

Morphology, Stratigraphy and Origin of Last Interglacial Beach Ridges at Bream Bay, New Zealand

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ABSTRACT

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This paper presents results of a morphological, sedimentological, and stratigraphical study of relict beach ridges formed on a prograded coastal barrier in Bream Bay, North Island New Zealand. Bream Bay is situated on a low mesotidal coast, influenced by low to moderate and refracted wave energy. Sediment supply for coastal progradation is dominated by marine deposits of reworked volcanoclastic sediment. The type section for beach ridge stratigraphy is exposed at One Tree Point where surveys of the contact between beach and foredune deposits (+4–5 m), and thermoluminescence dating indicate deposition of the beach ridges during the Last Interglacial sea-level highstand (isotope sub-stage 5e to 5a). Outcrop mapping, supplemented with ground penetrating radar data suggest that swash processes are important in the formation of these particular beach ridges. A model for the development and preservation of the One Tree Point beach-ridge system is presented with a focus on the role of relative sea level.

ADDITIONAL INDEX WORDS: *Relative sea-level, ground penetrating radar, thermoluminescence.*

INTRODUCTION

Prograded coastal barriers hold the greatest potential among all coastal depositional systems for yielding a long-term (10^2 – 10^3 years) record of nearshore, beach and dune sedimentary processes. By definition, a prograded barrier is a regressive coastal landform that exists because the interplay between sediment supply, sea level and shoreline processes has been weighted in favour of deposition and preservation of incoming sediment. In many instances a succession of relict shorelines, commonly termed beach-ridges, is the most striking evidence for a history of shoreline advance. The mode of formation and conditions for preservation of beach-ridges is a topic long represented and debated in coastal literature (e.g. JOHNSON, 1919; SHEPARD, 1937; DAVIES, 1957; MCKENZIE, 1958; THOM, 1964; TANNER and STAPOR, 1972; SUNAMARA, 1975; CARTER, 1986; TANNER, 1995, 1996; CURRAY, 1996). A review of beach-ridge literature by TAYLOR and STONE (1996) highlights the diversity of explanations that have been put forward for beach-ridge formation and preservation, and accounts for this in terms of the wide range of settings in which beach-ridge plains have developed. Here, the beach-ridge definition offered by OTVOS (2000) is adopted, which recognises all relict coastal ridges as beach-ridges regardless of dominance by wave/swash or aeolian sediment facies.

In recent years, several authors have considered the potential for using the coastal depositional record to identify long-term trends or cycles in paleo-environmental conditions (e.g. ANDERSON *et al.*, 1992; FINKL, 1995). Beach-ridge plains in

particular, have been singled out as a depositional system that may yield a proxy record of variations in shoreline processes that could in turn be linked with climatic variability (e.g. ENSO-cycles) (SANDWEISS, 1986; STAPOR *et al.*, 1991; ORTLIEB *et al.*, 1995; SEMENIUK, 1995; THOMPSON and BAEDKE, 1995, 1997; TAYLOR and STONE, 1996). In many coastal situations, however, the ability to resolve such a record is confounded by local factors such as complex nearshore morphodynamics and/or terrestrial processes (e.g. river floods).

This paper presents a case study of a relict beach-ridge system that has evolved under the influence of a marine-dominated sediment supply, allowing attention to be given to the relationship between the depositional record, sea level and wave action. The objectives are to (i) document the morphology, stratigraphy and facies of the beach ridges, (ii) propose a depositional model for beach-ridge formation and preservation, and (iii) evaluate the deposit for its potential as a proxy for defining trends or cycles in the coastal depositional record.

BREAM BAY BARRIER

Physiography

Bream Bay is located on the north-east coast of North Island New Zealand, forming a gently arcuate shoreline aligned northwest to southeast and bound to north and south by major headlands formed in volcanic outcrop (Figure 1). The coastal barrier under investigation here extends ~8.5 km along the northern end of Bream Bay, north of the Ruakaka River mouth and terminates at the southern shore of Whan-

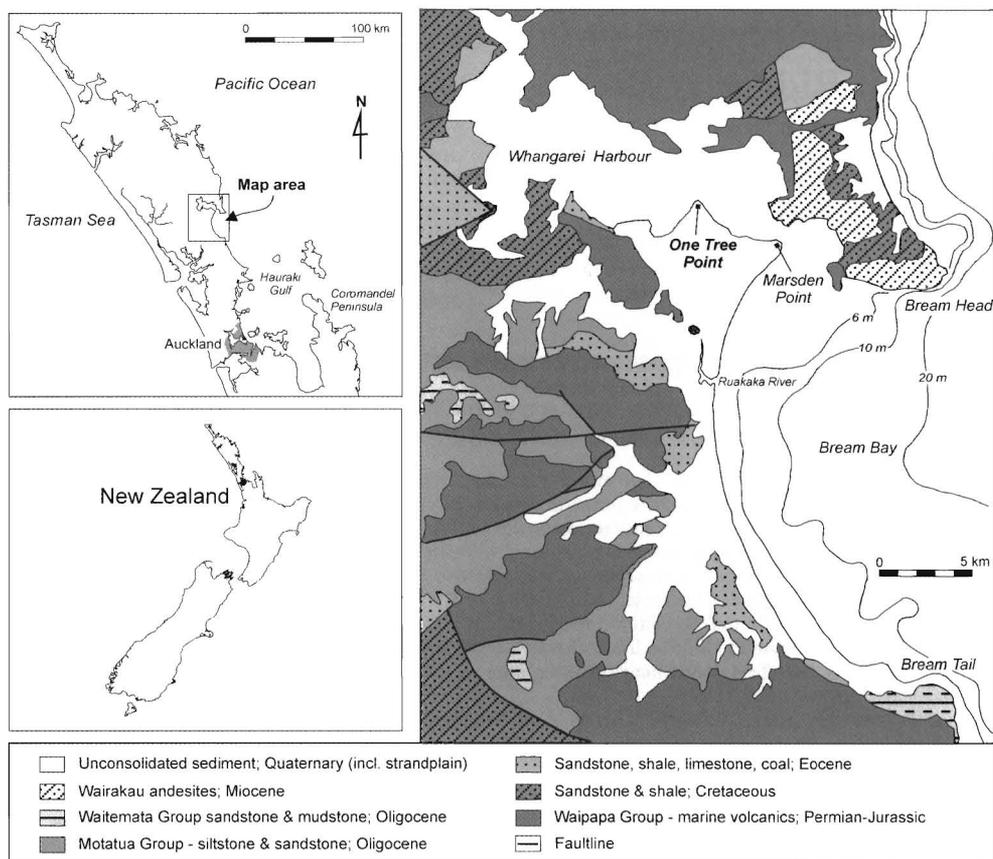


Figure 1. Location map of study area and generalised geology map of Bream Bay hinterland (source: Thompson, 1961).

garei Harbour. Volcanic outcrop (Waipapa Group; THOMPSON, 1961) forms the landward boundary along the southwest margin of the barrier. The topography of the barrier divides into two forms, an area of hummocky dunes covering the eastern one-third of the barrier (the outer barrier) and a raised area of linear sand ridges to landward (the inner barrier) (Figure 2). OSBORNE (1983) examined the shallow stratigraphy of the hummocky dunes and documented shelly beach deposits 0.5 m below mean sea level at a site 900 m landward of the present shoreline. A bulk radiocarbon assay on eight shell valves from the beach sand yielded an age of 5750 ± 140 years B.P. (NZ-6376A), indicating a mid-Holocene age for initial progradation of the hummocky dunes (OSBORNE, 1983).

The area of raised sand ridges is contiguous with the hummocky dunes, covering the northwest portion of the barrier and includes the small promontory of One Tree Point (Figure 2). One Tree Point is a remnant of a more extensive ridge system, as evidenced by a continuous 6 to 8 m-high cliff that fringes the promontory and an area occupied by Blacksmiths Creek estuary that partially bisects the raised ridges (Figure 2). Raised ridges are also preserved to the east of Blacksmiths Creek, but were not examined in this study, due to lack of outcrop. The cliff outcrop around One Tree Point presents a near-continuous cross-section through 20 ridges, revealing

well-preserved sedimentary structures and stratigraphic surfaces. It is these ridges and their outcrop exposures that are the focus of this paper.

Modern Nearshore Environment

Bream Bay experiences a low- to moderate-energy wave climate due to its leeward position on North Island. Wave-rider buoy data collected at different intervals at two sites in Bream Bay provide some measure of wave conditions on the coast, including storm waves. The first (non-directional) buoy was deployed by Northland Harbour Board 2 km offshore from the Ruakaka River mouth in 18 m of water, between 1978 and March 1980. This period included a major storm in July 1978 during which maximum wave height was recorded at 9 m (DUDER and CHRISTIAN, 1983). A second wave-rider buoy was located offshore from Mangawhai Heads to the south of Bream Bay in 30 m water depth between March 1995 and June 1997. Deployed by the National Institute of Water and Atmospheric Research (NIWA), the wave-rider recorded wave statistics every three hours. Maximum wave height ranged from 0.04–8.1 m (mean: 1.2 ± 0.9 m) with a corresponding mean period of 11.5 ± 2.6 seconds, and significant wave height varied between 0.02 and 5.6 m (mean: 0.7 ± 0.6 m).

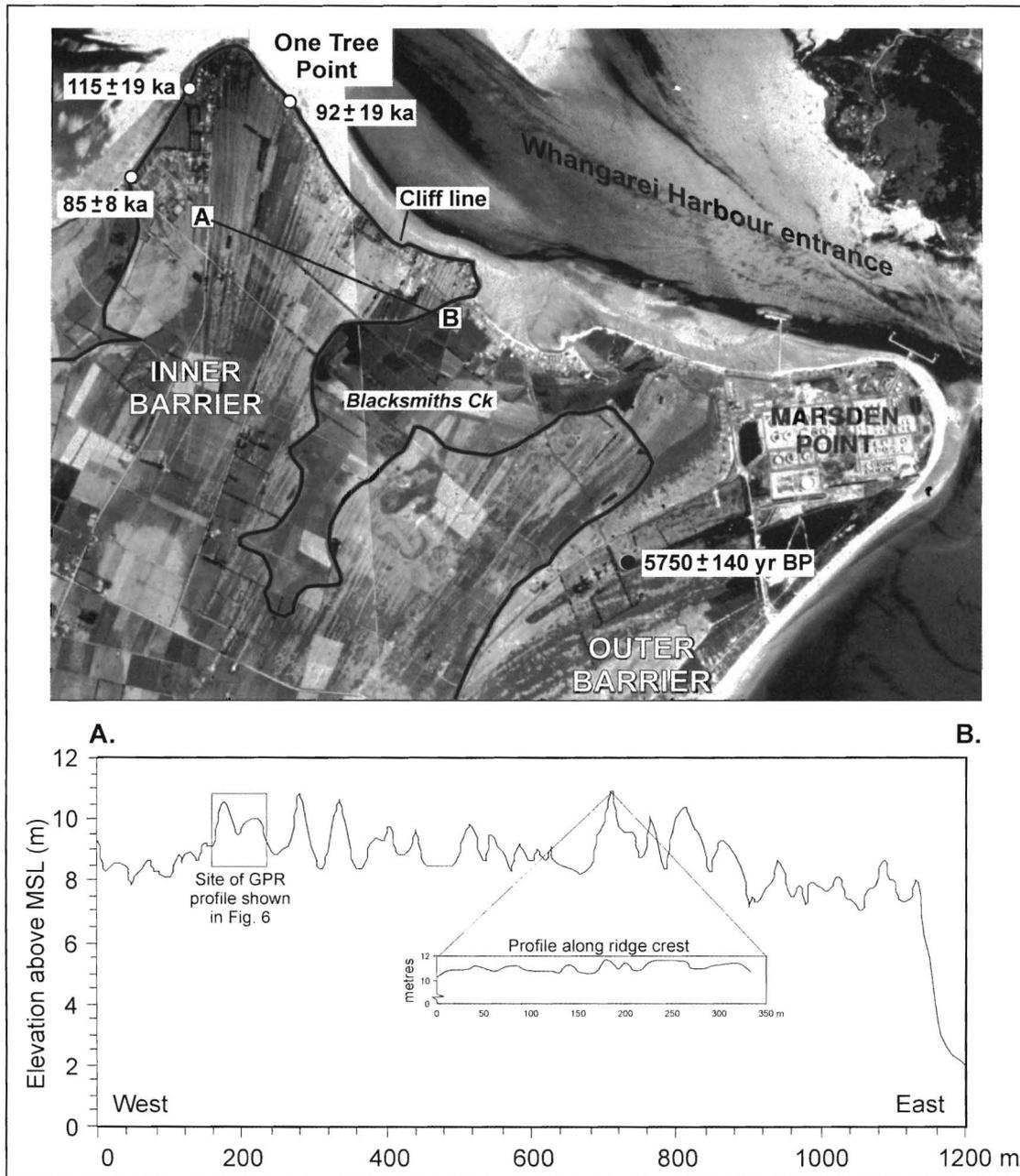


Figure 2. Air photo of One Tree Point, showing linear beach-ridges covering the western part of Bream Bay barrier at the entrance to Whangarei Harbour with a cross-sectional profile of ridges and swales along transect A-B. Site localities for three thermoluminescence ages on dune sand are also indicated. Dunes on the outer barrier are mid-Holocene in age based on a radiocarbon date of 5750 ± 140 yr BP reported by Osborne (1983).

The northeast to east sector is the principle direction of swell incidence to the Bream Bay coast. During the period of the NIWA wave-rider deployment waves from the northeast quadrant (0° – 80°) arrived for 76% of measurement time. In contrast, wave approach from the southeast quadrant (100° – 180°) was relatively infrequent, occupying 16% of measurement time, due to the shelter provided by islands in the Hauraki Gulf and the Coromandel Peninsula (Figure 1).

One Tree Point is afforded further shelter from waves by the promontory of Bream Head, which forces waves arriving from the northeast sector to refract fully before reaching the shoreline. In addition, swell waves cross a 3-km reach of shallow (<6 m) water occupied by an ebb-tidal delta located seaward of the Whangarei Harbour entrance. This delta comprises a sand shoal complex that is contiguous with the beach face, producing a low gradient nearshore zone that has a dis-

sipative effect on incident waves. This observation is supported by a wave refraction model for northern Bream Bay that shows focusing of wave energy on the shoreline to the south of the ebb-tidal delta (DUDER and CHRISTIAN, 1983).

Tidal range as measured at Marsden Point at the entrance to Whangarei Harbour during a 15 month period in 1984–1985 ranges from 1.1 m at neaps to 2.6 m at springs (ROYAL NEW ZEALAND NAVY, 1985). However, storm setup and surge along the north-east coast of North Island can elevate mean water level several metres above mean sea level, as demonstrated by the 0.82 m surge at Marsden Point in July 1978 (HUME, 1979). This event resulted in approximately four metres of foredune retreat at Marsden Point.

Sediment Sources

There are a limited number of sediment sources for the Bream Bay barrier. River input of sediment to the shoreline is negligible due to the presence of Whangarei Harbour, a broad estuary covering 100 km² that effectively traps all sand-sized sediment arriving from the catchment. Also, streams discharging into Whangarei Harbour drain relatively small catchments, covering a combined area of 300 km² (MILLAR, 1980). Inputs from erosion of headlands and cliffs are also relatively low, due to the resistant volcanic (andesite) lithology of promontories at Bream Head and Bream Tail (Figure 1). Therefore, the primary sediment source for barrier construction has been nearshore and inner shelf deposits on the floor of Bream Bay (SCHOFIELD, 1970). These deposits belong to the Hauraki B Sand Facies (typical composition: 67% feldspar; 25% quartz; 4% mafic minerals, and; 4% rhyolitic rock fragments; SCHOFIELD, 1970), which is interpreted as a reworked derivative of the Hauraki A Sand Facies. The Hauraki A Facies is found to the south of Bream Bay in the Hauraki Gulf and has a richer mafic and rock residue content. Both Hauraki A and B Facies derive from the rhyolitic provenance of central north island and were delivered to the continental shelf by the Waikato River during low sea level of the last glacial maximum (SCHOFIELD, 1970).

ONE TREE POINT SAND RIDGES

Morphology

The One Tree Point ridges are striking for their uniform morphology, characterised by linear planform and broadly consistent crest elevations (Figure 2). The elevation of ridge crests ranges from 8 to 11 m above present mean sea level, with a distinct eastward (seaward) trend toward lower ridge heights. The height between ridge crests and adjacent swales varies between 0.5 and 2.6 m, and spacing between crests ranges from 20 to 85 m. In cross-section, all ridges are near symmetrical, with seaward and lee slopes ranging from 4–5°, resulting in ridge widths of 10–70 m. The orientation of ridges does vary, progressing systematically from true north at the innermost ridge to bearing 23° (true) at the most seaward ridge. Ridge length also differs, ranging between 200 m and 2 km, but this is largely a function of position relative to eroded sections of the barrier.

Sedimentary Facies

Method

Field mapping of the One Tree Point deposits involved survey of the elevation and thickness of sedimentary facies along 3.4 km of cliff outcrop. Each facies was sampled for grain size analysis on 18 samples using a 1.8 m long settling tube with computerised data collection and processing of summary statistics. Data presented here is based on mapping of the local type-section exposed in a cliff face along the west facing shore of One Tree Point (Figure 3). This 8-m high section reveals the internal structure and sedimentology along a strike-section of one ridge.

Results

Three sediment facies are recognised, as follows.

Facies 1. The lowermost facies in outcrop is a medium- to coarse-grained sand (moderately-sorted) comprising mostly quartz but with minor (<1%) amounts of heavy mineral (titanomagnetite) that are organised as millimetre-thick laminae in small-scale, trough and planar cross-beds (Figure 4a). Locally, fossil imprints of *Pecten* (scallop) shells and isolated gravel clasts are preserved near the base of the cliff section. This facies is of unknown thickness and in places is sub-lithified and dark brown in color, indicating B-horizon development in a podzolic soil profile.

Facies 2. A gradational contact defines the upward transition from facies 1 to horizontal tabular-bedded and laminated, fine- to medium-grained sand (moderate- to well-sorted) of mixed quartz and mafic mineralogy. Laminae are highlighted by heavy mineral concentrations, generally less than one centimetre thick (Figure 4b). Locally, burrow traces (*e.g.* *Skolithos*) preserve the variable feeding and dwelling behaviour of infauna, but at relatively low density (Figure 4c). This deposit has an average thickness of 2.5 m and its upper contact is defined by a continuous planar bed of heavy mineral sand that in the type section follows a northward strike slope of about 1° and ranges in thickness from 5 to 50 mm (Figure 3). This uppermost heavy mineral bed is also exposed in cross-section at other locations along the One Tree Point cliff exposure, where it dips seaward at 3° to 6°.

Facies 3. The uppermost facies in the type-section comprises a 2 m-thick deposit of generally massive quartz sand (well sorted). Local physical structures include indistinct medium- to large-scale trough cross-bedding and high-angle planar cross-bedding that lack strong definition in outcrop due to the quartz-dominant mineralogy (Figure 3). Where exposed in cross-section along the north-east shore of One Tree Point this facies is thickest beneath ridges and in intervening swales is overlain by 1–2 m of peat

Along the northeast facing shoreline of One Tree Point the contact between facies 2 and facies 3 can be traced along 3.4 km of dip-section. At many localities this facies contact is defined by the position of the uppermost heavy mineral bed, though not exclusively. The elevation of this contact dips seaward from a maximum of +6 m to +3 m with variations of ±2.5 m from the trend line (Figure 5).

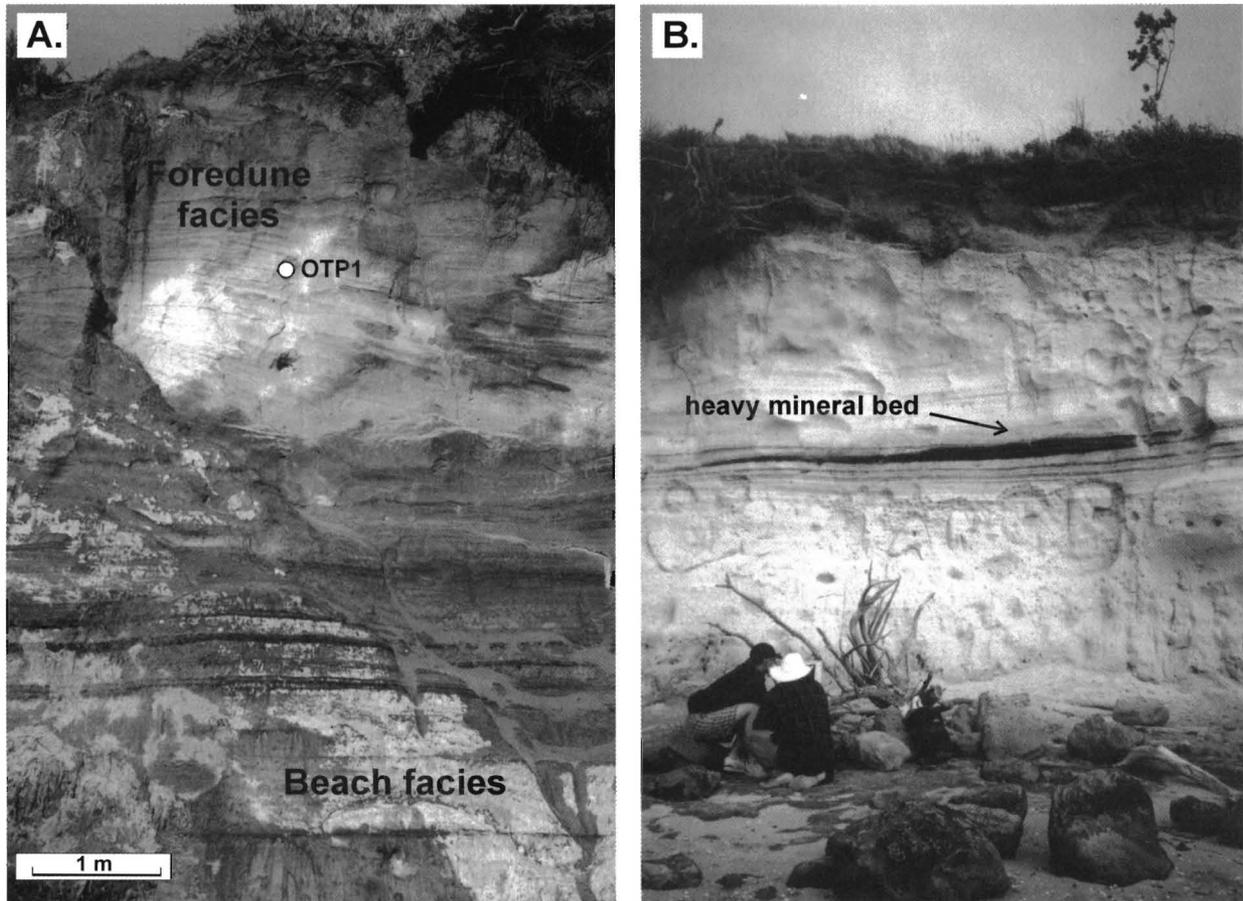


Figure 3. Cliff exposure at the type-section for One Tree Point beach ridges (Grid reference: NZMS260-Q07 417966). (A) Large-scale dune cross-bedding overlying horizontal tabular-bedded beach facies. The location of TL sample OTP1 is also indicated. (B) Heavy mineral bed at the contact between foredune and beach facies at 4.6 m above present MSL. This deposit is interpreted as a high tide swash deposit that approximates paleo sea-level at One Tree Point during the Last Interglacial highstand.

Ground Penetrating Radar Stratigraphy

Method

Subsurface mapping of a representative cross-section over the One Tree Point ridges was conducted using a ground penetrating radar (SIR-10A+ Geophysical Survey Systems Inc.) linked to a 35 MHz (Radarteam) monostatic antenna. Data collection was undertaken in continuous mode along a 600-m section of paved, straight and flat lying road that crossed 14 ridges. The single antenna was mounted on the back of a vehicle, and data collected at speeds of approximately 10 km/hr, with the antenna approximately 10 cm above the surface. Continuous mode collection was favoured over step mode in this instance because it allowed a very large number of scans to be collected at close measurement interval in a fraction of the collection time of step-mode. Step mode may have provided slightly more depth penetration, however a very large number of scans need to be collected to obtain the same image quality as continuous mode.

Post-processing was carried out using RADAN v1.4 software. Horizontal and vertical finite impulse response (FIR)

filters were applied to remove minor antenna ringing, and gain adjustments made to increase signal amplitude. Conversion from travel time to depth was calculated assuming a dielectric value of six, based on other radar work in these types of conditions (e.g. DAVIS and ANNAN, 1989; JOL and SMITH, 1991).

Results

The stratigraphy of the One Tree Point ridge system as recorded by radar is summarised here by a 55 m section of survey line that includes two ridges and a swale, with a mean elevation of 9 m above present sea level. The position of the survey line is shown in Figure 2. The radar image shows five radar facies, with the following characteristics (Figure 6a):

Radar Facies I. The basal radar facies is characterised by an essentially reflector-free area of the image which is indicative of a uniform lithology and structure that is either massive or contains bedding at a scale beyond the resolving power of a low frequency (*i.e.* 35 MHz) radar antenna.

Radar Facies II. This is the most extensive facies on the

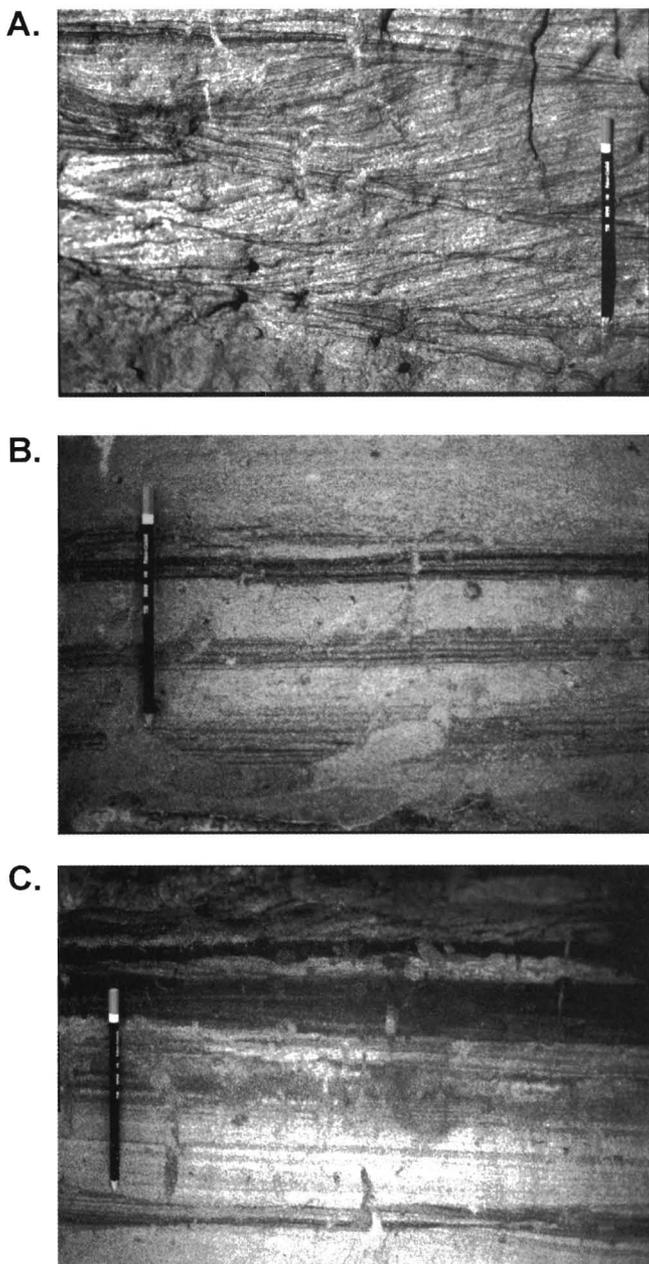


Figure 4. Examples of sedimentary structures exposed in cliff section at One Tree Point, showing (A) small-scale trough cross-bedding in medium-grained sand of nearshore facies, (B) tabular and laminar bedding in fine- to medium-grained sand of the beach facies, and (C) heavy mineral beds in the upper part of the beach facies with vertical (*Skolithos*) burrow traces. Pencil in photos is 18 cm long.

survey line. It is dominated by very high amplitude, discontinuous reflectors that dip to seaward at an average angle of 10° . The thickness of this facies varies from 3 to 5 m and appears thickest directly below ridge crests. The upper limit of the facies is also variable, being shallowest (+3 m above MSL) beneath ridge crests and deepest (-1 m below MSL) below the swale.

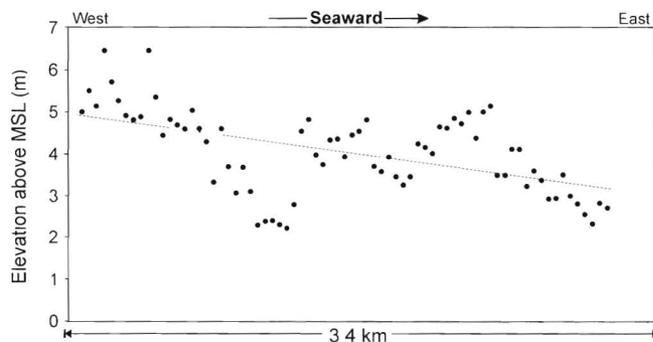


Figure 5. Plot of elevation of the contact between beach and dune facies exposed in cliff section along the north-east facing shoreline of One Tree Point, showing an overall seaward reduction in height of the paleo-beach face that is interpreted to reflect falling sea level. The slope of the dashed line was calculated using linear regression. Outliers on this plot are attributed to local variations in beach morphology (e.g. beach cusps).

Radar Facies III. Situated immediately seaward of the first foredune ridge on the survey line and within a swale, this radar facies is characterised by horizontal, moderate- to high-amplitude reflectors that extend a maximum distance of 10 m. Maximum observed thickness of this facies is 2.8 m.

Radar Facies IV. Located to seaward of facies III and at the same depth interval, this radar facies displays low amplitude, discontinuous horizontal reflectors and reflector free areas, indicating weak to non-existent dielectric contrasts in subsurface sediment perhaps associated with uniform lithology.

Radar Facies V. This facies is characterised by discontinuous, high amplitude (darker shades in Figure 6a) convex reflectors positioned between +9 m (ground surface) and +4 m. The facies is shown at two locations in Figure 6a, centred on 10 m and 50-m positions of the survey line where it coincides with two ridges. Beneath the first ridge on the survey line, seaward sloping reflectors dip at about 30° .

Luminescence Age of Ridges

Method

Three thermoluminescence (TL) ages on sands taken from the cliff outcrop at One Tree Point are reported here as a preliminary step toward establishing the absolute age of the raised ridges on Bream Bay barrier. All samples were collected from cross-bedded sand interpreted as aeolian deposits, and therefore most likely to have undergone resetting of the TL signal prior to burial. Since the absorbed dose rate to the materials was calculated only from the bulk sediment sampled for dating, care was taken to sample at least 1 m from heavy mineral beds to minimise the affect of radiation originating from these sediments. Samples of modern sand exposed to solar radiation were collected for determination of residual TL. Analysis was performed at the University of Wollongong Luminescence Laboratory on the 90–125 micron diameter fraction using the combined additive/regenerative technique. Uranium and thorium activity was measured by thick source alpha counting using a 42 mm-diameter scintillation screen of 28 sample aliquots.

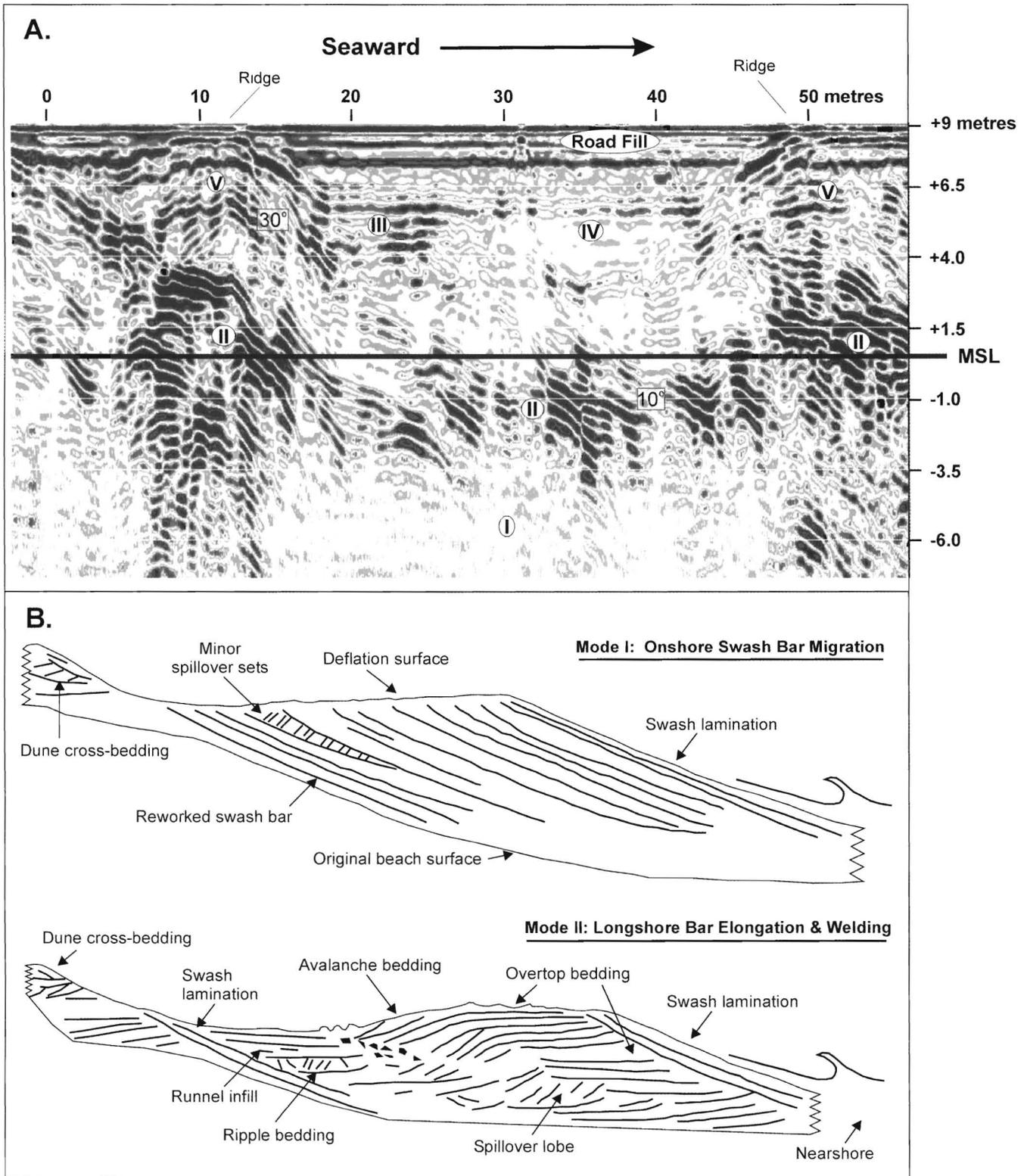


Figure 6. (A) Ground penetrating radar image of ridge and swale structure, One Tree Point, collected using GSSI 35 MHz single antenna in continuous sampling mode. The location of survey line is shown in Figure 2. (B) Two styles of beach-ridge architecture used as models for interpreting the mode of ridge formation at One Tree Point (adapted from Carter, 1986).

Table 1. Thermoluminescence results, One Tree Point dune sand. Sample locations are shown in Figure 2.

Sample	OTP1	OTP2	OTP3
Plateau region (°C)	300–500	275–400	300–450
Analysis Temp (°C)	375	350	375
Palaeodose (Gy)	95.9 ± 14.5	107 ± 22.0	78.4 ± 6.2
K content (%)	0.55 ± 0.1	0.8 ± 0.1	0.6 ± 0.1
Rb content (ppm)	50 ± 25	50 ± 25	50 ± 25
Moisture content (% by weight)	2.9 ± 3.0	3.8 ± 3.0	4.5 ± 3.0
Specific activity (Bg/kg U + Th)	7.8 ± 0.2	9.6 ± 0.3	8.2 ± 0.3
Cosmic ray dose (μGy/yr assumed)	150 ± 50	150 ± 50	150 ± 50
α, β & γ dose rate (μGy/yr)	833 ± 49	1168 ± 49	925 ± 48
TL age (Ka)	115 ± 19	92 ± 19	85 ± 8

Results

The TL age results are as follows: 115 ± 19 ka for sample OTP1 taken from a ridge at the western edge of the barrier; 92 ± 19 ka for sample OTP2 collected from a ridge approximately midway in the ridge sequence, and; 85 ± 8 ka yielded sample OTP3 from the southwestern edge of the barrier (Figure 2; Table 1). While not providing a detailed or ordered chronology of ridge formation, these results do point to formation of the One Tree Point portion of the Bream Bay barrier during the Last Interglacial period, most likely spanning δO¹⁸ isotope substages 5e (~125 ka) to 5a (~80 ka) (MARTINSON *et al.*, 1987). Within this age range, the most probable period for deposition at an elevation of 4–5 m above present sea level is substage 5e when sea level stood at this height (CHAPPELL and SHACKLETON, 1986). This age assignment rests upon the assumption that tectonic uplift has not occurred in Bream Bay since formation of the One Tree Point beach ridges. This assumption of tectonic stability for the Northland region is in accord with the interpreted late Quaternary uplift history for North Island (GIBB, 1986; PILLANS, 1986, 1990).

INTERPRETATION

On the basis of the marine to estuarine context of the One Tree Point deposit, the facies succession described here is interpreted as a record of progradational deposition, incorporating nearshore, beach and dune facies. Thus, sediment facies 1 is recognised as a nearshore deposit with key criteria being stratigraphic position, grain size and sedimentary structures. In particular, planar cross-beds and trough cross-beds in coarse sand are interpreted as signatures for two- and three-dimensional bedforms, respectively (ASHLEY, 1990). Bedform development of this type indicates a relatively energetic sediment transport regime, with nearshore being the most likely environment in this context. The presence of scallop shell imprints in this facies is also consistent with a shallow marine environment where some shell valves may be deposited in bedform troughs and rapidly buried.

The planar and laminar bedding that characterises sediment facies 2 is interpreted as a product of wave depositional processes on a beach face, with swash sorting the most likely mechanism for producing the heavy mineral concentrates and laminae (LI and KOMAR, 1992a,b). The uppermost heavy mineral bed, situated at about +4 m, is therefore recognised as a high tide (storm?) swash deposit and hence as a proxy of maximum paleo sea-level.

Sediment facies 3 is interpreted as a foredune deposit, on the basis of larger scale cross-bedding and stratigraphic position beneath a ridge crest. However, because not all ridges exposed at One Tree Point display heavy mineral beds at the boundary between beach and foredune facies, facies 3 may also incorporate berm deposits of the upper beach. In these instances, the contact between beach and foredune is interpreted as gradational.

The GPR data from One Tree Point are also interpreted within the framework of a progradational succession of facies, as follows. Radar facies I is located at the same depth interval as the basal nearshore sediment facies observed in cliff exposures. In outcrop, this facies includes a quartz-dominant lithology with a range of mm- to cm-scale sedimentary structures. The scale of these bedding styles is considered too small for resolution by low frequency radar, hence the reflector free character of this radar facies. Notwithstanding, the stratigraphic position of this radar facies is the main basis for its interpretation as an image of a nearshore deposit.

In radar facies II, the high amplitude character of seaward-dipping reflectors is a function of strong dielectric contrasts in the subsurface, most likely related to variations in mineralogy. Such variations are consistent with interbedding of quartz-dominant and heavy mineral-dominant sands, as seen in outcrop. The seaward dip to these reflectors also correlates well with the dip of beach facies observed in ridge cross-section. Thus, on the basis of reflector amplitude, geometry and stratigraphic position, radar facies II is interpreted as an image of an accreted beach face.

Radar facies III and IV both display horizontal reflectors but differ in terms of the amplitude of reflectors, with the lower amplitude of facies IV reflectors interpreted as a function of weaker dielectric contrasts within the sediment. This low dielectric contrast could reflect a more homogeneous (quartz-dominant) lithology. Because these radar facies lie between two ridges and have horizontal reflectors, it is reasonable to assume that they represent some style of runnel infill. CARTER (1986) presents a depositional model for a runnel infill in the context of a longshore bar welding to a beach face (Mode II in Figure 6b). This model is used here to suggest that the horizontal bedding imaged in radar facies III/IV represents infill deposits of a shallow runnel located to landward of another ridge.

The character of radar facies V is also interpreted in this framework. The diagnostic feature of this facies is the set of

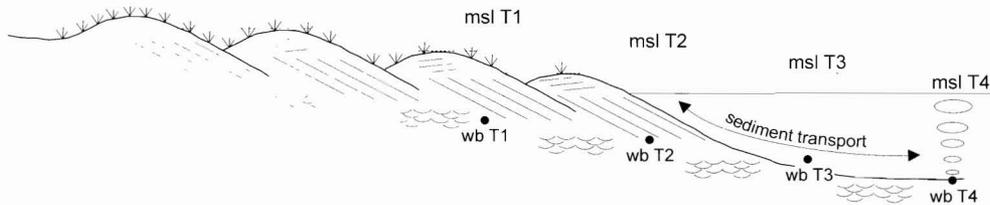


Figure 7. Summary schematic model for One Tree Point beach-ridge system, highlighting the role of swash processes, marine-dominated sediment supply and falling relative sea-level. “msl T1 . . . T4” denotes mean sea level at time 1 to time 4; “mwb T1 . . . T4” denotes maximum wave base (limit of wave-initiated sediment transport) at time 1 to time 4. Not to scale.

convex reflectors, which resemble bedsets of a longshore bar that has become welded to a beachface, forming a swash bar (Mode II in Figure 6b). On the radar profile, the landward-dipping arm of each convex reflector in facies V is interpreted as berm bedding and the seaward-dipping limb is taken to correspond to swash laminae.

DISCUSSION

Development of Uniform Ridge Shape

Assuming that the wave regime currently operating in Bream Bay also prevailed during the Last Interglacial, the One Tree Point ridges are aligned to the inferred dominant swash direction for waves that have refracted upon entering Bream Bay. Replication of this swash-aligned form among all ridges in the One Tree Point system is strong evidence for a dominantly shore normal sediment transport regime. The importance of swash processes to ridge formation is also evident from the preservation of seaward-dipping laminae in the beach facies exposed in outcrop and imaged in GPR data.

The symmetrical cross-sectional profile of ridges and lack of evidence for reworking suggests that each ridge remained within the dune, beach and nearshore sediment exchange system for a limited time. Differences in individual ridge height and width are attributable to variations in sediment supply which could in turn be linked to the length of time a particular ridge was part of the sediment exchange system. However, this time period was short enough to preclude blow-out formation or storm washover but sufficient to allow accretion of ridges to supratidal levels, stabilisation by dune plants, and eventual foredune formation. Based on studies of modern foredune ridges in eastern Australia, it is likely that individual ridges became stranded within less than a decade (HESP, 1984).

The following stages in the formation of a sand ridge at One Tree Point are recognized: (i) onshore migration of a nearshore bar; (ii) accretion of a beach berm via bar welding on the lower beach face, swash accretion on the upper beach face and overwash deposition on the berm (backshore); (iii) accretion of an incipient continuous foredune with windblown sand, and; (iv) stabilization of the foredune by pioneer grasses and sedges with further minor dune accretion.

Because development of a beach-ridge and foredune is partly a function of the interaction between sand supply and vegetation growth, the formation and preservation of a discrete ridge and swale topography requires that sediment supply be

intermittent to periodic. If it were continuous, it would be difficult for vegetation to maintain a uniform ridge form and a more irregular topography would likely result (HESP, 1984). Given that the One Tree Point system does preserve a clear ridge and swale topography and that sediment can only have been sourced from offshore, it follows that onshore sand transport must have occurred during episodes of particular wave, wind and sea-level conditions.

In the context of marine-dominated sediment supply a schematic model is offered to account for shoreline progradation at One Tree Point (Figure 7). The model incorporates a set of physical mechanisms and related sedimentary processes that occur simultaneously but operate at different time scales. These mechanisms should, therefore, be viewed as a nested hierarchy of depositional controls.

The key variable in this model is relative sea-level. The seaward dip in elevation of the beach-dune facies contact at One Tree Point is interpreted as evidence for a fall in relative sea level; hence One Tree Point is an example of forced regression (*sensu* POSAMENTIER *et al.*, 1992), but with an abundant sediment supply providing for quasi-continuous deposition. Based on luminescence age results, this sea-level fall most likely occurred toward the end of the Last Interglacial period (isotope substage 5e to 5a). As a consequence, nearshore and inner shelf deposits were progressively introduced to wave reworking and onshore transport, providing large amounts of sediment so that coastal deposition was maintained. This is represented in the model by successive time steps (T1 . . . T4) depicting the shift in position of maximum wave base and sea level (Figure 7). With each time step, at least one ridge formed and was preserved via the processes outlined above.

In the absence of detailed chronological information for each of the 20 beach ridges comprising the One Tree Point system, it is not possible to resolve the number of ridges belonging to each stage in sea-level fall nor to determine the absolute age range for the ridge system. However, it is likely that the fall in relative sea-level was relatively rapid, perhaps on the order of centuries. A rapid sea-level fall would favour isolation of beach ridges from the nearshore sediment exchange system and preservation of the ridge morphology, as is the case at One Tree Point. This scenario is consistent with the conclusions of NEUMANN and HEARTY (1996) who argue for rapid sea level fall following the Last Interglacial commencing about 118 ka on the basis of stranded notches and reef corals on the Bahamian coast.

The style of shoreline progradation interpreted for the Last Interglacial at One Tree Point is quite different to that for the Holocene, with modern coastal deposits of Bream Bay barrier characterised by hummocky dune topography. Beach ridges are not clearly preserved on the outer barrier (Figure 2). This contrast may be a function of the more exposed position of the Holocene shoreline compared to the paleo-shore of One Tree Point, or it may indicate a contrast in the nature of mechanisms driving coastal sedimentary processes.

CONCLUSION

The One Tree Point portion of the Bream Bay barrier is an important site because it records coastal progradation under a marine-dominated supply and assumed falling relative sea-level. The sheltered setting with regard to incident swell waves has provided for coastal deposition strongly influenced by shore normal sediment transport with swash processes recognised as the primary agent for initiating sediment accretion and ridge formation. The uniform ridge morphology and lack of erosion surfaces within deposits indicates that each ridge formed relatively quickly and was rapidly stranded from the nearshore, beach and dune system.

In terms of recognising cycles in the depositional record that may be related to variability in external forcing functions such as climate (e.g. ENSO), it is tempting to call upon the regularity of ridge form as evidence for cyclic repetition of particular depositional conditions. Other workers have used beach ridges to argue for small-scale (decimetre) oscillations in sea (and lake) level and propose that preservation of a ridge requires such a fluctuation (TANNER, 1995; THOMPSON and BAEDKE, 1995, 1997). In the case of the One Tree Point deposit it is difficult to isolate any such pattern from the overall trends identified in this study. Indeed, it is not necessary to call upon cyclic variations in sea level to explain this particular beach ridge system. Falling sea-level, marine-dominated sediment supply and a shore-normal sediment flux regime are adequate (and demonstrable) interpretations in this case.

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