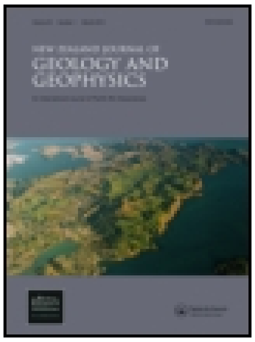

New Zealand Journal of Geology and Geophysics

ISSN: 0028-8306 (Print) 1175-8791 (Online) Journal homepage: https://www.tandfonline.com/loi/tnzg20

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Bruce W. Hayward , Hugh R. Grenfell , Anna Sandiford , Phil R. Shane , Margaret S. Morley & Brent V. Alloway

New Zealand Journal of Geology & Geophysics, 2002, *Vol. 45*: 467–479
0028–8306/02/4504–0467 $7.00/0

Foraminiferal and molluscan evidence for the Holocene marine history of two breached maar lakes, Auckland, New Zealand

BRUCE W. HAYWARD
HUGH R. GRENFELL
ANNA SANDIFORD
PHIL R. SHANE
Department of Geology
University of Auckland
Private Bag 92 019
Auckland, New Zealand

MARGARET S. MORLEY
Auckland War Memorial Museum
Private Bag 92 018
Auckland, New Zealand

BRENT V. ALLOWAY
Wairakei Research Centre
Institute of Geological & Nuclear Sciences Ltd
Private Bag 2000
Taupo, New Zealand

Abstract Drillhole records of fossil Foraminifera and Mollusca, together with sparse tephra age control, document similar Holocene marine histories of two of Auckland's breached maars—Pukaki Lagoon, Manukau Harbour, and Onepoto Lagoon, Waitemata Harbour. Following eruption, both maars slowly accumulated carbonaceous mud in freshwater lakes, until they were breached by rising sea level in the early Holocene (c. 8100 cal. yr at Onepoto, c. 7600 cal. yr at Pukaki). Following breaching, both became saltwater tidal lagoons with silled, subtidal basins rapidly accumulating marine mud as the underlying sediment compacted. Onepoto Lagoon may have had deeper water than Pukaki, because it was colonised by a foraminiferal fauna (*Bolivina*, *Bulimina*, *Buliminella*, *Spiroloxostoma*) that prefers quiet, dysoxic bottom conditions.

Both fossil groups identify where the lagoons shallowed from subtidal to low tidal depths. This occurs c. 15 m downhole (6900 cal. yr) in Pukaki and c. 9.5 m downhole in Onepoto, after sea-level rise had levelled off at about its present height (7000 cal. yr). Marine mud sedimentation slowed in the intertidal, accumulating largely in response to 12 m and 5 m compaction of the maar fill, respectively.

Subtidal and low tidal fringe foraminiferal faunas of both lagoons are characterised by *Ammonia-Haynesina* associations, whereas intertidal faunas above mean low water are dominated (>90%) by *Ammonia*. Pukaki Lagoon foraminiferal faunas differ from Onepoto by their higher subtidal diversity of benthic foraminiferal tests and the presence of planktic tests in the subtidal section. These differences are inferred to relate to the significantly more exposed conditions outside the entrance to Manukau Harbour, where juvenile benthic tests were lifted into suspension and, together with the planktics, carried by the strong tidal currents up the harbour channels into Pukaki Lagoon. These introduced tests settled out of suspension in the quiet subtidal waters and accumulated in the sediment. Once Pukaki Lagoon had been filled with mud to intertidal depths, most introduced tests were apparently flushed away by the outgoing tides and did not accumulate.

The presence in the Onepoto sequence (9.8–8.7 m) of the gastropods *Micrelenchus huttonii* and *Notoacmea helmsi* f. *scapha* indicate that *Zostera* seagrass once grew in the lagoon at around spring low tide level.

Keywords benthic foraminifera; Mollusca; New Zealand; Auckland; Pukaki Lagoon; Onepoto Lagoon; Holocene; tidal elevation; compaction

INTRODUCTION

The late Quaternary Auckland Volcanic Field (Fig. 1) contains c. 50 small, basaltic, volcanic centres that have erupted over the last 150 000 yr (Kermode 1992; Allen & Smith 1994), and now occupies a 140 km^2 area of low relief (–20 to 180 m above present sea level) in the northern North Island, between the Waitemata (Pacific Ocean) and Manukau (Tasman Sea) Harbours. A variety of eruptive styles created a combination of scoria cones, small shield volcanoes, and maar craters surrounded by low tuff rings (Kermode 1992). Though poorly dated, most of Auckland's volcanoes are considered to have erupted between 100 000 and 8000 yr ago, when sea level was lower than present and the Waitemata and Manukau Harbours were forested river valleys.

There are c. 13 maar explosion craters in the Auckland Field, all of which have flat floors underlain by sediment that records the post-eruptive history of the region (e.g., Coomber 1998; Sandiford 2001). It would appear that most of these maar craters initially ponded freshwater lakes, and many developed overflow streams that progressively eroded down through their tuff rings, with the resulting sill level controlling the eventual level of sediment infill.

Eight of the lower elevation maar lakes were breached by rising sea level after the end of the Last Glaciation, and were topped up with marine sediment (e.g., Coomber 1998). When Europeans settled in the Auckland region in the

G01037; published 6 December 2002
Received 1 November 2001; accepted 8 August 2002

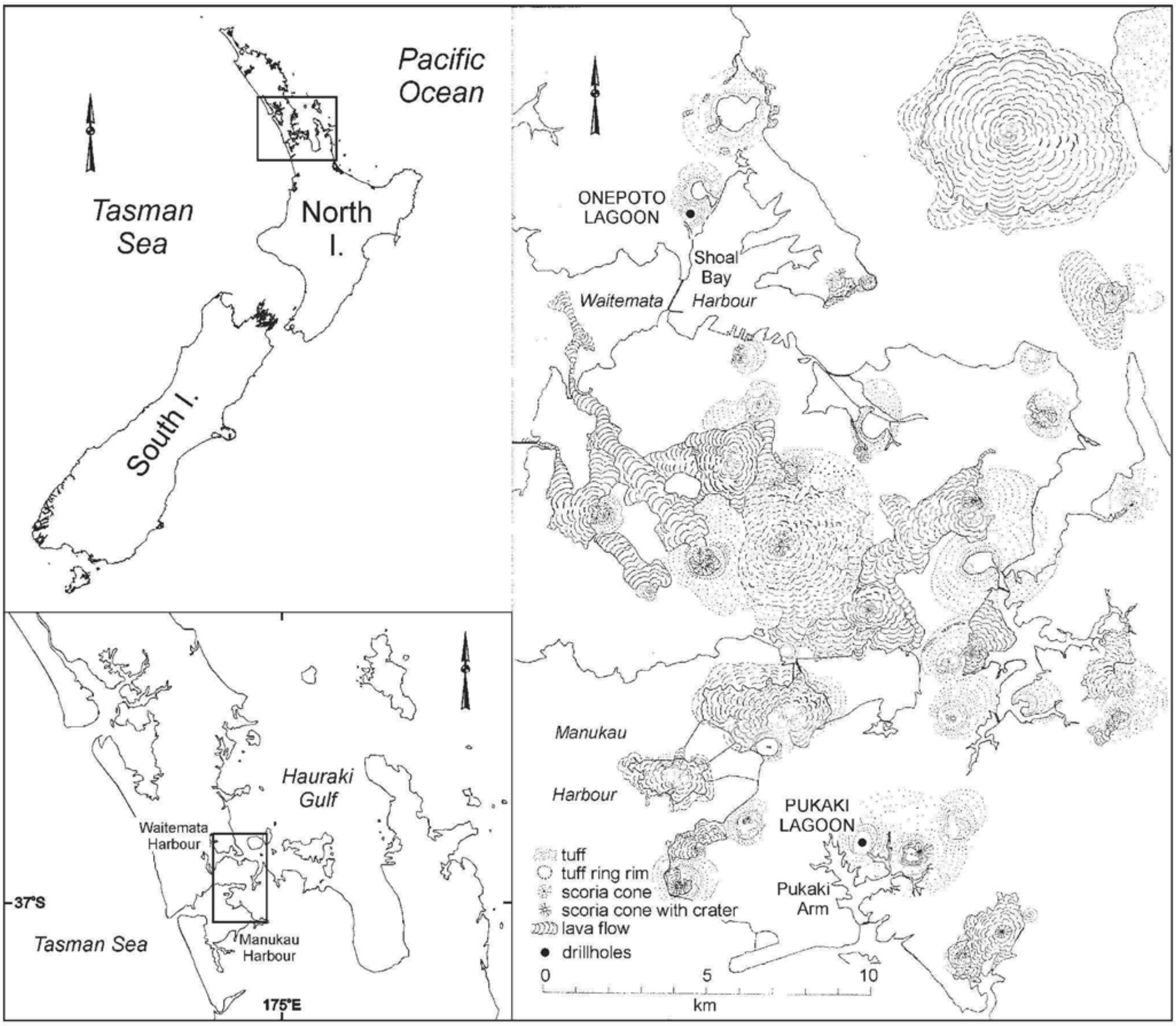

Fig. 1 Location of the Auckland Volcanic Field in northern New Zealand, and the sites of the drillholes in Pukaki and Onepoto breached maar lakes (adapted from Kermode 1992).

1840s, all eight breached maars were mangrove and saltmarsh filled or fringed, intertidal inlets around the shores of the Waitemata and Manukau Harbours. Since then, some of these inlets have been reclaimed for dry land activities.

Up until recently, there had been no drillhole coring of the sediment fill of any of Auckland's maars, and their post-eruptive history was mostly speculative. Recently, two of the reclaimed maars, Pukaki Lagoon on the Manukau Harbour and Onepoto Lagoon on the Waitemata Harbour (Fig. 1), have been drilled to obtain a palynological record of Auckland's late Quaternary vegetation and climate change (e.g., Sandiford 2001) and a tephra record of local basalt eruptions, and distal andesitic and rhyolitic eruptions from the Taupo Volcanic Zone and Mt Taranaki (Sandiford et al. 2001).

Most of these records (c. 7000–60 000+ yr) are contained within the slowly accumulated, laminated, freshwater-lake sediments, but both sequences are capped by 35–45 m of shallow-marine mud. The marine mud contains scattered molluscan shells and more abundant microscopic foraminiferal shells, the study of which unlocks further information about the post-breaching marine history of these two maar lakes.

Sea-level influence

The timing of the marine breaching of Auckland's maar lakes was influenced by the the sill level of their small overflow streams and by sea level as it rose towards the present height in the early Holocene. The most complete and currently accepted Holocene sea-level curve for New Zealand is largely based on data from tectonically "quiet" areas near Dunedin and Auckland (Gibb 1986). For the purposes of this study, Gibb's (1986, fig. 4) curve has been translated from carbon years to calibrated years, based on Stuiver et al. (1998). Thus, sea level rose from c. 25 m below present at c. 9000 cal. yr to reach its present height at c. 7000 cal. yr. Since then, sea level has been no more than 1 m above and no more than 0.5 m below the present height (Gibb 1986).

Fig. 2 Aerial photograph of Pukaki Lagoon, with location of drillhole site indicated.

Fig. 3 Aerial photograph of Tank Farm Lagoon (right) and Onepoto Lagoon (left), with location of drillhole site indicated.

Ecological distribution of present-day molluscs and foraminifera

Interpreting the fossil mollusc and foraminiferal record in the maar marine mud relies on our knowledge of their present-day ecological distribution in sheltered harbours and tidal inlets in northern New Zealand. The ecological distribution of modern benthic foraminifera has been documented in the upper Waitemata Harbour (Hayward et al. 1997a) and in many other similar environments around the New Zealand coast (Hayward et al. 1999a). These studies have shown that tidal elevation and salinity are the major environmental factors influencing benthic foraminiferal distribution in these settings (e.g., Hayward & Triggs 1994; Hayward et al. 1996, 1999a, b). Post-mortem transport in suspension or along the bottom by strong tidal currents or waves can have an important influence in some harbour and estuarine environments (e.g., Murray et al. 1982; Wang 1992; Hayward et al. 1999a).

The ecological and depth distribution of modern molluscs has been documented in the Manukau and Waitemata Harbours (Grange 1982; Hayward et al. 1997b, 1999c) and other parts of northern New Zealand (e.g., Morton & Miller 1968; Beu et al. 1990; Morley & Hayward 1999). Strong tidal currents and storm waves can transport and erode mollusc shells in harbour channels and across exposed tidal flats.

Methods

Drillholes were sited near the centre of the maars (Fig. 2, 3) to sample the thickest record of the post-formation late Quaternary history. Both drillholes were cored using a hydraulic piston coring method which is pushed into the sequence and extracts core in c. 2 m lengths. The Pukaki Lagoon drillhole was cored in 1997 and the Onepoto Lagoon drillhole in 2000.

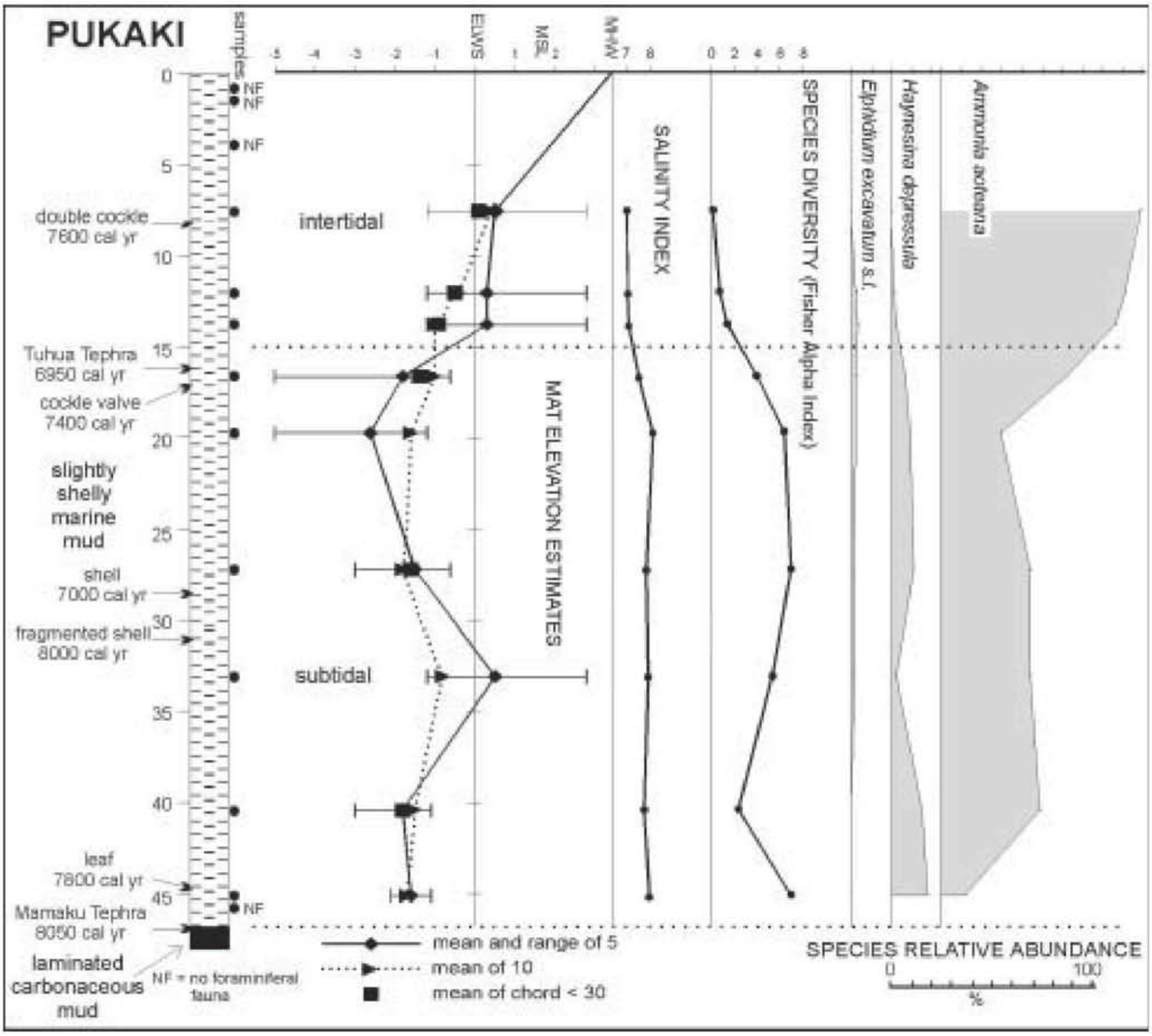

Fig. 4 Pukaki Lagoon drillhole showing sample location, lithologic column, relative abundance of common foraminiferal species, species diversity (Fisher alpha index), absolute abundance of foraminifera, and estimated paleosalinity (salinity index) and paleoelevation curves, together with an interpretation of Holocene environmental changes. Three modern analogue technique (MAT)-estimated paleoelevation curves are presented based on different methods of selecting modern analogue samples.

Samples (20 cm^3) were taken at regular intervals from the centre of the split cores from throughout the marine sections of both holes, with closer spacing where major lithologic or faunal changes were recognised. Thirteen samples were taken from Pukaki and 23 from Onepoto. Samples were washed over a 0.063 mm sieve, dried, and those samples with low abundances of foraminifera were floated off using carbon tetrachloride. The washed sand fraction was microsplit down to an amount containing c. 100–200 benthic foraminifera, then identified and counted under the microscope. Counts were standardised as percentages for analysis and interpretation (Appendices 1, 2). Total molluscan remains in each washed sample were identified and counted.

The Fisher Alpha Index (α) of species diversity (Murray 1991) was calculated for each foraminiferal fauna.

Estimates of paleosalinity and tidal elevation

The paleosalinity and tidal elevation at which each fossil foraminiferal fauna accumulated was estimated using the techniques described in Hayward et al. (submitted) based on their benthic foraminiferal census counts.

A formula for calculating a relative salinity index (freshwater = 0, normal salinity = 10) based on the benthic foraminiferal composition has been devised using transect data up Rangitopuni Estuary at the head of the Waitemata Harbour (Hayward et al. submitted). Index values were computed for each fossil foraminiferal fauna in these two drillholes and show salinity trends through the sequences (Fig. 4, 6).

A modern analogue technique using the chord dissimilarity coefficient was used to determine the compositionally most similar modern foraminiferal faunas to each fossil fauna using a dataset of 189 samples from New Zealand sheltered harbours and shallow inlets (Hayward et al. submitted). From these results, three estimates of the tidal elevation or water depth were computed for each fossil fauna (Fig. 4, 6): (1) the mean elevation and range of the five most similar modern faunas; (2) the mean of the 10 most similar modern faunas; (3) the mean of all faunas with chord dissimilarity values <30 (Hayward et al. submitted). In these calculations, tidal ranges are standardised and converted to the range of the study sites (4 m for Pukaki Lagoon, 3.5 m for Onepoto Lagoon). The reliability of these elevation estimates depends on a number of factors, not the least of which is the breadth of environmental coverage represented by the modern dataset.

PUKAKI LAGOON

Setting and previous work

Pukaki Lagoon maar (Fig. 1, 2) is located in Mangere, near Auckland International Airport, at the head of the narrow Pukaki Arm of the Manukau Harbour. The flat-floored, 600 m diameter, near-circular crater is surrounded on all sides by a 20–30 m high tuff ring with a total internal catchment of c. 1 km^2. The Pukaki Arm is the small stream valley that formerly took the c. 30 m wide overflow from Pukaki maar lake, before being drowned by rising sea level in the early Holocene. In historic times, Pukaki Lagoon was an intertidal basin, filled with mangroves and salt marsh, and inundated by most high tides. The breach in the tuff ring which provided access for the tide was dammed c. 80 yr ago, and the reclaimed crater floor and inner slopes of the tuff ring are now in farmland.

The 1997 drillhole was spudded in near the centre of the reclaimed crater floor (Fig. 2) at an elevation close to mean high water (near upper limit of mangrove forest prior to reclamation). The stratigraphy of this 52.5 m deep hole comprises 6 m of finely laminated, carbonaceous, freshwater clay (28 000–7600 cal. yr) overlain by 46.6 m of homogeneous, marine silty clay with scattered shell (Coomber 1998; Sandiford et al. 2001). Detailed tephrostratigraphy of at least 40 ash layers in the hole provides good age control for the lake sediments (Sandiford et al. 2001). Two interbedded tephras provide critical age constraints for the marine section (Fig. 4): Mamaku Tephra (8050 cal. yr, Lowe et al. 1999) situated within the top of the freshwater clay at 46.63 m; and Tuhua Tephra (6950 cal. yr) within the overlying marine mud at 15.90 m (Sandiford et al. 2001). Radiocarbon ages on four cockle (*Austrovenus stutchburyi*) shells and a leaf within the marine section (Fig. 4) provide some additional age support, although reversal of ages with respect to each other and the Tuhua Tephra suggest that three of the dates may be on reworked shells or shells contaminated by older carbonate from the nearby Kaawa Shellbed (Sandiford et al. 2001).

In February 2001, a second drillhole was spudded in close to the site of the first drillhole and recovered an additional c. 20 m of carbonaceous freshwater lake mud and mm-dm thick tephra beneath the marine section (James Schulmeister pers. comm. 2001).

Mollusca

Identifiable mollusc shells occur in four samples (Appendix 1). The most common is the mid-tidal to shallow subtidal cockle *Austrovenus stutchburyi* and the small low tidal to subtidal bivalve *Arthritica bifurca*. Also common are broken fragments of the green mussel *Perna canaliculus* and the small intertidal acorn barnacle *Austrominius modestus*.

All shell fragments are of species commonly found washed up on beaches around the Manukau Harbour today. The mud snail *Amphibola* and small acorn barnacle *Austrominius* live between mid and high tide level, but are commonly transported to lower tidal levels and subtidally after death. Both species likely lived within Pukaki Lagoon. The cockle *Austrovenus*, trough shell *Cyclomactra ovata*, and wedge shell *Macomona liliana* mostly live infaunally in the intertidal zone, but also live in shallow subtidal depths (down to c. 4 m, Hayward et al. 1999c) and undoubtedly lived in Pukaki Lagoon.

The green-lipped mussel *Perna* and mud oyster *Ostrea* live attached to hard substrates around low tide levels and could have lived attached to tuff outcrops or shells around the tidal entrance channel when the Manukau Harbour was less muddy in prehuman times. *Pecten* frequents shallow subtidal and spring low tidal levels in the middle and outer parts of the harbour today but possibly extended up into the upper harbour in prehuman times. Its shells were possibly transported into Pukaki Lagoon.

The small bivalves *A. bifurca* and *Nucula hartvigiana* live infaunally at low tide and greater depths and were clearly inhabitants of Pukaki Lagoon, as was the tiny gastropod *Chemnitzia*. *Tawera* only lives in the outer part of the Manukau Harbour today and probably did not live in Pukaki Lagoon—the small juvenile shell was possibly washed in.

The carbon ages on some cockles (Fig. 4) suggest they are possibly reworked, but waves and tidal currents inside Pukaki Lagoon are unlikely to have been strong enough to erode them. Waves in the wide Manukau Harbour certainly are strong enough to erode and rework older cockle shells. These shells could have been introduced into Pukaki Lagoon by tidal currents moving them along the Pukaki Arm channel bottom or transporting them in, floating on the surface. On calm days, cockle shells, lying concave upwards on the shore, can be floated off and carried along by the incoming tide (Hayward & Stilwell 1995).

Foraminifera

Four of the 13 samples processed contain no foraminifera. The three highest (0.44, 1.24, 3.72 m) may have lost their foraminiferal fauna through deep weathering. The lowest (45.87 m), from the base of the grey, marine mud interval, has either lost its calcareous foraminifera through dissolution, or it predated foraminiferal colonisation of the newly created, subtidal, saline lagoon. Foraminiferal tests are common and well preserved in the remaining nine samples, between 45.1 and 7.5 m (Fig. 4).

All faunas are dominated by fresh, non-abraded specimens of *Ammonia aoteana* in a wide range of sizes. Other taxa present as adults as well as small juveniles, include *Haynesina depressula* and *Elphidium excavatum* s.l. (Appendix 1). All three taxa were inhabitants of Pukaki Lagoon.

The foraminiferal census data show the following trends, from bottom up (Fig. 4): (1) increasing relative abundance of *A. aoteana*, 47–78% of the fauna below 16 m, and 93–100% above 14 m; (2) decreasing relative abundance of *H. depressula*, mostly 7–18% of the fauna below 16 m and

0–2% above 14 m; and (3) decreasing diversity, especially above 16 m.

A. aoteana lives in greatest abundances in intertidal substrates, but also lives in considerable numbers in shallow subtidal environments. *H. depressula* is almost exclusively a subtidal to extreme low tidal inhabitant (Hayward et al. 1999a). The trends in abundance of these two species suggest subtidal conditions between 45 and 16 m and intertidal above 14 m. These conclusions are supported by the modern analogue technique estimates, which indicate that the site was subtidal up to c. 16 m, with slightly shallower estimates (low tidal to shallow subtidal) for the 33.08 m fauna, resulting from the lower relative abundance of *H. depressula*. All estimate methods show a clear shallowing trend above 20 m, culminating above 14 m, with elevation estimates around or just above extreme low water spring level. Estimates for the highest sample (7.59 m) give elevation values of 0.1–0.5 m above extreme low water spring.

Although modern analogue technique estimates of subtidal water depths are 0.8–2.6 m, these are likely to be underestimates, as our modern analogue database lacks any faunal census data from a similar, silled, subtidal lagoon (Hayward et al. submitted).

The subtidal fauna differs from the intertidal in having a small but consistent percentage of planktic foraminifera that were clearly transported into the lagoon in suspension from the open ocean beyond the entrance to the Manukau Harbour (Hulme 1964; Hayward 1986).

The subtidal benthic fauna is significantly more diverse (α2.4–7) than the intertidal (α <1.5), because of the presence of a large number of additional, juvenile, well preserved, normal salinity, benthic foraminiferal species (Appendix 1). The good preservation of these thin-shelled tests, and absence of heavy adult specimens, suggests that they, like the planktics, were also transported in suspension into Pukaki Lagoon. Storms outside the harbour entrance, or strong tidal currents entering the harbour and flowing up its narrow subtidal channels, are likely to have lifted the lightweight benthic foraminifera into suspension and carried them along (cf. Murray et al. 1982; Wang 1992).

After being transported into the subtidal lagoon by the incoming tide, the suspended benthic and planktic tests settled below the tidally exchanged upper layers as current strength dissipated for several hours with the change in tide. These tests were thus trapped in the subtidal portion of the lagoon and eventually accumulated on its floor. Once the lagoon floor had filled to intertidal levels, there was no quiet subtidal lagoonal waters to trap the incoming suspended tests. We infer that most tests were flushed out again by the outgoing tide, thus explaining their general absence above 14 m.

Salinity index (SI) values (Fig. 4) show moderately saline conditions throughout (SI 7–8.1), but with a slight decrease in salinity in the upper part of the hole, from >7.5 below 16 m to 7–7.1 above 14 m.

Interpretation

Combining the tephrochronology with the foraminiferal elevation estimates, we conclude that Pukaki maar lake was breached by the sea at c. 7600 cal. yr, when sea level was c. 5 m lower than present (Gibb 1986), at a time when the lake was 20 ± 15 m deep, and possibly considerably shallower (because of later compaction-related subsidence). Salinity rapidly equilibrated with that of the adjoining Manukau Harbour. Suspended marine mud was transported into the lagoon by the tides, and in 700 yr accumulated a 36 ± 6 m thick sequence in quiet subtidal conditions (Fig. 5). In the succeeding 7000 yr, a further 15 m of intertidal mud accumulated, as it and the underlying sediment compacted another 12 m.

The presence of Tuhua Tephra (6950 cal. yr) at 15.9 m indicates that sea level was approximately the same level as present when the middle of the lagoon was filled to spring low tidal mark (Fig. 5). This level is now c. 11 m lower than extreme low water spring level. There is no evidence that the Manukau Harbour region has subsided at all in the last 7000 yr. Thus, compaction of the sediment that fills Pukaki crater is the only likely explanation for this subsidence.

ONEPOTO LAGOON

Setting and previous work

Onepoto Lagoon maar is located in Northcote, on Auckland's North Shore (Fig. 1, 3), at the head of the short Onepoto Arm of Shoal Bay, Waitemata Harbour. The flat-floored, 400 m diameter circular crater is surrounded on most sides by a 30 m high tuff ring with a total catchment of c. 0.5 km^2. The Onepoto Arm is the small Onepoto Stream valley that formerly flowed around the southern side of the tuff ring and also took the overflow from Onepoto maar lake, before being drowned by rising sea level in the early Holocene. In historic times, Onepoto Lagoon was an intertidal basin, filled with mangroves and salt marsh, and inundated by most high tides (Searle 1964, pl. 47). The c. 40 m wide breach in the tuff ring which provided access for the tide, was dammed in the late 1950s, and the reclaimed crater floor is now playing fields and a recreational pond.

The 2000 drillhole was spudded in on a low mound of fill near the sports pavilion, c. 100 m east of the crater centre, at an elevation c. 2 m above mean high water.

The stratigraphy of this c. 61 m deep hole comprises 25 m of laminated, carbonaceous, freshwater mud and tephra overlain at 36.0 m by c. 34 m of grey, slightly shelly, marine mud and c. 2 m of recent soil fill. No tephra are recognised within the marine sequence, and the youngest in the freshwater sequence is Rotoma Tephra (9500 cal. yr) at 36.25 m (P. Shane unpubl.), 0.25 m below the freshwater/marine contact. Projecting upwards, an average freshwater sedimentation rate of 0.18 m/ka, gives an age of c. 8100 cal. yr for the time of marine breaching of the Onepoto freshwater lake, which is consistent with the absence of Mamaku Tephra (8050 cal. yr) from the lake record.

Mollusca

Identifiable whole or fragmented molluscan shell material is present in all samples except three (Appendix 2).

Single and double shells of the small bivalves *Arthritica bifurca* and *Nucula hartvigiana* are present almost continuously from the second to deepest sample (35.42 m) up to 8.4 m (with one shell of *Arthritica* in 7.76 m). These species are abundant in the modern Waitemata Harbour in subtidal and low tidal sediment (Hayward et al. 1997b, 1999c), and imply that this interval accumulated below mean low water. Three specimens of the horn shell *Zeacumantus lutulentus*, are present at 8.4 m. Today it lives in large

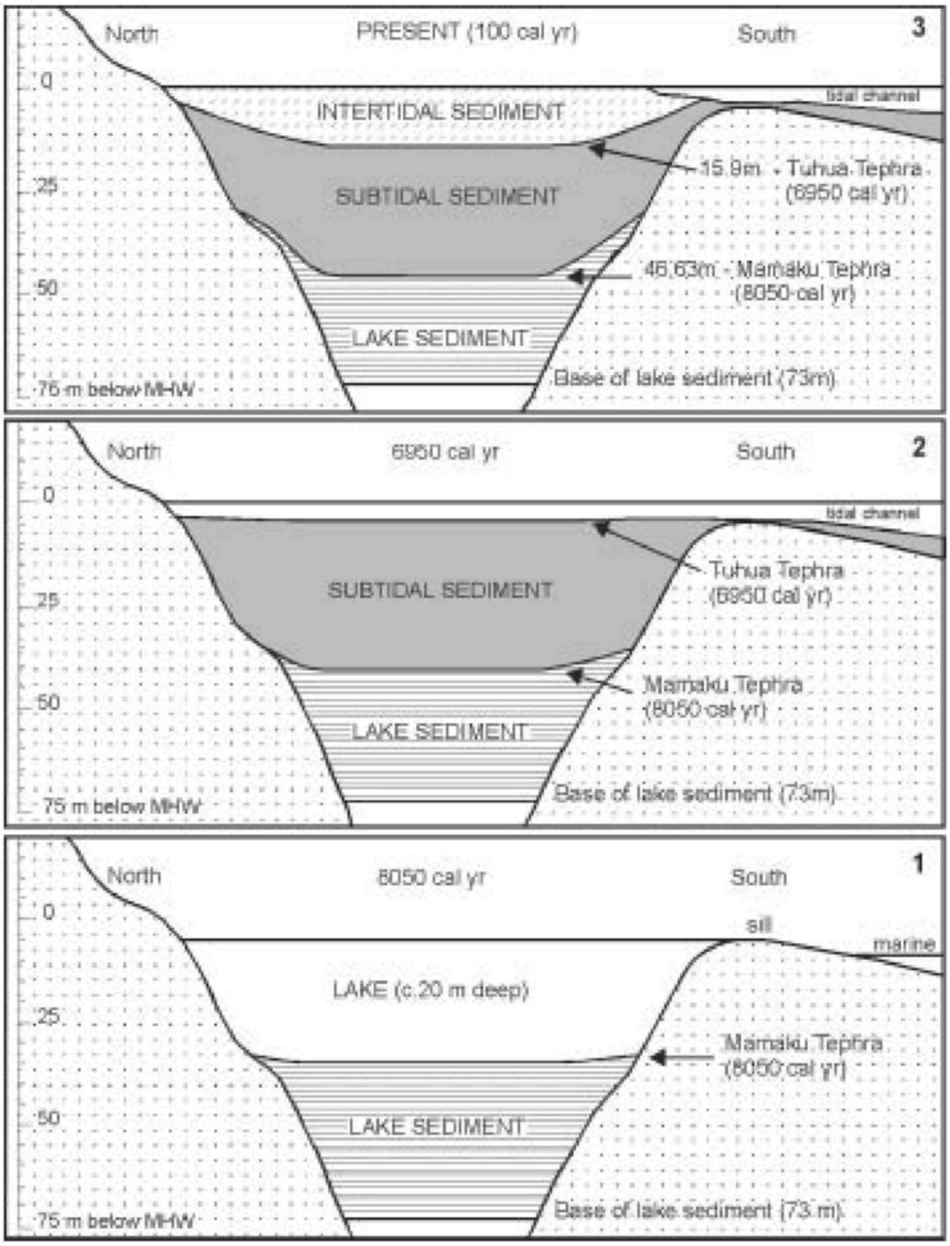

Fig. 5 Schematic north–south cross-sections (vertical exaggeration 5:1) through Pukaki Lagoon, illustrating its changing Holocene paleogeography as: (1) a freshwater lake at the time of the Mamaku Tephra eruption (8050 cal. yr), just before breaching by rising sea level; (2) a low tidal lagoon at the time of the Tuhua Tephra eruption (6950 cal. yr); and (3) a high tidal lagoon 100 yr ago (before its reclamation).

numbers around the Waitemata Harbour on soft sediment at mid to low tide level and is unknown living subtidally (Hayward et al. 1999c). A level no deeper than spring low tide is inferred for this core depth.

Single or broken valves of the cockle *Austrovenus stutchburyi* and wedge shell *Macomona liliana* are fairly consistently present from 16 to 5.56 m. These common, larger bivalves live in the Waitemata Harbour today at intertidal (mid tide and lower) and shallow subtidal (<4 m) depths (Hayward et al. 1997b, 1999c). Their consistent presence above 16 m probably indicates that both were living in the lagoon during this time (three double shells of cockle present at 8.4 m). Lagoon depths may have been too great for them before this. The broken fragments of cockle at 36 m were possibly carried into the recently breached, subtidal lagoon by tidal currents.

Specimens of the small gastropod *Micrelenchus huttonii* occur between 9.8 and 8.7 m. It lives in abundance today in sheltered harbours restricted to *Zostera* seagrass beds or subtidal rocky seaweeds (Hayward et al. 1999c). One specimen of the small, parallel-sided *scapha* form of *Notoacmea helmsi* occurs at 8.7 m. This limpet is adapted for attachment to the blades of seagrass. The presence of these two species suggests the presence of seagrass beds in the central part of Onepoto Lagoon at this time. In unpolluted harbours around New Zealand today, *Zostera* seagrass is largely confined to the mid-tidal to shallow subtidal zone, where there is sufficient light penetration for photosynthesis. It is most abundant around low to spring low tide level (Hayward et al. 1999c), which is the inferred tidal elevation in this interval.

Foraminifera

Common, well-preserved foraminifera are consistently present between 35.42 and 5.56 m. Rare specimens are present in the lowest and highest samples. In the highest

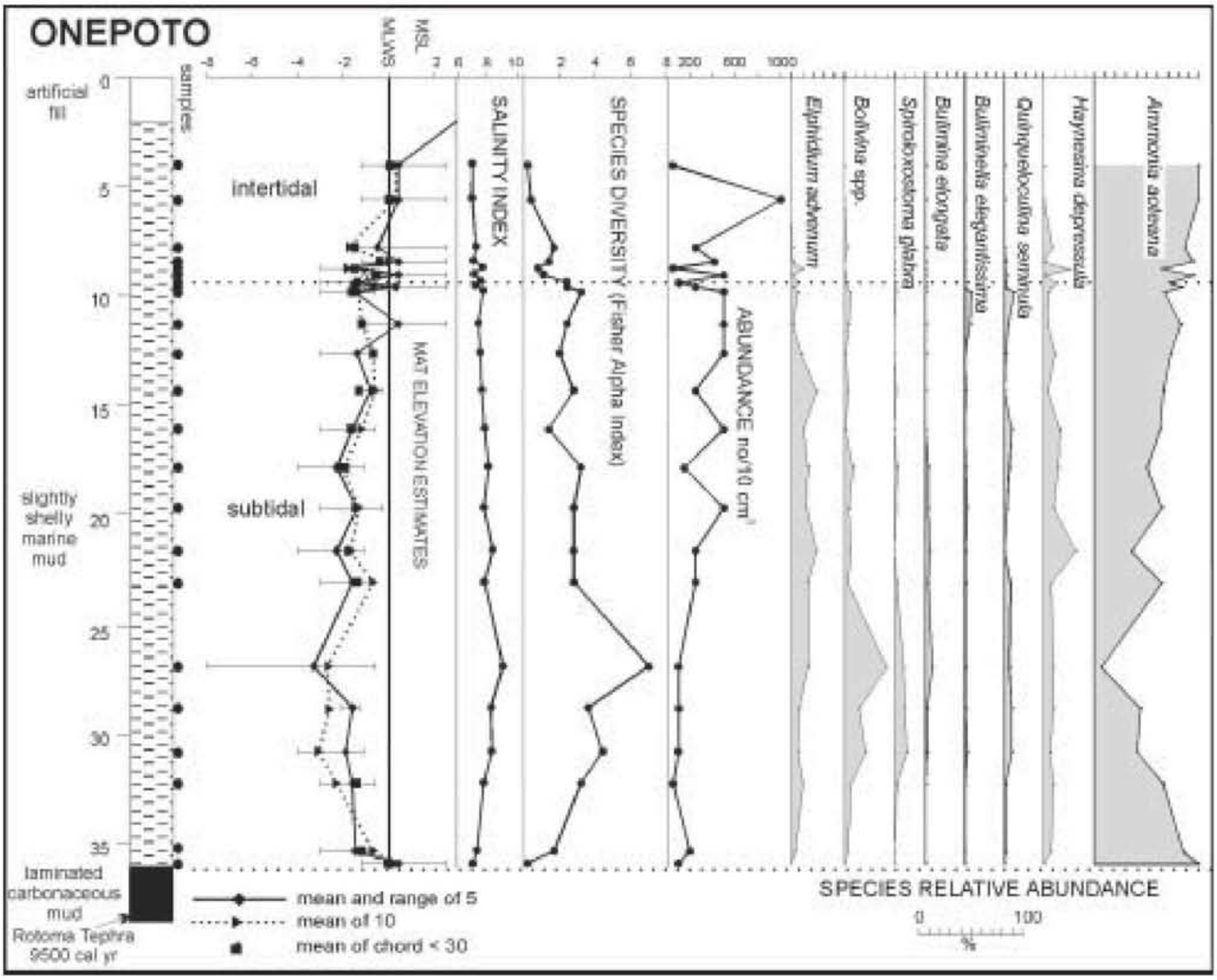

Fig. 6 Onepoto Lagoon drillhole showing sample location, lithologic column, relative abundance of common foraminiferal species, species diversity (Fisher alpha index), absolute abundance of foraminifera, and estimated paleosalinity (salinity index) and paleoelevation curves, together with an interpretation of late Holocene environmental changes recorded. Three modern analogue technique (MAT)-estimated paleoelevation curves are presented based on different methods of selecting modern analogue samples.

sample (4 m), the specimens are opaque and show signs of partial decalcification with weathering following reclamation of the lagoon.

The estimate of elevation for the lowest sample (36 m) is low tidal (Fig. 6), but the total fauna of 10 specimens of *Ammonia aoteana* is abraded, suggesting possible introduction into the subtidal lagoon from the intertidal mudflats of Shoal Bay, soon after breakthrough by the sea.

Elevation estimates for faunas in the interval 35.42–9.36 m are, with one exception (11.3 m), shallow subtidal. These faunas are moderately diverse (α 1.4–7) and dominated by a shallow subtidal association (Hayward et al. 1999a) of *Ammonia* (7–84%), *Elphidium advenum* (1–23%), and *Haynesina depressula* (3–31%). Other dominantly subtidal taxa common in this interval are *Spiroloxostoma glabra*, *Buliminella elegantissima*, *Bulimina elongata*, and *Bolivina* spp. (Fig. 6). A significantly greater abundance of *S. glabra* and *Bolivina* spp. between 30.9 and 17.9 m, with *B. elongata* restricted to this interval, suggests that the lagoon was deepest during this time and shallowed upwards.

Elevation estimates between 12 and 8 m are erratic and variable between shallow subtidal and mean low water spring level. They reflect the erratic relative abundances of *Ammonia* (64–95%) and largely subtidal *Haynesina* (0–25%). The fauna through this interval indicates tidal depths at around mean spring low water ±0.5 m. The highest significance occurrence of *Bolivina*, *Buliminella elegantissima*, and *Spiroloxostoma glabra* at 9.54 m is taken as being a close approximation of the subtidal/low tidal boundary (Fig. 6). Above this, the fauna at 5.56 and 4 m is dominantly *Ammonia aoteana* (9–100%), giving truly intertidal elevation estimates near mean low water.

Salinity index values indicate relatively saline conditions throughout with a slight decreasing salinity trend with uphole shallowing. Lowest salinity index values correspond with the indicated intertidal section, where rainfall would have temporarily lowered salinity in the surface sediment when the tide was out.

Interpretation

Onepoto maar lake was breached by the sea c. 8100 cal. yr, when sea level was 10–15 m below present (Gibb 1986), at a time when the lake was 12 ± 8 m deep, and probably somewhat shallower (because of later compaction-induced subsidence). Salinity rapidly equilibrated to near that of the adjoining Waitemata Harbour. The earliest marine fossils are abraded and broken intertidal foraminifera and cockles that were possibly transported in by tidal currents from Shoal Bay.

The lagoon was colonised first by the foraminifera *Ammonia*, *Haynesina*, and *E. advenum*, and not till a little while later by the deeper water assemblage of *Bolivina*, *Bulimina*, *Buliminella*, and *Spiroloxostoma*. This latter assemblage is suggestive of oxygen-deficient bottom conditions, typically found in poorly circulating, deeper waters of silled basins (Hayward 1999a). The foraminifera indicate upwards shallowing, probably coincident with compaction of the underlying fine-grained freshwater sediments, reaching spring low tide level by c. 9.5 m. *Zostera* seagrass grew for some time around spring low tide level in the centre of the lagoon. The interval between 9.5 and 7.5 m was around spring low water mark, with the fauna possibly being affected by slight sea-level changes. Above 7.5 m, the site became truly intertidal, with sediment continuing to accumulate as the lagoon floor subsided with compaction of the underlying sequence.

DISCUSSION

Accuracy of subtidal depth estimates

The modern analogue technique elevation estimates (mean and range of the five most similar benthic foraminiferal faunas in our modern dataset) give subtidal depths (below extreme low water spring level) of 1.5–2.6 m (0.6–5 m range) for the subtidal sequence of Pukaki Lagoon (except the faunal sample from 33.08 m, Fig. 4) and depths of 0.8–3.3 m (0.3–8 m range) for the subtidal sequence in Onepoto Lagoon (Fig. 6). These estimates cannot give depths beyond the range of that in the modern dataset, which is limited to New Zealand sheltered harbour environments, with only 54 faunas from depths of 0–5 m, 5 from 5–10 m depths, and none deeper than 10 m.

There are no tidal lagoons (normal salinity to slightly brackish) with silled, subtidal basins deeper than 2–3 m around the modern New Zealand coast, from which potential analogue faunas can be obtained. Several overseas studies (e.g., Apthorpe 1980; Murray 1991, pp. 180, 210) show *Ammonia*-dominated faunas with secondary *Haynesina* and *Elphidium* (similar to the faunas in this study) present at 0–c. 20 m water depth in silled coastal lagoons in a wide range of brackish to normal marine salinities. Thus, although we have no modern New Zealand examples, it is probable that the fossil subtidal faunas in these two maars lived at considerably greater depths than estimated by the modern analogue technique.

Mollusca and Foraminifera as paleoenvironmental indicators

The presence of whole or fragmentary shells of marine molluscs and foraminifera is usually good evidence of marine or estuarine conditions. Both have the potential to be reworked and transported by waves and tidal currents (on the bottom, in suspension, or floating). In this study, most of the larger molluscs recorded were *Austrovenus stutchburyi* and *Macomona liliana*, both of which live intertidally and in shallow subtidal estuarine and harbour settings, from mid tide to 4 m depth (Beu et al. 1990; Hayward et al. 1994, 1997b, 1999c). They are present throughout most of the Pukaki marine section, but their absence from samples in the Onepoto interval 35–12.6 m is suggestive of deeper water.

Two other useful bivalves are the small *Arthritica bifurca* and *Nucula hartvigiana*, both of which live today in northern New Zealand harbours from about mean low water down to c. 15 m (Hayward et al. 1997b, 1999c, 2001; Morley & Hayward 1999). They have a patchy record throughout the Pukaki marine section, but occur most abundantly in the subtidal 35–9.8 m interval in Onepoto.

As paleodepth indicators, the benthic foraminifera appear to be better in these shallow subtidal and intertidal settings than molluscs, although both fossil groups provide similar histories. Part of the advantage of foraminifera may be in their greater abundance and therefore more detailed record. Of particular paleodepth value in benthic foraminiferal faunas is their greater subtidal diversity (both living and post-mortem introduced), and the subtidal to spring low tidal living range of *Haynesina depressula*, *Elphidium advenum*, *Bolivina* spp., and *Bulimina elongata*.

In New Zealand there are no foraminifera that live exclusively on or beneath *Zostera* seagrass (Hayward et al. 1999a). The gastropods *Micrelenchus huttonii* and *Notoacmea helmsi* f. *scapha*, however, provide unequivocal evidence for the presence of seagrass in Onepoto Lagoon in the interval 9.8–8.7 m.

The deeper water Onepoto foraminiferal assemblage of *Bolivina*, *Bulimina*, *Buliminella*, and *Spiroloxostoma* additionally provides evidence of oxygen-deficient bottom conditions (Hayward 1999a).

Geohistory plots

These two maars have similar Holocene marine histories (Fig. 7). Onepoto freshwater lake was breached by rising sea level c. 500 yr before Pukaki freshwater lake was breached, after a further 5–10 m sea-level rise. Presumably, this was because the Waitemata River (and its Shoal Bay and Onepoto tributary streams) was more deeply incised than the south Manukau River (and its Pukaki Creek tributary), and the Onepoto lake sill was lower than the Pukaki lake sill. The junction of Waitemata River and Shoal Bay Stream is 30 m below MSL (Searle 1959).

Following breaching, both became silled, subtidal, saline lagoons with twice-daily tidal exchange of the surface waters. Tidal currents transported in suspended small foraminiferal tests, occasional mollusc shells (some floating), and mud, which settled to the bottom in the quiet, ponded subtidal waters. This mud accumulated rapidly (50 m/ka in Pukaki Lagoon) until the lagoons were full to intertidal levels. The subtidal mud that filled the lagoons was partly accommodated by compaction of the underlying freshwater and marine mud. The exact relative contributions of compaction and original water depth to the thickness of the subtidal mud is unknown, but a range of possible values is shown in the geohistory plots (Fig. 7).

Fossil evidence indicates that the transition from subtidal to intertidal sediments (reached after sea level had stabilised

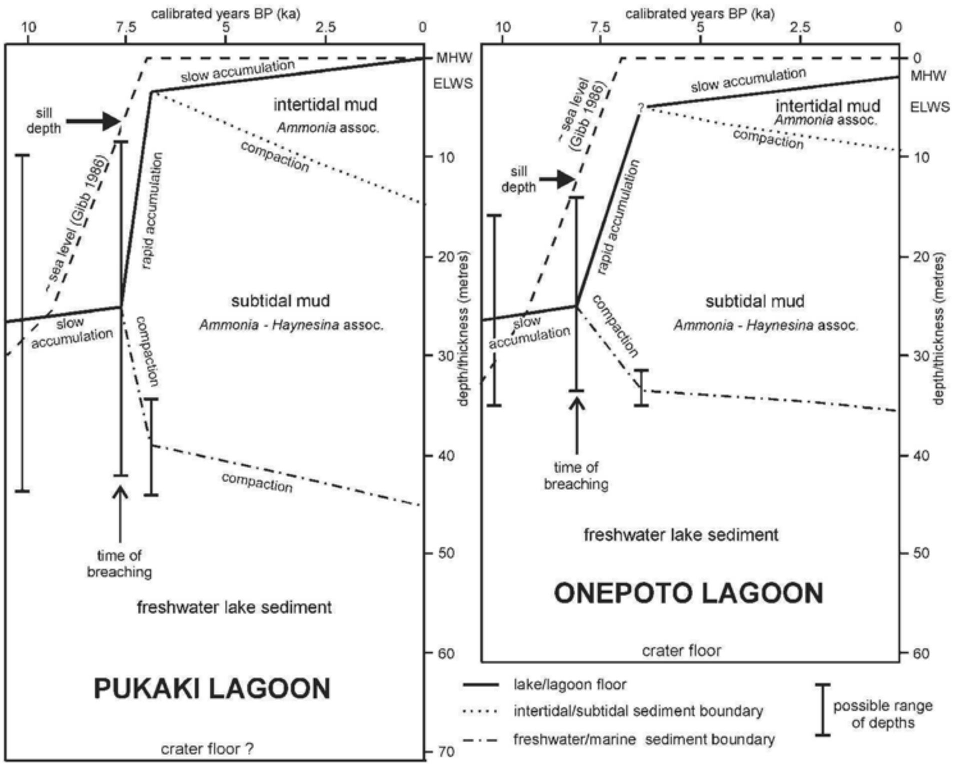

Fig. 7 Geohistory plots for Pukaki and Onepoto drillholes showing parallel histories of marine breaching of their freshwater lakes, with rapid subtidal marine mud accumulation and associated compaction of underlying sediment, followed by slower intertidal sedimentation keeping pace with compaction. The New Zealand Holocene sea-level curve (Gibb 1986) has been converted to calibrated years using Stuiver et al. (1998). The time at which Onepoto Lagoon became intertidal is estimated.

close to its present height, inferred for Onepoto Lagoon) is now at c. 15 m below mean high water in Pukaki Lagoon and c. 7.5 m below mean high water in Onepoto Lagoon. As there is no evidence of Holocene subsidence in the Auckland region, there must have been c. 12 m and c. 5 m of late Holocene compaction of the sediment fills in Pukaki and Onepoto Lagoons, respectively, as intertidal sedimentation kept pace with the base level change. The differences in the amount of late Holocene compaction is consistent with the greater total and subtidal sediment fill in Pukaki Lagoon, but differences in sediment properties were also influential.

Compaction

The consolidation of a column of sediment caused by its own weight (sometimes called autocompaction) can be significant in Holocene coastal sedimentary environments, especially fine-grained organic-rich sediments (Pizzuto & Schwendt 1997). Holocene compaction ratios of c. 0.5 and c. 0.2 have been recorded from estuarine mud and organic freshwater mud, respectively (Bloom 1964; Pizzuto & Schwendt 1997). A similar magnitude of compaction could be expected in these two Auckland maars. It is possible that the c. 25 m thick sequence of freshwater, carbonaceous mud in Pukaki Lagoon was at least twice as thick at the time of breaching by the sea (Fig. 7), and that the lagoonal basin may never have been more than a few metres deep, with sediment accumulation keeping pace with compaction. A similar scenario is conceivable for Onepoto (Fig. 7), although fossil evidence suggests that the lagoonal basin was initially deeper than that at Pukaki.

Pukaki – Onepoto comparisons

Although these two marine-breached maars have similar histories, their fossil faunas have significant differences, which possibly relate, at least in part, to the character of the adjacent harbours. Both the Waitemata and Manukau Harbours lack any major freshwater input from large rivers and therefore both have similar salinities, as indicated by the salinity index values from Pukaki (7.0–8.1) and Onepoto Lagoons (7.0–8.4). The Manukau has a slightly larger tidal range (4 m) than the Waitemata (3.5 m) and potentially slightly stronger tidal currents. Pukaki Lagoon is nearer the headwaters of its harbour than Onepoto, and is linked to the Manukau Harbour entrance by long, winding intertidal and subtidal channels bordered by extensive mud and sand flats. Onepoto Lagoon has just a short intertidal channel linking it to subtidal Shoal Bay and the main subtidal Waitemata Harbour channel.

The Manukau Harbour entrance opens to the exposed west coast of Auckland, where persistent onshore waves and storms lift foraminiferal tests into suspension, and onshore winds and currents transport them into the Manukau Harbour (Hulme 1964; Hayward 1986). The Waitemata Harbour opens to the more protected Hauraki Gulf, where only occasional northeast storms are likely to lift foraminiferal tests into suspension.

The more exposed condition outside the Manukau Harbour entrance, together with the greater tidal channel current strength, likely explains the presence of planktic foraminifera and numerous, small, normal-salinity benthic foraminifera (e.g., *Cassidulina carinata*, *Discorbinella bertheloti*, *Pileolina* spp., *Virgulopsis turris*, *Zeaflorilus parri*) in Pukaki and their virtual absence from Onepoto. Resulting from this is the greater species diversity in Pukaki (40 benthic foraminifera species) than in Onepoto (27 species).

The stronger tidal currents are probably the explanation for the presence of a number of broken shells of molluscs from outside the lagoons (e.g., *Pecten novaezelandiae*, *Perna* *canaliculus*, *Tawera spissa*, *Ostrea lutaria*, *Xenostrobus pulex*) in Pukaki and their absence from Onepoto.

It is unclear why a subtidal benthic foraminiferal fauna with common *Bolivina* spp., *Bulimina elongata*, *Buliminella elegantissima*, and *Spiroloxostoma glabra* became established in Onepoto and not in Pukaki. Why would Onepoto Lagoon have lower bottom oxygen conditions than Pukaki, unless perhaps Onepoto was initially deeper water than Pukaki? If this were the case, then the Pukaki Lagoon sediments must have compacted considerably more than the Onepoto, during the period of marine sedimentation.

ACKNOWLEDGMENTS

We thank George Scott for providing the programme for generating modern analogue technique estimates of tidal elevation. Scott Nichol, Claire Coomber, Paul Augustinus, Ian Smith, and Jamie Schulmeister kindly allowed us to use some of their unpublished observations on the various drillholes. The foraminiferal research in this paper was funded by the New Zealand Public Good Science Fund. Drilling in Pukaki Lagoon was funded by the New Zealand Marsden Fund (contract UoA 609 to B. Alloway) and in Onepoto Lagoon by the University of Auckland Research Committee.

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Appendix 1 Percentage relative abundance of Foraminifera and qualitative estimates of abundance of Mollusca from Pukaki Lagoon drillhole. New Zealand Fossil Record File number R11/f202.

Depth (metres)	7.59–7.63	12.06–12.10	13.82–13.86	16.66–16.70	19.74–19.78	27.23–27.27	33.08–33.12	40.40–40.44	45.11–45.15
Salinity index	7.0	7.1	7.1	7.5	8.1	7.8	7.9	7.7	8.0
Species diversity (Fisher alpha index)	0.2	0.8	1.4	4	6.4	7	5.4	2.4	7
Planktic foraminiferal (%)	0	0	0	1	3	4	1	1	1
Benthic foraminifera (%):									
Ammonia aoteana	100	96	93	78	58	67	67	70	47
Ammonia pustulosa	0	0	0	0	0	0	1	0	4
Astrononion novozealandicum	0	0	0	1	0	0	0	0	0
Bolivina cacozela	0	0	0	2	1	1	2	1	1
Bolivina neocompacta	0	0	0	1	0	1	0	1	6
Bolivina spathulata	0	0	0	0	1	0	0	0	0
Bolivina striatula	0	0	0	0	1	0	0	0	0
Bolivina subexcavata	0	0	0	1	0	0	1	0	0
Bulimina gibba	0	0	0	0	0	0	0	0	1
Bulimina marginata f. *marginata*	0	0	1	0	1	0	0	0	0
Buliminella elegantissima	0	0	0	0	1	1	0	0	0
Cassidulina carinata	0	0	0	1	9	2	5	4	4
Cibicides marlboroughensis	0	0	0	0	0	1	0	0	0
Cornuspira involvens	0	0	0	0	1	0	3	0	1
Discorbinella bertheloti	0	0	0	0	1	1	0	0	0
Elphidium advenum	0	0	0	0	0	1	0	0	3
Elphidium charlottense	0	0	1	0	2	1	0	0	1
Elphidium excavatum f. *clavatum*	0	2	2	2	2	1	0	0	0
Elphidium excavatum f. *excavatum*	0	0	1	0	0	0	1	0	0
Elphidium gunteri	0	0	0	0	0	0	0	0	0
Evolvocassidulina orientalis	0	0	0	1	0	0	0	0	0
Fissurina lucida	0	1	0	0	0	1	3	0	2
Fissurina sp.	0	0	0	1	0	1	1	0	0
Gavelinopsis praegeri	0	0	0	0	4	2	3	1	1
Globocassidulina subglobosa	0	0	0	0	0	0	1	0	0
Haynesina depressula	0	1	2	7	9	11	2	15	18
Jadammina macrescens	0	0	0	0	0	0	1	0	0
Lagena striata	0	0	0	1	0	0	0	0	0
Miliolinella subrotundata	0	0	0	0	0	0	0	1	2
Notorotalia finlayi	0	0	0	0	1	0	0	0	0
Oolina globosa	0	0	0	0	0	1	0	0	0
Pileolina patelliformis	0	0	0	0	3	1	4	0	1
Pileolina zealandica	0	0	0	0	3	0	1	0	0
Quinqueloculina delicatula	0	0	0	0	0	1	0	0	0
Quinqueloculina seminula	0	0	0	0	0	1	0	4	3
Quinqueloculina tenagos	0	0	0	0	0	0	0	0	1
Rosalina irregularis	0	0	0	0	0	0	0	0	1
Trochammina inflata	0	0	0	0	0	0	0	0	0
Virgulopsis turris	0	0	0	3	1	4	4	3	2
Zeaflorilus parri	0	0	0	1	1	0	0	0	1
Mollusca: Gastropoda:									
Amphibola crenata	0	0	0	p	0	0	0	0	0
Chemnitzia sp.	0	0	0	0	p	0	0	0	0
Cominella adspersa?	p	0	0	0	0	0	0	0	0
Mollusca: Bivalvia:									
Arthritica bifurca	c	0	0	p	p	0	0	p	0
Austrovenus stutchburyi	c	0	0	p	0	0	0	0	0
Macomona liliana	0	0	0	0	p	0	0	0	0
Cyclomactra ovata ?	p	0	0	0	0	0	0	0	0
Nucula hartvigiana	0	0	0	0	0	0	0	p	0
Ostrea lutaria	0	0	0	p	0	0	0	0	0
Paphies australis ?	p	0	0	0	0	0	0	0	0
Pecten novaezelandiae	0	0	0	p	0	0	0	0	0
Perna canaliculus	p	0	0	p	0	0	0	0	0
Tawera spissa	0	0	0	p	0	0	0	0	0
?Xenostrobus pulex	p	0	0	0	0	0	0	0	0
Barnacles:									
Austrominius modestus	c	0	0	c	0	0	0	0	0

c, common; p, present. No fauna in samples: 0.44–0.48 m, 1.24–1.28 m, 3.72–3.76 m, 45.87–45.91 m

Appendix 2 Percentage relative abundance of Foraminifera and qualitative estimates of abundance of Mollusca from Onepoto Lagoon drillhole. New Zealand Fossil Record File number R11/f199.

Depth (metres)	4.0–4.04	5.56–5.6	7.76–7.8	8.41–8.45	8.71–8.75	9.01–9.05	9.36–9.4	9.54–9.58	9.79–9.83	11.3–11.34	12.6–12.64	14.3–14.39	16.1–16.14	17.9–17.94	19.7–19.74	21.7–21.74	23.1–23.14	27.0–27.04	28.9–28.94	30.9–30.94	32.32–32.36	35.42–35.46	35.96–36.0
Number/10 cm³	50	1000	250	417	50	500	100	250	500	500	500	250	500	152	500	250	250	100	100	100	50	200	100
Salinity index	7.0	7.0	7.3	7.1	7.7	7.1	7.6	7.3	7.7	7.4	7.5	7.6	7.9	8.1	7.8	8.4	7.8	9.1	8.3	8.3	7.8	7.3	7.0
Species diversity (Fisher alpha index)	0.2	0.4	1.7	1.4	0.8	1.1	2.4	2.4	3.2	2.4	2	2.8	1.4	3.2	2.8	2.8	2.8	7	3.6	4.4	3.2	1.7	0.2
Ostracods per 100 foraminifera	0	0	25	17	5	3	6	10	8	2	0	35	6	27	27	20	13	75	95	160	115	2	0
Benthic foraminifera (%):																							
Ammonia aoteana	100	99	86	95	64	95	72	84	67	83	73	66	63	50	65	35	64	7	44	40	66	85	100
Ammonia pustulosa	0	0	0	0	0	0	0	1	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0
Bolivina cacozela	0	0	1	0	0	0	1	0	0	2	0	0	1	0	2	1	0	6	2	1	3	0	0
Bolivina neocompacta	0	0	0	0	0	0	0	0	5	0	0	2	0	4	0	1	1	22	8	12	0	2	0
Bolivina striatula	0	0	1	0	0	1	0	1	0	2	1	1	0	4	2	3	2	11	4	6	3	1	0
Bolivina subexcavata	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0
Bulimina elongata	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2	3	2	5	1	1	0	0	0
Bulimina marginata f. *marginata*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Buliminella elegantissima	0	0	0	0	0	0	0	0	5	4	0	1	0	1	2	1	1	1	1	2	0	0	0
Cassidulina carinata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	2	0	0	0	0	0
Cornuspira involvens	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	2	3	4	1	0	0
Elphidium advenum	0	0	1	1	10	1	5	2	5	1	9	23	11	15	14	23	15	15	7	5	10	3	0
Elphidium charlottense	0	0	0	1	1	0	4	0	0	0	4	0	3	3	0	1	0	1	0	2	3	0	0
Elphidium excavatum f. *excavatum*	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Elphidium excavatum f. *clavatum*	0	1	2	0	0	0	2	2	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0
Elphidium excavatum f. *williamsonii*	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0
Fissurina lucida	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Fursenkoina schreibersiana	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Haynesina depressula	0	0	8	0	25	1	13	7	4	3	10	3	15	14	9	31	7	9	9	6	9	7	0
Lenticulina gibba	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0
Miliammina fusca	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Miliolinella subrotundata	0	0	1	1	0	0	0	0	1	1	0	0	0	0	0	0	0	2	5	0	0	0	0
Quinqueloculina seminula	0	0	0	1	0	2	1	1	9	3	1	0	7	4	2	0	5	4	7	7	1	1	0
Quinqueloculina tenagos	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Paratrochammina bartrami	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Rosalina irregularis	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	1	0	0
Spiroloxostoma glabra	0	0	0	0	0	0	0	1	1	0	0	1	0	2	1	0	2	8	9	12	2	0	0
Mollusca: Gastropoda:																							
Cominella sp.	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Micrelenchus huttonii	0	0	0	0	1	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Notoacmea helmsi f. *scapha*	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Zeacumantus lutulentus	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mollusca: Bivalves:																							
Arthritica bifurca	0	0	1	0	3	0	0	7	14	2	1	2	2	8	30	12	10	0	0	3	1	10	0
Austrovenus stutchburyi (fragments)	0	6	1	3	0	1	2	2	0	2	0	0	1	0	0	0	0	0	0	0	0	0	5
Austrovenus stutchburyi (double)	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Macomona liliana	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Nucula hartvigiana	0	0	0	2	2	1	0	0	0	1	2	2	1	0	8	0	0	0	0	0	0	0	0