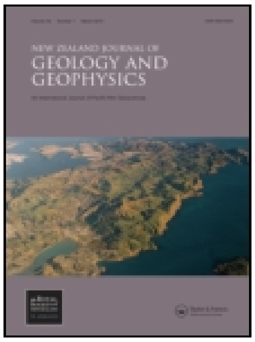

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Towards a record of Holocene tsunami and storms for northern Hawke's Bay, New Zealand

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Abstract Eleven sand layers occur within Holocene low-energy estuarine and marginal marine sequences of blue-grey silty clay at two sites on the coastal plain between Wairoa and Mahia Peninsula, northern Hawke's Bay, New Zealand. The sedimentology and fossil assemblages of these layers are consistent with deposition by high-energy influxes to the sites. Three influxes are terrestrial in nature and are thought to represent alluvial flood events. All other sand layers are marine derived and are likely to be the result of storm surges or tsunami. Tsunami inundation is favoured for two sand layers that occur in association with evidence for sudden subsidence at c. 6300 and c. 4800 yr BP. The c. 6300 yr inundation also coincides with previously identified evidence for a tsunami at a site 10 km westwards along the coast. Further investigation is required to distinguish between tsunami and storm surge deposition for the remaining six layers.

Keywords Holocene; Wairoa; Mahia Peninsula; Hawke's Bay; coastal hazards; floods; microfossils; sedimentology; storm surges; tsunami

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INTRODUCTION

The geological record is increasingly being used to contribute to knowledge of natural hazard events and to provide estimates of likely location, magnitude, and frequency of future events (e.g., Liu & Fearn 1993; Clague 1997; Pinegina et al. 2003). Coastal hazards are of particular significance in New Zealand because of the country's long length of inhabited coastline. Tsunami have received attention recently (e.g., Goff et al. 1998, 2000; Goff & Chagué-Goff 1999; Nichol et al. 2003) as a result of increased worldwide awareness of the hazard. The active tectonic setting of New Zealand provides numerous sources for locally generated tsunami, and the country's oceanic setting makes it vulnerable to distantly generated tsunami also. Geo-archaeological and historical reports have highlighted the disrupting effects of tsunami inundation on coastal communities in New Zealand (Grapes & Downes 1997; Downes et al. 2000; Goff & McFadgen 2001). On a more frequent basis, the coast is also vulnerable to flooding and storm surges. Documenting geological evidence for past severe storms aims to improve understanding of the risks involved in increasing the development of the coastal zone.

In 2002, several estuarine and marginal marine sedimentary sequences were collected as cores from the east coast of the North Island of New Zealand for high-resolution paleoenvironmental reconstruction. In this paper we examine two of those sequences for evidence of high-energy influxes of sediment that may represent past large floods, storm surges, and tsunami. We aim to document the sedimentary evidence, attempt to determine the source of each deposit, and correlate events between sites and with previous studies. Ultimately, this information will contribute to a more complete record of past large storms and tsunami for northern Hawke's Bay, and to the national probabilistic tsunami hazard model (Downes & Stirling 2001).

SETTING

The coast of Hawke's Bay, eastern North Island, New Zealand, is located 100–200 km west of the Hikurangi Trough, where the Pacific plate subducts obliquely beneath the Australian plate (Fig. 1A). In this tectonically active region, potential sources of local tsunami are numerous. For example, Hawke's Bay is estimated to lie above the downdip edge of the seismogenic zone of the subduction interface (Reyners 2000) so it could be expected to experience coseismic subsidence and inundation by tsunami resulting from a subduction interface earthquake (L. Wallace & W. Power pers. comm. 2005). There are also numerous smaller offshore faults (Barnes et al. 2002) that may be capable of triggering tsunami when they rupture. In northern Hawke's Bay, at Mahia Peninsula, a stepped sequence of emergent shore platforms is attributed to five large, mid–late Holocene earthquakes on the Lachlan Fault c. 20 km offshore (Berryman 1993). Modelling of a local tsunami was undertaken for a credible

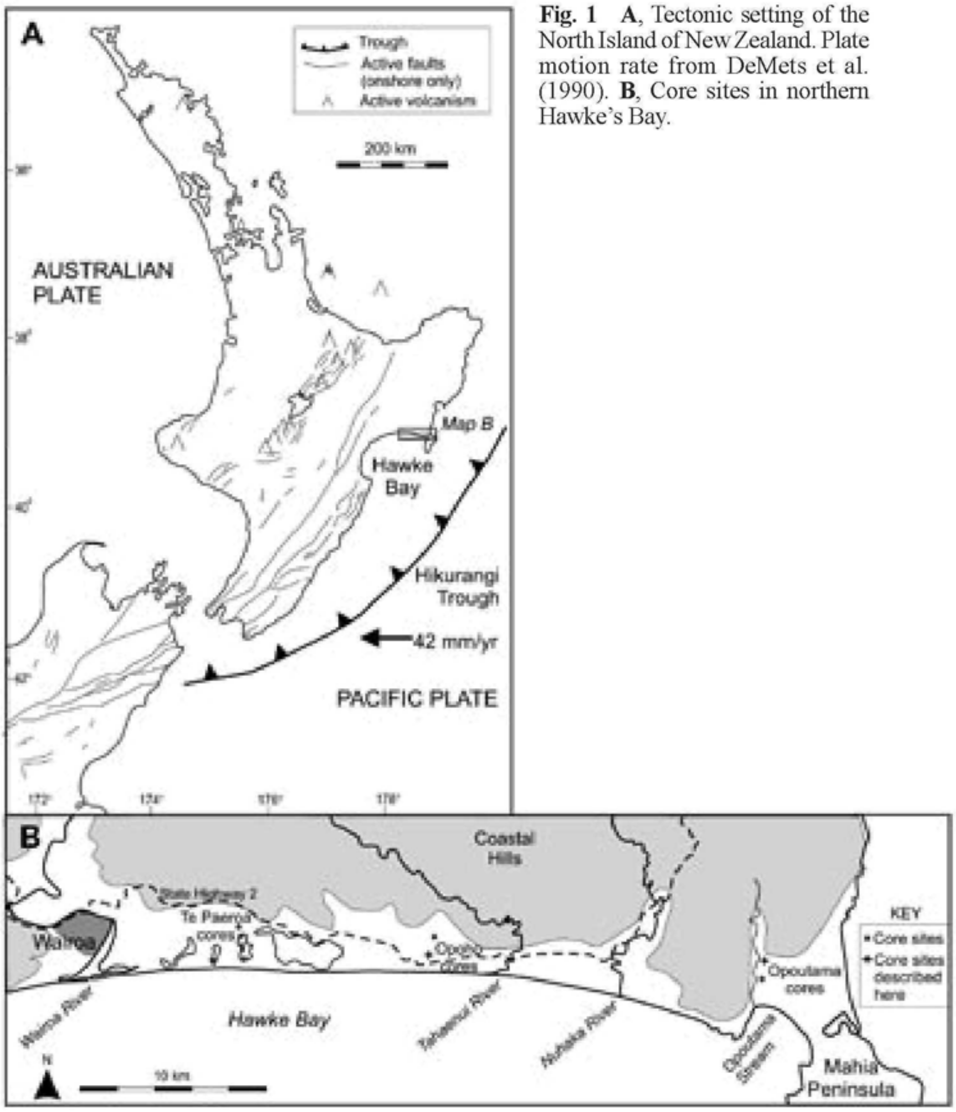

Fig. 1 **A**, Tectonic setting of the North Island of New Zealand. Plate motion rate from DeMets et al. (1990). **B**, Core sites in northern Hawke's Bay.

rupture scenario of the Lachlan Fault in a large earthquake (R. Walters & P. Barnes pers. comm. 2004). Preliminary results indicate that parts of northern Hawke's Bay could be inundated by peak crest-to-trough wave heights exceeding 3 m. A number of tsunami have occurred in Hawke's Bay in historical times (De Lange & Healy 1986) but the 160 yr of written record in New Zealand is too short to reliably estimate the frequency of large tsunami for Hawke's Bay.

New Zealand is also prone to climatic hazards such as heavy rainfall and strong winds as it lies between the subtropical anticyclonic belt to the north and the mid-latitude belt of westerlies in the south (Salinger 1998). Hawke's Bay has been subjected to some of the highest intensity rainfall recorded in New Zealand, including Cyclone Bola in 1988, the largest rainstorm recorded in nearly a century of records (Page et al. 1994). Evidence of past large storms has been identified, for example, as landslide deposits in Lake Tutira, where 365 storms are recognised over a 2250 yr period (Eden & Page 1998). However, records of storm impacts at the coast are less common because few sites have been studied for this purpose.

Study sites

In northern Hawke's Bay east of Wairoa, a low-lying coastal plain >1 km in width (Fig. 1B) consists of Holocene estuarine and alluvial sediments (Berryman 1988). A study of these sediments indicated that this area has experienced several metres of net tectonic subsidence in the late Holocene (Ota et al. 1989). Detailed investigation of the sedimentary record of Te Paeroa Lagoon provided evidence for the occurrence of a large tsunami c. 6300 yr BP (Chagué-Goff et al. 2002). In this study, sediment cores were taken at Opoho and Opoutama, sites 10 km and almost 30 km to the east of Te Paeroa Lagoon. At Opoho, there is a plain almost 2 km wide that is bordered by dunes at its seaward edge and has small streams meandering across its surface. The location of core Opoho-2 is c. 750 m landward of the current shoreline and the top of the core is 5.3 m above mean sea level. Opoutama is located near the base of the isthmus that joins Mahia Peninsula to the mainland. Opoutama Stream is of moderate size and cuts through a coastal plain consisting of estuarine sediments and a series of relict beach ridges. The location of core Opoutama-1 is almost 1500 m from the present shoreline, and the top of the core is 6.4 m above mean sea level.

METHODS

Sediment cores were collected using a truck-mounted, hydraulic drill rig. At each site a number of cone penetrometer probes and two cores were taken in a shore-normal transect. We present results from one core at each site. Tephra identification and radiocarbon analysis of shell and wood samples were used to construct chronologies for the sequences (Table 1). Examination of the sediments, macrofossils, spores and pollen, diatoms, and foraminifera enabled reconstruction of past environments throughout each sequence. Sediments were visually assessed for their structure, grain size, and organic content. Macrofossils were identified and their habitat preferences used to provide information about their likely source environment. Microfossils were concentrated from sediment samples using standard processing techniques (e.g., Lennie 1968; Faegri & Iversen 1989 for spores and

Table 1 Radiocarbon and tephra samples used to construct chronologies for cores from Opoho and Opoutama.

Sample depth (m)	Sample material	Dating technique	$\delta^{13}C$ (‰) (radiocarbon samples)	Name (tephra samples)	Radiocarbon age* (radiocarbon years BP)	Laboratory number
Opoho						
4.81–4.85	Wood	Standard radiocarbon	–28.9		1727 ± 44	Wk 11010
5.29–5.31	Tephra	Identification by glass chemistry		Whakaipo	2685 ± 20	
5.82–6.13	Tephra	Identification by mineralogy and context		Waimihia	3280 ± 20	
7.45–7.7	Tephra (inferred)	Inferred only		Whakatane	4830 ± 20	
9.56–9.59	Twigs, seeds, bark	AMS	–27.1		6139 ± 55	NZA 16418
10.27–10.30	Wood	Standard radiocarbon	–28.5		6434 ± 155	Wk 11009
11.33–11.39	Wood	Standard radiocarbon	–27.3		6278 ± 67	Wk 10902
12.13–12.16	Wood	Standard radiocarbon	–24.6		7130 ± 72	Wk 11008
13.00–13.03	Shell *Austrovenus stutchburyi*	Standard radiocarbon	–0.8		7404 ± 123	Wk11011
16.99–17.01	Shell *A. stutchburyi*	AMS	–1.5		8384 ± 60	NZA 15403
19.71–19.88	Shell *Macomona liliana*	AMS	–2.4		8672 ± 60	NZA 15017
Opoutama						
2.81–3.14	Tephra	Glass chemistry and context		Waimihia	3280 ± 20	
3.22–3.27	Twigs, seeds, bark	Standard radiocarbon	–26.4		3521 ± 49	Wk 11012
5.89	Wood	Standard radiocarbon	–25.9		6993 ± 142	Wk 10903
8.70–8.73	*M. liliana*	AMS	0.7		7300 ± 40	NZA 16598
	Amalda novae-zealandiae	AMS	2.8		7277 ± 45	NZA 16599
	Chiton glaucus	AMS	1.4		7257 ± 40	NZA 16600
9.98–10.02	*A. stutchburyi*	AMS	1.7		7481 ± 50	NZA 16627
	Zeacumentus lutulentus	AMS	4		7514 ± 60	NZA 16628
	M. liliana	AMS	1.6		7508 ± 65	NZA 16629
10.45–10.50	Shell	AMS	–1.3		7693 ± 60	NZA 15404
13.50	Shell *Melagraphia aethiops*	AMS	1.9		7641 ± 45	NZA 16601
15.59–15.61	Wood	Standard	–28		7546 ± 124	Wk 11013
16.26–16.28	Tephra	Glass chemistry		Mamaku or Rotoma	7250 ± 20 8530 ± 10	
17.83–17.85	Shell *M. liliana*	AMS	1		8127 ± 55	NZA 15018

Wk, The University of Waikato Radiocarbon Dating Laboratory; NZA, Institute of Geological & Nuclear Sciences Rafter Radiocarbon Laboratory.
*Conventional radiocarbon age before Present (AD 1950) after Stuiver & Polach (1977). Ages of named tephra are from Froggatt & Lowe (1990).

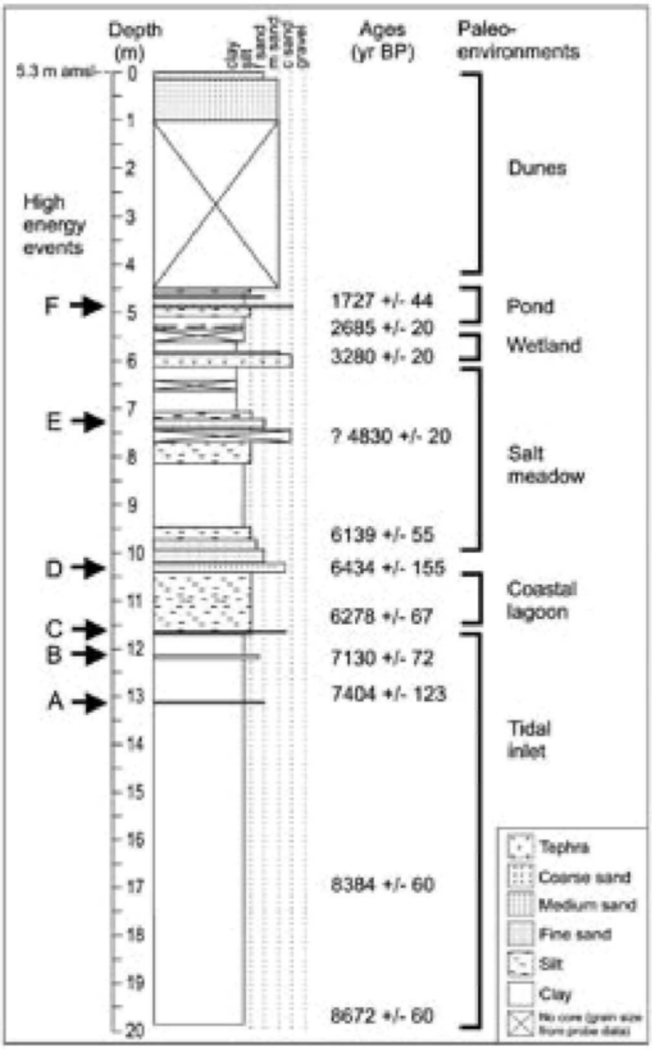

Fig. 2 Sedimentary sequence of core Opoho-2 with tephra, conventional radiocarbon ages, and paleoenvironments. Anomalous units A–F marked with arrows.

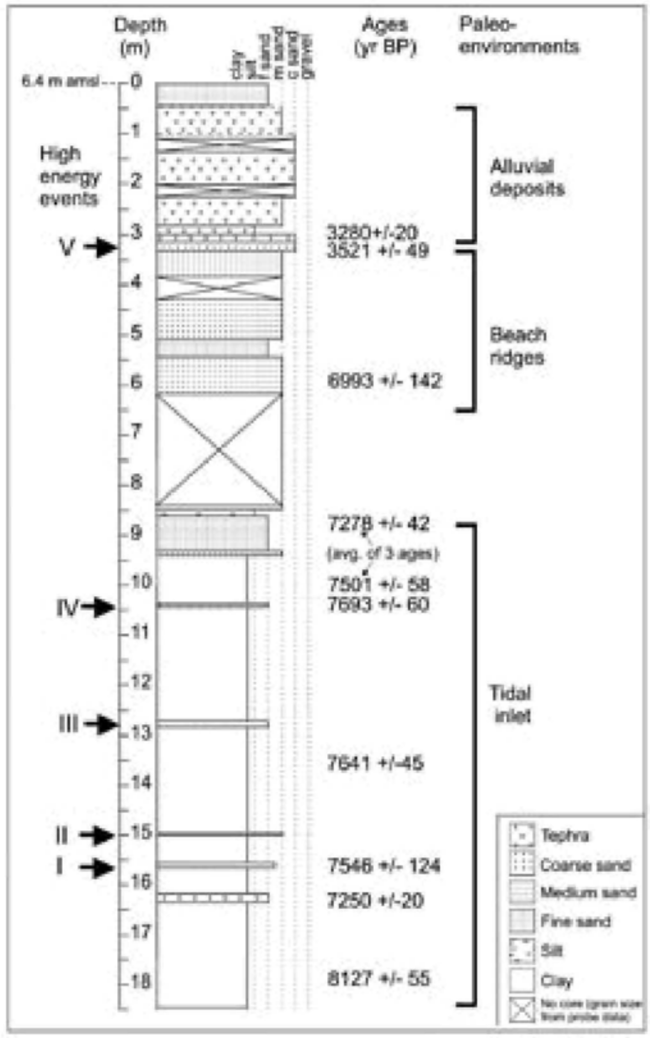

Fig. 3 Sedimentary sequence of core Opoutama-1 with tephra, conventional radiocarbon ages, and paleoenvironments. Anomalous units I–V marked with arrows.

pollen; Battarbee 1986 for diatoms; Hayward et al. 1999 for foraminifera). Species were identified and counted, and published preferences were used to determine past depositional environment for each sample (Large & Braggins 1991; Moar 1993; van Dam et al. 1994; Hayward et al. 1999; Krammer & Lange-Bertalot 1991, 1999a,b, 2000; Witkowski et al. 2000). The focus of this paper is the presence of anomalous units that may represent high-energy influx events. Coarse-grained chaotic units were sampled and analysed for this purpose, and details of these units are reported here.

RESULTS

Description of anomalous units

Reconstruction of past environments on the coastal plain of northern Hawke's Bay over the last 8000 yr shows changes up-sequence from tidal inlet conditions to lagoons, ponds, and finally dunes and alluvial deposits (Fig. 2, 3). Most of the sediments in these sequences represent steady-state deposition in relatively low energy regime coastal environments. However, a number of units appear to have been deposited by high-energy processes. These are summarised in Table 2.

At Opoho, six anomalous high-energy units were recognised, five of which appear to have a marine source (Table 2). Units A and B occur within a low-energy, silty clay dominated tidal inlet environment. Unit A consists of fine sand with clay clasts, a sharp lower contact, and high concentrations of shell fragments and foraminifera. Unit B has a sharp lower contact and contains chaotically mixed silt and fine sand. The high numbers of mangrove pollen suggest the site was within or very near a mangrove forest, as mangrove pollen does not transport well (Mildenhall 2001). However, the large pieces of wood are filled with wood-borer tubes and shells and so are thought to be driftwood transported to the site. A higher proportion of the extreme low tidal to shallow subtidal foraminifera *Haynesina depressula* suggests a short-lived increase in marine influence following deposition of unit B. Rare open marine foraminifera have also been transported to the site.

Units C and D at Opoho both occur at transitions between two different but low-energy paleoenvironments (Table 2). Unit C has an abrupt lower contact and consists of chaotically mixed medium and coarse sand—much coarser sediment

Table 2 Characteristics of anomalous units recognised in cores from Opoho and Opoutama.

Anomalous units (depth m)	Sedimentology	Macrofossils	Foraminifera	Diatoms	Palynology	Paleoenvironment of enveloping sediments
Opoho						
F: 4.67–4.90	Organic clayey silt with sand scattered throughout and bands of reworked tephra. Sharp upper and lower contacts	Numerous wood fragments. Pumice lapilli to 1.5 cm	No sample	No change in assemblage	No change in assemblage	Freshwater pond
E: 7.23–7.39	Fine sand with clay clasts. Lower contact sharp, upper contact gradational over 6 cm	Sparse pieces of wood	No sample	Assemblage not preserved	High numbers of dinoflagellates. Poorly preserved spores and pollen	Salt meadow
D: 10.23–10.41	Silt and medium–coarse sand. Chaotically mixed. Contacts gradational over 1 cm	Numerous shell fragments, small gastropods and pieces of wood	Intertidal and reworked species with fresh and brackish water indicators	No change in assemblage	No change in assemblage	Coastal lagoon to salt meadow transition
C: 11.63–11.66	Medium and coarse sand. Chaotically mixed. Sharp upper and lower contacts	Abundant shell fragments	No sample	Low concentration. Peak in marine planktonic and sand-dwelling species	High numbers of dinoflagellates	Low-energy tidal inlet to coastal lagoon transition
B: 12.12–12.20	Silt with pockets of fine sand. Chaotically mixed. Sharp upper and lower contacts	Two large pieces of wood, numerous small pieces of wood and shell fragments	Occasional open marine species. Peak in *Haynesina depressula* immediately above unit	No change in assemblage	High numbers of mangrove pollen	Low-energy tidal inlet
A: 13.11–13.15	Fine sand with clay clasts. Sharp lower contact and burrowed upper contact	Shell fragments	Very high concentration	No change in assemblage	Low concentration	Low-energy tidal inlet
Opoutama						
V: 3.21–3.33	Clayey silt and coarse sand with clay clasts. Chaotically mixed. Sharp contacts	Numerous large pieces of wood to 2 cm, twigs and seeds	No sample	Shallow, freshwater pond assemblage	Freshwater pond assemblage	Beach ridge to alluvial transition
IV: 10.36–10.43	Well-sorted fine sand. Contacts gradational over 2 cm	Shell fragments, whole *Melagraphia aethiops*, small gastropods	High concentration	Peak in marine sand-dwelling species	Low concentration. Freshwater algae present	Low-energy tidal inlet
III: 12.71–12.80	Fine sand with mudstone clasts. Sharp lower contact, gradational upper	Small pebbles, wood and shell fragments to 2 cm	No change in assemblage. Peak in *Haynesina depressula* immediately above unit	Peak in brackish benthic species	Freshwater algae present	Low-energy tidal inlet
II: 14.95–15.00	Medium sand with clay clasts. Sharp contacts	Small shell fragments	No change in assemblage	Peak in marine sand-dwelling and brackish benthic species	No change in assemblage	Low-energy tidal inlet
I: 15.56–15.66	Organic fine sand with pockets of medium sand. Grades upwards to clayey silt. Very sharp lower contact, gradational, burrowed upper contact	Numerous pieces of wood and twigs especially in upper 6 cm	No foraminifera	Freshwater soil assemblage	High concentration of tree and shrub pollen, low diversity, no marine and few freshwater components	Low-energy tidal inlet

than the units above and below. Abundant shell fragments, marine planktonic and sand-dwelling diatoms, and a high concentration of dinoflagellates occur in the sand and indicate it had a marine source. Unit D is also a chaotic mixture of sediment sizes and contains components derived from both seaward (shells) and landward of the site (foraminifera reworked from the catchment, brackish-fresh ostracods and gastropods, and fresh-brackish algal spores).

Unit E occurs within a low-energy, silt-dominated, slightly brackish salt meadow environment. It consists of fine sand, and the high concentration of dinoflagellates suggests the unit was marine derived. Unit F occurs near the top of the sequence at Opoho within an organic, freshwater pond. It comprises sand and numerous wood fragments scattered throughout organic clayey silt. Coarse sand-sized pumice lapilli are scattered throughout the base of the unit and fine sand-sized pumice occurs near the top of the unit. All components are likely to be terrestrially derived.

At Opoutama, five anomalous units were identified, three of which have a marine source and two a terrestrial source (Table 2). Units I, II, III, and IV were all deposited in a low-energy, silty clay dominated intertidal estuary. Unit I is a terrestrially derived unit as it is highly organic, contains numerous twigs and pieces of wood, soil diatom species, and high concentrations of tree and shrub pollen. There are no foraminifera or marine indicators of any type. The unit is 10 cm thick, contains fine and medium sand, and has a sharp basal contact. Units II, III, and IV all consist of sand with shell fragments; some also have clay clasts and pebbles present. The increase in *Haynesina depressula* immediately above unit III could be the result of a temporary increase in marine influence. The occurrence of the rocky shore gastropod *Melagraphia aethiops* in unit IV suggests a seaward source. The presence of brackish benthic diatoms and fresh-brackish algal spores suggests a lagoonal source also—an enclosed brackish water body that could have existed either seaward or landward of the estuary. Unit V contains clay clasts within organic muddy coarse sand, numerous pieces of wood, twigs and seeds, and freshwater diatoms, spores, and pollen. It is interpreted to be of terrestrial origin and occurs at the transition between a beach ridge sequence and alluvial/slopewash deposits.

Age and extent of anomalous units

The oldest sediments at the base of cores from Opoho and Opoutama are over 8000 yr old, but the length of useful record for identifying tsunami and storm deposits is much less than 8000 yr, particularly at Opoutama (Fig. 3). This is because parts of the sedimentary sequences represent paleoenvironments that are unlikely to preserve high-resolution evidence of coastal events. For example, the highly mobile nature of beach ridge and dune sediments makes them unlikely to preserve any event stratigraphy intact. Anomalous units A–F at Opoho span nearly 6000 yr of time between c. 7500 and c. 1700 yr BP (Fig. 2). At Opoutama, anomalous units I–IV occur in rapid succession around 7600 yr BP. Unit V is much younger at c. 3300 yr BP (Fig. 3).

The extent of any anomalous unit along and across the coastal plain can provide clues as to source, mode of deposition, and size of depositional event. Although units were not mapped in this study, the location of core Opoho-2, almost 1 km from either the hill country or the sea, dictates that any units in the core derived from these sources are likely to be of reasonable extent. Although the coastal plain was probably narrower in the past, paleoenvironmental interpretations suggest the sea has not been immediately proximal to the core site in the last 8500 yr. Another indication that anomalous units are extensive across the coastal plain at Opoho is that a second core (Opoho-1) c. 350 m inland from the main core (Opoho-2), although not studied in detail, appears to contain correlatives of units C, D, and E. The ages of units A and B are not represented by the time span of Opoho-1, and the record around the time of unit F is very compressed.

The core site at Opoutama is currently farther from the sea than at Opoho but closer to the coastal hills which are drained by a sizeable stream. The two cores collected at Opoutama do not overlap in time so the landward extent of anomalous units is uncertain. However, there is overlap in time with the record at Opoho, 20 km to the west. Anomalous units I and V, those with a terrestrial source, do not appear to have correlatives at Opoho. This is probably because the core site at Opoho is >1 km seaward of the coastal hills compared with a distance of a few hundred metres at Opoutama. Anomalous units II, III, and IV occur at a similar time to unit A at Opoho, but the existing resolution of radiocarbon dating prohibits any clarification as to which of these units may be correlatives.

DISCUSSION

Origin of anomalous units

The characteristic features of anomalous units recognised at Opoho and Opoutama include:

(1) coarse grain size (sand) in comparison with surrounding sediments (clay/silt);

(2) sediments of differing grain sizes chaotically mixed and/or clay clasts present in sand;

(3) sharp lower contacts;

(4) macrofossils and microfossils in unusual concentrations and/or sourced from seaward or landward of the existing paleoenvironment.

Coarse grain size implies that high-energy currents deposited the sediment, and chaotic mixing of sediment sizes may indicate deposition under turbulent flow. Clay clasts within sand are likely to be rip-up clasts, and sharp lower contacts may be evidence of erosion caused by the flow. Components that are allochthonous to the existing paleoenvironment indicate transport has taken place. All of these features are indicative of high-energy processes, so we assume that the origin of the above anomalous units was some kind of high-energy influx into the existing low-energy environments.

Origin of high-energy influxes

High-energy influxes of sand with high proportions of organic terrestrial components—unit F at Opoho and units I and V at Opoutama—are considered to have a source landward of the core site. Deposition of these units was probably a consequence of a storm event involving high rainfall in the catchment. This would mobilise forest floor litter, and flooding of local streams could result in deposition of this organic material into a coastal pond (as at Opoho in unit F) or across the tidal inlet at Opoutama (in the case of unit I) and beach ridges (at the time of unit V) that existed at the mouth of the valley. Units F at Opoho and V at Opoutama were deposited at similar times to past large earthquakes involving uplift at Mahia Peninsula (Berryman 1993) (Fig. 4). It is possible

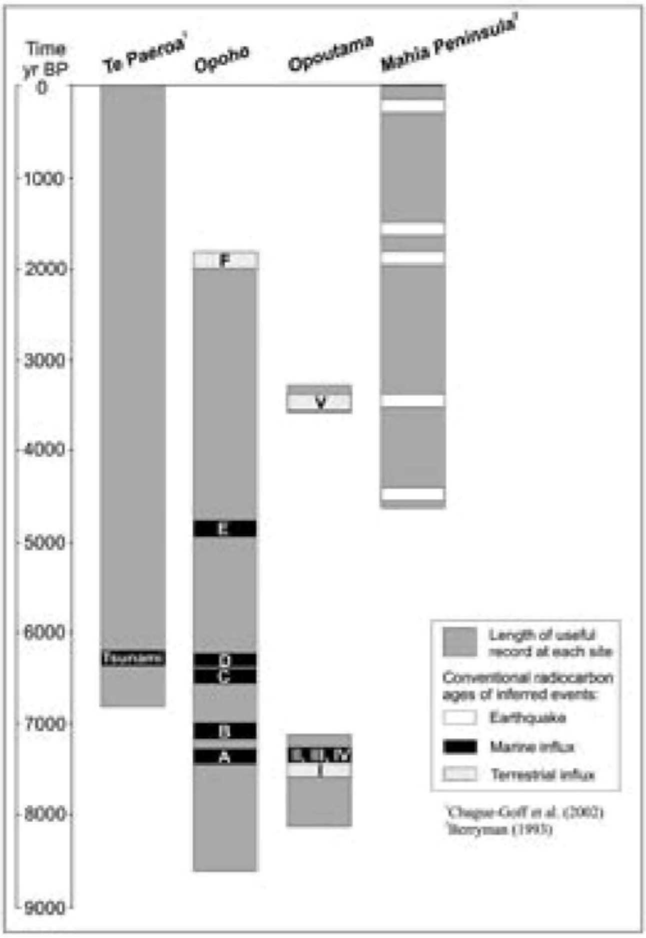

Fig. 4 Timeline of high-energy coastal influx events for northern Hawke's Bay in radiocarbon years before Present. Ages of marine terraces thought to have been uplifted in large earthquakes at Mahia Peninsula are shown for comparison.

that ground shaking in such an earthquake could cause damage to forest on the surrounding hillsides, providing a source of loose organic material. However, flooding of some sort would have been required to transport organic material to a beach ridge environment (unit V), and further evidence is needed to implicate an earthquake in the origin of the deposits.

High-energy influxes of sediment containing marine components are likely to have involved transport of material from positions seaward of the core sites. There are a number of high-energy processes that could act to deposit such material in low-energy parts of a tidal inlet—for example, inundation by the sea during storm surge or tsunami. Storm surge can result in overtopping of beach ridges and deposition of an overwash fan in a localised, back-barrier setting (Liu & Fearn 2000), but flooding of the entire coastal plain could occur where storm surge inundates a tidal inlet and coincides with high rainfall and run-off from the catchment. The ability of tsunami to inundate kilometres of coastal plain and deposit sediment is well documented (Minoura et al. 1996; Gelfenbaum 2001; Peters et al. 2001; Nanayama et al. 2003). In both cases, such coastal flooding is likely to involve entrainment and redeposition of marine, brackish, and terrestrial material, thereby explaining those units that contain a chaotic mix of marine and terrestrial components (units B, D, E at Opoho and II, III, IV at Opoutama). Unit A at Opoho may be an example of deposition resulting from landward surge of the sea in a moderate storm—requiring only slightly stronger currents than average to deposit fine sand and to concentrate shell fragments and foraminifera at the site. Other units represent higher energy processes so are more likely to be the result of tsunami or large storms involving high sea levels and flooding.

Various features of high-energy marine deposits, such as sedimentary characteristics, microfossil content, lateral extent, and effect on depositional environment, can be used to distinguish between tsunami and storm surge (Goff et al. 2004; Tuttle et al. 2004). However, in many cases, the context in which the deposit is found may be the most reliable way of attributing a causal event to the deposit (Gelfenbaum et al. 2002). Coincidence of tsunami deposits with evidence for vertical deformation caused by earthquakes in the sedimentary record is widely reported in international literature, especially at subduction zone boundaries (e.g., Atwater 1987; Hutchinson et al. 2000; Pinegina & Bourgeois 2001; Nanayama et al. 2003). In most cases the earthquake is assumed to be the triggering mechanism for the tsunami.

In this study, two high-energy influxes coincide with evidence for sudden subsidence. Units D and E at Opoho occur at positions in the sequence where earthquake-related subsidence is inferred to explain creation of new accommodation space on the coastal plain—thus allowing continued deposition of marginal marine sediments (Cochran et al. "Paleoecological insights into subduction earthquake occurrence, eastern North Island, New Zealand", submitted). Subsidence of c. 1.5 and 0.75 m is inferred to have occurred at the time of deposition of units D and E, respectively. Unit D also coincides in time with a tsunami deposit identified at Te Paeroa Lagoon, 10 km away (Fig. 4). The tsunami deposit at Te Paeroa Lagoon has been dated at 6300 yr BP and extends at least 2 km inland (Chagué-Goff et al. 2002). The size of tsunami inferred from this landward extent indicates it is likely to have impacted other sites along the coast. The uniqueness of evidence for subsidence and marine inundation in the stratigraphic records of both sites, and the overlap of radiocarbon ages for the inundation, suggests that unit D at Opoho was deposited by a tsunami.

Unit E at Opoho has an age of c. 4800 yr BP (Fig. 4), and no evidence for a tsunami was detected at Te Paeroa Lagoon at this time (Chagué-Goff et al. 2002). However, that may be because the associated earthquake was smaller than the c. 6300 yr event (0.75 m subsidence compared with 1.5 m) and the tsunami generated was not capable of overtopping the barrier at Te Paeroa. Presumably, increasingly larger waves would have been required to inundate sites as barrier and dune heights increased over time between earthquakes. However, a smaller tsunami may still have reached the core site at Opoho at this time and been responsible for deposition of unit E.

Tsunami deposits can also exist without associated evidence of an earthquake where the trigger for the tsunami was a distant earthquake, submarine landslide, volcanic eruption, or other mechanism. Therefore, without further detailed investigation, it is difficult to distinguish between tsunami and storm surge as the cause of the remaining six high-energy marine influxes (units A, B, C at Opoho and units II, III, IV at Opoutama).

Frequency and magnitude of events

Comparisons of the magnitude-frequency relationships for storms and tsunami in the historical and geological record have been used to determine likely source of sand deposits in coastal marsh settings (Witter et al. 2001). However, the historical record of tsunami for Hawke's Bay is too short to provide accurate estimates of tsunami frequency, and the geological record is still under investigation. A record of sediments between c. 8500 and 1700 yr BP is present at Opoho, and within this time frame evidence of two tsunami events and three other high-energy marine influx events has been identified. The occurrence of two tsunami triggered by large local earthquakes in a 6500 yr time interval implies a relatively low frequency of events. This is inconsistent with the geological and seismological estimates currently used in the National Seismic Hazard Model, which suggest c. 500 yr recurrence for large to great earthquakes on the subduction interface in Hawke's Bay (M. Stirling pers. comm. 2004). Even if all three remaining marine influxes are considered to be the result of large storms, the apparent storm frequency is also very low when compared with the 365 storms recognised from lake records in a 2250 yr period (Eden & Page 1998). We conclude that the high-energy influxes at Opoho are either extremely large, infrequent events or that a particular set of circumstances has preserved only a few records in this 6500 yr time interval. The catchment-derived flood and marine influx events at Opoutama occur within two short windows of time around 7500 and 3500 yr BP. The limited amount of useful sedimentary record at Opoutama needs to be supplemented by further records to gain information about the frequency of events over time.

Some indication of the magnitude of events can be gained by estimating the lateral extent of anomalous units across the coastal plain and distance from their sediment source. At Opoho it is likely that only deposits of the largest tsunami and storms reached the core sites because of the inferred distance from the shoreline throughout this time. Anomalous units C, D, and E are extensive over a distance of at least several hundred metres, and unit D has a correlative 10 km away implying that a large magnitude event was responsible for its deposition. However, further mapping of the units, paleogeographic reconstructions, and wave modelling would be required to provide quantitative estimates of tsunami/storm surge magnitude. At Opoutama, both terrestrial and marine sediment sources would have been within a few hundred metres of the core sites. However, little further is known about the extent of anomalous units because other cores at the site do not overlap in time. Sites with greater potential for high-resolution paleoenvironmental reconstruction are required to elucidate the history of storms and tsunami for this extreme northeastern part of Hawke's Bay.

CONCLUSIONS

Sedimentary sequences of low-energy estuarine and marginal marine environments at two sites on the coastal plain of northern Hawke's Bay include 11 coarse-grained anomalous units that provide a record of high-energy flows that have episodically inundated the sites during the Holocene. Three deposits appear to have been transported from the catchment in floods and two deposits are likely to be the result of tsunami inundation because they coincide with evidence for tectonic subsidence and tsunami inundation at a previously studied site. The remaining units are marine-derived influxes for which a storm versus tsunami origin is indistinguishable at present. These deposits are a partial contribution to the history of storm and tsunami impact in northern Hawke's Bay because only large events are likely to have deposited sediment at the sites, the time spans represented are short and incomplete, and not all influxes would be preserved in the type of paleoenvironments present at the sites. Investigation of additional sites along the coast will provide an increasingly thorough picture of coastal hazards in this region.

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