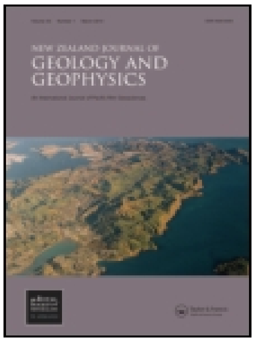

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Foraminiferal paleoecology and initial subsidence of the early Miocene Waitemata Basin, Waiheke Island, Auckland

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Abstract Data from 29 fossil foraminiferal faunas from early Miocene strata (Waitemata Group; Kawau Subgroup) on Waiheke Island are analysed by cluster analysis. The dominant species are grouped into six species associations that occur in different inferred environments: *Elphidium*—beach or shallow subtidal sand; *Buliminella*—high energy, inner shelf; *Cribrorotalia*—moderately exposed, inner to mid shelf; *Quinqueloculina*—inner and shallow mid shelf; *Nonionella*—deep inner to mid-shelf muddy sand; and *Cassidulina*—outer shelf. The samples are grouped in terms of relative species abundances into seven sample associations, and their paleoenvironments have been determined using the inferred environments of their constituent species associations.

These assessed paleoenvironments of the seven sample associations are used to reconstruct the changing paleogeography of the Waiheke area during the early Miocene. The Waiheke strata accumulated during a period of subsidence of about 200 m early in the formation of the Waitemata flysch basin. The strata were deposited in three depressions or bays on the sides of the Waiheke greywacke "paleoisland". The nonmarine and beach conglomerate of Te Rere Point and Fossil Bay accumulated first in their respective bays. With further subsidence the transgressive, inner to mid-shelf sandstone of Fossil Bay was deposited, while nonmarine breccia accumulated to the northeast in the W (Double-U) Bay – Oneroa depression. Subsidence continued, possibly submerging all of the Waiheke "paleoisland". Muddy sandstone, which continued to accumulate around the drowned rocky high, only began filling the northeastern depression when it had subsided to mid-shelf depths. The highest sediments at W Bay and Oneroa record continued deepening to outer shelf depths.

These are the richest foraminiferal faunas and most complete sequences that document the initiation of the Waitemata Basin. The continued subsidence to mid-bathyal depths during a period of sediment starvation is documented by a piecemeal stratigraphic record in other places.

Keywords Waiheke Island; Waitemata Basin; subsidence; Kawau Subgroup; Waitemata Group; foraminifera; paleoecology; paleoenvironment; Miocene; Otaian; cluster analysis

INTRODUCTION

Geological setting

The Waitemata Basin extended across the Auckland and southern Northland regions of New Zealand during the early Miocene (Ballance 1974; Hayward 1993). It was the depocentre for a large body of flysch and minor associated sedimentary deposits (Waitemata Group) that are the dominant rocks outcropping in these regions today. Outcropping east of Auckland are a number of thin, highly variable sequences (0–45 m) of early Miocene, shallow water sedimentary strata (Waitemata Group, Kawau Subgroup; Hayward & Brook 1984) that bury an irregular paleotopography of Mesozoic greywacke (Waipapa Group) basement and are abruptly overlain by deep water mudstone and flysch (Warkworth Subgroup; Ballance 1976). These thin, early Miocene (Otaian Stage) sequences, and their passage into the deep water flysch, document the relatively rapid tectonic subsidence that formed the Waitemata Basin (Ballance 1974; Ricketts et al. 1989), as part of the response of northern New Zealand to the initiation of the modern plate boundary through the country around that time (Hayward 1993).

Early Miocene geology of Waiheke Island (Fig. 1)

Some of the thickest, finest grained, and most fossiliferous shallow water sequences of Kawau Subgroup sequences outcrop in three localities on the western end of Waiheke Island (Powell & Bartrum 1929; Powell 1938, 1976; Halcrow 1956; Kermode 1992), 20 km east of Auckland City. These contain rich, well-preserved foraminiferal microfaunas, which provide detailed information on the paleoecological associations and the deepening environment in which the strata were deposited. The thickest sequence occurs in Fossil Bay (sometimes known as Church or Squadron Bay), where Kawau Subgroup strata fill a former embayment. Here the greywacke promontories that once formed either side of the early Miocene embayment are now exhumed to form the points on either side of modern Fossil Bay.

In the cliffs and shore platform on the southern side of Fossil Bay, a 17 m thick basal conglomerate laps onto and buries an irregular greywacke paleotopography. The

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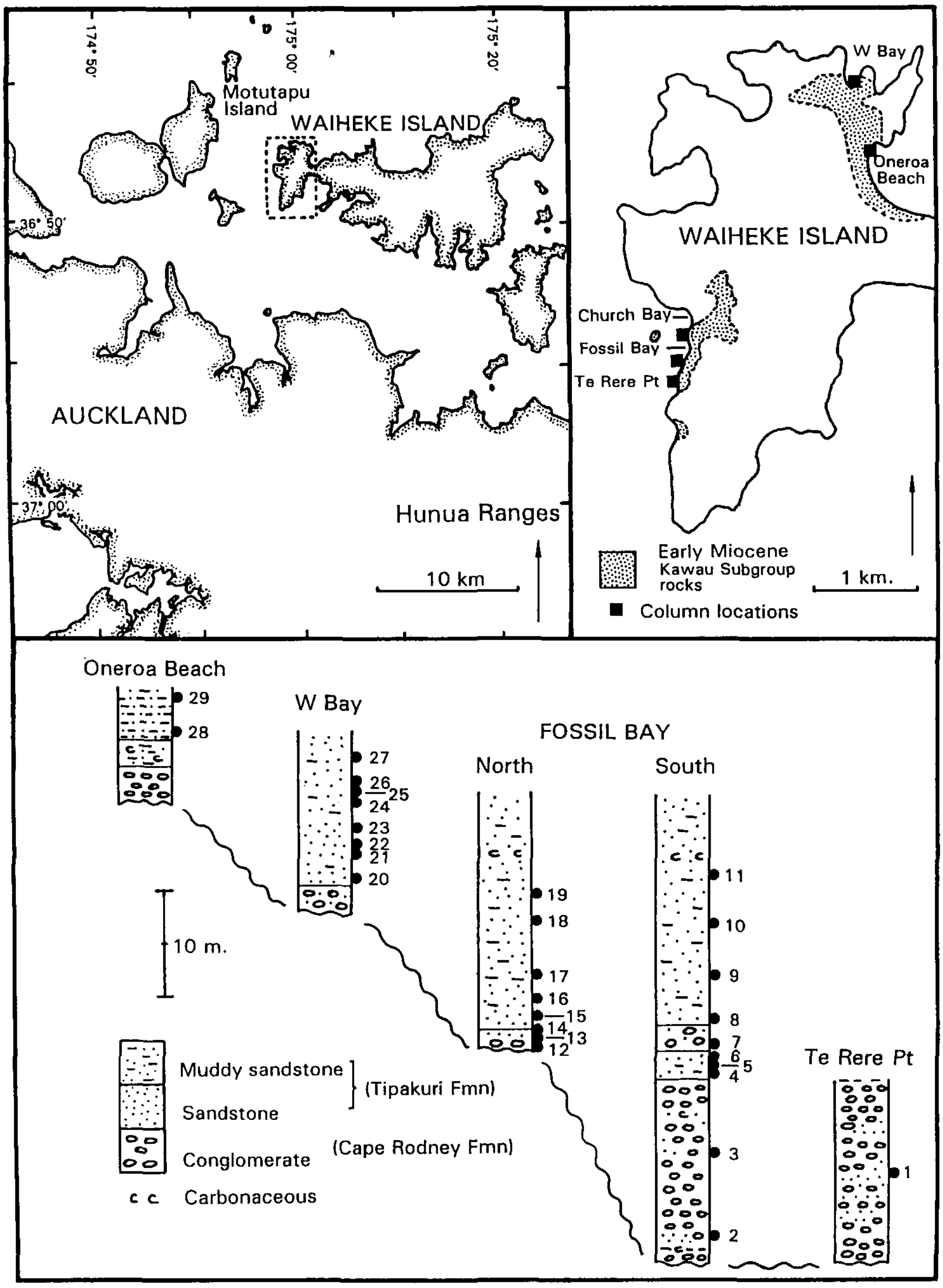


Fig. 1 Sample locations and stratigraphic columns within the early Miocene sequence on western Waiheke Island, Auckland.

conglomerate is weakly bedded, consisting of subangular to rounded pebbles and cobbles of greywacke (Cape Rodney Formation; Hayward & Brook 1984). It also contains several thin lenses of laminated, carbonaceous coarse sandstone, and broken fossil shells are scattered through several conglomerate horizons. The upper 10 m exhibits 2 m-scale foreset bedding. The conglomerate is overlain by 27 m of macrofossiliferous, massive to weakly stratified, calcareous, muddy fine sandstone with occasional carbonaceous horizons (Oneroa Member of Tipakuri Formation; Hayward & Brook 1984). A 3 m thick lens of shelly, recrystallised, calcareous, sandy pebble conglomerate occurs within the muddy fine sandstone sequence, 3 m above its base, on the southern side of Fossil Bay.

On the northern side of Fossil Bay the exposed sequence consists of a 1.5 m thick graded bed of shelly pebble conglomerate to coarse sandstone lapping onto the greywacke basement and overlain by 22 m of muddy fine sandstone (Oneroa Member).

Two hundred metres south of Fossil Bay, at Te Rere Point, a further 18 m thick lens of basal sandy conglomerate fills a depression in the irregular greywacke basement surface.

At W Bay (= Double-U Bay), on the north coast of Waiheke Island, the early Miocene sequence overlying greywacke basement consists of 0–2 m of basal, slightly carbonaceous, noncalcareous, sandy pebble breccia (Cape Rodney Formation) overlain by 15 m of weakly stratified, macrofossiliferous, calcareous, muddy fine sandstone (Oneroa Member). A similar but thinner (5 m) sequence occurs in low cliffs and beneath the seasonal sand at the northwestern end of Oneroa Beach.

All the Kawau Subgroup sequences on Waiheke Island are truncated by erosion. Unlike thinner Kawau sequences on nearby Motuihe and Motutapu Islands, no Waiheke sequences can be seen to pass upwards into deep water, Waitemata Basin flysch sediments (Warkworth Subgroup).

Previous foraminiferal work

The paleoecology of the foraminiferal faunas of the central Waitemata Basin flysch (Warkworth Subgroup) and the volcaniclastic sediments on its western margin (Waitakere Group) has been documented and interpreted by Hayward & Buzas (1979). Scott (1970) interpreted the paleoecology of foraminiferal faunas from the shallow northwestern margin (Kaipara area) of the basin. Initial interpretation of the foraminiferal faunas and their paleoecology in the shallow water, basal Waitemata sequences (Kawau Subgroup), including Waiheke, has been summarised in Hayward (1984) and Ricketts et al. (1989, tables 3, 5). A more detailed interpretation of the foraminiferal paleoecology has been made of the subsiding Kawau Subgroup sequence in the Hays Stream area of the northern Hunua Ranges, 30 km south of Waiheke Island (Eagle & Hayward 1992).

Field and laboratory methods

Fresh samples of rock for processing were collected by digging into the bank up to 0.3 m to reach less weathered blue-grey sediment (Appendix 1). In trial sample processing, we noted that miliolids and aragonitic foraminiferal tests were selectively dissolved out of the faunas with near-surface weathering. Rock samples were processed by drying, gentle crushing, and emersion overnight in warm water, kerosene or petrol, followed by washing over a 0.075 mm sieve and gentle drying of the resulting disaggregated sediment.

Each sample was split many times using a microsplitter to obtain only enough sediment containing c. 300 benthic foraminiferal tests. All benthic tests in the microsplit were picked, mounted, identified and counted, and the number of planktic foraminiferal tests was also recorded during picking. The dataset consisting of raw counts of 123 species (Appendix 2) in 29 samples was computerised for analysis.

Computer methods

Because the number of individuals picked was standardised at c. 300 benthics, the data are more analogous to species proportions than species densities. The dataset was standardised by converting counts to proportions of sample totals. Unweighted pair group cluster analysis, using arithmetic averages of a Bray-Curtis distance matrix, was used to produce a dendrogram classification of samples (Fig. 2) from which sample associations were selected. Similar cluster analysis of a distance matrix, produced using Horn's (1966) modified version of Morista's (1959) index for proportions, was used to produce a dendrogram classification of dominant species (Fig. 2) from which species associations were selected. Mathematical definitions of the Bray-Curtis and modified Morista coefficients are given in Sneath & Sokal (1973) and Rohlf (1989). The modified Morista index downweights the more abundant species and produces a more realistic clustering of species that commonly occur together. The above cluster analyses were computed using the "NTSYS" statistical package (Rohlf 1989).

FORAMINIFERAL SPECIES ASSOCIATIONS

Inspection of the dendrogram classification of dominant species (>4% in at least one sample) produced by cluster analysis (Fig. 2) led us to select the following six associations of species. Most of these dominant species are illustrated in Fig. 3.

Association 1 *Elphidium*

SPECIES: *Bucella frigida, Elphidium advenum, Elphidium gibsoni, Elphidium kanoum.*

PALEOENVIRONMENTAL ASSESSMENT: Foraminiferal faunas consisting predominantly of *Elphidium* are characteristic today of mid to low tidal, moderately sheltered environments (e.g., Hayward 1982; Hayward & Hollis in press). In modern seas, *B. frigida* and *E. advenum* are most common in somewhat sheltered situations, often in slightly lowered salinities (e.g., Hayward & Hollis in press). *E. gibsoni* is the most abundant taxon in this association. It closely resembles the modern New Zealand species, *E. charlottensis*, which occurs in similar high abundances (20–50%) in low tidal and shallow subtidal sands (0–2 m), in moderately sheltered situations and normal salinity in northern New Zealand (Hayward 1982).

Association 2 *Buliminella*

SPECIES: *Bolivina arta, Buliminella elegantissima Melonis simplex.*

PALEOENVIRONMENTAL ASSESSMENT: *Bolivina arta* and *Melonis simplex* are both extinct and their genera have wide environmental tolerances. Modern *Buliminella elegantissima* and other species of the genus are most abundant in relatively high energy situations at inner shelf depths (e.g., Hayward 1982), and this association is probably from this environment.

Association 3 *Cribrorotalia*

SPECIES: *Cibicides mediocris, Cribrorotalia ornatissima.*

PALEOENVIRONMENTAL ASSESSMENT: The genus *Cribrorotalia* is extinct as is *Cibicides mediocris*. In modern seas the genus *Cibicides* lives in a wide range of environments and depths. Studies on other fossil faunas throughout New Zealand (Hayward & Buzas 1979; Hayward 1986; Eagle & Hayward 1992) show that *Cribrorotalia* occurs most abundantly in association with taxa that are today characteristic of moderately turbulent, normal salinity, coarse sediment environments at inner shelf depths (c. 0–50 m) and that *C. mediocris* is most common in mid to outer shelf fossil faunal associations. Thus, a moderately exposed, inner to mid-shelf (20–70 m) environment is inferred.

Association 4 *Quinqueloculina*

SPECIES: *Quinqueloculina seminula, Quinqueloculina* sp. A, *Quinqueloculina* sp. B.

PALEOENVIRONMENTAL ASSESSMENT: Species of *Quinqueloculina* in modern seas live in greatest abundance in tropical and subtropical temperatures at inner and shallow mid-shelf depths (0–70 m) in sheltered lagoons to moderately exposed bays (Murray 1973; Boltovskoy & Wright 1976;

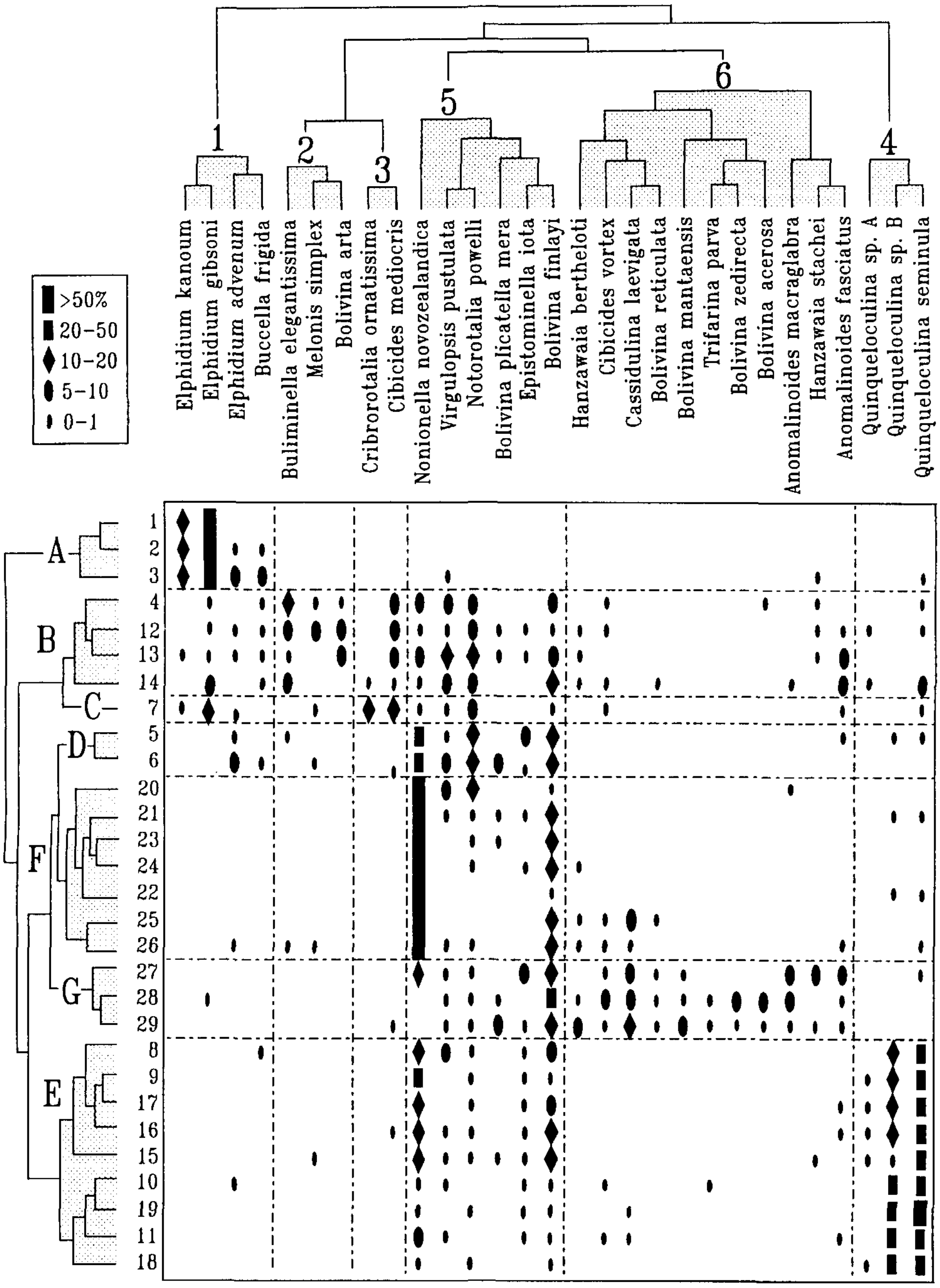


Fig. 2 Dendrogram classifications of Waiheke Island samples (left) produced by cluster analysis using Bray-Curtis distance and of foraminiferal species (top) produced by cluster analysis using modified Morista distance (Rohlf 1989). The seven sample associations (A–G) and six species associations (1–6) were selected by the authors after inspection of the dendrograms. The relative abundance of each species in each sample is summarised in the chart.

Hayward 1986). This association is the same as the early Miocene thanatope F of Hayward & Buzas (1979), which was interpreted as an inner shelf fauna.

Association 5 *Nonionella*

SPECIES: *Bolivina finlayi*, *Bolivina plicatella mera*, *Epistominella iota*, *Nonionella novozealandica*, *Notorotalia powelli*, *Virgulopsis pustulata*.

PALEOENVIRONMENTAL ASSESSMENT: All these species are extinct. The most abundant of these taxa, *Nonionella novozelandica*, is quite similar in form to *Nonionella flemingi*, which is abundant today off New Zealand in relatively quiet conditions at deep inner shelf to uppermost bathyal depths (c. 40–400 m). *Notorotalia powelli* is a robust species similar to modern *N. olsoni* and *N. zelandica*, both of which are characteristic of shelf depths (Hayward 1986). Whereas *Epistominella* is most usually characteristic of modern deep bathyal conditions, one present species, *Epistominella vitrea*, lives in quiet conditions as shallow as mid shelf (Hayward et al. 1984).

Virgulopsis today is generally an inner to mid-shelf genus. An association co-dominated by *Notorotalia finlayi* and *Nonionella flemingi* has recently been recognised in 20–40 m depth in land-locked harbours at Port Fitzroy, Great Barrier Island (unpubl. obs.) and at Port Pegasus, Stewart Island (Hayward et al. in prep. "Foraminiferal associations in Port Pegasus, Stewart Island, New Zealand"). This seems to be an excellent modern analogue of this fossil association, which is therefore inferred to have lived in a relatively quiet, fine sediment environment at deep inner to mid-shelf depths (20–100 m).

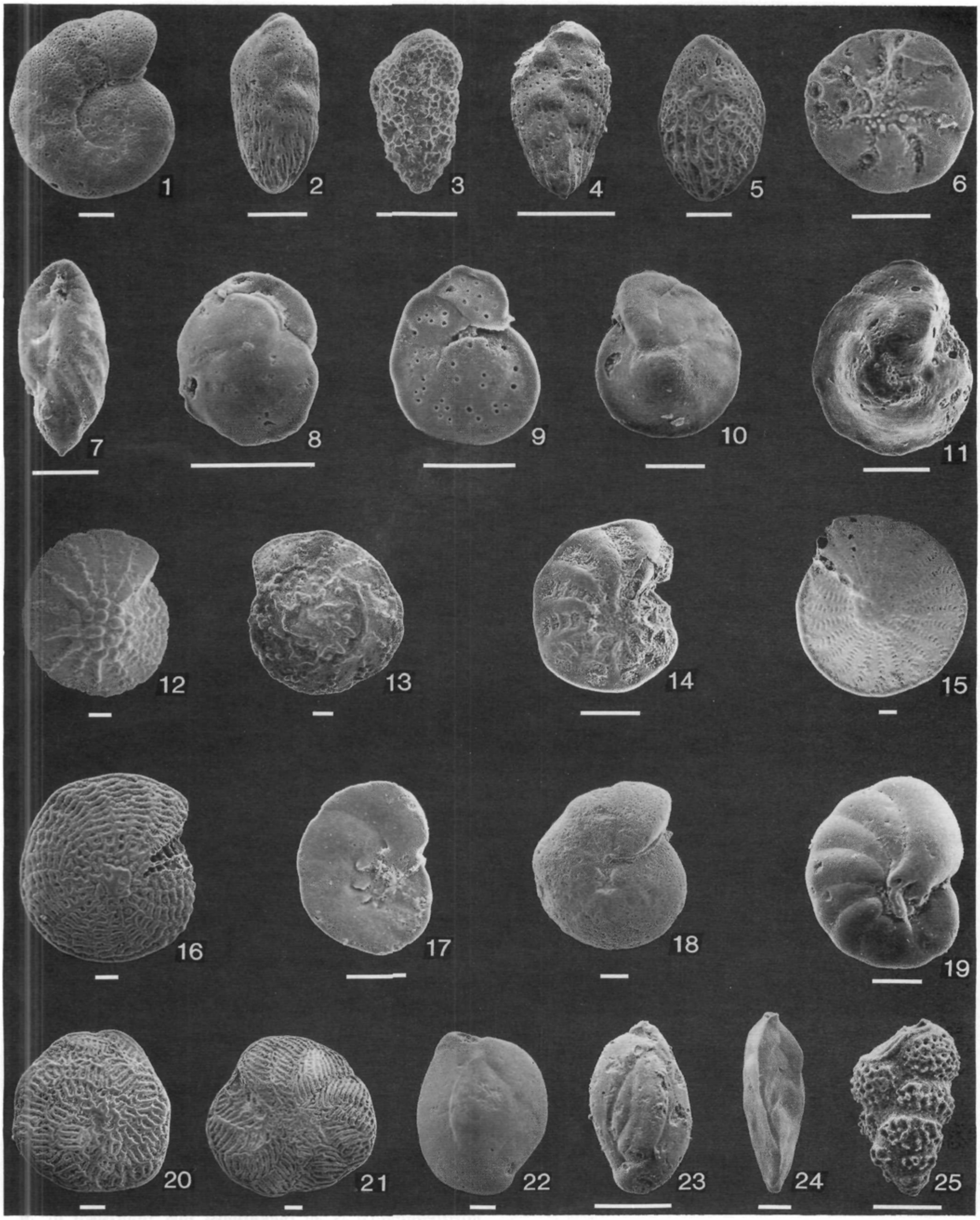


Fig. 3 Scanning electron micrographs of dominant foraminiferal species in the early Miocene of Waiheke Island. **1**, *Anomalinoides macraglabra*, FP4054; **2**, *Bolivina finlayi*, FP4032; **3**, *Bolivina plicatella mera*, FP4033; **4**, *Bolivina mantaensis*, FP4034; **5**, *Bolivina reticulata*, FP4035; **6**, *Bucella frigida*, FP4036; **7**, *Buliminella elegantissima*, FP4055; **8**, *Cassidulina laevigata*, FP4037; **9**, **10**, *Cibicides mediocris*, FP4038–9; **11**, *Cibicides vortex*, USNM243334; **12**, **13**, *Cribrorotalia ornatissima*, FP4040–1; **14**, *Elphidium advenum*, FP4042; **15**, *Elphidium gibsoni*, FP4043; **16**, *Elphidium kanoum*, FP4044; **17**, *Hanzawaia bertheloti*, FP4045; **18**, *Melonis simplex*, FP4046; **19**, *Nonionella novozelandica*, FP4047; **20**, **21**, *Notorotalia powelli*, FP4048–9; **22**, *Quinqueloculina seminula*, FP4050; **23**, *Quinqueloculina* sp. A, FP4051; **24**, *Trifarina parva*, FP4052; **25**, *Virgulopsis pustulata*, FP4053. Scale bar = 0.1 mm.

Association 6 *Cassidulina*

SPECIES: *Bolivina acerosa, Bolivina mantaensis, Bolivina reticulata, Bolivina zedirecta, Cassidulina laevigata, Cibicides vortex, Hanzawaia bertheloti, Trifarina parva, Anomalinoides fasciatus, Anomalinoides macraglabra, Hanzawaia stachi.*

PALEOENVIRONMENTAL ASSESSMENT: Most of these species are extinct, and today all the genera live in a wide range of depths, most commonly in quiet, fine-grained sediment environments at mid-shelf to mid-bathyal depths (c. 100–2000 m; e.g., Boltovskoy & Wright 1976). As there are no bathyally restricted taxa (e.g., *Vulvulina, Pleurostomella, Osangularia, Karreriella, Eggerella*) in any of the study samples, a mid-shelf to uppermost bathyal depth is inferred.

SAMPLE ASSOCIATIONS AND THEIR PALEOENVIRONMENTAL INTERPRETATION

Inspection of the dendrogram classification of samples produced by cluster analysis based on their foraminiferal compositions (Fig. 2) led us to select the following seven associations (Appendices 3–5):

Association A

SAMPLES: 1, 2, 3 (Te Rere Point and south side Fossil Bay, basal sandy conglomerate unit).

DOMINANT SPECIES ASSOCIATION: 1. *Elphidium.*

PLANKTIC FORAMINIFERAL PERCENTAGE: 0%.

PALEOENVIRONMENTAL ASSESSMENT: Mid to low tide beach or shallow subtidal (0–2 m depth); normal salinity; moderate shelter at head of a bay.

Association B

SAMPLES: 4, 12, 13, 14 (both sides of Fossil Bay, sandy shelly conglomerate and basal muddy fine sandstone).

DOMINANT SPECIES ASSOCIATION: 2. *Buliminella*, 5. *Nonionella.*

PLANKTIC FORAMINIFERAL PERCENTAGE: 0–2%.

PALEOENVIRONMENTAL ASSESSMENT: Moderately high energy, possibly strong current environment, at deep inner shelf depths (c. 10–40 m), sheltered from oceanic influence (low planktic content). The considerable intersample variation in this association is suggestive of some possible postmortem current mixing of tests from several source populations.

Association C

SAMPLE: 7 (south side Fossil Bay, sandy shelly conglomerate bed).

DOMINANT SPECIES ASSOCIATIONS: 3. *Cribrorotalia*, 1. *Elphidium.*

PLANKTIC FORAMINIFERAL PERCENTAGE: 0%.

PALEOENVIRONMENTAL ASSESSMENT: The presence together of these two foraminiferal associations suggests a moderately exposed, coarse sediment, inner shelf (0–30 m) environment, sheltered from any oceanic influence. It is similar in overall composition to association B and possibly contains tests mixed from several population sources.

Association D

SAMPLES: 5, 6 (south side Fossil Bay, lower muddy fine sandstone unit).

DOMINANT SPECIES ASSOCIATION: 5. *Nonionella.*

PLANKTIC FORAMINIFERAL PERCENTAGE: 0%.

PALEOENVIRONMENTAL ASSESSMENT: Moderately quiet, fine sediment environment at deep inner shelf depths (c. 20–50 m), sheltered from any oceanic water circulation. This association is dominated by infaunal opportunist species.

Association E

SAMPLES: 8, 9, 10, 11, 15, 16, 17, 18, 19 (both sides Fossil Bay, muddy fine sandstone).

DOMINANT SPECIES ASSOCIATIONS: 4. *Quinqueloculina*, 5. *Nonionella.*

PLANKTIC FORAMINIFERAL PERCENTAGE: 3–40%.

PALEOENVIRONMENTAL ASSESSMENT: Moderately quiet, fine sediment environment at inner to mid-shelf depths (c. 30–70 m), with increasing influence of oceanic water (increasing planktic percentage).

Association F

SAMPLES: 20, 21, 22, 23, 24, 25, 26 (W Bay, muddy fine sandstone).

DOMINANT SPECIES ASSOCIATION: 5. *Nonionella.*

PLANKTIC FORAMINIFERAL PERCENTAGE: 0–63%.

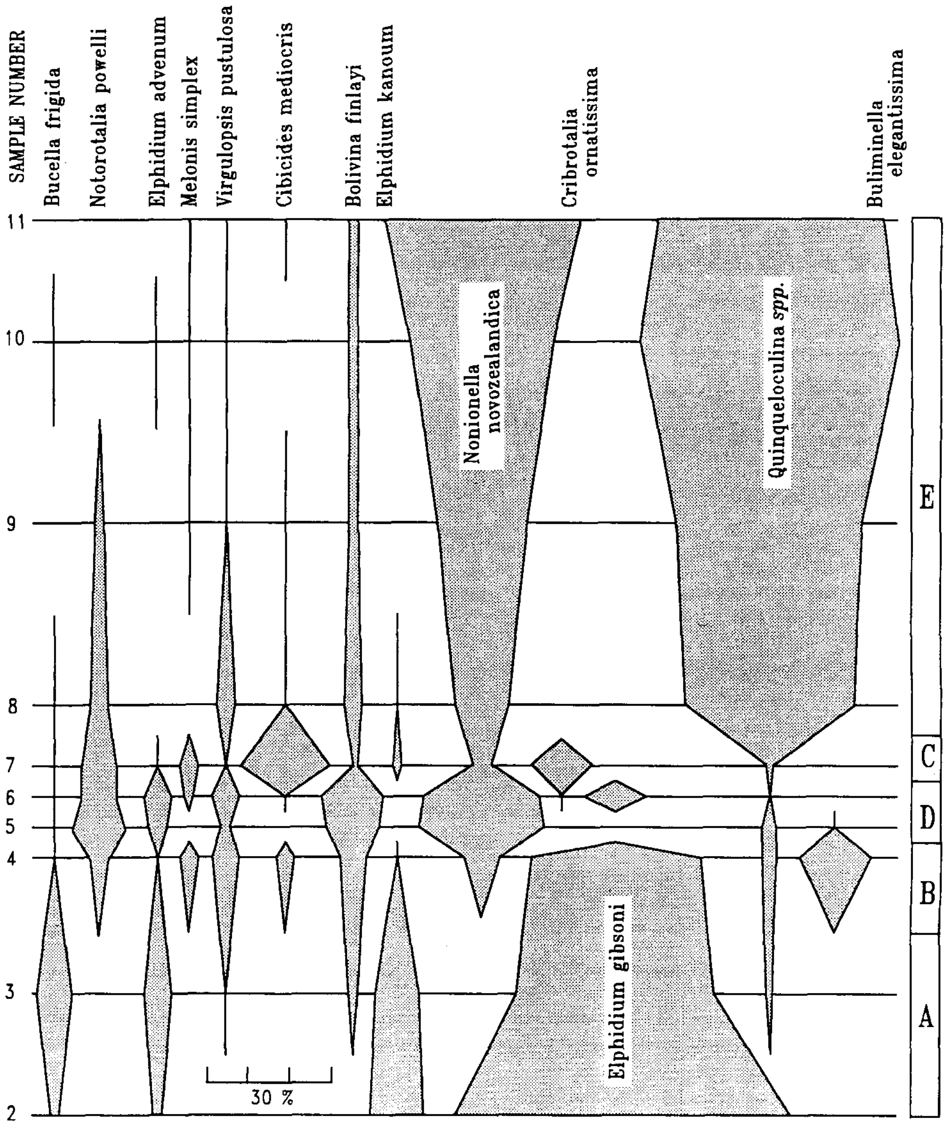
PALEOENVIRONMENTAL ASSESSMENT: Relatively quiet conditions in fine sediment at around mid-shelf depths; lower samples (20, 21) contain common shallow water *Notorotalia powelli* and *Virgulopsis* (Fig. 2) and probably lived at shallow mid-shelf depths (c. 30–70 m), whereas higher samples (25, 26) contain elements of the deeper water *Cassidulina* association (Fig. 2) and probably lived at deep mid-shelf depths (60–120 m), with greater oceanic water influence (63% planktics).

Samples in this association have a somewhat low diversity and inequitable distribution (Appendix 5), which may suggest that the dominant species *Nonionella novozealandica* is an opportunist that flourished in an unusual high nutrient environment, notably all in the W Bay section.

Association G

SAMPLES: 27, 28, 29 (W Bay and Oneroa, muddy fine sandstone).

Fig. 4 Histograms showing trends in relative abundance of common benthic foraminifera and the sample associations (A–G) in the south Fossil Bay stratigraphic sequence.



DOMINANT SPECIES ASSOCIATIONS: 6. *Cassidulina*, 5. *Nonionella*.

PLANKTIC FORAMINIFERAL PERCENTAGE: 65–74%.

PALEOENVIRONMENTAL ASSESSMENT: Fine sediment, quiet environment at outer shelf depths (c. 100–200 m), beneath marginally oceanic water (moderately high planktic content). These faunas have the highest equitability and diversity in the study (Appendix 5), consistent with the inferred greatest depth. They lack any bathyally restricted taxa and are therefore inferred to be still at shelf depths.

PALEOENVIRONMENTAL INTERPRETATION OF THE WAIHEKE SEQUENCE

The stratigraphic and geographic distribution of the sample associations are shown in Fig. 4–8 and their planktic percentage and paleodepth interpretations summarised in Fig. 8.

South Fossil Bay and Te Rere Point (Fig. 4)

The thickest and most complete sequence occurs on the southern side of Fossil Bay. The lowermost 1–2 m of slightly carbonaceous conglomerate at both Te Rere and south Fossil Bay sections contains no fossil foraminifera and is possibly a nonmarine alluvial or storm beach deposit. The bulk of the slightly shelly, massive, and cross-bedded basal conglomerate unit at both localities contains fossil foraminiferal faunas (association A), which indicates a tidal or shallow subtidal beach setting in a depth of 0–2 m.

The sharp lithologic boundary between the conglomerate and overlying muddy fine sandstone corresponds with a foraminiferal change from association A to B, which indicates a deepening to deep inner shelf depths of about 10–40 m in a moderately strong current-swept environment. The foraminiferal fauna rapidly passes upwards into association D, indicating continued subsidence to moderately quiet, deep inner shelf depths of c. 20–50 m.

The 3 m thick, shelly conglomerate lens within the fine sandstone on the southern side of Fossil Bay has an association C fauna, which strongly suggests that this

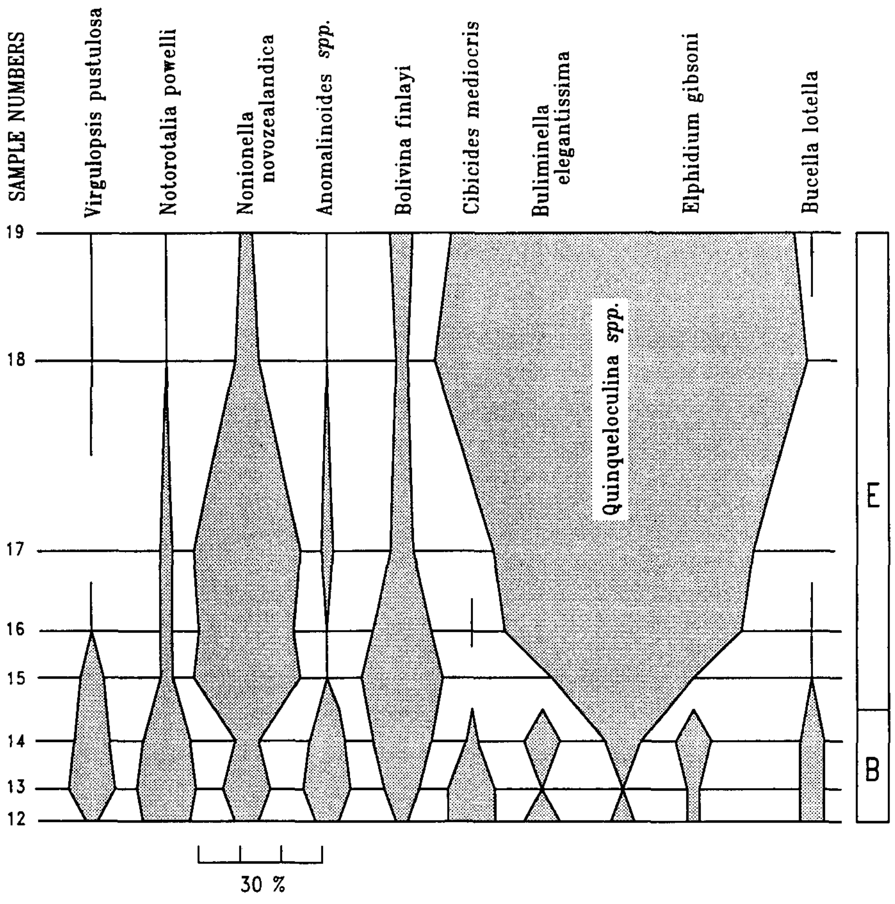


Fig. 5 Histograms showing trends in relative abundance of common benthic foraminifera and the sample associations (A–G) in the north Fossil Bay stratigraphic sequence.

sediment and its foraminiferal content had been redeposited by slumping from a moderately exposed, inner shelf environment (0–30 m).

The upper 20 m of muddy fine sandstone in the south Fossil Bay section has association E foraminiferal faunas, which are inferred to have accumulated at deep inner to mid-shelf depths of 30–70 m. Whereas the benthic fauna is relatively similar throughout this part of the section, the planktic percentage increases progressively from 3 to 40%, which indicates increasing penetration of oceanic water into the bay. This increased oceanic influence is probably related to continued subsidence and deepening, but is insufficient to impact on the benthic foraminiferal fauna.

North Fossil Bay (Fig. 5)

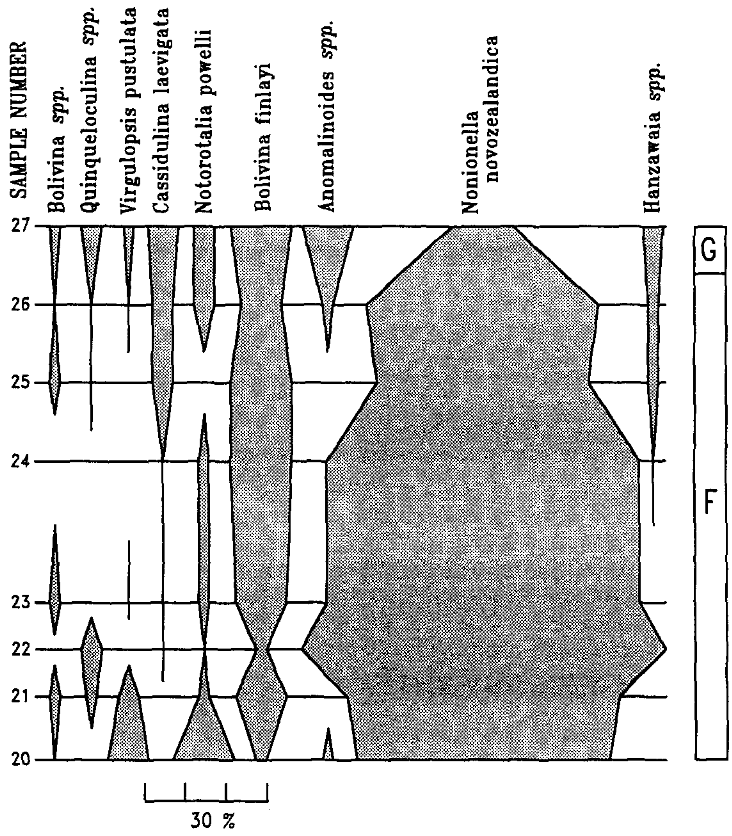
The basal graded bed of shelly conglomerate and sandstone on the northern side of Fossil Bay contains association B foraminiferal faunas, which are interpreted as having lived in a moderately high energy, inner shelf environment of c. 10–40 m depth. The bed may in part be redeposited or merely reworked by strong currents and burrowing organisms. Foraminiferal faunas in the overlying 20 m of muddy fine sandstone are similar to those in the equivalent strata in the south Fossil Bay sequence. They all belong to association E from deep inner to mid-shelf depths, and the planktic percentage increases progressively from 4 to 16%, which also supports the inferred continued subsidence.

W Bay (Fig. 6)

The basal carbonaceous breccia contains no fossil foraminifera and, assuming there has been no deep leaching of foraminifera, it is probably a nonmarine deposit. If this is correct then the abrupt lithologic change into the overlying muddy fine sandstone represents a period of considerable subsidence with no sediment accumulation in this locality. The foraminiferal faunas in the lower 12 m of the sandstone belong to association F, which is interpreted to be a largely mid-shelf assemblage. The upper 3 m of the sandstone has a fauna belonging to association G from inferred outer shelf depths.

The eight foraminiferal faunas in this section show a consistent increase in planktics from 0 to 74%, which indicates that the site moved from a sheltered location bathed in purely neritic water to a more open situation with marginally oceanic water circulation overhead. In virtually all modern situations, this massive increase in planktics would be associated with a considerable increase in depth. The one known exception, as shown in land-locked Port Pegasus, Stewart Island (Hayward et al. in prep. "Foraminiferal associations in Port Pegasus, Stewart Island, New Zealand"), is where consistent onshore swells and winds and strong tidal currents sweep abundant small planktic tests into a relatively deep sheltered harbour, where they are trapped and settle to the bottom in the less turbulent waters. The fossil Waiheke planktics are generally small, and the sequence sits in a fossil embayment in greywacke,

Fig. 6 Histograms showing trends in relative abundance of common benthic foraminifera and the sample associations (A–G) in the W Bay stratigraphic sequence.



and thus a sheltered harbour or bay environment at mid-shelf depths is consistent with the fauna.

The benthic fauna, other than the two dominant species, also changes progressively through the sequence (Fig. 6). Lower faunas (20, 21) contain common shallower water species and probably lived at deep inner shelf depths, whereas the stratigraphically highest faunas (25–27) contain deeper water elements and are interpreted to be deep mid to outer shelf assemblages from 80 to 200 m depths.

Oneroa Beach (Fig. 7)

The basal breccia and carbonaceous muddy sandstone at Oneroa Beach contains no fossil foraminifera and, assuming there has been no deep leaching that would have removed any fossil tests, it is probably also a nonmarine deposit. The abrupt lithologic change into the overlying muddy fine sandstone probably represents a period of subsidence with no sediment accumulation. Both foraminiferal faunas in the muddy fine sandstone belong to association G. They have 65–70% planktics and are interpreted to be outer shelf assemblages.

Interpretation of tectonic subsidence

The faunally based sample associations indicate that there is a steady progressive deepening in the Kawau Subgroup sequences on Waiheke and that they accumulated during a period of subsidence of c. 200 m early in the formation of the Waitemata flysch basin. These are the most complete sedimentary sequences known that document this early basin subsidence. All other Kawau Subgroup sequences are more fragmentary in their preserved sedimentary record (Ricketts et al. 1989).

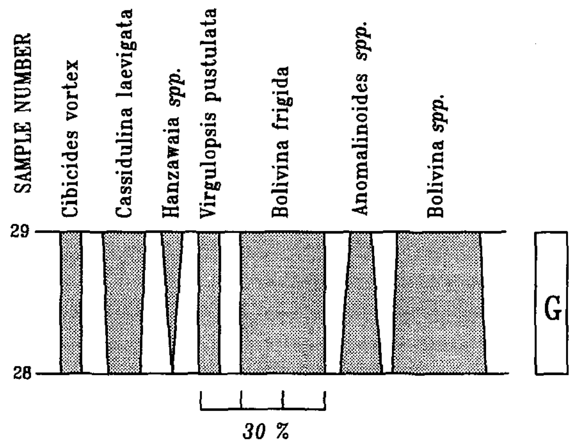


Fig. 7 Histograms showing trends in relative abundance of common benthic foraminifera and the sample associations (A–G) in the Oneroa Beach stratigraphic sequence.

South Fossil Bay, W Bay, and Oneroa Beach sequences each contain a significant gap in the sequence between the basal conglomerate or breccia and the overlying fine sandstone. In south Fossil Bay, this gap represents c. 10–20 m of subsidence from beach to inner shelf depths. At W Bay the gap represents c. 40 m of subsidence from nonmarine to deep inner or shallow mid shelf, and at Oneroa Beach it represents slightly over 100 m of subsidence from nonmarine to outer shelf depths. Subsidence probably progressed in jumps with earthquake-related stepdowns, but it is likely that the gaps in the sequence each relate to more than one drop. This was probably also a period of time when there

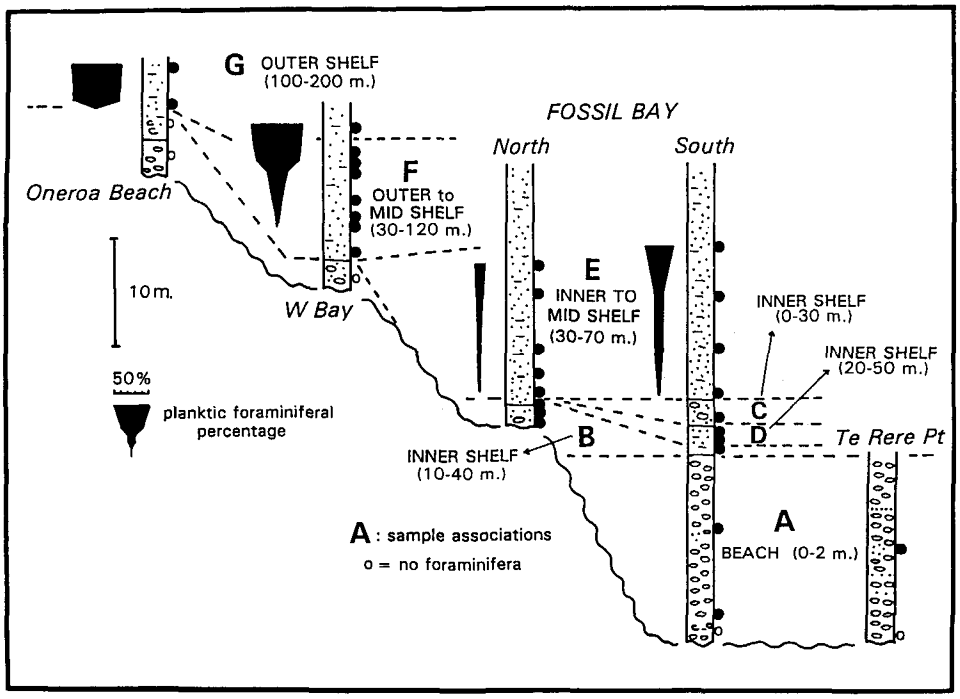


Fig. 8 Planktic foraminiferal percentages, sample associations, and paleoenvironmental interpretation of the early Miocene sequences on Waiheke Island. See Fig. 1 for sample numbers on columns.

was no net sediment accumulation in these sites, with any sediment being swept away or later eroded away by storm waves and strong currents.

Interpretation of paleogeography

The faunal sample associations also establish that within the muddy fine sandstone (Oneroa Member), the Oneroa Beach sequence accumulated at greater depths than most of the W Bay sequence, which was slightly deeper than most of the lower Fossil Bay sequence. There are two possible explanations for this observed paleodepth difference.

1. The Oneroa Member at each site could have accumulated at more or less the same time following a period of strong current and storm wave erosion. The observed paleodepth differences would then reflect the paleotopography during that short interval. This option is not favoured, because the deepest sequence (Oneroa Beach) lies between the two shallower sequences.
2. The Oneroa Member at each site could have accumulated at different times as the regional basin subsidence progressed. In this favoured scenario, the Fossil Bay sequences are mostly older than W Bay, which are mostly older than Oneroa Beach. There is possibly a time overlap between the upper Fossil Bay and lower W Bay sequences and between the upper W Bay and lower Oneroa Beach sequences (both association G).

The Te Rere Point, Fossil Bay, and W Bay plus Oneroa Beach sequences accumulated in three separate depressions or bays on the sides of an early Miocene island or landmass composed of greywacke basement. Assuming option (2) above to be the more likely, then nonmarine and beach conglomerate of Te Rere Point and Fossil Bay accumulated first in their respective bays on the western side of the island. As subsidence progressed, muddy fine sandstone accumulated at shelf depths around much of the island and extended into the Fossil Bay depression. The W Bay – Oneroa depression was probably higher up on the side of the island, and the nonmarine breccia and sandstone possibly accumulated as the inner or mid-shelf sandstone was being deposited in Fossil Bay.

Continued subsidence took the W Bay – Oneroa depression and eventually all of the "paleoisland" below sea level. By this time, sediment supply may have waned, with fewer nearby land areas, and the submerged island remained as an upstanding topographic feature on the seafloor for quite some time. Muddy sandstone possibly continued to accumulate slowly around the submerged high and only began filling the W Bay – Oneroa depression on its northeastern side once the surrounding background sediment had built up to this level. By this time, the base of the W Bay – Oneroa depression had subsided to mid-shelf depths.

There is no sedimentary record at Waiheke that documents the continued subsidence down into bathyal depths. This regional subsidence to at least mid-bathyal depths (1500–3000 m) is recorded on nearby Motutapu and Motuihe Islands by a gap in the sedimentary record between thin, shallow water Kawau Subgroup rocks and the abruptly overlying deep water flysch of the Warkworth Subgroup (Ricketts et al. 1989). The gap is widespread throughout the Waitemata Basin and is attributed to a combination of rapid subsidence and sediment starvation (Hayward 1993).

PALEOECOLOGICAL TRENDS WITH DEEPENING

The progressive deepening observed in the Waiheke sequences and supported by the progressively increasing oceanic water circulation (as recorded by planktic percentage) provides an excellent opportunity to document early Miocene foraminiferal paleoecologic trends that will be useful in paleodepth assessments of faunas from more isolated faunas.

The stratigraphy (Fig. 4–8) suggests that the identified sample associations lived in the following order of increasing depth: A, B, D, E, F and G. Association C appears to be redeposited and is inferred from its fauna to have lived at depths comparable to association B (inner shelf).

Examination of the correlation chart between sample and species associations (Fig. 2) indicates the following order of increasing depth preference for the species associations: *Elphidium*, *Buliminella* and *Cribrorotalia*, *Quinqueloculina* and *Cassidulina*. The *Nonionella* association appears to have a wide paleodepth range, from inner through to outer shelf depths, overlapping with all the other associations except *Elphidium*.

The chart and histograms (Fig. 2, 4–7) show that each common species has an abundance peak at a certain depth range and a tail of more scattered abundance at depths beyond this. In order of increasing depth preference (depths inferred above), some of these common species are:

Beach and shallow inner shelf (0–30 m): *Elphidium gibsoni*, *E. kanoum*, *Buccella frigida*;

Inner shelf (10–40 m): *Buliminella elegantissima*, *Cribrorotalia ornatissima*;

Beach and inner shelf (0–50 m): *Elphidium advenum*;

Inner and shallow mid shelf (10–70 m): *Quinqueloculina* spp., *Virgulopsis pustulata*, *Notorotalia powelli*;

Mid and outer shelf (50–200 m): *Epistominella iota*, *Bolivina plicatella mera*, *Hanzawaia bertheloti*, *Cibicides vortex*, *Cassidulina laevigata*, *Bolivina zedirecta*, *Bolivina acerosa*, *Anomalinoides macraglabra*.

Several common species appear to have a much broader depth range and are abundant at inner, mid, and outer shelf depths (10–200 m): *Nonionella novozealandica*, *Bolivina finlayi*, *Anomalinoides fasciatus*.

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APPENDIX 1 Foraminiferal study samples from Waiheke Island.

Sample	F.R. No.	Locality	Assoc.	% planktics	Lithology
1	R11/f23	Te Rere	A	0	shelly sandstone lens
2	R11/f8	Fossil Bay	A	0	sandy conglomerate
3	R11/f9	Fossil Bay	A	0	sandy conglomerate
4	R11/f10	Fossil Bay	B	0	shelly fine sandstone
5	R11/f130	Fossil Bay	D	0	shelly fine sandstone
6	R11/f11	Fossil Bay	D	0	shelly fine sandstone
7	R11/f21	Fossil Bay	C	0	shelly conglomerate
8	R11/f12	Fossil Bay	E	3	shelly fine sandstone
9	R11/f13	Fossil Bay	E	10	shelly fine sandstone
10	R11/f14	Fossil Bay	E	14	shelly fine sandstone
11	R11/f15	Fossil Bay	E	40	shelly fine sandstone
12	R11/f17	Fossil Bay	B	2	shelly conglomerate
13	R11/f18	Fossil Bay	B	1	shelly coarse sandstone
14	R11/f124	Fossil Bay	B	0	shelly medium sandstone
15	R11/f7	Fossil Bay	E	4	shelly fine sandstone
16	R11/f125	Fossil Bay	E	5	shelly fine sandstone
17	R11/f126	Fossil Bay	E	3	shelly fine sandstone
18	R11/f128	Fossil Bay	E	11	shelly fine sandstone
19	R11/f127	Fossil Bay	E	16	shelly fine sandstone
20	R10/f10	W Bay	F	0	shelly fine sandstone
21	R10/f11	W Bay	F	4	shelly fine sandstone
22	R10/f79	W Bay	F	5	shelly fine sandstone
23	R10/f12	W Bay	F	15	shelly fine sandstone
24	R10/f81	W Bay	F	28	shelly fine sandstone
25	R10/f82	W Bay	F	58	shelly fine sandstone
26	R10/f83	W Bay	F	63	shelly fine sandstone
27	R10/f84	W Bay	G	74	shelly fine sandstone
28	R11/f26	Oneroa Beach	G	65	shelly fine sandstone
29	R11/f27	Oneroa Beach	G	70	shelly fine sandstone

APPENDIX 2 List of foraminifera identified in the early Miocene rocks of Waiheke Island.

Benthic foraminifera

Alabamina tenuimarginata (Chapman, Parr & Collins); Hayward & Buzas 1979, pl. 4, fig. 41.

Amphistegina aucklandica Karrer; Hayward & Buzas 1979, pl. 4, fig. 48, 49.

Anomalinoides fasciatus (Stache); Hornibrook et al. 1989, fig. 18:7.

Anomalinoides macraglabra (Finlay); Hayward & Buzas 1979, pl. 5, fig. 52, 53. This paper Fig. 3:1.

Astrononion parki Hornibrook; Hornibrook et al. 1989, fig. 17:23.

Astrononion stelligerum (d'Orbigny); Hayward & Buzas 1979, pl. 5, fig. 57.

Bolivina acerosa Cushman; Hayward & Buzas 1979, pl. 6, fig. 63.

Bolivina arta Macfadyen; Hornibrook 1961, pl. 10, fig. 184.

Bolivina finlayi Hornibrook; Hayward & Buzas 1979, pl. 6, fig. 67. This paper Fig. 3:2.

Bolivina mahoenuica Hornibrook; Hornibrook 1961, pl. 10, fig. 178, 179.

Bolivina mantaensis Cushman; Hayward & Buzas 1979, pl. 6, fig. 69, 70. This paper Fig. 3:4.

Bolivina plicatella mera Cushman & Ponton; Hayward & Buzas 1979, pl. 5, fig. 61, 62. This paper Fig. 3:3.

Bolivina reticulata Hantken; Hayward & Buzas 1979, pl. 6, fig. 72. This paper Fig. 3:5.

Bolivina semitruncata; Hornibrook et al. 1989, fig. 20:13.

Bolivina silvestrina Cushman; Hayward & Buzas 1979, pl. 6, fig. 73, 74.

Bolivina subcompacta Finlay; Hayward & Buzas 1979, pl. 6, fig. 75.

Bolivina targetensis Hornibrook; Hornibrook 1961, pl. 10, fig. 182, 183.

Bolivina zedirecta Finlay; Hornibrook et al. 1989, fig. 21:23.

Bolivinopsis cubensis; Hornibrook et al. 1989, fig. 15:5.

Buccella frigida; Hornibrook 1961, pl. 15, fig. 314–316. This paper Fig. 3:6.

Bueningia creeki Finlay; Hornibrook et al. 1989, fig. 18:20.

Bulimina cf. *gibba*; Barker 1960, pl. 50, fig. 1–4.

Bulimina pupula Stache; Hayward & Buzas 1979, pl. 7, fig. 83.

Bulimina truncana Gumbel; Hayward & Buzas 1979, pl. 7, fig. 87, 88.

(*Continued*)

APPENDIX 2 (*Continued*)

Buliminella elegantissima (d'Orbigny).
Buliminella missilis Vella; Hayward & Buzas 1979, pl. 7, fig. 89.
Cancris laevinflatus Hornibrook; Hornibrook 1961, pl. 15, fig. 328, 331, 332.
Cancris lateralis Finlay; Hornibrook et al. 1989, fig. 17:24.
Cassidulina laevigata d'Orbigny; Hayward & Buzas 1979, pl. 7, fig. 90. This paper Fig. 3:8.
Cassidulina margareta Karrer; Hayward & Buzas 1979, pl. 7, fig. 91.
Cibicides ihungia Finlay; Hornibrook et al. 1989, fig. 22:5.
Cibicides lobatulus (Walker & Jacob); Hayward & Buzas 1979, pl. 10, fig. 124–126.
Cibicides mediocris Finlay; Hayward & Buzas 1979, pl. 10, fig. 127–129. This paper Fig. 3:9–10.
Cibicides notocenicus Dorreen; Hayward & Buzas 1979, pl. 10, fig. 132–134.
Cibicides novozelandicus Karrer; Hornibrook et al. 1989, fig. 20:7.
Cibicides perforatus (Karrer); Hornibrook et al. 1989, fig. 20:8.
Cibicides refulgens de Montfort; Barker 1960, pl. 92, fig. 7–9.
Cibicides temperatus Vella; Hayward & Buzas 1979, pl. 11, fig. 135–137.
Cibicides vortex Dorreen; Hornibrook et al. 1989, fig. 17:9. This paper Fig. 3:11.
Cribrorotalia ornatissima (Karrer); Hornibrook et al. 1989, fig. 35:6. This paper Fig. 3:12–13.
Cyclammina rotundata Chapman & Crespin.
Discorbinella cf. *vitrevoluta* Hornibrook; Hornibrook 1961, pl. 13, fig. 275–277.
Discorbis balcombensis Chapman, Parr & Collins; Hayward & Buzas 1979, pl. 11, fig. 147.
Discorotalia tenuissima (Karrer); Hornibrook 1961, pl. 18, fig. 387–388.
Dyocibicides biserialis Cushman & Valentine; Hayward & Buzas 1979, pl. 12, fig. 155.
Elphidium advenum (Cushman); Hayward & Buzas 1979, pl. 12, fig. 157. This paper Fig. 3:14.
Elphidium gibsoni Hayward; Hayward & Buzas 1979, pl. 12, fig. 156–160. This paper Fig. 3:15.
Elphidium kanoum Hayward; Hayward & Buzas 1979, pl. 13, fig. 169, 170. This paper Fig. 3:16.
Elphidium nigarense Cushman; Hayward & Buzas 1979, pl. 13, fig. 161–165.
Eoeponidella scotti Hayward; Hayward & Buzas 1979, pl. 14, fig. 171–175.
Epistominella cassidulinoides Hornibrook; Hornibrook 1961, pl. 17, fig. 360, 362, 364.
Epistominella iota Hornibrook; Hornibrook 1961, pl. 17, fig. 359, 361, 363.
Eponides broeckhianus (Karrer); Hornibrook 1961, pl. 15, fig. 321–322.
Evolvocassidulina orientalis (Cushman); Hayward & Buzas 1979, pl. 14, fig. 181.
Fissurina aperta Seguenza; Hayward & Buzas 1979, pl. 16, fig. 200–201.
Fissurina laevigata Reuss; Barker 1960, pl. 114, fig. 8.
Fissurina lucida (Williamson).
Fissurina marginata (Walker & Boys); Hayward & Buzas 1979, pl. 16, fig. 207.
Florilus stachei (Cushman); Hayward & Buzas 1979, pl. 17, fig. 211.
Fursenkoina schreibersiana (Czjzek); Hayward & Buzas 1979, pl. 17, fig. 212.
Gaudryina convexa (Karrer); Hornibrook 1971, pl. 1, fig. 8–15.
Glabratella sp.
Globocassidulina subglobosa (Brady); Hayward & Buzas 1979, pl. 17, fig. 219, 220.
Guttulina problema d'Orbigny; Hornibrook 1961, pl. 7, fig. 118.
Gyroidina subzelandica Hornibrook; Hornibrook 1961, pl. 16, fig. 345–347.
Gyroidina zelandica Finlay; Hayward & Buzas 1979, pl. 18, fig. 221–223.
Hanzawaia bertheloti (d'Orbigny); Hornibrook 1961, pl. 14, fig. 286. This paper Fig. 3:17.
Hanzawaia complanata (Sidebottom); Hornibrook 1961, pl. 27, fig. 532.
Hanzawaia laurisae (Mallory); Hayward & Buzas 1979, pl. 18, fig. 229, 230.
Hanzawaia stachi (Asano); Hayward & Buzas 1979, pl. 8, fig. 97–99.
Haplophragmoides sp.
Haynesina depressulus (Walker & Jacob); Hayward & Hollis in press, pl. 5, fig. 13–16.
Karreria maoria (Finlay); Hayward & Buzas 1979, pl. 19, fig. 233, 234.
Kolesnikovella australis (Heron-Allen & Earland); Hornibrook et al. 1989, fig. 17:8.
Lagena distoma Parker & Jones; Hayward & Buzas 1979, pl. 19, fig. 236.
Lagena cf. *spiralis* Brady; Barker 1960, pl. 114, fig. 9.
Lagena sp.
Lagenoglandulina annula (Stache); Hayward & Buzas 1979, pl. 19, fig. 241.
Lagenosolenia sp.
Lenticulina loculosa (Stache); Hornibrook et al. 1989, fig. 19:25.
Lenticulina nitida (Reuss); Hayward & Buzas 1979, pl. 20, fig. 248, 249.
Lenticulina pseudocalcarata (Stache); Hornibrook et al. 1989, fig. 19:24.
Massilina secans (d'Orbigny).
Melonis simplex (Karrer); Hayward & Buzas 1979, pl. 20, fig. 254, 257. This paper Fig. 3:18.
Miliolinella sp.
Mississippina concentrica (Parker & Jones); Hornibrook et al. 1989, fig. 17:5.
Nodosaria filiformis d'Orbigny; Hornibrook 1961, pl. 6, fig. 92.
Nonion cassidulinoides Hornibrook; Hornibrook 1961, pl. 11, fig. 214, 215.
Nonionella novozealandica Cushman; Hayward & Buzas 1979, pl. 21, fig. 266–271. This paper Fig. 3:19.
Notorotalia powelli Finlay; this paper Fig. 3:20–21.
Oolina globosa (Montagu); Hayward & Buzas 1979, pl. 23, fig. 284, 285.
Oridorsalis umbonatus (Reuss); Hayward & Buzas 1979, pl. 24, fig. 295, 296.
Pileolina cf. *patelliformis* (Brady); Barker 1960, pl. 89, fig. 1.
Pileolina radiata Vella, 1957, pl. 8, fig. 170–171.
Pileolina zealandica Vella; Hornibrook 1961, pl. 13, fig. 254–256.
Planoglabratella semiopercularis Hornibrook; Hornibrook 1961, pl. 13, fig. 260–262.
Quasibolivinella finlayi Hayward; Hornibrook et al. 1989, fig. 40.
Quinqueloculina buchiana d'Orbigny; Hayward & Buzas 1979, pl. 3, fig. 29–31.
Quinqueloculina plana d'Orbigny; Hayward & Buzas 1979, pl. 3, fig. 32–33.
Quinqueloculina schroekingeri Karrer; Hayward & Buzas 1979, pl. 2, fig. 22–23.
Quinqueloculina seminula (Linnaeus); Hayward & Buzas 1979, pl. 3, fig. 34. This paper Fig. 3:22.
Quinqueloculina spp.
Rectobolivina maoriella Finlay; Hayward & Buzas 1979, pl. 24, fig. 305, 306.
Reussella spinulosa (Reuss); Hayward & Buzas 1979, pl. 27, fig. 330.
Sigmavirgulina tortuosa (Brady); Hornibrook et al. 1989, fig. 18:16.
Sigmoidella elegantissima (Parker & Jones); Hornibrook 1961, pl. 7, fig. 119.
Sigmoidina pacifica Cushman & Ozawa; Hayward & Buzas 1979, pl. 15, fig. 198, 199.
Siphotextularia awamoana Finlay; Hornibrook et al. 1989, fig. 20:5.

(*Continued*)

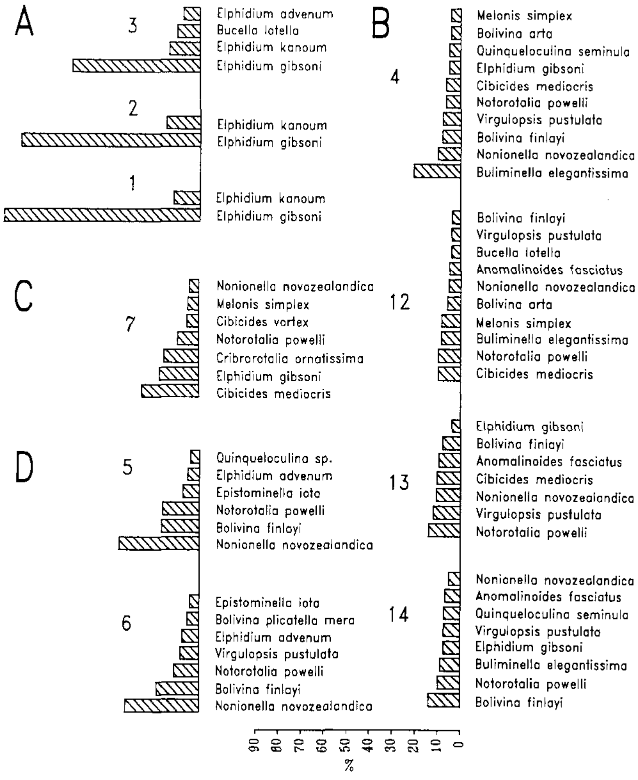
APPENDIX 2 (*Continued*)

Siphouvigerina proboscidea (Schwager); Hayward & Buzas 1979, pl. 27, fig. 334.
Stilostomella fijiensis (Cushman); Hayward & Buzas 1979, pl. 28, fig. 340.
Stilostomella pomuligera (Stache); Hayward & Buzas 1979, pl. 28, fig. 341, 342.
Textularia awamoana Hornibrook; Hornibrook 1961, pl. 1, fig. 11, 12.
Textularia hayi Karrer; Hornibrook 1971, pl. 1, fig. 1–7.
Trifarina bradyi Cushman; Hayward & Buzas 1979, pl. 28, fig. 344.
Trifarina costornata (Hornibrook); Hayward & Buzas 1979, pl. 28, fig. 345.
Trifarina esuriens (Hornibrook); Hayward & Buzas 1979, pl. 28, fig. 346.
Trifarina parva Hornibrook; Hornibrook et al. 1989, fig. 17:7. This paper Fig. 3:24.
Triloculina tricarinata d'Orbigny; Barker 1960, pl. 3, fig. 17.
Triloculina trigonula (Lamarck); Hayward & Buzas 1979, pl. 3, fig. 39.
Uvigerina minima (Vella, 1961), pl. 2, fig. 8–10.
Valvulineria cf. *saulcyi* (d'Orbigny); Hornibrook et al. 1989, fig. 21:15.
Virgulopsis cf. *costata* Hornibrook; Hornibrook et al. 1989, fig. 20:20.
Virgulopsis pustulata Finlay; Hornibrook et al. 1989, fig. 21:17. This paper Fig. 3:25.

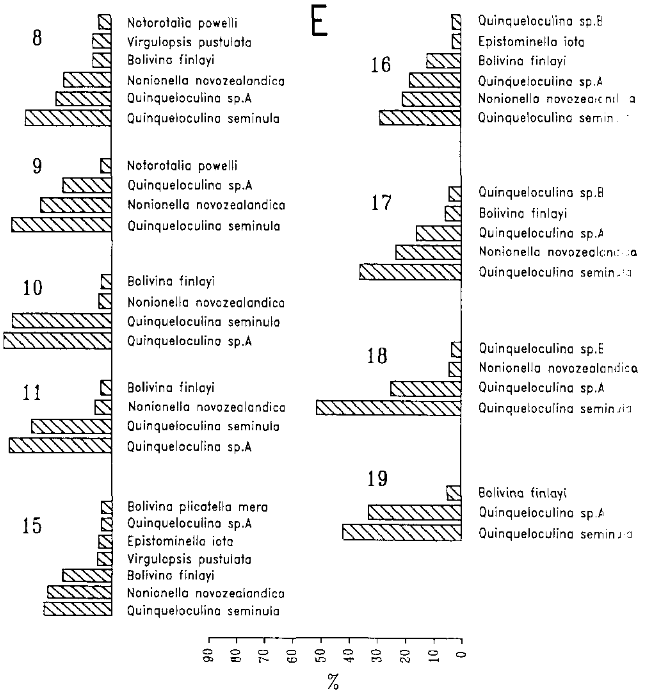
Planktic foraminifera

Globigerina ciperoensis Bolli; Hornibrook et al. 1989, fig. 26:15.
Globigerina falconensis Blow; Jenkins 1971, pl. 16, fig. 463–465.
Globigerina woodi Jenkins; Hornibrook et al. 1989, fig. 27:5.
Globigerinita incrusta Akers; Jenkins 1971, pl. 19, fig. 585–587.
Globoquadrina dehiscens (Chapman, Parr & Collins); Hornibrook et al. 1989, fig. 26:18.
Globorotalia nana Bolli; Hornibrook et al. 1989, fig. 25:18.

APPENDIX 3 Abundance histograms for dominant species (>3%) in samples in associations A, B, C and D.



APPENDIX 4 Abundance histograms for dominant species (>3%) in samples in association E.



APPENDIX 5 Abundance histograms for dominant species (>3%) in samples in associations F and G.