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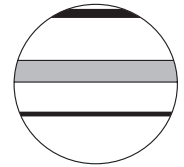
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Microfossil record of the Holocene evolution of coastal wetlands in a tectonically active region of New Zealand

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Abstract

The shallow tidal Wairau coastal lagoons, New Zealand, are in a prime location for investigating the relative roles of tectonic and eustatic sea level on their palaeogeographic evolution. The Wairau lagoons are unique in New Zealand for their wide seasonal and tidal salinity range, from hyposaline (10–20 psu) to hypersaline (35–54 psu). Foraminiferal and ostracod associations are recognised, using Q-mode cluster analysis, living in and around these lagoons and detrended canonical correspondence analysis (DCCA) shows that their distributions are strongly correlated with tidal elevation and salinity.

Analyses of the modern analogue faunal data combined with Holocene microfaunal data from five 2.5–9 m deep cores enables direct palaeoenvironmental interpretation of the fossil faunas and elucidation of the lagoons' palaeogeographic evolution. The area was inundated by rising eustatic sea level from 8.5 ka onwards, forming a fully marine, sheltered, subtidal bay. Sediment supply outpaced local tectonic subsidence and the bay filled with mud, shallowing to intertidal by 4.5–3.5 ka, still with an open mouth to the sea. Since then sediment supply has kept pace with 3–4 m of inferred tectonic subsidence. At ~1.5 ka the calcareous-dominated foraminiferal faunas suddenly changed to agglutinate-dominated faunas, indicating a switch to a semi-closed lagoon linked to the Wairau River estuary, with highly varied salinity like today. We infer this was caused by northwards extension of the Wairau Boulder Bank across the bay's mouth in response to a sharp eustatic sea-level fall after 2 ka. Sediment supply switched to fluvially derived sand which built a flood-delta into the lagoon dividing it into three water bodies. Relative sea-level rise in the last 600 years from earthquake-related compaction (AD 1855) and accelerating eustatic rise (0.6 m) has resulted in increased marginal erosion of the lagoons and their re-amalgamation into one linked water body.

Keywords

earthquakes, foraminifera, New Zealand, ostracods, Wairau coastal lagoons

Introduction

In recent decades the ecological distribution of foraminifera, ostracods, diatoms and dinoflagellates have been sufficiently well-documented in coastal wetland systems in many parts of the world (e.g. Yassini and Jones, 1995; Sen Gupta, 1999) to be useful in inferring changes in coastal conditions using their microfossil record in Holocene sedimentary sequences. For example, Holocene foraminiferal microfossils from coastal settings are now regularly utilised to investigate earthquake cycles above plate subduction zones (e.g. Guilbault *et al.*, 1996; Cochran *et al.*, 2006; Hayward *et al.*, 2006a; Nelson *et al.*, 2008), displacement histories of active faults (e.g. Hayward *et al.*, 2007), impacts of tsunamis, storm surges and hurricanes (e.g. Goff *et al.*, 2000; Scott *et al.*, 2003; Cochran *et al.*, 2005), eustatic sea-level changes (e.g. Gehrels, 1994; Edwards and Horton, 2000), climate changes such as rainfall (e.g. Willard *et al.*, 2003), impacts of human-related activities such as deforestation (e.g. Hayward *et al.*, 2007), pollution (e.g. Alve, 1995; Yanko *et al.*, 1999), aquaculture (e.g. Scott *et al.*, 1995; Grenfell *et al.*, 2007), artificial coastline modifications and structures (e.g. Debenay *et al.*, 2001; Scott *et al.*, 2005), and the natural processes of evolution of these geologically young (<10 kyr) geomorphological systems (e.g. Culver *et al.*, 2006; Cearreta *et al.*, 2007).

In this study we evaluate the relative usefulness of three groups of microfossils (foraminifera, ostracods, diatoms) for unravelling

the Holocene development of a coastal lagoon complex located on an active tectonic plate boundary at the north end of the Wairau Valley, Marlborough, New Zealand (Figure 1). Microfossils are used in this study to help determine the relative importance for this coastal evolution of sediment supply (riverine, marine, coastal cliffs), fault-related uplift and subsidence, eustatic sea-level changes, long-shore drift, and most recently human activities.

To achieve this we first document the modern distribution of dead foraminifera and ostracods in this unusual group of coastal lagoons with seasonally variable salinity. We then count microfossils from five Holocene sediments cores and use the distinctive faunal associations defined from the modern samples to interpret the palaeoenvironment of our fossil samples. Diatom

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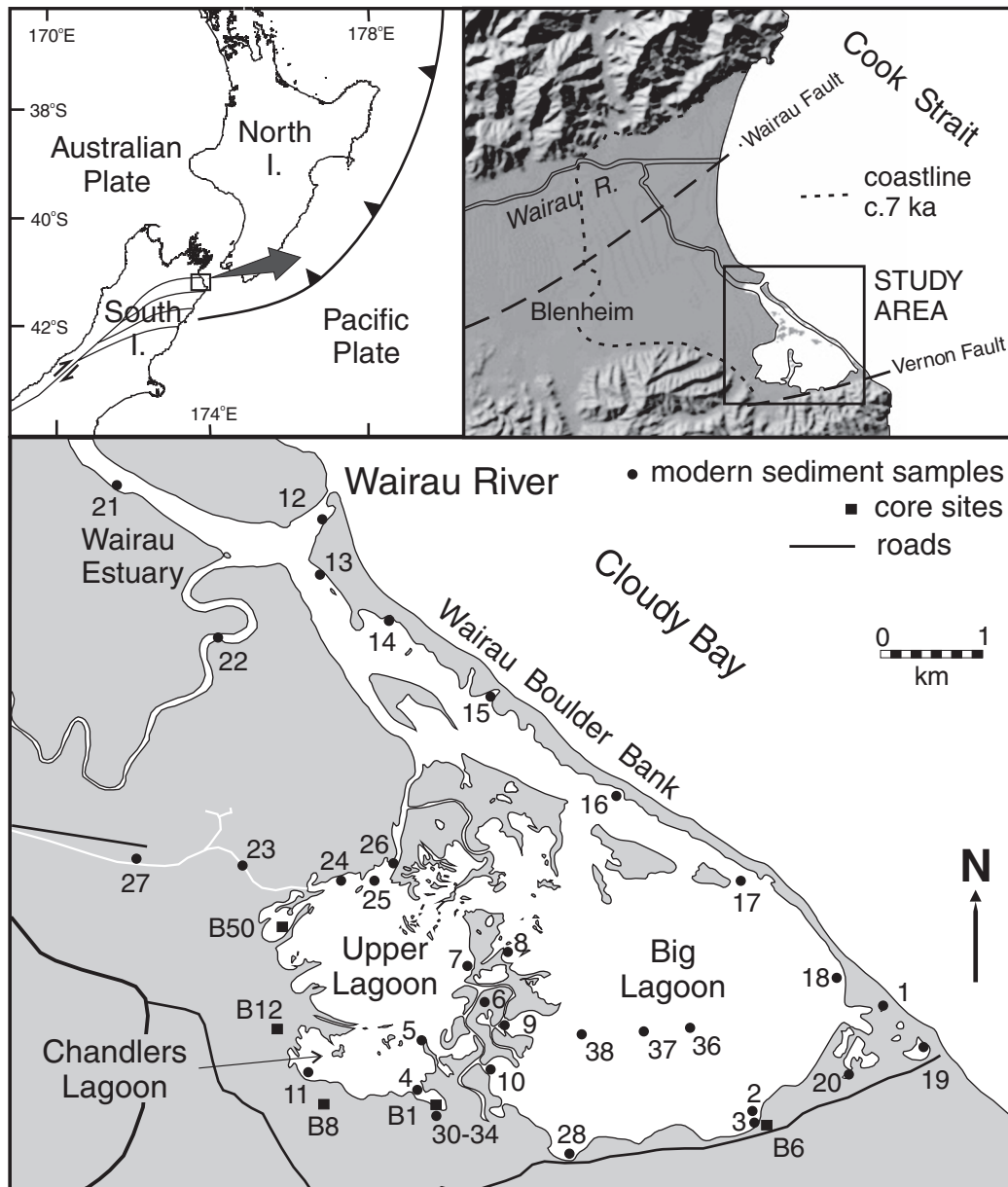


Figure 1. Location of modern foraminiferal surface samples and sediment core sites in the wetlands in and around Big and Upper Lagoons, Marlborough Province, South Island, New Zealand

analysis of a few core samples is used to complement the foraminiferal results. The Holocene evolution of the site is presented using a radiocarbon chronology and various drivers of change are discussed.

Geographic setting of Wairau coastal lagoons

The study area is on the northeast coast of New Zealand's South Island ($41^{\circ}32'S$, $174^{\circ}05'E$) on the southern side of the lower Wairau Valley (Figure 1). Here the Wairau coastal lagoons comprise three, shallow, interconnected tidal lagoons – Big Lagoon (~800 ha), Upper Lagoon (~250 ha) and Chandlers Lagoon (~100 ha). The lagoons are separated from the open sea of Cook Strait by the narrow (50–150 m wide) Wairau Boulder Bank, which is breached by storms several times a century and quickly restored by natural longshore drift. A 3–4 km long, 200–500 m wide, 0.5–1.5 m deep

channel links the lagoons to the modern Wairau River estuary near its mouth at the north end of the boulder bank (Figure 1). The mean spring tidal range in Cloudy Bay at the estuary mouth is 1.2 m, but less than 1 m in the lagoons. On the incoming tide during periods of lower river flows, sea water pushes up the Wairau Estuary and then through the shallow channels into the lagoons. During times of high rainfall, the incoming tide slows the river's path into the sea and diverts mostly freshwater into the lagoons via the linking channels. In summer, Marlborough Province is characterised by long dry periods with strong, warm, northwesterly winds that promote evaporation in the lagoons. Thus the salinity in the Wairau coastal lagoons varies between hyposaline (~10–20 psu) and hypersaline (~40+ psu). The sediment substrate is slightly muddy sand.

The lagoons are fringed by extensive areas of high tidal salt marsh rush (*Leptocarpus similis*, *Juncus maritimus*) and saltwort (*Sarcocornia australis*) interspersed with low-growing salt meadow (dominated by *Selliera radicans* and *Salmolus repens*). Within

these salt marsh areas there are scattered smaller lagoons and ponds, with salinities ranging between freshwater and hypersaline (up to 60 psu) depending on their elevation, frequency of flooding by spring tides, and the amount of recent rainfall or evaporation.

Hypersaline lagoons are rare in temperate oceanic climates such as that of New Zealand, because of relatively high rainfall and low rates of evaporation. In summer, northeast Marlborough is among New Zealand's driest (average monthly summer rain <40 mm) and warmest (average daily maximum summer temperature 24°C) coastal localities, and the prevalent warm dry northwest winds promote evaporation. These conditions make the Wairau lagoons unique in New Zealand for their highly variable, particularly high summer, salinity range – attributes more commonly associated with coastal lagoons in hotter and dryer climates.

Tectonic setting

This coastal area at the northern end of the South Island lies above the boundary between the Australian and Pacific tectonic plates. This region is in the transition zone between the subduction-dominated plate boundary to the north and the transcurrent displacement-dominated (Wairau-Alpine Fault) plate boundary to the southwest (Figure 1).

The Wairau Valley has been eroded along the course of one of New Zealand's largest and most tectonically active transcurrent faults – the Wairau Fault (Figure 1) with a slip rate of 3–5 mm/yr (Zachariassen *et al.*, 2006). The extensive fluvial plains of the lower Wairau Valley extend west and northwest of the Wairau coastal lagoons. To the south the lagoons are bounded by the uplifted Vernon Range (250–300 m) composed of Neogene conglomerate and other sedimentary rocks. Much of the uplift occurred along the Vernon Fault which runs subparallel to the Wairau Fault along the northern side of the range on the southern edge of Big Lagoon (Figure 1).

Previous fossil studies in Wairau coastal lagoons

There has been no previous study on the modern or Holocene foraminifera or ostracods of the Wairau coastal lagoons. Fossil

Holocene molluscs obtained from auger cores (2–7 m deep) around the lagoons by Ota *et al.* (1995) indicate accumulation in an estuarine environment (Beu, 1995). Diatoms from two cores on the southern shore of the lagoons (in the vicinity of our cores B1 and B6) showed a change in flora between 2.7 and 2 m downcore (Kashima and Taguchi, 1995). The floras indicated a switch from a slightly brackish marine environment up into a brackish lagoon with significant numbers of freshwater species, that were probably transported in by rivers (Kashima and Taguchi, 1995).

New Zealand Holocene eustatic sea-level curve

Changes in eustatic sea level clearly influenced the microfossil record of the palaeogeographic evolution of the Wairau coastal lagoons. Knowledge of New Zealand's Holocene sea-level fluctuations are not as precise as in other regions, but seem to parallel the general trends recorded in southeast Australia (e.g. Sloss *et al.*, 2007) and the tropical South Pacific (e.g. Dickinson, 2009). Clement *et al.* (2008) assessed all available New Zealand data and presented a generalised eustatic sea-level curve with a broad band of uncertainty (Figure 2). They concluded that sea level reached present levels ~7.6 ka and was above present level from then until ~1.5 ka, with peaks of ~+1 m or more at 4.5 and 2.7–2 ka. Recent salt marsh foraminiferal studies in the latest Holocene indicate that sea level around New Zealand's South Island was ~-0.6 m at AD 1300, -0.3 m at AD 1880, rising 0.3 m to the present level in the last 120 years (Figure 2) (Gehrels *et al.*, 2008; Grenfell *et al.*, 2009).

Materials and methods

Sampling and coring

Thirty-six surface sediment samples (upper 2 cm) were taken by hand from in and around the Wairau coastal lagoon (Figure 1) in order to sample the widest range of modern environments. Marginal environments were sampled more extensively because of the difficult access to central parts of the shallow lagoons and because previous studies have indicated that faunal zonation relative to

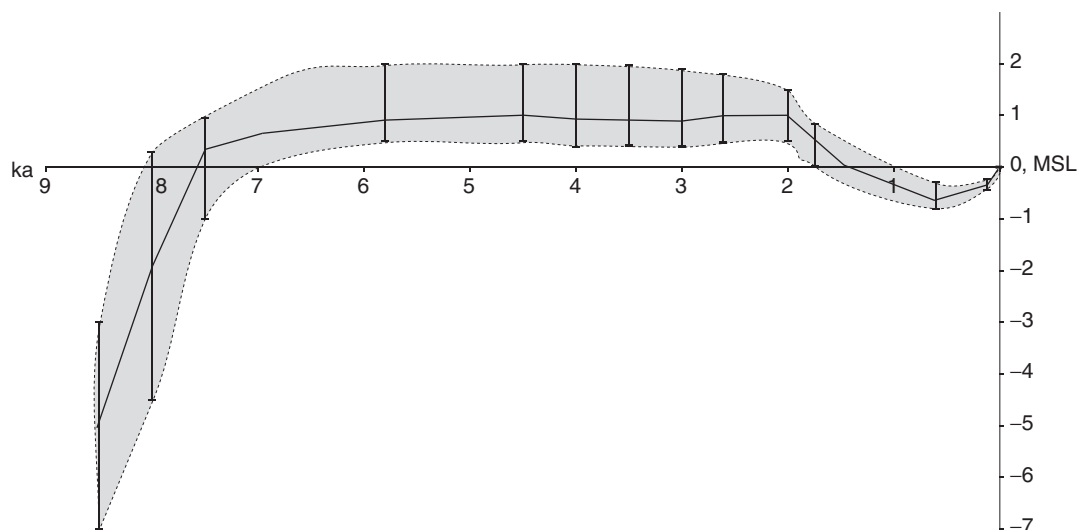


Figure 2. Generalised Holocene eustatic sea-level curve (with accuracy band) for New Zealand, based on Clement *et al.* (2008), with modification in the latest Holocene (last 700 yr) from Gehrels *et al.* (2008) and Grenfell *et al.* (2009)

tidal elevation are narrow and useful at and above mean high water level (e.g. Hayward *et al.*, 1999a, b). The elevations of all samples were surveyed and related to mean high water spring level (upper limit of *Selliera radicans* salt meadow).

Salinity readings were taken using a hand-held refractometer from each sample site where water was present at the time of sampling in the summer dry season. One-off salinity measurements were collected as an indication only and no attempt was made to characterise the full seasonal or tidal variability for each site.

Five cores were obtained (Figure 1): core B1 using a vibrator, cores B6, B8 and B12 using a truck-mounted drill rig, and core B50 using an Eijkelpkamp gouge auger. Cores were split, logged and sampled soon after they were extracted. Small push tube samples (20–40 ml) were taken along one half of each core for foraminiferal and ostracod studies. Separate smaller samples were taken for diatom studies.

Microfossil processing

A total of 36 surface and 61 core samples were processed for foraminiferal analysis. Following collection the surface and core-top samples were stained and fixed overnight in rose Bengal and 70% alcohol to detect live specimens (Lutze and Altenbach, 1991). Later all samples were washed over a 63 µm sieve and dried. The dry sand fraction was microsplit down to a volume containing 100–200 foraminiferal specimens, all of which were identified (Appendix A) and counted (Appendix B, available online), except for any rose Bengal stained (live) specimens. Stained specimens were excluded from counts to remove bias that results from differential taphonomic loss of some species soon after death (Murray, 2000). For the purposes of this study a census of 100–200 dead specimens per sample has sufficient accuracy to identify clearly the major changes that have occurred in the relative abundances of the few dominant species (Patterson and Fishbein, 1989). For the ostracod studies, the total >125 µm sand fraction from all surface samples and core samples from B1 were examined and all ostracod shells picked, identified and counted (Appendices A, B. Appendix B available online).

A small number of core samples were also investigated for their diatom flora (22 samples from cores B6, B8 and B12: Appendix C, available online) to provide a comparison with the foraminiferal results and additional information where foraminifera were not preserved. Samples were processed and diatoms identified using the standard techniques detailed in Cochran *et al.* (2007). In most samples, however, only 100–200 diatoms were

counted instead of the usual 300–400 valves required for quantitative analysis. This was considered appropriate for providing the broad, qualitative assessment of salinity and habitat types required for comparison with foraminiferal results.

Statistical analyses

Only those samples with >100 foraminifera or >50 ostracod shells were used in the two separate computer analyses. Unfortunately this resulted in the removal of all but one fossil ostracod sample, because of poor fossil ostracod preservation. The data consist of census counts of 26 foraminiferal species from 67 samples and 10 ostracod species from 18 samples. The two separate data matrices were standardised by converting counts to proportions of sample totals of foraminifera or ostracods. A Q-mode cluster analysis dendrogram classification was produced using the Chord dissimilarity coefficient for the foraminiferal samples and ostracod samples separately. Detrended canonical correspondence analysis (DCCA; Kovach, 1993) was used to summarise the benthic foraminiferal faunal distribution and assist in its interpretation with respect to tidal elevation and salinity. Ordinations of the samples and species were plotted on the first two detrended correspondence analysis axes. The direction and length of the environmental vectors (arrows) indicate the direction and strength of their correlation with the modern faunas. The Holocene faunas were plotted passively on the ordination (i.e. no associated environmental data).

Undertaking cluster and correspondence analyses on a combined modern and Holocene data set is a departure from more traditional methods. This one-stage approach provides more robust and direct interpretations of their modern and palaeoenvironmental settings than the usual more cumbersome two or more stage analyses of the modern and fossil data separately.

Sample nomenclature and data repositories

Surface samples have been given sequential numbers from 1–38. The five cores have a B prefix and samples are given in the format: core number, downcore depth in cm (e.g. B6,123).

Each core has been registered in the New Zealand Fossil Record File data base (<http://data.gns.cri.nz/fred/about.jsp>) (Table 1). Washed foraminiferal and ostracod surface samples and core samples from B1 and B50 are held in the collections of the Geology Department, University of Auckland. Diatom and foraminifera slides from cores B6, B8 and B12 are held in the collections of the Institute of Geological & Nuclear Sciences Ltd, Lower

Table 1. Location, elevation, depth of sediment cores at Wairau lagoons, Marlborough Province, South Island of New Zealand (Figure 1)

Core	Grid ref. ^a	FR no. ^b	Elevation	Depth	Site vegetation
B1	997608	P29/f80	MHW	7.31 m	Mud, on seaward edge of salt marsh
B6	027606	P29/f77	MHWS ^c	8.7 m	Saltwort
B8	981608	P29/f78	MHWS ^c + 0.2 m	6.7 m	Grass paddock
B12	977615	P29/f79	MHWS ^c + 0.2 m	5.9 m	Grass paddock
B50	982626	P29/f81	MSL	2.5 m	Intertidal mud flat

^aGrid ref.: grid reference on NZMS 260, 1:50 000 map P29.

^bFR no., New Zealand Fossil Record File number.

^cMHWS, mean high water spring.

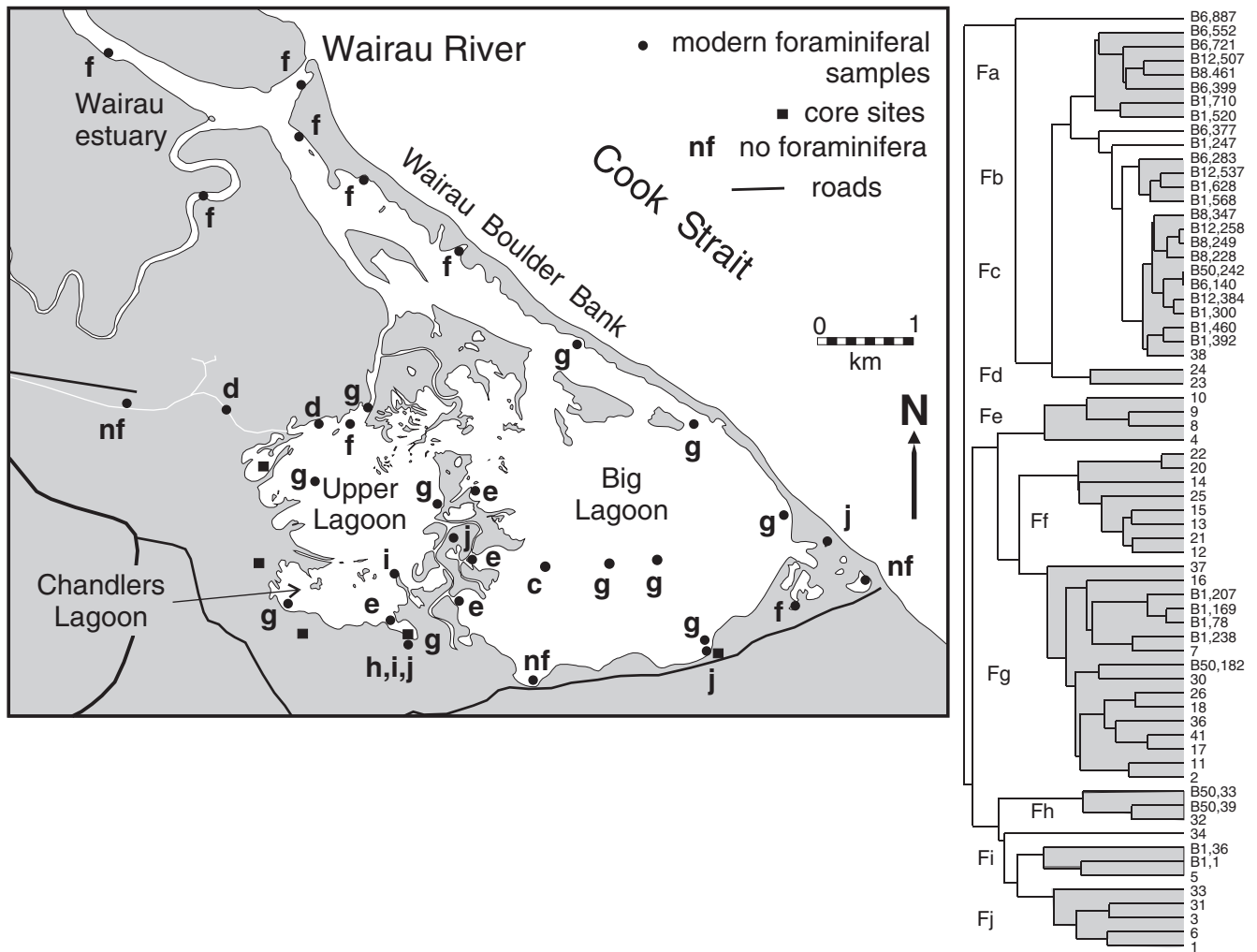


Figure 3. Cluster analysis dendrogram (chord dissimilarity coefficient) of modern (no prefix) and fossil (cores prefixed by B, followed by sample depth in cm) foraminiferal samples together, and map of the modern distribution of the resulting faunal groups (Fa–Fj)

Hutt. Census counts of foraminifera, ostracods and diatoms from surface sediment and cores in the Wairau coastal lagoons are presented online in Appendices B and C.

Foraminiferal associations

From the cluster analysis dendrogram (Figure 3) we recognise ten distinct foraminiferal associations (Fa–Fj). Eight contain modern foraminiferal samples, which assist in inferring their environmental range. In previous studies in coastal wetlands around New Zealand (summarised in Hayward et al., 1999a) we determined that the two most significant drivers of foraminiferal distribution are tidal elevation and salinity. The associations are here shown on the DCCA ordination (Figure 4) which allows their environmental distribution to be interpreted in terms of the salinity and tidal elevation vectors, derived from measurements on the modern samples. The length of the two vector arrows indicates considerable correlation with the faunas. The strongest correlation is with tidal elevation, parallel to axis 1, indicating increasing elevation of the associations from right (Fa) to left (Fh, Fj) on the ordination (Figure 4). The salinity vector is subparallel to axis 2 with lower salinity associations in the upper left (Ff, Fh) and higher salinity associations in the lower and right areas (Fa–c, Fj).

Association Fa

This association comprises seven fossil faunas (B1,520 and 710; B6,399, 522 and 721; B8,461; and B12,507) that are dominated by *Ammonia* spp. (29–68%) with subdominant *E. advenum* and *H. depressula* (each 6–40%). This combination of dominants is characteristic of shallow subtidal (0–10 m) depths in normal marine salinity to slightly brackish (30–35 psu) conditions in sheltered bays and harbours (Hayward et al., 1999a).

Association Fb

Four fossil faunas (B1,568 and 628; B6,283; and B12,537) comprise this association, which is strongly dominated by *Ammonia* spp. (79–92%) with subsidiary *E. advenum* and *H. depressula* (each 3–11%). This association has the same three main species as Fa, but the greater dominance of *Ammonia* suggests slightly shallower (low tidal–2 m) and perhaps slightly more brackish conditions (25–30 psu).

Association Fc

One modern (38) and ten fossil samples (B1,300, 392 and 460; B6,140; B8,228, 249 and 347; B12,258 and 384; and B50,242) belong to this association, which is strongly dominated by

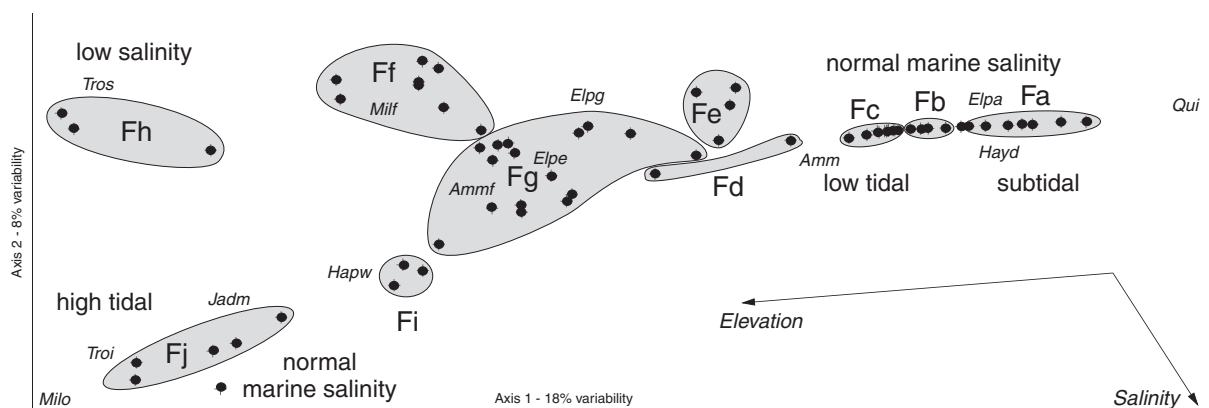


Figure 4. Detrended canonical correspondence analysis ordination of foraminiferal faunas (dots) and common species (3–4 letter abbreviations in Appendix A) from the Wairau lagoons' modern sediment and cores. Groups (Fa–Fj) from the cluster analysis dendrogram (Figure 3) are overlain on the ordination. Salinity and elevation vector arrows are derived from the modern samples, whereas the Holocene faunas are plotted passively

Ammonia spp. (80–100% of fauna) with subsidiary *Elphidium excavatum* s.l. (0–4%). The modern sample occurs in the middle of Big Lagoon at mean low water level. Elsewhere around New Zealand faunas with this composition typically occur at low to mid tide levels in unvegetated mud or sand substrates with slightly brackish to near normal marine salinity (30–35 psu) in sheltered bays or harbours (Hayward *et al.*, 1999a).

Association Fd

This association comprises two modern samples (23, 24), which occur near mean high water level on the northwest fringe of Upper Lagoon (Figure 3). The faunas are dominated by *Ammonia* (44–69%) with subdominant *Haplophragmoides wilberti* and *Elphidium gunteri*, both of which suggest slightly lowered salinity (20–30 psu) conditions (Hayward *et al.*, 1999a) associated with the small stream that flows into the lagoon in this location.

Association Fe

This association comprises four modern samples (4, 8–10) that all occur close to mean high water level on either side of the peninsula between Big, Upper and Chandlers Lagoons (Figure 3). The faunas are dominated by two species of *Elphidium* (40–90%) – *E. excavatum* and *E. gunteri*, which elsewhere are characteristic of sheltered environments with variable hyposaline to hypersaline conditions at intertidal depths. During our summer sampling, the salinity at these stations was 41–43 psu, possibly as they are located around the head of Big and Chandlers Lagoon where the water may not be flushed out during tidal cycles nor diluted by the incoming fresher water from the Wairau estuary.

Association Ff

Eight modern samples (12–15, 20–22, 25) comprise this association, which is strongly dominated by *Miliammina fusca* (55–100%), with subdominant *H. wilberti*. This fauna occurs on the intertidal sides of the Wairau River estuary and the tidal channels linking the Wairau estuary to the lagoons. One fauna (20) occurs in a small isolated lake on the southeast fringe of Big Lagoon (Figure 3) which had a salinity of 19 psu at the time of sampling in summer. Previous studies (Hayward *et al.*, 1999a) indicate that this fauna is

characteristic of brackish (10–25 psu) intertidal conditions, and this is supported by its geographic distribution in this study.

Association Fg

Eleven modern (2, 7, 11, 16–18, 26, 30, 36–37, 41) and five fossil (B1,78, 169, 207 and 238; B50,182) samples are in this large association. The faunas are dominated by *Ammonia fragile* (18–78%). The modern samples have subdominant *M. fusca* (4–47%) and variable abundance of *Ammonia* spp, *E. excavatum* and *E. gunteri*, whereas the fossil samples have subdominant *H. wilberti* (15–32%), variable *M. fusca* and *E. excavatum* and no *Ammonia* nor *E. gunteri*. Faunas dominated by *A. fragile* have not previously been recorded in New Zealand. The association's modern distribution throughout the eastern half of Big Lagoon and around the fringes of Upper and Chandlers Lagoons at low to high tidal elevations suggests that it is adapted to highly variable, tidally influenced salinities from hyposaline to hypersaline (measured in summer dry season at 30–54 psu) in sheltered sandy substrates. A similar palaeoenvironment is inferred for the fossil faunas, although possibly with slightly lower overall salinity in the upper half of the tidal range.

Association Fh

This consists of one modern (32) and two fossil samples (B50,33 and 39) with faunas dominated by *Trochammina salsa* (48–77%) with subdominant *Jadammina macrescens* (12–19%). The modern sample comes from salt meadow at mean high water spring level on the south side of Chandlers Lagoon – a similar environment to other faunas with this composition in New Zealand (Hayward *et al.*, 1999a, b).

Association Fi

This association includes two modern (5; B1,1) and one fossil (B1,36) samples. The two modern faunas come from unvegetated mean high tidal level sites on the edge of salt marsh on the south side of Chandlers Lagoon. The faunas are dominated by *H. wilberti* (48–96%) with subdominant *Trochammina inflata* and *J. macrescens*. Elsewhere in New Zealand, faunas with this

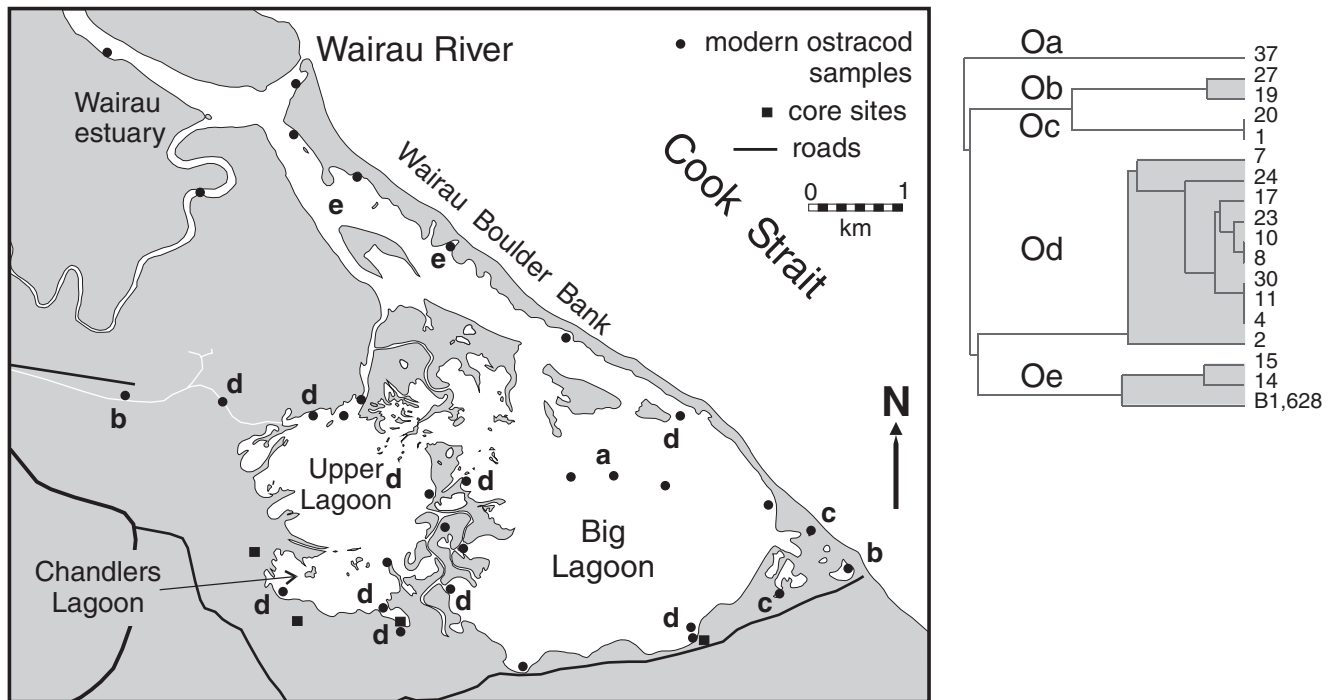


Figure 5. Cluster analysis dendrogram (chord dissimilarity coefficient) of the modern (no prefix) and fossil (prefixed by B) ostracod faunal samples, and map of the modern distribution of the resulting faunal groups (Oa–Oe)

composition usually occur above mean high water level in salt meadow or salt marsh (Hayward *et al.*, 1999b).

Association Fj

Five modern samples (1, 3, 6, 31, 33) comprise this association, which is dominated by *J. macrescens* with subdominant *T. inflata* and/or *Miliammina obliqua*. All occur in salt meadow or saltwort saltmarsh between mean high water and mean high water spring levels, just as this fauna does elsewhere in New Zealand (Hayward *et al.*, 1999a, b).

Ostracod associations

Five associations (Oa–Oe) are subjectively recognised on the ostracod cluster analysis (Figure 5):

Association Oa

This comprises one sample (37) from low water level in the middle of Big Lagoon. Its fauna is co-dominated by *Phlyctenophora zealandica* and *Swansonella novaesealandica* – species characteristic of sheltered low tidal and shallow subtidal estuary mouths elsewhere in New Zealand (Morley and Hayward, 2006).

Association Ob

Two modern faunas (19, 27) comprise this association, which is strongly dominated by *Ilyocypris cf. fallax* and *Cypris* sp. Both faunas occur in small, ephemeral ponds that probably have highly variable salinity from fresh water to hypersaline. Both species are recorded from fresh water elsewhere in New Zealand (Hornibrook, 1955; Barclay, 1968).

Association Oc

This comprises two modern samples (1, 20), both from ponds on the southeast corner of Big Lagoon (Figure 5), one of which had a salinity of 19 psu when sampled in summer. Their faunas are composed entirely of *Cypris* sp., a normally freshwater ostracod (Hornibrook, 1955).

Association Od

Ten modern faunas (2, 4, 7–8, 10–11, 17, 23–24, 30) cluster in this association. All occur in the unvegetated mid-high tidal fringes of the Wairau lagoons (Figure 5) with measured summer salinities of 34–54. Their faunas are dominated by *Leptocythere lacustris* (66–100%), a species that is characteristic of brackish, intertidal environments elsewhere in New Zealand (Morley and Hayward, 2007; Hayward *et al.*, 2008).

Association Oe

Two modern (14–15) and one fossil (B1,628) samples occur in this association, which is dominated by *Callistocythere neoplana*, a species characteristic of sheltered slightly brackish intertidal mud or sand flats elsewhere in New Zealand (Hayward *et al.*, 2006b; Morley and Hayward, 2007; Hayward *et al.*, 2008). Both modern samples occur intertidally on the banks of the tidal channel joining the Wairau estuary and Big Lagoon (Figure 5).

Modern microfaunal distribution

The fringing salt meadow and saltwort marsh above mean high water level around Wairau lagoons has foraminiferal faunas belonging to associations Fh–j, dominated by various combinations of five agglutinated species: *Haplophragmoides wilberti*, *Jadammina macrescens*, *Miliammina obliqua*, *Trochammina*

inflata and *Trochammina salsa*. These are the usual high marsh species encountered elsewhere around New Zealand (Hayward *et al.*, 1999a, b). Ostracod and micromolluscs are absent from these habitats in this study. *J. macrescens*, *M. obliqua* and *T. inflata* are more dominant in higher salinity situations, such as the saltwort marsh where rain water would quickly soak into the sand. *T. salsa* and to a lesser extent *H. wilberti* inhabit lower salinity habitats near stream mouths or where rain water would be retained longer in the more leafy salt meadows.

Four ephemeral, hyposaline ponds were sampled. Each had abundant freshwater ostracods (Ob, Oc) dominated by *Cypris* sp. and *Illyocypris* cf. *fallax*, and three had common charophytes from this slightly brackish-tolerant group of algae. The brackish gastropod *Potamopyrgus estuarinus* was also present. Foraminifera were absent from the two freshest ponds, but agglutinated faunas (Ff, Fj) typical of higher tidal levels or lower salinity were present in the other two.

The distribution of foraminiferal and ostracod faunas (Ff, Oe) dominated by *Miliammina fusca*, *H. wilberti* (Ff) and *Callistocythere neoplana* (Oe) indicate that lower salinity brackish water extends from the Wairau estuary most of the way down the channel connecting the estuary to Big Lagoon (Figures 3, 5).

The ostracod and micromollusc faunas living in the lagoons are less varied than the foraminifera, being dominated by *Leptocythere lacustris* and the small bivalve *Arthritica bifurca*. Only near the centre at low tide level in Big Lagoon is the ostracod fauna different (Oa) with a dominance of *Phlyctenophora zealandica* and *Swansonella novaeseelandica*. The Wairau lagoons are unusual in New Zealand for their abundance of the foraminifer *Ammotium fragile*. The distribution of this species in the lagoons

(Figure 6) and the association dominated by it (Fg) is across the northeast half of Big and Upper Lagoons and around stream mouths on the fringes of Upper and Chandlers Lagoons (Figure 3). These are areas that probably receive the greatest flushes of fresh water during rainy periods, particularly fresh water from Wairau River being diverted by the incoming tide into northeast Big and Upper Lagoons. During the long dry summers that are characteristic of Marlborough regional climate, the small streams entering the lagoons dry up and evaporation raises the salinity of trapped lagoonal water. Thus we infer that that *A. fragile* may be better adapted to cope with highly variable salinity and at times hypersaline conditions. Only one previous sample from New Zealand has been recorded with >15% *A. fragile* (Hayward *et al.*, 1999a). Usually this species occurs around New Zealand in moderately brackish intertidal estuarine settings, which never experience salinities >35 psu. Elsewhere in the world, this or morphologically similar species of *Ammotium* (e.g. *A. salsum*) are widespread in brackish, higher tidal settings, such as mangroves and salt marshes (e.g. Murray, 1991, 2006). Associations dominated by *Ammotium* have been recorded in a few subtropical-tropical estuaries and lagoons where wet and dry season salinities can be highly variable (e.g. central America: Seiglie, 1971; Poag, 1976). An extreme example of this highly variable setting is in the Casamance Estuary in Senegal where *Ammotium* is more euryhaline than the associated *Ammonia* and *E. gunteri* and is strongly dominant in places where salinities periodically exceed 50 psu (Debenay and Pagès, 1987).

Ammonia and *Elphidium* spp. are the dominant species (Fc, Fd, Fe) in areas of the lagoons with lower abundances of *A. fragile* presumably where salinities are less variable. *E. excavatum* has its

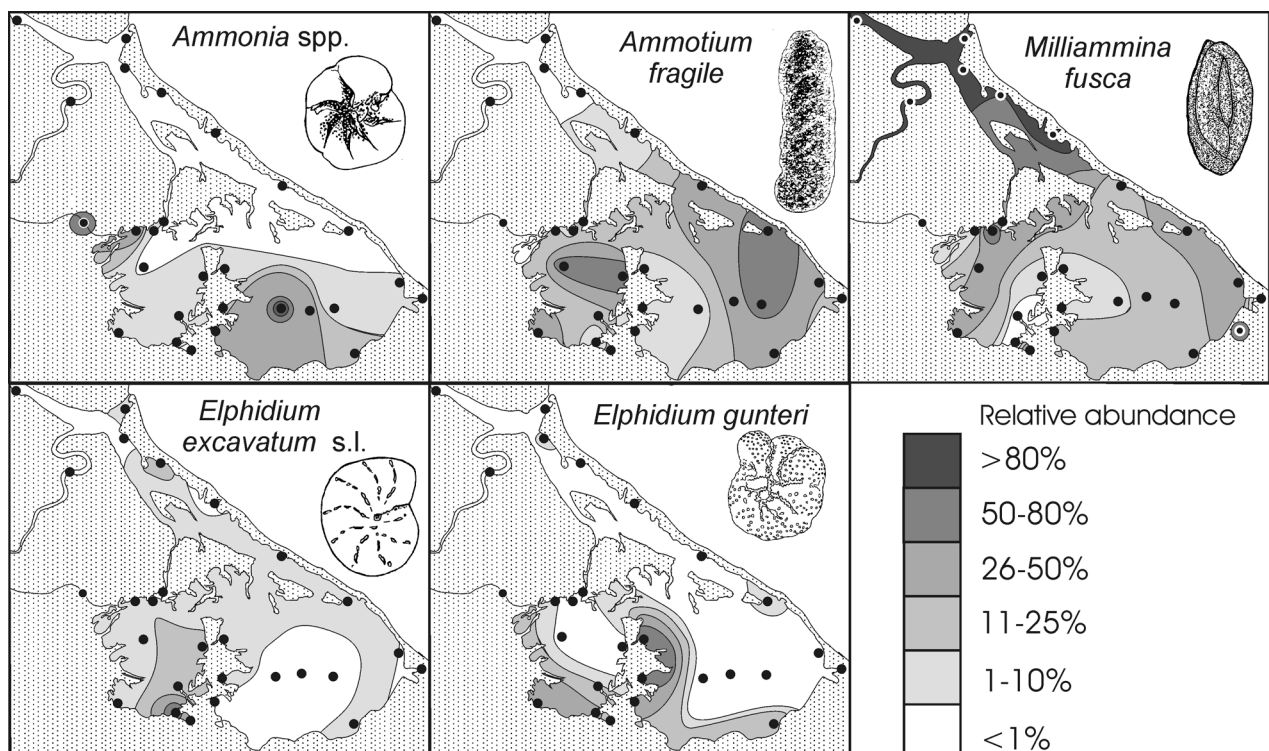


Figure 6. Contoured distribution of the present-day relative abundance of the five most common foraminiferal species in the Wairau lagoons coastal wetlands complex

greatest abundances in Upper and Chandlers Lagoons and *E. gunteri* at mid tidal depths around Chandlers Lagoon and along the west side of Big Lagoon (Figure 6).

Holocene core stratigraphy

The base of cores B6, B9 and B12 is gravel or coarse sand (although at variable elevations). Basal coarse sediment or basement was not reached in B1 (Figure 7), but a probe at the same location indicates hard sediment, probably sand, is present at 9 m depth with hard gravel 1 m lower. In cores B8 and B12 the basal sand or gravel contains marine mollusc shells (Figure 7). Overlying the coarse basal sediment is blue-grey mud and muddy fine sand with scattered bivalve shells. This calcareous shell-bearing unit thins westwards (8 m in B6, 5 m in B1, 2.5 m in B8 and B12). At ~2.4–1 m depth in each core (including B50) there is a transition from this mud up into slightly coarser, carbonaceous sand that lacks molluscs but contains more common wood and finer carbonaceous material. Between 0.4 and 0.31 m in core B50 is a chocolate-brown carbonaceous muddy soil with a bioturbated upper contact overlain by orange-brown oxidised mud.

The location of dated shells (Table 2) that provide the chronostratigraphic framework for this study are shown on the columns in Figure 7.

Preservation and usefulness of Holocene microfossil groups

In our cores of Holocene sediment, foraminiferal faunas are more commonly preserved and therefore more valuable for palaeoenvironmental interpretations than ostracods or diatoms. Both calcareous and agglutinated foraminiferal faunas are preserved throughout core B1 probably because the core was taken at MHW level and the upper part does not dry out in summer. The lack of preserved foraminifera in the upper 1 m of B6 and upper 2 m of B8 and B12 (Figures 7, 8) probably relates to their slightly higher elevations and greater distances from the edge of the modern lagoons, which allowed a lowering of the ground water level during Marlborough's hot, dry summers, resulting in oxidative weathering.

Ostracods were only searched for in core B1, where they were found to be mostly rare or absent, with only one relatively rich fauna lower in the shell-bearing section. This supports our previous observations that the more Mg-rich calcite of ostracod shells makes them more prone to dissolution in brackish water, that is often slightly more acidic (pH ~7.5) than normal sea water.

Preservation of siliceous diatoms was patchy with good floras in the upper 1.4 m of B6, but not preserved below 3.7 m in this core (Table 3). In B8 and B12, seven samples contained good diatom floras and three had none preserved. Often where foraminifera are well preserved, diatoms are not, and *vice versa*. As in several other studies, we found that the foraminiferal and diatom fossil preservation compliments one another to create a full record. In the calcareous-rich sediment of New Zealand's Hawkes Bay tidal lagoons, foraminiferal faunas are well preserved and diatoms sparse (Hayward *et al.*, 2006a). In the glassy, tephra-rich sediment of Bay of Plenty's harbours, diatoms are rich and calcareous foraminifera dissolve (Hayward *et al.*, 2004). Here around the edge of the Wairau lagoons, oxidative weathering has removed all trace of foraminifera in Holocene sediment that dries out, but diatoms remain and provide useful palaeoenvironmental information.

Holocene fossil record and palaeogeographic history

Water bore and auger records indicate that the 15 km wide mouth of the Wairau Valley is underlain at depth by last glacial and younger (>~9 ka) alluvial gravels (Brown, 1981; Ota *et al.*, 1995). These are overlain by a wedge of Holocene marine sediment (Dillons Point Formation) extending 7 km inland beneath the present-day lower Wairau Valley plains from the Cloudy Bay coast. In the middle of the valley these are up to 40 m thick and thin inland to the limit of maximum transgression (~7 ka) beneath Blenheim City (Figure 1). Beneath the northern side of the lower Wairau Valley this sediment is dominantly gravel and sand that has accreted on the seaward side of a southeast-advancing gravel barrier. In the south in the Wairau lagoons study area the Holocene marine sediment is largely silt and sand that accumulated in sheltered bay or lagoon environments behind a northwest-advancing gravel barrier (Brown, 1981; Ota *et al.*, 1995).

Prior to ~8.5 ka, with sea level considerably lower (>10 m) than present, the area was an alluvial plain with the non-fossiliferous gravel at the base of B6 and B8 probably being fluvial in origin. The shelly coarse sand at the base of B12 may be a beach deposit.

The lowest mud section of each core (except B50) contains foraminiferal faunas belonging to the shallow subtidal to low tidal, near normal marine salinity associations Fa and Fb (Figures 7, 8). Neither of these associations are present in the lagoons today and indicate a significantly different setting prior to ~4 ka – deeper and less variable salinity than the modern lagoons. The fauna is characteristic of a sheltered harbour and not an open coast and thus a partial gravel barrier must have existed across some of the bay entrance (Figure 9). Association Fa is inferred to be slightly deeper water faunas than Fb, which probably lived close to low tidal level. The thickness and age of this lower section differs between cores (Figure 7) and records the initial early Holocene eustatic sea-level rise and transgression into the lower, more seaward Big Lagoon area (~8.5 ka, core B6) followed by later transgression (~7 ka) over Chandlers Lagoon area (cores B1, 8, 12).

Overlying this subtidal section is a 1.5–2.5 m thick mud interval with foraminiferal faunas belonging to association Fc (Figures 7, 8), inferred to have accumulated at low to mid tide levels in a slightly brackish intertidal inlet that had an open mouth to the sea. The base of short core B50 sampled the top of this unit (B50,242). Scattered throughout this and the subtidal unit are the shells of the bivalves *Austrovenus stutchburyi* and *Cyclomactra* spp. and the mud snail *Amphibola crenata*. All three species are characteristic of sheltered harbours and inlets with normal marine to slightly brackish salinity (Hayward *et al.*, 1999c). Ostracod shells are rare in these intervals with one fauna from B1,628 belonging to association Oe, also characteristic of sheltered, slightly brackish harbours or inlets. Diatom floras from this unit (B6,81 and 140, B8,249, B12,258) indicate a shallow brackish lagoon or inlet with a direct opening to the sea.

The shallowing from subtidal to intertidal appears to have occurred about the same time (~3.5–4.5 ka) in all cores (Figure 7). Because these faunas indicate relatively high salinities (30–35 psu) we infer that at this time (Fa–c) the tidal inlet was not part of the estuary of the large Wairau River, as the lagoons are today.

The intertidal inlet unit is the upper foraminiferal-bearing section in cores B6, 8 and 12, because of inferred taphonomic loss of the faunas higher in the cores. A further stage in the evolution of these coastal wetlands is recorded however by the

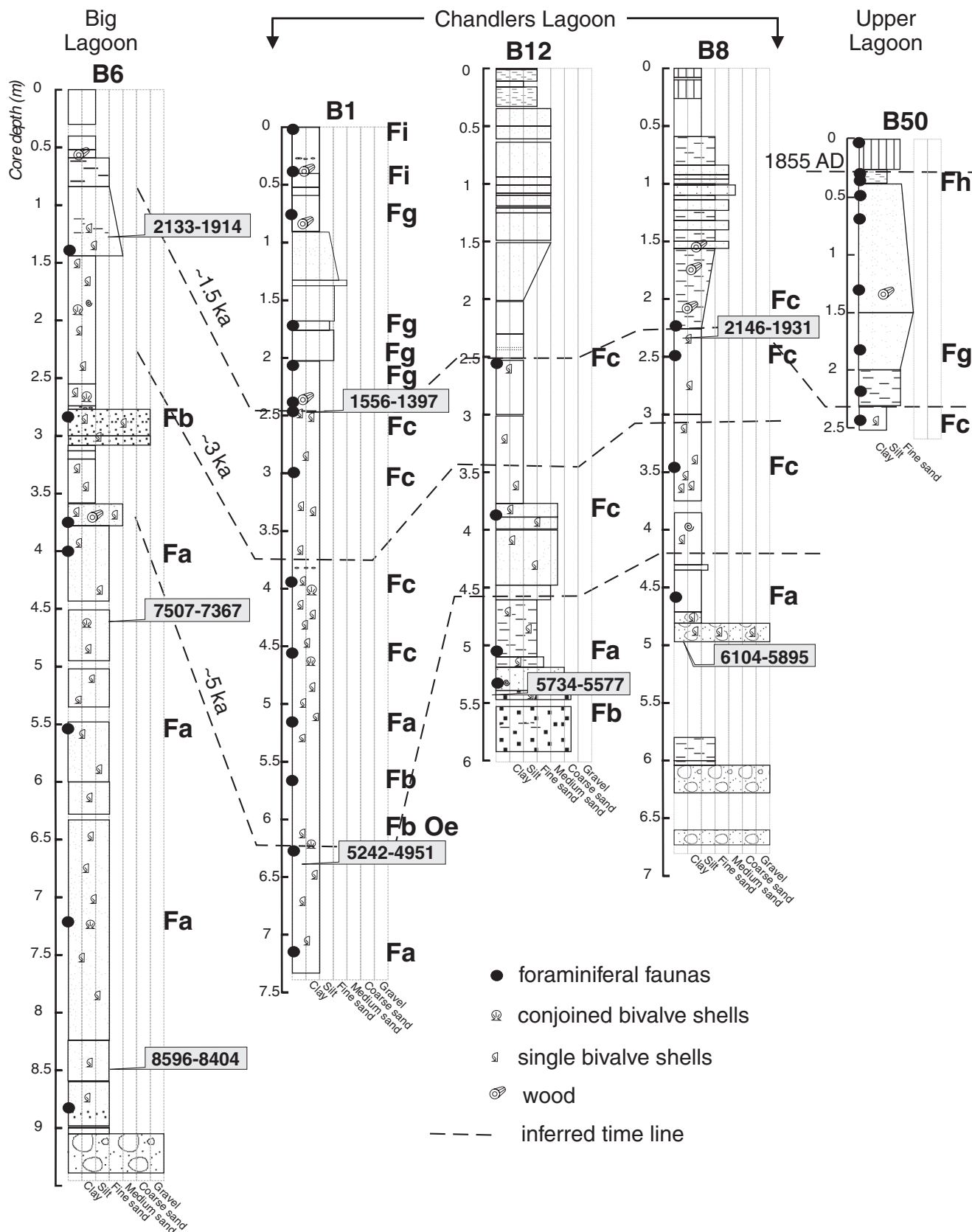


Figure 7. Lithologic logs, radiocarbon ages, foraminiferal and ostracod association distributions for the five cores from the Wairau coastal lagoons, Marlborough Province. Approximate time line correlations are shown for the periods for which palaeogeographic reconstructions have been inferred (Figure 9)

foraminifera in cores B1 and B50. In these cores there was an abrupt change in the foraminiferal faunal composition at 2.3–2.4 m downcore, from near 100% calcareous, *Ammonia*-dominated association Fc up into an 80–100% agglutinated,

Ammotium-dominated association Fg (Figures 7, 8). This change probably records the creation of the present lagoon system, presumably with the growth of the Wairau Boulder Bank by longshore drift from the south and consequent closure of the

Table 2. Radiocarbon ages from Big and Upper Lagoon cores

Core and depth (m)	Material dated	$\delta^{13}\text{C}$ (‰)	Age (conventional radiocarbon years BP)	Calibrated years BP (confidence)
B1				
2.45	Single <i>A. stutchburyi</i>	-1.6	NZA 30260 : 1907±20	1556–1397 (95%)
6.45–6.2	<i>A. stutchburyi</i> fragments	-0.6	NZA 27377: 4801 ± 30	5246–4951
B6				
1.28–1.3	<i>A. stutchburyi</i> fragments	-1	NZA 27872: 2365 ± 35	2133–1914
4.57–4.63	<i>Cyclomacra tristis</i> , large fragments	1.2	NZA 27873: 6897 ± 35	7507–7367
8.45–8.49	<i>Cyclomacra tristis</i> , fragments	-0.3	NZA 27874: 8024 ± 35	8596–8404
B8				
2.27–2.29	<i>A. stutchburyi</i> fragment	-3.7	NZA 27875: 2382 ± 35	2146–1931
4.9–4.92	<i>Maoricolpus roseus</i>	2.7	NZA 27876: 5564 ± 30	6104–5895
B12				
5.36–5.38	Single <i>Cyclomacra tristis</i>	1.5	NZA 27877: 5269 ± 30	5734–5577

Radiometric carbon dates by GNS Science, Rafter Laboratory (NZA catalogue numbers). ^{14}C ages have been converted into calibrated ages using the program OxCal v3.9 (Bronk Ramsey, 2005) with a delta-R value of -30 ± 13 .

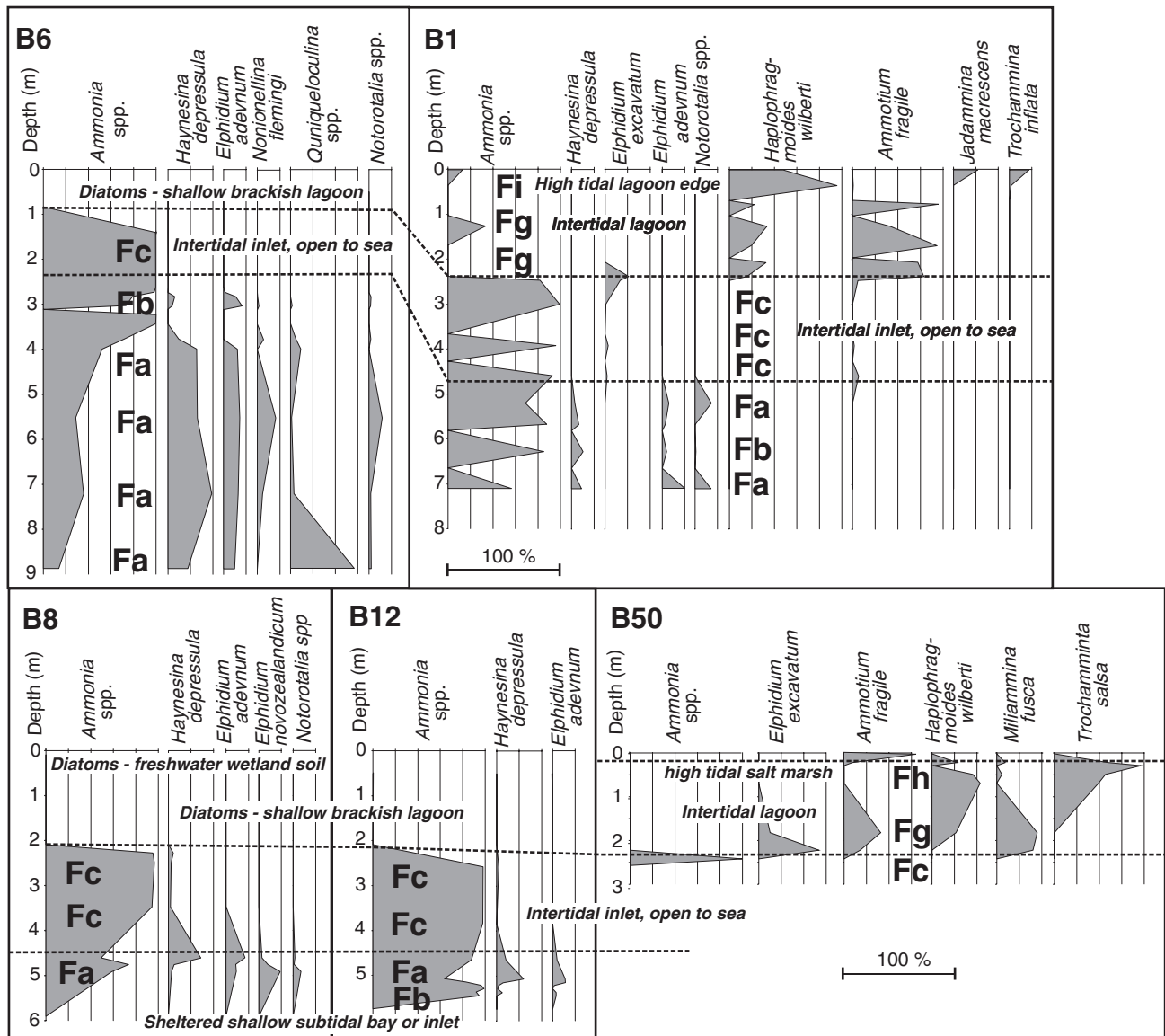


Figure 8. Distribution of the relative abundance of the common species of foraminifera and of foraminiferal associations (Fa–Fj) in the five cores from the Wairau lagoons, Marlborough Province, New Zealand. Interpreted palaeoenvironmental settings are indicated

Table 3. Preservation (Pres.), abundance (Abund.), and dominant habitat groups (Dom. Gps) of diatoms and their palaeoenvironmental assessments from cores B6, B8 and B12, Wairau coastal lagoons. Based on diatom census counts (Appendix C, available online)

Sample	Pres.	Abund.	Dom. Gps	Palaeoenvironmental assessment
<i>Core B6</i>				
0.49–0.51	Good	High	B,I (S,BM)	Shallow brackish lagoon with connection to the sea
0.55–0.57	Good	High	B,I (S)	Shallow brackish lagoon with no direct marine connection
0.80–0.82	Good	High	BM,B	Lagoon with tidal connection to the sea
1.39–1.41	Good	Mod.	BM	Lagoon with tidal connection to the sea
2.82–2.84	None			
3.10–3.12	Good	Mod.	B,F,I,T	Fresh-brackish lagoon with no direct marine connection or an influx event
3.76–3.78	None			
3.98–4.00	None			
5.51–5.53	None			
7.20–7.22	None			
8.86–8.88	None			
<i>Core B8</i>				
0.08–0.10	Good	Mod.	FS (B)	Freshwater wetland/soil occasionally brackish
0.30–0.32	None			
2.09–2.11	Good	V high	B,I,T (F,BM)	Shallow brackish lagoon with no direct marine connection
2.48–2.50	Good	High	BM,B,I,T	Shallow brackish lagoon with tidal connection to the sea
4.60–4.62	Good	Mod.	BM,B,T,P	Brackish marine inlet
5.90–5.92	None			
<i>Core B12</i>				
0.50–0.52	None			
1.66–1.68	Good	Mod.	F,I,T (B)	Shallow fresh/fresh-brackish lagoon with no sea connection
2.57–2.59	Good	High	BM,I,T	Shallow brackish marine lagoon with tidal connection to sea
5.06–5.08	Good	Mod.	BM,P (F,S)	Brackish marine inlet

Habitat Groups: B, brackish benthic; BM, brackish marine benthic; F, freshwater benthic; FS, freshwater soil; I, indifferent benthic; P, planktic; S, soil; T, tycho planktic.

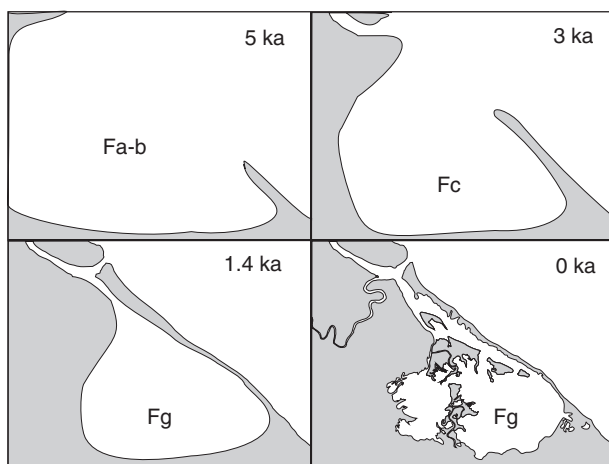


Figure 9. Inferred Holocene palaeogeographic evolution of the Big and Upper Lagoons area on the south side of the mouth of the Wairau Valley, Marlborough Province. Major foraminiferal associations (Fa–g) are indicated

former entrance to the sheltered inlet (Figure 9). We infer that as the boulder bank grew northwards, so too did an overflow channel from the newly enclosed lagoons along the inside of the bank until it eventually linked with the Wairau estuary (Figure 9) and widened and deepened creating the present tidal link (Figure 1). The timing of the growth of the boulder bank was ~1.5–1.4 ka, coinciding with the culmination of a rapid eustatic sea-level drop between 2 and 1.5 ka (Figure 2).

This inferred creation of the present Wairau Boulder Bank at ~1.5 ka, based on the microfossil evidence that it was open up until that time, contrasts with a previous model that inferred, on purely geomorphological evidence, that the Boulder Bank formed much earlier in the Holocene (Pickrill, 1976).

After 1.5 ka there was a change to more sandy sediment, a loss of all mollusc shells and an increase in the quantity of wood and carbonaceous fragments – all changes that can be explained as a result of the switch from an open inlet to the present more closed lagoon complex with highly variable salinity. As a consequence there was a major increase in periodic freshwater input from the Wairau River together with river-supplied sand and plant material. Similar macroscopic changes are recorded in the foraminifera-lacking upper parts of cores B6, 8 and 12 (Figure 7), thereby also recording the creation of the lagoon system. Diatom floras above 0.6 m in B6, and above 2.2 m in B8 and B12 (B6,50 and 56; B8,210; B12,167), indicate that this more sandy sediment accumulated on the high tidal fringe of a shallow brackish lagoon with little or no direct connection to the open sea. Kashima and Taguchi's (1995) studies indicate a substantial increase in the proportion of freshwater diatoms in this unit which they infer were transported in by rivers.

We infer that the enclosed lagoon was initially one larger body of water and, since it was created, a delta of more sandy sediment, supplied during Wairau River floods, grew into it from the north eventually reaching the southern bank. This created three separate lagoons (Big, Upper and Chandlers) which were present when first mapped in 1848 (Figure 10).

Latest Holocene history (last 0.7 ka)

Humans first colonised New Zealand ~750 years ago and one of the oldest-known occupation sites was on the Wairau Boulder Bank dated at ~AD 1285–1300 (Higham *et al.*, 1999). Since then, humans have cleared much of the original forest in the surrounding area and Wairau River catchment, resulting in increased erosion and likely increased sedimentation in and around the Wairau lagoons, but how much is hard to determine from our limited

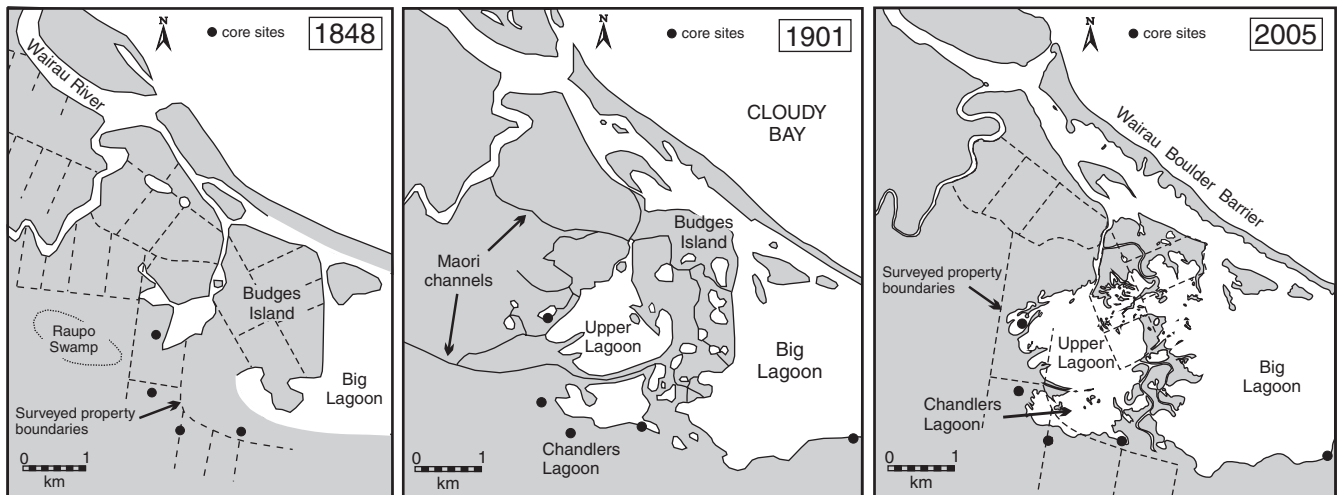


Figure 10. Changes in the Wairau coastal lagoons since 1848, as documented by maps. The 1848 map is the earliest known map of the area, produced by the New Zealand Company and titled ‘Rural lands in the Wairau and Wakefield (i.e. Awatere) Districts, Settlement of Nelson, Middle Island of New Zealand’ probably after an 1847 survey made by William Budge (Grapes and Downes, 1997). The 1901 map is titled ‘Topographic plan of part of Clifford Bay Survey District (20 chains to an inch)’ by J.L.D. Irvine (Map 621 – Land Information New Zealand). The 2005 map is from Land Information New Zealand NZMS 260 map series, 1:50 000 map P29

coring and limited age control. Around AD 1700, the local Maori used wooden digging implements to construct a network of sinuous, shallow canals (1 m deep, 3–4 m wide) between the three lagoons and surrounding swamps and streams (Skinner, 1912). These canals (Figure 10) were used for seasonal eel and waterfowl harvesting activities (Skinner, 1912) but also impacted on the geomorphology. It is possible that one arcuate canal was actually constructed through the middle of the western lagoon and its banks constructed of mud dug from the canal divided it into the separate Upper and Chandlers Lagoons (Figure 10). These canals clearly assisted tidal flow and stream floodwater passage between lagoons and may have contributed to some of the extensive erosion that has occurred since the first map of the lagoons was made in 1848 (Figure 10). The 1848 map indicates that the channel linking Wairau lagoons to the estuary was much narrower than today and that Upper Lagoon was less than half its present size and was not connected (except by canals) to Big or Chandlers Lagoons (Figure 10).

The large 1855 Wairarapa Earthquake (M_w 8.2, Grapes and Downes, 1997) that caused major fault displacements and damage on the southern end of the North Island (100 km across Cook Strait from Wairau Lagoons) was strongly felt in the lower Wairau Valley (Buick, 1900; Cotton, 1954). There are reports of localised subsidence, ground rents and sandblows close to Upper Lagoon and the Wairau River (Hoke, 2008) that suggest earthquake shaking-induced liquefaction of soft sediment beneath some parts of the Wairau lagoons in 1855. These have sometimes been reported as occurring during the Awatere Earthquake of 1848 (Eiby, 1980; Grapes and Wellman, 1986). Core B50 is located close to the mapped 1848 shoreline of Upper Lagoon and records a sharp lithologic change at 0.31 m down core from a peat soil with a mean high water spring salt-marsh fauna (Fh), up into unvegetated sand now located at mean sea level. We infer this upper sediment in B50 to document local subsidence of ~0.5 m during the 1855 earthquake shaking. Probe coring around B50 delimited an area of ~50 m × 50 m that had preserved displaced peat, consistent with a model of patchy liquefaction-driven subsidence.

The mapped increase in size of the Wairau lagoons (especially Upper Lagoon) between 1848 and 1901 was probably mostly attributable to the 1855 earthquake subsidence and increased erosion of the marginal salt marshes as a result of this patchy subsidence and 0.1 m of eustatic sea-level rise during this time (Gehrels *et al.*, 2008). A further 0.25 m of sea-level rise since 1901 (Gehrels *et al.*, 2008) has probably caused the continued marginal erosion of the lagoons that has now linked all three together over the last 100 years (Figure 10).

Palaeogeographic influence of tectonic and eustatic sea-level changes

The Holocene geographic evolution of the Wairau coastal lagoons has been influenced by the interplay between sediment supply and sediment accommodation space.

The mud that accumulated in the early–mid Holocene open bay-inlet was most likely introduced in suspension from out at sea, where it had been carried around the coast from river discharges to the south. The gravel and sand that built up the prograding sequence of beach ridges on the north side of the Wairau Valley mouth was likely carried down from the Wairau River itself and redistributed by beach transport processes. Also sourced from the Wairau River during floods was the plant-rich sand that built the flood-delta into the Wairau lagoons in the late Holocene, after the Wairau Boulder Bank was built across the mouth of the inlet (Figure 9). The third sediment source, which supplied the gravel that built the Wairau Boulder Bank by northwards longshore drift, was from erosion of the coastal cliffs of Miocene conglomerate at the south end of Cloudy Bay. The cliffs are at the seaward end of a 300 m-high line of hills that had been uplifted on the south side of the Vernon Fault (Figure 1) by tectonic forces during the Quaternary.

The microfossil record provides some clues as to the relative importance to the evolution of the Wairau lagoons of tectonic and eustatic sea-level changes. Clearly rapid eustatic sea-level rise in

the early Holocene, prior to ~7 ka, resulted in the marine transgression into the Wairau Valley, and the subsequent accumulation of subtidal mud in the sheltered bay.

By 4–3 ka, much of the bay had shallowed to intertidal (assoc Fc) as a result of mud accumulation and perhaps aided by an interval of inferred slightly lower eustatic sea level between the two Holocene peaks of +1 m (Clement *et al.*, 2008). In cores B1, B8 and B12, these low-tidal foraminiferal faunas (Fc) occur at 4.5 m down core, and ~3 m below present low tide level. As eustatic sea-level was 0.5–1 m higher than at present, and the spring tidal range at present is only 1.2 m, there must have been 3–4 m of tectonic subsidence along the south side of the Wairau lagoons in the last 3–4 kyr (1 m/kyr). In the southern area close to the Vernon Fault, there is no evidence that would support the existence of soft compactable sediment beneath most of our core sites that would account for this subsidence occurring as auto-compaction during earthquake-shaking. Further north, beneath Upper Lagoon (B50) and towards the Wairau River estuary, the evidence of liquefaction in 1855 suggests the likely role of compaction of soft sediment in creating accommodation space for thicker sequences of Holocene shell-bearing mud.

Apart from the sudden lithologic change at 0.31 m in B50, attributed to the 1855 earthquake, there is no other observable lithologic or microfossil evidence of sudden subsidence events that might have produced the 3–4 m of downdrop. We therefore infer gradual subsidence or a series of small downthrows on the north side of the Vernon Fault. This produced accommodation space for the accumulation of 3–4 m of intertidal sediment.

Between 2 and 1 ka eustatic sea level appears to have dropped by ~1.5 m (Figure 2), but the shallowing effect of this was partly counteracted by tectonic subsidence of ~1 m. The major change from an open inlet to a closed lagoon at ~1.5 ka resulting from the growth of the Wairau Boulder Bank was likely strongly influenced by the inferred rapid eustatic sea-level fall at this time.

Between 0.7 and 0.12 ka, the eustatic sea-level rise in New Zealand of ~0.3 m (Figure 2) once again partly counteracted the inferred gradual tectonic subsidence of ~0.5 m. In the last 120 years however, the accelerated sea-level rise of 0.3 m (Gehrels *et al.*, 2008) appears to be outpacing sediment supply and resulting in increased marginal erosion and increased size of the Wairau lagoons and the channel linking them to the Wairau estuary.

As noted earlier, human-induced increase in sediment supply and increased erosion because of shallow canal construction appear to have had only a minor influence on the lagoons' latest Holocene evolution.

Conclusions

(1) The distribution of foraminifera and ostracods in the Wairau coastal lagoons are strongly influenced by salinity, with tidal elevation also a major influence on foraminiferal assemblages.

(2) The strong dominance of *Ammonia fragilis* in Big and Upper Lagoons is unique for New Zealand and we attribute this to the unusual highly variable salinity (hyposaline to hypersaline) of these water bodies.

(3) Foraminifera are well preserved in the cored Holocene bay and lagoon sediment so long as it has not dried out during dry periods exposing the tests to oxidative weathering.

(4) The Mg-rich calcite shells of ostracods are poorly preserved in the Holocene coastal lagoon sediment because of dissolution by slightly acidic, brackish conditions.

(5) Siliceous diatoms are better preserved in the Holocene lagoon sediment (even when subjected to oxidative weathering) than they are in the more calcareous bay sediment.

(6) Five sediment cores and their contained microfossils (mainly foraminifera) record the Holocene palaeogeographic evolution of the Wairau coastal lagoons.

(7) With rising eustatic sea level in the early Holocene, the sea transgressed westwards across the Wairau Valley fluvial gravels forming a fully marine, sheltered, subtidal bay (*Ammonia-Haynesina-Elphidium advenum* dominated) with its greatest advance (7 km inland) at ~7 ka.

(8) The bay progressively filled with mud and in the vicinity of our cores shallowed to intertidal (*Ammonia*-dominated) by 4.5–3.5ka, but still had an open mouth to the sea.

(9) At 1.5–1.4 ka the calcareous-dominated foraminiferal faunas suddenly changed to agglutinate-dominated (*A. fragile*) faunas indicating a switch to a semi-closed lagoon system like today. We infer this was caused by a rapid eustatic sea-level fall that allowed the Wairau Boulder Bank to grow across the bay's entrance.

(10) The occurrence of low-tidal foraminiferal faunas at 3–4 m below the level at which they were deposited, implies this amount of tectonic subsidence along the southern margin of the Wairau lagoons in the last 3.5–4.5 kyr.

(11) One core contains lithologic and microfossil evidence that confirms historic accounts of significant (~0.5 m) liquefaction-related subsidence around Upper Lagoon during shaking that accompanied the magnitude 8+ AD 1855 Wairarapa Earthquake.

(12) Patchy AD 1855 subsidence coupled with rapid eustatic sea-level rise in the last 150 years has resulted in increased marginal erosion and significantly increased size of the Wairau lagoons.

(13) The Holocene evolution of the Wairau coastal lagoons was influenced by the interplay between sediment supply from three sources, sea-level change, longshore drift and in a minor way human activities.

(14) Microfossils suggest that the two most significant drivers of geographic evolution in this locality was tectonic subsidence and eustatic changes in sea level.

Acknowledgements

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Appendix A. Foraminiferal and ostracod reference list

List of all Foraminifera and Ostracoda from Big Lagoon mentioned in the text or figures, with citation of recent references where species are illustrated. Three/four letter abbreviations for foraminiferal species are used in Figure 4.

Foraminifera

- Amm* = *Ammonia* spp. Hayward et al. (1999a: plate 16, figures 4–12).
- Ammf* = *Ammotium fragile* Warren – Hayward et al. (1999a: plate 1, figures 21–22).
- Bolivina* spp. Hayward et al. (1999a: plate 8, figures 8–22).
- Bulimina* spp. Hayward et al. (1999a: plate 9, figures 6–17).
- Elpa* = *Elphidium advenum* Cushman – Hayward et al. (1999a: plate 17, figures 1–5).
- Elphidium charlottense* (Vella) – Hayward et al. (1999a: plate 17, figures 7,8).
- Elpe* = *Elphidium excavatum* sl. (Terquem) – Hayward et al. (1999a: plate 17, figures 11–20).
- Elpg* = *Elphidium gunteri* Cole – Hayward et al. (1999a: plate 17, figures 21,22).
- Elphidium novozealandicum* Cushman – Hayward et al. (1999a: plate 17, figures 23,24).
- Evolocassidulina orientalis* (Cushman) – Hayward et al. (1999a: plate 8, figure 28).
- Fissurina* spp. Hayward et al. (1999a: plate 7, figures 15–26).
- Hapw* = *Haplophragmoides wilberti* Andersen – Hayward et al. (1999a: plate 1, figures 25,26).
- Hayd* = *Haynesina depressula* (Walker and Jacob) – Hayward et al. (1999a: plate 15, figures 10,11).
- Jadm* = *Jadammina macrescens* (Brady) – Hayward et al. (1999a: plate 1, figures 27–29).
- Milf* = *Miliammina fusca* (Brady) – Hayward et al. (1999a: plate 1, figures 5,6).
- Milo* = *Miliammina obliqua* Heron-Allen and Earland – Hayward et al. (1999a: plate 1, figures 7,8).
- Nonionellina flemingi* (Vella 1957) – Hayward et al. (1999a: plate 15, figures 14,15).
- Notorotalia* spp. Hayward et al. (1999a: plate 16, figures 13–36).
- Pileolina* spp. Hayward et al. (1999a: plate 12, figures 1–18).
- Portatrochammina sorosa* (Parr) – Hayward et al. (1999a: plate 2, figures 4,5).
- Qui* = *Quinqueloculina* spp. – Hayward et al. (1999a: plate 4, figures 11–28, plate 5, figures 1–15).
- Scherochorella moniliforme* (Siddall) – Hayward et al. (1999a: plate 1, figures 13,14).
- Textularia earlandi* Parker – Hayward et al. (1999: plate 2, figures 22,23).
- Troi* = *Trochammina inflata* (Montagu) – Hayward et al. (1999a: plate 2, figures 6–8).
- Tros* = *Trochammina salsa* (Cushman and Bronnimann) – Hayward et al. (1999a: plate 1, figures 30–32)
- Virgulopsis turris* (Heron-Allen and Earland) – Hayward et al. (1999a: plate 8, figure 33).

Ostracoda

- Bradleya* sp. 1 – Hornibrook (1952: plates 6–8).
- Callistocythere neoplana* Swanson (1979: figures 26a–c).
- Cypris* sp. 1 Hornibrook (1955: figures 8, 22, 27).
- Illoocypris* cf. *fallax* Barclay (1968: figure 6a).
- Kotoracythere formosa* Swanson (1979: figure 25).
- Leptocythere lacustris* De Deckker – Yassini and Jones (1995: figures 220, 222, 224, 226).

Microcytherura hornibrooki (Mckenzie) – Yassini and Jones (1995: figures 582, 584).

Phlyctenophora zealandica Yassini and Jones (1995: figures 623, 625, 627).

Swansonella novaezealandica Hartmann (1982: figures 2, 1–14).

Tasmanocypris sp. Yassini and Jones (1995: figures 103, 106).

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