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Origin and Formation of an Estuarine Barrier Island, Tapora Island, New Zealand

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ABSTRACT

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Barrier islands in sheltered settings are rare coastal geomorphic features. Here we present a case study of controls on the evolution of Tapora Island, North Island, New Zealand. Tapora Island is an active barrier island located opposite the entrance to the Kaipara Harbour on a high-energy coast. Subsurface facies form an aggradational barrier island succession from subtidal to subaerial elevations. This facies succession, combined with surface samples and geomorphic and geologic relationships, indicates that Tapora Island is the most recent barrier island at this location in the estuary and forms part of a prograded coast opposite the entrance. Wave data indicate that ocean swell waves penetrate the inlet for approximately 2 hours either side of high tide and are capable of transporting sand onto the island. The combined effects of swell waves, abundant sediment supply, and exposed aspect are the critical factors that have formed the barrier island. Despite the "sheltered' estuarine setting, Tapora Island has formed under conditions that are more akin to open ocean coasts. The origin and development of Tapora Island broadly conforms to the accumulating barrier island model.

ADDITIONAL INDEX WORDS: *Swell waves, fetch-limited, Holocene, facies, tidal-modulation.*

INTRODUCTION

Barrier islands occur on approximately 13% of the world's coastlines (Cromwell, 1973). They are more common on wave-dominated and mixed-energy coasts characterised by abundant sediment supply (usually sand) and a relatively low-gradient shelf (Stutz and Pilkey, 2001). Along such coasts, barrier islands often form a chain of low relief offshore islands, separated by tidal inlets that allow sediment and tidal exchange with the open ocean, and are backed by a low-energy lagoon (Oertel, 1985).

The origin of barrier islands has been the subject of considerable debate (*e.g.,* Stutz and Pilkey, 2001). However, there is general agreement that the development of barrier islands results from the effects of waves and tides overprinted by sea level transgressions and regressions. Spatial and temporal patterns in barrier island facies will thus reflect the interaction between sediment supply and sea level rises and falls (*e.g.,* Nishikawa Ito, and Sugimoto, 1998).

The interest in understanding the origin and depositional histories of barrier islands has culminated in a number of alternative theories regarding their formation and evolution. An approach proposed by Otvos (1981) treats barrier islands as "accumulating" sediment bodies, originating from the transport of inner-shelf and nearshore sediment toward the coast by ocean swell waves (*e.g.,* Davis, 1994; Reinson, 1984, 1992). The accumulating model has formed the basis of numerous studies comparing the processes of formation and sedimentary facies relationships in barrier island sequences (*e.g.,* Glaeser, 1978; Hayes, 1994; Heron, *et al.,* 1984; Leatherman, 1985; Thom and Roy, 1985). However, high-resolution hydrodynamic and geophysical studies of processes and deposits associated with barrier island systems (*e.g.,* Siringan and Anderson, 1993) indicate that this model cannot fully explain the formation of all barrier islands. This is because few modern prograding barrier island facies successions contain nearshore sediments below lagoon deposits landward of the active shore face (*cf.* Reinson, 1992).

Historically, studies of barrier islands have largely been restricted to examples located on open ocean coasts, principally the southern and eastern margins of the United States (*e.g.,* Fields, Katuna, and Mirecki, 1999; Heron *et al.,* 1984; Hippensteel and Martin, 1999; Leatherman, Rice, and Goldsmith, 1982; Morton, Paine, and Blum, 2000; Thieler *et al.,* 2001). Cooper, Lewis, and Pilkey (2007), Cooper, Pilkey, and Lewis (2007), and Pilkey, Cooper, and Lewis (2009) provide the first systematic global study of barrier islands in sheltered settings, highlighting the fetch-limiting conditions associated with their formation and evolution. In a fetch-limited setting, locally generated waves are the primary mechanism that drives barrier island evolution. In the context of the global survey of fetch-limited barrier islands, we present a field-based study of Tapora Island, Kaipara Harbour, New Zealand. In their study, Pilkey, Cooper, and Lewis (2009) refer to Tapora Island as an example of an inlet-associated barrier island. The location of Tapora Island inside a large es-

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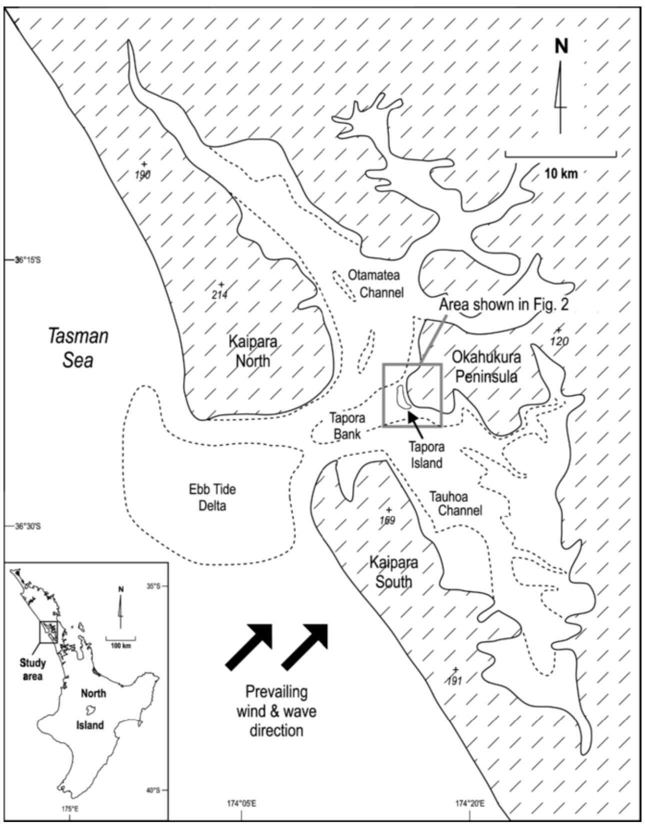

Figure 1. Map showing the location of Kaipara Harbour, Tapora Island, and features cited in the text. Spot heights are in metres.

Table 1. *Summary properties for Kaipara Harbour.*

Feature	Dimensions
Surface area	947 km^{2a}
Exposed area (at low tide)	409 km^{2a}
Cross-section (mid spring tide)	82,000 m^{2a}
Spring tide range	2.68 m^{a}
Neap tide range	1.52 m^{a}
Spring tidal prism	1990 $\times$ 10^{6} m^{3a}
Neap tidal prism	1130 $\times$ 10^{6} m^{3a}
Entrance width	7.5 km^{a}
Entrance depth (max.)	35 m^{a}
Ebb tide delta volume	1.23 $\times$ 10^{10} m^{3b}

[a] Heath (1975).

[b] Hicks and Hume (1996).

tuary, partially protected from ocean swell waves, and exposed to upper-meso tidal ranges raises an interesting question that we address in this paper. What are the sediment dynamics and supply conditions responsible for the formation of a barrier island inside an estuary? Our study extends the work of Cooper, Pilkey, and Lewis (2007), and Pilkey, Cooper, and Lewis (2009) through an analysis of the finer-scale details of process and form using stratigraphy and oceanography.

REGIONAL SETTING

The Kaipara Harbour is a 947 km^2 semi-enclosed coastal embayment on the west coast of the North Island, New Zealand (Figure 1; Table 1). The harbour occupies a drowned river valley network that has been repeatedly inundated throughout the late Quaternary (Ballance and Williams, 1992; McMahon, 1994). Associated with rises in sea level, sand was principally transported from the continental shelf supplemented by longshore transport to form the barriers, shoals, and beaches that now partly occupy the antecedent river valleys (Hicks and Hume, 1996; Schofield, 1975). Strong southwest and westerly winds associated with the regular easterly passage of low pressure systems across the Tasman Sea (Figure 1) generate ocean swell waves that regularly attain heights of $>$3 m with periods of between 8 and 15 s (Pickrill and Mitchell, 1979). These ocean swell waves rework nearshore shelf sediment towards the mouth of the Kaipara Harbour.

Approximately 40% of the area of Kaipara Harbour is occupied by sand shoals (Table 1). The shoals are constantly rearranged by strong tidal currents that are produced by the exchange of between 1.1 and 1.9 million m^3 of seawater between the harbour and ocean. The harbour is partially protected from the high-energy ocean swell waves by two $>$200 m high sandy barriers (Kaipara North and South) of Pleistocene and Holocene age (Schofield, 1989). However, ocean swell waves do penetrate the entrance and affect the inlet coast inside the harbour.

Tapora Island is 3.5 km long and 1 km wide, and located $\sim$8 km east of the entrance to Kaipara Harbour. The island consists of a dissipative beach with a wide backshore, backed by a dune complex that grades to an intertidal back-barrier marsh and sand flat that separates it from the Okahukura Peninsula (Figure 1). Tapora Island is fronted by a wide, shallow-gradient, subtidal to intertidal shoal known as Tapora Bank that is flanked by two deep channels (Figure 1). A comparison of aerial photos and published maps indicates that Tapora Island has grown to the south about 2 km over the last 100 years (Smith, 1999). Spring tidal ranges in the vicinity of the island attain $>$2.5 m and waves regularly attain $>$1.5 m in height (Parnell, 1995).

METHODS

A level survey was undertaken across Tapora Island in April 1998 extending from 0.9 m below chart datum, 470 m west of the island, to the landward edge of Okahukura Peninsula, a distance of approximately 1650 m (Figure 2). Surface elevations at 54 stations along the survey transect were determined using a Sokkia Set5E total station and prism. The surveyed elevations were then corrected to the level of mean sea high water springs (MHWS) at Pouto located on North Kaipara Head (*i.e.,* 3.2 m above chart datum; Land Information New Zealand, 2008).

A total of 31 surface sediment samples were collected from different sedimentary environments to characterise the texture and composition of the sedimentary deposits of Tapora Island (Figure 2). Two 1-m^3 pits were also dug in the beach face to document shallow subsurface structures and facies.

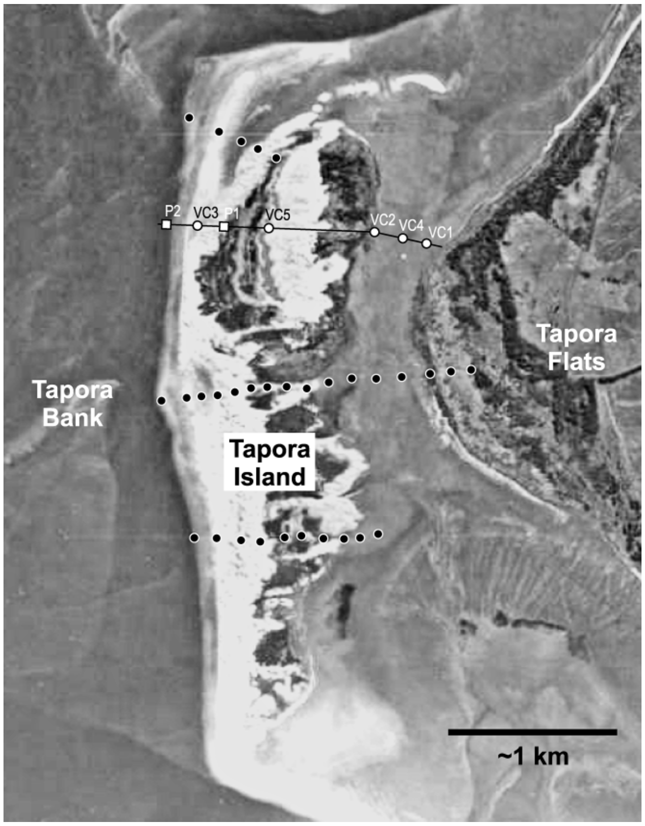

Figure 2. Aerial photograph of Tapora Island and western margin of Okahukura Peninsula showing location of cross-shore survey transect, vibrocores (○), pits (□), and surface samples (●). Over the last 100 years Tapora Island has prograded south by >2 km (Smith, 1999).

The first pit (P1) was dug between the beach berm and foredunes at the position of MHWS and the second (P2) was dug at low tide at the position of mean low water springs (MLWS). A total of five samples of 250 g were taken from the sides and base of each pit. Finally, vibrocores were collected at five sites across the survey transect from the shore face, interdune swales, and back-barrier flats (Figure 2). Sites were chosen to penetrate as much of the barrier island sequence as possible. Core lengths ranged from 3 to 5.5 m with less than 5% compaction.

In the laboratory, approximately 50 g of sediment was subsampled from the bulk surface samples, pit samples, and down each core for analysis of grain size and physical properties. Individual bulk samples were rinsed in tap water, sieved through a 1-mm mesh, and then air dried at 20°C for 24 hours. The bulk composition of the coarse fraction for 20 samples was examined using an Olympus S740 binocular microscope. The bulk grain size distribution was determined for the fine fraction using a GALAI laser particle sizer, which determines the grain size distribution by time of transition of particles in a constant stream of sediment (Jantschik, Nyffeler, and Donard, 1992; Molinaroli *et al.,* 2000). Each sample was initially dispersed in Calgon, suspended in tap water, and then passed in front of the laser. Samples were run until a 99% confidence was obtained in the measurements. Repeat analyses indicate that this procedure produces grain size distributions with modes accurate to ±0.5 μm.

Conventional radiocarbon ages were determined at the University of Waikato Radiocarbon Dating facility on a shallow marine shell from a core recovered from Tapora flats in a separate study by Hutcheon (2006). This sample WK-17480 was calibrated using OxCal v.3.1 (Bronk Ramsay, 2001). In addition, two conventional radiocarbon ages were obtained on articulated shells collected from the beach face of Tapora Island for the Kaipara sand study (Hume *et al.,* 2003).

RESULTS

Survey Profile

Tapora Island is characterised by a shallow gradient beach of which ~500 m is exposed at low water during spring tides (Figure 3). A transition in the gradient of the beach occurs at −2.2 m MHWS; the gradient of the lower beach face is >1.5°, whereas the gradient of the upper beach face is <0.7°. The beach is backed by steep-fronted foredunes up to 5 m high, followed by a ~200 m wide deflation surface, and then by another sequence of larger transverse dunes up to 12 m high (Figure 3). Interdune swales on the deflation surface are partly vegetated and contain ephemeral freshwater ponds at ~1.0-m MHWS. Further to the east of the transverse dunes is a vegetated hummocky plain at ~1- to 2-m MHWS that

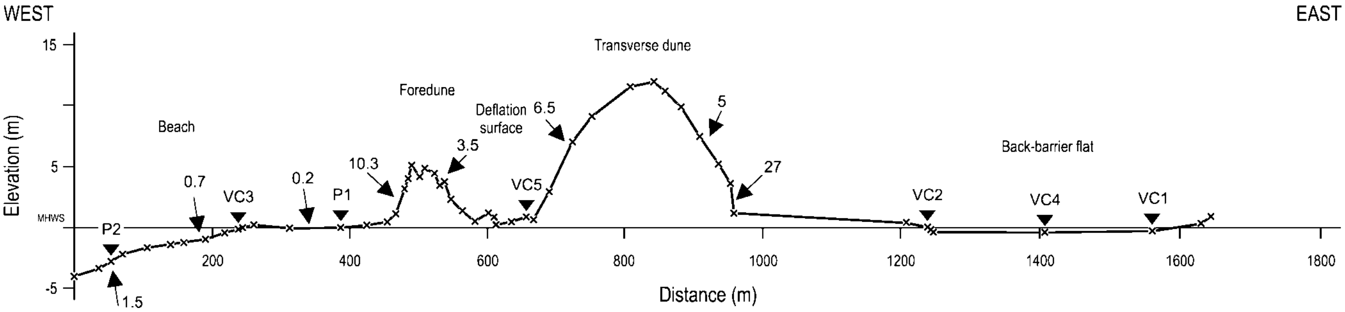

Figure 3. Cross-shore level survey profile showing elevations and gradients for the major morphological features and sedimentary facies of Tapora Island.

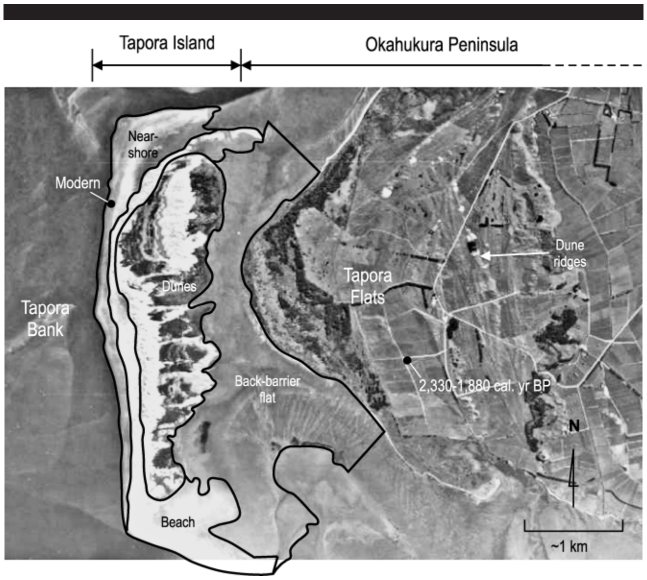

Figure 4. Map showing the distribution of surface sediment facies on Tapora Island. Locations of cores used for radiocarbon age determinations are also shown.

contains brackish swamps. This surface slopes gently landwards to a 400 m wide low-relief intertidal back-barrier sand flat, which separates Tapora Island from the mainland.

Surface Facies

Six sedimentary facies were defined from the surface samples on Tapora Island: nearshore bar, nearshore trough, beach, dune, back-barrier tidal flat, and supratidal salt marsh (Figure 4). The facies are composed mostly of moderate to very well sorted fine to medium sand consisting of subangular to subrounded quartz and feldspar grains (Table 2). Across the island, the mean grain size of the surface sediment ranges from 170 to 210 μm, and quartz and feldspar concentrations are 54%–63% and 15%–37% by weight, respectively (Smith, 1999). Marine sediment located elsewhere on the west coast of the North Island (including the entrance, shoals, and channels of the Kaipara Harbour), has a mean grain size of between 150 and 290 μm (Hume *et al.,* 2001), and quartz and feldspar concentrations of between 50%–60% and 8%–41% by weight, respectively (Schofield, 1975). The bulk texture and composition of surface sediment on Tapora Island are thus quantitatively similar to surface sediment located on the beaches of west coast of the North Island and other shoals in the Kaipara Harbour. On Tapora Island, carbonate concentrations are greatest in the nearshore trough, beach, and back-barrier tidal flat facies, where they locally attain >50% by weight. The carbonate fraction is predominantly composed of mollusc fragments, although *in-situ* and articulated shallow marine bivalves *Mactra murchisoni* and *Spisula aequilateralis* are abundant in the nearshore trough facies. Mafic grains are restricted to the upper slope of the beach facies, where they occur as thin (<0.01 m) beds. Silt-sized grains occur only in the back-barrier tidal flat facies.

Suburface Facies

Six facies were identified from sediment contained in the vibrocores and sampled in the pits (Figures 5A and 5B; Table 2). All depths are reported with respect to MHWS.

Nearshore Shell Lag

A shell lag occurs in cores VC1, VC2, and VC4 at depths of −4.7, −5.4, and −5.0 m, respectively (Figure 5A). This nearshore shell lag is composed of moderately sorted, slightly silty fine sand (Figure 5B), which attains 0.2 m thickness. Grains are mostly subangular to subrounded. Samples from this facies contain average quartz and feldspar concentrations of 59% and 33%, respectively. The carbonate fraction comprises freshly preserved, whole valves of the shallow marine bivalves *Dosinia anus* and *Spisula aequilateralis.*

Tidal Flat

Immediately seaward of Tapora Island, a bed containing abundant articulated and *in situ* valves of *Mactra murchisoni* and *Spisula aequilateralis* occurs between −3.4 to −2.8 m in pit P2 (Figure 5A). This bed consists of well-sorted fine sand (Figure 5B), which attains 0.6 m thickness. Grains are sub-

Table 2. *Sedimentary facies characteristics for Tapora Island.*

	Surface					
	Nearshore Bar	Nearshore Trough	Beach	Dune	Back-Barrier Tidal Flat	Supratidal Salt Marsh
Sediment type	Medium sand	Fine sand	Medium sand	Fine sand	Fine sand	Fine sand
Mean grain size (μm)	280	153	216	172–180	172	186
Sorting	Moderate	Very well	Very well	Well	Well	Well
	Subsurface					
	Nearshore Shell Lag	Tidal Flat	Foreshore	Beach	Lagoon	Back-Barrier Tidal Flat
Sediment type	Slightly silty fine sand	Fine sand	Fine sand	Fine sand	Silty fine sand	Fine sand
Structures	Massive	Massive	Parallel and cross beds	Parallel and cross beds	Lamination	Flaser/lamination
Mean grain size (μm)	185–220	153	170	190	180	180
Sorting	Moderate	Well	Very well	Very well	Poor	Well
Thickness (m)	>0.2	>0.6	<2.5	<3	<1.5	<1.5

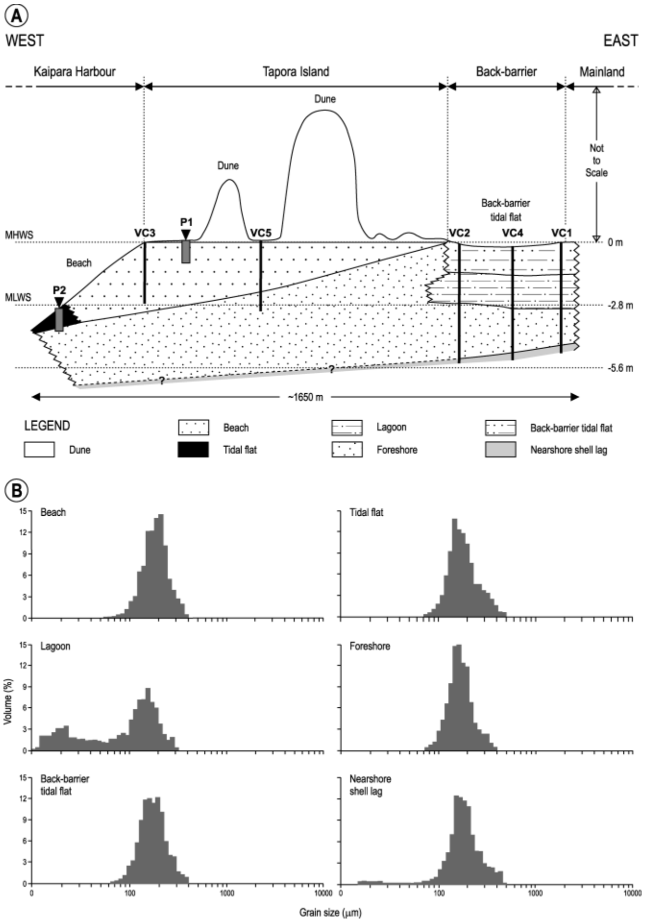

Figure 5. (A) Stratigraphy of the Tapora Island barrier island sequence. Vertical black lines are vibrocores. Location and depth of pits dug into the tidal flat and beach facies are indicated. (B) Graphs of representative grain size distributions for each of the subsurface facies.

angular. Samples from this facies contain average quartz and feldspar concentrations of 54% and 28%, respectively. The carbonate fraction consists mainly of *in situ* marine bivalves *Mactra murchisoni* and *Spisula aequilateralis.*

Foreshore

This facies occurs in cores VC1, VC2, VC4, and VC5 at −2.9, −2.8, −2.9, and 2.1 m, respectively, is up to 2.5 m thick, and comprises very well sorted fine sand (Figures 5A and 5B). Grains are subangular to subrounded. Samples from this facies contain average quartz and feldspar concentrations of 58% and 23%, respectively. The carbonate fraction is composed of whole (articulated and disarticulated) valves of *Spisula aequilateralis* and abundant shell hash. The unit is generally bioturbated throughout, but cross-beds and parallel beds containing heavy mineral layers of magnetite and ilmenite are locally present, with beds dipping towards the west (*i.e.,* seaward) at 10°.

Beach

This facies occurs in cores VC3 and VC5 at +0.1 and +0.2 m, respectively, attains 3 m thickness, and is composed of very well sorted fine sand (Figures 5A and 5B). Grains are mostly subangular to subrounded. Samples from this facies contain average quartz and feldspar concentrations of 66% and 19%, respectively. The carbonate fraction comprises mollusc shell fragments <0.05 m in diameter. The unit is mostly massive throughout, but parallel beds up to 0.02 m thick and dipping towards the west at ~20–30° occur locally.

Lagoon

The lagoon facies attains 1.5 m thickness and occurs in cores VC1, VC2, and VC4 at −1.5, −1.3, and −1.4 m, respectively (Figure 5A). This facies comprises alternating beds of poorly sorted silty fine sand (Figure 5B). The fine sand beds contain subangular quartz and feldspar grains with interbedded laminations of heavy minerals, pebbles, organic matter, and weathered shell fragments. Samples from the silty-sand beds contain average quartz and feldspar concentrations of 62% and 31%, respectively. The silty-sand beds also contain silt-sized faecal pellets, horizontal to wavy laminations, and silt flasers throughout.

Back-Barrier Tidal Flat

This facies occurs at the top of cores VC1, VC2, and VC4, is up to 1.5 m thick, and consists of well sorted fine sand (Figures 5A and 5B). Samples from this facies contain average quartz and feldspar concentrations of 51% and 38%, respectively. The carbonate fraction is composed of mollusc fragments <0.05 m in diameter. This facies contains silt-sized grains (2.4%–7.5%) that appear to be pelletised faecal material, probably from infauna. The occurrence of silt decreases with depth. The facies is generally massive, although laminations of medium sand are present.

Radiocarbon Ages

Two *in situ* (growth position) shells buried within an outcrop of muddy sand exposed near the low tide line on the beach face returned modern ages (Figure 4; Table 3). The calibrated radiocarbon age derived from the shell at 2.46 m depth in a core from Tapora Flats is 2330–1880 cal y BP (WK-17480). These ages confirm the late Holocene formation and evolution of prograded coast opposite the Kaipara Harbour inlet.

Development of Okahukura Peninsula and Tapora Island

Previous geologic studies have demonstrated that the Okahukura Peninsula consists of two phases of dune development (*e.g.,* Ballance and McCarthy, 1975; Brothers, 1954; Issac *et al.,* 1994; Figure 6). The oldest and most landward of the coastal dunes attain 25 m in height and comprise weakly cemented sand, capped by clay-rich sandy paleosols that form flat and rounded slopes (Issac *et al.,* 1994). These dunes are inferred to be remnants of a progradational coastal sequence

Table 3. *Sample details for radiocarbon age determinations on shell samples from cores taken from the tidal flat facies and Tapora flats.*

Location	Material	Depth (cm)	Conventional C-14 Age (y BP)	Calibrated C-14 Age (y BP)*	Lab Code
Tapora Flats	Single valve (*Paphies subtriangulata*)	246	2449 ± 93	2330–1880	Wk-17480
Tidal flat	Articulated bivalve (*Mactra* sp.)	5	Modern	Modern	Wk-8021
Tidal flat	Articulated bivalve (*Mactra* sp.)	5	Modern	Modern	Wk-8022

NB: Wk-17480 is reproduced from Hutcheon (2006); Wk-8021 and Wk-8022 are used with permission of the Kaipara Sand Study Working Group.
* Radiocarbon age calibration calculated using OxCal version 3.1 (Bronk Ramsay, 2001) and marine data from Hughen *et al.* (2004) with a delta *R* value of −7 ± 11.

that developed during the last interglacial high stand. These are now separated from younger dunes to the west by an unconformity that formed during the glacial low stand (Issac *et al.,* 1994). The younger dunes form a series of north–south trending ridges that are composed of well-sorted fine sand and attain heights of up to 20 m above MHWS (Ballance and McCarthy, 1975). Swampy, vegetated former back-barrier flats and interdune swales composed of silty sand separate the ridges (Ballance and McCarthy, 1975). The texture, composition, and elevation of these ridges and swales indicate that this sequence represents a second phase of dune development on the peninsula (Issac *et al.* 1994).

Given its seaward location on the Okahukura Peninsula, Tapora Island represents the most recent of two or three phases of barrier island development (Figure 6). At the base of this barrier island facies succession is the nearshore shell lag facies. The presence of the shallow marine bivalve *Dosinia anus* in this facies indicates that sandy shallow open ocean conditions existed at this location prior to the formation of the barrier island. It is inferred from the mostly convex-up orientation of the valves that the site was subject to high-energy wave conditions. Between cores VC1, VC2, and VC4, the upper surface of this unit slopes downwards towards the west at ~0.1–0.2°. The gradient of this surface is comparable to the gradient of the intertidal surface of Tapora Bank of 0.2–0.7° (Hume *et al.,* 2001), immediately west of Tapora Island, although this surface may have been eroded by waves. We interpret from this, and the associated sediment texture and composition, that this unit was deposited in a nearshore environment similar to the present-day Tapora Bank during a previous phase of (late) Holocene dune development on the Okahukura Peninsula, possibly during the construction of the beach ridges on Tapora Flats.

Above the nearshore shell lag facies is an aggradational barrier island succession of foreshore, lagoon, back-barrier tidal flat, beach, and dune facies (Figure 5). The foreshore facies extends beneath Tapora Island and was presumably deposited during construction of the beach ridges on Tapora Flats. The presence of local accumulations of heavy minerals indicate that this facies accumulated in a wave-dominated environment wherein heavy mineral grains were concentrated into layers by differential entrainment in the nearshore and swash zones (*cf.* Hamilton and Collins, 1998).

Higher in the succession, the lagoon facies is separated from the foreshore facies by a local unconformity. The boundary between these facies presumably formed by tidal and wave erosion during the initial formation of Tapora Island. Alternating fine-sand/silty-sand units of the lagoon facies may document the changing strength of hydrodynamic conditions in this environment. In the Kaipara Harbour inlet, silt-sized grains are rare because they are winnowed from the sediment by the action of tidal currents and waves (Hume *et al.,* 2001). The presence of silty-sand beds indicates deposition under relatively low-energy conditions. Conversely, the abundance of fine quartzose sand, and presence of heavy mineral grains, small pebbles, and abundant shell hash in the fine sand beds implies that these units were deposited under relatively high energy conditions, possibly during storm events.

Overlying these deposits is the back-barrier tidal flat facies

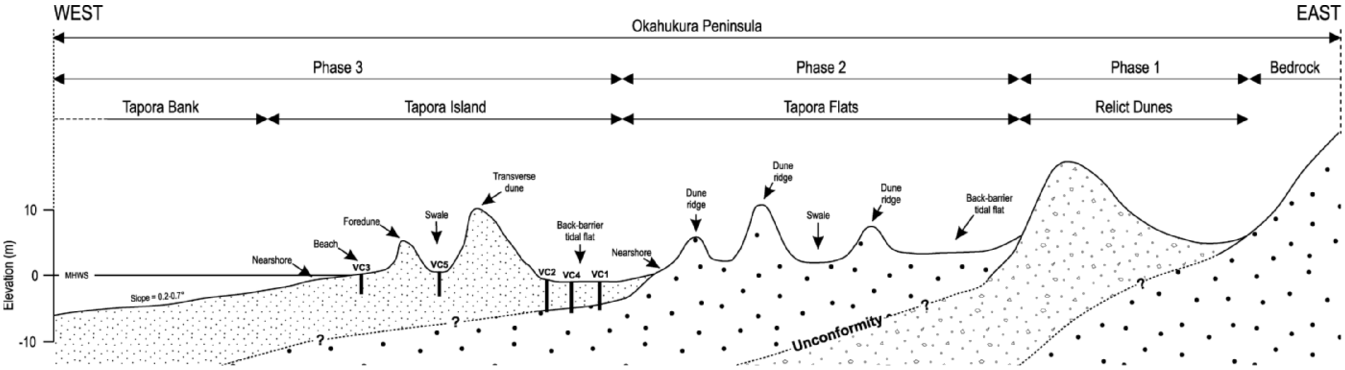

Figure 6. Schematic cross-section of Tapora Island and Okahukura Peninsula showing subsurface relationships and stratigraphic units for three phases of barrier island formation. Facies relations are interpreted from aerial photographs, surface sediments, and subsurface sediments contained in the vibrocores and pits. Vertical black lines are vibrocores. Distance not to scale.

that indicates deposition under low-energy conditions. The occurrence of wavy to horizontal laminations and flasers is indicative of small-scale migrating wave ripples, formed by small wind waves that occur in the shallow-water back-barrier environment. The beach facies contains seaward dipping cross-beds, indicating deposition by swash processes (*e.g.,* Wang, Davis, and Kraus, 1998). Capping the sequence is the dune facies that represents recent accumulation and construction of Tapora Island to higher subaerial elevations. The Tapora Island facies succession conforms to the model of an "accumulating" barrier island (Otvos, 1981) because we recognise open-marine sediments and organisms buried below the back-barrier tidal flat.

The two radiocarbon ages from the tidal flat provide further information on the evolution of Tapora Island. These samples yielded modern ages (*i.e.,* <200 y BP) from articulated bivalves (*Mactra* sp.) recovered from an outcrop of muddy sand exposed near the low tide line on Tapora Beach and are interpreted as *in situ.* The depositional environment for the muddy sands is interpreted as a tidal flat with shelter from regular wave action, thereby allowing for settling out of fine-grained sediments. For such an environment to have developed in the location of the present beach face requires that the location was once in the lee of a sand bank or shoal, now removed. The modern radiocarbon ages suggest that this environmental change occurred within the last 250 years. This is consistent with historical charts for Kaipara Harbour that show Tapora Island has grown several kilometres in length since the mid-nineteenth century and in particular, show the area to seaward of the island in 1854 was an intertidal bank of mud and shingle (Smith, 1999). There is also historical anecdotal evidence for a subaerial shoal located approximately 5 km inside the harbour and opposite the entrance that was destroyed during a large storm (Spring-Rice, 1996). It is likely that the sediments that once made up this island would have been redistributed into Tapora Island and other shoals inside the harbour. Together, the available evidence demonstrates that Tapora Island is a recent product of a dynamic estuarine setting characterised by high sediment supply and energetic tide, wave, and wind conditions.

DISCUSSION

Here we review the environmental conditions of the Kaipara Harbour that have led to the formation of a barrier island inside an estuary. First, we consider the potential sources of sediment contributing to the barrier island deposits. Second, we examine the potential hydrodynamic processes acting inside the estuary in the vicinity of Tapora Island that may be responsible for its formation and evolution.

Potential Sediment Sources for the Formation of Tapora Island

The Holocene eustatic sea-level history for New Zealand is characterised by a rise from -33.5 m at *ca.* 10 ky BP to present levels *ca.* 6.5 ky BP, and then followed by minor fluctuations of ± 1–2 m (Gibb, 1986). With this rise in sea level, large volumes of sand stored on the continental shelf during low stand were transported towards the coast by shoreline processes. This sand now forms the beaches and dunes along the coast, and has infilled the coastal embayments to various degrees, forming the ebb and flood tide deltas and shoals that now partly occupy the antecedent topography (Brockbank, 1983; Schofield, 1975).

Previous sedimentological studies (*e.g.,* Kirk, 1988; Parnell, 1995) worked it through and demonstrated that sediment moving along the west coast of the North Island, under the influence of the large ocean swells, is transported into the estuary by strong flood tide currents. Longshore drift in the vicinity of the harbour entrance has been estimated at 1–5 $\times 10^6$ m^3 y^{-1} (Kirk, 1992). Transport of this sediment has contributed to an ebb tidal delta containing approximately 1.23×10^{10} m^3 of sand (Hicks and Hume, 1996). Both of these sources represent a significant amount of sand available for transport and deposition into the estuary. The sand is transported through the entrance channels by flood tide currents that attain speeds of 1.1 m s^{-1} in the throat (Hume and Herdendorf, 1993) and 0.9 m s^{-1} in the estuarine channels (Hume *et al.,* 2003). In addition, sediment resuspended by ocean swell waves from the top of the ebb tide delta is driven into the estuary and across Tapora Bank. These sediment transport pathways, coupled with flood tide currents over Tapora Bank, which attain 0.8 m s^{-1} and are capable of entraining the fine to medium sands (Hume *et al.,* 2003), represent the principal sources of sediment for the formation of shoals.

The three radiocarbon ages (Table 3) assist with our interpretation of Tapora Island's formation and evolution. The sample in the core recovered from Tapora Flats provides a maximum age for the former tidal flat environment, on the basis that the shell sample was disarticulated and therefore most likely reworked. Nonetheless, this result provides indirect evidence that Tapora Island is a relatively young landform, constructed during the late Holocene.

Construction of an Estuarine Barrier Island

Wave data collected adjacent to Tapora Island during April 2001 for the Kaipara sand study (Green, MacDonald, and Liefting, 2002) indicate that the wave conditions inside the harbour change their intensity with the rise and fall of the tide (Figure 7). Late in the ebb stage and during low tide, significant wave height was <0.4 m with periods of 6–10 seconds. During the flood stage, significant wave height attained 1 m with periods of 9–12 seconds, which occurred in concert with increasing water depth. Wave conditions approximately 2 hours either side of high tide at Tapora Island are very similar to those found outside the Kaipara Harbour, where ocean swells regularly attain 1–2 m with periods of between 8 and 12 seconds (Pickrill and Mitchell, 1979). These data indicate that ocean swell waves are penetrating the inlet because water depths over the ebb tidal delta and inlet shoals increase. Approximating the wave conditions influencing Tapora Island at high tide using the methods of Komar and Miller (1975), these swell waves would produce maximum orbital near-bed velocities across Tapora Bank of 0.7 m s^{-1} where water depths are 2–4 m at high water.

We infer from this that two principal factors have governed the formation and evolution of Tapora Island. First, for ap-

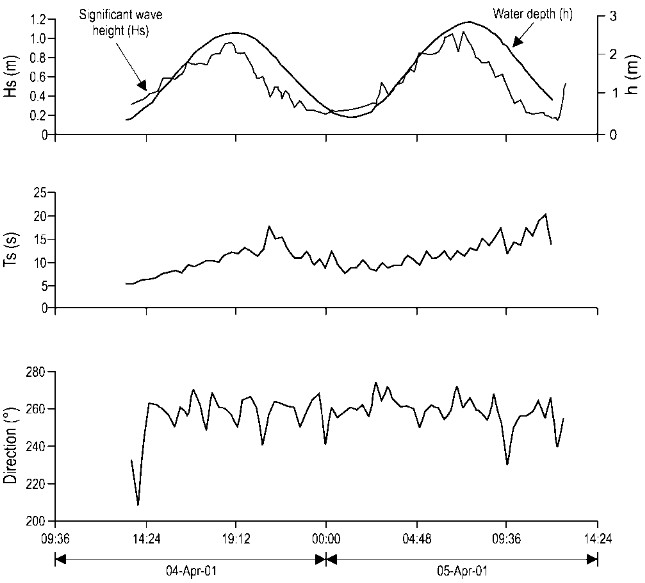

Figure 7. Graphs showing water depth (h), significant wave height (Hs), significant wave period (Ts), and wave direction at Tapora Island for two complete high tide cycles (reproduced with permission from Kaipara Harbour Sand Study Working Group).

proximately 2 hours either side of high tide, water depths are sufficiently deep enough in the inlet and over the intertidal flats to allow ocean swell and infragravity waves to penetrate the inlet and drive sand shorewards. During the ebb stage and low tide, the presence and influence of ocean swell waves decrease because they are prevented from penetrating the inlet. Locally generated waves then become more significant, but these short, steep waves break on offshore shoals and their influence on Tapora Island is negligible. Second, the location of the island directly opposite the inlet creates a direct approach for prevailing westerly winds to drive aeolian transport onto Tapora Island.

In summary, the combined effects of tidal modulation of ocean swell waves, abundant sediment supply, and exposed aspect are the critical factors in forming Tapora Island. These are not the fetch-limiting conditions (*i.e.,* dominated by locally generated waves) as proposed by Cooper, Pilkey, and Lewis (2007), and Pilkey, Cooper, and Lewis (2009). However, our findings support their contention that these landforms are the product of highly variable processes.

CONCLUSIONS

Tapora Island is a barrier island located ~8 km east of the entrance of the Kaipara Harbour, a large coastal embayment on the high-energy west coast of the North Island of New Zealand. The location of Tapora Island in the estuary, opposite the entrance, represents an unusual setting for the development of a barrier island when compared with models for their formation. Surface samples and subsurface sediment data, and extrapolation of geomorphic and geologic units on the mainland, indicate that Tapora Island is an aggradational barrier island that forms the latest stage of a Holocene prograded coast opposite the entrance to the Kaipara Harbour. Tapora Island comprises a succession of nearshore, foreshore, lagoon, back-barrier, beach, and dune facies that record the aggradation from subtidal to subaerial elevations. The combined effects of ocean swell waves penetrating the harbour entrance for approximately 2 hours either side of high tide, abundant sediment supply, and exposed aspect are the critical factors that have formed the barrier island. Our findings show that the processes forming barrier islands in sheltered coastal settings can be more akin to open ocean coasts. The accumulating barrier island model appears to be the best explanation for the origin and development of Tapora Island.

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