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Anatomy of sand beach ridges: evidence from severe Tropical Cyclone Yasi and its predecessors, northeast Queensland, Australia

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Abstract

Four well-identified tropical cyclones over the past century have been responsible for depositing distinct units of predominantly quartzose sand and gravel to form the most seaward beach ridge at several locations along the wet tropical coast of northeast Queensland, Australia. These units deposited by tropical cyclones display a key sedimentary signature characterized by a sharp basal erosional contact, a coarser grain size than the underlying facies and a coarse-skewed trend toward the base. Coarse-skewed distributions with minimal change in mean grain size also characterize the upper levels of the high-energy deposited units at locations within the zone of maximum onshore winds during the tropical cyclone. These same coarse skew distributions are not apparent in sediments deposited at locations where predominantly offshore winds occurred during the cyclone, which in the case of northeast Australia is north of the eye-crossing location. These sedimentary signatures, along with the geochemical indicators and the degraded nature of the microfossil assemblages, have proven to be useful proxies to identify storm-deposited units within the study site and can also provide useful proxies in older beach ridges where advanced pedogenesis has obscured visual stratigraphic markers. As a consequence, more detailed long-term histories of storms and tropical cyclones can now be developed.

Keywords

queensland, northeast, predecessors, its, sand, yasi, cyclone, tropical, severe, australia, evidence, anatomy, ridges, beach

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Anatomy of sand beach ridges: Evidence from severe Tropical Cyclone Yasi and its predecessors, northeast Queensland, Australia

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[1] Four well-identified tropical cyclones over the past century have been responsible for depositing distinct units of predominantly quartzose sand and gravel to form the most seaward beach ridge at several locations along the wet tropical coast of northeast Queensland, Australia. These units deposited by tropical cyclones display a key sedimentary signature characterized by a sharp basal erosional contact, a coarser grain size than the underlying facies and a coarse-skewed trend toward the base. Coarse-skewed distributions with minimal change in mean grain size also characterize the upper levels of the high-energy deposited units at locations within the zone of maximum onshore winds during the tropical cyclone. These same coarse skew distributions are not apparent in sediments deposited at locations where predominantly offshore winds occurred during the cyclone, which in the case of northeast Australia is north of the eye-crossing location. These sedimentary signatures, along with the geochemical indicators and the degraded nature of the microfossil assemblages, have proven to be useful proxies to identify storm-deposited units within the study site and can also provide useful proxies in older beach ridges where advanced pedogenesis has obscured visual stratigraphic markers. As a consequence, more detailed long-term histories of storms and tropical cyclones can now be developed.

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1. Introduction

[2] The origin of beach ridges has long been a controversial issue [*Johnson*, 1919; *McKenzie*, 1958; *Tanner*, 1995, 1996; *Curray*, 1996; *Taylor and Stone*, 1996; *Hesp*, 2006]. A variety of processes have been suggested for their formation such as wave and wind processes combined [*Davies*, 1968; *Bird*, 1960; *Mason*, 1992], fair weather waves [*Curray et al*., 1969; *Tanner and Stapor*, 1971], storm waves [*Psuty*, 1965; *Tanner*, 1995], and fluctuations in sea levels. *Hesp* [2006] recently redefined beach ridges as swash-aligned, swash- or storm-built deposits at or above the normal spring high tide level. While there is an increasing acceptance that sand and coarser-grained beach ridges are a function of swash and storm waves, there is still a poor understanding of the processes leading to their formation. For example, eyewitness accounts show that an entire coral shingle beach ridge up to several meters in height and hundreds of meters in length can be emplaced during a single storm event [*Blumenstock*, 1958; *Maragos et al*., 1973; *Nott*, 2003]. However, it is uncertain if the same is true for the formation of sand beach ridges or if multiple events are required. If sand beach ridges are a function of multiple events then questions remain as to the intensity and number of events required to build a ridge of certain height. Such questions are important for coastal hazard mitigation and risk reduction because sand beach ridges, which occur along many coasts globally, can preserve a record of late Holocene storm histories [*Nott et al*., 2009]. Understanding the details of the processes responsible for beach ridge formation and their relationship to extreme marine inundations allows us to better interpret the nature of the storms responsible, recover more complete and detailed storm records, and make better estimates of the magnitude and frequency of these events for a given location.

[3] Two recent intense landfalling tropical cyclones (TCs) in 2006 and 2011 in the Cairns region of north-eastern Australia deposited substantial units of sand and gravel along an approximately 100 km length of coast. These sedimentary units were deposited onto the existing front beach ridge. Excavation of this ridge at several locations revealed aspects of the sedimentology and stratigraphy not only of these two events but also deposits associated with two previous and

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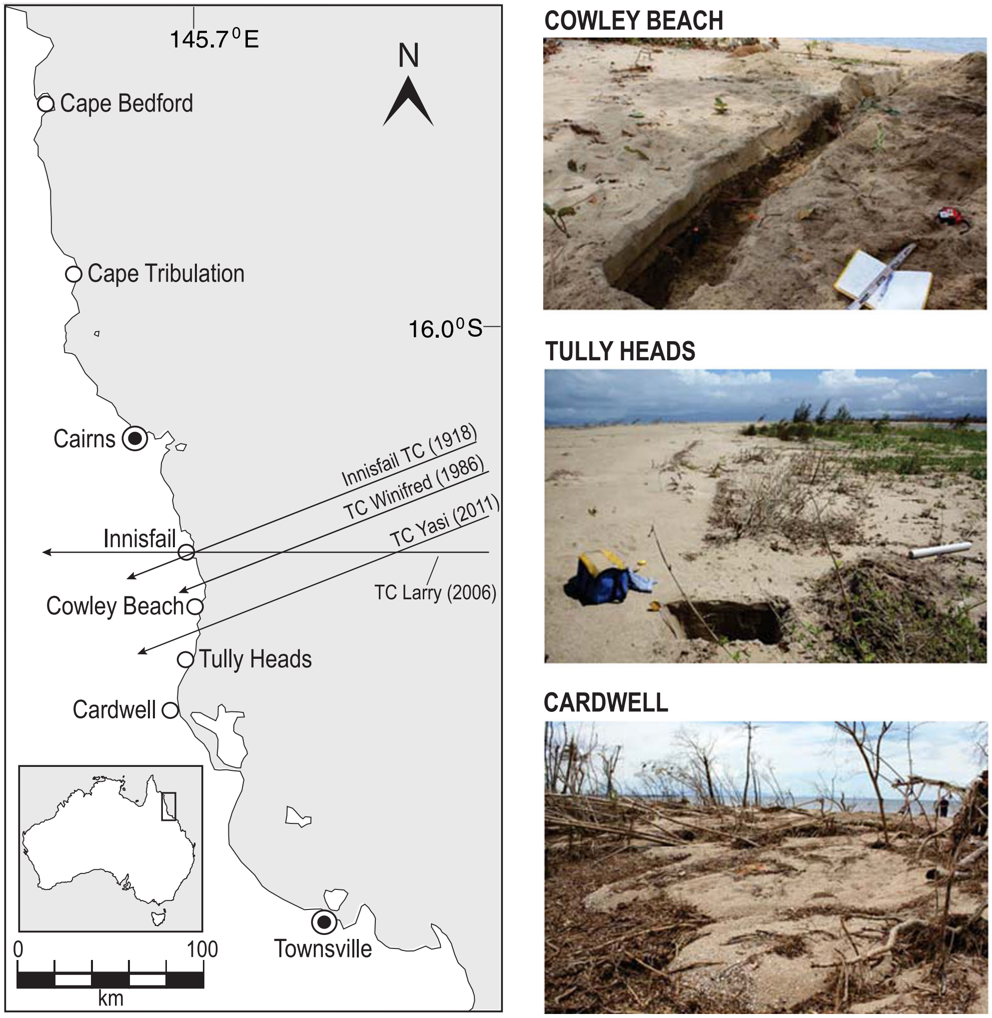

Figure 1. NE coast of Australia showing the key sites mentioned in the text and the paths of the past four intense TCs to cross the coastline in the area. Photographs show trench locations at the three study sites: Cowley Beach, the study transect extended inland another 20 m to the bottom left of the photo; Tully Heads, the study transect extended 40 m seaward (left) and 40 m landward (right) of the photo; and Cardwell, the study transect extended seaward 40 m from the sand lobe in the foreground to the sea in the distance.

well-known intense TCs that occurred in this region over the past 100 years. The sedimentary units from these four TCs allow for the first time the documentation of a sedimentary beach ridge record of successive storm-induced extreme marine inundations. The detailed sedimentological, stratigraphic, geochemical, and microfossil analysis presented in this study not only provides insight into storm surge deposits and the nature of beach ridge construction in this region but also presents a case study that utilizes multiproxy analysis for identifying paleostorm deposits and the deciphering of the long-term history of TCs for a region.

2. Setting and Processes

[4] Coastal embayments of north-eastern Queensland are dominated by sand beach ridge plains. In the wet tropics (between Cardwell and Cape Tribulation) (Figure 1), these ridges are composed dominantly of coarse-grained moderately to poorly sorted quartz-rich sands. To the south, the drier tropical coast is also dominated by beach ridge plains, but the grain size of the ridges is generally finer, which appears to reflect, at least in some localities, the nature of the sediments being delivered to the coast by streams and the composition of the beaches.

[5] Tropical cyclones regularly impact the northeast Queensland coast during the summer months from November to April, and the associated storm tide and wave action typically erode sand from the beaches and transports it landward, depositing it often as a sheet across the crest of the first and sometimes second beach ridges (or incipient ridge and first main ridge). *Nott et al*. [2009] suggested that the coarse-grained ridge plains along the wet tropical coast had been deposited by successive TCs over the past 5–6 ka. In much the same manner, coral shingle beach ridges, which often develop on coral atolls and continental islands of the south Pacific and along the Great Barrier Reef, are also a product of TC inundations. In these instances, however, eyewitness accounts state the entire ridge can be deposited during a single TC event [*Nott*, 2003]. The nature of sand sheet deposition by recent TC inundations along the mainland northeast Australian coast

would suggest that unlike coral shingle ridges, each sand beach ridge is a function of multiple TC inundation events with each of these adding a new unit of sand, causing the ridge to progressively increase its height. What has not been known until now is approximately how many sedimentary units or TC events are required to construct a beach ridge and how thick these units might be. The same is true for the sedimentary, geochemical, and microfossil characteristics of these units.

3. Tropical Cyclone Inundations Over the Past Century

[6] Four intense TCs have struck the wet tropics region south of Cairns in northeast Australia over the past century. These were the "Innisfail cyclone" of March 1918, TC Winifred in February 1986, TC Larry in April 2006, and TC Yasi in February 2011. Each of these TCs crossed within an approximately 90 km length of coast between Innisfail and Tully Heads (Figure 1), and each caused a substantial marine inundation. The 1918 "Innisfail cyclone" crossed the coast near Innisfail and had a measured pressure of 926 hPa (this may not have been the minimum pressure). It generated a storm inundation of 4.65 m above the tide at the time (or +5 m Australian Height Datum—AHD) at one location and left debris 7 m high in trees at Mission Beach (between Tully Heads and Cowley Beach; Figure 1). Tropical Cyclone Winifred crossed the coast at Cowley Beach with a central pressure of 958 hPa. The total inundation was approximately 2 m above the tide at the time (+2.5 m AHD). Tropical Cyclone Larry crossed the coast near Innisfail and had a recorded minimum pressure of 955 hPa. It generated an inundation reaching to +4.6 m AHD or 4.4 m above the tide at the time. Tropical Cyclone Yasi crossed the coast at Mission Beach with a measured central pressure of 929 hPa. It generated an inundation above 6 m AHD or 7 m above the event tide at Cardwell. All of these events caused substantial inundations at Cowley Beach and Tully Heads. At Cowley Beach, for example, the latter two TCs caused an inundation of +3.4 m AHD (TC Larry) and +2.8 m AHD (TC Yasi). These latter two TCs also resulted in the landward transport of sand and gravel as a sheet that covered the crest of the first beach ridge. Given the proximity of the landfalling locations of the earlier two TCs (Innisfail TC and TC Winifred), it could have been expected that they too would have deposited sand/gravel sheets across this same first ridge.

4. Methods

[7] Three sites were selected to examine the sedimentary units deposited by TC Yasi and the three preceding TCs over the past century. These were Cowley Beach, Tully Heads, and Cardwell. At each location, pits were dug along a transect extending from the rear of the beach, across the first ridge to approximately 40 to 80 m inland of the spring high tide limit. The pits varied in depth from 30 to 90 cm. Six pits were dug at Cowley Beach, five at Tully Heads, and three at Cardwell. Sediment samples were collected from the vertical pit face at 5 to 10 cm intervals. Care was taken to sample buried soil horizons and the zones immediately above and below these soils. Grain size analysis was performed using a Malvern laser particle sizer (<1 mm diameter) and sieves (>1 mm diameter). Data were combined using methods described in *Dinis and Castilho* [2012]. Surface samples were also examined for diatoms, foraminifera, and geochemistry. At Cowley Beach, additional samples were collected at the debris line and beyond for geochemistry and diatom analysis. Diatom samples were prepared, and taxa were identified and grouped according to their salinity preference as in *Nichol et al*. [2007], while samples for foraminifera analysis were dried and picked using a binocular microscope.

[8] Geochemical analysis of dried sediment samples was carried out with an Olympus INNOVX portable X-ray fluorescence, following methods outlined in *Chagué-Goff et al*. [2012a], while the water-leachable ion content of selected samples was determined as described in *Chagué-Goff et al*. [2012b]. The heights of the sedimentary units were also topographically surveyed using a total station (electronic theodolite and distance measurer) and the results related to Australian Height Datum (AHD).

5. Results

[9] The pit exposures revealed a sequence of coarse- to medium-grained sand units and some gravel, separated by weakly developed soil profiles at Cowley Beach and Tully Heads (Figures 2–4). At Cardwell, the coarse-grained unit deposited by TC Yasi was exposed in the pits overlying a weakly developed soil (Figure 2). Four separate sand units were evident at Cowley Beach, and three separate sand units were exposed at Tully Heads (Figure 2).

5.1. Grain Size Analyses

5.1.1. Cowley Beach

[10] The results of grain size analysis for the samples at Cowley Beach (17.692°S, 146.114°E) can be seen in Figures 2 and 3. Pits 1 and 2 were dug at the rear of the beach, with Pit 2 located 4.5 m further inland or west of Pit 1. Both pits are dominated by medium- to coarse-grained sands with some gravel (2–8 mm) in Pit 1, indicating the base of the unit deposited during TC Yasi. The lower boundary of this unit occurs at 10 cm depth. Below the TC lain deposit lies buried vegetation, which covered the previous (back) beach surface. This unit grades upward into a sand unit by 7 cm depth. There is also a coarse skewing and decrease in sorting at 10 cm depth in Pit 1 (Figure 3). For the remainder of the approximately 10 cm thick unit, there is a shift to a more fine-skewed distribution. In Pit 2, the skewness shows four distinct coarse distributions, three of which occur within the TC Yasi sedimentary unit. The base of the TC Yasi unit occurs immediately above a buried soil at approximately 38 cm depth. The base of this unit is marked by a coarse-skewed distribution to approximately 27 cm depth.

[11] Pits 3 and 4 were excavated into the seaward facing slope of the first beach ridge and inland of Pits 1 and 2. Medium-grained sands varying between 450 and 600 microns dominate Pit 3. The 57 cm thick unit was underlain by a buried soil and was characterized by a coarsening of sediment from 52 cm to 37 cm depth. Coarse-skewed distribution occurred from the base of the unit to 52 cm depth and then further stronger coarse-skewed distribution to 37 cm depth. The coarsest unit of sediment in Pit 3 occurs at 37 cm depth.

[12] Medium to coarse-grained sands dominate the sequence in Pit 4 (Figure 3). Up to 10% gravel also occurs and the most prominent increase in gravel occurs between

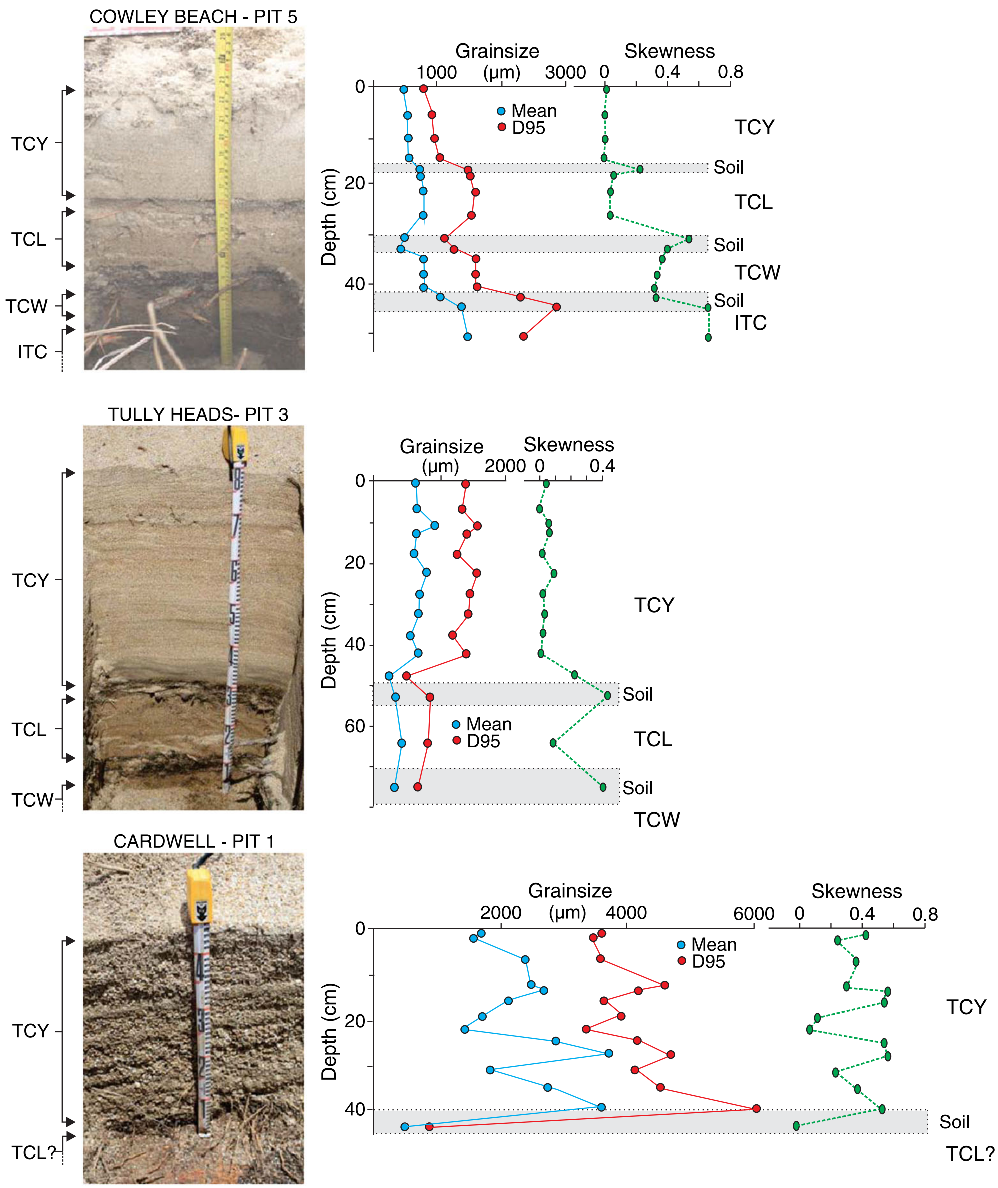

Figure 2. Pit photographs from a single pit at each site, together with grain size (mean and D95) and skewness variations associated with individual TC units and soil layers. TCY = Tropical Cyclone Yasi, TCL = Tropical Cyclone Larry, TCW = Tropical Cyclone Winifred, and ITC = Innisfail Tropical Cyclone.

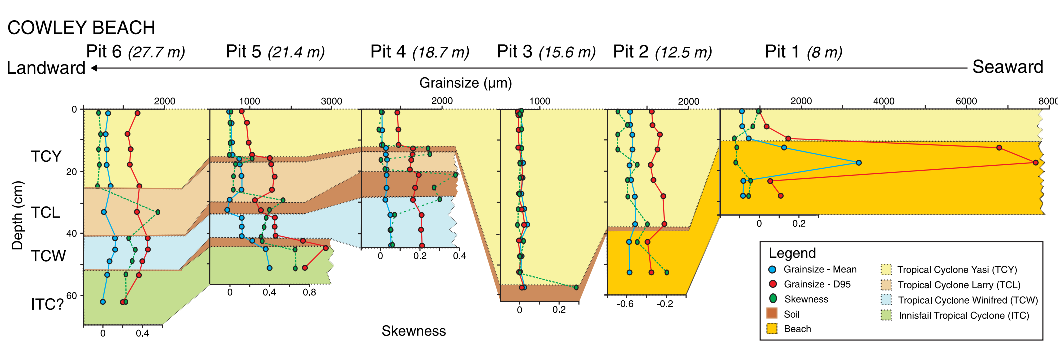

Figure 3. Cowley Beach—landward variations in grain size and skewness as discussed in the text. The figure in brackets after the Pit No. indicates the distance inland from the sea. The horizontal grain size scale is consistent for all pits (note that the skewness scale varies between pits).

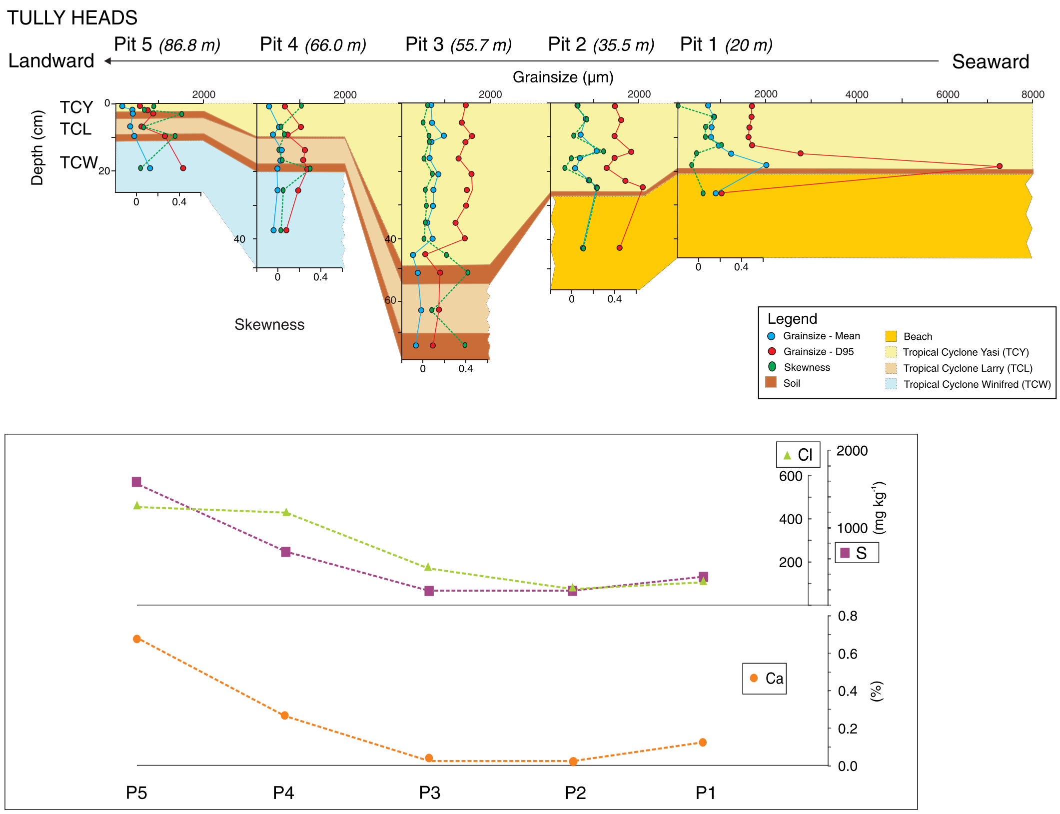

Figure 4. Tully Heads—landward variations in grain size, skewness, and geochemistry as discussed in the text. The figure in brackets after the Pit No. indicates the distance inland from the sea. The horizontal grain size and skewness scales are consistent for all pits. Cl = chlorine, S = sulphur, and Ca = calcium.

approximately 30 and 22 cm depth. This corresponds to a coarse-skewed distribution between 30 and 26 cm depth. Another slight increase in mean grain size grading to gravel occurs between 20 and 13 cm depth and a coarse-skewed distribution occurs between 20 and 17 cm depth. This coarse-skewed distribution marks the base of the unit interpreted to be associated with TC Larry in 2006. The changes in grain size corresponding with the increases in gravel and the coarse-skewed distributions mark the boundary between different sedimentary units. A buried soil occurs at 13–12 cm depth, and this along with another coarse-skewed distribution separates the unit deposited by TC Yasi and the underlying unit most likely deposited by TC Larry. In this instance, there was no substantial increase in grain size associated with this sedimentary unit boundary.

[13] Three weakly developed buried soils are evident in Pits 5 and 6 (Figure 3). These pits were excavated into the crest of the first beach ridge. The buried soils in these pits appear to have developed at the upper level of each of the major sedimentary units. In Pit 5, the three buried soils occur at 44.5, 29.5, and 16.5 cm depth. Three distinct coarse-skewed distributions occur between 44.5 and 42 cm, 29.5 and 25.5 cm, and 16.5 and 14.5 cm depth. The sorting decreases in the lowest of these intervals (44.5 and 42 cm depth) and increases between each of the higher intervals. Mean grain size decreases in the lowest of these intervals, increases between 29.5 and 25.5 cm depth, and then decreases in the highest of these intervals (16.5 to 14.5 cm depth). Medium to coarse-grained sands dominate Pit 6. Here the skewness and the sorting covary. Two prominent coarse-skewed distributions occur between 44.5 and 41.5 cm depth, and 35 and 24.5 cm depth. Both of these coarse-skewed distributions correspond with increases in sorting and an increase in grain size.

5.1.2. Tully Heads

[14] Five pits were excavated into a broad convex upward shaped sand spit rising to 2.5 to 3 m above AHD (18.025°S, 146.055°E). This sand spit separates the Tully River from the Coral Sea. The Tully River drains to the sea at the southern end of this spit. The spit was largely devoid of trees after TC Yasi, and over the following year, 1 to 2 m high saplings had started to cover much of the spit. The pits were dug in a transect from the beach to the landward side of the spit adjacent to the Tully River. The results of grain size analyses are shown in Figure 4.

[15] Coarse-grained sands dominate the sediments recovered in Pits 1 and 2. Pit 1 was located at the seaward end of the transect, toward the rear of the beach or near the high tide limit. Two distinct sedimentary units are exposed in Pits 1 and 2, both separated by a thin, weakly developed soil horizon. In Pit 1, a gravel unit occurs at the base of the uppermost unit between 19 and 17 cm depth. The sediments here show a coarse-skewed distribution and are less well sorted compared to the sediments toward the top of this unit. In Pit 2, a thin (approximately 2 cm thick) gravel unit occurs at 26 cm depth and it is likely that this corresponds with the base of the uppermost sedimentary unit.

[16] Two buried soils separating three sedimentary units are evident in Pits 3 and 4. In Pit 3, the top of the lowermost soil occurs at approximately 69 cm depth and the higher one

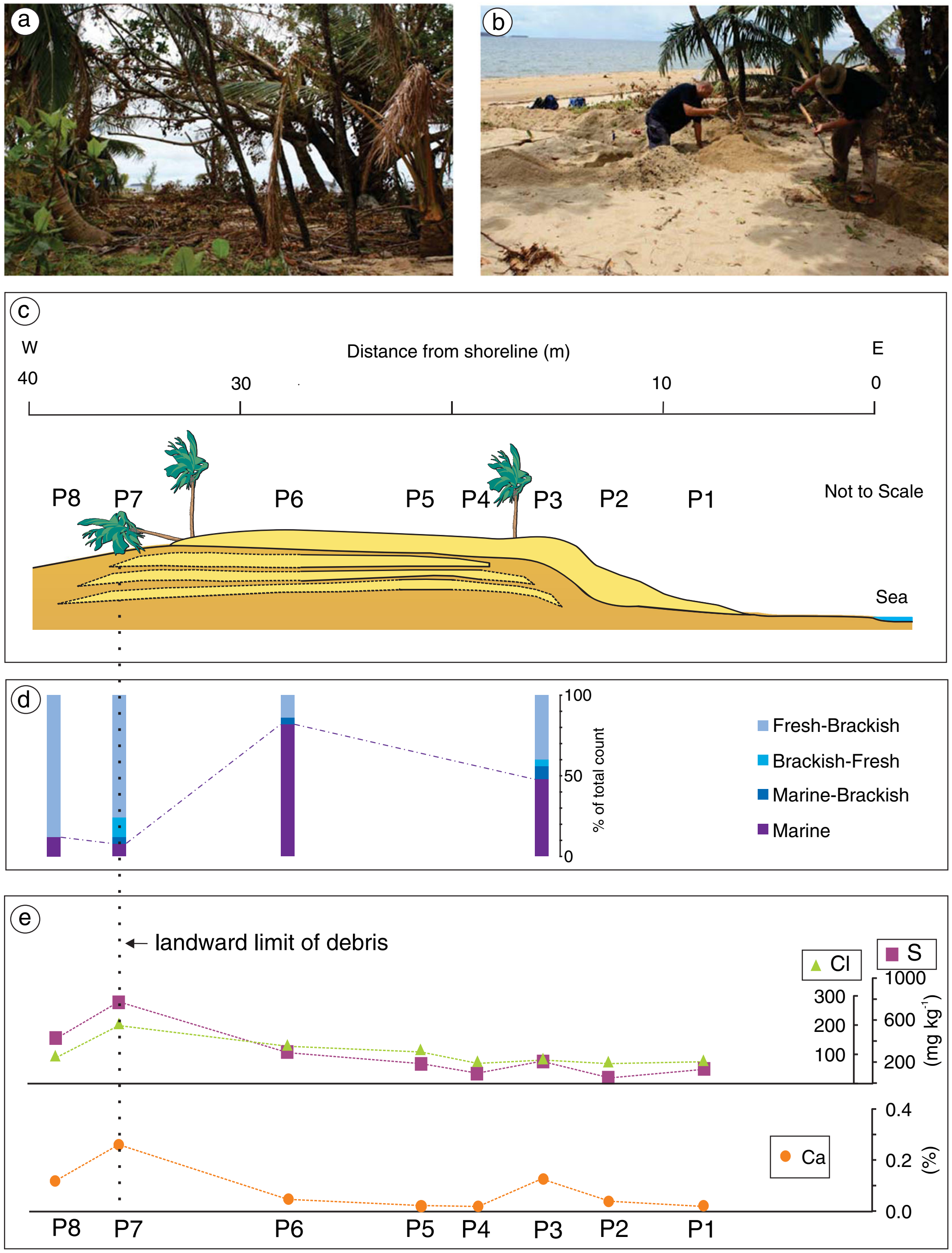

Figure 5. Cowley Beach: (a) Landward and (b) seaward views of study transect; (c) diagram showing internal structure of beach ridge (thickness was recorded where sand layers are outlined by a solid line; dashed lines indicate where sand layer thickness was not measured). Pits are numbered seaward to landward: P1–P8; (d) diatom affinities and percentages measured from surface samples; (e) geochemistry of surface samples (Cl = chlorine, S = sulphur, and Ca = calcium).

at approximately 49 cm depth. There is a substantial coarsening of sediment between 47 and 42 cm depth marking the base of the uppermost unit of sediment. There is also a coarse-skewed distribution at this same level along with an increase in sorting. Grain size increases between approximately 74 and 52 cm depth, and the top of the lowermost soil occurs at approximately 70 cm depth indicating that this is the base of the middle or next lowest unit of sediment. The sediments in Pit 4 display similar characteristics to those in Pit 3. They are coarse-grained and display coarser layers associated with a coarse-skewed distribution directly above the buried soils.

[17] The sediments in Pit 5 display a coarse-grained layer between 7 and 2 cm depth. In general, the sediments are finer

grained in Pit 5 compared to any of the other pits, in particular the top layer (with 44% silt and clay). This is because it is the furthest inland and it is also possible that this finer-grained sediment layer has been deposited by the Tully River during the last TC event when the river was either flooded by terrestrial waters or by marine waters during the storm tide inundation.

5.1.3. Cardwell

[18] Two units (strata) of sediment were evident in the pits dug at Cardwell (18.271°S, 146.033°E). Only the upper section of the lower unit was exposed and this was marked by a buried soil (Figure 2). The results of grain size analyses are only shown for Pit 1 (Figure 2). The unit deposited by TC Yasi dominated each of the pit exposures. This unit was 20 to 93 cm thick and was composed of coarse-grained sands with gravel (up to 3.4 mm) lenses. There were a series of coarse-skewed distributions upward through this unit. The deposit occurred across the crest of the first ridge at an elevation of 3.6 m AHD. The sedimentary unit terminated abruptly toward the base of the landward slope of this beach ridge (Figure 1).

5.2. Microfossils

[19] Diatoms and foraminifera were present, but sparse, in a number of the samples taken from the Cowley Beach pits. Only data where 250 or more diatom frustules are shown, and in all cases between 50 and 85% of those counted were broken (Figure 5). At Cowley Beach, the highest percentage of marine diatoms was recovered from Pits 3 (*Cocconeis scutellum*) and 6 (*Melosira westii*). In contrast, freshwater diatom species dominated Pit 7 (*Eunotia* spp) and Pit 8 (*Melosira octogona*), although marine to marine-brackish species were still present in low numbers at both pits (*Melosira moniliformis*). Foraminifera were also sparse and poorly preserved. They were planispiral coiled in shape and resembled *Elphidium* sp. but they were too damaged to be clearly identified.

5.3. Geochemistry

[20] Low concentrations of total sulphur (S) and chlorine (Cl) were recorded at the surface of the pit sediments (P1 to P6) at Cowley Beach, as well as at the site approximately 3 m beyond the limit of inundation (P8), while higher concentrations were present at the debris line characterized by organic-rich material (P7) (Figure 5). Higher water-leachable ions (chloride and sulphate) were also recorded at the debris line than at any other sites (data not shown). A strong positive relationship between total S and sulphate ($R^2 = 0.91$, $n = 7$) and total Cl and chloride ($R^2 = 0.66$, $n = 7$) indicates that most S and Cl probably occur as marine salts. Calcium (Ca) concentrations were also generally low in the surface samples of the pit sediments and higher at the debris line (P7) and are attributed to the presence of fine shell hash.

[21] At Tully Heads, total S, Cl, and Ca concentrations were also low at the surface of Pits 1 to 3 and increased landward. The landward increase is linked with an increase in silt and clay at the surface of Pits 4 and 5 (from less than 2% in Pits 1 to 3 to 8.8% and 44%, in Pits 4 and 5, respectively), which also results in a decrease in mean grain size (Figure 4).

6. Discussion

[22] There is little doubt that the sedimentary units described here at Cowley Beach, Tully Heads, and Cardwell, as well as the sediments comprising the beach ridge plains backing these locations and elsewhere throughout this region, were deposited by TC inundations. Tsunamis are unlikely to be responsible. No known historical tsunamis of any substantial size (>0.5 m high) have occurred here nor have they been known to deposit sediments in this region or be responsible for ridge construction elsewhere. Only storm-generated waves and inundations are known and have been witnessed to be responsible for deposition of the sedimentary units comprising sand ridges in this region [*Nott*, 2003, 2006, 2010]. Likewise, aeolian contributions appear to be minimal. *Pye* [1982, 1983] identified and described those sections of coast backed by aeolian dunes in this region. These dunes are typically parabolic in form and are not the parallel beach ridges that typically back the majority of this coastal region. These aeolian dunes usually occur where the coast faces directly into the prevailing southeasterly trade winds and where the beaches are composed of fine-grained sand. Elsewhere, along the majority of this coast, the beaches are composed of medium to coarse-grained sand and gravel, and this material is the source of sediment for the beach ridge plains at Cowley Beach, Tully Heads, Cardwell, and elsewhere. The predominant winds in this region are the southeasterly trade winds and they rarely, if ever, obtain velocities sufficient to entrain coarse-grained sand and gravel. And while TCs can generate winds of more than sufficient velocity to entrain coarse-grained sand, at these times the beach is submerged below the associated storm tide and inundation so there is no source of sand for this to occur. There is also heavy rainfall occurring at these times, especially where the wind is onshore, so this in itself would impede the entrainment of sand under these conditions. In short, tsunamis and aeolian activity contribute little, if at all, to the construction of the beach ridges at the sites of investigation in this study and elsewhere throughout this region. Also, there have been a number of pre-TC and post-TC event surveys undertaken in recent years [*Nott*, 2006, 2010] that suggest that TC inundations are the key mechanism for the deposition of beach ridges in this region.

[23] The four sedimentary units separated by poorly developed and thin soil profiles at Cowley Beach were deposited during TCs. Eyewitness reports and observations by the authors confirm TC Yasi deposited the uppermost unit here and TC Larry deposited the next lower one. The lower two units were very likely deposited by TC Winifred and the 1918 Innisfail TC as these are the only two historical events known to have generated a sufficiently high inundation to have deposited these units.

[24] The three sedimentary units separated by poorly developed and thin soils at Tully Heads were also due to the proximal landfall of TC Yasi, TC Larry, and TC Winifred. Again, eyewitness reports support deposition of the upper two units by TCs Yasi and Larry, and TC Winifred was the only other historical event that could have generated a sufficiently high storm inundation to have deposited the lowest unit here. There does not appear to be evidence of any deposition by the 1918 Innisfail TC at Tully Heads; this may be because the sand spit, which now houses the deposits from the three more recent TCs, was not well developed nearly a century ago.

[25] Sediments deposited by TC Yasi dominated the pits exposures at Cardwell. However, there was a buried soil within coarse-grained sediments below the TC Yasi unit.

[26] There appears to be a distinct sediment signature associated with each of the TC sedimentary units. Most of the TC sedimentary units display a pronounced coarse-skewed distribution associated with coarse-grained sediments at the base of each unit—this is apparent at both Cowley Beach and Tully Heads. For example, the texture data from Pit 5 at Cowley Beach (CB-P5) suggest the base of each of the TC sedimentary units is marked by a coarse skew associated with deposition of a unit of coarse-grained sediment. The upward fining sequence of sediments within each of these units coincides with a fine-skewed distribution and each unit has a weakly developed soil in its upper levels. For instance, in CB-P5, a coarse skew occurs at about 41 cm depth then a fine-skewed distribution to about 35–34 cm depth. The fine-skewed distribution occurs within an upward fining component of the TC sedimentary unit. The next unit above this starts with a coarse skew at about 26 cm depth and then fine skew up to about 16 cm depth (again the next upward fining TC unit). The next coarse skew starts at about 15–14 cm depth then a slight fine skew representing the unit deposited during TC Yasi. Pit 5 at Cowley Beach therefore displays three TC sedimentary units—TC Winifred (41 to 34 cm depth), TC Larry (30 to 17 cm depth), and TC Yasi (15 cm upward). The soils separating each of these TC sedimentary units have developed in the upper levels of the upward fining components of each sedimentary unit. The coarser-grained units, marking the initial sedimentary deposits of the next overlying TC sedimentary unit, are here composed of either gravel or sand—whichever is the coarsest fraction in that deposit.

[27] Each phase of deposition associated with the initial inundation at Cowley Beach is marked by a sharp erosional base overlain by a coarser-grained unit composed of either gravel or coarse sand. The fining-up sequence and increase in fine sediments indicate an increase in supply of finer sediment from suspension during the storm surge. The soils separating each of these TC sedimentary units have developed in the upper levels of the upward fining components of each sedimentary unit.

[28] A similar relationship between sediment grain size and skewness is evident in the sediments analyzed from the pits at Tully Heads. The coarser-grained sedimentary unit associated with the onset of deposition associated with TC Yasi in Pit 1 at Tully Heads (TH-P1) starts at 19 cm depth, directly above a soil profile. The sediments start to become finer grained at 16 cm depth at the same level that there is a finer-skewed distribution. From 12.5 cm depth upward, the sediment texture remains fairly constant; however, there are two other coarse skew units, the first at 12.5 cm depth and the second at 4 cm depth. We interpret these coarse-skewed trends to be pulses of slightly coarser-grained sediment during the later stages of the inundation associated with TC Yasi.

[29] In TH-P3, the texture and skewness plots identify the sedimentary units deposited by both TCs Larry and Yasi. The first or lowest coarse skew unit starts with a sharp erosional base over the lowest soil (approximately 64 cm depth), after which the sediments fine upward to about 52 cm depth. The next major coarse-skewed unit starts at 46.5 cm depth directly above a weakly developed soil in the uppermost sediments, associated with the TC Larry deposit. As in TH-P1, there are some finer-skewed trends upward through the TC Yasi deposited unit, despite an absence of substantial changes in mean grain size. Interestingly, sorting covaries with the skewness in TH-P3, while it counters opposite in TH-P1. The same trend occurs in the sediments analyzed from the pits at Cowley Beach. Each of the other pits at Tully Heads also shows covariance between the skewness and sorting, particularly TH-P4 and TH-P5, while TH-P2 shows some covariance but it is not as pronounced as in the other three more westward or inland pits. Pit 1 at Tully Heads (TH-P1) is the most eastward or seaward pit of all of those dug at this location. It is likely that there was more vigorous wave action at this location than further inland (westward), where there was likely substantial wave diminution. Hence, deposition of the coarser units associated with the onset of a new TC sedimentary unit are poorly sorted in this more turbulent higher-energy wave zone. The other pits, particularly TH-P3 to TH-P5, may have been influenced by the calmer conditions associated with proximity to the Tully River, which flows immediately to the west of TH-P5. In other words, the sorting and skewness trends appear to covary when there is some influence of the calmer conditions associated with the river, which would have been flooded by storm tide at the time, but would have had much diminished wave action and a higher fine-grained sediment load compared to the areas closest to the shoreface.

[30] It is interesting to note that the coarse-skewing trends above the base of the TC Yasi deposit occur in all of the pits at Tully Heads and at Cardwell. However, this trend was not observed at Cowley Beach. We suspect this is because Tully Heads and Cardwell experienced greater wave action than Cowley Beach during TC Yasi as Cowley Beach was located north of the eye; hence, the winds here were blowing predominantly offshore. Tully Heads was just inside the southern boundary of the TC Yasi eyewall and Cardwell was well south of the eye-crossing location, so at these two locations, the winds were predominantly onshore, hence there would have been considerably greater wave action compared to Cowley Beach.

[31] The sudden coarsening and associated coarse-skewing trends appear to be a key sedimentary signature in defining the onset of TC sedimentary units within a beach ridge. This is not surprising as studies of the sedimentary characteristics of aeolian dune sands and beach sands have shown that the latter tend to be coarser grained and more coarse skewed than the former [*Chappell*, 1967; *Aboudha*, 2003]. The beach is also the source of sand for beach ridge deposition here during TC inundations, and the beaches fronting the coarse-grained beach ridge plains in this region are typically coarser grained and have coarser skewness values than beaches fronting those less abundant sections of coast backed by aeolian sand dunes [*Pye*, 1982, 1983]. Wave deposition of coastal sands is typically associated with coarser sediment textures and coarser skewness values, and this appears to be generally the case with the onset of the sedimentary units deposited here during tropical cyclone inundations.

[32] This association with texture and coarse skewing, however, was not always evident, and there are some instances, such as Pit 2 Cowley Beach and Pit 2 Tully Heads, where a coarse-skewed distribution within the TC associated deposits occurs but there is a corresponding decrease in grain size. However, in the majority of cases, the coarse-skewed trend was associated with a textural coarsening and this signature may be useful for identifying TC sedimentary units within older beach ridges where the visual stratigraphic markers (buried soils) evident in the most seaward ridge become obscured

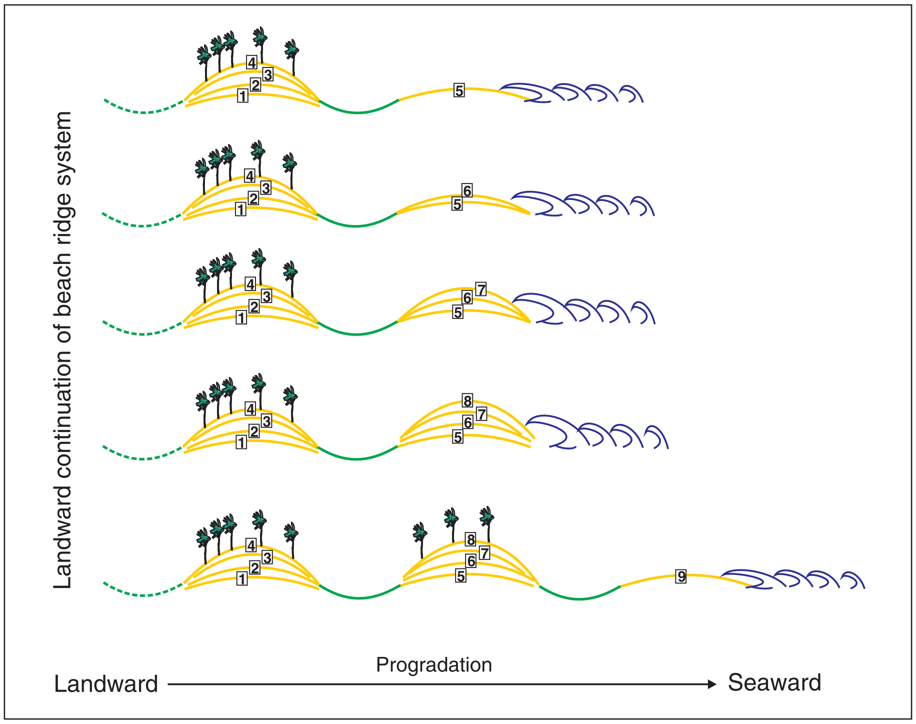

Figure 6. Schematic sequence of accretion of sand beach ridges in northeast Queensland. The number and thickness of individual units will vary between ridges. In this sequence, unit 1 is the oldest and unit 9 the most recently deposited. Lower units can be deposited by low magnitude inundations but increasingly higher inundations (hence higher magnitude storms) are required to deposit uppermost units on a ridge.

by more advanced pedogenesis. The older ridges have well developed podsolised soils, and the demarcation between separate TC sedimentary units by the weakly developed buried soils is removed. Detailed textural analysis of these older more inland ridges using the sedimentary characteristics identified here would allow the number and thickness of units within these older ridges to be identified. In this fashion, the total number of TC inundations and associated sedimentary deposits within a beach ridge plain could be identified and a more detailed history of these events could be unraveled.

[33] The marine geochemical indicators measured within the TC Yasi deposit at Cowley Beach suggest that these chemical signatures can be used to constrain the limit of inundation by the storm tide. At Cowley Beach, these geochemical indicators (Cl, S, and Ca) are associated with organic debris deposited beyond the limit of sand and/or gravel deposit. Their preferential retention in organic-rich material might also provide a means to identify the limit of past cyclone inundation in the sedimentary record.

[34] The fairly high concentrations of Cl, S, and Ca at Tully Heads (surface of TH-P4 and TH-P5) can be partially attributed to the higher amount of fine sediment due to the better retention capacity of this fine and organic-rich material compared to coarser sand [*Chagué-Goff*, 2010; *Chagué-Goff et al.*, 2012a]. However, their occurrence does reflect a marine geochemical influence [*Chagué-Goff*, 2010], most likely associated with flooding by the storm tide at the time of TC Yasi.

[35] The diatom record at Cowley Beach shows that marine and/or marine-brackish species were present throughout the deposit and beyond the landward limit of the debris. The species diversity and spatial extent of the diatom assemblage may well prove useful in conjunction with geochemical data to help chart the limit of cyclone deposition, but poor preservation may negate their usefulness.

[36] Despite the possibility that the number of individual TC sedimentary units and events could be identified using the key sedimentary, geochemical, and microfossil characteristics identified here, it is unlikely that the magnitude of all of these events could be determined using this methodology. The stratigraphic position of a TC sedimentary unit does not give an indication of the magnitude of the inundation unless that unit is close to, or at the crest of, the ridge (Figure 6). It is possible for low stratigraphic units, being only 1 or 2 m above mean sea level, to have been deposited by either an extreme magnitude inundation or one associated with noncyclonic conditions (strong trade winds and spring high tides). The intensity of a storm responsible for an inundation of a certain magnitude (height) can be calculated when deposition of the sedimentary units occurs at an elevation above that able to be reached by inundations generated during nonstorm conditions. *Nott et al.* [2009] detailed the methodology for determining the central pressures of TCs responsible for depositing the sedimentary units near the crests of the ridges. High intensity TCs, generally category 4 and 5 events on the Saffir-Simpson scale, are required to deposit sediments on ridge crests that stand higher than 4 to 5 m AHD in this region [*Nott et al.*, 2009; *Forsyth et al.*, 2010]. These are minimum estimates as the inundation may be higher than the height of the ridge, hence these determinations are usually only made for the upper units comprising a beach ridge.

[37] The thickness of a sedimentary unit also does not appear to relate to the intensity of the TC or the height of the

inundation. The thickness of the sedimentary unit deposited by TC Yasi varied from over a meter to less than 20 cm between locations. The same was true of the sedimentary unit deposited by TC Larry in 2006. It is likely that many other factors such as the volume of available sediment, the geomorphic setting, and wave height and period play a substantial role in determining the thickness of the sedimentary unit deposited during a TC inundation. Further research is needed to determine whether chemical indicators and microfossils can be used to assess the height of the inundation, since they appear to be preserved near the inundation limit. However, so far, little is known about the preservation potential of chemical signatures and microfossils (such as diatoms) following cyclones.

7. Conclusions

[38] Like coral shingle beach ridges and those constructed from marine shells, sand beach ridges can also be the product of TC generated marine inundations. However, sand beach ridges appear to be composed of multiple depositional units resulting from a number of separate storm inundation events rather than deposition of an entire ridge during a single storm. In the Cairns region of northeast Queensland, four sedimentary units in one beach ridge have resulted from the four most intense TCs and associated marine inundations to have occurred here over the past nearly 100 years.

[39] A key sedimentary signature, being a sudden textural coarsening and coarse-skewed distribution, has been used to identify the onset of deposition of individual TC sedimentary units. Coarse-skewed trends with minimal change in mean grain size also appear to characterize the upper levels of these deposits when the sedimentary unit is deposited at a location within the zone of maximum onshore winds. These same coarse-skewed trends are not apparent in sediments deposited at locations that experience predominantly offshore winds during the TC event, which in the case of eastern Australia is north of the eye-crossing location. Hence, it may be possible to identify the relative coastal crossing location of past TCs using this diagnostic sedimentary signature.

[40] This coarse-skewed sedimentary trend, along with the initial textural coarsening of each event unit, may be useful for identifying TC sedimentary units in older beach ridges where advanced pedogenesis has obscured visual stratigraphic markers which are evident in more recent storm-built beach ridges. Results from this research have also shown that geochemical signatures and microfossil data (diatoms and foraminifera) can potentially be used to identify paleo-cyclone deposits as well as the limit of inundation of older cyclones and thus help distinguish them from other deposits associated with fair-weather conditions.

[41] The identification of the nature and characteristics of TC sedimentary units within beach ridges suggests that these features may now be used more extensively as late Holocene records of TCs. Beach ridges occur along the coasts of many regions globally affected by TCs such as the Gulf of Mexico, India, Japan, and Madagascar. Increasing the number of these records globally can help to reduce risk associated with this natural hazard as well as providing a better understanding of the causes of long-term global TC variability.

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References

Aboudha, J. O. Z. (2003), Grain size distribution and composition of modern dune and beach sediments, Malindi Bay Coast, Kenya, *J. Afr. Earth Sci.*, *36*, 41–54.

Bird, E. C. F. (1960), The formation of sand beach ridges, *Aust. J. Sci.*, *22*, 349–350.

Blumenstock, D. (1958), Typhoon effects on Jaluit Atoll in the Marshall Islands, *Nature*, *182*, 1267–1269.

Chagué-Goff, C. (2010), Chemical signatures of palaeotsunamis: A forgotten proxy?, *Mar. Geol.*, *271*, 67–71.

Chagué-Goff, C., A. Andrew, W. Szczuciński, J. Goff, and Y. Nishimura (2012a), Geochemical signatures up to the maximum inundation of the 2011 Tohoku-oki tsunami – Implications for the 869AD Jogan and other palaeotsunamis, *Sediment. Geol.*, *282*, 65–77.

Chagué-Goff, C., P. Niedzielski, H. K. Y. Wong, W. Szczuciński, D. Sugawara, and J. Goff (2012b), Environmental impact assessment of the 2011 Tohoku-oki tsunami on the Sendai Plain, *Sediment. Geol.*, *282*, 175–187.

Chappell, J. (1967), Recognizing fossil strand lines from grain-size analysis, *J. Sediment. Res.*, *37*, 157–165.

Curray, J. R. (1996), Origin of beach ridges: Comment on Tanner, W.F, 1995, Origin of beach ridges and swales, *Mar. Geol.*, *136*, 121–125.

Curray, J. R., F. J. Emmel, and P. J. S. Crampton (1969), Holocene history of a strand plain, lagoonal coast, Nayarit, Mexico, in *Lagunas Costeras, Un Simposio (Coastal Lagoons, A Symposium). Memoir of the Intl. Symposium on Coastal Lagoons, UNAM-UNESCO, Mexico, Nov. 28-30, 1967*, edited by A. A. Castanares and F. B. Phleger, pp. 63–100.

Davies, J. L. (1968), Beach ridges, in *Encyclopaedia of Geomorphology*, edited by R. Fairbridge, Van Nostrand Reinhold, New York, pp. 156–157.

Dinis, P., and A. Castilho (2012), Integrating sieving and laser data to obtain bulk grain-size distributions, *J. Sediment. Res.*, *82*, 747–754.

Forsyth, A. J., J. Nott, and M. D. Bateman (2010), Beach ridge plain evidence of a variable late-Holocene tropical cyclone climate, North Queensland, Australia, *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, *297*(3–4), 707–716.

Hesp, P. A. (2006), Beach ridges – Definition and re-definition, *J. Coastal Res.*, Special Issue, *39*, 72–75.

Johnson, D. W. (1919), *Shore Processes and Shoreline Development*, pp. 584, Wiley, N. Y.

Maragos, J., G. Baines, and P. Beveridge (1973), Tropical cyclone Bebe creates a new land formation on Funafuti Atoll, *Science*, *181*, 1161–1164.

Mason, O. K. (1992), A geoarchaeological methodology for studying prograding coastal sequences: Beach-ridge geomorphology in Kotzebue Sound, Alaska, in *Paleoshorelines and Prehistory: An Investigation of Method*, edited by L. L. Johnson, pp. 55–81, CRC Press Inc., Florida.

McKenzie, P. (1958), The development of sand beach ridges, *Aust. J. Sci.*, *20*, 213–214.

Nichol, S., J. Goff, R. Devoy, C. Chagué-Goff, B. Hayward, and I. James (2007), Lagoon subsidence and tsunami on the West Coast of New Zealand, *Sediment. Geol.*, *200*, 248–262.

Nott, J. (2003), Intensity of prehistoric tropical cyclones, *J. Geophys. Res.*, *108*(D7), 4212, doi:10.1029/2002JD002726.

Nott, J. (2006), Tropical cyclones and the evolution of the sedimentary coast of Northern Australia, *J. Coastal Res.*, *22*, 49–62.

Nott, J. (2010), A theory (involving tropical cyclones) on the formation of coarse-grained sand beach ridges in NE Australia, *Spec Publ. Geol. Soc. Lond*, *346*, 7–22.

Nott, J., S. Smithers, K. Walsh, and E. Rhodes (2009), Sand beach ridges record 6000 year history of extreme tropical cyclone activity in northeastern Australia, *Quat. Sci. Rev.*, *28*(15–16), 1511–1520.

Psuty, N. P. (1965), Beach-ridge development in Tabasco, Mexico, *Ann. Assoc. Am. Geogr.*, *55*, 112–124.

Pye, K. (1982), Negatively skewed aeolian sands from a humid tropical coastal Dunefield, Northern Australia, *Sediment. Geol.*, *31*, 249–266.

Pye, K. (1983), Dune formation on the humid tropical sector of the North Queensland coast, Australia, *Earth Surf. Processes Landforms*, *8*, 371–381.

Tanner, W. F. (1995), Origin of beach ridges and swales, *Mar. Geol.*, *129*, 149–162.

Tanner, W. F. (1996), Origin of beach ridges – Reply, *Mar. Geol.*, *136*, 127–130.

Tanner, W. F., and F. W. Stapor (1971), Tabasco beach-ridge plain: An eroding coast, *Trans. Gulf Coast Assoc. Geol. Soc.*, *21*, 231–232.

Taylor, M. J., and G. W. Stone (1996), Beach ridges: A review, *J. Coastal Res.*, *12*(3), 612–621.