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Techniques for estimation of tidal elevation and confinement (~salinity) histories of sheltered harbours and estuaries using benthic foraminifera: examples from New Zealand

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Abstract: Techniques for estimating tidal elevation and confinement (proxy for salinity) using modern benthic foraminiferal census data from New Zealand harbours and lower-salinity estuaries are described and assessed for their utility for reconstructing the depositional settings of late-Holocene sequences. We describe a simple modern analogue technique for estimating tidal or subtidal elevation of Holocene fossil faunas, utilizing the modern data set most applicable to the Holocene setting (sheltered tidal harbours and inlets, or lower-salinity estuaries). Canonical correspondence analysis was used to extract a synthetic confinement gradient from foraminiferal census data in transects down five New Zealand estuaries. This gradient was used to develop a New Zealand Confinement Index that can be computed for New Zealand modern and Holocene estuarine and harbour samples based on their foraminiferal composition. The value of the method for estimating Holocene elevational and confinement (palaeosalinity) histories was assessed for a tidal inlet and the middle reaches of an estuary. Two earthquake-related vertical displacements are recognized in a 1.1 m core from Ahuriri Inlet, Hawkes Bay: (1) a 1–2 m subsidence (*c.* 500 BP) from low tidal to subtidal; (2) a 1.5–2.5 m uplift (1931 Napier Earthquake) from subtidal to high tidal, followed by progressively increasing confinement in a much smaller inlet. A substantial confinement increase (probable salinity decrease) is recognized in a 0.8 m core from Rangitopuni Estuary, Auckland, accompanying the widespread disappearance of cockle beds. Palynology shows that this event is associated with forest clearance in the watershed following earliest significant human settlement (*c.* 600–800 BP). Taphonomic dissolution of calcareous tests was a significant factor in the lesser accuracy of elevational estimates in our estuarine study core, although dissolution appears to correspond with increased freshwater runoff. Taphonomic disaggregation and loss of agglutinated foraminifera did not appear to be significant in these short cores.

Key words: New Zealand, Ahuriri Inlet, Rangitopuni Estuary, modern analogue technique, benthic foraminifera, tidal elevation, confinement, salinity, palaeosalinity, taphonomy, late Holocene.

Introduction

A powerful method of determining natural and human-induced environmental change in late-Holocene coastal marine environments is through the analysis of the fossilized record of biotic change in young sedimentary sequences. The record of macroscopic fossils is usually patchy and not easily recovered in its entirety from a single sedimentary sequence or core, whereas microscopic fossils are usually more abundant and their history

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can easily be determined from small core samples. Foraminifera have a particularly good record and their taxonomic composition and general ecological distribution in these environments is well known, with many taxa having cosmopolitan, climatically influenced distributions (e.g., Scott *et al.*, 1990; 1996; Wang, 1992; Hayward *et al.*, 1999a; Debenay, 2000).

Quantitative studies of benthic foraminiferal faunas collected along transects through tidal marshes have shown that the distribution of certain assemblages and species are strongly influenced by tidal elevation, especially in the vicinity of high tide level (e.g., Scott and Medioli, 1986; Scott and Leckie, 1990; Gehrels 1994; Gehrels, *et al.*, 2001; Jennings *et al.*, 1995; Haslett *et al.*, 1998; 2001; Hayward *et al.*, 1999a; 1999b; Horton, 1999; Horton *et al.*, 1999a). This has led to recent studies utilizing foraminifera to document Holocene sea-level changes (e.g., Scott and Medioli, 1980; Thomas and Varekamp, 1991; Scott *et al.*, 1995; Haslett *et al.*, 1998; Edwards and Horton, 2000; Edwards, 2001; Cann *et al.*, 2002; Gehrels, 2002; Hayward *et al.,* 2002) or earthquake-related vertical displacements of coastal areas (e.g., Jennings *et al.*, 1995; Guibault *et al.*, 1996; Nelson *et al.*, 1996; Shennan *et al.*, 1999; Goff *et al.*, 2000; Chagué-Goff *et al.*, 2000). These studies have usually used subjective methods to deduce the elevational ranges at which fossil foraminiferal faunas accumulated by comparing their faunal associations with modern counterparts.

The relationship between tidal elevation and benthic foraminifera has been calibrated using a data set of contemporary intertidal and marsh faunas from around the coasts of the United Kingdom (Horton *et al.*, 1999a) and Maine (Gehrels, 1994) and a foraminiferal-based transfer function for estimating former sea levels from intertidal foraminiferal faunas developed for these two regions (Horton *et al.*, 1999b; Gehrels, 2000). Transfer functions or other methods, based on taxonomic census data of benthic foraminifera in one region of the world, are not directly transportable for use in other regions, because of some differences in faunal composition.

Most recent studies have focused on the use of marsh foraminifera for estimating former tidal elevations because of their narrow zonation ranges around high tide mark (e.g., Hayward *et al.*, 1999b), with accuracies of ±0.1–0.5 m, depending on tidal range. Fossil Cenozoic foraminiferal faunas are also routinely used in basin analysis for estimating former water depths in normal salinity shelf, bathyal and abyssal environments (e.g., Hayward, 1990; King *et al.*, 1993), but these estimates have accuracies of ±10–2000 m depending on water depth. Studies using fossil foraminifera to estimate the Holocene elevational history of coastal marine environments below mid-tide level (subtidal-intertidal) are rare (e.g., Scott *et al.*, 1976; Hayward *et al.*, 2002), largely because of the broader elevational zonation and tidal current and wave transport of tests that occurs in the unvegetated intertidal and shallow subtidal region, even in moderately sheltered estuarine and harbour environments (e.g., Wang and Murray, 1983).

In some environments, such as the Great Marshes, Massachusetts, foraminiferal distribution patterns do not appear to relate to tidal elevation (de Rijk, 1995; de Rijk and Troelstra, 1997). Here distribution patterns reflect variations in salinity resulting from changes in the balance between freshwater seepage, rainfall, flooding and tidal saltwater inundation. Similar groundwater seepage explanations have been invoked to explain the occurrence of low-salinity *Trochamminita salsa* association faunas above mean high water on the fringe of near-normal-salinity tidal inlets in New Zealand (e.g., Hayward *et al.*, 1996; 1999a).

In tropical and subtropical estuaries and coastal lagoons, foraminiferal faunas exhibit consistent compositional changes from diverse calcareous assemblages to low-diversity agglutinated assemblages with increasing distance from the open sea (Debenay, 2000; Debenay *et al.*, 2000). The concept of confinement in these environments has been defined as 'the lapse of time taken by the dissolved elements of the marine reservoir to reach any given point in the paralic domain' (Guélorget and Perthuisot, 1992), which usually, but not always, correlates with decreasing salinity. Debenay (2000) proposed a confinement index, Ic, based on the taxonomic composition of tropical paralic foraminiferal faunas, and showed that in non-arid areas there was a good correlation between his increasing confinement index and general decreasing salinity trends in estuaries. Although point measurements of salinity are readily made, data over diurnal and longer time series from confined waters are seldom available. As a proxy, we use the standardized distance between the head and mouth of estuaries and harbours.

In this paper we investigate the use of a modern analogue technique for estimating the former tidal elevation or subtidal depth, and propose a New Zealand Confinement Index for estimating confinement changes, as a proxy for salinity. These are applied to two New Zealand late-Holocene harbour and estuarine sequences based on benthic foraminiferal census data. These methodologies should provide more objective, consistent and, at times, more precise results than qualitative assessments.

Factors influencing the distribution of brackish-water foraminifera

Previous quantitative studies have concluded that tidal elevation and 'salinity' are the two strongest factors (out of 15 assessed; Figure 11 in Hayward *et al.*, 1999a) responsible for producing the mappable distribution patterns of brackish-water foraminifera in temperate harbours and estuaries in New Zealand (Hayward and Hollis, 1994). To illustrate these relationships, cluster and detrended canonical correspondence analyses were run on our total data set of 281 benthic foraminiferal census counts from New Zealand sheltered harbours, tidal inlets and estuaries (Figure 1; Table 1). Fourteen sample associations were picked from the cluster analysis dendrogram and overlaid on the two-dimensional detrended canonical correspondence analysis (Canoco, ter Braak, 1985) ordination (Figure 2).

Data configured on the Canoco plot (Figure 2) are largely distributed between the vectors for tidal elevation (proxy for exposure during tidal cycles) and confinement (= proportional distance between freshwater and normal marine salinity – a probable proxy for salinity). The plot confirms previous work (e.g., Hayward *et al.*, 1999a) showing that, at normal to near-normal salinity, associations dominated by *Jadammina macrescens* (J), *Miliammina obliqua* (Mo) and *Trochammina inflata* (Tn) characterize the highest tidal levels. With decreasing salinity, these levels may become dominated by *Haplophragmoides wilberti* (H) or *Trochamminita salsa* (Tr) associations. Mid- to low tidal elevations are dominated by combinations of *Ammonia aoteana* and *Elphidium excavatum* s.l. (Ec, Ew) at near-normal salinity, and with decreasing salinity by *Miliammina fusca* (M), *Haplophragmoides wilberti* and finally *Trochamminita salsa*. Low tidally to subtidally there is a zonation with decreasing salinity from a normal marine salinity association (mar), dominated by a wide diversity of shallow marine species (e.g., *Elphidium charlottense, Patellinella inconspicua, Quinqueloculina* spp.), to an association (AH) dominated by *Ammonia aoteana*, *Haynesina depressula* and *Elphidium advenum* s.l., to a more brackish *Scherochorella moniliforme-Textularia earlandi* association (STx).

Previously published diagrams illustrating the approximate distribution of brackish-water foraminiferal associations in New Zealand with respect to tidal elevation and salinity (Hayward and Hollis, 1994; Hayward *et al.*, 1999a) have been modified to show the distribution of the 14 associations (Figures 3 and 4) newly determined here on the basis of the enlarged data set.

Several of the more brackish associations (especially AM, M,

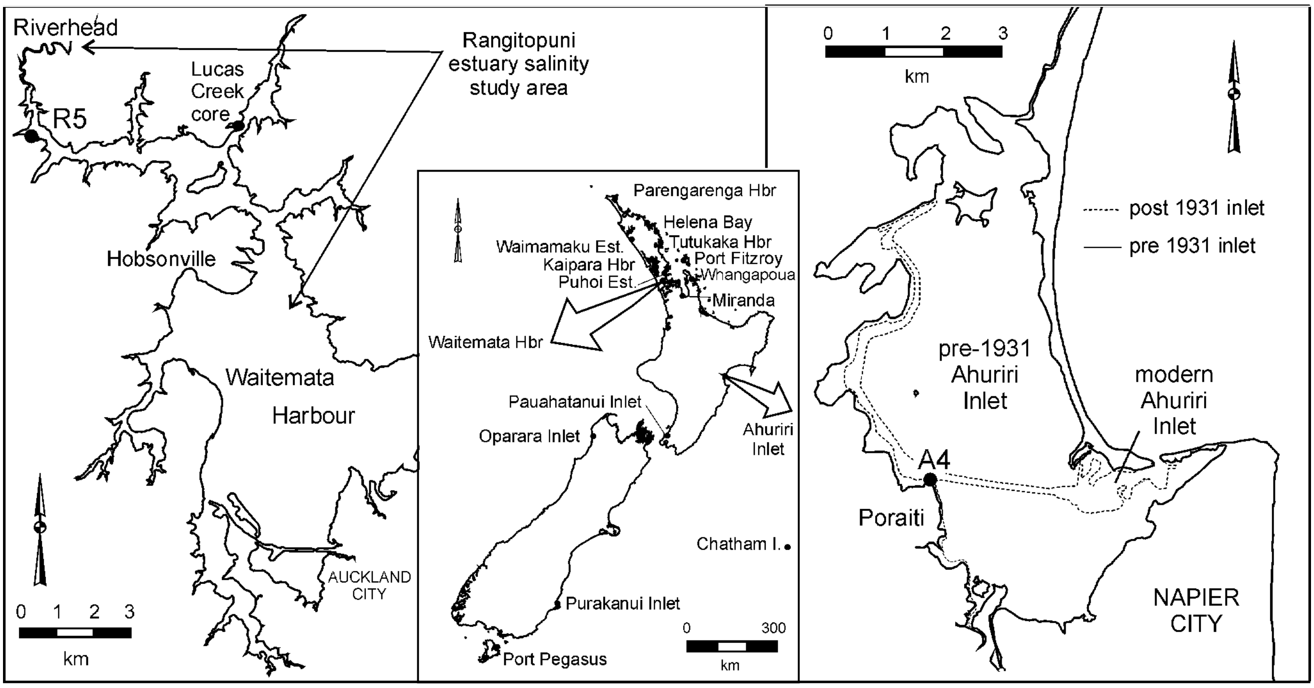

Figure 1 Map of New Zealand showing location of study areas from which modern analogue samples are derived, and location of cores from Rangitopuni Estuary, R5 (left), and Ahuriri Inlet, A4 (right).

H, Tr) that are characteristic of higher tidal levels in higher-salinity settings around the edges of sheltered harbours and inlets have a much broader elevational range in lower-salinity conditions in estuaries (Figures 3 and 4). For example, both the *Miliammina fusca* and *Trochamminita salsa* associations sometimes occur at or above mean high water level in harbours (e.g., Hayward *et al.*, 1996), but may extend throughout the intertidal and even into the subtidal in less saline parts of estuaries (e.g., Hayward *et al.*, 1997). This trend of decreasing tidal elevation of some associations with decreasing salinity is presumably related to salinity stratification in estuaries with fresher water above denser, more saline water (e.g., Debenay *et al.*, 2000). The presence of the lowest-salinity *Trochamminita salsa* association in salt meadows at spring high water level on the fringes of near-normal-salinity harbours and inlets (e.g., Hayward *et al.*, 1996) probably results from freshwater ground seepage and rainfall impact on the site during the weeks between spring tidal inundations.

The broad elevational range of foraminiferal associations in the lowest-salinity upper reaches of estuaries decreases their value for estimating tidal elevation or former sea levels in these settings. Some of these same associations (e.g., *Miliammina fusca*, *Haplophragmoides wilberti*), however, have considerable potential use for recognizing higher tidal levels around the fringes of near-normal-salinity sheltered harbours and inlets. For these reasons, our modern census data has been divided into two sets for use in estimating tidal elevations in the two different settings – harbours and estuaries.

Data and methods

A data set of 281 modern census counts of benthic foraminiferal faunas has been assembled for this study from a number of previous studies in New Zealand sheltered harbours and estuaries (Table 1; Figure 1). The majority of faunas were obtained from 10 cm^3 samples taken from the upper 1 cm of sediment with a short hand-held core. Many of the samples were collected at intervals of 5–20 cm tidal elevation along transects orientated normal to the tide line, whereas others come from studies aimed at mapping the spatial distribution of foraminiferal associations. The census data set contains a large diversity of rare species, particularly those carried in from open-ocean environments (Hayward *et al.*, 1999a). To simplify faunal comparisons, many of these rarer species were lumped together into generic or higher taxonomic characters (Appendix 1). The data set counts are on total or dead assemblages only and avoid most of the seasonal variability and clumped population problems of using live census counts.

The two cores studied were taken with 1.2 m lengths of aluminium tubing (7.62 cm diameter) pushed into the sediment by hand, plugged and pulled out. Cores were cut in half lengthwise, lithologically logged, and 10 or 20 cm^3 samples taken at regular intervals and near distinct lithologic changes. Surface and core samples were washed over a 0.063 mm sieve, dried and those samples with low abundances of foraminifera were floated off using carbon tetrachloride. Samples were microsplit down to an amount containing approximately 100–200 benthic foraminifera, then identified and counted under the microscope. Samples from the upper 5 cm of each core were treated with rose bengal to identify specimens that were living at the time of collecting, so that census counts of just the dead fauna could be made.

New Zealand Confinement Index (proxy for salinity)

Salinity in estuaries is highly variable, being related to the type of estuary (salt wedge, partially mixed, well mixed; Pinet, 1992), tidal cycles, freshwater runoff variation and water-column stratification. A single reading or even a day's monitoring at each site will not necessarily provide meaningful results for comparison between sites and between estuaries. Further, the causal relation between salinity and foraminiferal distributions is poorly understood, although assemblage composition is presumably influenced by some combination of the total range and mean salinity in a year, a monthly tidal cycle and a single tidal cycle. Additionally there may be seasonal, extreme climatic and storm effects.

Continuous recording over one year is a minimal requirement at each station to accurately calibrate foraminiferal distributions

Table 1 Source of census data used as modern analogue sets for estimating New Zealand Holocene sheltered harbour and estuarine environments. Location of study sites is shown in Figure 1. Copies of unpublished data can be obtained from the corresponding author

Locality	No. of samples	Source
Estuarine analogue set		
North Island		
Waimamaku Estuary	15	Hollis *et al.*, 1995
Helena Bay estuary	6	Hayward, 1993
Waitemata Harbour	33	Hayward *et al.*, 1997
Pauatahanui Inlet	31	Hayward *et al.*, 1999b
South Island		
Oparara Inlet	11	Hayward and Hollis, 1994
Total	92	
Sheltered harbour analogue set		
North Island		
Parengarenga Harbour	1	Hayward and Hollis, 1994
Tutukaka Harbour	5	Brook *et al.*, 1981
Port Fitzroy	4	Hayward and Grenfell, 1994
Kaipara Harbour	28	Hayward *et al.*, 1999b
Waitemata Harbour	28	Hayward *et al.*, 1997
Miranda	9	Hayward *et al.*, 1999b
Whangapoua Harbour	5	Unpublished
Ahuriri Inlet	10	Carter *et al.*, 2000
Pauatahanui Inlet	45	Hayward and Triggs, 1994
South Island		
Oparara Inlet	11	Hayward and Hollis, 1994
Purakanui Inlet	52	Hayward *et al.*, 1996
Stewart Island		
Port Pegasus	5	Hayward *et al.*, 1994
Chatham Island lagoon	2	Hayward and Grenfell, 1999
Total	189	

with salinity. As the logistics and cost of such projects are substantial, proxies for salinity distributions in estuaries should be investigated. Expectedly, estuaries will exhibit a salinity gradient from fully marine water at their mouths to fresh water where streams or rivers flow in at their head. Although mixing may be complex diurnally, averaged over longer periods salinity in estuaries declines progressively. We here investigate two different approaches in using confinement (= the proportional distance between the mouth and head of estuaries) as a proxy for salinity.

Regression analyses

Here we assume that salinity increases progressively down an estuary and might be approximated by some linear or quadratic function of the distance between the landward and seaward ends. We study the relation between foraminiferal abundances and a distance measure through a single, well-studied brackish estuarine environment.

The channelized, brackish estuary of Rangitopuni Stream is at the head of the Waitemata Harbour, Auckland, New Zealand (Hayward *et al.*, 1997). The estuary (Figure 1) is 16 km long, narrow in its upper reaches (10–200 m wide) widening to a maximum width of 1 km near its mouth where it merges with the middle reaches of the Waitemata Harbour. There are several major re-entrants but the principal source of fresh water is Rangitopuni Stream. Tidal range is 2.6–3.5 m (extreme neap and spring). Salinity ranges are approximately 0–20‰ at the head of the estuary to 30–35‰ at its mouth (Slinn, 1968). Samples were taken in pairs (one subtidal, one at *c*. MHW) at intervals down the estuary and a transect of samples through the intertidal zone was taken midway down the estuary. The scheme provides a conspectus of assemblages in the estuary, although the inclusion of samples over the tidal range considerably increases variability in species abundances relative to distance up the estuary. The census recorded 68 species, but some sparsely distributed taxa were placed in generic or higher groups (Appendix 1) which reduced the analysed data set to 43 taxa from 56 stations. Species diversity ranges between 3 and 24 taxa. Species abundances are highly inequitable in several assemblages in which specimens of *Ammonia aoteana*, *Miliammina fusca* and *Trochammina inflata* exceed 75%. Most widely distributed are *Miliammina fusca*, *Ammonia aoteana* and *Trochammina inflata* (46, 37 and 32 stations, respectively).

Equations (transfer functions) empirically derived from known distributions are commonly used to estimate past environmental parameters (Sachs *et al.,* 1977). We use linear regression to relate species abundances with distance, scaled as a percentage, down Rangitopuni Estuary. The abundance of many taxa shows little or no relation with the distance measure, in part because of their strong relationship to elevation. Data points are widely dispersed in plots, patterns are not discernible, and regression statistics reject linear relationships. This group includes most of the calcitic taxa whose abundance and persistence, primarily near the mouth of the estuary, is low. Some like *Elphidium advenum*, might show a relationship, but the data are insufficient to establish its significance. *Trochammina inflata* is an example of a more populous species, distributed through the estuary, whose abundance is unrelated or weakly related with distance, as are *Ammonia pustulosa*, *Ammotium fragile*, *Elphidium excavatum*, *Elphidium gunteri*, *Haynesina depressulus*, *Miliammina obliqua* and *Schlerochorella moniliforme.*

Of the populous species distributed throughout the estuary, *Ammonia aoteana* is one whose abundance tends to decrease with distance up the estuary. Although the regression is significant at the 1% level, goodness of fit is poor ($R^2 = 0.24$). *Portatrochammina sorosa* behaves similarly ($R^2 = 0.29$). However, the fit improves ($R^2 = 0.45$) in a multiple regression (equation 1), which is based on data from 13 stations between 5 and 65% of distance up the estuary:

$$d1 = 46.1 - 1.537 \times 1 - 0.375 \times 2 \qquad (1)$$

where d = %distance, ×1 = % *P. sorosa*, ×2 = % *A. aoteana*). The abundance of *Miliammina fusca*, *Trochamminita salsa* and *Haplophragmoides wilberti* increase with distance up the estuary and the linear relationship is significant (1% level) for each. Data for *Miliammina fusca* show the best fit ($R^2 = 0.36$). This populous, persistent species is the best single estimator of distance (possibly because it has the widest elevational range), using data from 46 stations between 5 and 100% of distance up the estuary:

$$d2 = 32.3 + 0.632 \times 1 \qquad (2)$$

where ×1 = % *M. fusca.* Fit with the linear model is considerably raised ($R^2 = 0.84$) in a multiple regression using the three taxa:

$$d3 = 25.4 + 0.822 \times 1 + 0.561 \times 2 + 0.871 \times 3 \qquad (3)$$

where ×1 = % *H. wilberti*, ×2 = % *M. fusca*, ×3 = % *T. salsa.* This estimate uses data from 25 stations between 29 and 100% of distance up the estuary.

Equation (3), with a root mean square error (RMSE) of 8.59% distance in Rangitopuni Estuary, should be used if all three taxa are present. Equation (2) produces a higher error

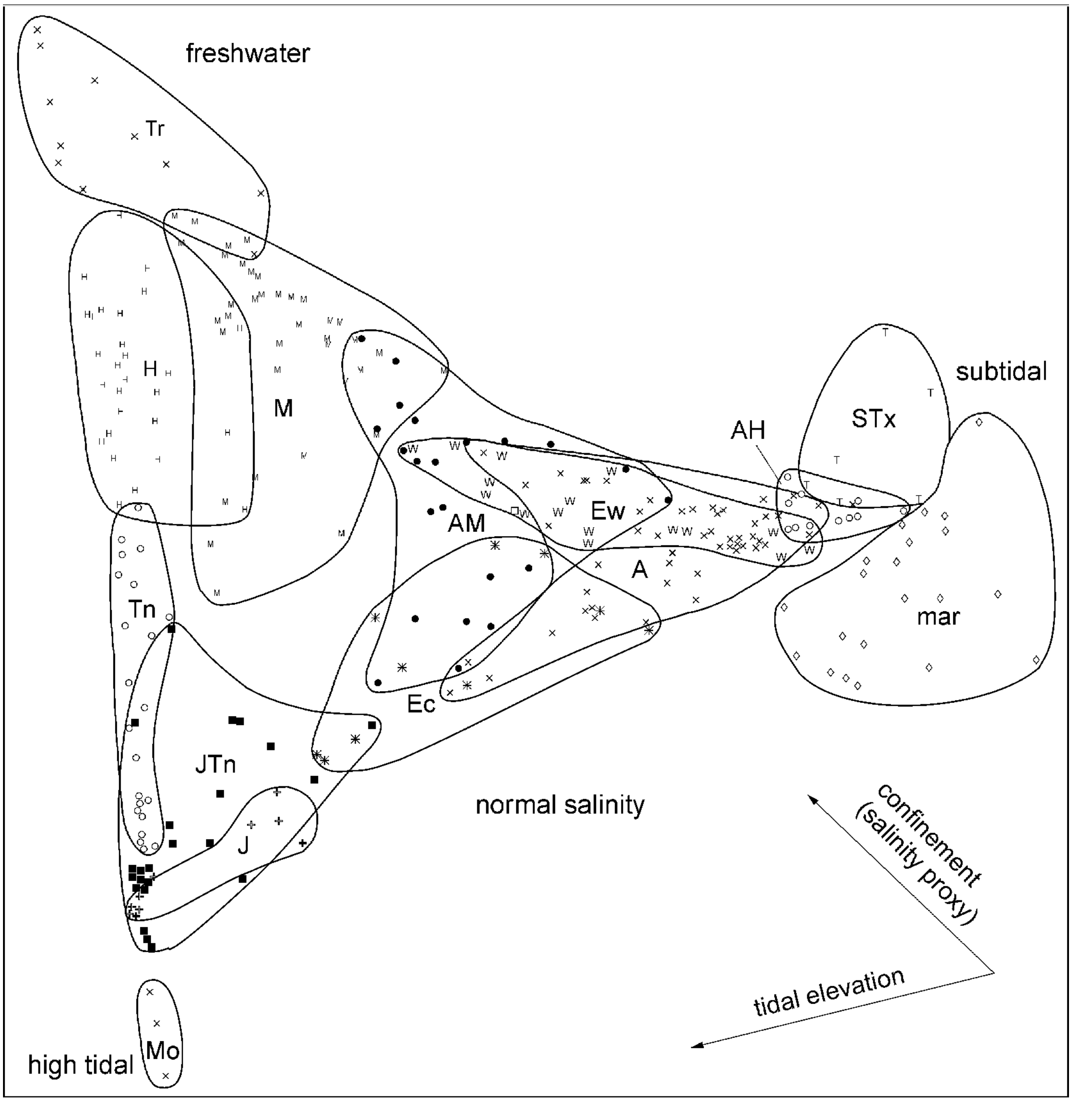

Figure 2 Two-dimensional configuration, produced by detrended canonical correspondence analysis (ter Braak, 1985), of the benthic foraminiferal samples from New Zealand sheltered harbours and estuaries. The vector axes of the two most highly correlated environmental factors are shown, together with the inferred elevational and salinity proxy trends. Samples are grouped into the 14 clusters (abbreviations explained in Figure 3) produced by cluster analysis using Bray-Curtis similarity coefficient (Rohlf, 1989).

(RMSE = 21.84% distance) but its utility is favoured by the wide distribution of *Miliammina fusca*. Equation (1), based on data from the outer and middle reaches of Rangitopuni Estuary, has an RMSE of 11.55% distance and may be useful in comparable settings.

Canonical correspondence analysis

Whereas regression analyses the data for geographic trends in the abundance of species, here the focus is on a low-dimensional representation of the occurrences of taxa based on their abundance. The census data from the Rangitopuni Estuary study (Hayward *et al.*, 1997) were combined with similar census data from Waimauku Estuary (Hollis *et al.*, 1995), Helena Bay estuary (Hayward, 1993), Puhoi Estuary (Topping, 1973) and Oparara Lagoon (Hayward and Hollis, 1994) to construct a detrended correspondence analysis ordination of the common species (Figure 5). Canonical correspondence analysis was used to extract a confinement vector for the distance up the estuary (to be used as a synthetic proxy for salinity). The score for each common species (c_i) on this vector axis was allocated a value between 0 and 100, proportional to the distance between the species with the lowest (*Elphidium charlottense*) and the highest (*Trochamminita salsa*) distances along the vector (Figure 5; Table 2).

These values are used to calculate a New Zealand Confinement Index value (NZCI) using the formula:

$$\text{NZCI} = \text{sum}\ (p_i \times c_i) \qquad (4)$$

where p_i = the percentage relative abundance of species i and c_i is the confinement value read from the canonical correspondence analysis vector (Figure 5). The resultant NZCI has values between 100 (fresh water) and 0 (~ full marine salinity, *c.* 35‰).

Modern analogue technique estimate of tidal elevation or water depth

Standardized tidal elevations

The extreme tidal range around New Zealand varies between 0.7 m (Cook Strait) and 5 m (northwest Nelson). Thus modern tidal elevation levels for faunas need to be converted to a standardized index for inclusion in the countrywide data sets utilized by the modern analogue technique. Resulting estimates of tidal elevation of fossil faunas, expressed in terms of the standardized index, then need to be converted back to the present-day tidal

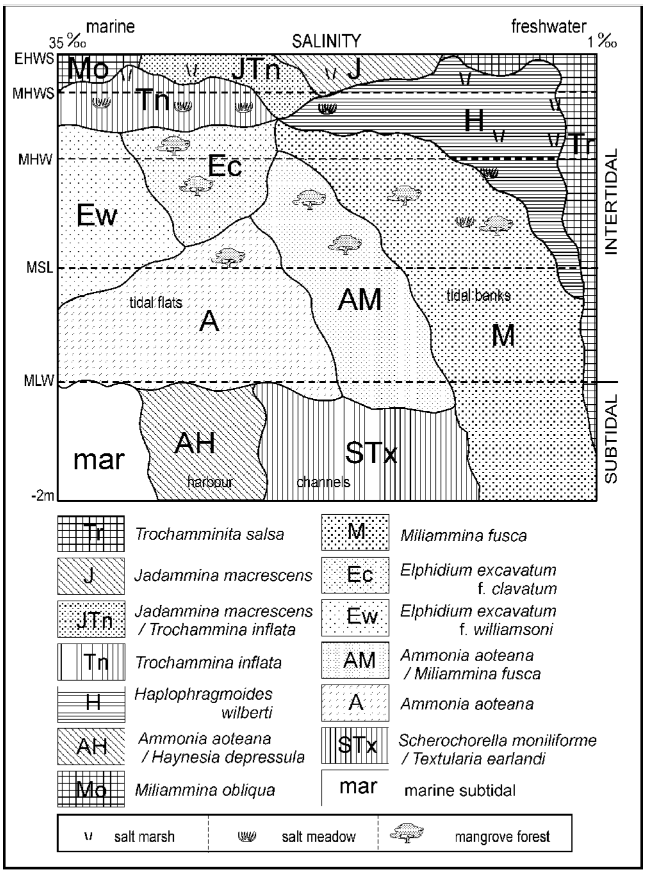

Figure 3 Distribution with respect to salinity and tidal elevation of the 14 benthic foraminiferal associations recognized in New Zealand sheltered harbours and estuaries. EHWS = extreme high water spring; MHWS = mean high water spring; MHW = mean high water; MSL = mean sea level and mid-tide; MLW = mean low water.

ranges of the study site. The standardized tidal level index (STLI) adopted here uses the following equation:

$$\mathrm{STLI} = A/T$$

where A = measured elevation (in m) above ELWS (extreme low water spring) and T = total tidal range (in m) between ELWS and EHWS.

Modern analogue technique (MAT)

Estimates of the tidal height or subtidal depth at which each fossil foraminiferal fauna from the cores was deposited were made using the modern analogue technique (MAT). This is a uniformitarian approach to the estimation of palaeoenvironmental parameters. MAT was preferred to transfer function methods because, in the area of sea-surface temperature estimation using modern planktic foraminiferal census data, MAT has been shown to provide more accurate estimates of modern sea-surface temperatures using core-top test data (e.g., Barrows *et al.*, 2000). In addition to its use in estimating sea-surface temperatures from faunal census data, MAT has been used previously with pollen and diatom data for estimating aspects such as pH and other palaeoenvironmental variables (e.g., Bartlein and Whitlock, 1993; Birks *et al.*, 1990).

We use one of the two modern data sets containing the relative abundance census data for benthic foraminiferal assemblages in present-day sheltered harbours or estuaries in New Zealand (Table 1) to find nearest analogues for fossil assemblages and use tidal heights of the modern assemblages as best estimates for fossil counterparts. Squared-chord distances were used as a measure of dissimilarity (Prell, 1985) between fossil and analogue assemblages. Algorithms were implemented in EXCEL macro language.

While the dissimilarity coefficient quantifies similarity, it does not have a sampling distribution so that tests of the significance are not available. The modern faunas with the most similar census composition (lowest dissimilarity coefficients) to each fossil fauna were selected as modern analogues for estimating the tidal elevation or subtidal depth of the fossil fauna. Three selection methods were trialled and their estimates compared (Figures 6–7):

(1) the mean and range of tidal elevation of the five most similar modern faunas;
(2) the mean tidal elevation of the 10 most similar modern faunas;
(3) the mean tidal elevation of all modern faunas with chord dissimilarity coefficient values <0.4. Ortiz and Mix (1996) chose a cutoff of <0.2 as reliably identifying analogues for estimating sea-surface temperatures.

The reliability of these estimates depends on several factors, particularly the breadth of environmental coverage represented by the analogue modern data set.

Sediment compaction effects

In graphing the past tidal elevation or subtidal water depth through each cored section based on the MAT estimates, we assume that the site shallows at a rate less than the sediment accumulation rate because of compaction of the underlying sediment. The amount of compaction depends on the thickness and texture of the underlying sediment, on the time involved and possibly also on the amount of episodic earthquake shaking-related dewatering and compaction. The foraminiferally based MAT estimates of elevation provide constraints on the relative influence of compaction and sediment accumulation at each site.

Holocene applications

Taphonomic loss of foraminiferal tests

A potential problem in the use of foraminifera as palaeoenvironmental indicators in brackish-water sequences is the susceptibility of the shells of some agglutinated species to post-mortem disaggregation, and of calcareous shells to be dissolved in acidic conditions. These processes have the potential to alter the overall composition of a fauna (if not remove it completely) and lead to erroneous interpretations.

Our observations (e.g., Carter *et al.,* 2000) suggest that different species of agglutinated brackish-water foraminifera have different susceptibilities to post-mortem, taphonomic disaggregation with increasing depth of burial. Thus thin-shelled *Miliammina obliqua* appears to disappear soon after death, followed later by the onset of disaggregation in *Haplophragmoides wilberti*, *Jadammina macrescens*, *Miliammina fusca* and *Trochamminita salsa.* Of the common intertidal agglutinated foraminifera, *Trochammina inflata* appears to be the most resistant to dissaggregation.

Some of the rapid taphonomic loss that occurs soon after death (e.g., near-surface carbonate dissolution) can be discounted by restricting all census counts to dead tests (i.e., excluding live specimens; Murray, 2000). If there is clear evidence of taphonomic loss in a sequence being studied, we recommend adjusting the fossil and comparative modern data sets by removing the offending species counts (e.g., *Miliammina obliqua* this study) and recalculating to percentage.

Reworking or post-mortem displacement of foraminiferal tests

The abundance of modern normal-marine salinity foraminiferal tests carried into a harbour or estuary is strongly influenced by the degree of exposure of the open coast at its mouth to storms

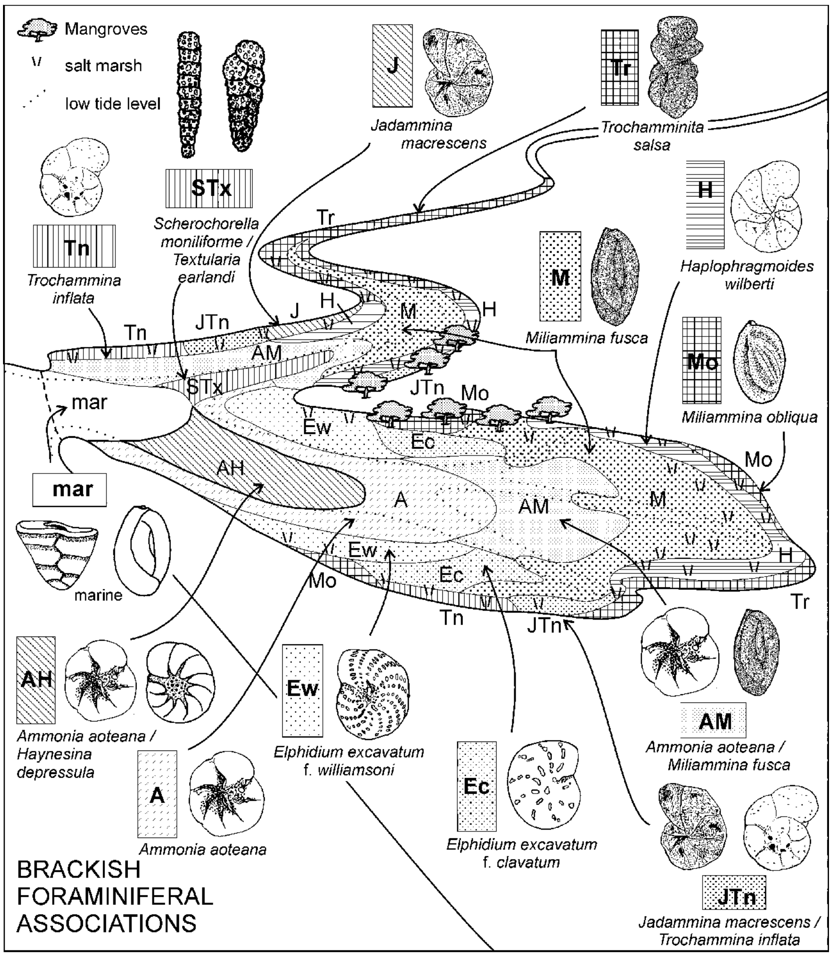

Figure 4 Schematic diagram summarizing the ecologic distribution of the 14 benthic foraminiferal associations recognized in New Zealand's sheltered harbours and estuaries.

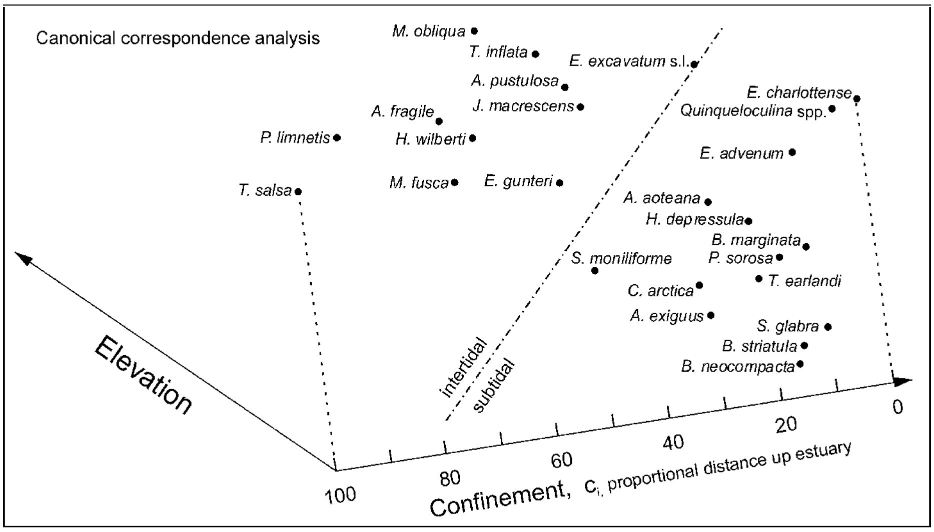

Figure 5 Two-dimensional configuration, produced by detrended correspondence analysis, of the common benthic foraminiferal species in 140 samples from five estuaries (Waimamaku, Helena Bay, Puhoi, Rangitopuni, Oparara). The vector axes produced by canonical correspondence analysis (ter Braak, 1985) of the two most highly correlated environmental factors – elevation (including water depth) and confinement (proportional distance between fresh water and normal marine salinity, a proxy for salinity) – are shown. Partial canonical correspondence analyses show that confinement accounts for 15.7% and elevation 14.5% of the variance in the foraminiferal data. Each common species is allocated a confinement score (c_i) by perpendicular projection of its plotted point onto the confinement vector, which has been calibrated between 0 and 100, proportional to the distance between the species with the highest (*Elphidium charlottense*) and the lowest (*Trochamminita salsa*) distances along the vector.

Table 2 The confinement scores (c_i) for common species in New Zealand sheltered harbours and estuaries, obtained from the canonical correspondence analysis of census data from five estuaries (Figure 5). These scores are used to compute the New Zealand Confinement Index value for foraminiferal faunas

Taxon	Score
Ammobaculites exiguus	30
Ammonia aoteana	28
Ammonia pustulosa	49
Ammotium fragile	72
Bolivina neocompacta	17
Bolivina striatula	16
Bulimina spp.	12
Cuneata arctica	52
Elphidium advenum s.l.	12
Elphidium charlottense	0
Elphidium excavatum s.l.	27
Elphidium gunteri	53
Haplophragmoides wilberti	67
Haynesina depressula	21
Jadammina macrescens	47
Miliammina fusca	72
Miliammina obliqua	64
Portatrochammina sorosa	17
Pseudothurammina limnetis	91
Quinqueloculina spp.	3
Scherochorella moniliforme	48
Spiroloxostoma glabra	10
Textularia earlandi	21
Trochammina inflata	53
Trochamminita salsa	100
Taxa scores estimated from other study sites	
Cribrostomoides jeffreysii	60
Helenina andersoni	60
Polysaccammina ipohalina	70
Saccammina sp.	30
All other taxa	0

and strong currents, which can lift the tests into suspension and carry them along (e.g., Murray *et al.*, 1982). The amount of mixing and transport of foraminiferal tests within a harbour or estuary is determined by the strength of the tidal currents (strongly influenced by tidal range; e.g., Wang, 1992) and the exposure of the site to wind-generated waves breaking on the shore. These transport and mixing processes can be considered to have impacted equally on the modern surface faunas as on the fossil Holocene faunas in the same setting, and therefore no adjustments need be made to the census data.

Reworking of pre-Holocene fossil foraminifera into harbour or estuarine settings is also possible where the catchment is eroding relatively soft, Cenozoic marine sedimentary rocks. Where reworked fossil foraminifera are recognized, they should be removed from the census data prior to analysis. Their presence should be noted, however, as it may indicate increased fluvial input (or a major slip in the catchment).

Ahuriri Lagoon, Napier, core A4

Setting and previous work

The 1931 Napier Earthquake (magnitude 7.8) was the most devastating earthquake in New Zealand in historic times, with loss of 256 lives. Associated vertical displacements affected a 75 km coastal strip with 1.8 m subsidence in the south to 2.7 m uplift in the north (Hull, 1990a). Napier's large and shallow Ahuriri Inlet was uplifted 1.3–2 m and transformed into high tidal flats, subsequently reclaimed for farms and Napier airport. Following uplift and reclamation, only a small tidal remnant of the inlet remains (Figure 1).

A 1.1 m core (A4) was taken from Poraiti corner, from a high tidal salt marsh (0.1 m below MHWS) on the edge of the modern Ahuriri Inlet (V21/408 841, Figure 1). This was adjacent to core site S2 (Chagué-Goff *et al.*, 1998), in which we had previously identified the Napier 1931 Earthquake uplift at 0.25 m, based on several widely spaced foraminiferal samples (Chagué-Goff *et al.*, 2000).

Three short intertidal 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). Only in one core was sedimentological (switch from mud to sand) or chemical techniques able to identify the 1931 earthquake uplift event (Chagué-Goff *et al.*, 2000). Studies of a deep excavation through peat and estuarine sediment on the southern edge of Ahuriri Inlet has shown that the region subsided *c.* 8 m between 3500 and 1700 BP, with a further *c.* 1 m subsidence *c.* 500 BP, and a reversal to uplift in the 1931 earthquake (Hull, 1986; 1990b).

Results (Figure 6; Appendix 2)

Core A4 consists of homogeneous green-grey mud with scattered cockle shells (*Austrovenus stutchburyi*) and a shelly horizon at 0.83–0.78 m. A slight darkening of the colour occurs above 0.30 m. One sample (0.16–0.14 m) had just six specimens in the 10 cm^3 sample, and thus estimates based on this are unreliable. Lower parts of the sequence (1.06–0.36 m) have high specimen abundances (800–8000 specimens/cm^3), decreasing (250–1000 specimens/cm^3) in the middle (0.33–0.19 m) and further (to 6–230 specimens/cm^3) in the upper part (<0.16 m). Species diversity (Fisher α index; e.g., Murray, 1991) at the bottom of the core is relatively low (α 2–3.5), increases to α 4–6 (0.84–0.46 m) and then decreases again to α 2–2.5 (0.40–0.19) and finally to α *c.* 1.5 (0.11–0.01 m). The only exception is one fauna (0.26–0.24 m) which has higher diversity than the surrounding samples.

Qualitative assignment of foraminiferal associations (Figure 4) shows the following sequence: *Ammonia* (A) association (1.06–0.93 m), *Ammonia-Haynesina* (AH) association (0.84–0.31 m), mixed *Ammonia, Ammonia-Miliammina* and *Elphidium excavatum clavatum* (A, AM, Ec) associations (0.30–0.14 m), and *Haplophragmoides* (H) association (0.11–0.01 m).

NZ Confinement Index values are relatively low (NZCI <25) below 0.31 m, with a slight increase in confinement (NZCI 28–42) between 0.30 and 0.14 m, and a substantial increase (NZCI 62–63) above 0.11 m. Regression equations d1 and d3 produce similar trends towards increased confinement above 0.3 m, particularly above 0.11 m. Regression equation d2, however, shows little change throughout, because of the relatively low abundance of *Miliammina fusca.*

Core A4 is clearly in a sheltered harbour or tidal inlet setting and therefore the harbour census data set was used for modern analogue estimates of tidal elevation. Ahuriri has a spring tidal range of 1.4 m. All three methods of selecting modern analogue samples give similar elevation curves, indicating initial accumulation (1.06–0.93 m) close to low tide level, followed by subsidence to subtidal depths of 1.5–3 m (0.73–0.31 m), and later 2–3 m of uplift (at c. 0.30 m) to upper tidal levels.

Interpretation

The foraminiferal faunas in this core from Ahuriri Inlet clearly record two rapid earthquake-related vertical displacements. The first records a MAT estimated subsidence of 1–2 m (from low-diversity, low tidal *Ammonia* association to higher-diversity, subtidal, *Ammonia-Haynesina* association) with no associated

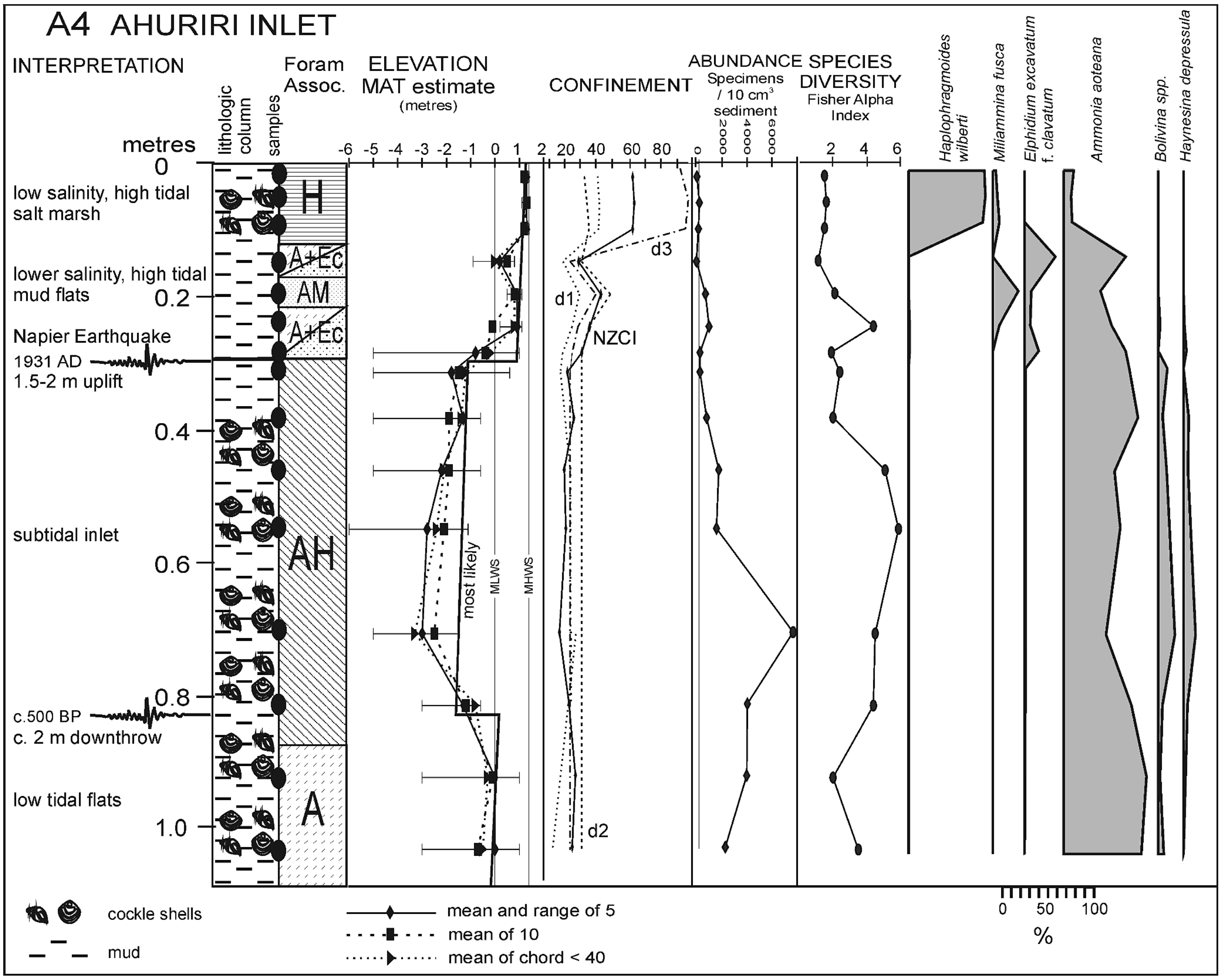

Figure 6 Ahuriri Inlet core (A4) showing lithologic column, relative abundance of common foraminiferal species, foraminiferal associations, species diversity, absolute abundance of foraminifera and estimated Confinement Index (NZCI) and palaeoelevation curves, together with an interpretation of late-Holocene environmental changes recorded. Three MAT-estimated palaeoelevation curves are presented based on different methods of selecting modern analogue samples. These are the mean tidal elevation of the five (1) and 10 (2) most similar modern faunas, and the mean of all modern faunas with chord dissimilarity coefficient values <40 (3). The range of elevation values for the five most similar modern sheltered harbour faunas is also shown. Four confinement estimate curves are presented: NZCI = New Zealand Confinement Index derived from Figure 5; d1, d2, d3 = equations derived from regression analyses.

salinity change. The MAT elevation estimate for the 0.84–0.82 m foraminiferal fauna suggests that it may straddle the subsidence event with faunas from both before and after the event contributing to the total fauna, and hence the intermediate depth estimate (Figure 6). This displacement coincides with the shelly horizon, which may have been accumulating at low tide level prior to the subsidence. This event is possibly correlative with the 500 BP subsidence (*c.* 1 m) recognized by Hull (1986; 1990b) from a peat to estuarine sediment change in a nearby excavation.

All three MAT curves suggest slight shallowing consistent with the accumulation of 0.5 m of subtidal sediment between the two displacement events. The second event (undoubtedly the 1931 Napier Earthquake uplift) is recognized at the level of the slight colour change (0.30 m) from subtidal association AH to intertidal association A. The MAT estimated uplift is 2–3 m, somewhat greater than the measured uplift of 1.3–2 m (Marshall, 1933; Hull, 1990a). The MAT estimated elevation following uplift is *c.* 0.4 m below MHWS, shallowing to *c.* 0.1 m below MHWS as 0.3 m of sediment accumulated. These latter estimates have tightly constrained ranges (Figure 6) and perfectly fit the modern setting. Assuming the historical measurements of uplift are correct, then our MAT estimates of subtidal depth are probably *c.* 1 m too deep, being strongly influenced by several deeper water (5–6 m) modern samples in the harbour analogue set.

As with the subsidence, the fauna straddling the uplift (0.30–0.28 m) event has an estimated elevation intermediate between the two end members, suggesting that it also is a mix of pre- and post-uplift foraminifera.

The MAT elevation estimate for the sample with just six specimens (0.16–0.14 m) is low-tidal, significantly lower than reality, but is unreliable. The higher diversity of sample 0.26–0.24 m is reflected in the lower tidal elevation estimate from the mean of 10 MAT method, suggesting a possible wash-in of tests of subtidal, higher-salinity foraminifera, possibly during a coastal storm.

Confinement conditions in the Ahuriri Inlet appear to have been relatively open and saline prior to the 1931 Napier Earthquake. Following this uplift, the inlet was greatly reduced in depth and size and the foraminiferal-based confinement index and to a lesser extent the regression equations indicate the expected slight increase. A more significant confinement increase is indicated

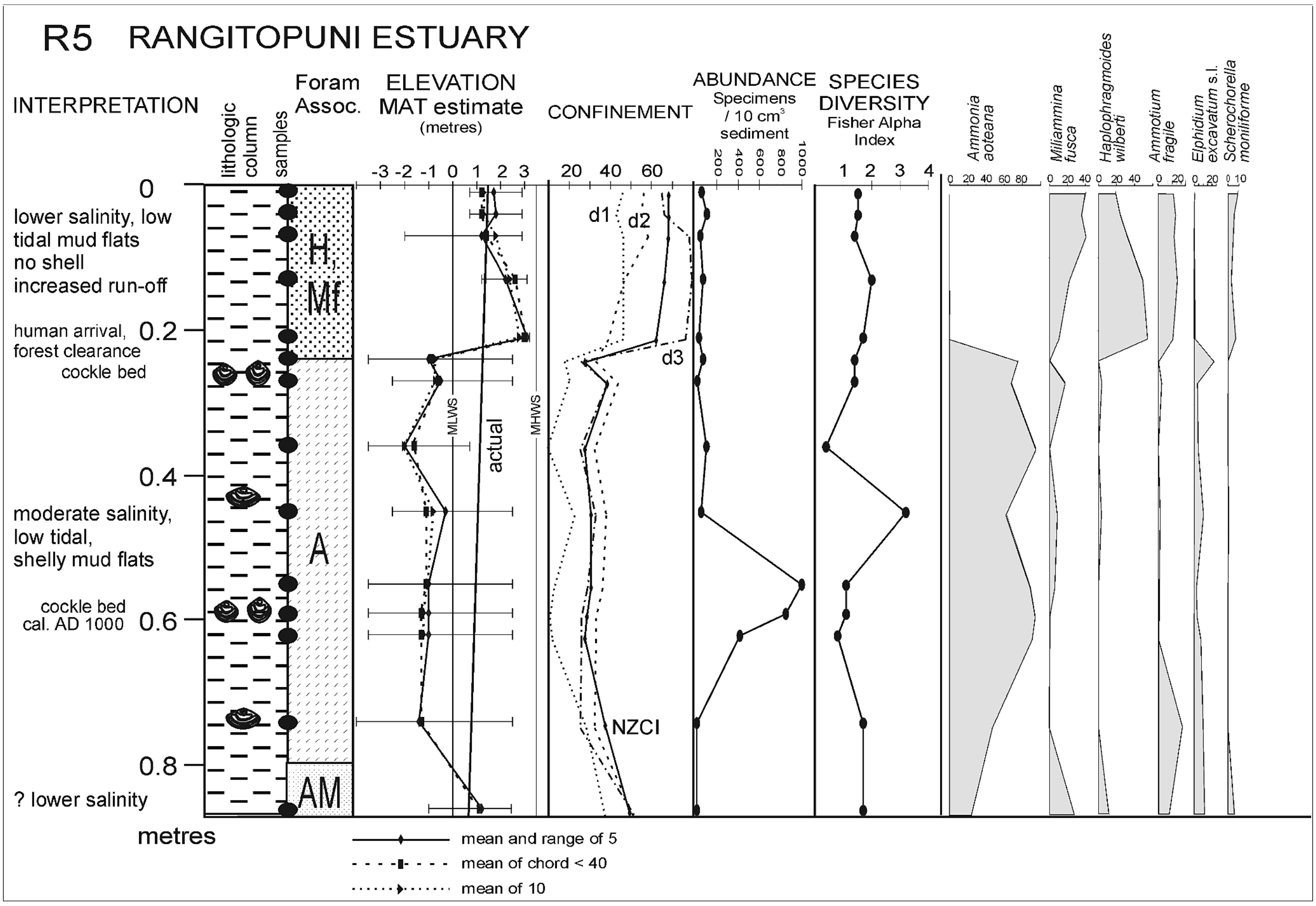

Figure 7 Rangitopuni Estuary core (R5) showing lithologic column, relative abundance of common foraminiferal species, foraminiferal associations, species diversity, absolute abundance of foraminifera and estimated Confinement Index (NZCI) and palaeoelevation curves, together with an interpretation of late-Holocene environmental changes recorded. Three MAT-estimated palaeoelevation curves are presented based on different methods of selecting modern analogue samples. These are the mean tidal elevation of the five (1) and 10 (2) most similar modern faunas, and the mean of all modern faunas with chord dissimilarity coefficient values <40 (3). The range of elevation values for the five most similar modern estuarine faunas is also shown. Four confinement estimate curves are presented: NZCI = New Zealand Confinement Index derived from Figure 5; d1, d2, d3 = equations derived from regression analyses.

with the incoming of the low-diversity *Haplophragmoides* association at 0.11 m, which is inferred to signify the extension of the present salt-marsh vegetation over the site, associated with a further decrease in salinity.

Rangitopuni Estuary, Auckland, core R5

Setting

The Rangitopuni is the largest stream flowing into the Waitemata Harbour, Auckland (Figure 1). Its subtidal estuarine channel between Riverhead and Hobsonville is bordered by intertidal mudflats underlain by thick deposits of soft gloopy mud (Hayward *et al.*, 1999c). In some channel banks the thick mud overlies cockle shell beds. A 0.9 m core (R5) near Riverhead, was sited *c.* 1.3 m above ELWS to sample one of these sequences. The Auckland region lies outside the zone of plate boundary deformation, with no evidence of Holocene tectonic movements.

A palynological study has been undertaken previously (Hume and McGlone, 1986) of a similar 0.8 m core sequence of estuarine mud overlying a shelly horizon in nearby Lucas Creek (Figure 1). The core spans the period of human arrival and impact (last 800 years) in New Zealand. The charcoal and pollen record above the shells documents firing and clearance of the original subtropical broadleaf-podocarp forest (increase in bracken fern spores), followed later by introduction of exotic pine and grass pollen (arrival of European settlers, *c.* 150 years ago).

Results (Figure 7; Appendix 3)

Core R5 consists of green-grey mud containing two 0.03 m thick shell beds (0.60–0.57, 0.32–0.29 m). The shell beds are dominated by cockles (*Austrovenus stutchburyi*), some in near-life position with two articulated valves. Scattered cockle shells occur within the mud from the bottom of the core (0.87 m) up to the higher shell bed (0.32 m). No shells are present above 0.29 m, nor in the surface mud within several km of the site. Double-valved cockle shells from the lower shell bed (0.60–0.57 m) have been radiocarbon dated at 1418 ± 39 BP (Wk 9397, cal. AD 1000; Stuiver *et al.*, 1998).

Because of lower abundances of tests in this core, 20 cm^3 samples were processed. Despite this, three samples (0.87–0.85, 0.75–0.73, 0.28–0.26 m) had fewer than 30 specimens total per sample, and their results are less reliable. Most of the section has moderately low abundances of 30–100 specimens/cm^3, except for three samples (0.63–0.54 m) clustered around the lower shell bed which have relatively high abundances of 400–1000 specimens/cm^3. Species diversity is very low (α 0.4–2) throughout most of the cored section with slightly higher diversity (α 3.2) in one sample (0.46–0.44 m).

Thus the low census counts are of less concern statistically for estimating palaeoenvironmental conditions.

Qualitative assignment of foraminiferal associations (Figure 4) shows the following sequence: *Ammonia-Miliammina* (AM) association (0.87–0.85 m), *Ammonia* (A) association (0.75–0.23 m), mixed *Haplophragmoides* and *Miliammina fusca* (H, Mf) associations (0.22–0 m).

Confinement Index values show the following sequence: moderately confined (NZCI 28–39) up to 0.23 m, with the lowest sample (0.87–0.85 m) indicating an earlier interval of increased confinement (NZCI 50). A substantial increase in confinement (NZCI 63–69) is indicated above 0.22 m. All three regression equations show the same trends to the Confinement Index (Figure 7).

Core R5 is clearly in an estuarine setting and therefore the estuarine census data set was used for modern analogue estimates of tidal elevation. The Waitemata Harbour has a spring tidal range of 3.5 m. All three methods of selecting modern analogue samples give similar elevation curves, which imply initial deepening (between 0.85 and 0.75 m) from low tidal to shallow subtidal depths. An abrupt shallowing to intertidal depths is indicated from 0.22 m and above. The fauna of one sample (0.22–0.20 m) has a MAT estimated elevation above MHW by all three methods.

Interpretation

There is no evidence for any Holocene tectonic movement in the Auckland region nor any eustatic sea-level change of any significance in the last 2000 years. Thus the MAT estimates of tidal elevation change are likely to be incorrect. Instead this core presumably records a shallowing with sediment accumulation and compaction all within the low tidal zone, reaching its present elevation of *c.* 1.3 m above ELWS. In all but one instance, the elevational range of the five most similar modern faunas includes acceptable low tidal values. The 0.22–0.20 m fauna with a clear high tidal signature might be explained as a result of post-mortem transport in a flood event. The poor MAT tidal estimates are clearly a result of the much broader elevational range of some foraminifera (e.g., *Miliammina*, *Haplophragmoides*) in these lower-salinity estuarine environments. The indicated elevational shifts are a result of distinct faunal and environmental changes, but not elevation.

The main Confinement Index increase and faunal change occurs at the top of the higher shell bed (at 0.23–0.22 m) and coincides with the disappearance of all cockles. If correlation of the stratigraphy with the palynologically dated nearby core in Lucas Creek (Hume and McGlone, 1986) is correct, then this level marks the onset of human impact on the watershed with initial clearance of the forest. The substantial increase in confinement presumably resulted from increased runoff with resultant decreased salinity. As cockles appear to have lived in similar mud prior to this event, it seems that increased fresh water and not fine sediment (as has often been proposed) was the major factor in their disappearance throughout most of the Rangitopuni Estuary.

Because of the possibility of taphonomic loss, census data on only the dead fauna was used to obtain elevational and Confinement Index estimates in this core. It was noticed however that the two highest samples (0.05–0 m) contained small numbers of live (stained with Rose Bengal) calcareous foraminifera (e.g., *Ammonia*, *Elphidium*), some already showing signs of dissolution. This observation suggests that at least some of the major faunal change recorded above 0.22 m (i.e., loss of all calcareous tests) resulted from the onset of carbonate-corrosive conditions (pH decrease) in the estuarine waters. This level also marks a 5- to 20-fold increase in absolute abundances (per cm^3 of mud) of agglutinated specimens and thus salinity decrease is also likely and linked to the pH change.

The two lowest samples, with low absolute abundances of foraminifera contain a mix of calcareous and agglutinated specimens. The agglutinated taxa are at similar low absolute abundance levels to those in *Ammonia* association faunas above (0.63–0.23 m), whereas the calcareous *Ammonia* and *Elphidium* tests are far fewer and show signs of strong dissolution. Thus there appears to have been an earlier period (pre-AD 1000) when pH was lower and dissolution of calcareous specimens significant. An explanation for this is currently unclear.

Discussion

These pilot studies of late-Holocene foraminiferal sequences clearly show the potential of MAT estimates of elevation and the New Zealand Confinement Index for higher-resolution interpretation of the environmental histories of intertidal and shallow subtidal estuarine and sheltered harbour settings.

MAT elevational estimates

In sheltered harbour or tidal inlet settings (e.g., Ahuriri Inlet), MAT estimates of tidal elevation appear to be relatively accurate. As in other parts of the world, high-precision elevational estimates are produced from the narrow tidal ranges of high tidal faunas (e.g., *Jadammina*, *Trochammina inflata*, *Haplophragmoides* associations). Less precise estimates are achieved for low and mid-tidal elevations, and even lower precision for subtidal. It seems possible however for MAT to distinguish intertidal from subtidal (below MLW) elevations based on the increased subtidal diversity (Figure 6) and decreased abundance of largely intertidal *Elphidium excavatum* s.l. Previous studies of the distribution of foraminifera in subtidal harbour and inlets around New Zealand (e.g., Hayward *et al.*, 1994; 1997) provide slim prospects for obtaining accurate MAT estimates of subtidal depths within the range 0–10 m in these sheltered environments.

In lower-salinity estuarine settings (e.g., Rangitopuni Estuary), MAT estimates of elevation are less reliable, as reflected in the broader elevational range of the five most similar modern estuarine faunas (Figure 7). This results from the greater intertidal and subtidal range of a number of common species in lower-salinity environments. In some estuarine situations, it should still be possible, however, confidently to identify high tidal or subtidal elevations based on the foraminiferal fauna. An enlarged modern estuarine foraminiferal faunal data set may help improve the accuracy of MAT estimates in lower-salinity settings.

Proxy salinity indices

Graphs produced by the NZ Confinement Index and regression equations (d1–d3), show exactly the same changes (except in one instance, d2 in A4) in both core examples. In both instances (Figures 6 and 7), the NZCI curve tends to average the extremes produced by d1 (based largely on *Ammonia*) and d3 (based largely on *Haplophragmoides* and *Miliammina*). Being based upon the full census count of each sample, the NZCI has the advantage over the regression equations (based on 1–3 species only) in being able to recognize confinement changes in faunas with more variable composition resulting from more varied environmental settings. This is because the NZCI is based on the full census data from five different estuarine and coastal lagoon settings and is not reliant on the presence of populations of the few species targeted by the regression equations. Regression models the abundance of species as a linear function of distance along the estuary, whereas the NZCI is based on canonical correspondence analysis which shows a low-dimensional view of species occurrences within the estuaries in relation to environmental variables. The position of a species in the ordination is primarily controlled by the samples which contribute most to its variance.

The NZ Confinement Index is therefore preferred for general use around New Zealand to provide curves that are more objective than qualitative assessments in determining degree of confinement. In temperate New Zealand's estuaries and coastal lagoons, increasing confinement appears to correlate closely with decreasing salinity and in most instances is likely to be a good proxy for salinity changes. In some high tidal harbour edge settings, decreased CI values may not necessarily reflect lowered salinity in harbour waters, rather increased freshwater seepage and retained rainfall in a salt marsh or salt meadow.

At Ahuriri, relatively soft late-Miocene and Pliocene mudstone outcrops in the catchment. Here reworked, well-preserved fossil foraminifera (often with time ranges up to the Recent) can be recognized because they are deep-water species clearly different from those that live in the shallow lagoon. Where reworked fossil foraminifera are recognized, they should be removed from the census data prior to analysis. Their presence should be noted, however, as it may indicate increased fluvial input (or a major slip in the catchment).

Taphonomic effects

No selective taphonomic loss of the original foraminiferal fauna was recognized in the Ahuriri core, although some post-mortem introduction of small reworked Pliocene and modern, normal-salinity foraminiferal tests is clear (especially in the subtidal faunas). Where recognized, the Pliocene foraminifera (distinguished from the modern shallow lagoon species because they are deep-water bathyal species), presumably carried in by flooded streams from the surrounding catchment, were removed from the census data prior to its use in estimating salinity and elevation. The modern open-coast inner-shelf elements, possibly introduced by an incoming tide during a coastal storm, were not removed from the census data as they are part of the modern death assemblage that characterizes subtidal environments in and near the mouths of harbours and inlets (e.g., Hayward *et al.*, 1996).

Partial and complete dissolution of the calcareous component of the foraminiferal faunas is recognized in the bottom and top, respectively, of the Rangitopuni Estuary core. This dissolution impacts on both the salinity and elevation estimates, with major shallowing and decreased salinity indicated where loss of the calcareous tests commences, at 0.23 m (Figure 7). Carbonate corrosiveness probably correlates with decreased salinity in this instance, but the indicated shallowing is an artifact of dissolution.

The Rangitopuni Estuary results indicate that caution should be shown in unquestionably accepting salinity and elevational estimates using these methods, until possible taphonomic influence can be excluded.

Blurring effects of bioturbation and infaunal depth

Both Ahuriri and Rangitopuni cores record apparently rapid environmental changes – earthquake-related vertical displacements (Ahuriri) and salinity change (Rangitopuni). The foraminiferal change across these boundaries is relatively rapid, despite potential blurring of the signal by sediment movement, invertebrate bioturbation or by the depths of substrate burrowing of the live foraminifera (up to 0.25 m; Ozarko *et al.*, 1997).

For example, there is only slight overlap across the Napier Earthquake boundary (0.31–0.30 m) between subtidal foraminifera below (e.g., *Bolivina, Haynesina, Nonionellina*) and intertidal foraminifera above (e.g., *Elphidium excavatum, E. gunteri*), although there is sufficient for both the NZCI and MAT elevation estimate for 0.30–0.28 m to be intermediate between the subtidal and intertidal end members (Figure 6). In the Rangitopuni core, there is a 98% faunal change across the 0.23–0.22 m boundary with almost no blurring, although some of this change is undoubtedly due to the rapid onset of dissolution of calcareous tests.

Acknowledgements

We thank Chris Hollis and Judy Zachariasen for assistance with fieldwork at Ahuriri Inlet. Catherine Chagué-Goff kindly provided samples and information from her earlier Ahuriri study that persuaded us to recore at Poraiti corner (A4). Jessica and Clare Hayward assisted with drafting some of the figures. Radiocarbon dating was undertaken by the University of Waikato Radiocarbon Dating Laboratory. This research was funded by the University of California's Pacific Rim Research Program and the New Zealand Public Good Science Fund.

Appendix 1: Taxa and taxonomic groupings of rarer species used in the modern analogue technique and regression analyses (for synonymic lists, see Hayward *et al*, 1999a)

Ammobaculites exiguus
Ammonia aoteana
Ammonia pustulosa
Ammotium fragile
Anomalina spherica
Astrononion novozealandicum
Bolivina hornibrooki
Bolivina neocompacta
Bolivina striatula
Bolivina subexcavata
Bolivina spp.
Bulimina elongata
Bulimina marginata
Cassidulina carinata
Cibicides marlboroughensis s.l.
Cibicides spp.
Cornuspira involvens
Cribrostomoides jeffreysi
Cuneata arctica
Elphidium advenum
Elphidium charlottense
Elphidium excavatum clavatum/williamsoni
Elphidium excavatum excavatum
Elphidium excavatum oirgi
Elphidium gunteri
Elphidium novozealandicum
Evolvocassidulina orientalis
Fissurina lucida
Gaudryina convexa
Gavelinopsis spp.
Haplophragmoides wilberti
Haynesina depressulus
Helenina andersoni
Jadammina macrescens
Miliammina fusca
Miliammina obliqua
Miliolinella spp.
Nonionellina flemingi
Notorotalia spp.
Oolina melo
Paratrochammina bartrami
Patellinella inconspicua
Pileolina spp.
Polysaccammina ipohalina
Portatrochammina sorosa
Pseudothurammina limnetis
Quinqueloculina spp.
Rosalina bradyi
Rosalina irregularis
Saccammina sp.
Scherochorella moniliforme
Spiroloxostoma glabra
Textularia earlandi
Trochammina inflata
Trochamminita salsa
Trochulina dimidiatus
Virgulopsis turris
Zeaflorilus parri
Unilocular miscellaneous
Other miscellaneous spp.

Appendix 2: Foraminiferal census data, absolute abundance, diversity (Fisher α index) for Ahuriri Inlet core, A4, New Zealand Fossil Record File number V21/f420

Ahuriri Core A4	0.01–	0.05–	0.09–	0.14–	0.19–	0.24–	0.28–	0.31–	0.38–	0.46–	0.55–	0.71–	0.82–	0.93–	1.04%
Sample depth (in metres)	0.03	0.07	0.11	0.16	0.21	0.26	0.30	0.33	0.40	0.48	0.57	0.73	0.84	0.95	1.06
Specimens/10 cu cm	38	230	164	6	720	1000	274	280	800	1776	1600	7680	4040	4000	2288
Diversity alpha	1.5	1.6	1.5	1.1	2.1	4.4	1.9	2.4	2.0	5.1	5.9	4.5	4.4	2.0	3.5
NZ Confinement Index	62	63	62	28	42	35	30	21	25	19	20	16	22	26	24
Regression scores, d1	42	43	43	21	31	27	21	20	15	25	22	29	18	12	15
Regression scores, d2	34	36	37	32	50	37	32	32	32	32	32	32	32	32	32
Regression scores, d3	94	97	96	25	41	30	27	25	25	25	25	25	25	25	25
Ammonia aoteana	11	8	9	67	40	52	67	71	82	55	63	46	74	91	85
Ammonia pustulosa	0	0	0	0	3	2	0	0	0	0	1	0	0	0	0
Astrononion novozelandicum	0	0	0	0	0	0	0	0	0	0	2	0	2	0	0
Bolivina hornibrooki	0	0	0	0	0	1	0	1	0	0	0	2	1	0	0
Bolivina striatula	0	0	0	0	0	2	1	14	2	9	8	18	4	0	6
Bolivinasubexcavata	0	0	0	0	0	0	0	0	4	5	2	3	1	0	0
Bolivina spp.	0	0	0	0	0	0	0	0	1	1	1	2	1	1	1
Bulimina elongata	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0
Bulimina marginata	0	0	0	0	1	0	0	0	1	1	0	0	0	0	0
Cassidulina carinata	0	0	0	0	0	0	0	0	0	2	2	1	0	1	1
Elphidium advenum s.l.	0	1	0	0	0	0	1	0	0	9	1	3	2	2	1
Elphidium charlottense	0	0	1	0	0	1	0	0	2	3	2	3	5	0	1
Elphidium excavatum f. *clavatum*	0	0	0	33	9	7	15	1	0	1	0	1	0	0	0
Elphidium excavatum f. *excavatum*	0	1	0	0	11	6	0	0	0	0	2	0	0	0	0
Elphidium gunteri	0	0	1	0	8	17	11	0	0	1	0	0	0	0	0
Haplophragmoides wilberti	82	83	80	0	0	1	1	0	0	0	0	0	0	0	0
Haynesina depressula	0	0	0	0	0	1	3	0	7	5	6	13	4	0	0
Jadammina macrescens	3	1	0	0	0	0	0	0	0	0	0	0	0	0	0
*Miliammina fusca*3	5	7	0	2	8	7	0	0	0	0	0	0	0	0	0
Nonionellina flemingi	0	0	1	0	0	1	1	3	0	4	4	4	0	1	1
Notorotalia spp.	0	0	0	0	0	0	0	0	0	0	1	0	0	1	1
Scherochorella moniliforme	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0
Spiroloxostoma glabra	0	0	0	0	0	0	0	2	1	1	0	0	0	0	0
Trochammina inflata	3	1	0	0	0	0	0	0	0	0	0	0	0	0	0
unilocular forms	0	0	0	0	0	1	0	1	0	0	0	2	1	2	1
other taxa	0	0	0	0	0	0	0	5	0	5	4	4	5	1	3

Appendix 3: Foraminiferal percentage census data, absolute abundance, diversity (Fisher α index) and salinity values for Rangitopuni Estuary core R5, New Zealand Fossil Record File number R10/f156

Rangitopuni Estuary, R5 core	0.00–	0.03–	0.06–	0.12–	0.20–	0.23–	0.26–	0.35–	0.44–	0.54–	0.58–	0.61–	0.73	0.85–
Sample depth (in metres)	0.02	0.05	0.08	0.14	0.22	0.25	0.28	0.37	0.46	0.56	0.60	0.63	0.75	0.87
Specimens/10 cu cm	55	106	41	67	29	69	14	100	51	1000	848	417	10	9
Diversity alpha	1.5	1.5	1.4	2.0	1.7	1.4	1.4	0.4	3.2	1.1	1.1	0.8	1.7	1.7
NZ Confinement Index	61	63	69	67	63	28	39	28	31	31	29	28	38	50
Regression scores, d1	45	43	46	46	46	18	21	10	23	13	11	12	28	37
Regression scores, d2	59	55	58	46	39	33	44	32	38	36	33	33	32	51
Regression scores, d3	61	66	78	79	76	26	38	25	33	29	26	26	25	52
Ammobaculites exiguus	0	0	0	1	4	0	4	0	0	1	0	0	0	0
Ammonia aoteana	0	0	0	0	0	75	68	95	62	89	94	91	47	24
Ammotium fragile	16	19	17	21	16	0	4	0	2	1	1	0	26	12
Cassidulina carinata	0	0	0	0	0	0	0	0	1	0	0	0	5	0
Buliminella elegantissima	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Elphidium excavatum f *clavatum*	0	0	0	0	0	13	0	5	4	3	1	5	5	0
Elphidium excavatum f *excavatum*	0	0	0	0	0	9	4	0	7	0	3	3	5	12
Elphidium gunteri	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Haplophragmoides wilberti	15	24	32	49	54	0	4	0	3	0	0	0	0	12
Miliammina fusca	43	36	41	22	11	1	18	0	9	6	1	1	0	28
Paratrochammina bartrami	0	0	0	0	4	0	0	0	8	0	0	0	5	6
Quinqueloculina spp	0	0	1	0	0	1	0	0	2	0	0	0	0	0
Scherochorella moniliforme	23	6	5	3	7	0	0	0	1	0	0	0	0	6
Textularia earlandi	2	0	0	2	0	0	0	0	0	0	0	0	0	0
Trochammina inflata	1	1	0	1	5	1	0	0	0	0	0	0	5	0
Trochamminita salsa	0	1	4	1	0	0	0	0	0	0	0	0	0	0

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