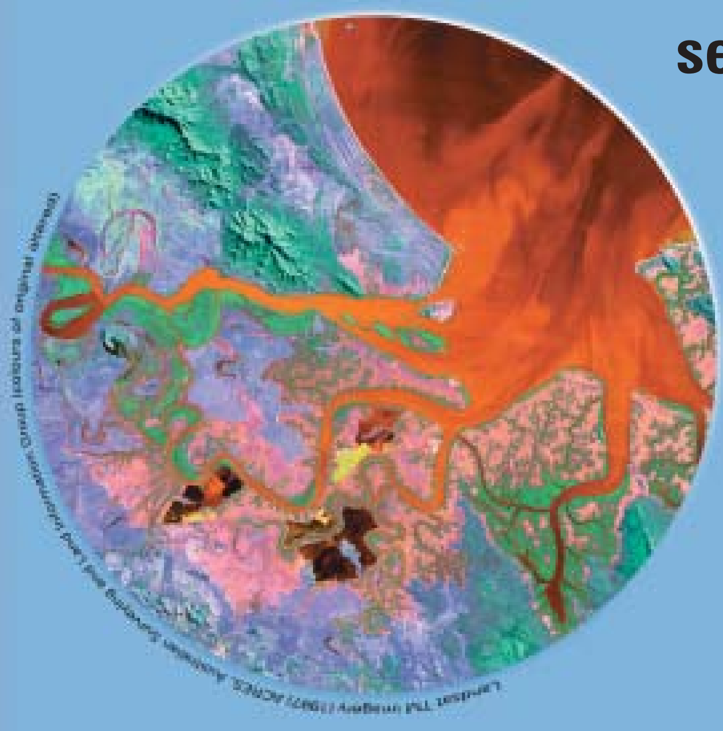
Cooperative Research Centre for Coastal Zone, Estuary & Waterway Management

Technical Report 51

A 1500 year record of coastal sediment accumulation preserved in beach deposits at Keppel Bay, Queensland, Australia



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CRC for Coastal Zone Estuary & Waterway Management

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2006

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Table of contents

List of figures

List of tables

Non-technical summary

The coastal plain formed by a series of relict beach ridges on the margin of Keppel Bay, central Queensland, Australia, preserves a detailed record of coastal sediment accumulation. Importantly, this record spans the historical period and extends back to early Holocene times, well before European settlement. The relict and modern beach ridges comprise fine sand that was originally deposited in Keppel Bay during flood discharge events of the Fitzroy River. This sediment was then reworked onto the shoreline by the prevailing tide, wave and wind-generated currents. Optically stimulated luminescence (OSL) ages of the ridges reveal a long-term positive coastal sediment budget in Keppel Bay and show that during approximately the last 1500 years, sets of beach ridges were emplaced in rapid episodes, up to a few decades long. The OSL ages of the ridges suggests there is a 500–200 yr periodicity to these phases of rapid sediment accumulation. Our preliminary interpretation of these data is that this pattern of formation relates to the recurrence interval of high magnitude flood discharge events of the Fitzroy River and there has been a general decline in the rate at which sediment has accumulated on the Keppel Bay coast during the last 1500 years. This reduction may reflect a long-term decline in major rainfall events in the Fitzroy River catchment. The trace element composition of ridges deposited during the last 100 yrs indicates there has been a greater contribution from areas of basaltic soils within the catchment. This trace-element record reveals the impact on river and coastal sediment composition brought on by changes in catchment land use.

Introduction

A key environmental issue in the coastal zone is the impact of enhanced loads of catchment-derived river sediment. Suspended sediment has been a major focus due to the deleterious effects on marine ecosystems of increased turbidity and contaminants that are often associated with fine sediment (Turner and Millward, 2002). Coarse sediment loads are also of concern due to the problems associated with coastal siltation, altered hydrodynamics and longshore sediment transport budgets but are difficult to measure and monitor, especially in semi-arid tropical rivers systems (Amos *et al.*, 2004). In this study we examine a succession of coastal beach-ridge deposits that comprise sandy sediment deposited by an adjacent river to provide insights into the rate and character of sediment delivery to the coast during both historical and pre-European times.

Beach ridges are regularly spaced, low amplitude (a few m thick) linear features that usually form on accreting coasts where landward directed waves and winds emplace sediment, ranging from sand to gravel, in foreshore and backshore settings (Otvis, 2000). They can develop during storms, in quiescent periods or with both modes of deposition depending on local conditions (Sanderson *et al.*, 1998; Otvis, 2000; Orford *et al.*, 2003). Because beach ridges mark the former position and composition of the shoreline, successions of these deposits can provide useful records of the character and rate of shoreline sediment accumulation, extension and past configuration, and relative sea level where diagnostic facies are preserved (Otvis, 2000; Orford *et al.*, 2003).

Numerous chronostratigraphic studies of beach ridge successions have been able to reconstruct shoreline depositional regimes that operated during the Late Quaternary (e.g. Mason and Jordan, 1993; Bruckner and Schellmann, 2003; Goy *et al.*, 2003). Few studies, however, have been able to gain reliable age control for ridge successions that extend from the present day back through the historical past and into the Holocene (e.g. Murray-Wallace *et al.*, 2002; Ballarini *et al.*, 2003).

In this study of the beach-ridge plain at Keppel Bay, on the central coast of Queensland, we examine ridge morphology, sediment texture and geochemistry. We build a detailed chronology for the ridge succession using the optically stimulated luminescence (OSL) dating method. Although our interpretations are preliminary, our results suggest that significant changes have occurred in the rate of shoreline accumulation of sediment, catchment sediment source areas, and that there have been minor falls in relative sea level.

Regional setting

Keppel Bay is a shallow embayment situated on the central coast of Queensland, within the southern section of the Great Barrier Reef Marine Park (Figure 1). The Capricorn Group of reefs and islands lie approximately 90 km offshore, protecting the bay from most swell. The prevailing winds are from the east-southeast from which the southern end of the bay is partially protected by Curtis Island. The Fitzroy River, which drains a very large catchment (~150 000 km^2), discharges into the southern end of the bay where it forms a funnel-shaped, tide-dominated estuary. The vigorous tidal currents are generated by the region's 5 m tides. Catchment-derived sediment is exported to Keppel Bay only during the highly seasonal summer flood events (discussed below).

Coastal sediment system

Deposits of very fine to fine quartzose sand in Keppel Bay are predominantly derived from the Fitzroy River (Beach Protection Authority, 1979; Radke *et al.*, 2005). The sediment is eroded from soils in the Fitzroy River catchment and comprises approximately 85% quartz, 10–20% feldspar minerals and around 5% biogenic carbonate, with up to 10% mud in the lower energy settings of the bay (Hekel, 1977). Marine quartz sand is also a significant sediment type in the middle and deeper offshore sections of Keppel Bay. This relict sand is coarser than the modern Fitzroy River sand, typically darkly stained fine to medium grained well-sorted quartz sand, with much less than 10% feldspar minerals and very little or no mud fraction (Hekel, 1977).

The distribution of Fitzroy River sediment in the bay and aerial photographs and satellite images of flood plumes suggest that during large floods sediment-laden density currents appear to form in the deeper channels of the estuary and then extend out into Keppel Bay. These flood-induced currents likely move sand up to several kilometres offshore (e.g. to Central Bank), north of the estuary mouth and to the east of Curtis Island, depending on the prevailing marine and atmospheric conditions (Beach Protection Authority, 1979). Suspended sediment is transported much further during floods events, up to several tens of kilometres north, east or south (around Curtis Is.) of the estuary mouth (Figure 1; Devlin and Brodie, 2005; McCulloch *et al.*, 2003).

Reworking of the fluvial sand occurs shortly after its deposition in Keppel Bay. Waves generated by the prevailing wind re-suspended fine sand that is then transported northwards and onshore by tidal currents. Also, the ebb flow out from the mouth of the Fitzroy River travels northwards at up to 0.15 m s^{-1} (Beach Protection Authority, 1979) further adding to the northwards transport of sediment.

In contrast to the depositional regime that operates under the predominant atmospheric and marine conditions, cyclones produce short periods of shoreline erosion in Keppel Bay. For example, all beaches of the Capricorn Coast receded by at least 4 m during cyclone David in 1976 (return period 12 yrs). The eroded sand is moved into the near-shore zone and subsequently, within a few weeks to months, transported back onshore under the normal wind, wave and tidal conditions (Beach Protection Authority, 1979).

Beach-ridge deposits

Immediately north of the mouth of the Fitzroy River there are three morphologically distinct sets of beach ridges. The outer oldest set (Series 1, Figure 1) includes a shell-rich deposit that has an uncorrected and uncalibrated radiocarbon age of 4420 ±165 yr BP (Beach Protection Authority, 1979). The second set of ridges, Series 2, extend from the southern margin of Series 1 south to the mouth of the Fitzroy River and occupy the outer strandplain between Red Hill and Joskeleigh (Figures 1, 2). These ridges rise up to approximately 3 m above the plain and exhibit a varied orientation. The third series of ridges (Series 3) are the focus of this study. These linear, shore parallel ridges extend to the north and east of Series 2, occupy an area of 36.83 km^2 and form a strandplain approximately 2–3 km wide and up to 17 km long (Figures 1, 2). The ridges comprise fine sand very similar to the modern beach sediment.

The boundaries of the Series 3 ridges (accretion units 3–6 between Cattle Point and Keppel Sands) are defined by swales that represent lower intertidal deposits and the end of a phase of ridge formation (Beach Protection Authority, 1979; Figure 1). Most of these morphological features are still clearly discernible in the landscape (Figure 2), however, the ridges have been modified to varying degrees since clearance of the land for pasture. At Cattle Point, around the mouth of the estuary, and along a 3 km section north of Cattle Point Series 3 ridges sit normal to the shoreline where they have been eroded (Figure 2c). Towards their northern extent at Joskeleigh, most of the relict ridges transform into a series of recurved spits composed of intertidal deposits (Figure 2a). This study examines the morphology, composition and age of the Series 3 ridges.

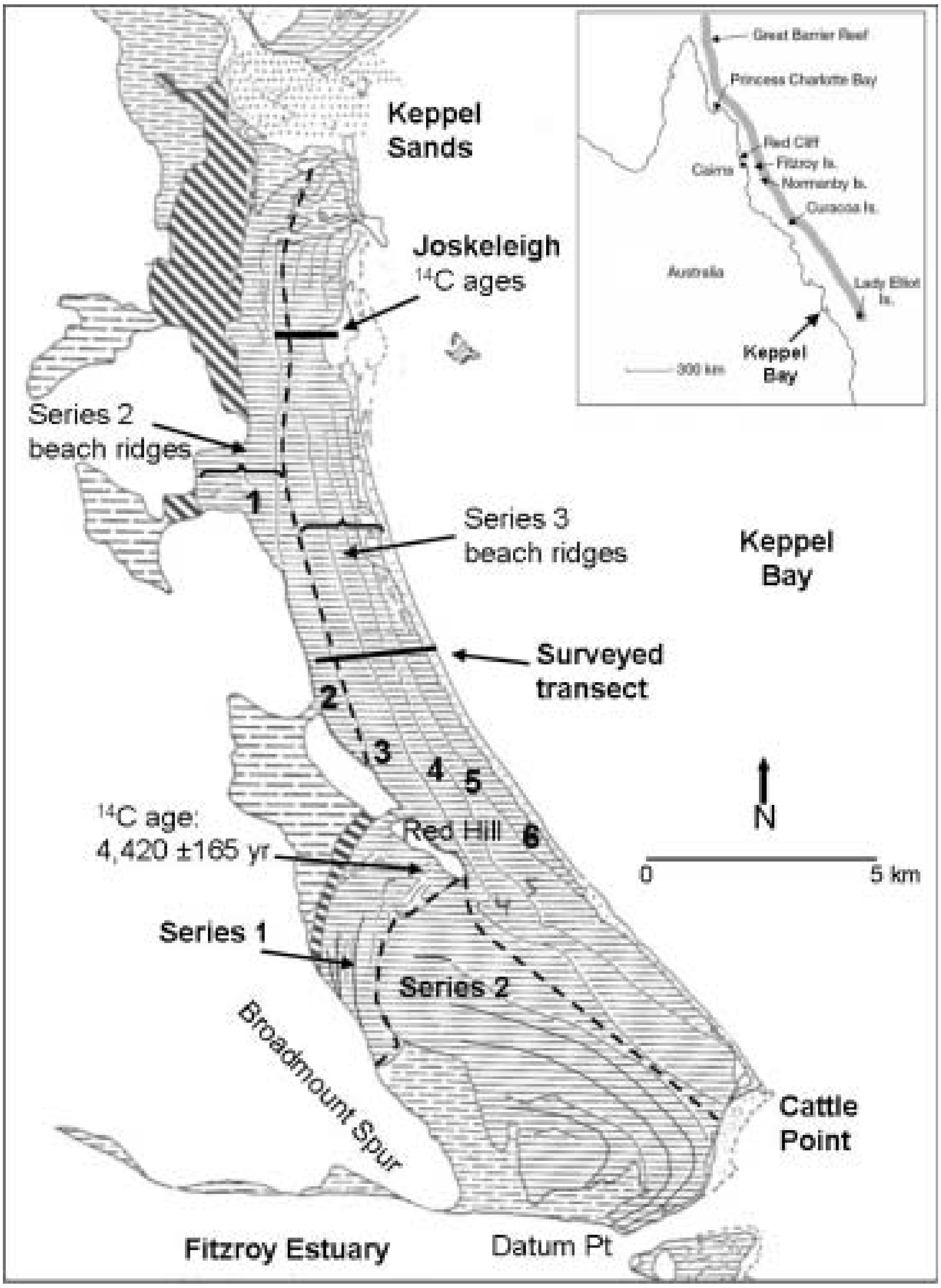


Figure 1: Location of Keppel Bay.
The bay sits near the southern end of the Great Barrier Reef lagoon (insert). Beach ridge deposits (hatching) make up the strandplain at Keppel Bay (bedrock is white). The major unconformities or boundaries between each series of beach ridges are shown as dashed lines, while the sets of beach ridges (accretion units) within each series are indicated by unbroken lines (after Beach Protection Authority, 1979). The insert shows the locations of dated coarse boulder deposits that have been used to derive a Holocene record of high-magnitude cyclone frequency for the GBR coast.

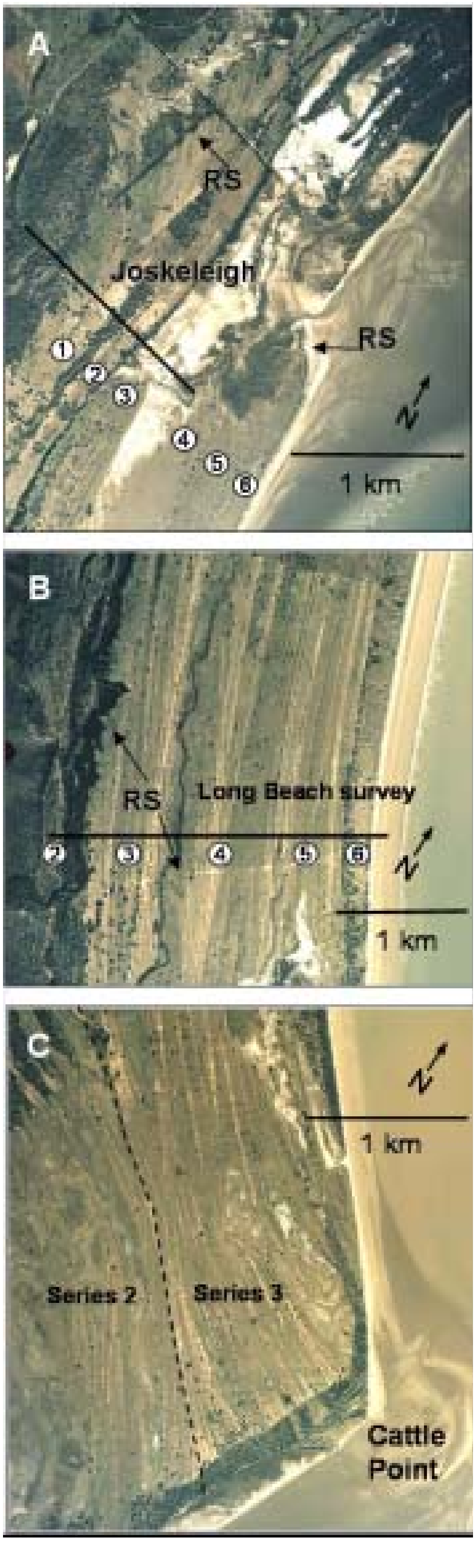


Figure 2: Aerial photographs of the Series 2 and 3 beach ridges.

A: The tidal inlet at Joskeleigh. Accretion units 1–6 and the surveyed transect are marked. The unconformity between Series 2 (units 1 and 2) and Series 3 (3–6) is clearly visible; B: The Long Beach transect, units 2–6; C: Series 2 and 3 ridges at Cattle Point. Recurved spits (RS) are evident in units 1 and 6 at Joskeleigh (A) and in units 3 and 4 at Long Beach (B).

Materials and methods

Field survey

As part of an earlier study of the Keppel Bay coast, relict shell-rich intertidal deposits at Joskeleigh were mapped and samples collected for ^{14}C dating (Figure 3). These previously unpublished data are included in this study to compare with the OSL ages of the more continuous succession of Series 3 ridges further south at Long Beach (Figure 2b), the focus of this study. Here, accretion units 2–6 were surveyed and sediment samples collected along a shore-normal transect between Long Beach and Red Hill (Figure 1, Figure 2b). This location was selected as the best accessible site where the shore-parallel alignment of the ridges indicates a relatively consistent record of deposition. The surveying was conducted using a staff and optical (dumpy) level. All elevations were reduced to the well-defined high water strandline on Long Beach and then related to MHWS based on the nearby Port Alma tide data for that day. A GPS was used to record the location of the survey points and sediment sample sites.

On the ridges selected for sampling, pits were dug to a depth of approximately 0.5–1.2 m to ensure the upper dry sand did not collapse the hole. Sediment samples were collected from the base of the auger hole and subsequently analysed for grain size, mineralogy and major and trace element geochemistry. Samples were also collected for OSL dating using specially designed stainless steel sample tubes that attach to the end of the auger rods. Prior to the collection of the samples for dating, the pits were covered with a light-proof black plastic sheet. The samples were then collected by hammering the sample tube into the bottom of the auger hole, well below any recent disturbance of the ridge surface. The sample tubes were extracted, capped and sealed before being exposed to light.

Sediment budget

The following methods were used to estimate the rate of shoreline sediment mass accumulation for the Series 3 ridges: 1. Accretion unit areas were measured from Landsat scenes of the beach-ridge plain (6a and 6b were identified on the survey transect but could not be accurately delineated in the images); 2. Unit volumes were derived from the mapped areas and an approximate average unit thickness. Due to the lack of deep drill hole data for the ridge deposits, thicknesses were derived from acoustic sub-bottom profiles of the subtidal Holocene deposit immediately offshore from Long Beach (Bostock *et al.*, 2006; Searle, 1974). The surveyed ridge profiles enabled an average subaerial thickness to be calculated, which was combined with the sub-bottom profile data to estimate an average total thickness; 3. The estimated dry bulk density of sand used in calculations was 1201 kg m^3. 4. The OSL chronology reported below was used to calculate the mass of sand that accumulated per year in units 3–6.

Sediment composition

Grain size was measured using a Malvern Laser Analyser. Sediment carbonate was determined by the CO_2 evolution or 'bomb' method (Muller and Gastner, 1971), with the mass of carbonate determined by a calibration curve of CO_2 gas pressure as a function of carbonate content. The accuracy of the method is ± 0.5%.

X-ray diffraction

Approximately 5 g of sample was ground with ethanol to a fine consistency in a mortar with a pestle. Each dried sample was randomly packed into a 50 x 50 mm sample holder and inserted into an automatic sample changer. The samples were scanned from 2° to 70° 2θ, at a speed of 2° per minute and a step size of 0.02°, using a Siemens™ D500/D501 series X-ray diffractometer. Mineral identification software (EVATM) was used to identify the d-spacings of a series of peaks corresponding to individual minerals. The software package Siroquant™ was used to quantify the mineral components based on the mineral peaks.

Major element oxides and trace elements

Major element concentrations were determined by x-ray fluorescence (XRF) at Geoscience Australia using a modified version of Norris and Hutton's (1969) method, whereby no heavy absorber was added to the flux. The instrumentation used was a Philips PW2404 4kW sequential spectrometer. The instrument was calibrated using a range of USGS and SARM (S. African Ref. Material) international standards.

Other trace elements

Other trace elements were determined by ICP-MS at Geoscience Australia using a Perkin Elmer Elan 6000. The instrument is calibrated against Australian Soil and Plant Analysis Council (ASPAC) standards, as well as a range of USGS and SARM soil standards.

Geochronology

Radiocarbon dating

The previously dated material comprised a number of individual shells or shell fragments that were selected from bulk samples of sediment collected from intertidal units within the Series 2 and Series 3 relict ridge deposits at Joskeleigh (Figure 3).

OSL dating

OSL dating was carried out at the CSIRO OSL Laboratory, Canberra, and the analytical methods employed are summarised below. Sample preparation was designed to isolate pure extracts of 180–212 μm light safe quartz grains following standard procedures (e.g. Aitken, 1998). Treatments were applied to remove contaminant carbonates, feldspars, organics, heavy minerals and acid soluble fluorides. The outer ~10 μm alpha-irradiated rind of each grain was removed by double etching each sample in 48% Hydrofluoric Acid.

OSL analytical methods

Burial doses were determined from measurement of the OSL signals emitted by single grains of quartz. The etched quartz grains were loaded on to custom-made aluminium discs drilled with a 10 x 10 array of chambers, each of 300 μm depth and 300 μm diameter (Botter-Jensen *et al.*, 2000). The OSL measurements were made on a Risø TL/OSL DA-15 reader using a green (532 nm) laser for optical stimulation, and the ultraviolet emissions were detected by an Electron Tubes Ltd. 9235QA photomultiplier tube fitted with 7.5 mm of Hoya U-340 filter. Laboratory irradiations were conducted using a calibrated 90Sr/90Y beta source mounted on the reader.

Equivalent doses (De) were determined using a modified SAR protocol (Olley *et al.*, 2004b). A dose-response curve was constructed for each grain. The OSL signals were measured for 1 s at 125°C (laser at 90% power), using a preheat of 240°C (held for 10 s) for the ‘natural’ and regenerative doses, and a pre-heat of 160°C (held for 10 s) for the test doses (0.5 Gy). The OSL signal was determined from the initial 0.1 s of data, using the final 0.2 s to estimate the background count rate. Each disc was exposed to infrared (IR) radiation for 40 s at 125°C prior to measurement of the OSL signal to bleach any IR-sensitive signal.

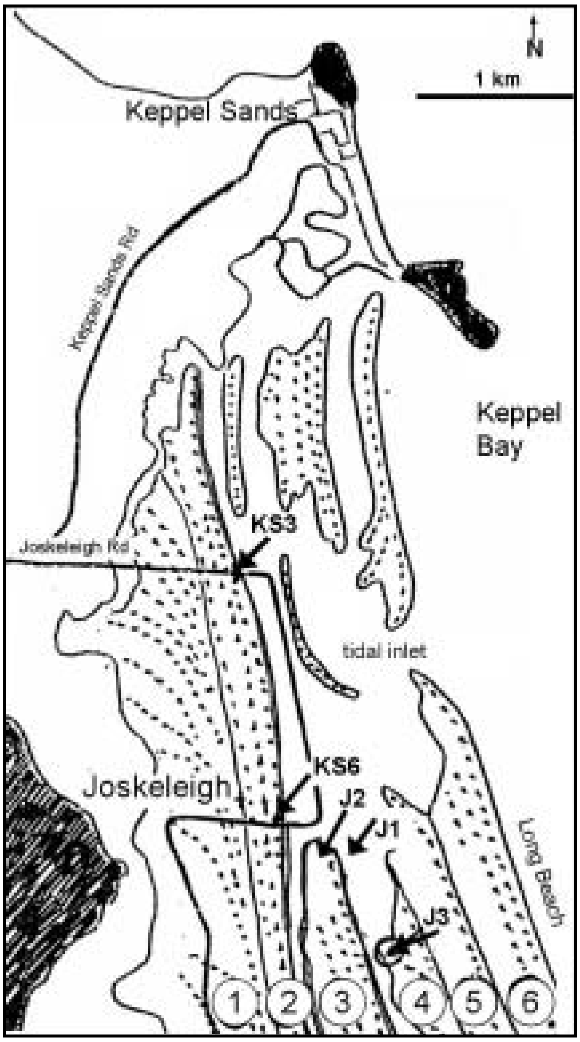


Figure 3: The tidal inlet at Joskeleigh showing the locations of the ^{14}C samples.

The northern margins of the accretion units (1–6) translate from shore-parallel ridges into recurved spits, to varying degrees, as indicated by the dashed lines that mark the crests of the individual ridges and spits. Areas of dark shading are bedrock hills.

Grains were rejected if they did not produce a measurable OSL signal in response to the 2 μGy test dose, had OSL decay curves that did not reach background after 1 s of laser stimulation, or produced natural OSL signals that did not intercept the regenerated dose-response curves ('Class 3' grains of Yoshida *et al.*, 2000). The 'central age model' of Galbraith *et al.*, (1999), has been used to identify samples having De distributions consistent with a single population, and to calculate a burial dose (the dose which all grains have received since burial - Db) based on the central tendency of the data. A distribution representative of a single population is one where the spread in the data can be wholly accounted for by measurement uncertainties on the individual data points. These uncertainties have been calculated using Analyst 3.1b, and include counting statistics, curve fitting errors and a 3.5% uncertainty to accommodate the reproducibility with which the laser can be positioned.

Using the central age model, the spread in a De distribution is assessed using the over-dispersion parameter, 'σ_d'. This parameter is calculated as the relative standard deviation of the single-grain De distribution after taking into account the measurement uncertainty for each grain (Galbraith *et al.*, 1999). If measurement uncertainty were the only source of spread in a distribution then σ_d would be 0%. Olley *et al.* (2004a) suggest a σ_d value < ~22% to be indicative of uniform bleaching prior to deposition, and for such samples they recommend use of the central age model to calculate a burial dose.

Lithogenic radionuclide activity concentrations in the OSL samples were determined using high-resolution gamma spectrometry (Murray *et al.*, 1987), with dose rates calculated using the conversion factors of Stokes *et al.* (2003). The β-attenuation factors were taken from Mejdahl (1979). Cosmic dose rates were calculated from Prescott and Hutton (1994).

Results

Ridge morphology and stratigraphy

At Joskeleigh, the low-amplitude recurved ridge morphology and exposed beds of coarse shelly sand indicated that much of the older Series 2 ridges (accretion units 1 and 2) and the terminations of Series 3 ridges (units 3–6) were emplaced in beach foreshore and tidal inlet settings, similar to the adjacent modern deposits (Figure 2a, Figure 3). The major unconformity between the Series 2 and Series 3 ridges and lower elevation of the Series 3 ridges is clearly evident at this site (Figure 4a, b). Coarse intertidal shelly sand beds within Series 2 and 3 ridges sit above adjacent modern intertidal and supratidal deposits (Figure 4a, b). These raised relict deposits may indicate that there was a fall in relative sea level of approximately 1 m after the Series 2 ridges were deposited, and by approximately 0.5 m following deposition of the Series 3 ridges. More detailed facies mapping and surveying of the intertidal deposits are required to test these initial field observations, however.

Accretion units 3–6 of the Series 3 succession are clearly discernible on the surveyed transect at Long Beach (Figure 2b, Figure 4c). Within this succession, there is some evidence of past episodes of shoreline erosion where a set of ridges are aligned obliquely to younger sets of ridges, such as in unit 4 (Figure 2b). However, most ridge crests are parallel and the accretion units record sustained episodes of shoreline progradation.

Phases of much slower deposition can be discerned morphologically by relatively tall ridges. These larger foredunes tend to form when there is a decrease in the rate of sediment delivery to the shoreline (e.g. Shepard, 1991). Ridges in unit 6 are significantly taller than the other ridges (Figure 4c), which suggests that they record a phase of slower shoreline sediment accumulation. Units 3–5 contain a few relatively high narrow ridges; and broad low-amplitude ridges that most probably reflect periods of rapid shoreline progradation when sediment accumulation predominantly occurred in the intertidal zone (e.g. Otvos, 2001). Relict curved berms or bars are evident in units 3 and 4 (Figure 2b) and form the terminations of low amplitude ridges that were probably laid down in the foreshore zone as the shoreline built out and migrated northwards. Modern equivalents of these upper intertidal deposits can be seen on the beach and in the mouth of the tidal inlet at Joskeleigh (Figure 2a).

Sediment characteristics

The Series 2 and 3 ridge deposits at Joskeleigh comprise slightly coarser sand than the Series 3 ridges at Long Beach, as well as comminuted and disarticulated shells, reflecting their tidal inlet depositional setting (Figure 3).

Also, in the previous Joskeleigh survey, a coarse gravely shell-rich unit, collected in a road cutting through the Series 2 ridges, sits approximately 1.5 m above adjacent modern intertidal deposits (^{14}C sample KS6, ~2 m MHWS; Table 3, Figure 4a, b). A coarse gravely unit, similar to that collected in the previous survey, was encountered at approximately 3.25 m depth (~ +1.5 m MHWS) in an auger hole in the seaward ridge of Series 2 (unit 2, Figure 4b).

There were no discernible down-hole changes in facies at the sample sites at Long Beach. These samples comprise very well-sorted fine–medium sand (Figure 5b). The slightly coarser and less well-sorted ridge samples from the Long Beach transect (Figure 5b) may reflect a foreshore rather than foredune depositional environment (Table 1). However, these are subtle differences and one of the modern beach samples, FK440, has a similar grain-size population to ridge samples that are clearly foredune deposits (Figure 5b).

XRD analysis of samples from the Long Beach transect shows they are mineralogically uniform and clearly derived from the Fitzroy River, with all samples comprising quartzose sand (~87% quartz) with more then 10% feldspar minerals (plagioclase, K-feldspar), apart from sample, FK454 (

Table 2). The $CaCO_3$ content of the beach ridge samples is low and variable (6 – 0 %) and the data shows a weak trend of decreasing $CaC0_3$ with distance inland, likely due to the effect of weathering (Figure 5a).

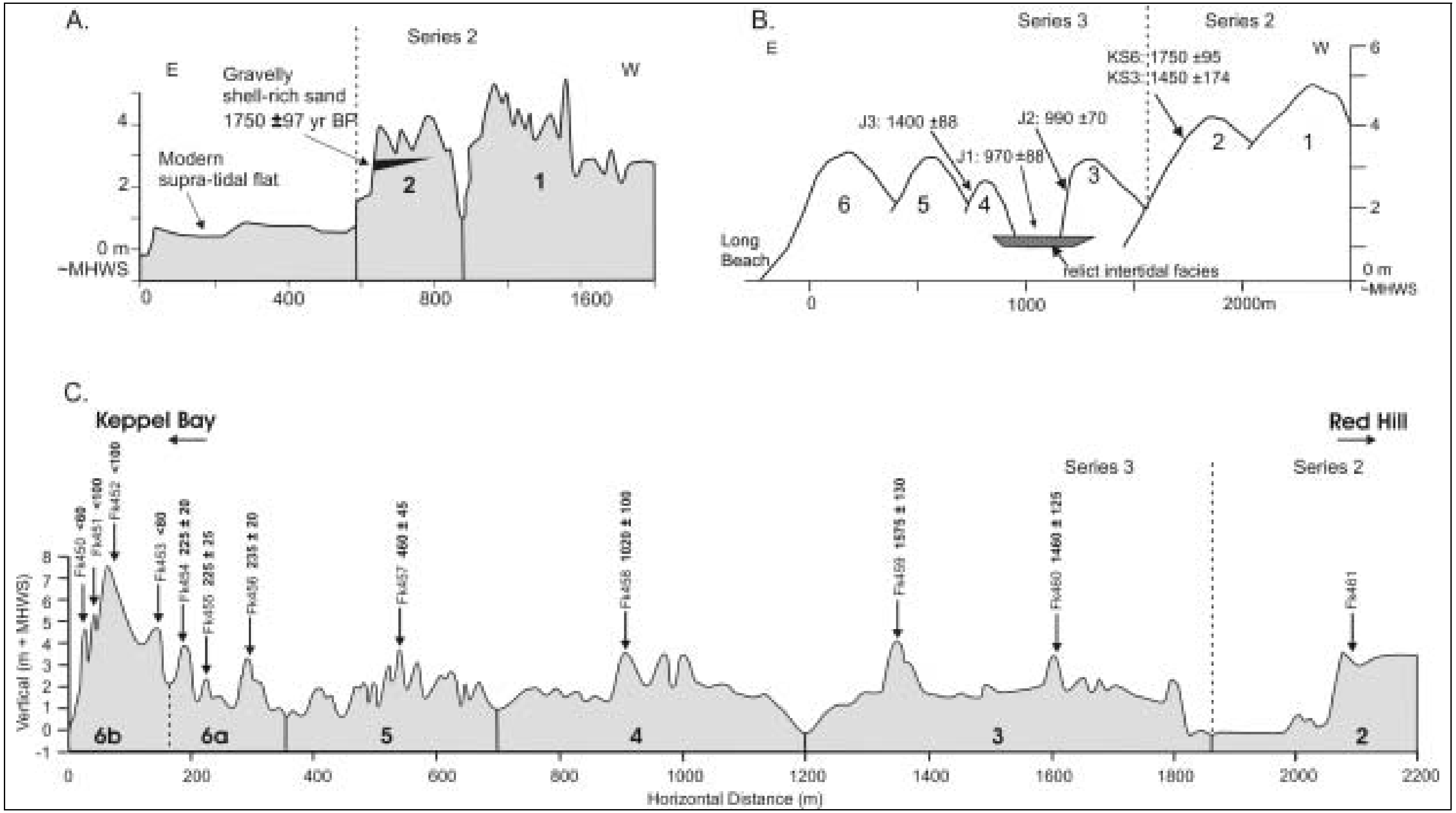


Figure 4: Cross-sections of the study sites at Joskeleigh and Long Beach.
A) Surveyed transect across accretion units 2 and 1 at Joskeleigh. The position of ^{14}C sample KS6 is shown adjacent to the modern supratidal deposits. B) Composite stratigraphic cross-section of the Joskeleigh area showing the position of the ^{14}C samples. C) Surveyed transect at Long Beach. Sample sites are indicated by black arrows. The OSL ages in years are shown above the sample numbers. Accretion units 6 to 2 and their boundaries (major swales) are indicated.

Table 1: Field data for the beach ridges sediment samples.

Sample no	Latitude, Longitude	Distance from beach	Ridge Elevation (MHWS)	Depth of auger (m)	Elevation of sample (MHWS)	Facies*
FK440	-23.42203, 150.81871	0	0	0.0	-0.800	modern beach
FK441	-23.42178, 150.81921	0	0	0.0	-0.020	modern beach
FK450	-23.42208, 150.81858	29.4	4.553	2.5	2.053	foredune
FK451	-23.42214, 150.81847	44.1	5.229	2.5	2.729	foredune
FK452	-23.42223, 150.81833	62.4	7.448	2.7	4.748	foredune
FK453	-23.42257, 150.81795	146.2	4.611	2.7	1.911	foredune
FK454	-23.42276, 150.81762	186.3	3.808	2.4	1.408	foredune
FK455	-23.42295, 150.81725	225.5	2.251	2.6	-0.349	beach
FK456	-23.42331, 150.81672	296.8	3.215	2.4	0.815	beach
FK457	-23.42461, 150.81489	539.5	3.609	2.3	1.309	beach
FK458	-23.42660, 150.81199	905.9	3.443	2.3	1.143	beach
FK459	-23.42891, 150.80863	1348.7	4.017	2.3	1.717	foredune?
FK460	-23.43025, 150.80658	1603.5	3.343	2.3	1.043	beach
JU2-1.5	-23.36826, 150.78290	-	4.45	1.5	2.5	foredune
JU1-1.5	23.36825, 150.78006	-	5.25	1.5	2.5	foredune

* Foreshore samples are taken as those that sit below 1.3 m above ~MHWS (max. measured water level, Beach Protection Authority, 1979); foredune samples are defined as those that sit more than 1.3 m above ~MHW.

Table 2: Mineral composition of beach ridge samples as measured by XRD (% weight).

Sample	Quartz	K-feldspar	Plagioclase	Calcite	Aragonite
FK440	85	7	8	1	
FK441	84	6	7	3	2
FK450	89	5	6		
FK451	87	5	8		
FK452	89	6	5		
FK453	86	7	7		
FK454	91	3	6		
FK455	89	4	7	1	
FK456	89	4	7	1	
FK457	84	7	9	1	
FK458	84	6	10	0	
FK459	87	5	8	0	
FK460	86	5	10		

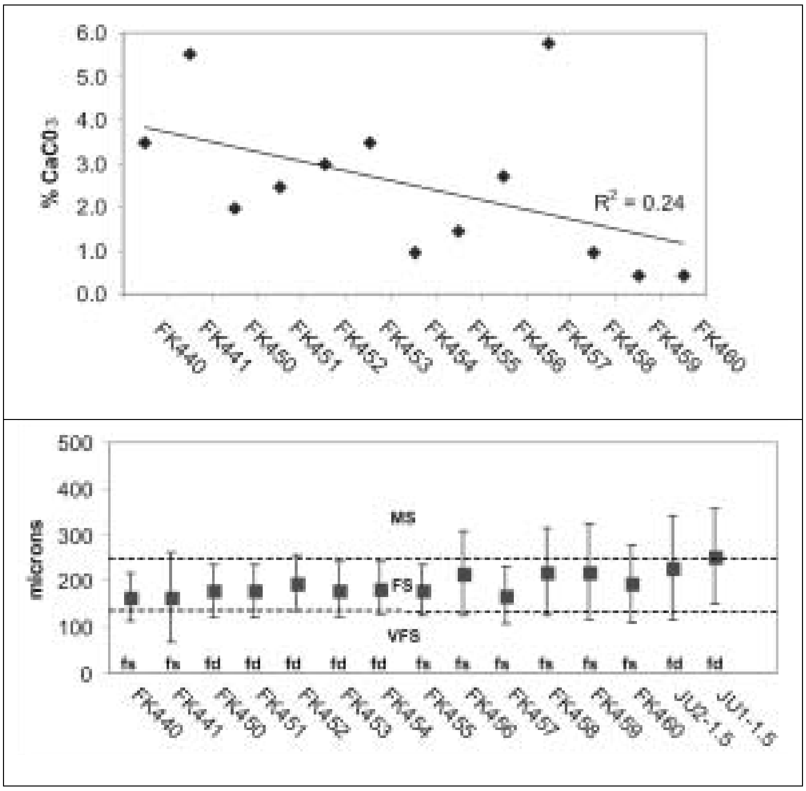


Figure 5: Sediment samples from the surveyed transects.

Top: $CaCO_3$ for samples from the Long Beach transect

Bottom: Mean and 1 standard deviation grain size of beach ridge samples from Long Beach (FK prefix) and Joskeleigh (J prefix). Most comprise fine sand (FS) and small proportions of very fine sand (VFS), while the samples from Joskeleigh (JU2-1.5, JU1-1.5) contain more medium sand (MS). Sediment facies are also indicated: foreshore, fs; foredune, fd (details in Table 1).

Geochronology

Radiocarbon ages

Samples KS3 and KS6 were collected from beds of coarse shelly sand in the ridge at the seaward margin of the Series 2 ridges (Figure 3, Figure 4a, b). Their marine reservoir corrected ^{14}C ages of 1450 ± 174 yr BP (KS3, ANU-7627, Table 3) and 1750 ± 97 yr BP (KS6, BETA-40522) are significantly different and suggest that there is varying proportions of older shell fragments incorporated into the deposit. Two ages for sample J2 from within the most landward ridge of the Series 3 succession, 990 ± 70 yrs BP and 940 ± 70 yrs BP (BETA-40520/ANU-7630), are similar to the age of sample J1, 970 ± 88 yr BP (ANU-7631), from a relict supratidal deposit that forms the base of or underlies this ridge (Figure 4b). An age reversal is apparent with sample J3 from the next seaward (younger) ridge, 1400 ± 88 yr BP (BETA-40521). Overall, the ^{14}C ages suggest that Series 2 ridges are at least approximately 1450 years old but are problematic because of the numerous shell fragments that comprise the samples (except J1, Table 3) that probably have quite divergent ages as indicated by the age inversion. Also, with the movement of rainwater through these deposits, the shell may have been weathered or incorporated younger organic material, or both processes may have occurred, which would likewise reduce the reliability of the ^{14}C chronology.

OSL ages

Concentrations of ^{238}U, ^{226}Ra and ^{210}Pb measured in the OSL samples are consistent with secular equilibrium in all samples, hence for all samples dose rates have been calculated using the as measured radionuclide contents (Table 4). The σ_d values indicate the samples were well-bleached prior to burial.

The OSL ages are stratigraphically consistent and clearly record the episodic emplacement of Series 3 accretion units 3–6 (Figure 4c; Table 4). Samples from the four relatively high foredunes immediately behind the modern beach were all deposited during the last 100 years (unit 6b, samples FK450–FK453, Table 4). Similarly, the next three ridges inland were emplaced during a period of 25 years or less (the OSL age uncertainty) approximately 230 years ago (unit 6a, FK454–FK456). The ages for one ridge only in each of the next two accretion units, 5 and 4, reveal that depositional episodes occurred 460 ± 45 (FK457) and 1020 ± 100 (FK458) years ago. It is possible that in these units there are additional phases of accretion that were not dated, however, these two sets of ridges are morphostratigraphically well-defined and reflect discrete depositional phases (Figure 4c). The OSL ages of the two widely separated samples from accretion unit 3, FK459 (1575 ± 130 yrs) and FK460 (1460 ± 125 yrs), identify an earlier episode of rapid shoreline progradation that occurred approximately 1,500 yr ago (Table 4).

The ^{14}C ages of samples from unit 3 in Series 3 at Joskeleigh are significantly younger than the OSL ages of the same unit sampled on the surveyed transect (^{14}C: 940 ± 97 and 970 ± 88 yr BP; OSL: 1575 ± 130 and 1460 ± 125 yr; Table 4). In contrast, the ^{14}C age for unit 4 is older than the OSL age (^{14}C: 1400 ± 88 yrs BP; OSL: 1020 ± 100 yrs). This comparison indicates that the ^{14}C ages do not represent well the depositional age of the accretion units.

Table 3: Radiocarbon ages of shell material collected from Series 3 beach ridge and spit deposits at Joskeleigh.

Field no.	Lab. no.	Accretion Unit[1]	OSL Age[2]	Material Dated	Location[3]	Conventional ^{14}C age	Corrected ^{14}C age[4]
KS3	ANU-7627	Series 2	-	Shell fragments (*Anadara trapezia*)	GR735153	1900 ± 170	1450 ± 174
KS6	BETA-40522	Series 2	-	Shell fragments (*A. trapezia*)	GR735135	2200 ± 90	1750 ± 97
J2	BETA-40520	Series 3 unit 1	1500	Shell fragments (*A. trapezia*)	GR742133	1440 ± 60	990 ± 70
J2a	ANU-7630	Series 3 unit 1	1500	Shell fragments (*A. trapezia*)	GR742133	1390 ± 90	940 ± 97
J1	ANU-7631	Series 3 unit 1	1500	Gastropod (unidentified)	GR743132	1420 ± 80	970 ± 88
J3	BETA-40521	Series 3 unit 2	1000	Shell fragments (*A. trapezia*)	GR745127	1850 ± 80	1400 ± 88

[1]Morphostratigraphic units (Beach Protection Authority, 1979).

[2]Approximate OSL age in years – details in Table 5.

[3]Grid Reference for Rockhampton 1:100,000 Topographic Sheet.

[4]Marine reservoir corrected age

Table 4: Lithogenic radionuclide activity concentrations, burial dose, measured water contents, dose rates and OSL ages for the beach ridge samples.

Sample	Accretion Unit	moisture	^{238}U	^{226}Ra	^{210}Pb	^{232}Th	^{40}K	Dose Rate (μGya^{-1})	De (Gy)	σ	Age (yrs)
FK450	6b	3.5	11.7 ± 2.2	13.5 ± 0.2	10.9 ± 1.2	15.9 ± 0.6	167 ± 4	1190 ± 90	0.02 ± 0.05	-	< 60
FK451	6b	0.9	8.9 ± 1.8	8.5 ± 0.2	8.1 ± 1.0	10.8 ± 0.2	185 ± 6	1130 ± 80	0.04 ± 0.07	-	< 100
FK452	6b	3.9	7.5 ± 1.9	6.4 ± 0.2	5.3 ± 1.0	8.8 ± 0.2	193 ± 6	1045 ± 70	0.05 ± 0.06	-	< 100
FK453	6b	4.5	5.5 ± 0.9	5.3 ± 0.1	5.2 ± 0.5	8.3 ± 0.1	223 ± 4	1110 ± 70	0.03 ± 0.07	-	< 80
FK454	6a	2.4	6.9 ± 1.0	6.8 ± 0.1	7.2 ± 0.5	9.3 ± 0.1	161 ± 4	990 ± 65	0.22 ± 0.02	0	225 ± 20
FK455	6a	8.6	7.8 ± 0.5	7.5 ± 0.1	6.8 ± 0.6	10.3 ± 0.1	201 ± 4	1070 ± 70	0.24 ± 0.02	0	225 ± 25
FK456	6a	3.5	4.9 ± 0.8	5.1 ± 0.2	3.9 ± 0.9	8.3 ± 0.1	207 ± 6	1050 ± 70	0.24 ± 0.02	0	230 ± 20
FK457	5	5	18.5 ± 2.6	22.2 ± 0.3	20.5 ± 1.6	28.4 ± 0.3	219 ± 6	1715 ± 140	0.79 ± 0.03	9	460 ± 45
FK458	4	2	10.0 ± 1.2	10.4 ± 0.1	9.6 ± 0.7	18.0 ± 0.1	270 ± 5	1380 ± 100	1.41 ± 0.08	0	1020 ± 100
FK459	31	3.9	7.5 ± 0.5	6.8 ± 0.1	6.4 ± 0.6	10.1 ± 0.2	227 ± 5	1185 ± 80	1.87 ± 0.08	3	1575 ± 130
FK460	3	3.4	9.6 ± 0.6	10.2 ± 0.1	9.7 ± 0.7	16.1 ± 0.2	311 ± 6	1615 ± 110	2.36 ± 0.09	8	1460 ± 125

All radionuclide values are in Bq kg^{-1}, with dose rate calculated using the measured water content and an assumed depth of 1 m (for calculation of cosmic contribution)

Discussion

Ridge formation

The OSL ages have sufficient resolution to show that accretion unit 6 comprises two distinct episodes of ridge formation, the first around 235 years ago, the second within the last 100 years (Figure 4c). Although there is an increase in the uncertainty of the OSL ages for the older ridges, the two ages for the ridges within accretion unit 3 (FK459: 1575 ± 130 yrs; FK460: 1460 ± 125 yrs) that are 255 m apart, are statistically indistinguishable and therefore, at a slightly lower level of resolution, support the morphostratigraphic mapping. These OSL ages indicate that the ridges in unit 3 were deposited rapidly, in a period shorter than that represented by the standard error of the ages, approximately 130 yrs. These chronostratigraphic data highlight the episodic mode of beach ridge formation, with a series of ridges rapidly emplaced following the movement of a pulse of sediment onshore.

Overall, the OSL ages provide clear geochronological evidence that during the last 1500 years, approximately every 500–200 yrs there has been rapid episodes of beach ridge formation that lasted a few decades or less. These phases of accretion are followed by a relatively quiescent period. There may have been phases of shoreline erosion within or between the periods of accretion, such as the rapid but short-lived erosional events induced by cyclones (Beach Protection Authority, 1979).

The morphology and stratigraphy of the relict ridges at Keppel Bay clearly demonstrates that they are formed during quiescent periods with constructional shoreline processes. Historical records of the formation of beach ridges on this coast likewise show that ridges form during average climatic conditions (BPA, 1979). In contrast, gravelly ridges on Lady Elliot Island, approximately 200 km southeast of Keppel Bay, were deposited during cyclonic storms when coarse fragments of coral and rock are reworked onshore to form storm ridges (Chivas *et al.*, 1986; Figure 1). An extensive succession of similar ridges has also been examined on Curacao Island, 700 km northwest of Keppel Bay, that were likewise deposited by cyclone-generated storm waves (Hayne and Chappell, 2001). On Lady Elliot Island, the gravel ridges were deposited at regular intervals over the last 4000 yrs (Chivas *et al.*, 1986). Similarly, ^{14}C ages for the ridge succession on Curacao Island indicate that the frequency of cyclonic storms, with a recurrence interval of 280 yrs, has not changed during the last 5000 yrs (Hayne and Chappell, 2001).

The frequency of high-magnitude (Category 5) cyclones within all regions of the GBR was calculated to be 200–300 yrs based on the age of these and several other similar storm-related deposits along the coast (Nott and Hayne, 2001; Figure 1). Beach ridge development at Keppel Bay has likely also been indirectly influenced by high-magnitude cyclones because when they track onshore major rainfall events occur in the coastal catchments. Its seems likely, therefore, that the 200–500 yr periodicity evident in the OSL chronology of the Keppel Bay ridges is related to major flood discharge events of the Fitzroy River that are induced by the onshore passage of high-magnitude cyclones (Devlin *et al.*, 2001)

Shoreline sediment accumulation

The OSL chronology for the beach ridges provides the opportunity to measure the rate at which sediment has accumulated and the shoreline prograded over the last 1500 years. However, the usefulness of these results in terms of an accurate representation of the mass of sediment deposited during each major phase of accretion is limited because there has clearly been a recent phase of shoreline erosion around and north of the mouth of the Fitzroy River (Figures 1 and 2c). As a consequence, unknown proportions of all these Series 3 accretions units have been removed.

Rates of accumulation for the ridges were calculated by dividing the sediment mass of each unit by an estimate of the time taken for the unit to be deposited (Table 5). Rates of shoreline progradation are based on the measured mean width of the units and the estimated duration of these depositional events (Table 6).

Table 5: Sediment mass accumulation data for Series 3 accretion units.
Maximum and minimum depositional periods (used to calculate the accumulation rates) are estimates of the time taken for an accretion unit to be deposited, based on the OSL ages of ridges in unit 3 (Min) and unit 5 (Max). For unit 6, these estimates are based on the OSL ages for unit 6a (Table 3).

Accretion Units	Area (km^2)	Volume (km^3)	Mass (Kilotonnes)	Deposition Period Min–Max (yr)	Accumulation Rate Max–Min (kt yr^{-1})
Unit 6	4.342	0.056	66 913	175–235	382–285
Unit 5	6.787	0.077	92 603	25–130	3704–712
Unit 4	10.169	0.118	142 057	25–130	5682–1093
Unit 3	6.822	0.078	93 387	25–130	3735–718
Total	28.120	0.332	398 699	1335–1705	299–234

Table 6: Rates of shoreline progradation for the beach-ridge accretion units examined at Long Beach (units 6 – 3) and Joskeleigh (units 2, 1).

Accretion Unit	Width (m)	Deposition Min–Max[1] (yrs)	Progradation Max–Min[2] (m yr^{-1})
6	380	175–235	2.17–1.62
5	320	25–130	12.80–2.46
4	500	25–130	20.00–3.85
3	625	25–130	25.00–4.81
Total strandplain	1825	1460–1575	1.25–1.16

[1] Deposition Min and Max – unit 6: shortest and longest period of emplacement indicated by OSL ages of unit 6a (Table 3); units 5–3: max and min periods based on OSL ages for unit 3 (max) and unit 6a (min).

[2] Progradation Max and Min based on Deposition Min and Max respectively.

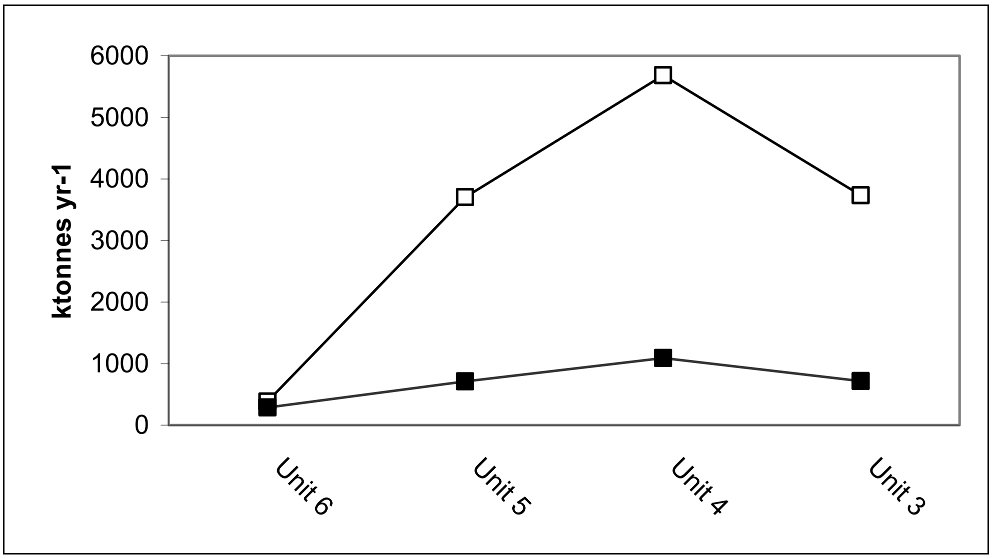


Figure 6: Maximum and minimum rates at which the six accretion units were emplaced.

Rates are based on measurements of the accretion unit volumes (Table 5) and OSL ages (Table 3, Table 4).

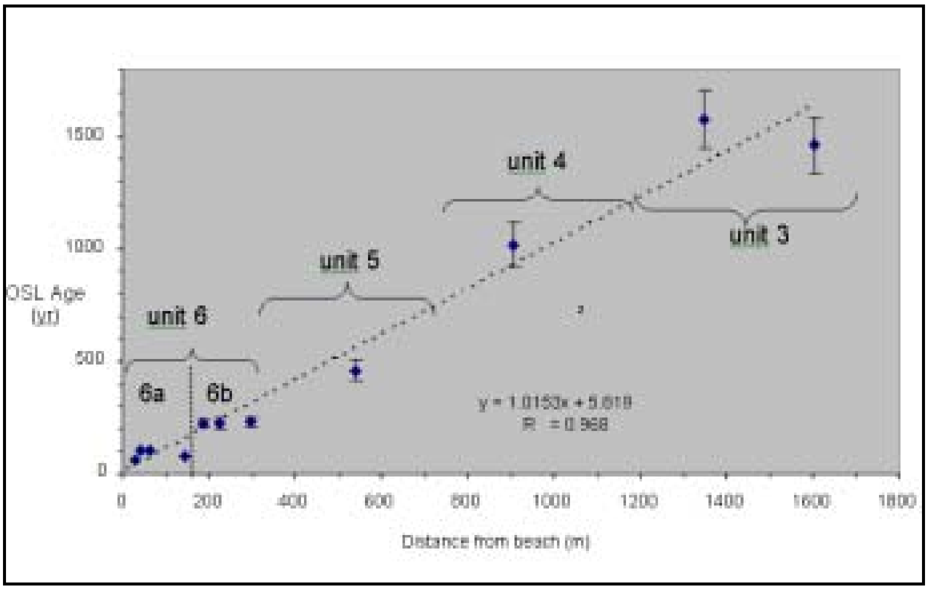


Figure 7: A plot of the OSL ages and distance inland from the modern beach of samples from units 6–3. The horizontal extent of each unit is indicated. Unit 6 contains two subunits, 6a and 6b.

Over the period during which units 3–6 were emplaced, the rate of mass accumulation appears to have been greatest during the period represent by unit 4, approximately 1020 yrs ago (1093–5682 kt yr^{-1}, Figure 6). Rates may have subsequently declined as the younger units were deposited, with the lowest rates for the succession during the most recent period when unit 6 was deposited (285–383 kt yr^{-1}). The rate at which the shoreline built out follows a similar pattern, with the highest rate of progradation during the period represented by units 4 and 3 (25–4.81 m yr^{-1}). During the period in which unit 3 was deposited, progradation was at least three times more rapid than has occurred during the last 200 years (2.17–1.62 m yr^{-1}, Table 6).

The rates of sediment accumulation for individual accretion units are significantly greater than rates for the entire Series 3 succession (234–299 kt yr^{-1}, Table 5), apart from unit 6. This clearly reflects the episodic character of sediment accretion on Long Beach, rather than the more gradual and continuous process that is indicated by estimates of mass accumulation or progradation for the entire standplain (Tables 5, 6). The apparent decline in the rate of sedimentation appears to reflect a long-term decline in the rate of sediment delivery to Keppel Bay. This in turn is likely reflecting a decline in the frequency or intensity of major cyclonic depressions that reach the Fitzroy River catchment, which is not reflected in the radiocarbon-dated boulder ridge deposits on Curacao or Lady Elliot Islands (Chivas *et al.*, 1986; Hayne and Chappell, 2001).

Possible links with global climate change

The apparent decline in the rate of ridge formation may be related to phases of a global climatic cycle that has a roughly 1500 year periodicity, which is best known on the basis of higher percentages of ice-rafted debris in North Atlantic sediments (Bond *et al.*, 2001). Wetter conditions seemed to have prevailed over south-eastern Australia during these Northern Hemisphere cooling events (Bowler, 1981; Radke, 2000), and this was probably also the case for coastal Queensland. The cause of the global 1500 year cycles is still controversial, but solar forcing was forwarded by Bond *et al.*, (2001) as a possible causal mechanism. More recently, Moy *et al.* (2002) recognised that these Bond events generally occurred during periods of low El Niño Southern Oscillation (ENSO) activity that immediately followed periods of high ENSO activity. Moy *et al.* (2002) concluded in suggesting that the Bond events and ENSO might be linked, but that ENSO dynamics operating independently could explain the millennial scale variability they observed in their records from southern Ecuador.

High-resolution Holocene palaeoclimate records (dated coral oxygen isotope and trace element ratios; terrestrial sediment core data) reveal significant changes in the character of the ocean-atmosphere interactions driven by the Indo-Pacific Warm Pool and ENSO in the middle to late Holocene, with a non-linear atmospheric response to changes in sea surface temperatures (SST; Gagan *et al.*, 2004). Of relevance to this study is that El Niño events were significantly more intense and longer in duration between 2500 and 1700 yrs ago (McGregor and Gagan, 2004), providing a possible explanation for the apparent decline in sediment delivery to the Keppel Bay coast over approximately the last 1500 yrs because ENSO exerts a significant control on the frequency of cyclones on the Queensland coast (Lough, 2001).

The new palaeoclimate records also show that during the last 350 yrs variations in precipitation in northeastern Queensland are not always linked to ENSO events, highlighting the distinctive character of climate in this region following the end of the Little Ice Age (McGregor and Gagan, 2004). It is worth noting that the Keppel Bay beach ridges deposited during this period, unit 6a/b, record much slower rates of sediment accumulation than the older units. Coral geochemical records have shown that the last few hundred years have been distinctly different in terms of major climatic circulations such as ENSO (Gagan *et al.*, 2004). It seems likely that past episodes of beach ridge development at Keppel Bay reflect both regional as well as global climate cycles. Late Holocene fluctuations in solar insolation, deep sea circulation and atmospheric convection (Gagan *et al.*, 2004) may have influenced the frequency of high-magnitude rainfall events in the Fitzroy catchment and consequently the delivery of sediment to the Keppel Bay coast.

Falls in sea level?

The coastal plain adjacent to Long Beach comprises beach deposits that preserve a detailed record of coastal sedimentation over approximately the last 1500 years. There is a high degree of preserved depositional morphology, with relict subtle coastal landforms such as foredunes, intertidal berms and recurved spits, as well as intertidal and supratidal flats (Figures 2, 3, 4). Relict intertidal deposits at Joskeleigh suggest that following the deposition of Series 2 ridges, prior to 1500 yr ago, the sea may have fallen by approximately 1 m. Similar deposits nearby (Figures 3, 4) also suggests sea level may have fallen approximately 0.5 m after Unit 3 ridges were deposited approximately 1,500 yrs ago. At the Long Beach transect, low-amplitude relict berms in accretion Units 3 and 4 sit up to 1 m above similar modern deposits on Long Beach (Figure 2b, Figure 4c). This difference in elevation may reflect a fall in sea level as noted for the tidal inlet deposits at Joskeleigh. Falls in sea level may be a driver of ridge formation if it they result in an enhanced delivery of sediment to the shoreline with the development of a new equilibrium beach profile (Dean and Maurmeyer, 1983). This situation is counter to the record of sediment mass accumulation and shoreline progradation for ridges 5 and 6 (Tables 5, 6), which indicate a decline in sediment delivery to the shoreline. To support these preliminary interpretations of sea-level change and better assess whether rapid drops in sea level have been a driver of beach ridge formation, more detailed facies mapping and surveying are required to better assess whether the raised deposits were emplaced under normal depositional conditions rather than during storms when sea level can be significantly elevated.

Records of Holocene sea level and sea surface temperatures (SST) for the eastern and south western coasts of Australia based on *in situ* fossil remains of intertidal tube worms and barnacles (Baker *et al.*, 2001, 2004) suggest an oscillating eustatic fall of the sea following a highstand around 2 m above present sea level. These data suggest that the peaks in a fluctuating sea level at approximately 5100, 3900 and 2000 years ago were followed by rapid regressions in the order of 1 m. The stratigraphic indicators of a possible drop in sea level following deposition of the Series 2 ridges at Joskeleigh may correlate with the rapid drop shortly after 2,000 years ago evident in the data of Baker *et al.* (2004).

Sediment geochemistry and provenence

Sediment samples from the modern beach and relict beach ridges display distinct variations in rare earth element (REE) and other trace element geochemistry with OSL ages. The majority of samples from the modern beach and accretion unit 6b (Figure 4c, <100 yrs old) have a strongly light rare earth element (LREE) enriched pattern with little or no negative Eu anomaly (lower Eu abundance than adjacent REE, Figure 7a). In contrast, the majority of ridge samples older than approximately 225 years have a less LREE enriched pattern with moderate to strong negative Eu anomalies (Figure 7a). These latter patterns indicate the probable presence of either zircon and/or garnet, with Zr, and Fe and Mn respectively similarly enriched in the older dunes sands and strongly correlated with the LREE/HREE (heavy rare earth element) ratio and Eu anomaly. Samples between ca. 225–230 years in age often have a mixed character and may mark a point of transition in the source(s) of sediment to the ridges.

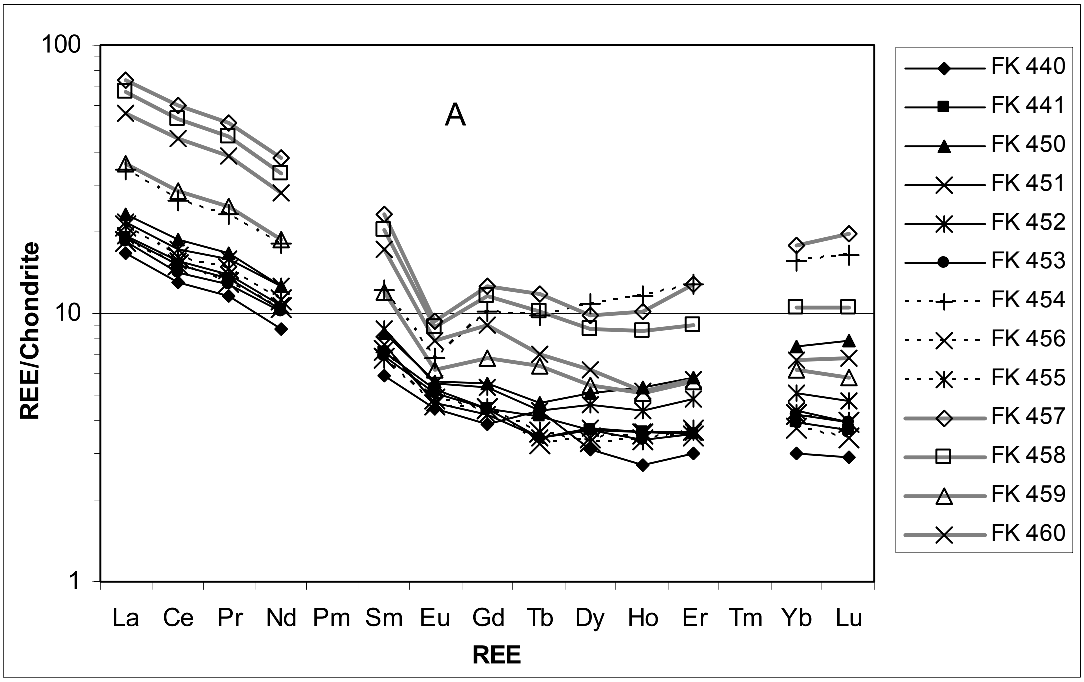
Comparison of the REE geochemistry of the beach-ridge sediment to an average crustal weathering composition, the Post Archean Australian Shale (PAAS), reveals that the recent beach and ridge sediment geochemistry is very similar with only a slight degree of HREE enrichment and positive Eu anomaly for the majority of samples (Figure 7b). Conversely, older ridges have a distinctive HREE and negative Eu anomaly due to the presence of zircon and/or garnet as described above.

The compositional similarity between the beach ridge samples which are predominantly quartz (~85%) with minor feldspars (~10–15%) and Fitzroy River sand indicates a common origin. Sands found further to the east in Keppel Bay are more strongly quartz-dominated (Radke *et al.*, 2005). The similarity of the trace element composition of many of the Fitzroy beach ridge samples to an average weathered crustal composition (PAAS, Figure 7b) is not unexpected given the size of the Fitzroy catchment and extent of weathering and sediment homogenization during sediment generation and transport. Sediment homogenization may have been further enhanced in the foredune facies because of the slight grain-size sorting effect of aeolian movement of sediment onto the ridges.

A variety of trace element ratios may be used to identify the major catchment sources of, and temporal variation in, sediment to the beach-ridge plain. The ratios of Sm/Nd, Ti/Zr, La/Th and Rb/Sr for beach and ridge sands less than 100 years in age (circled in Figure 9) are all typical of basaltic soils located in the Fitzroy catchment (Douglas *et al.*, 2004). This increased occurrence of these basaltic sediments in the more recent dunes may document anthropogenic destabilisation of the catchment. European settlement occurred in 1855, but the major vegetation type (the Brigalow scrub) was almost completely cleared or burned about 100 years later, between 1960 and 1980 (Furnas, 2003). The Brigalow clearing scheme impinged on the basaltic parts of the catchment

(Kuhnen, 2004), which may explain the enhanced basaltic signature of samples from unit 6b and the modern beach.

As identified in analysis of the REE geochemistry, ridge samples of approximately 225–230 years in age are often transitional in their composition, between the younger samples with a basaltic signature and older ridge samples with a geochemical signature more dominated by heavy minerals, in particular zircon and garnet. Interestingly, ridge deposits older than ca. 225–230 years in age in general define a linear to sub-linear array for the ratios Sm/Nd, Ti/Zr and La/Th as a function of age, suggesting either (i) little or no change in the provenance of sediments over time, and/or (ii) extensive reworking of older ridge deposits to supply material for younger ridge-building events, thus ensuring a degree of compositional uniformity with time. Given the high rates of shoreline progradation during each episode of beach-ridge formation, however, scenario (i) is more likely. The greater variation of the Rb/Sr ratio for ridge samples older than ca. 225–230 years in age relative to Sm/Nd, Ti/Zr and La/Th is primarily a function of the alkali feldspar content in the older ridges and the higher carbonate content in the younger deposits.



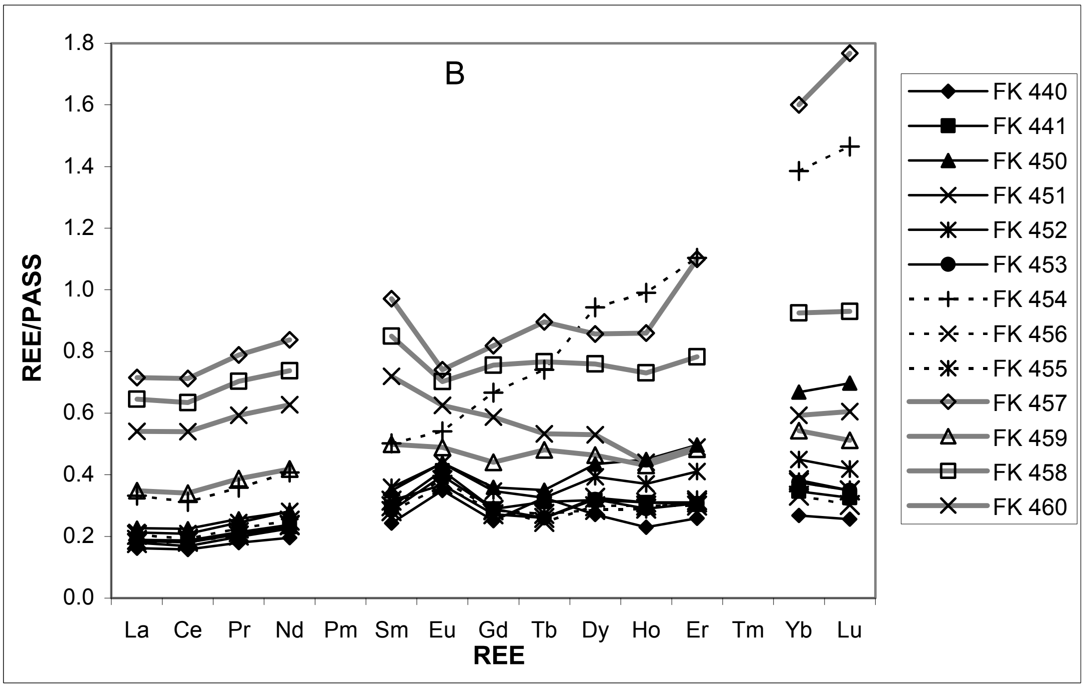


Figure 8: Rare earth element (REE) geochemistry of beach and beach ridge samples (data points for the modern deposits (FK440–453) are joined by black lines, dashed lines indicate ridges approximately 225 yrs old (FK454–456), and the older ridges (FK457–460) are highlight by grey lines): A) Data are normalized to Chondritic values; and B) Data are compared to the Post Archean Australian Shale (REE/PAAS). Sample FK454 is unusual in that it has the steepest HREE enrichment pattern, which likely indicates a mixed source area.

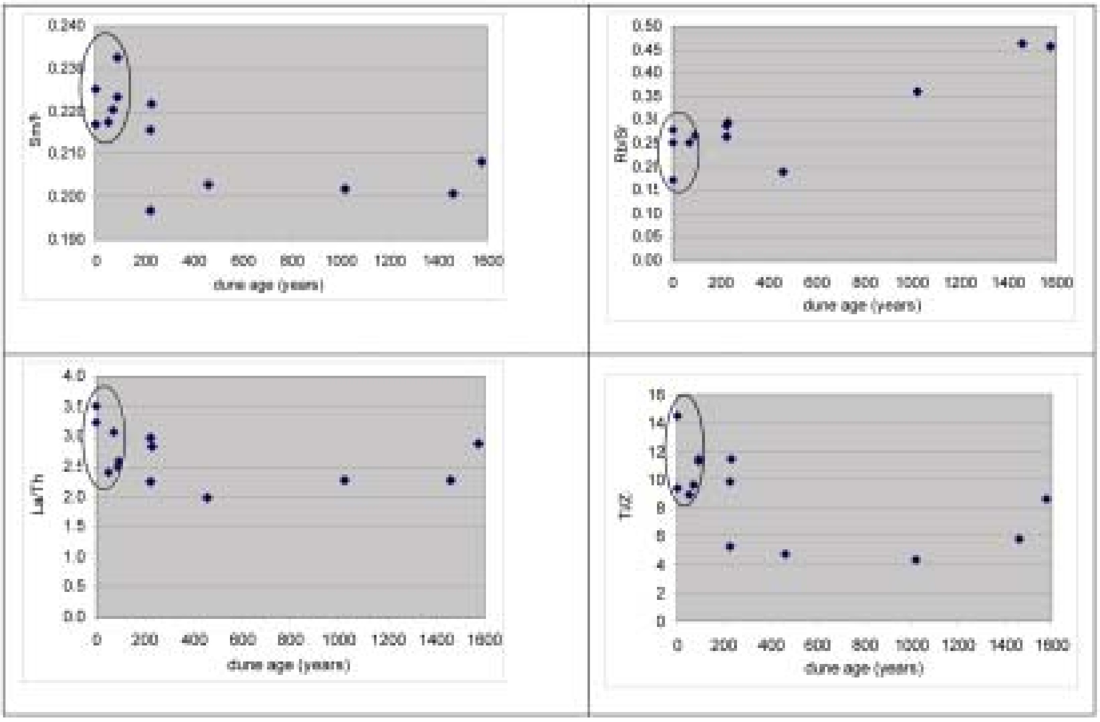


Figure 9: Sample age versus selected trace element ratios (Sm/Nd, Rb/Sr, La/Th and Ti/Zr) for the beach and beach ridge samples.

Circled samples are youngest with a higher basaltic component.

Conclusions

This study demonstrates the value of examining the depositional history and sediment composition of a succession of well-preserved beach ridges. The Keppel Bay beach-ridge plain provides a detailed record of beach sediment accumulation that spans the historical period through to the early Holocene. Our preliminary conclusions are:

1) The sandy beach ridge plain at Long Beach comprises sediment that was deposited in Keppel Bay by the Fitzroy River and then reworked onshore under the prevailing climatic and oceanographic conditions.

2) During the last 1500 years ridges were emplaced in rapid episodes following periods of relatively high sediment discharge from the Fitzroy River, approximately once every 500–200 years. During these episodes sediment accumulated rapidly, up to 1093 kt yr^{-1}, which is far greater than the current rate, 285 kt yr^{-1}.

3) There are appears to have been a general decline in the rate at which sediment has accumulated at Long Beach during the last 1500 years that likely reflects a long-term decline in major rainfall events in the Fitzroy River catchment.

4) Ridges deposited during the last 230 years record a distinct change in trace element composition that reflects a greater contribution from basaltic soils within the Fitzroy River catchment. This change is probably related to a change in the type(s) of sediment (soil) being delivered due to large-scale clearing of native vegetation in the Fitzroy Basin.

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