR profile reveals that shoreline progradation was driven by deposition onto the beachface and shoreface, as has been shown for many other beaches (e.g. Jol et al., 1996; Bristow & Pucillo, 2006; Rodriguez & Meyer, 2006; Tamura et al., 2008; Oliver & Woodroffe, 2016). At Cowley Beach, the high beachface, with up to 3 m of relief (Fig. 3), forms under the ca 3 m tide that broadens the vertical range of wave run-up. The hummocky structure in the upper radar facies is inferred to represent the relict beach berm based on its similarity in shape and elevation to the modern berm. Modern berm deposits also show the sub-parallel lamination (Fig. 6H) that is consistent with the hummocky structure. The nucleus of the beach ridges is thus interpreted as having been built by fair-weather swash up to at least +2.5 m AHD. The seaward-dipping truncation surfaces in the upper radar facies are interpreted as imprints of scarps, similar to those recognized at the backshore limit of the modern beach (Fig. 2E and F), consistent with interpretations of similar structures in a variety of other beaches (e.g. Buynevich et al., 2004, 2007; Bristow & Pucillo, 2006; Dougherty, 2014). Pit sections at 35 m and 240 m inland from the modern beach (Figs 4B and 5) exhibit coarser-grained layers corresponding with truncation surfaces. Especially at 35 m, an abrupt change in sand colour and OSL age is present across the truncation surface (Figs 5 and 6E).

Tidally modified beaches with a distinctive low-tide terrace (Masselink & Short, 1993; Short, 2006) like Cowley Beach, tend to show relatively large topographic changes caused by storm erosion (Masselink & van Heteren, 2014). Nott et al. (2015) reported the scarping and flattening of Queensland beaches in a post-cyclone survey after Tropical Cyclone Yasi. The common presence of the truncation surfaces in the GPR profiles of Cowley Beach thus indicates that a beach scarp is generated during storm-wave conditions associated with cyclones. The lower extent of these truncation surfaces is generally obscured by the strong reflection of the groundwater table, but some clearly continue down to the discontinuity in the sequence of seaward-dipping reflections in the lower facies (for example, around 120 m, 150 m, 230 m, 310 m, 530 m, 560 m, 600 m and 610 m of the profile; Figs 4 and 5), recording pronounced beach erosion. These stratigraphic features indicate that the beach-ridge sequence at Cowley Beach records a ‘cut and fill’ pattern (Davies, 1957), where the fair-weather swash deposition and berm building are punctuated by erosion during storm conditions (Oliver et al., 2017).

Reflections in the lower radar facies indicate the characteristic sedimentation pattern of the beach-shoreface at Cowley Beach. Seaward-dipping reflections have sigmoidal geometry and/or two sets of concave cross-bedding, and their gradient is much gentler around 0 m AHD. The level and gradient of the gentler part are similar to those of the present low-tide terrace (Fig. 3B). The lower steep reflections occur at a level equivalent to the lower intertidal beach to subtidal shoreface, and indicate that progradation

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Fig. 7. The median and 10th percentile grain sizes of all samples taken from pit sections and auger holes (A) and the surface of modern beach (B), plotted against elevation. The median and 10th percentile grain sizes of wind ripples at 5 m of transect CB-6 are shown for comparison. Some samples above +2.5 m AHD are finer than wind ripples, indicating the possibility of aeolian sand transport to the beach ridge.
occurs with sediment accretion on a smooth slope. These shoreface reflections contrast with those in a barred shoreface, which tend to be more complicated (e.g. Tamura et al., 2008). Although there is no available data of the off-shore bathymetry, the ‘low-tide terrace + rip’ beach typically has a barless, steep shoreface (Masselink & Short, 1993) which is consistent with the GPR reflections at Cowley Beach.

Other mesotidal beach systems have similarities with and differences to Cowley Beach in terms of their radar facies. A GPR profile of a fine-sand mesotidal beach deposit on the northern Pacific coast of the USA show a ca 4 m thick facies characterized by beach face reflections that consistently dip seaward (Jol et al., 1996). A mixed sand–gravel beach on the coast of south-western British Columbia, Canada, is characterized by an upper and lower beach face, bounded by an intertidal berm (Engels & Roberts, 2005). These deposits show only continuous GPR reflections that dip consistently seaward. Therefore, the dipping GPR reflections characterized by sigmoidal geometry and/or two sets of concave cross-bedding at Cowley Beach are considered to be unique to this mesotidal, barless coarse-sand beach-shoreface.

**Cyclone inundation**

While fair-weather swash accounts for building the lower ridges and the cores of higher ridges, processes responsible for emplacing sand at
elevations up to +4 to 6 m AHD at Cowley Beach are an important feature of this distinctive type of beach ridge. Although there is an argument that the beach ridge should refer to a purely wave-built landform (Hesp, 2006), a broad definition of the beach ridge of Ötvös (2000), which allows for some components of aeolian sand, is adopted here.

Cyclone inundation has been considered the primary process responsible for building the coarse-sand beach ridge in north-eastern Queensland (e.g. Nott et al., 2009; Nott, 2014). The post-cyclone survey after TC Yasi confirmed that debris and a 10 to 60 cm thick sand layer were emplaced on the soil that caps Ridge 1 at Cowley Beach (Nott et al., 2013, 2015). Thus, cyclone-generated shoreline regimes contribute not only to the erosion of the beach face/berm, which results in a scarp in the beach, but also to the vertical accretion of the beach ridges. These surge-emplaced layers were found beneath the soil horizon and were inferred to be deposits of TC Larry, TC Winfred and Innisfail TC, based on their stratigraphic order and eyewitness accounts of shoreline deposition during these events (Nott et al., 2013).

Three pits in Ridge 1 examined in this survey of Cowley Beach reveal discrete sand layers. The pit at 20 m along transect CB-6 has a pumice layer at 25 cm deep, separating the uppermost massive sand layer from the underlying bioturbated sand (Figs 5 and 6G). The modern OSL age of the uppermost layer contrasts with OSL ages of the underlying sand – samples at 60 cm, 80 cm and 150 to 165 cm deep are almost identical (ca 95 years) and no stratigraphic subdivisions were evident in the sand. At the 25 m pit, a surface sand layer is separated by a weak podsol layer between 35 cm and 55 cm deep, across which there is a clear gap in OSL age (Fig. 6F). The pit at 35 m also shows a surface layer which is distinctly younger than the underlying layers, and appears to correlate with surface layers at 20 m and 25 m, which occur above +2.9 m AHD. Nott et al. (2013) reported that the TC Yasi run-up level was +2.8 AHD. The surface layer on Ridge 1 is unlikely to be the deposit of TC Yasi inundation and no TC Yasi deposit was preserved at these sites. In general, the pits at Ridge 1 of the present study showed fewer layers than those of Nott et al. (2013) indicating spatial variations in preservation potential. Other pits on or inland of Ridge 2 generally show a section of massive sand except for weak layers defined by pumice gravel. At these sites, primary sedimentary structures may have been erased by bioturbation, especially by plant roots, and pedogenesis.

**Aeolian sedimentation**

Aeolian processes have been discounted for transporting significant volumes of coarse sand to the beach ridges of north-eastern Queensland because non-cyclonic trade winds were considered to be too weak to transport coarse sands. The beach face was thought to be completely submerged during the period when cyclones make landfall and generate extreme onshore winds (e.g. Nott et al., 2009; Nott, 2014). However, the observations herein of wind ripples on the backshore (Fig. 2C) indicate that even non-cyclonic winds are able to transport coarse sand on Cowley Beach. Many samples from the upper levels of the beach ridges (Fig. 7A) and surface samples on Ridge 1 (Figs 3 and 7B) are finer than samples obtained from the wind ripples and thus could have been at least partially transported by non-cyclonic winds.

Extreme onshore winds associated with cyclone landfall are also possibly responsible for the transport of coarse sediment onshore. Tamura (2012, 2014) pointed out the possibility of coarse-sand transport under lower category cyclones associated with winds of >100 km/h as the transport threshold of coarse sand, which can be reduced by the impact of medium sand (Mountney, 2006), which is also a major component of sediment at Cowley Beach. Nott (2014) argued that the beach is submerged during the lower category cyclones. However, estimates by Nott (2012) suggest that a Category 1 cyclone, if it makes landfall during the mean tide level or lower, does not submerge the berm and backshore at Cowley Beach. Higher category cyclones may submerge the beach during the high to mean tide, but the exposure of the beach is highly likely during low tide when the still water level can drop to −1.7 m AHD (Fig. 9B). It was also noted that some recent cyclones had caused aeolian sand transport on the Queensland coast (Nott, 2010). In contrast, cyclones dominated by offshore winds, like TC Yasi (Nott et al., 2013), are unlikely to have generated aeolian transport of sand onshore; and rainfall associated with cyclones may wet the beach and reduce the potential for aeolian transportation of sand.

Pumice gravels are also conspicuous components of the ridge deposits at Cowley Beach. In general, pumice gravels are easily entrained in currents and their propensity to float in water
often results in pumice clasts being concentrated along the upper limit of swash or surge deposits. However, Douillet et al. (2014) showed in wind tunnel experiments that pumice grains with diameters of 8 to 16 mm and density of 1.4 g/cm³ initiated movement by saltation with wind <72 km/h, and interacted with scoria grains 4 mm in diameter, which have a density close to quartz and feldspar sands. Much stronger onshore winds can occur during tropical cyclones and are likely to transport larger pumice gravels. Therefore, sediment texture is not an unambiguous indicator of the sediment transportation processes responsible for depositing sediment on beach ridges at Cowley Beach.

The detailed investigation at Cowley Beach indicates that surge and aeolian processes are responsible for building the ridges above the fair-weather swash limit. However, it is still not possible to quantify the relative contribution of these processes. So far, only cyclone-inundations have been observed to deposit distinct, relatively thick (for example, 0-6 m) deposits on the beach ridges, and thus are considered to be the dominant depositional process. However, the contribution of aeolian deposition should be carefully checked in future post-cyclone surveys.

Coarse-sand beach ridges: an intermediate type between fine-sand and gravel ridges?

The grain size of constituent sediments of beach ridges is generally an important factor in their formative processes. Fine-sand and gravel ridges are likely to be wave-built and/or wind-built, and wave-built, respectively. Mixed sand–gravel ridges are reported to form as gravel ridges with or without a coarse sand matrix, capped by wind-deposited fine sand (Orford et al., 2003; Billy et al., 2014). Cowley Beach appears to have features typical of both fine-sand and gravel beach ridges, with fair-weather and storm-driven processes involved in ridge construction, including the building of the berm by fair-weather swash, emplacement of overwash layers by cyclone inundation and some aeolian deposition.

In addition to their grain size, the beach ridges at Cowley Beach are also influenced by low-energy fair-weather waves, >3 m tide range, a long-term positive sediment budget for the beach system, and episodic cyclone erosion and inundation, the combination of which may be specific to the north-eastern Queensland coast. Fair-weather waves are fetch-limited because offshore swells are attenuated by the Great Barrier Reef, while tropical cyclones generate much higher storm waves only for a few hours to days, with an average recurrence interval for the Cairns region of around five to six years. Berm formation up to 2.5 m higher than the mean sea-level is related to the tide-modulation of the low-energy fair-weather swash, and further sediment accumulation above the berm occurs during cyclone inundation, with a likely minor component from aeolian input. These compound processes form the beach ridges at Cowley Beach and probably at other locations in north-eastern Queensland.

Several past case studies have observed the formation of beach ridges during storms. Storm-built sandy beach ridges have been investigated on the western coast of the Baltic Sea, where the prevailing wave climate is low-energy (Bendixen et al., 2013). Along the microtidal beach at Feddet, Denmark, the specific storm conditions associated with the passage of low pressure caused >1 m coastal set up and storm waves to form a sandy berm above the fair-weather swash.
limit, which then was isolated as a beach ridge with an aeolian sand cap (Bendixen et al., 2013). Storm waves at Feddet are associated with moderate onshore winds of 36 to 54 km/h, and thus may still be favourable to the construction of a berm. Storm waves at Cowley Beach, in contrast, are caused by tropical cyclones and can be >4 m high, leading to the erosion of the berm and beach scarping. These waves contribute to ridge construction because they add to storm surge that washes over the shoreline and deposits sediment on the nucleus of the beach ridge that has been isolated from the shoreline through progradation of the beach during fair-weather conditions.

Clemmensen et al. (2014) documented the coastal impact of the Baltic Sea storm event in 1872, in which the peak inundation level reached +2.8 m above mean sea-level, which is higher than the storm-built berm. This inundation eroded the foredune ridge and formed washover fans, the margins of which were later reworked by wind into dunes. The onshore and vertical sediment accretion by the 1872 storm and resultant aeolian processes are similar to the ridge-forming processes at Cowley Beach. Geomorphology and sediment records of the Bodil storm in 2013 were reported at a mixed sand–gravel beach on the eastern coast of the Belt Sea (Clemmensen et al., 2016). Similarly, this storm emplaced a gravelly berm at a level that coincides with the maximum inundation level (+2.35 m above mean sea-level), and also formed a scarp and washover fans seaward and landward of the berm, respectively. Billy et al. (2014), in contrast, reported that the level of a mixed sand–gravel ridge is similar to the level of the berm that forms by fair-weather swash, rather than a storm berm. These comparisons indicate that there are considerable variations in ridge-forming processes, even with beach ridges for which storm processes play an important role.

Cyclone records preserved in beach ridges

Key issues to be considered in reassessing the utility of beach ridges in north-eastern Queensland as records of past cyclones are the feasibility of identifying the number of cyclone-generated surge events that contribute to the development of an individual beach ridge, beach-ridge chronology, and the relationship between cyclone magnitude and the elevation of ridges.

Pit sections of the more inland ridges do not appear to show any individual sediment layers, similar to other beach-ridge deposits in this region (e.g. Forsyth et al., 2010). This characteristic limits the ability to identify any multiple individual cyclone inundation events that are likely to accrete to form a ridge. In contrast, where these structures are preserved, as seen in geological records of tsunami and hurricanes, reconstruction of past events can rely on clear alternations of discrete sand layers and marsh deposits (e.g. Donnelly et al., 2001; Sawai et al., 2012). Detailed investigation of modern and historical cyclone deposits can help to characterize their realistic thickness, and this could be used for estimating the approximate number of events recorded in a ridge. The assumption of average thickness, however, would introduce further uncertainty given that the TC Yasi deposits varied spatially from 10 to 60 cm thick.

Determining the duration required for a single ridge to be built is critical for modelling ridge building over longer intervals of time. The studied beach-ridge sequence consists of 10 ridges and was formed over the last 2500 to 2700 years, indicating that a ridge was formed over an apparent interval of 250 to 270 years. However, there could be a hiatus in ridge formation (Nott, 2012; Scheffers et al., 2012), which may be caused by a depleted sediment supply, significant storm erosion and shoreline re-orientation (for example, beach rotation; Short et al., 1995; Goodwin et al., 2006). Moreover, most of the ridges surveyed contain multiple truncation surfaces both in the upper and lower GPR facies units that represent breaks in deposition and erosion of the beach (e.g. Bristow & Pucillo, 2006). These data reveal that beach-ridge deposits at Cowley Beach are composite structures. Inaccuracy and/or uncertainty of the chronology could also result in an apparent hiatus. For example, three OSL ages obtained in Ridge 8 at 486 m show an age reversal of up to 500 years. If the oldest age (2500 years) is applied, there appears to be a large gap or slowdown of progradation before Ridge 5 was formed at 355 m, where the beach-ridge sand has an OSL age of 1100 years. However, adoption of the youngest age (1800 years) at 486 m indicates more constant progradation from 655 to 355 m. The OSL ages are normally associated with 5 to 10% uncertainties relative to their age, which also makes it harder to examine the detailed chronology of inland, older ridges. Ridges younger than 500 years, in contrast, allow for a decadal-scale examination of progradation. Ridge 2 has an internal age structure that shows that the ridge accreted seaward as well as
Assuming that the older age at 75 m, 390 years, is excluded as an outlier that was overestimated due to the insufficient reset of the OSL signal before deposition, this ridge started to build up above the swash limit 250 to 260 years ago and was completed 180 years ago. The formation of Ridge 1 then started about 110 years ago. A 70 year gap between Ridges 1 and 2 is observed, which can be attributed to the erosion revealed by the truncation surface seen at 35 m. Similarly, a 170 year gap occurs between Ridges 2 and 3, and it is uncertain whether this gap reflects an actual period of no ridge formation or was caused by significant beach erosion. In the former case, the gap may reflect a quiescent period, whereas the latter case implies that the beach-ridge sequence is an incomplete record characterized by sporadic preservation of ridge topography, and that it is inappropriate to assume an apparent average interval for ridge formation.

The validity of the coarse-sand ridge elevation as an indicator of surge run-up and cyclone magnitude is yet to be robustly tested. Assuming that beach morphology has been preserved, the mid-Holocene sea-level highstand up to +3 m above the present level qualitatively accounts for the relatively high beach ridges in the middle part of the coastal plain at Cowley Beach that were dated as 5000 to 6000 years (Nott et al., 2009). These ridges are a few metres higher than the younger ridges (Fig. 1C). The uncertainty of the Holocene highstand sea-level is up to 3 m in Queensland (Lewis et al., 2013) and without an accurate and precise reference sea-level curve it is hard to quantitatively assess the run-up level above mean sea-level at the time of ridge formation. Apart from sea-level fluctuations, the highest ridge at 486 m (Ridge 8) may have been formed by relatively high storm surge. It is however worth noting that cyclone inundation above +5-1 m AHD was observed during TC Yasi at Cardwell, +6-9 m AHD, while inundation caused by TCs Larry and Yasi during low tide reached +3-4 m and +2-8 m AHD, respectively, at Cowley Beach (Nott et al., 2013), highlighting the likelihood of a past surge reaching +5-1 m at Cowley Beach. The TC Yasi data also highlight the large spatial variability in the elevation of surge deposition during a single event. Astronomical tides are independent of cyclone generation and also introduce uncertainty in estimates of the net inundation level of prehistorical cyclones (Fig. 9A). Thus, the coincidence of cyclone landfall with spring high tides may have resulted in the more extraordinary levels of inundation. In summary, the elevation of coarse sand ridges at Cowley Beach could be a practical indicator of the run-up level of past storm surge, but they do not record the higher levels of run-up that may have occurred over the last 2700 years. Older ridges are more problematic indicators of surge elevation because of the uncertainty in past sea-level history. Astronomical tides and the spatial variability of maximum surge run-up level observed in a single cyclone (The State of Queensland, 2012) likewise introduce uncertainty in the assessment of the magnitude of past cyclones based on the elevation of beach ridges.

As is known from the variations of modern beach morphology (e.g. Wright & Short, 1984; Masselink & Short, 1993; Hesp, 1999; Short, 2006), the formative processes of beach ridges are influenced by a range of factors, such as grain size, wind climate and tide range. The high spatial variability in the influence of storms in ridge formation adds further complexity. Therefore, at present, the beach-ridge landform does not provide a reliable record of past storm inundation. Deciphering the depositional history preserved in beach ridges requires a thorough understanding of their formative sedimentary processes which, as shown in this sedimentological investigation of ridges at Cowley Beach, is a complex challenge.

CONCLUSIONS

The detailed examination of medium to coarse-sand beach ridges at Cowley Beach indicates composite formative processes. Ground penetrating radar (GPR) profiles and modern beach topographic data provide unique insights into beach-ridge-building processes in north-eastern Queensland. The nucleus of the beach ridge is formed as a berm at +2-5 m Australian Height Datum (AHD), the observed fair-weather swash limit. Surges and high waves associated with tropical cyclones cause beach erosion and result in the formation of a scarp in the backshore, as well as the vertical accretion of the beach ridge. Like many other beach-ridge systems, the beach-ridge deposits below +2-5 m AHD accrete episodically in a cut and fill pattern, where fair-weather and storm waves lead to progradation and retreat of the beach, respectively.

Cyclone inundations result in surge that deposits coarse sand and pumice gravel that contributes to the vertical accretion of ridges
above the fair-weather swash limit. Aeolian sand accumulation represents a subordinate contribution to ridge deposits. Wind ripples found on the backshore during the present survey indicate some coarse-sand transportation by wind, even by non-cyclonic winds, and ridges therefore are likely to comprise an aeolian component.

Astronomical tides also have a key role in the formation of beach ridges at Cowley Beach, and more broadly in north-eastern Queensland, where there is a >3 m tide range. Storm surge up to the level of the highest ridge in the main transect examined (for example, +5 m AHD) could occur during an intense cyclone comparable to Tropical Cyclone Yasi, and is more likely if the cyclone landfall coincides with high tide. Cyclone landfall during low tide may lead to the subaerial exposure of the upper beach area, promoting sand transport by strong/extreme onshore winds. For older ridges, uncertainties in Holocene sea-level also make it hard to assess the surge run-up above mean sea-level at the time of ridge formation.

Pit sections show that the initial sedimentary structure in these tropical beach ridges is rapidly lost over time due to bioturbation and pedogenesis. This limits the ability to ascribe an individual cyclonic event to a discrete sediment layer. Similarly, any aeolian contribution present in the ridges cannot be readily differentiated from sediment emplaced by surges during cyclones. Therefore, although ridges that sit above the vertical limit of swash deposits predominantly record the impact of a cyclone on the coast, the sedimentary characteristics of the ridges limit the utility of these types of beach-ridge deposits as indicators of past cyclone frequency and intensity. The limitation is also emphasized by the sporadic, incomplete depositional record preserved in the beach-ridge sequence, as shown by the optically stimulated luminescence (OSL) chronology and multiple truncation surfaces evident within a single ridge in the GPR data. The coarse-sand ridges at Cowley Beach serve to highlight the many factors in addition to grain size that influence the development of storm-built sandy beach ridges.

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