UC Berkeley
Other Recent Work

Title
Micropaleontological evidence of large earthquakes in the past

Permalink
https://escholarship.org/uc/item/95w413pf

Author
Jere Lipps

Publication Date
2006-08-30

Peer reviewed

Micropaleontological evidence of large earthquakes in the past 7200 years in southern Hawke's Bay, New Zealand

Bruce W. Hayward[a,*], Hugh R. Grenfell[a], Ashwaq T. Sabaa[a], Rowan Carter[a,1], Ursula Cochran[b], Jere H. Lipps[c], Phil R. Shane[d], Margaret S. Morley[a,e]

[a]*Geomarine Research, 49 Swainston Rd, St Johns, Auckland, New Zealand*
[b]*Institute of Geological and Nuclear Sciences, P.O. Box 30 368, Lower Hutt, New Zealand*
[c]*Department of Integrative Biology and Museum of Paleontology, University of California, Berkeley, CA 94720, USA*
[d]*Department of Geology, University of Auckland, Private Bag 92 019, Auckland, New Zealand*
[e]*Auckland War Memorial Museum, Private Bag 92 018, Auckland, New Zealand*

Abstract

Foraminiferal and diatom assemblages in 11 cores (3–7.5 m deep) of Holocene sediment from brackish marine Ahuriri Inlet in southern Hawke's Bay, New Zealand, provide a record of 8.5 m of subsidence followed by 1.5 m of uplift in the last 7200 cal years, in a region overlying the subduction zone between the Australian and Pacific Plates.

Modern Analogue Technique was used to estimate paleotidal elevation of the 97 richest foraminiferal assemblages. The most precise estimates are for high-tidal salt marsh assemblages cored in marginal settings in the north and south of the former inlet. The least precise estimates are from low-tidal and subtidal assemblages from cores in the middle of the inlet. These paleoelevation estimates combined with sediment thicknesses, age determinations (from tephrostratigraphy and radiocarbon dates), the New Zealand Holocene sea level curve, and estimates of compaction, identify the Holocene land elevation changes and earthquake-displacement events in each core.

The following major, earthquake-related displacements are inferred: ca 7000 cal yr BP (> -0.6 m displacement); ca 5800 cal yr BP (> -0.5 m; ca 4200 cal yr BP (ca -1.5 m); ca 3000 cal yr BP (-1.4 to -1.8 m); ca 1600 cal yr BP (ca -1.7 m); ca 600 cal yr BP (ca -1 m); 1931AD Napier Earthquake ($+1.5$ m). Further smaller events involving regional subsidence or earthquake-shake compaction are indicated during the 7000–3000 yr BP interval, but cannot be identified precisely. The six (possibly subduction interface) subsidence events in the last 7000 years have had a return time of 1000–1400 years. Identified displacement events have a range of sedimentary expressions, from an eroded and burrowed hiatus surface, to an abrupt lithologic switch from mud to sand, or peat to shelly mud, or in some places no change in sediment character whatsoever.

1. Introduction

On the morning of 3 February 1931 a magnitude of 7.8 earthquake rocked New Zealand's Hawke's Bay region resulting in 256 lives lost and extensive damage to property and infrastructure. This event (Napier Earthquake) was the strongest and most devastating earthquake to occur in the region's recorded human history and highlighted the vulnerability of this area to large seismic events. An elongate coastal strip of southern and central Hawke's Bay (Fig. 1) was uplifted during the Napier Earthquake (Henderson, 1933; Marshall, 1933; Hull, 1990a). The 1–2 m uplift around Napier City extensively modified the large Ahuriri Inlet by uplifting it above sea level and transforming it into land suitable for reclamation for farms and the Napier airport.

The 1931 Napier Earthquake is the only recorded earthquake in historic times (since ca1840) in Hawke's

---

*Corresponding author. Tel.: +64 9 578 1491.
E-mail address: b.hayward@geomarine.org.nz (B.W. Hayward).
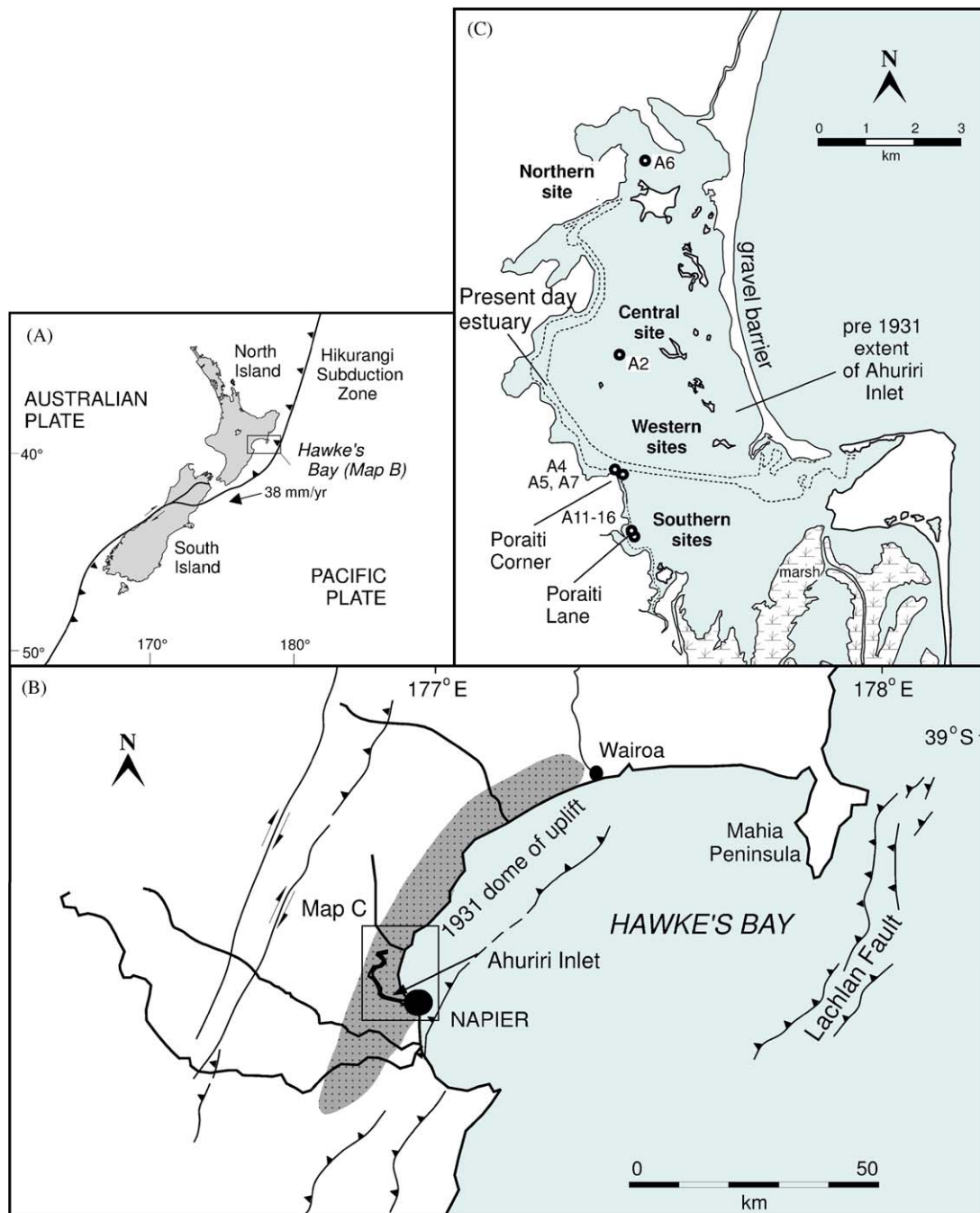[1]Current address: Auckland Regional Council, Private Bag 92012, Auckland, New Zealand.

Fig. 1. (A) Map of New Zealand showing location of Hawke's Bay above the Hikurangi Subduction Zone on the Pacific-Australian plate boundary. (B) Map of Hawke's Bay region showing location of major active fault zones (Barnes et al., 2002) and elongate dome of land uplifted during the 1931 Napier Earthquake (Hull, 1990a). (C) Core site locations within the pre-1931 extent of Ahuriri Inlet. The dashed extent of the existing post-1931estuary is also shown.

Bay that has resulted in loss of life and land displacement. A longer record, at least back through the Holocene, is needed to answer questions about earthquake hazards and return times of large earthquake events. One method for obtaining a longer record is to study the elevational record of microfossils in coastal inlet sediments (e.g., Shennan et al., 1999; Sherrod, 1999, 2001).

The best microfossil groups for this purpose appear to be foraminifera and diatoms. Foraminifera can provide direct

estimates of past elevations as sheltered inlet and estuarine foraminiferal faunas exhibit zonations in response to changes in salinity and tidal elevation (e.g., Hayward et al., 1999a; Edwards and Horton, 2000). Several transect studies in modern New Zealand sheltered coastal environments have documented foraminiferal distribution patterns with respect to tidal elevation and salinity (e.g., Hayward et al., 1997, 1999a, b, 2004a). Computer-generated comparisons of fossil faunas with these modern analogues allow

quantitative estimates to be derived for the tidal elevation of older Holocene paleoenvironments.

Foraminifera are entirely brackish and marine, whereas diatoms also live in freshwater and non-marine soil environments, and thus their fossil floras additionally record these paleoenvironments. Unlike foraminifera, intertidal diatom distribution is not strongly influenced by elevation, but largely by salinity and to a lesser extent by substrate (Denys and de Wolf, 1999). A calibration set of modern New Zealand diatom floras has been compiled from a range of coastal water bodies (Cochran, 2002), and can be used to determine paleoenvironmental settings and provide quantitative estimates of salinity.

The foraminiferal and diatom fossil records are complimentary. Diatoms occur in a broader range of environments, but in intertidal settings foraminifera provide a better estimate of tidal elevation. Foraminifera, being infaunal and larger, are less subject to post-mortem transport and mixing than the surface-dwelling or planktic diatoms. In more alkaline burial environments (e.g., in carbonate-rich sediment as in some Ahuriri sections), siliceous diatoms are often destroyed by dissolution whereas calcareous foraminiferal tests survive (e.g. Chagué-Goff et al., 2000a). In more acidic burial environments (e.g., in peat or silicic tuff-rich sediment) calcareous foraminiferal tests (but not agglutinated forms) may be dissolved away, whereas diatom valves usually survive (e.g. Hayward et al., 2004b).

The use of foraminiferal and diatom fossils in the study of earthquake displacements began on the west coast of North America (e.g., Hemphill-Haley, 1995; Guibault et al., 1996; Nelson et al., 1996a; Kelsey et al., 1998, 2005; Hawkes et al., 2005), and has now been applied in other earthquake-prone parts of the globe (e.g., Sawai et al., 2002). Several recent New Zealand studies utilise foraminifera and diatoms in combination to recognise Holocene earthquake displacements in coastal inlet and lagoon environments (Goff et al., 2000; Hayward et al., 2004b; Cochran et al., in press).

This study looks at the record from many cores in four different parts of the former Ahuriri Inlet to try to decipher the Holocene history of co-seismic vertical land displacements in this part of Hawke's Bay as a contribution to the assessment of large earthquake hazards in the region.

1.1. Holocene tectonic setting

Hawke's Bay is in the centre of the east coast of New Zealand's North Island, where the westward-dipping Hikurangi Subduction Zone of the Pacific-Australian Plate boundary lies 15–20 km beneath the surface (Ansell and Bannister, 1996).

Study of uplifted Holocene and late Pleistocene marine terrace sequences along this east coast led to the recognition of segmented deformation above the subducted Pacific plate (Berryman et al., 1989). Each regional segment of the coast has had a separate deformation history, with most

segments having been uplifted by a sequence of co-seismic events (uplift ca 1–4 m each) at recurrence intervals of 400–2000 years (Berryman et al., 1989). Unlike most areas, the inner part of Hawke's Bay has no uplifted marine terraces, and is inferred to have generally subsided during the Holocene (Ota et al., 1988). The only exception seems to be the uplift in the 1931 Napier Earthquake (Hull, 1990a).

Hypocentres and composite focal mechanisms of microearthquakes from coastal Hawke's Bay indicate that tension within the subducting Pacific Plate is the dominant cause of recent earthquakes in this region, with only a small number of earthquakes indicating seismic slip along the plate interface itself (Reyners, 1980; Bannister, 1988). While few earthquakes are currently occurring in the overriding Australian Plate, earthquake geology studies indicate that many large earthquakes in the eastern North Island (like the Napier Earthquake) are apparently generated by slip at shallow depths on steeply dipping faults within the accretionary wedge of this Australian Plate (Hull, 1990a).

In addition to these sources the tectonic setting of Hawke's Bay may also be exposed to the largest and most damaging earthquakes known—those which occur on subduction interfaces at relatively shallow depths, although none has been recorded on the Hikurangi Subduction Zone in historic times (since 1840). Shallow subduction interface earthquakes, such as the magnitude 9.2 event in Alaska in 1964, can cause extensive vertical deformation to the overriding plate (Plafker, 1965), which is likely to be recorded by microfossils in sheltered intertidal sedimentary sequences of coastal regions (e.g., Nelson et al., 1996b; Shennan et al., 1996, 1998, 1999; Hawkes et al., 2005).

1.2. Hawke's Bay earthquake displacements

Several previous studies documented the elevational record of late Holocene earthquakes in the sediment of Ahuriri Inlet. Hull (1986, 1990b) recorded the stratigraphy in temporary excavations containing up to 8 m of peat overlain by 0.7 m of estuarine sediment near the southwestern corner of the inlet (near our southern sites). From radiocarbon dating and stratigraphy, Hull (1986) concluded that the area had undergone an overall subsidence of ca 8 m between 3500 and 1750 radiocarbon years BP, followed by a further ca 1 m subsidence 500 years BP, and a reversal of movement in the 1931 earthquake with 1 m of uplift.

In the late 1990s, three short cores (0.7–1.2 m deep) from the modern Ahuriri Inlet were analysed using sedimentological, chemical and geochronological techniques (Chagué-Goff et al., 1998, 2000a, b). Only in the core taken on the southern shore of the present day outer inlet were sedimentological (switch from mud to sand) or chemical techniques able to identify the 1931 earthquake uplift event. Benthic foraminifera in two short cores at Poraiti corner (our western core sites) were used to infer the

location of the 1.5 m of uplift associated with the 1931 Napier earthquake, although sedimentary and geochemical characteristics could not distinguish it at this locality (Chagué-Goff et al., 2000b; Hayward et al., 2004a).

Soon after the 1931 earthquake, Henderson (1933) published a detailed description of surface faulting and vertical land movements that accompanied it. Marshall (1933) surveyed the Hawke's Bay coast and estimated elevational changes in relation to the pre-1931 high-tide levels. Post-1931 relevelling of the Wellington–Gisborne railway line, which passes along the gravel barrier separating Ahuriri Inlet from the sea, provided some of the best data on elevational changes (for summary see Hull, 1990a). The earthquake resulted in uplift of a 90×17 km NE-trending dome, with the axis passing through Ahuriri Inlet (Fig. 1). Maximum uplift (2.7 m) was 25 km north of the inlet, with uplifts of 1–1.8 m recorded for the inlet itself. Doming is attributed to folding of young elastic rocks above a buried causative fault. Surface faulting occurred only in an area 20 km to the south of the inlet (Hull, 1990a).

Microfossil-based paleoenvironmental investigations of the sedimentary record in several present and former coastal lagoons and inlets in northern Hawke's Bay, 60–80 km north of Ahuriri, have provided evidence for the occurrence of two large earthquakes involving substantial subsidence at ca 7100 and 5500 cal yr BP (Cochran et al., in press). Marine-derived sand and gravel layers in the dominantly mud sequences suggest that both earthquakes generated large tsunamis (Chagué-Goff et al., 2002; Cochran et al., 2005). Whether or not these earthquakes involved slip on a local fault in the upper plate or on the subduction interface is not known.

2. Methods

2.1. Coring

Nine sites, at present-day elevations between mean sea level (MSL) and mean high water (MHW), were selected for coring in the floor of the uplifted (in 1931) Ahuriri Inlet (Table 1, Fig. 1C). Two sites were cored more than once to recover longer or more complete records (e.g. A5, A7; A12, A15). Sheltered sites away from the inlet entrance or large stream mouths were chosen to reduce the amount of transport and mixing of the microfossil record, or salinity and sediment changes caused by migrating stream channels. Most sites were vibracored (7.5 cm diameter cores), with the penetration depth limited by the length of the aluminium tubing (7 m), sediment stiffness or presence of wood. A truck-mounted drill rig with hydraulic piston and rotary augering (for harder sediment) capability was used for deeper coring. Coring problems in wood-bearing peat and cemented sediment resulted in the drilling of two sites (A13, A14) with a 1.2 m diameter auger and direct sampling of the walls of the open hole.

2.2. Micropaleontological processing

For foraminiferal studies, 147 core samples (10–20 cm^3) were washed over a 0.063 mm sieve. Dried samples were microsplit down to an amount containing approximately 100–200 benthic foraminifera, for identification and census count. In this study, the advantages of drying samples (ease and speed of splitting, picking, slide mounts for checking identifications, same method as analogue faunas) outweigh the disadvantages (loss of some thin-walled agglutinated elements of marsh faunas, which comprise a small portion of the samples). Species were identified with reference to Hayward et al. (1999a). Clearly reworked, pre-Holocene species (bathyal–abyssal taxa, some extinct) eroded from the surrounding Pliocene and Pleistocene strata, were excluded and the remainder were standardised as percentages for interpretation. A second data set was created for additional interpretation by excluding taxa that only live in subtidal normal marine settings (e.g., Hayward and Hollis, 1994; Hayward et al., 1999a) and had presumably been transported into the inlet through the sea entrance.

Thirty samples were analysed for diatoms where additional paleoenvironmental information was required to supplement the foraminiferal data. Sediment (ca 1 g dry weight) was digested in H_2O_2 to remove organic matter and heated in HCl to remove carbonates. Sand was removed by settling through a water column. Clay was removed by washing with dilute sodium hexa-metaphosphate and repeated decanting of suspended fines. Diatom slides were prepared by drying small aliquots of suspension onto cover slips and mounting them in Naphrax diatom mountant.

Where possible, 300 diatom valves were identified for each sample using standard reference floras (e.g., Hendey, 1964; Hustedt, 1985; Krammer and Lange-Bertalot, 1986; Krammer, 1988, 1991a, b; Hartley, 1996; Witkowski et al., 2000). Species were grouped into salinity categories according to their environmental preferences (Table 2) and this information was used to provide qualitative estimates of paleoenvironment for each sample.

2.3. Analysing foraminiferal faunas

Cluster analysis was used to assist the interpretation of the environmental meaning of the fossil foraminiferal faunas (Fig. 2). R-mode cluster analysis using the modified Morista coefficient (Kovach, 1993) was used to cluster species in the reduced data set with all inferred transported Holocene specimens removed. Two measures of species diversity were calculated for each fossil fauna. These were the species richness measure, Fisher Alpha Index, α, and the evenness measure, E (Hayek and Buzas, 1997).

2.4. Quantitative paleoelevation estimates

The tidal elevation at which each fossil foraminiferal fauna accumulated, was estimated using the modern analogue technique (MAT) described in Hayward et al.

Table 1
Ahuriri Inlet Holocene core sites

Core	Grid ref[a]	FR no.[b]	AU cat[c] number	Tidal elevation	Total depth	Core type
Northern						
A6	V20/415904	V20/f411	AU17821	1.0 m	3.0 m	Vibracore
Central						
A2	V21/411863	V21/f422	AU17818	0.8 m	6.0 m	Vibracore
Western (Poraiti Corner)						
A4	V21/408841	V21/f420	AU17819	1.2 m	1.1 m	Vibracore
A5	V21/408840	V21/f421	AU17820	0.2 m	6.8 m	Vibracore
A7	V21/408840	V21/f431	AU17822	0.3 m	21 m	Hydraulic piston & rotary
Southern (Poraiti Lane)						
A11	V21/408830	V21/f435	AU17826	0.8 m	11.3 m	Vibracore, hydraulic piston & rotary
A12	V21/411828	V21/f438	AU17829	0.7 m	12 m	Hydraulic piston & rotary
A13	V21/410830	V21/f439	AU17830	0.8 m	7.3 m	0.9 m diam auger
A14	V21/409830	V21/f440	AU17831	0.8 m	3.2 m	0.9 m diam auger
A15	V21/411828	V21/f441	AU17836	0.7 m	4.6 m	Vibracore
A16	V21/409828	V21/f442	AU17837	0.8 m	4.3 m	Vibracore

[a]Grid ref. = on New Zealand metric map series NZMS260.
[b]FR no. = catalogue number of the New Zealand Fossil Record system.
[c]AU cat. = catalogue number of the Geology Department, University of Auckland, New Zealand.

Table 2
Diatom salinity categories

Abbreviation	Category	Salinity (g l^{-1})[a]
F	Fresh	<0.3
FB	Fresh-brackish	0.3–2.0
B	Brackish	2–10
BM	Brackish-marine	10–25
M	Marine	25–30
U	Unreliable	—

[a]Approximate salinity values quoted in grams per litre (g l^{-1}).
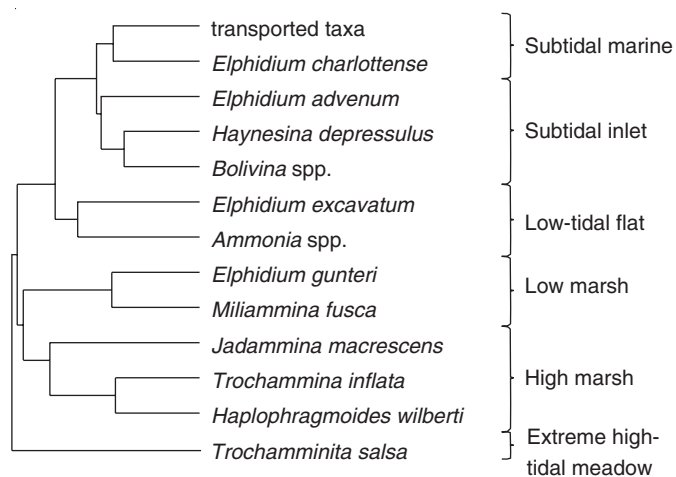

Fig. 2. Dendrogram classification of common benthic foraminiferal species in Ahuriri Inlet cores produced by unweighted pair-group R-mode cluster analysis using arithmetic averages of the modified Morista coefficient distance matrix. The species groups were selected by inspection of the dendrograms. Habitat interpretations are based on detailed distributional studies in estuaries and harbours around New Zealand (Hayward et al., 1999a,b).

(2004a), based on the benthic foraminiferal census counts. A squared chord dissimilarity coefficient was used to determine the compositionally most similar modern foraminiferal faunas to each fossil fauna using a data set of 272 samples from New Zealand sheltered harbours and shallow inlets (Hayward et al., 2004a). The process was repeated using the two data sets—one where the clearly reworked pre-Holocene taxa had been excluded and the second where the presumably transported normal marine Holocene taxa had been excluded and both fossil and analogue faunas restandardised to 100%. From these results, two estimates of the tidal elevation or water depth were computed for each fossil fauna: (1) the mean elevation and range of the five most similar modern faunas (reworked excluded) and (2) the mean of the five most similar modern faunas (transported excluded). In these calculations, tidal ranges are standardised and converted to the extreme spring tidal range of the study site (1.8 m for Ahuriri Inlet). The reliability of these elevation estimates depends on a number of factors, not least of which is the breadth of environmental coverage represented by the modern data set, which is partly reflected in the squared chord dissimilarity value for the fifth most similar modern analogue which was calculated for each fossil fauna.

2.5. Calculating the land elevation record, LER

The land elevation record (LER) is an index for graphically portraying land elevation changes caused by earthquake-related vertical displacements (Hayward et al., 2004b). Also graphed are the elements (e.g. core depth, indicative depth, Holocene sea level curve, inferred compaction) used in calculating the LER in a cored sequence.

The LER can be estimated for each core sequence using the formula:

$$LER = D + I + T - C - H,$$

where D is the sample depth downcore; I the indicative depth at which microfossils accumulated; T the sea-level height with respect to present level (using composite Holocene sea level curve); C the inferred compaction; H the height of core at surface. I, T and H are calculated with respect to New Zealand datum (extreme spring low tide level). LER values are determined for key sample points through each core section and plotted on a time-depth diagram. Key sample points are those that have good indicative depth (I) estimates from the fossil biotas, or where sudden changes of I are indicated.

A Holocene eustatic sea-level curve for the New Zealand region is not accurately constrained and that used here is a composite of the curves of Schofield (1960 from the tectonically stable northern North Island), Gibb (1986, summary of New Zealand-wide studies), and Baker et al. (2001, south and east Australia). Sea level is inferred to have risen to the present level by ca 7200 cal yr BP and to have further risen to at least 1 m above present by ca 6000 cal yr, dropping to ca 0.7 m by ca 3000 cal yr and to the present level by ca 2000 cal yr BP.

The amount of compaction (C) is constrained by the depth to penetrated basement of compacted Pliocene or Pleistocene rocks at some sites. Varying the amount of inferred compaction alters the estimated value of LER. In this study, we have inferred compaction values of 10–50% of sediment accumulation thickness, dependent upon the nature and thickness of the cored sediment, especially peat.

2.6. Sample and data repositories

Each core has been registered in the New Zealand Fossil Record File database (Table 1). Washed foraminiferal samples and picked faunas are held in the collection of the Geology Department, University of Auckland. Diatom residues and slides are stored at the Institute of Geological and Nuclear Sciences, Lower Hutt. Foraminiferal census count data are available on line in Appendix A.

2.7. Tephra and radiocarbon ages

Glass shards from tephra samples were analysed by electron microprobe and compared to those of known-age tephra from the Taupo Volcanic Zone following methods described by Shane (2000). Ferromagnesian minerals in the tephra layers were also examined to aid identification. Quoted ages are in calibrated years following Lowe et al. (1999). Additional radiometric carbon dates were done on shell and plant material by the Radiometric Dating Laboratory, University of Waikato. All ^{14}C ages (Table 3) have been converted into calibrated calendar ages using the program OxCal v3.9 (Bronk Ramsey, 2003).

3. Results

3.1. Core locations and stratigraphy

3.1.1. Northern (Fig. 3)

A single vibracore (A6) was taken from the northern, formerly embayed, portion of Ahuriri Inlet, which is partly surrounded by low spurs and a small island (Fig. 1). The recovered 3 m of pre-1931 sediment consists of carbonaceous mud, with occasional pebbly, shelly, or fine sand interbeds and two pumice tephra horizons. A bioturbated and possibly eroded contact is present at 2.36 m. Scattered mid-tidal to subtidal cockle (*Austrovenus stutchburyi*) shells occur throughout most of the section, except for two lower intervals (3.00–2.36, 2.00–1.70 m) that are non-calcareous. The tephra have been chemically identified as Waimihia Tephra (3500 cal yr BP, 2.74 m) and Taupo Tephra (1850 cal yr BP, 1.75 m).

3.1.2. Central (Fig. 4)

A single vibracore (A2) was taken from the centre of the uplifted and reclaimed tidal flats of Ahuriri Inlet (Fig. 1). The 6 m core is a mix of shelly mud and sand and thin shell hash beds. The lower and upper portions of the core are dominantly shelly mud, whereas the middle (4.85–0.79 m) is dominantly slightly shelly fine and medium sand. No distinct tephra horizons are preserved. Possible hiatus or erosional episodes are indicated by bioturbated zones just below 1.1, 1.9 and 4.87 m, and by thin (2–5 cm) shell hash beds at 2.15 and 4.85 m. A radiocarbon age on single cockle valves of ca 4200 cal yr BP was obtained from 4.86 m.

3.1.3. Western (Fig. 5)

Three cores, taken within 20 m of each other at Poraiti Corner on the western margin of the inlet, have been spliced together to give a composite stratigraphic section. The upper 1.1 m of the composite section is from A4, located near MHW in a present day salt meadow and containing a record of sediment accumulation prior to and after the 1931 uplift. Cores A5 and A7 were located in farmland inside the stop bank and spudded into uplifted, cultivated and weathered pre-1931 sediment. Following post-1931 farming, de-watering and compaction, these latter core sites have subsided to 0.2 m above extreme low water spring level (ELWS). Vibracore A5 provides the section from 1.1 to 7.2 m, whereas hydraulic piston cores from A7 on the same site provide an overlapping section from 4.5 to 7.7 m. Rotary drilling with recovery of cuttings continued down to 22 m. Below 7.64 m the section consists of compacted shelly grey mudstone with a Pliocene outer shelf-bathyal foraminiferal fauna. A 15 cm-thick pumice sand at 7.2 m could not be chemically identified and therefore is older than 50,000 years. If this is a primary deposit it lies just below the base of the Holocene inlet sequence, but if it is reworked it could lie within the base of the target sequence. The upper 7.5 m of sequence is

Table 3
Radiocarbon and tephra ages from Ahuriri cores

Core and depth	Material dated	$\delta^{13}C$ (‰)	Age (conventional radiocarbon years BP)	Calibrated calendar years BP (confidence)
A2				
4.86	Single *Austrovenus stutchburyi*	−1.8	Wk16242: 4187 ± 100	4550–3950 (95.4%)
A4–A5–A7				
4.73 mcd	Articulated *A. stutchburyi*	−1.4	Wk15806: 4716 ± 36	5120–4840 (95.4%)
6.54 mcd	Wood	−26.0	Wk15807: 5125 ± 36	5920–5740 (95.4%)
A6				
1.75 m	Taupo Tephra		1850 ± 10	1830–1710 (95.4%)
2.44 m	Waimihia Tephra		3280 ± 20	3580–3450 (94.3%)
A7				
7.42 m	Unidentified tephra			> 50,000
A11				
5.90 m	Wood	−24.7	Wk15808: 6356 ± 39	7330–7090 (88.2%)
A13				
4.70 m	Unidentified tephra			> 50,000
A14				
1.25 m	Articulated *A. stutchburyi*	0.0	Wk15809: 2100 ± 88	1920–1500 (95.4%)
A15				
1.25 m	Reworked Waimihia Tephra		3280 ± 20	3580–3450 (94.3%)
2.12 m	Wood	−27.9	Wk15810: 2895 ± 33	3080–2870 (93.7%)
3.58 m	Wood	−28.0	Wk15811: 4151 ± 113	5000–4250 (95.4%)
4.00 m	Whakatane Tephra		4830 ± 20	5610–5580 (54.9%) 5530–5480 (40.5%)
A16				
2.09 m	?Waimihia Tephra		3280 ± 20	3580–3450 (94.3%)
2.75 m	Peat	−28.4	Wk15812: 4497 ± 67	5310–4950 (86.4%)
Excavation (Hull, 1986)				
0.3 m	Articulated *A. stutchburyi*	0.3	NZA5612: 774 ± 45	510–320 (96.8%)
0.6 m	Articulated *A. stutchburyi*	0.2	NZA5613: 859 ± 82	630–340 (95.2%)
0.8 m	Tree in growth position	−27.2	NZA5611: 1791 ± 60	1825–1535 (96.8%)
0.8 m	Peat and twigs	−27.0	NZA5610: 1735 ± 60	1735–1510 (95.2%)
1.5 m	Taupo Tephra		1850 ± 10	1830–1710 (95.4%)

Tephra identified using mineral content and glass chemistry and quoted ^{14}C ages follow Lowe et al. (1999); radiometric carbon dates by University of Waikato, Radiometric Dating Laboratory (Wk catalogue numbers). ^{14}C ages have been converted into calibrated calendar ages using the program OxCal v3.9 (Bronk Ramsey, 2003). Four radiometric ages by Institute of Geological and Nuclear Sciences (NZ catalogue numbers) from Hull (1986) are given together with their newly calibrated calendar ages (pers. comm. R. Sparks, 2004). mcd = metres composite depth.

dominantly composed of shelly mud and muddy fine sand. The lower and upper parts of this sequence are shell-bearing mud or slightly sandy mud, but shell is lacking from the 4.5–2.5 m interval which comprises muddy fine sand (4.5–3.04 m) overlain by dark carbonaceous mud (3.04–2.53 m). Two possible hiatuses are indicated by irregular bioturbated contacts at 2.28 and 2.53 m. An unusual 5 cm thick, shelly, fine greywacke pebble gravel is present at 4.7 m.

Two radiocarbon ages were obtained giving ca 5800 cal yr BP at 6.54 m (wood) and ca 5000 cal yr BP at 4.73 m (on cockle).

3.1.4. Southern (Figs. 6–8)

Five sites within a 200 × 150 m area were cored around the end of Poraiti Lane in the mouth of a small former bay

on the western margin of the southern part of the inlet (Fig. 1). All spudded into pre-1931 sediment that had been uplifted, reclaimed, de-watered, weathered, ploughed and subsided and now lie at 0.7–0.8 m above ELWS. At two sites, pre-Holocene slightly shelly sand was penetrated (12–4.5 m in A15; 11–5.7 m in A11).

The stratigraphy of the north-eastern auger hole (A13) differed from all others by the presence, between 7.3 and 0.8 m, of hard, partly cemented, non-calcareous pumiceous sand and silt with thin gravel beds. Probing in the vicinity showed that this was part of a narrow, former spit of cemented sand. The equivalent sequence below 1.5–2 m in the other four sites (A11, A14–16) was a mix of carbonaceous mud, peat, sometimes rootlets, wood fragments and rare muddy sand. An interval of shell-bearing (high tide mudsnail, *Amphibola crenata*) mud occurs at

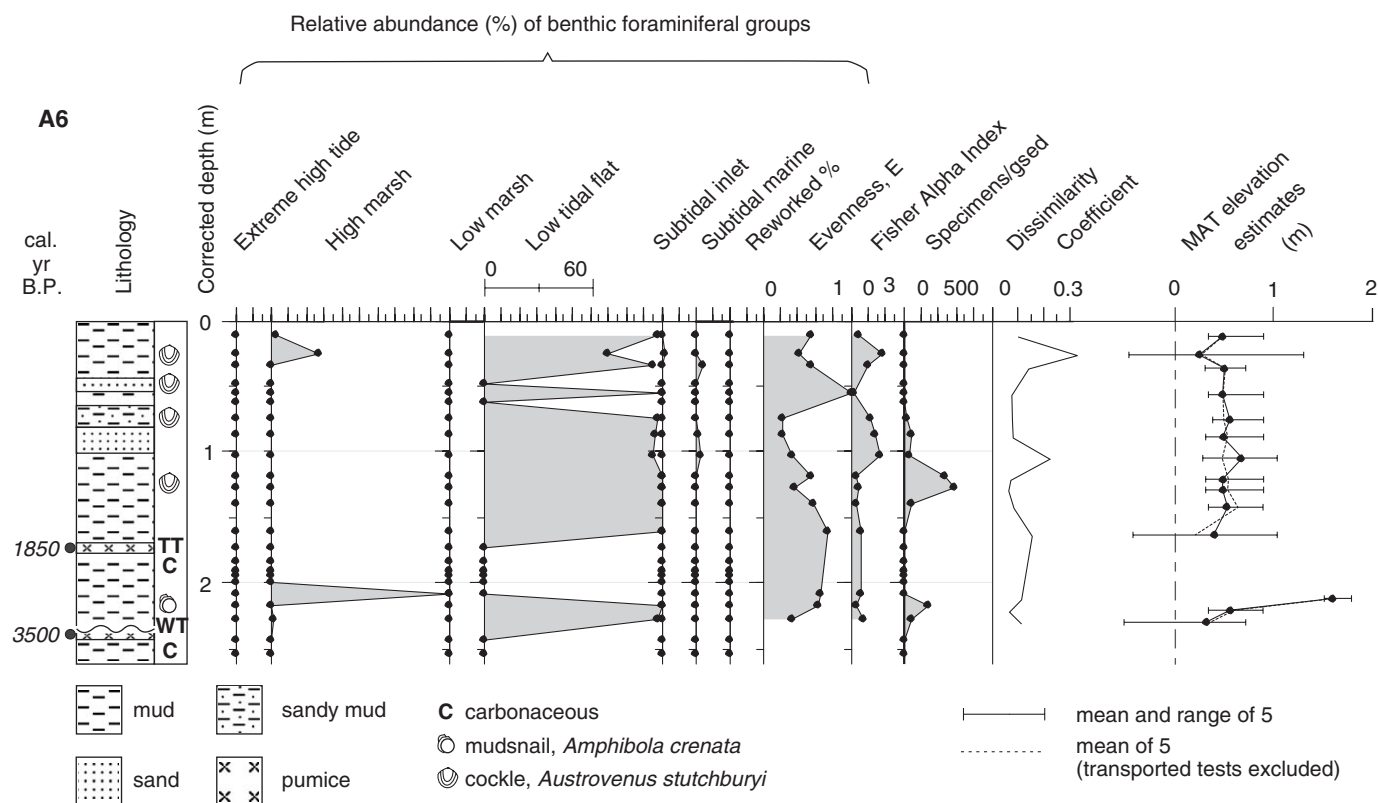Relative abundance (%) of benthic foraminiferal groups

Fig. 3. Stratigraphy of core A6, northern Ahuriri Inlet, showing (from left to right) age control; lithology; relative abundance of foraminiferal species grouped according to habitat (from Fig. 2); relative abundance of reworked pre-Holocene foraminifera; species evenness, E; species richness, Fisher Alpha Index; absolute abundance of foraminifera (specimens per g sediment); chord dissimilarity coefficient value for the fifth most similar modern analog; MAT paleo-tidal elevation estimates based on foraminiferal census counts (mean and elevational range of the 5 most similar modern faunas; and mean of the 5 most similar modern faunas (with all possibly transported species counts deleted). TT = Taupo Tephra, WT = Waimihia Tephra.

5.5–4.6 m in A11. A 5 cm layer of pumice at 4 m in A15 has been chemically identified as Whakatane Tephra (5500 cal yr BP). A 0.1–0.2 m bed of pumice tephra (identified as Waimihia Tephra, 3500 cal yr BP) occurs within the top of the thick peat (1.7–2 m) in A11, A14 and A16, and reworked within carbonaceous mud at 1.3–1.1 m in the south-eastern core, A15 (Fig. 7). All five cored sequences are capped by 0.8 (A15)–1.8 m (A13–14) of shell-bearing (mostly *A. crenata*) sandy mud or mud.

Around the head of this bay, 200 m west of our southern core sites across a stop bank and drainage ditch (Fig. 1), excavations have previously revealed 4 m+ of peat interpreted as overlying Waimihia Tephra (Hull, 1986). Taupo Tephra was identified in lenses within the top of the peat and the peat is overlain by up to 1 m of shell-bearing, sandy mud (Fig. 8). In situ trees within the top of the peat have been dated at ca 1750 cal yr BP and shells near the base of the mud at ca 500 cal yr BP (Hull, 1986). Our studies suggest that the tephra underlying the thick peat is unlikely to be Waimihia Tephra and is probably an older deposit. The reported deep occurrence was based on a description by the land-owner and was not observed nor sampled for the 1986 study (A. Hull, pers. comm., 2005).

3.2. Foraminiferal faunal groups

In the R-mode cluster analysis dendrogram (Fig. 2) we identify six species groupings, the relative abundance of each group in the cores is presented graphically in Figs. 3–7 and are useful in later interpretations of paleoenvironments. The six groupings (Table 4) are:

Extreme high tide meadow, Trochamminita salsa: In New Zealand this species inhabits the lowest salinity environments of any test-bearing foraminifer (Hayward et al., 1999a) and in less brackish harbours and inlets it occurs at extreme high water spring level in mixed salt meadows, where freshwater seepage is greatest (e.g. Hayward et al., 1996). This group is rare in Ahuriri cores and only occurs in high relative abundances (and low absolute abundances) in several samples in southern core A16 (Fig. 7).

High marsh, Haplophragmoides Wilberti–Trochammina inflata–Jadammina macrescens: This association of three agglutinated species is typical of slightly reduced salinity salt marsh or meadow environments between mean high water and extreme high water spring levels (Hayward et al., 1999a, b). This group is the most common of the high tide assemblages at Ahuriri, occurring in high relative abundances (but low absolute abundances) in parts of northern, western and southern cores (Figs. 3–7).
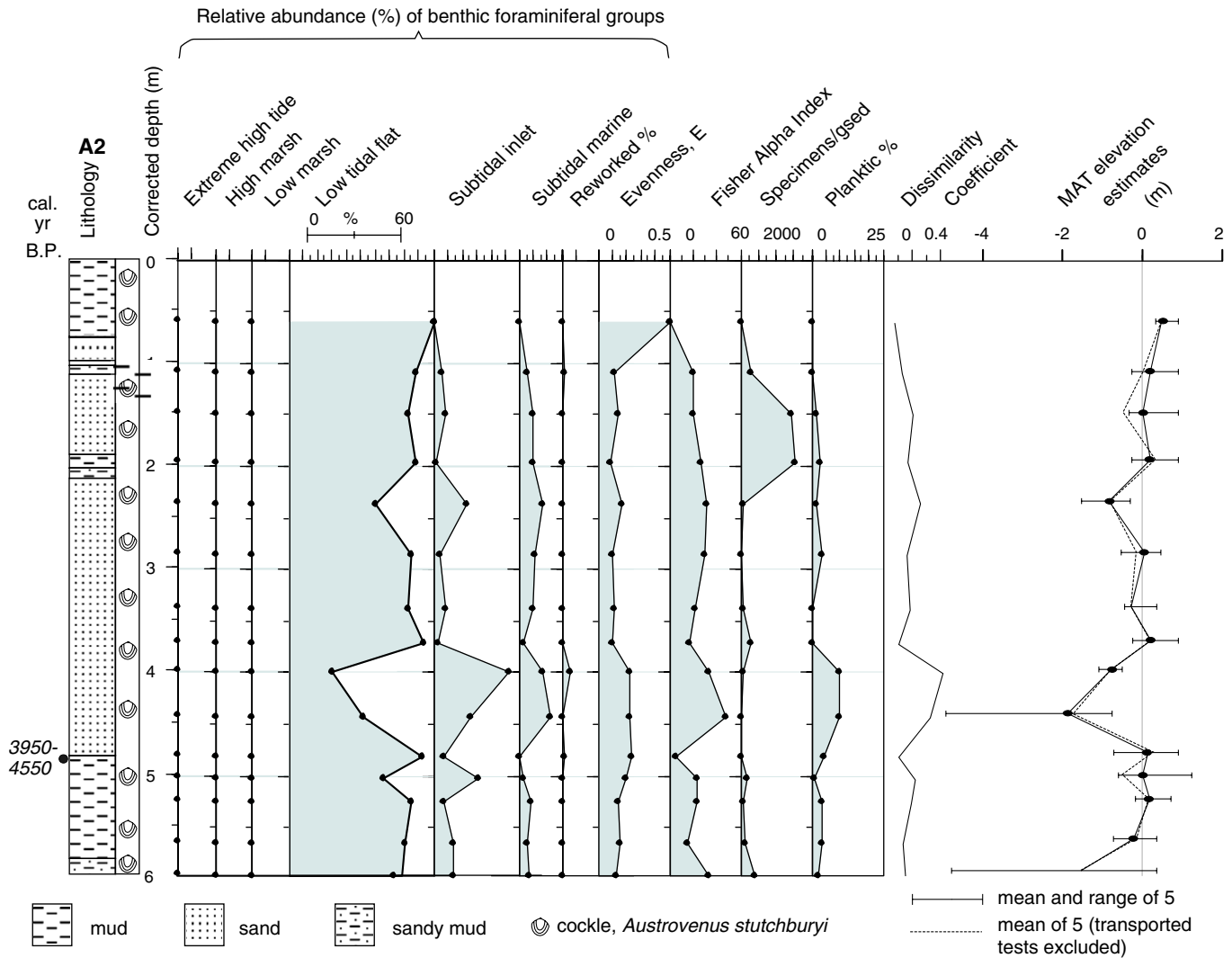
Fig. 4. Stratigraphy of core A2, central Ahuriri Inlet, showing foraminiferal data and MAT estimates of paleo-tidal elevation, as for Fig. 3.

Low marsh, Miliammina fusca–Elphidium gunteri: These two species occur together with *M. fusca* dominant at all tidal levels in moderately low salinities in the middle reaches of New Zealand estuaries (e.g., Hayward et al., 1997) and around the fringes of less brackish estuaries in lower parts of salt marshes and salt meadows between mean high water neap and mean high water spring (e.g. Hayward et al., 1996, 1999a). This group of foraminifera is rare in Ahuriri cores, only occurring in relative abundances >10% in western composite core A4–A5–A7 (Fig. 5).

Low-tidal flat, Ammonia spp.–*Elphidium excavatum* s.l.: Faunas dominated by these two taxonomic groups are widespread throughout New Zealand and elsewhere and characterise mostly unvegetated, low and mid tidal mud and sand flats in sheltered harbours (e.g. Hayward and Hollis, 1994; Hayward et al., 1999a). Common *Ammonia* also lives in sheltered, shallow subtidal habitats but always in association with a higher diversity fauna (e.g. Hayward et al., 1997). *Ammonia aoteana* is the most abundant foraminifer in all Ahuriri cores, presumably reflecting the large area of intertidal flats in the Holocene inlet.

Subtidal inlet, Haynesina depressula–Elphidium advenum–Bolivina spp.: These taxa seldom live intertidally and then only in the extreme low-tidal zone. All three commonly co-occur in shallow subtidal settings in sheltered harbours and inlets (e.g., Hayward et al., 1994, 1996, 1999a). This group of species is largely confined to central and western cores (Figs. 4–5).

Subtidal marine, Elphidium charlottense—transported species: *E. charlottense* is one of the most common species around New Zealand in normal marine salinity, inner shelf depths (0–50 m) where it co-occurs with a wide diversity of other shallow marine taxa (e.g., Hayward and Grenfell, 1994; Reid and Hayward, 1997). This group of species is most abundant in central and western cores (Figs. 4–5) and in several samples in southern core A16 (Fig. 7).

3.3. Diatom assemblages

Diatom studies are limited to the southern study area, particularly in cores A11, A15 and A16. Many samples contain very rare diatoms or poorly preserved assemblages
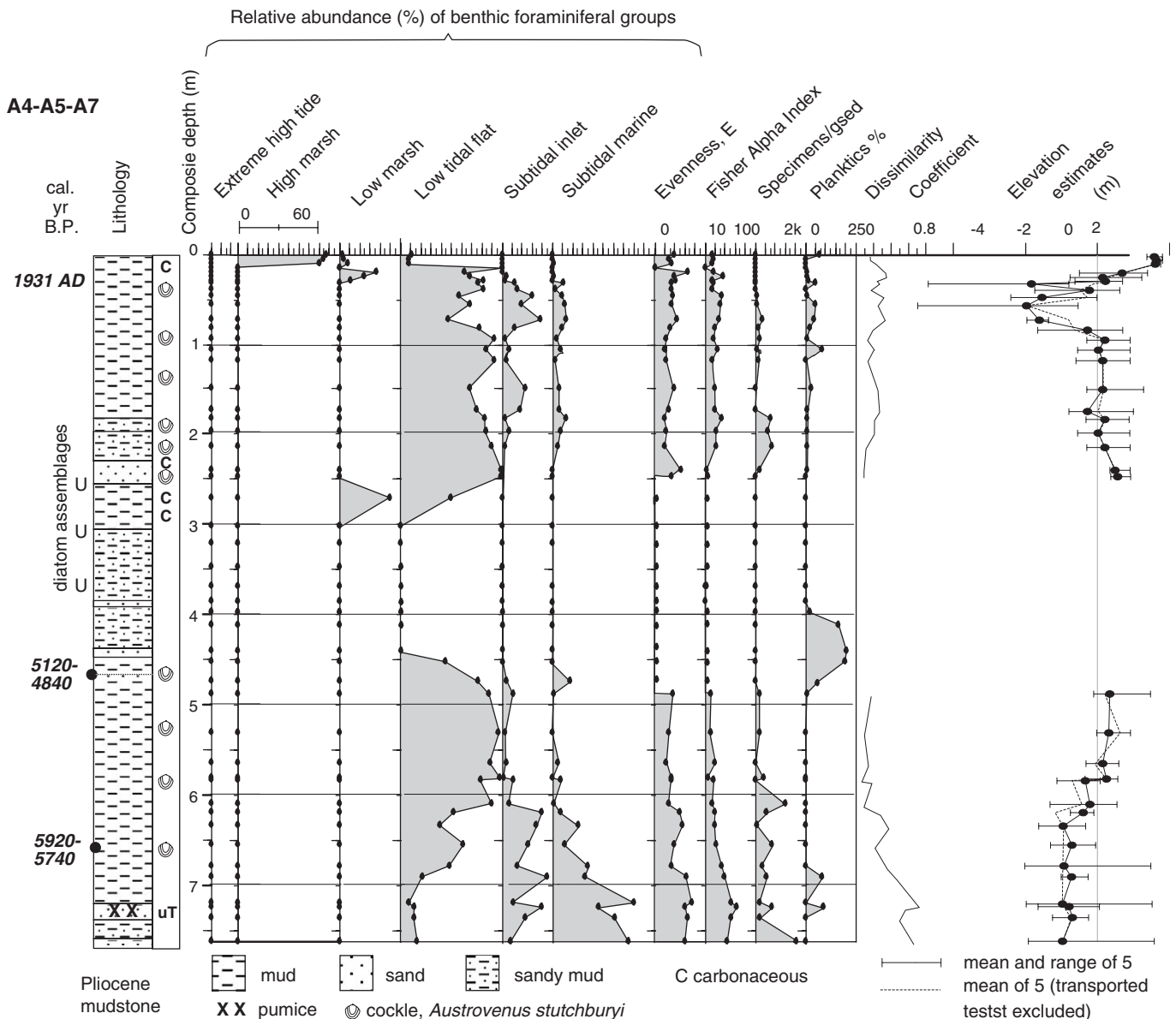
Fig. 5. Composite stratigraphy of cores A4, A5 and A7 spliced together, Poraiti Corner, western Ahuriri Inlet, showing foraminiferal data and MAT estimates of paleo-tidal elevation, as for Fig. 3. Distance downhole is given in metres composite depth (mcd).

so full counts were not possible and resulting paleoenvironmental indications are unreliable. However five samples from each of the cores A11, A15 and A16 contain pristine diatom assemblages from which alternations between brackish marine and fresh water environments can be inferred (Figs. 6–7).

3.4. Elevational estimates

MAT estimates of the elevation (relative to sea level) at which marine and brackish sediment accumulated, based on foraminiferal microfaunas, are given in Figs. 3–7. The accuracy of these elevational estimates and the ability to recognise vertical displacement events depends upon the faunal assemblage. Salt marsh and salt meadow forami-

niferal faunas have much narrower elevational ranges than those living at mid- and low-tidal elevations, which in turn are an order of magnitude narrower than those of shallow subtidal faunas (e.g. Hayward et al., 1999a, b). Thus the accuracy of elevational estimates becomes less precise with increasing depth. This is clearly seen in the plotted range of elevations of the five most similar modern faunas (Figs. 3–7).

The squared-chord dissimilarity values between the fossil fauna and the fifth most similar modern analogue fauna (transported specimens deleted) generally record relatively good matches (<0.3; e.g., A6, A11, A15; Figs. 3, 6, 7). Exceptions with considerably higher chord values occur where the fossil assemblages are more diverse, possibly as a result of post-mortem transport and mixing with the in situ
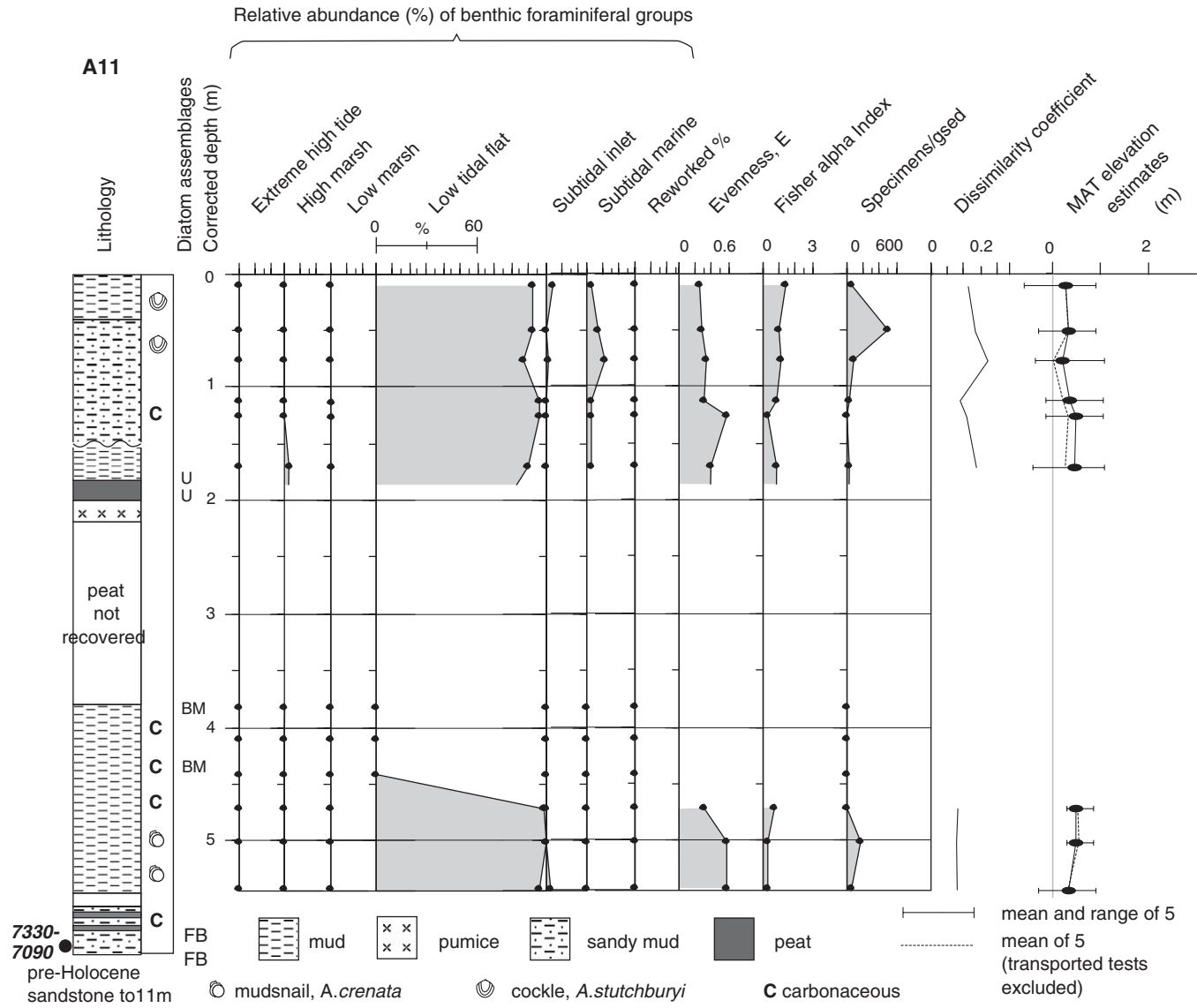
Fig. 6. Stratigraphy of core A11, southern Ahuriri Inlet, showing foraminiferal data and MAT estimates of paleo-tidal elevation, as for Fig. 3.

fauna (e.g., A2, 4.5–4 m; A4–A5–A7, basal 1.5 m; A16, 1.25 m; Figs. 4, 5, 7).

Comparison of the plots (Figs. 3–7) of the two MAT elevation estimates for each fauna shows only minor variations between those based on the two different data sets (with reworked specimens excluded; and transported specimens excluded). These estimates are used as a guide when calculating the land elevational record below, with the plotted range providing limits. More significantly the plots provide a guide to periods of shallowing or instances of abrupt elevational change.

Because of their different locations within the inlet the four sites have somewhat different records of the elevational history. Lower amplitude elevational displacements may not be obvious in the subtidal or low-tidal record from deeper parts of the inlet, but may cause major paleoenvironmental changes around the high-tidal margins (e.g., southern and northern cores).

3.5. Paleoenvironmental reconstructions

The composition of the fossil foraminiferal faunas reflects the location of each core within Ahuriri Inlet. Subtidal, normal marine salinity group foraminifera are most abundant in western cores and in southern core A16 (Figs. 5 and 7). These benthic specimens are inferred to have been transported into Ahuriri Inlet from outside the entrance by tidal currents. The western and to a lesser extent southern core sites are closest to the entrance at present (Fig. 1) and the foraminiferal record suggests that this was true for much of the late Holocene. Studies elsewhere suggest that tests transported into sheltered harbours and inlets preferentially accumulate subtidally, rather than intertidally (e.g., Hayward and Grenfell, 1994; Hayward et al., 2002). This is consistent with MAT elevational estimates that indicate that western cores record lengthy subtidal intervals (Fig. 5).
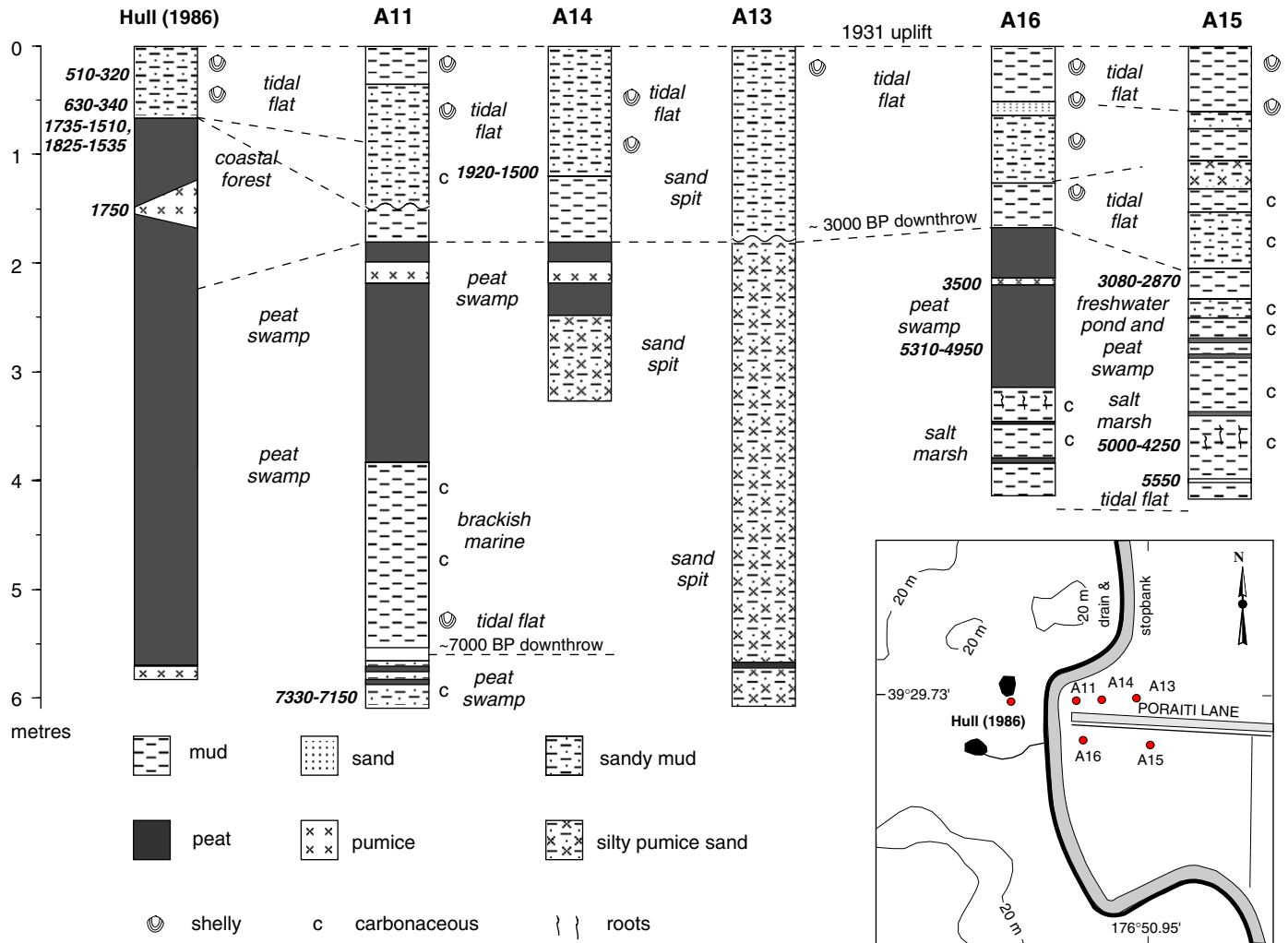
Fig. 7. Stratigraphy of cores A15 and A16, southern Ahuriri Inlet, showing foraminiferal data and MAT estimates of paleo-tidal elevation, as for Fig. 3. WT = in situ (A16) and reworked Waimihia Tephra (A15).

Subtidal sheltered inlet foraminifera have distributions coincident with the transported normal marine subtidal group in western cores (Fig. 5), but also occur throughout much of central inlet core A2, where they generally exceed displaced normal marine group specimens in abundance. Thus central and western parts of Ahuriri Inlet had substantial subtidal intervals through the Holocene, whereas

the general absence of subtidal inlet foraminifera from northern and southern cores (Figs. 3, 6, 7) suggests that these areas were mostly intertidal or supratidal.

Diatom floras are best-suited for distinguishing freshwater, soil, brackish and normal marine environments and thus studies were restricted to the cores from the southern site, where inlet margin paleoenvironments

Fig. 8. Generalised Holocene lithostratigraphy of five southern Ahuriri Inlet cores plus that record in a nearby excavation by Hull (1986). Radiocarbon and tephra ages are shown (in cal yr BP). Identified vertical displacement events and inferred paleoenvironments are labelled. Inset map shows core locations in the south-west corner of Ahuriri Inlet (Fig. 1).

Table 4
Foraminiferal habitat groupings

Extreme high tide (meadow)	*Trochamminita salsa:*
High marsh (high tide)	*Haplophragmoides wilberti—Trochammina inflata—Jadammina macrescens*
Low marsh (mid-high tide)	*Miliammina fusca—Elphidium gunteri*
Low-tidal flat (mid-low tide)	*Ammonia spp.—Elphidium excavatum s.l.*
Subtidal inlet (low-subtidal)	*Haynesina depressula—Elphidium advenum—Bolivina spp.*
Subtidal marine (transported)	*Elphidium charlottense—subtidal normal marine spp. (e.g. Astrononion, Bulimina, Cassidulina, Cibicides, Discorbinella, Gavelinopsis, Nonionellina, Notorotalia, Patellinella, Quinqueloculina, Rosalina, Zeaflorilus)*

Identified by cluster analysis (Fig. 2), of Ahuriri Inlet foraminiferal data.

prevailed through much of the Holocene. Mollusc shells in the cores are mostly derived from marine environments with some of the rarer species being indicators of high (e.g. mudsnail *Amphibola crenata*), low or subtidal elevations (e.g., small bivalves *Arthritica bifurca*, *Nucula hartvigiana*).

3.5.1. Northern, core A6 (Fig. 3)

An absence of both foraminifera and molluscs from the base of core A6 up to the bioturbated contact at 2.36 m (ca 3400 cal yr BP) suggests a non-marine environment. Above this contact the foraminiferal faunas record a sea-level rise followed by a short regressive interval of tidal mudflat sediment (2.36–2.17 m) passing through high salt marsh (2.09 m) to unfossiliferous, carbonaceous mud (2.00–1.72 m) of inferred non-marine origin (ca 1850 cal yr BP at top). The presence of high-tidal, mud snail fossils (2.3–2.2 m) is consistent with this interpretation.

Another rise in relative sea level is recorded above 1.7 m with all the overlying sediment containing shell fragments (mostly intertidal *Austrovenus stutchburyi*) and dominantly low-tidal foraminiferal faunas. The uppermost 1 m consists of interbedded shelly mud, shelly fine sand, and pebbly shell hash that suggest proximity to the changing course of a small tidal channel, and the low absolute abundance of foraminifera suggests increased sedimentation rate. This would provide an explanation for the mixed tidal flat and

high marsh foraminiferal fauna at 0.25 m, with the high-tidal specimens having been transported down the channel.

3.5.2. Central, core A2 (Fig. 4)

The shells of molluscs that live in mid-tidal to shallow subtidal sheltered inlet settings are scattered through the core and include the bivalves *Austrovenus stutchburyi*, *Cyclomactra ovata*, *Macomona liliana*, *Nucula hartvigiana* and gastropods *Diloma subrostrata*, *Maoricolpus roseus*, and *Micrelenchus huttonii*. The benthic foraminifera throughout the core are dominated by the low-tidal flat group with variable additions from the subtidal inlet, subtidal marine and transported groups. There is no evidence of any high tidal, freshwater or subaerial deposits. Subtidal intervals (e.g. 6–5.5 m, 4.5–3.8 m, 2.5 m, 1.5 m) with higher diversity benthic foraminiferal faunas containing increased abundances of subtidal group species are interspersed with lower diversity, lower evenness faunas dominated by *Ammonia* that are indicative of mid-low-tidal paleoenvironments. These alternating subtidal and intertidal faunas indicate sediment accumulation and shallowing interspersed with periodic subsidence events. The faunal trends that indicate shallowing following sudden elevational drops (Fig. 4), argue against an alternative interpretation of possible landward displacement of subtidal sediment during storms.

3.5.3. Western, composite core A4–A5–A7 (Fig. 5)

The lowest ca 3 m (7.6–4.5 m) of the Holocene section is a regressive sequence of slightly shelly mud with the lower part dominated by subtidal foraminifera and associated subtidal to low-tidal bivalves (e.g., *Nucula hartvigiana*, *Arthritica bifurca*) with increasing relative abundance of the low-tidal foraminiferal group upwards. The high relative and absolute abundance of presumably transported subtidal marine group foraminifera in the basal 1.5 m (Fig. 5) compared with all other cored sequences, suggests that the boulder spit that encloses Ahuriri Inlet may still have been forming and the inlet mouth may have been wider and deeper than today, although still directly seaward of this western site.

Above 4.7 m the abundance of foraminifera declines dramatically, with a switch to dominantly subtidal marine and planktic groups (4.7–3.5 m), all of which are probably reworked. The absence of mollusc and ostracod shells and increased abundance of carbonaceous matter in the interval 4.5–2.5 m is consistent with a non-marine environment. This could not be confirmed with diatoms as none are preserved.

An irregular bioturbated contact between mud and shelly sand at 2.48 m appears to mark a rise in relative sea level with a return of marine molluscs, ostracods and more abundant benthic foraminifera. The interval 2.48–1.8 m is dominated by the tidal flat group of benthic foraminifera suggestive of low-mid tidal depths, but an increase in the subtidal inlet group suggests another relative rise in sea level at ca 1.8 m. This is followed by a regressive sequence

from subtidal to intertidal foraminifera, that is interrupted once again at 0.85 m by another rapid rise in relative sea level as indicated by the foraminiferal faunas.

At 0.3 m low marsh foraminifera suddenly appear, presumably as a result of the 1.5 m uplift during the 1931 earthquake. As sediment accumulated in the salt marsh the faunal composition switches to high salt marsh above 0.15 m (Hayward et al., 2004a).

3.5.4. Southern, cores A11–16 (Figs. 6–7)

The sediment and microfossils in these cores, together with the sequence in the earlier excavations to the west (Hull, 1986), provide a picture of the changing paleogeography of this corner of Ahuriri Inlet over the last 7000 years (Fig. 8).

Probing indicates that the cemented unfossiliferous pumice-rich sand that forms most of core A13 (below 0.8 m) is part of a buried elongate sand spit that extends southwards part-way across this embayment from Poraiti Point (Fig. 8). Today, high-tide level sand and shell spits like this are common at the entrance to small bays on the edges of tidal inlets and estuaries in many parts of New Zealand (e.g. Hayward et al., 1999c). This spit appears to have strongly influenced the paleoenvironments in these southern cores for much of the Holocene with the development behind it of salt marsh and freshwater peat swamp.

The oldest cored sediment in this area indicates that the paleogeography was influenced by pre-Holocene topography with higher dry land to the south (A15, A16) and freshwater peat swamp (ca 7200 cal yr BP, A11, 5.9 m) in behind the earliest sand bar (A13). By ca 6000 cal yr BP sea level had risen and tidal flat foraminifera and mud snails are preserved in mud (A11, A15) that accumulated in the small tidal embayment that developed behind the spit.

By ca 5000 cal yr BP the small bay had been transformed into a shallow freshwater pond (A11) margined by peat swamp on the landward side and by salt marsh along the south-western margin, where extreme high-tidal and high-marsh foraminiferal groups were dominant in A15 and A16 (Fig. 7). Between ca 4500 and 3000 cal yr BP relative sea level was even lower and a freshwater peat swamp filled the entire bay behind the spit (Fig. 8) with freshwater and soil diatoms, massulae from the water fern *Azolla filiculoides* (Large and Braggins, 1993), but no foraminifera, in the carbonaceous mud and peat.

A major relative sea level rise is recorded ca 3000 cal yr BP (ca 1.8–2 m) in all cores, with the freshwater peat overlain by mud and sandy mud containing tidal flat foraminifera (A11, A14–16). The sand spit in A13 continued in existence, although its upper 1 m of sand is less cemented than that below 1.8 m. Hull's (1986) studies indicate that peat swamp, with in situ coastal trees, continued in existence around the margins of the bay until about 1800 cal yr BP (Fig. 9). A further rise in relative sea level occurred ca 500 cal yr BP (Hull, 1986), with shelly mud accumulating right across the bay and also burying
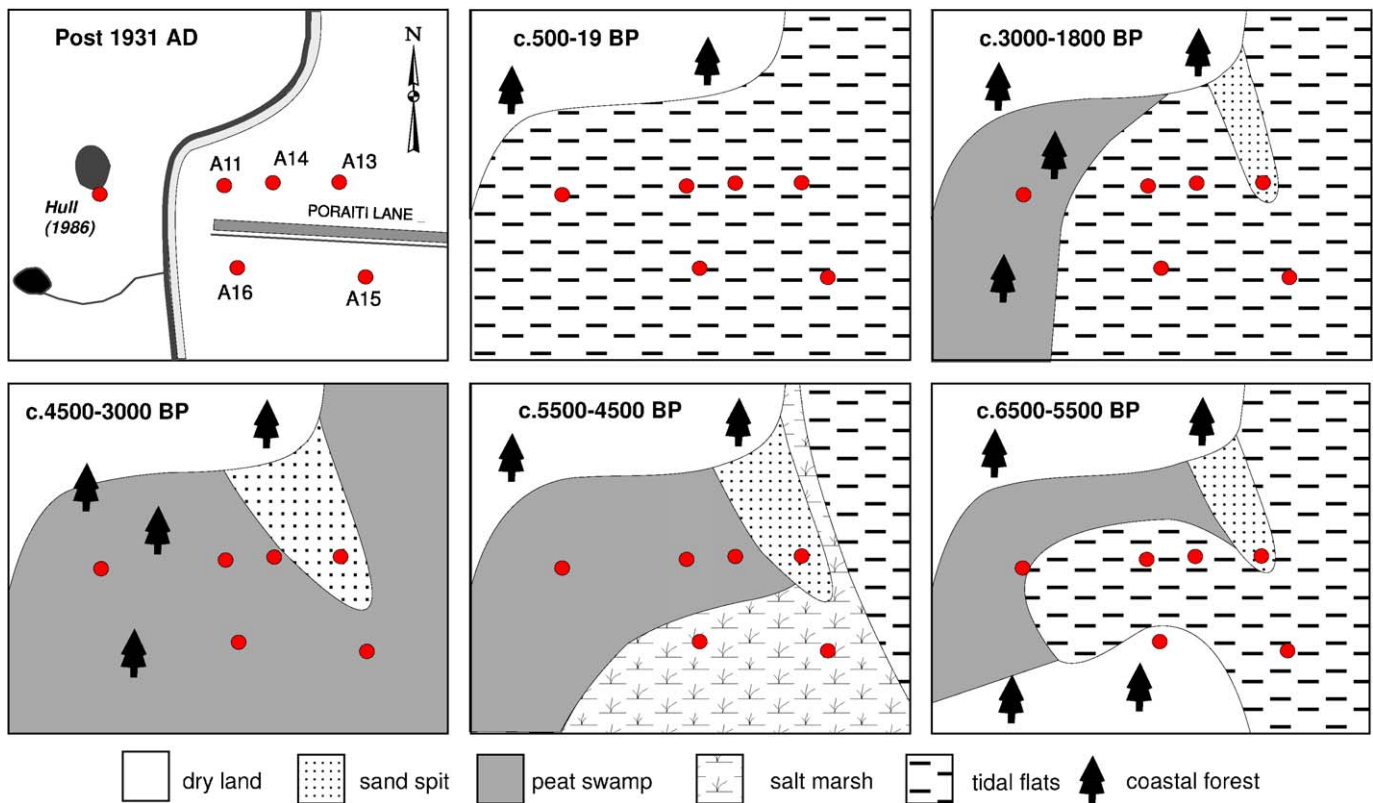
Fig. 9. Inferred paleogeographic history of the southern Ahuriri Inlet core site, based on the sedimentary and microfossil record in five cores and one excavation. The location of this area within Ahuriri Inlet is shown in Fig. 1.

the sand spit up until the time of the 1931 earthquake uplift. This shelly mud contains common cockles (*Austrovenus stutchburyi*), high-tidal mud snails *(Amphibola crenata)* and foraminiferal faunas dominated by the mid-low-tidal flat group.

4. Discussion

4.1. Compaction versus tectonic subsidence

Sediment consolidation can be significant in Holocene coastal environments, especially fine-grained, organic-rich sediment (Pizzuto and Schwendt, 1997; Haslett et al., 1998; Allen, 1999; Gehrels, 1999). Holocene compaction ratios of ca 0.5 and 0.2 have been recorded from estuarine mud and organic freshwater mud, respectively (Bloom, 1964; Pizzuto and Schwendt, 1997). Compaction is likely to have played a significant role in determining the elevation of all Ahuriri core sites during accumulation of the cored sediment. Fortunately the depth to compacted pre-Holocene "basement" mudstone or sandstone overlying Pliocene limestone was determined in both the western (A7, 7.6 m) and southern core sites (A11, 5.9 m; A12 = A15, 4.5 m), thus providing absolute limits on the amount of compaction. At the northern and central sites the depth to "basement" has not been determined and the amount of compaction of the sequence beneath these cores can only be estimated.

It is possible to calculate the compaction at the northern, central and southern sites (ca 1–1.2 m) following the 1.5 m of uplift in 1931 (mostly by dewatering of the upper mud units following stopbank and drain construction and conversion to farmland), because the pre-1931 and present elevations are known. Western core A4 was taken from the present day salt marsh where 0.3 m of sediment has accumulated since 1931 with little if any subsidence.

Compaction may have been slow and progressive and is only recognisable where there are overthick intertidal or freshwater sequences. Compaction could also have been rapid when associated with earthquake shaking (Ota et al., 1995; Nelson et al., 1996b). Thus, a record of sudden subsidence in a core probably signifies a large earthquake, but it may be due to either tectonic vertical displacement or compaction, or possibly both. The full magnitude of the 1931 earthquake uplift may have exceeded the 1.5 m recorded for the Ahuriri Inlet seafloor (Hull, 1990a) because it was probably accompanied by shaking-related compaction of the underlying Holocene sediment.

4.2. Co-seismic, vertical displacement events

For those cores that penetrated the full Holocene sequence and bottomed in compacted sediment, it is possible to calculate the total tectonic vertical displacement that has occurred since the start of Holocene sediment

Table 5
Land elevation record analysis

Site	Northern	Central	Western	Southern				
Core	A6	A2	A4–A5–A7	A11	A14	A15	A16	Hull
19 BP (1931 AD)	+1.5	+1.5	+1.5	+1.5	+1.5	+1.5	+1.5	+1.5
ca 600 BP			−1.0					— ?
ca 1650 BP	−1.7							— ?
ca 3000-19 BP	−2.5	−2.2	−2.8	−2.3	−2.2	−2.8	−2.2	
ca 3000 BP	−1.7	−1.4	−1.7	−1.6	−1.7	−1.8	−1.6	
ca 4200 BP		−1.5						
ca 5000-19 BP				−6.1		−6.6	−6.4	
ca 6500-19 BP		−6.9	−6.9	−7.9		−7.1	−7.4	
ca 7200-19 BP				−8.5				

Land elevation record analysis calculations (in m) of total vertical displacements (corrected for estimated compaction) for various Holocene time intervals as recorded by the microfossils and sediment in Ahuriri cores and the excavations of Hull (1986). All ages given in calibrated calendar years BP. Ages for A2 have been estimated based on correlations with other cores.

accumulation. Core A11 has the oldest dated Holocene sediment (ca 7200 cal yr BP) with 7 m net subsidence (8.5 m downthrow, 1.5 m uplift) recorded since then (Table 5). The oldest ages in cores A4–A5–A7 (1.1 m above basement) and A16 (0.5 m above basement) are ca 5800 and 5200 cal yr BP, respectively. These two cores record ca 5.5 m net subsidence (7 m downthrow, 1.5 m uplift) in the last 6500–6000 years (Table 5). Although basement was not reached in central area core A2, an indicated net tectonic subsidence of 5.5 m suggests that the basal sediment is ca 6000 cal yr (by correlation to A4–A5–A7 and A15).

The land elevation record plots for each core identify significant vertical displacement events in each core (Figs. 10 and 11) and also periods during which tectonic subsidence occurred, although large, discrete events cannot be identified. Because of different paleoenvironments not all cores precisely record the same displacement events. Thus the composite record of all cores provides the most complete history of earthquake-related events.

The 1931 AD uplift of 1.5 m is shown on all plots (based on post-earthquake survey records), although the uplift is only recorded in the microfossil record of western core A4 (Fig. 5).

The most prominent subsidence event in the Holocene record of Ahuriri Inlet is the abrupt switch from non-marine (peat or carbonaceous sediment) to marine (often shelly mud) sediment that occurs at depths of 1.6–2.3 m below the 1931 surface in cores from the northern, western and southern sites (A6, A5, A11, A14, A15, 16). LER plots calculate a tectonic subsidence of 1.4–1.8 m for this event (Figs. 10 and 11). In northern and southern cores the event post-dates the 3500 cal yr Waimihia Tephra with a maximum of 0.4 m of peat (A16) separating the two. A piece of wood (Wk15810) 0.07 m below the event horizon in core A15 has been dated at 2950 cal yr BP (3080–2870 cal yr), giving an approximate age of 3000 cal yr BP for this major event.

The abrupt contact between woody peat and shelly tidal mud in Hull's (1986) excavations has been dated (NZA5610, Table 3) as slightly younger than ca 1600 cal yr BP (1735–1510 cal yr) and records a separate tectonic subsidence event, as the inlet encroached further over the marginal coastal land. Cockle shells (NZA5613) from near the base of the overlying mud have been dated at ca 500 cal yr BP (630–340 cal yr) and suggest that sediment may not have accumulated here during the ca 1600–600 cal yr interval, with the peat surface exposed and possibly eroding at around high tide level. Hull's stratigraphy suggests a net tectonic subsidence of at least 1.5 m in the last 2000 year. This could have occurred in one or several events. The record in nearby cores suggests that the latter option is more likely, with at least two significant events at ca 1600 and 600 cal yr BP.

LER plots estimate cumulative tectonic subsidence between the 3000 cal yr subsidence event and the 1931 uplift in our cores (Table 5) to range between 2.8 m (A4–A5–A7, A15) and 2.2 m (A2, A14, A16). Substantial individual subsidence events within this period are identifiable in several cores. In the north, core A6 exhibits a ca 1.7 m tectonic subsidence less than 0.1 m above the 1770 cal yr Taupo Tephra (Figs. 3 and 10). This is probably the same event as that dated at ca 1600 cal yr in Hull's (1986) excavations in the south. The LER plot identifies a further 0.8 m of tectonic subsidence post 1600 in A6 (Fig. 10).

A substantial, undated, tectonic subsidence event (−1 m) is identifiable at 0.95 m downcore in A4, and as the LER plot identifies no younger subsidence event, it may be the same event as that dated at ca 600 cal yr in Hull's (1986) excavations. This correlation is supported by the LER plot for A4–A5–A7, which indicates a further ca 1.8 m of subsidence between this and the 3000 cal yr event (Fig. 10).

Identification and dating of major tectonic subsidence events prior to 3000 cal yr is more difficult, because of a predominance of non-marine sediment that lacks microfossil evidence of paleoelevational changes. LER plots for southern cores A15 and A16 indicate ca 2.2–2.6 m of tectonic subsidence between 5000 and 3000 cal yr BP and a
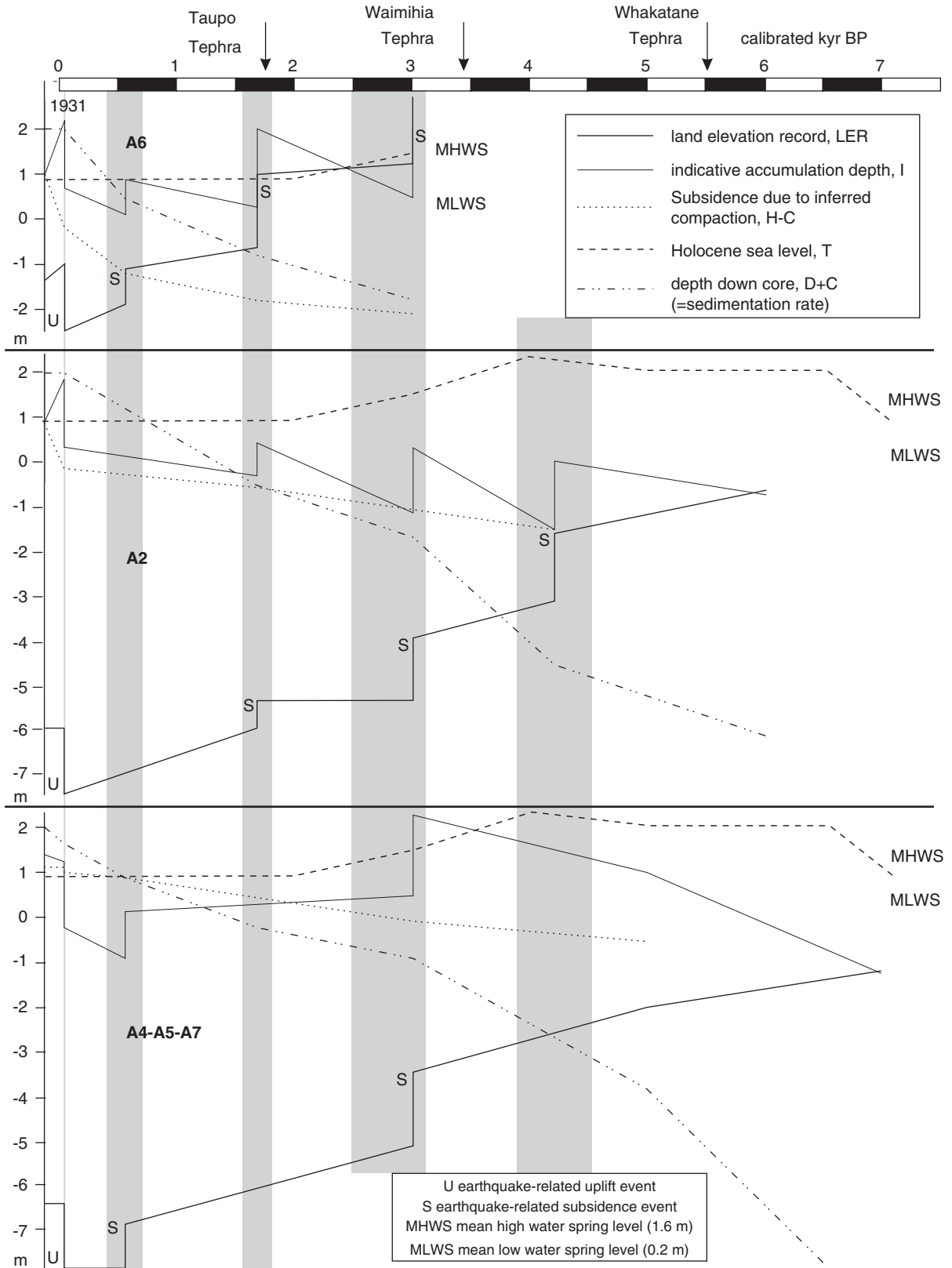
Fig. 10. Inferred Holocene, land elevational record (LER) histories of cores A6, A2 and A4–A5–A7 from northern, central and western Ahuriri Inlet. The LERs are derived primarily from the microfossil-based paleo-elevational estimates (I), and compaction-adjusted (C), sedimentation rates (H−D). A composite New Zealand eustatic sea-level curve (T) is used to further adjust the elevational record. H = height of top of core above MLWS (New Zealand datum); D = depth down core. Grey shading shows dating accuracy limits of displacement events.
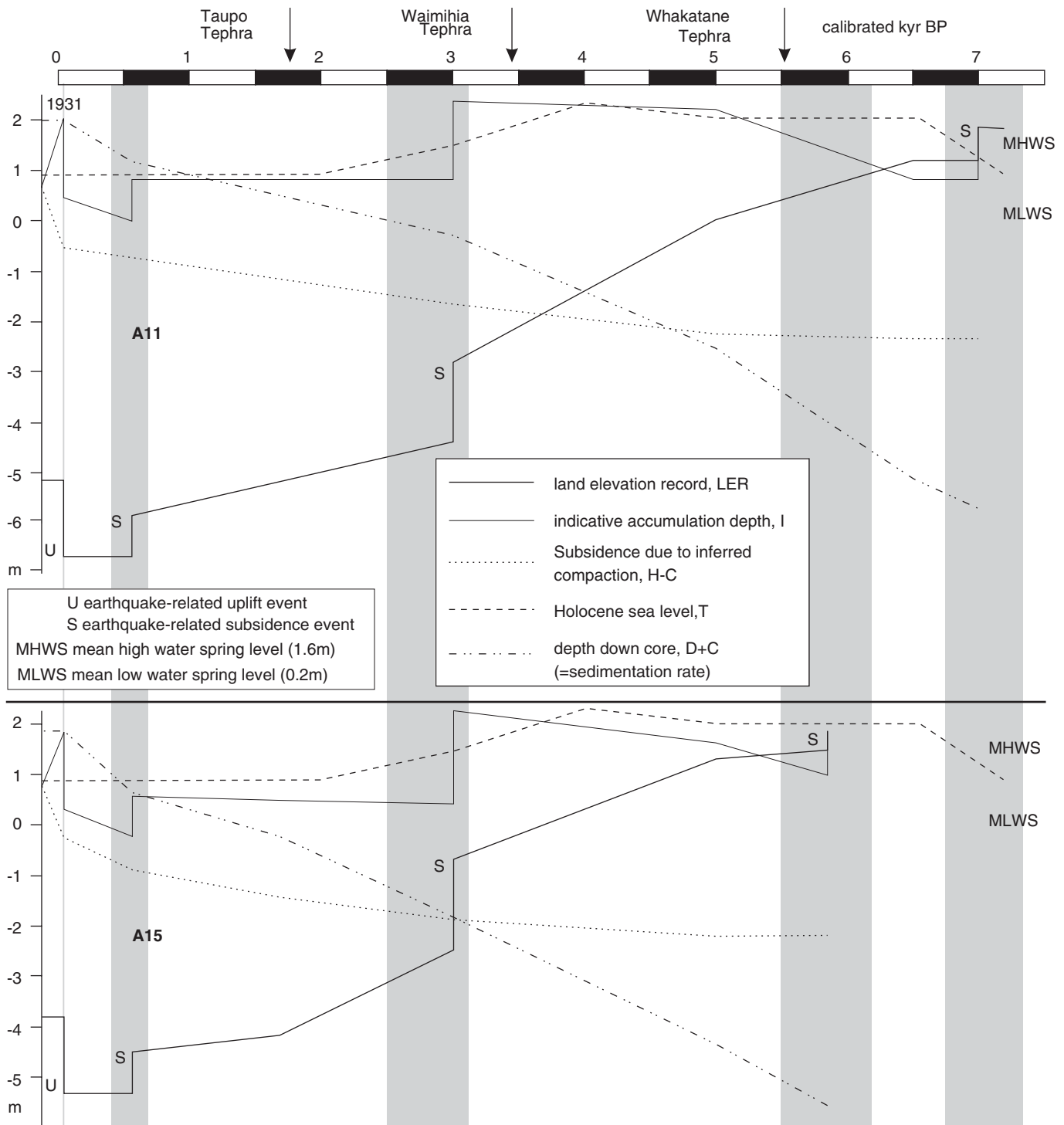
Fig. 11. Inferred Holocene, land elevational record (LER) histories of cores A11 and A15 from southern Ahuriri Inlet. The LERs are derived primarily from the microfossil-based paleo-elevational estimates (*I*), and compaction-adjusted (*C*), sedimentation rates (*H*−*D*). A composite New Zealand eustatic sea-level curve (*T*) is used to further adjust the elevational record. *H* = height of top of core above MLWS (New Zealand datum); *D* = depth down core. Grey shading shows dating accuracy limits of displacement events.

further ca 0.5–1 m between ca 6500 and 5000 cal yr BP (Fig. 11). The abrupt change from terrestrial to mid-low-tidal sediment near the base of the Holocene sequence in southern core A11 presumably records a tectonic subsidence event of at least 0.6 m at ca 7000 cal yr BP (Fig. 11).

Central inlet core A2 has the only pre-3000 cal yr sequence to be entirely marine. Its LER plot indicates ca 3.3 m of tectonic subsidence with at least one significant subsidence event (dated at ca 4200 cal yr) of ca −1.5 m at 4.85 m downcore (Figs. 4 and 10), where sand abruptly overlies mud.

4.3. Sedimentary record of earthquake events

A vertical displacement event could alter the sedimentary environment in a tidal inlet, but not always affect coastal terrestrial or freshwater settings. The altered conditions might result in an abrupt change in sediment character or in a period of non-deposition or erosion. Similar features could be produced by events unrelated to vertical displacements and earthquakes, such as shifting stream mouths, migrating tidal channels, floods, storm surges and strong winds.

In our cored Ahuriri sequences the identified episodes of vertical displacement have a wide range of sedimentary expressions. Some events have no visible record in the sediment, such as the 1931 uplift event at 0.3 m in core A4, where massive mud deposition persists despite 1.5 m of displacement. As mentioned previously, the ca 3000 cal yr subsidence of 1.4–1.8 m has the most obvious sedimentary record in most cores with peat or carbonaceous sediment overlain sharply by shelly mud. In almost all instances (e.g., A4–A5–A7, A6, A15, A16) this contact is irregular, presumably erosional, with some burrowing along it. This suggests that the contact is a burrowed hiatus surface that formed after the earthquake. Whether or not the erosion resulted from an earthquake-induced tsunami or merely from the changed base level cannot be determined.

Two of the identified subsidence events in central core A2 (at 4.81 and 1.94 m) and one in southern core A16 (at 1.2 m) are marked by sharp contacts between shelly mud and overlying shelly medium sand. These overlying sand units are > 0.5 m thick and contain typical tidal flat and subtidal inlet group foraminifera and probably are not earthquake-induced tsunami deposits.

The presence of displaced microfossils from open marine environments in Ahuriri Inlet sediment would provide evidence of either a tsunami or storm surge transporting sediment in from offshore. One such fauna that comprises anomalously high relative and absolute abundances of displaced subtidal marine group foraminifera is at 1.25 m in southern core A16 (Fig. 7) and it could be attributed to either mechanism.

Reworked Pliocene and Pleistocene foraminifera were presumably derived by erosion of softer lithologies in low coastal cliffs forming some of the landward boundary of Ahuriri Inlet (especially near the western core site) or transported into the inlet by streams at times of high runoff and landslides.

4.4. Regional comparisons

Comparison with other Holocene earthquake records in the region may provide insights into the magnitude and mechanism of coseismic rupture if events are found to be synchronous along the margin. Vertical deformation from the 1931 Napier earthquake is known from historical records to have been restricted to southern and central

Hawke's Bay and the causative fault is a local structure in the upper plate (Hull, 1990a). It is unlikely that there was some movement on the subduction interface beneath Hawke's Bay in the same event (Doser and Webb, 2003). The sedimentary earthquake record presented here confirms Hull's (1986) suggestion that earthquakes involving subsidence are more common for the inner Hawke's Bay coastline than those such as the Napier Earthquake involving uplift. If such subsidence is caused by slip on the subduction interface then these events are likely to be more widespread that those triggered by movement on local upper plate structures.

Berryman et al. (1989) document raised marine terraces as evidence for at least 21 earthquakes involving uplift in the last ∼2500 years and propose that these have occurred in about 10 distinct subregions along the outer coast of eastern North Island. In the Hawke's Bay region there is one raised marine terrace at Cape Kidnappers on the outer coast at the southern end of the bay that is thought to have been raised in an earthquake ca 2000 cal yr BP (Hull, 1987). In northern Hawke's Bay on Mahia Peninsula (Fig. 1) Berryman (1993) has mapped and dated a series of uplifted and west-tilted Holocene terraces with major co-seismic uplifts at 260–410, 1510–1700, 2035–2040, 3825–4020 and 5110–5390 cal yr BP These displacements have been attributed to movement on a major west-dipping reverse fault (Lachlan Fault) located offshore < 10 km east of Mahia Peninsula. Dislocation modelling indicates that with large enough amounts of slip on either local upper plate faults and/or the subduction interface, coseismic subsidence occurs inland from the region of uplift (Cochran et al., in press). Therefore subsidence at Ahuriri Lagoon possibly occurred in the same event as uplift at Mahia Peninsula or Cape Kidnappers. The 1510–1700 cal yr BP earthquake at Mahia Peninsula appears to have a correlative at Ahuriri Lagoon with the ca 1600 cal yr BP event but higher resolution age control would be required to confirm their synchroneity.

Evidence for earthquakes involving subsidence is harder to uncover than uplift and has only recently been sought at a couple of sites in northern Hawke's Bay. A tsunami deposit has been recognised in Te Paeroa Lagoon sediments dated at 7100 cal yr BP; with ca 2 m of subsidence (not compaction corrected) between 7100 and 5500 cal yr BP, a further 0.5–1 m between 5500 and 3450 cal yr BP, and no significant post-3450 cal yr tectonic subsidence (Chagué-Goff et al., 2002). 10 km further east at Opoho in northern Hawke's Bay, Cochran et al. (in press) have recorded ca 6 m of subsidence (including an unknown compaction component) in tidal lagoon sediments during at least two earthquakes, dated at ca 7100 and 5500 cal yr BP. These earthquakes may correlate with our poorly dated ca 7000 and 5800 events recorded at Ahuriri Lagoon in A11 and A15, respectively (Fig. 11). Large to great earthquakes would be inferred to explain vertical deformation that occurred synchronously in northern and southern Hawke's Bay. However, further definition of the extent and

timing of vertical deformation is required before proposing any Hawke's Bay-wide Holocene earthquakes.

Other subsidence events identified at Ahuriri Lagoon (ca 3000 and 600 cal yr BP) may be the result of earthquakes that only caused deformation locally in the vicinity of Napier or may be found to be part of more widespread deformation once further records have been investigated.

5. Conclusions

(a) Eleven cores of Holocene sediment were recovered from northern (3 m +), central (6 m +), western (7.7 m) and southern (4.5–5.7 m) parts of Ahuriri Inlet, southern Hawke's Bay.

(b) Six habitat groups of benthic foraminifera and four distinct diatom assemblages are identified and used to infer the subtidal and intertidal inlet and coastal swamp paleoenvironments in which these sediments accumulated.

(c) Reworked Pliocene and Pleistocene foraminifera from open marine shelf and bathyal environments are common in some sections (especially in the terrestrial section of the western core site) and were excluded when inferring paleoenvironments.

(d) Three airfall rhyolitic tephra (Taupo, Waimihia, Whakatane) are present in some, mostly non-marine sequences and help provide age control, which is supplemented by radiocarbon ages on shell, wood and peat samples. Reworked tephra-rich layers are present in some intertidal sequences, especially in a high-tidal sand spit sequence cored in the southern part of the inlet.

(e) Modern analogue technique, based on benthic foraminiferal faunas, has been used to estimate the paleoelevations at which marine and brackish sediment accumulated and aid in the recognition of instances of abrupt elevational change.

(f) Microfossil-based paleoelevation estimates have been combined with sediment thicknesses, age determinations, the New Zealand Holocene sea level curve, and estimates of compaction, to identify the Holocene land elevation record (LER) of each core.

(g) The LER plots identify a net tectonic subsidence of 7 m (8.5 m downthrow followed by 1.5 m uplift) in the last 7200 cal yr.

(h) The following earthquake-related vertical displacement events are identified from the LER plots:
    1931 AD Napier Earthquake, +1.5 m displacement
    ca 600 cal yr BP, ca −1 m
    ca 1600 cal yr BP, ca −1.7 m
    ca 3000 cal yr BP, −1.4 to −1.8 m
    ca 4200 cal yr BP, ca −1.5 m
    ca 5800 cal yr BP, −0.5 m +
    ca 7000 cal yr BP, −0.6 m +.

(i) The six subsidence events in the last 7000 years have had a return time of 1000–1400 years in southern Hawke's Bay.

(j) A further ca 1–2 m of tectonic subsidence is inferred to have occurred during smaller earthquake events during the interval 7000–3000 cal yr BP.

(k) Identified displacement events have a range of sedimentary expressions. In many places the 3000 cal yr event is marked by an eroded and burrowed hiatus surface. An abrupt switch from mud to sand coincides with several other events, whereas elsewhere there is no change in sediment character.

(l) There are possible correlations with earthquake records in northern Hawke's Bay but further work on the extent and synchroneity of events is required to investigate correlations.

Appendix A. Supplementary Materials

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.quascirev.2005.10.013.

References

Allen, J.R.L., 1999. Geological impacts on coastal wetland landscapes: some general effects of sediment autocompaction in the Holocene of northwest Europe. The Holocene 9, 1–12.

Ansell, J.H., Bannister, S.C., 1996. Shallow morphology of the subducted Pacific plate along Hikurangi margin, New Zealand. Physics of the Earth and Planetary Interiors 93, 3–20.

Baker, R.G.V., Haworth, R.J., Flood, P.G., 2001. Inter-tidal indicators of former Holocene sea levels in Australia: a summary of sites and a review of methods and models. Quaternary International 83–85, 257–273.

Bannister, S.C., 1988. Microseismicity and velocity structure in the Hawkes Bay region, New Zealand; fine structure of the subducting Pacific Plate. Geophysical Journal of the Royal Astronomical Society 95, 45–62.

Barnes, P.M., Nicol, A., Harrison, T., 2002. Late Cenozoic evolution and earthquake potential of an active listric thrust complex above the Hikurangi subduction zone, New Zealand. Geological Society of America Bulletin 114, 1379–1405.

Berryman, K.R., 1993. Age, height, and deformation of Holocene marine terraces at Mahia Peninsula, Hikurangi Subduction Margin, New Zealand. Tectonics 12, 1347–1364.

Berryman, K.R., Ota, Y., Hull, A.G., 1989. Holocene paleoseismicity in the fold and thrust belt of the Hikurangi subduction zone, eastern North Island, New Zealand. Tectonophysics 163, 185–195.

Bloom, A.L., 1964. Peat accumulation and compaction in a Connecticut salt marsh. Journal of Sedimentary Petrology 34, 599–603.

Bronk Ramsey, C., 2003. OxCal v3.9 Computer Program. Radiocarbon Accelerator Unit, University of Oxford.

Chagué-Goff, C., Nichol, S.L., Ditchburn, R.G., Trompetter, W.J., Sutherland, V.T., 1998. Earthquake and human impact on the sedimentology and geochemistry of Ahuriri Estuary, Hawke's Bay. Institute of Geological and Nuclear Science Report 98/23, 43pp.

Chagué-Goff, C., Nichol, S.L., Jenkinson, A.V., Heijnis, H., Hayward, B.W., 2000a. 150 years of change in a New Zealand estuary: earthquake, floods, humans and tsunami. In: Schnack, E. J., Murray-Wallace, C. V. (Eds.), Patagonia 2000. International Conference on "Coastal Interactions During Sea-level Highstands", IGCP Project 437, Annual Meeting, Puerto Madryn, Argentina, October 2000. Abstract volume, pp. 21–24.

Chagué-Goff, C., Nichol, S.L., Jenkinson, A.V., Heijnis, H., 2000b. Signatures of natural catastrophic events and anthropogenic impact in an estuarine environment, New Zealand. Marine Geology 167, 285–302.

Chagué-Goff, C., Dawson, S., Goff, J.R., Zachariasen, J., Berryman, K.R., Garnett, D.L., Waldron, H.M., Mildenhall, D.C., 2002. A tsunami (ca. 6300 years BP) and other Holocene environmental changes, northern Hawke's Bay, New Zealand. Sedimentary Geology 150, 89–102.

Cochran, U., 2002. Detection of large Holocene earthquakes in the sedimentary record of Wellington, New Zealand using diatom analysis. Unpublished Ph.D. Thesis, Victoria University of Wellington, Wellington, New Zealand.

Cochran, U., Berryman, K.R., Mildenhall, D.C., Hayward, B.W., Southall, K., Hollis, C.J., 2005. Towards a record of Holocene tsunami and storms for Northern Hawke's Bay, New Zealand. New Zealand Journal of Geology and Geophysics 48, 507–515.

Cochran, U., Berryman, K., Mildenhall, D.C., Hayward, B.W., Southall, K., Hollis, C.J., Barker, P., Wallace, L., Alloway, B.V., Wilson, K., in press. Paleoecological insights into subduction zone earthquake occurrence, eastern North Island, New Zealand. Geological Society of America Bulletin.

Denys, L., de Wolf, H., 1999. Diatoms as indicators of coastal paleoenvironments and relative sea-level change. In: Stoermer, E.F., Smol, J.P. (Eds.), The Diatoms: Applications for the Environmental and Earth Sciences. Cambridge University Press, Cambridge, pp. 227–297.

Doser, D.I., Webb, T.H., 2003. Source parameters of large historical (1917–1961) earthquakes, North Island, New Zealand. Geophysical Journal International 152, 795–832.

Edwards, R.J., Horton, B.P., 2000. Reconstructing relative sea-level change using UK salt-marsh foraminifera. Marine Geology 169, 41–56.

Gehrels, W.R., 1999. Middle and late Holocene sea-level changes in eastern Maine, reconstructed from foraminiferal salt marsh stratigraphy and AMS C-14 dates on basal peat. Quaternary Research 52, 350–359.

Gibb, J.G., 1986. A New Zealand regional Holocene eustatic sea-level curve and its application to determination of vertical tectonic movements. Royal Society of New Zealand Bulletin 24, 377–395.

Goff, J.R., Rouse, H.L., Jones, S.L., Hayward, B.W., Cochran, U., McLea, W.W., Dickinson, W.W., Morley, M.S., 2000. Evidence for an earthquake and tsunami about 3100–3400 years ago, and other catastrophic saltwater inundations recorded in a coastal lagoon, New Zealand. Marine Geology 170, 231–249.

Guibault, J.-P., Clague, J.J., Lapointe, M., 1996. Foraminiferal evidence for the amount of coseismic subsidence during a late Holocene earthquake on Vancouver Island, west coast of Canada. Quaternary Science Reviews 15, 913–937.

Hartley, B., 1996. An Atlas of British Diatoms. Biopress Ltd, Bristol.

Haslett, S.K., Davies, P., Curr, R.H.F., Davies, C.F.C., Kennington, K., King, C.P., 1998. Evaluating late-Holocene relative sea-level change in the Somerset Levels, southwest Britain. The Holocene 8, 197–207.

Hawkes, A.D., Scott, D.B., Lipps, J.H., Combellick, R., 2005. Evidence for possible precursor events of megathrust earthquakes on the west coast of North America. Geological Society of America Bulletin 117, 996–1008.

Hayek, L.-A.C., Buzas, M.A., 1997. Surveying Natural Populations. Columbia University Press, New York 563pp.

Hayward, B.W., Grenfell, H.R., 1994. Foraminiferal associations around northern Great Barrier Island, New Zealand. Records of Auckland Institute and Museum 31, 231–273.

Hayward, B.W., Hollis, C.J., 1994. Brackish Foraminifera in New Zealand: a taxonomic and ecologic review. Micropaleontology 40, 185–222.

Hayward, B.W., Hollis, C.J., Grenfell, H.R., 1994. Foraminiferal associations in Port Pegasus, Stewart Island, New Zealand. New Zealand Journal of Marine and Freshwater Research 28, 69–95.

Hayward, B.W., Grenfell, H.R., Cairns, G., Smith, A., 1996. Environmental controls on benthic foraminiferal and thecamoebian associations in a tidal New Zealand inlet. Journal of Foraminiferal Research 26, 150–171.

Hayward, B.W., Grenfell, H.R., Pullin, A.D., Reid, C., Hollis, C.J., 1997. Foraminiferal associations in the upper Waitemata Harbour, Auckland, New Zealand. Journal of the Royal Society of New Zealand 27, 21–51.

Hayward, B.W., Grenfell, H.R., Reid, C.M., Hayward, K.A., 1999a. Recent New Zealand shallow-water benthic foraminifera: taxonomy, ecologic distribution, biogeography and use in paleoenvironmental assessment. Institute of Geological and Nuclear Sciences Monograph 21, 264pp.

Hayward, B.W., Grenfell, H.R., Scott, D.B., 1999b. Tidal range of marsh foraminifera for determining former sea-level heights in New Zealand. New Zealand Journal of Geology and Geophysics 42, 395–413.

Hayward, B.W., Morley, M.S., Stephenson, A.B., Blom, W.M., Grenfell, H.R., Prasad, R., Rogan, D., Thompson, F., Cheetham, J., Webb, M., 1999c. Intertidal and subtidal biota and habitats of the central Waitemata Harbour. Auckland Regional Council Technical Publication 127, 40pp.

Hayward, B.W., Grenfell, H.R., Sandiford, A., Shane, P.A.R., Morley, M.S., Alloway, B.V., 2002. Foraminiferal and molluscan evidence for the Holocene marine history of two breached maar lakes, Auckland, New Zealand. New Zealand Journal of Geology and Geophysics 45, 467–480.

Hayward, B.W., Scott, G.H., Grenfell, H.R., Carter, R., Lipps, J.H., 2004a. Estimation of tidal elevation and salinity histories of sheltered harbours and estuaries using benthic foraminifera. The Holocene 14, 218–231.

Hayward, B.W., Cochran, U., Southall, K., Wiggins, E., Grenfell, H.R., Sabaa, A.T., Shane, P.A.R., Gehrels, R., 2004b. Micropaleontological evidence for the Holocene earthquake history of the eastern Bay of Plenty, New Zealand. Quaternary Science Reviews 23, 1651–1667.

Hemphill-Haley, E., 1995. Diatom evidence for earthquake-induced subsidence and tsunami 300 yr ago in southern coastal Washington. Geological Society of America Bulletin 107, 367–378.

Henderson, J., 1933. Geological aspects of the Hawke's Bay earthquakes. New Zealand Journal of Science and Technology 15, 38–75.

Hendey, N.I., 1964. An Introductory Account of the Smaller Algae of British Coastal Waters. Her Majesty's Stationery Office, London.

Hull, A.G., 1986. Pre-A.D. 1931 tectonic subsidence of Ahuriri Lagoon, Napier, Hawkes Bay, New Zealand. New Zealand Journal of Geology and Geophysics 29, 75–82.

Hull, A.G., 1987. A Late Holocene marine terrace on the Kidnappers Coast, North Island, New Zealand: some implications for shore platform development processes and uplift mechanism. Quaternary Research 28, 183–195.

Hull, A.G., 1990a. Tectonics of the 1931 Hawkes Bay earthquake. New Zealand Journal of Geology and Geophysics 33, 309–322.

Hull, A.G., 1990b. 1931 Hawkes Bay Earthquake. In: Nathan, S., Compiler, Conference Field Trips: Geological Society of New Zealand Miscellaneous Publication 50B, pp. 61–80.

Hustedt, F., 1985. The Pennate Diatoms. Koeltz Scientific Books, Hirschberg.

Kelsey, H.M., Witter, R.C., Hemphill-Haley, E., 1998. Response of a small Oregon estuary to coseismic subsidence and postseismic uplift in the past 300 years. Geology 26, 231–234.

Kelsey, H.M., Nelson, A.R., Witter, R.C., Hemphill-Haley, E., 2005. Tsunami history of an Oregon coastal lake reveals a 4600 year record of great earthquakes on the Cascadia subduction zone. Geological Society of America Bulletin 117, 1009–1032.

Kovach, W.L., 1993. MVSP Shareware, Multivariate Statistics Package. Kovach Computing Services, Pentraeth, Wales.

Krammer, K., 1988. Bacillariophyceae 2: Bacillariophyceae, Epithemiaceae, Surirellaceae. Gustav Fischer Verlag, Stuttgart/New York.

Krammer, K., 1991a. Bacillariophyceae 3: Centrales, Fragilariaceae, Eunotiaceae. Gustav Fischer Verlag, Stuttgart/Jena.

Krammer, K., 1991b. Bacillariophyceae 4: Achnanthaceae. Gustav Fischer Verlag, Stuttgart/Jena.

Krammer, K., Lange-Bertalot, H., 1986. Bacillariophyceae 1: Naviculaceae. VEB Gustav Fischer Verlag, Jena.

Large, M.F., Braggins, J.E., 1993. Spore morphology of New Zealand *Azolla filiculoides* Lam (Salviniaceae). New Zealand Journal of Botany 43 (4), 419–423.

Lowe, D.J., Newnham, R.M., Ward, C.M., 1999. Stratigraphy and chronology of a 15 ka sequence of multi-sourced silicic tephras in a montane peat bog, eastern North Island, New Zealand. New Zealand Journal of Geology and Geophysics 42, 565–579.

Marshall, P., 1933. Effects of earthquake on coastline near Napier. New Zealand Journal of Science and Technology 15, 79–92.

Nelson, A.R., Jennings, A.E., Kashima, K., 1996a. An earthquake history derived from stratigraphic and microfossil evidence of relative sea level change at Coos Bay, southern coastal Oregon. Geological Society of America Bulletin 108, 141–154.

Nelson, A.R., Shennan, I., Long, A.J., 1996b. Identifying coseismic subsidence in tidal-wetland stratigraphic sequences in the Cascadia subduction zone of western North America. Journal of Geophysical Research 101 (B3), 6115–6135.

Ota, Y., Berryman, K.R., Hull, A.G., Miyauchi, T., Iso, N., 1988. Age and height distribution of Holocene transgressive deposits in eastern North Island, New Zealand. Paleogeography, Paleoclimatology, Paleoecology 68, 135–151.

Ota, Y., Brown, L.J., Berryman, K., Fujimori, T., Miyauchi, T., Beu, A.G., Kashima, K., Taguchi, K., 1995. Vertical tectonic movement in northeastern Marlborough: stratigraphic, radiocarbon, and paleoecological data from Holocene estuaries. New Zealand Journal of Geology and Geophysics 38, 269–282.

Pizzuto, J.E., Schwendt, A.E., 1997. Mathematical modeling of auto-compaction of a Holocene transgressive valley-fill deposit, Wsolfe Glade, Delaware. Geology 25, 57–60.

Plafker, G., 1965. Tectonic deformation associated with the 1964 Alaska earthquake. Science 148, 1675–1687.

Reid, C.M., Hayward, B.W., 1997. Near-shore foraminifera from Taiwawe Bay, Northland, New Zealand. Tane 36, 113–130.

Reyners, M., 1980. A microearthquake study of the plate boundary, North Island, New Zealand. Geophysical Journal of the Royal Astronomical Society 63, 1–22.

Sawai, Y., Nasu, H., Yasuda, Y., 2002. Fluctuations in relative sea-level during the past 3000 yr in the Onnetoh estuary, Hokkaido, northern Japan. Journal of Quaternary Science 17, 607–622.

Schofield, J.C., 1960. Sea level fluctuations during the last 4000 years as recorded by a chenier plain, Firth of Thames, New Zealand. New Zealand Journal of Geology and Geophysics 3, 467–485.

Shane, P.A.R., 2000. Tephrochronology: a New Zealand case study. Earth Science Reviews 49, 223–259.

Shennan, I., Long, A.J., Rutherford, M.M., Green, F.M., Innes, J.B., Lloyd, J.M., Zong, Y., Walker, K.J., 1996. Tidal marsh stratigraphy, sea-level change and large earthquakes, I: A 5000 year record in Washington, USA. Quaternary Science Reviews 15, 1023–1059.

Shennan, I., Long, A.J., Rutherford, M.M., Innes, J.B., Green, F.M., Walker, K.J., 1998. Tidal marsh stratigraphy, sea level change and large earthquakes—II: Submergence events during the last 3500 years at Netarts Bay, Oregon, USA. Quaternary Science Reviews 17, 365–393.

Shennan, I.A., Scott, D.B., Rutherford, M., Zong, Y., 1999. Microfossil analysis of sediments representing the 1964 earthquake, exposed at Girdwood Flats, Alaska, USA. Quaternary International 60, 55–73.

Sherrod, B.L., 1999. Gradient analysis of diatom assemblages in Pujet Sound salt marsh: can such assemblages be used for quantitative paleoecological reconstructions? Paleogeography, Paleoclimatology, Paleoecology 149, 213–226.

Sherrod, B.L., 2001. Evidence for earthquake-induced subsidence about 1100 yr ago in coastal marshes of southern Pujet Sound, Washington. Geological Society of America Bulletin 113, 1299–1311.

Witkowski, A., Lange-Bertalot, H., Metzeltin, D., 2000. Diatom Flora of Marine Coasts I. A.R.G. Gantner Verlag K.G., Ruggell.