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## Recent benthic foraminifera from offshore Taranaki, New Zealand

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**Abstract** Paleobathymetric estimates based on fossil foraminiferal faunas play an important role in understanding the paleogeographic, structural, and burial history of New Zealand's most important hydrocarbon-bearing sedimentary basin—the Taranaki Basin. Bathyal and abyssal estimates have large ranges of uncertainty, which might be improved using knowledge of the depth distribution patterns of Recent benthic foraminifera in the same region.

Four benthic foraminiferal groups (and 9–10 associations) are recognised and mapped in the offshore Taranaki region (0–2150 m depth, eastern Tasman Sea), based on two separate cluster analyses of census data (231 species, 39 samples) on faunas with tests  $>63$  and  $>150$   $\mu\text{m}$ . The same depth pattern can be identified using 63 or 150  $\mu\text{m}$  faunas, although there are major differences in the dominant taxa. Canonical correspondence analysis and correlation coefficients suggest that the distribution patterns are strongly depth related: (1) inner shelf (0–50 m) associations (both shell-size fractions) are dominated by *Rosalina irregularis* and *Zeaflorilus parri*; (2) outer shelf–uppermost bathyal (50–550 m) associations are dominated by *Bulimina marginata* s.s. and *Discorbinella bertheloti* (both sizes) plus *Cassidulina carinata* ( $>63$   $\mu\text{m}$ ) or *Cibicides dispars* ( $>150$   $\mu\text{m}$ ); (3) middle–lower bathyal (500–1500 m) associations are dominated by *C. carinata-Alabaminella weddellensis-Abditodentrix pseudothalmanni* ( $>63$   $\mu\text{m}$ ) and *Uvigerina peregrina-Bulimina marginata* f. *aculeata* ( $>150$   $\mu\text{m}$ ); and (4) lower bathyal to upper abyssal (1400–2150 m) associations are dominated by *B. marginata* f. *aculeata* and *Globocassidulina subglobosa* (both) plus *A. weddellensis* ( $>63$   $\mu\text{m}$ ) or *U. peregrina-Oridorsalis umbonatus* ( $>150$   $\mu\text{m}$ ).

Comparison of the  $>63$   $\mu\text{m}$  Taranaki (west coast) faunal data with a similar dataset from east of New Zealand shows significant differences in composition, relative abundance levels, and depth ranges of common species, which appear to be a result of differences in primary productivity, translated into organic carbon flux (food). Since organic carbon flux

reaching the seafloor decreases progressively with increasing water depth, we infer that this is the major factor producing the strong depth-related distributional pattern of deep-sea benthic foraminiferal faunas observed around New Zealand. Thus, highly accurate estimates of paleobathymetry are unlikely using benthic foraminifera, unless organic carbon flux has remained unchanged.

Notwithstanding the differences between the west and east coasts, there are sufficient similarities and trends that are bathymetrically consistent to be useful in improving paleobathymetric estimates. These include, in decreasing order of reliability: upper depth limits of key benthic species; recognition of benthic foraminiferal associations; and relative abundance of planktic foraminifera. Species diversity measures show no useful pattern with depth.

**Keywords** New Zealand; offshore Taranaki; New Caledonia Basin; deep-sea benthic foraminifera; species associations; paleobathymetric assessment; species diversity; upper water depth limits; primary productivity; carbon flux

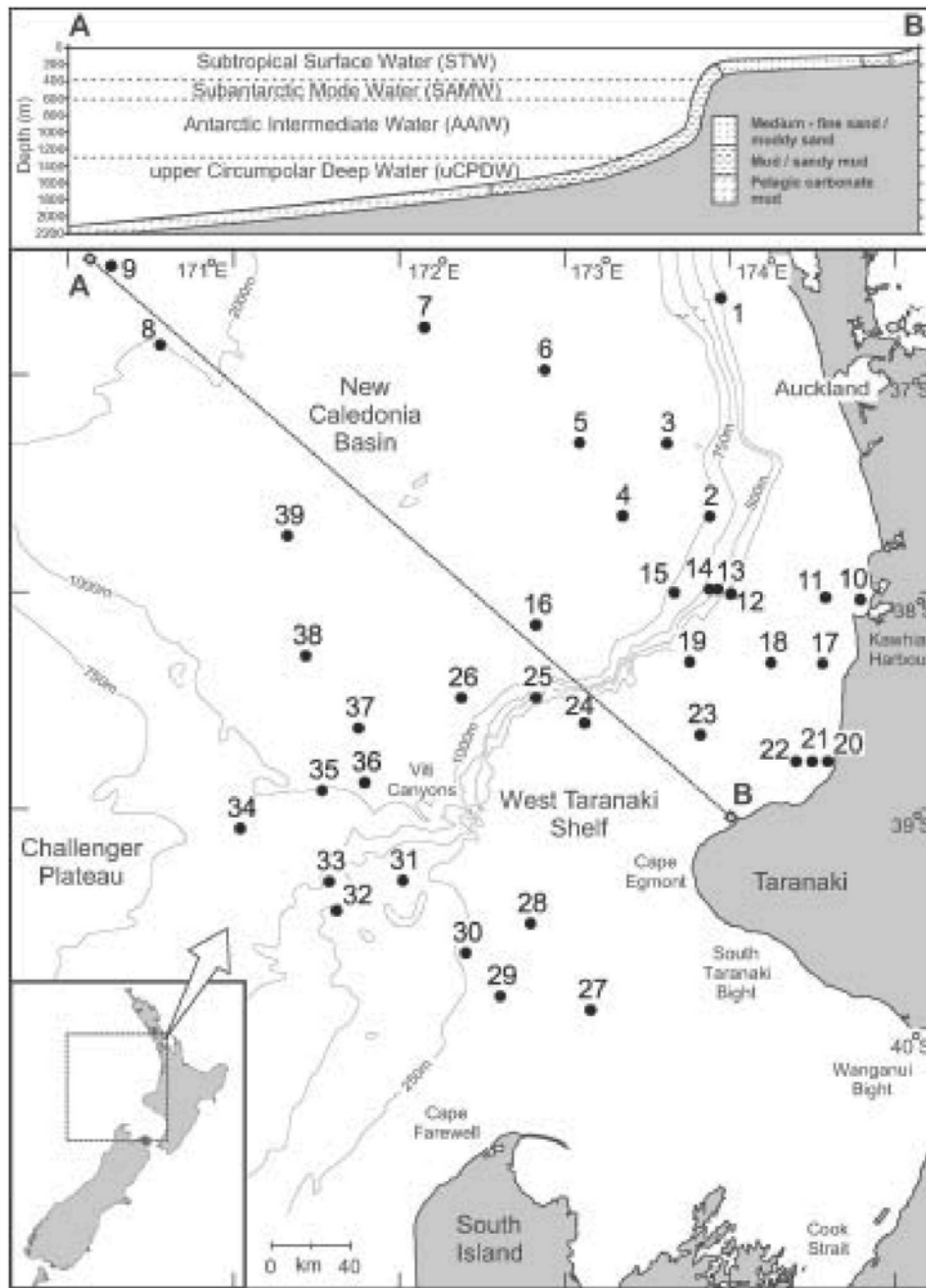
### INTRODUCTION

This paper documents the present-day depth distribution of benthic foraminifera in the east Tasman Sea, west of New Zealand, targeting various aspects of the faunal composition that may be of potential use in improving the precision of paleobathymetric estimates of fossil Neogene foraminiferal faunas, particularly those in the adjacent and underlying Taranaki hydrocarbon basin (King & Thrasher 1996). We also use proxy environmental data in an attempt to determine the more significant environmental causes of the observed distributional pattern of the benthic foraminiferal faunas.

The ecological distribution of deep-sea benthic foraminifera is determined by the complex interplay of a number of physical and biological factors (e.g., Murray 1995). The resulting benthic foraminiferal distribution usually exhibits a zonation that is roughly coincident with increasing water depth, but absolute depths and taxonomic composition of these zonations vary from region to region (e.g., Culver 1988; Murray 1991).

### Previous work

The only previous work on Recent benthic foraminifera from the study area has been the lists of species recorded by Brady (1884) from Challenger stations 166 and 167 (100–800 m) off the southwest corner of the outer Taranaki shelf. To the north of the study area, off the west coast of Northland, Hedley et al. (1965) recorded and illustrated a fauna of 53 benthic foraminifera from 87 m off Northland. Southeast of the study area, Vella (1957) listed and described the benthic foraminifera in a number of stations in the Cook Strait region, and Hayward et al. (1997) documented and mapped the ecological distribution of benthic foraminiferal faunas in 30



**Fig. 1** *Bottom*: Location of seafloor sediment samples in the Tasman Sea, west of New Zealand. *Top*: Bathymetric cross-section (A–B) through the study area showing idealised water mass distribution (after Garner 1962, 1967; Garner & Ridgeway 1965).

stations at 10–110 m depth in Wanganui Bight. Other nearby studies have focused on foraminiferal faunas in intertidal or shallow harbour and estuarine settings—intertidal west Northland (Hayward 1979, 1986a), intertidal New Plymouth, Taranaki (Hedley et al. 1967), Waimamaku Estuary, west Northland (Hollis et al. 1995), Manukau Harbour, Auckland (Hulme 1964), Queen Charlotte Sound, Marlborough (Hayward et al. 1997), and Pauatahanui Inlet, Wellington (Hayward & Triggs 1994).

A similar quantitative study to that reported here on deep-water benthic foraminiferal distribution patterns has been undertaken off the east coast of New Zealand at depths of 100–4600 m (Hayward et al. 2001, 2002). The only other quantitative studies of deeper water faunas (>100 m) around New Zealand are described in the unpublished theses of Thompson (1975) and Hoskins (1978), both east of the

northern North Island. There have been numerous other New Zealand studies documenting the depth distribution of shallow-water (<100 m) benthic foraminifera based on quantitative census counts of faunas (summarised by Hayward et al. 1999).

#### Paleobathymetric assessment methods

Vella (1962) and Kennett (1962) documented a method for determining the depth of deposition of New Zealand Neogene foraminiferal faunas. This was achieved by the qualitative recognition of eight foraminiferal assemblages, based on their dominant benthic genera and the percentage of planktics. This method has been used to determine paleobathymetry in a number of studies of New Zealand's late Miocene and younger sequences (e.g., Vella 1963; Kennett 1966; Collen 1972).

Another method of rapid paleobathymetric assessment using New Zealand Cenozoic foraminiferal faunas was suggested by Hayward (1986b) and Hayward et al. (1999). Instead of recognising assemblages, it utilises the known modern depth ranges around New Zealand of each of the dominant benthic species in the fauna, together with the planktic percentage and upper depth limits of key rarer benthic species. This method was used in an analysis of over 1000 Cenozoic assemblages in a study of the paleogeographic and tectonic history of Taranaki Basin (Hayward 1990). Similar methods have been used in conjunction with multivariate analysis techniques for studies of New Zealand sedimentary basin paleogeography and evolution (e.g., Scott 1970, 1971; Hayward & Buzas 1979; King et al. 1993; Hayward & Brook 1994), and Pliocene–Pleistocene sequence stratigraphy (e.g., Haywick & Henderson 1991; Naish & Kamp 1997; Kamp et al. 1998).

A non-uniformitarian method was used by Hayward (1990) and Crundwell et al. (1994), whereby upper depth limits of key bathyal species were determined in prograding Neogene drillhole sequences off Taranaki. The highest occurrences of these species was calibrated to absolute depths by determining their decompacted depth below the seismically determined shelf break of c. 200 m depth.

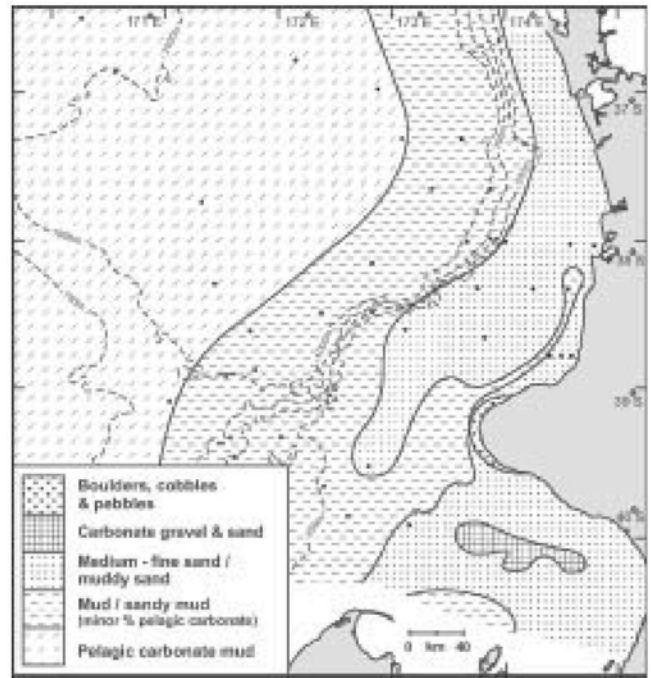
These, and similar methodologies used outside the New Zealand region (e.g., Murray 1991) to estimate paleobathymetry from fossil foraminiferal faunas, mostly utilise a combination of the planktic foraminiferal percentage, benthic foraminiferal taxonomic composition (species, genus, and order levels) and relative abundance, and benthic species diversity measures. These are discussed below. Several workers outside New Zealand (e.g., Gary et al. 1989; Spencer 1996) have utilised intraspecific morphological variation of benthic foraminifera with depth to assist paleobathymetric determinations, but this aspect has not been investigated here, except in the case of the various forms of *Bulimina marginata*.

### Location

The study region of c. 150 000 km<sup>2</sup>, lies beneath the eastern Tasman Sea, west of the North Island of New Zealand, between latitudes 36 and 40°S and longitudes 170 and 175°E. The region was chosen because it directly overlies the hydrocarbon-bearing Cretaceous–Cenozoic Taranaki sedimentary basin (King & Thrasher 1996) and its northwestern extension beneath the New Caledonia Basin. Stations were chosen to provide several transects across the shelf, down the continental slope, and out to upper abyssal depths of 2150 m in the New Caledonia Basin.

### Physiographic setting

The area studied extends out into the New Caledonia Basin to the northwest and is bounded by the Challenger Plateau to the southwest and coast of the North Island to the east (Fig. 1). It includes a broad continental shelf (the West Taranaki Shelf which widens to the south), a narrow continental slope, the gentle slopes of Challenger Plateau (mid-bathyal), and the flat floor of the New Caledonia Basin (lower bathyal). Bathymetric terminology in this paper follows van Morkhoven et al. (1986): inner shelf = 0–50 m, mid-shelf = 50–100 m, outer shelf = 100–200 m, upper bathyal = 200–600 m, mid-bathyal = 600–1000 m, lower bathyal = 1000–2000 m, upper abyssal = 2000–4000 m.

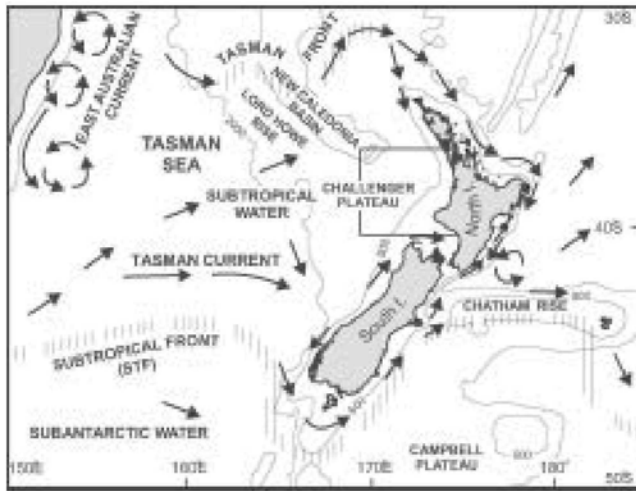


**Fig. 2** Seafloor sediment patterns in the offshore Taranaki study area, west of New Zealand (after Lewis & Eade 1974; McDougall 1975; Arron & Doyle 1983; Nodder et al. 1992).

### Modern sediments

On the shelf, the surficial sediment distribution in a simplified form (Fig. 2) consists of belts of sediment paralleling the coast (Kibblewhite 1974; Lewis & Eade 1974; McDougall 1975; Arron & Doyle 1983; Nodder et al. 1992). The area is dominated by mud or sandy mud but significant bodies of fine to medium sand, coarse sand and shell gravel (probably relict), and cobble and boulder beds are also present. The broad, flat continental shelf between Kawhia Harbour and Cape Egmont is covered by medium to fine sand or muddy medium to fine sand. To the south and west of Cape Egmont, the shelf is mainly floored with mud or sandy mud. The area to the southwest of the Viti Canyons is covered by a variety of sediment types, some of which may be relict, including sand with subsidiary gravel. The South Taranaki and Wanganui Bights have a variety of sediments, some of which are probably relict ranging from mud, medium to fine sand, benthos carbonate, to cobble and pebble gravel. Beyond the continental shelf break and to a depth of c. 1600 m the sediment is sandy mud, with the sand fraction being >20% pelagic carbonate. In the New Caledonia Basin at lower bathyal depths, the sediment is pelagic carbonate mud or sandy mud. In general terms, grain-size data from our suite of samples support the previously determined sediment distribution pattern (Fig. 2).

Martinez (1994) estimated the modern lysocline at c. 3100 m in a southwest–northeast transect through the New Caledonia Basin (east Tasman Sea). Thus, the area studied lies well above the calcium carbonate compensation depth (CCD).



**Fig. 3** Surface currents (from Heath 1985) around New Zealand and through the study area off Taranaki, west of New Zealand (boxed).

### Water masses, currents, food supply/productivity

Two major surface water gyres cross the Tasman Sea (Fig. 3). A warm subtropical anticyclonic gyre coming from the northeast produces the East Australian Current, which is deflected from the Australian coast at c. 30°S along the Subtropical Divergence (the Tasman Front). A second cool subtropical cyclonic gyre originates in the southern part of the west Tasman Sea and meets subantarctic waters along the Subtropical Front (STF) at c. 45°S (Martinez 1994).

The study area is covered by a cool subtropical surface water mass (Subtropical Surface Water, STW). Surface circulation is dominated by the east–northeast-flowing Tasman Current. This current results from the interaction of the Subantarctic Surface Water (SASW) of the West Wind Drift to the south with a complex system of anticyclonic eddies formed off southeastern Australia and tropically derived waters of the East Australian Current (Stanton 1973; Head & Nelson 1994). Geostrophic flow in the area is weak, but an anticyclonic eddy may exist (Garner 1970; Ridgway et al. 1975; Bradford & Roberts 1978). Sea surface temperatures ( $T$ ) for the area in February/March are 18–20°C and salinity ( $S$ ) is  $35.3 \times 10^{-3}$  (Heath 1985). Annual mean sea-surface temperatures of 16–17°C have been calculated from satellite-derived data (Uddstrom & Oien 1999).

The deeper water masses in the area include in deepening order (Fig. 1): Subantarctic Mode Water (SAMW; c. 400–600 m), Antarctic Intermediate Water (AAIW; c. 600–1300 m,  $T$  3–6°C,  $S$   $34.4 \pm 0.1 \times 10^{-3}$ ), and Circumpolar Deep Water (CPDW; c. 1300–4000 m,  $T$  1–3°C,  $S$   $34.7 \pm 0.1 \times 10^{-3}$ ). The upper CPDW is characterised by an oxygen minimum of 3.0–3.5 mol/kg). The northward-flowing AAIW is derived from cooling and sinking of surface waters at the Antarctic Convergence (55–60°S) (Warren 1973; Gordon 1975; Heath 1985; Head & Nelson 1994). Heath (1972) found evidence for cyclonic movement in AAIW at c. 800 m on the northern boundary of the Challenger Plateau. Deeper waters, such as lower CPDW and Antarctic Bottom Water (AABW), are present only in the west Tasman Sea, as the Lord Howe Rise acts as a barrier preventing these waters from flowing directly into the east Tasman Sea (Martinez 1994).

### Nutrients

Over and southwest of the Challenger Plateau, scattered high values of reactive phosphorus indicate some nutrient enrichment, but the values are generally low (Bradford & Roberts 1978). Although based on scant data, surface chlorophyll  $a$ , primary productivity, and integrated primary productivity concentrations also appear to be low over the area studied (Bradford 1980b–e) and can be correlated with reactive phosphorus. The analysis of satellite chlorophyll data by Behrenfeld & Falkowski (1997) suggests that this area of the Tasman Sea has only a low annual and a moderate seasonal phytoplankton primary production rate ( $100\text{--}200 \text{ g C m}^{-2} \text{ yr}^{-1}$ ). Murphy et al. (2001) presented satellite chlorophyll  $a$  data for a 3 yr period (1997–99). For the spring bloom period (Sep–Nov), chlorophyll  $a$  concentrations varied from c.  $0.3\text{--}1.0 \text{ mg m}^{-3}$  (1997), c.  $0.5\text{--}1.0 \text{ mg m}^{-3}$  (1998), to c.  $0.3\text{--}1.6 \text{ mg m}^{-3}$  (1999). Moderate to high values of zooplankton biomass are recorded for the continental shelf areas of the North and South Taranaki Bights (Bradford & Roberts 1978; Bradford 1980a). Although no upwellings are reported in the area studied, upwelling in the vicinity of Cape Farewell off the West Coast of the South Island does result in the northwards transport of zooplankton and its enhanced productivity into the south Taranaki Bight (Foster & Battaerd 1985).

### Samples

Thirty-nine seafloor sediment samples used in this study (Appendix 1) were largely taken from the store of the National Institute for Water and Atmospheric Research (NIWA), having been sampled by a variety of grab and piston core techniques over the past 20–30 yr. This set of samples was supplemented by two seafloor dredge samples taken by the authors from close inshore off northern Taranaki and held by the Auckland War Memorial Museum (L24022, L24025). Grabs, piston cores, and dredges often “blow-away” and do not collect soft, flocculent sediment that may be on the seafloor surface. The samples in this study presumably came from the upper 5–7 cm of seafloor sediment, and because the majority were from archival material, no staining could be undertaken to identify foraminifera that were live at the time of sampling. Thus, this study is based on the total faunas (dead plus live) in the near-surface seafloor sediment.

Samples from the steep, 1000 m high, continental slope are under-represented in the study because of unavailability. Faunal slides (prefixed by F202...) and figured specimens (prefixed by BWH or FP) are housed in the collections of the Institute of Geological & Nuclear Sciences, Lower Hutt.

### Laboratory methods

Weighed samples were washed over a 63  $\mu\text{m}$  sieve and the sand residue dried, weighed, and microsplit to an amount containing c. 200 benthic specimens. All benthic foraminifera were picked from the split, mounted on faunal slides, identified, and counted. The percentage of planktic specimens in each foraminiferal fauna was determined during picking. Similar census data were obtained for foraminiferal faunas in splits of  $>150 \mu\text{m}$  sand in the same 39 samples. As the archival sediment samples had not been preserved or stained at the time of collection, it was not possible to distinguish between specimens that were dead or live at the time of collection. A reference list of the common species referred to in this paper is given in Appendix 2 and most are figured

in Fig. 4. Faunal samples from sand  $>63 \mu\text{m}$  have been given an S suffix; those from sand  $>150 \mu\text{m}$  have been given an L suffix.

To determine the planktic foraminiferal fragmentation index (FRAG), a second microsplit of the sand residue ( $>63 \mu\text{m}$ ) was examined and the numbers of whole (4 or more chambers together) and fragmented planktic foraminiferal tests were counted. FRAG was calculated using the formula of Le & Shackleton (1992), where each planktic foraminiferal test is assumed to fragment along the less calcified sutures into eight pieces during dissolution.

## RELATIVE ABUNDANCE OF PLANKTIC FORAMINIFERA

The percentage relative abundance of planktic forms in a fossil foraminiferal fauna is often used as a general indication of the paleodepth of accumulation (e.g., Gibson 1989; Hayward et al. 1999; Van der Zwaan et al. 1999), as there is usually, but not always, a trend of increasing relative abundance with increasing water depth in modern seafloor sediments (e.g., Hayward et al. 2002). In this study, the planktic percentage (Fig. 5) displays the normal pattern of increase with increasing degree of oceanicity and increasing depth (e.g., Hayward et al. 1999, fig. 41). Similar patterns and ranges of values are given by both the  $>63 \mu\text{m}$  and the  $>150 \mu\text{m}$  faunal data (Fig. 5). At inner shelf depths (0–50 m), planktics comprise 0–16%; mid-shelf depths (50–100 m) 13–28%; outer shelf depths (100–200 m) 23–51%; upper and mid-bathyal (200–1000 m) 42–92%, except one station (12) with unusually low values of 22 and 35% at 238 m; lower bathyal (1000–2000 m) 63–96%. These values are similar to those observed in several samples west of the northern North Island (Hayward 1986a), except in that study inflated values of 3–40% planktics were recorded intertidally due to persistent onshore winds and seas.

At shelf and upper bathyal depths in the present study, planktic percentage patterns more strongly reflect the bathymetry than distance from land (Fig. 5). At middle–lower bathyal depths, however, the reverse is true, with planktic percentage correlating more with distance from land than bathymetry (as reflected in the 90% abundance contour in Fig. 5).

These planktic percentage values are similar with respect to bathymetry to those documented east of New Zealand (Hayward et al. 2001) and confirm their general validity as a proxy for paleobathymetry as well as paleoceanicity. As a general guide, a value  $<50\%$  is suggestive of shelf depths and  $>50\%$  is suggestive of bathyal or abyssal depths above the CCD.

## PLANKTIC FORAMINIFERAL FRAGMENTATION INDEX

Progressive carbonate dissolution of foraminiferal shells on the seafloor occurs within the foraminiferal lysocline (Berger 1968). This is where bottom waters start to become undersaturated in carbonate, but dissolution is also controlled by seafloor sediment pH as influenced by the abundance of organic carbon content, independent of water depth (Martinez 1994; Weaver et al. 1997), and by bottom currents that stir corrosive solutions around sedimented carbonate particles (Le & Shackleton 1992).

One of the most commonly used methods for assessing carbonate dissolution of seafloor sediments is the ratio of fragmented to whole planktic foraminiferal tests (Planktic Foraminiferal Fragmentation Index, FRAG, Le & Shackleton 1992; Martinez 1994). In our study, FRAG has its highest values (8–80%) at inner shelf depths off the coast of North Taranaki (Fig. 6). These sporadically elevated values are clearly unrelated to carbonate dissolution and are probably the result of physical fragmentation in relatively high energy conditions.

A belt of slightly elevated FRAG values (10–20%) approximates the position of the continental slope with extensions onto the outer shelf and into lower bathyal depths around the foot of the slope (Fig. 6). The explanation for these higher values is unclear, but they could result from abrasion with increased levels of downslope transport in the vicinity of the steeper seafloor. They could also be a result of enhanced dissolution, if organic carbon content of the sediment in this belt is higher, but we have no data on this.

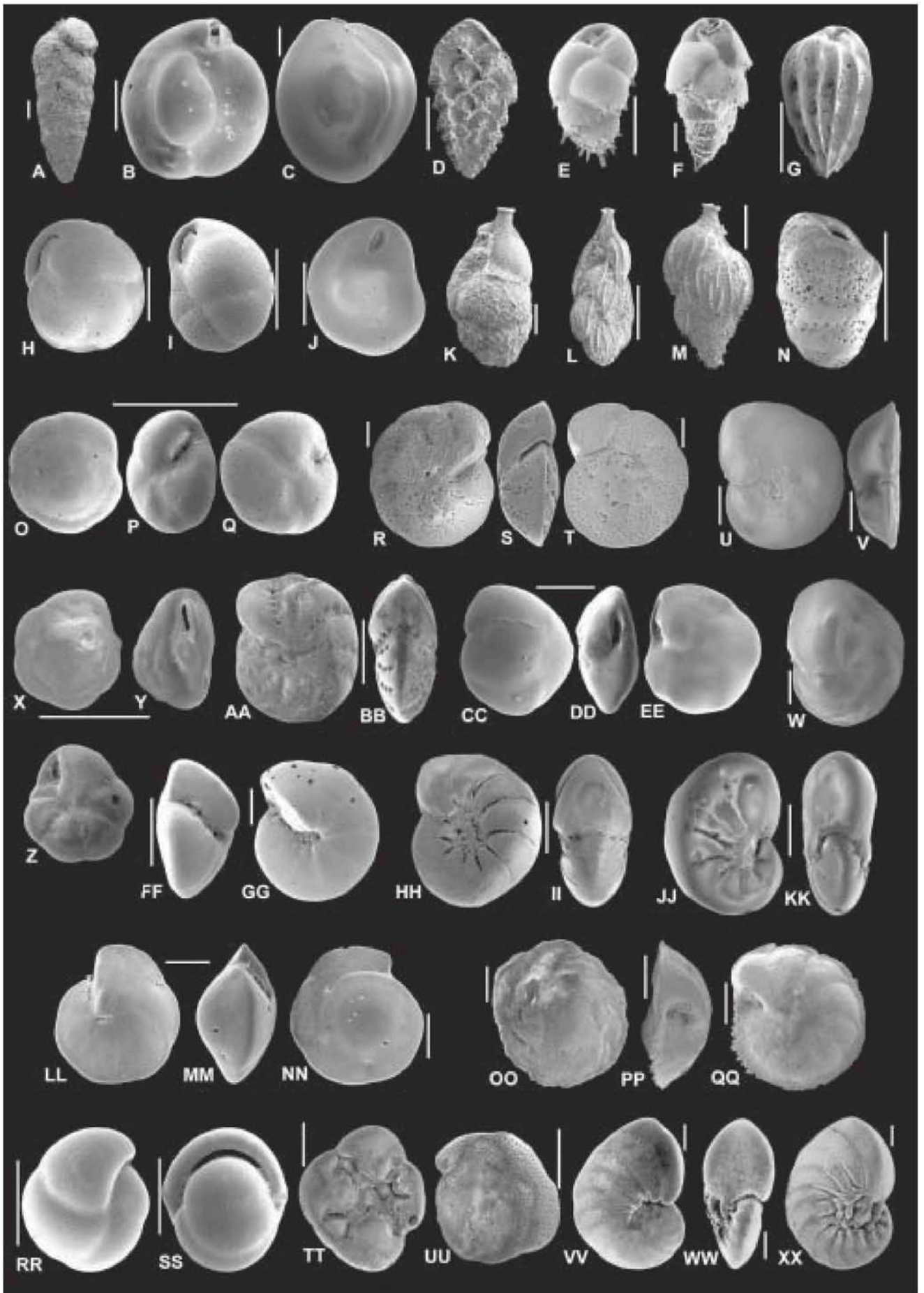
The deepest samples (2000–2150 m) in this study have low FRAG values of  $<10\%$ , indicating that the foraminiferal lysocline is considerably deeper.

## SPECIES DIVERSITY

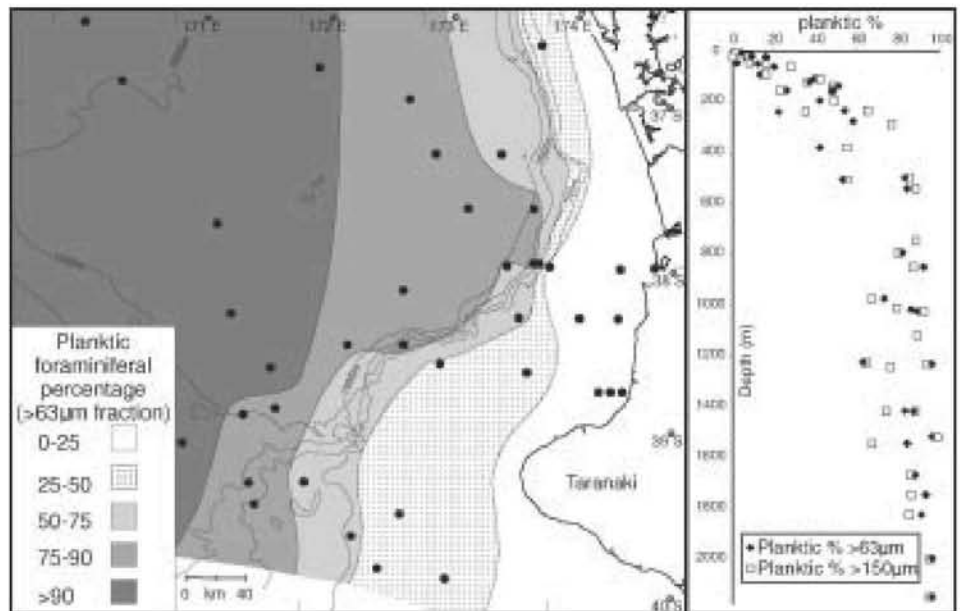
Four indices of species diversity of benthic foraminiferal faunas are sometimes suggested as useful indicators of paleobathymetry and paleoenvironment (Buzas & Gibson 1969; Murray 1973; Hayward & Buzas 1979). These indices (described and defined in Hayek & Buzas 1997) are: (1) species richness, S (number of species in raw census count); (2) Fisher Alpha Index,  $\alpha$  (number of species standardised by number of individuals); (3) Information Function, H (dependent on combination of the evenness of species counts and to a lesser extent the number of species present); and (4) Evenness, J (a measure of dominance versus evenness of species counts). Calculated values for each of our foraminiferal faunas (both  $>63 \mu\text{m}$  and  $>150 \mu\text{m}$ ) are presented in Appendix 1, and  $\alpha$  and J are plotted against depth in Fig. 7.

Our values for  $\alpha$ , H, and J for shelf, bathyal, and upper abyssal faunas (both size fractions) are within the range reported elsewhere for these depths (e.g., Culver & Buzas 2000; Hayward et al. 2001). Species diversity ( $\alpha$ ) ranges between 3 and 18, with values slightly higher overall for  $>63 \mu\text{m}$  faunas than for the coarser fraction (Fig. 7). With minor exceptions (e.g., stations 20 and 25) there is a trend towards increasing alpha across the shelf to a peak in the upper bathyal ( $\alpha=16$ –18) and declining again to more even values in the lower bathyal and upper abyssal (Fig. 7). This trend is the same as that observed in benthic foraminiferal diversity in the North Atlantic, where species diversity also increased to a maximum at upper bathyal depths before a gentle decline into the abyssal (Buzas & Gibson 1969; Gibson & Buzas 1973). East of New Zealand, however, species diversity lacks an upper bathyal peak and continues to increase through the bathyal and abyssal (Hayward et al. 2001). Evenness ranges between 0.54 and 0.90, with values slightly higher overall (greater dominance) for  $>63 \mu\text{m}$  faunas than for the coarser fraction (Fig. 7). There is no apparent correlation nor trend between J, H, and bathymetry (Fig. 7).

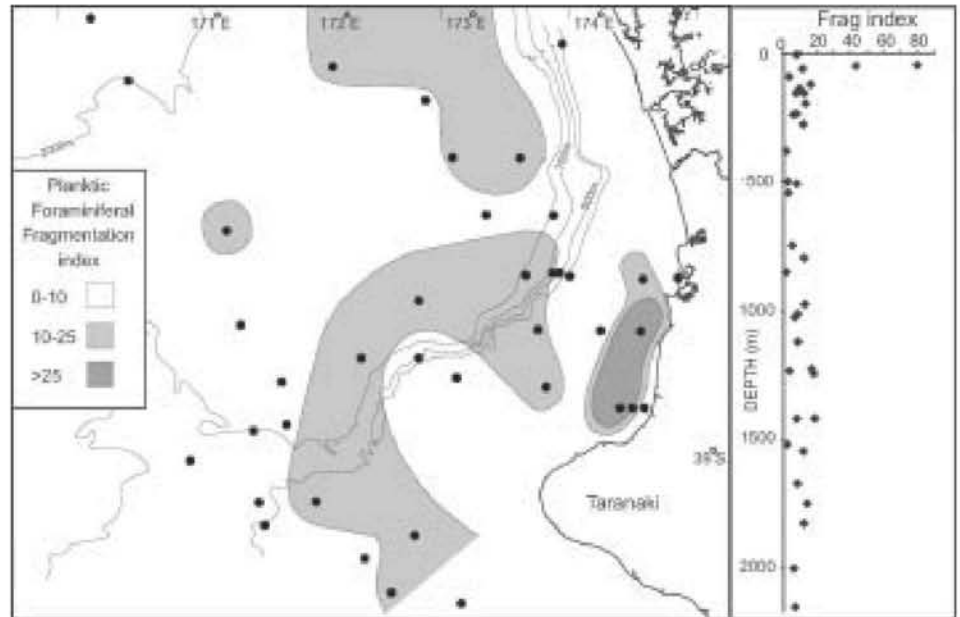
Our data suggest that only the Fisher Alpha Index has potential value in helping to discriminate between shelf, upper bathyal, and greater depths (600–2150 m).



**Fig. 5** Mapped distribution of the planktic percentage composition of total seafloor foraminiferal faunas (>63 µm), west of New Zealand, and graph of planktic percentage (>63 and >150 µm) against water depth.

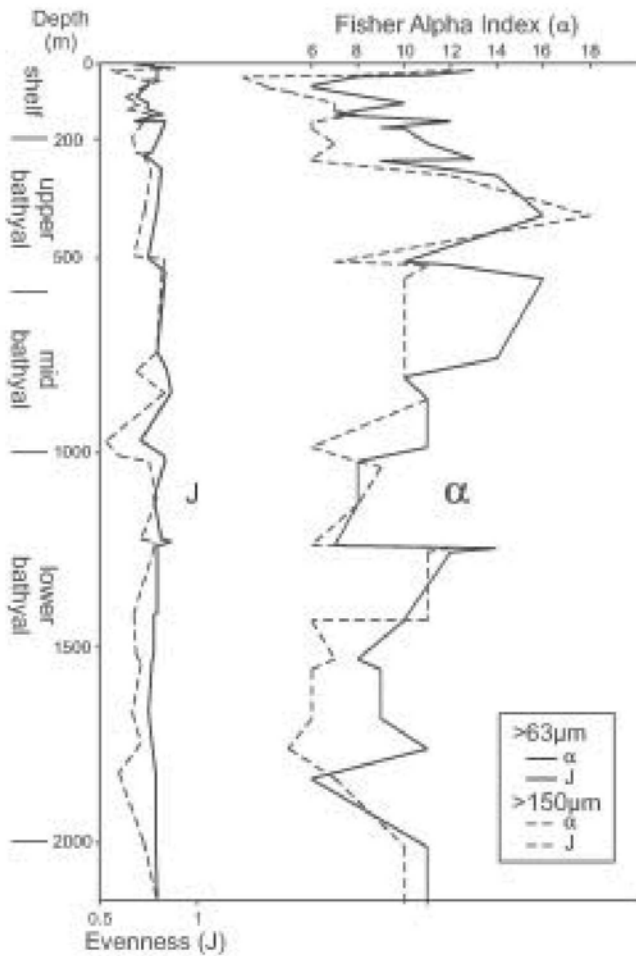


**Fig. 6** Mapped distribution of planktic foraminiferal fragmentation index (in >63 µm faunas) in seafloor sediment samples, and graph of fragmentation index against water depth (>63 µm) in the offshore Taranaki study area, west of New Zealand.



**Fig. 4** (opposite) Scanning electron photographs of common deep-sea benthic foraminifera from New Zealand (scale bars = 100 µm). **Order Textulariida:** **A**, *Siphotextularia rolshauseni* Phleger & Parker. BWH137/41, NIWA stn H380, 100 m. **Order Miliolida:** **B**, *Miliolinella subrotunda* (Montagu) BWH118/15, stn K769, 57 m. **C**, *Quinqueloculina seminula* (Linnaeus). BWH154/34, stn C271, 91 m. **Order Bulminida:** **D**, *Abditodentrix pseudothalmani* (Boltovskoy & Guissani de Kahn). BWH138/8, stn R657, 1408 m. **E**, *Bulimina marginata* f. *aculeata* d'Orbigny. BWH138/32, stn J1008, 2840 m. **F**, *Bulimina marginata* f. *marginata* d'Orbigny. BWH118/5, stn K784, 85 m. **G**, *Bulimina truncana* Gumbel. BWH138/11, stn R657, 1408 m. **H**, *Cassidulina carinata* Silvestri. BWH138/2, stn J1008, 2840 m. **I**, *Cassidulina nørvangi* Thalmann. BWH140/28, stn J1003, 2332 m. **J**, *Globocassidulina subglobosa* (Brady). BWH154/10, stn G831, 1748 m. **K**, *Neouvigerina proboscidea* (Schwager). BWH140/21, stn C618, 623 m. **L**, *Trifarina occidentalis* (Cushman). BWH139/19, stn F755, 854 m. **M**, *Uvigerina peregrina* Cushman. BWH140/4, stn U938, 2700 m. **N**, *Virgulopsis turris* (Heron-Allen & Earland). BWH154/38, stn L24022, 22 m. **Order Rotaliida:** **O–Q**, *Alabaminella weddellensis* (Earland). BWH138/4–5, stn H599, 2424 m. **R–T**, *Cibicides dispars* (d'Orbigny). BWH154/1,4, stn E898, 506 m. **U–W**, *Discorbinella bertheloti* (d'Orbigny). BWH 154/11,12, stn B657, 155 m. **X–Z**, *Eilohedra levicula* (Resig). BWH154/17,16,18 stn E898, 506 m. **AA, BB**, *Elphidium charlottense* (Vella). BWH154/41, stn C279, 18 m. **CC–EE**, *Epistominella exigua* (Brady). BWH138/37,35,39, stn H559, 2424 m. **FF, GG**, *Gyroidinoides soldanii* (d'Orbigny). BWH139/11,9, stn C620, 752 m. **HH, II**, *Haynesina depressula* (Walker & Jacob). BWH154/43, stn C279, 18 m. **JJ, KK**, *Nonionellina flemingi* (Vella). BWH154/48, stn L24025, 6 m. **LL–NN**, *Oridorsalis umbonatus* (Reuss). BWH125/26,27, N554, 98 m. **OO–QQ**, *Osangularia bengalensis* (Schwager). BWH154/22,21, stn G831, 1748 m. **RR**, *Pullenia bulloides* (d'Orbigny). BWH141/56, stn Q859, 3654 m. **SS**, *Pullenia bulloides* (d'Orbigny). BWH138/19, stn J1008, 2840 m. **TT**, *Rosalina irregularis* (Rhumbler). BWH154/44, stn L24025, 6 m. **UU**, *Rosalina irregularis* (Rhumbler) BWH154/46, stn L24025, 6 m. **VV**, *Zeafloorilus parri* (Cushman). BWH116/14; stn H692, 24 m. **WW, XX**, *Zeafloorilus parri* (Cushman). BWH116/13, stn H692, 24 m.





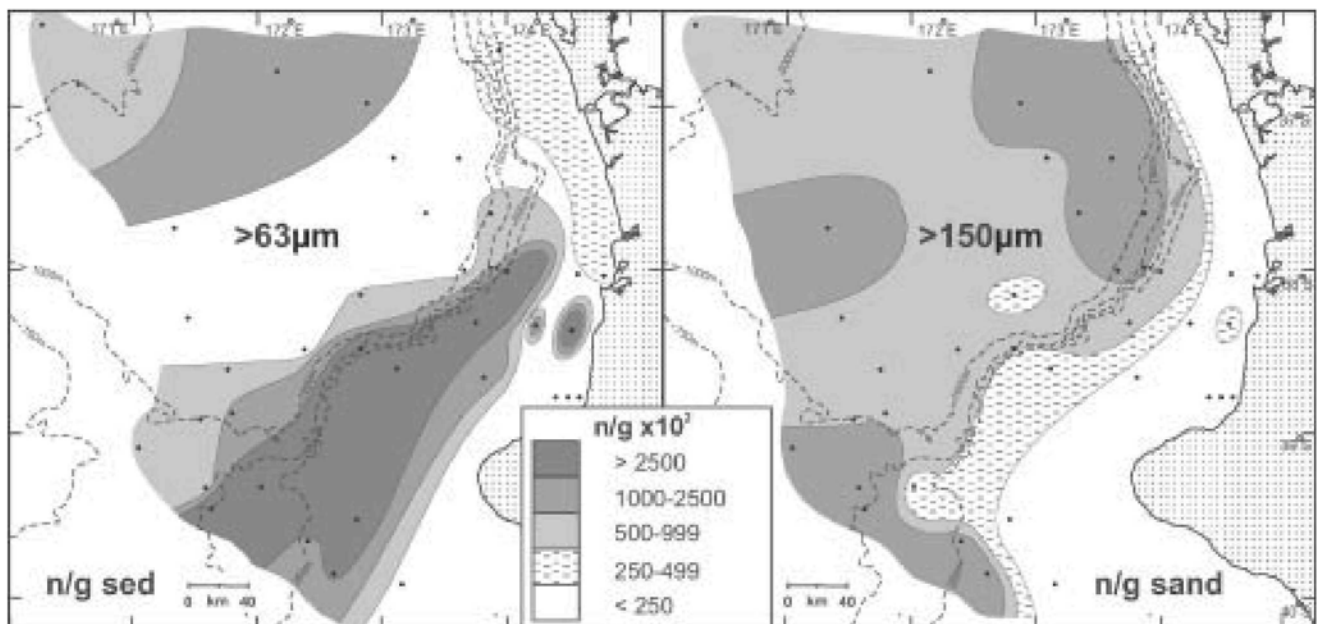
**Fig. 7** Species diversity (Fisher Alpha Index,  $\alpha$ ) and Evenness (J) for  $>63 \mu\text{m}$  and  $>150 \mu\text{m}$  faunas, plotted against depth.

**ABSOLUTE ABUNDANCE OF BENTHIC FORAMINIFERA**

The absolute abundance of benthic foraminiferal tests per gram of total sediment or per gram of sand may be a proxy for productivity of the benthos produced by increased food supply (organic carbon flux), or it may reflect differences in terrigenous sediment input and sedimentation rate. The lack of information about sedimentation rates prevents the calculation of benthic foraminiferal test accumulation rates per unit time, which is a better proxy for productivity and carbon flux (e.g., Herguera 1992).

In the present study, there are two regions of higher absolute abundance ( $>63 \mu\text{m}$ ) per gram of sediment (Fig. 8). A belt of enhanced absolute abundance runs along the outer Taranaki shelf and on the upper parts of the continental slope in sand and sandy mud substrates. This may be an area of relative sediment starvation during the high sea level of the present interglacial, or it may reflect actual higher benthic productivity, with faunas having relatively high abundances of opportunistic, higher flux indicator taxa, such as *Bolivina*, *Cassidulina carinata*, *Trifarina angulosa*, and *Neouvigerina* (all of which have moderately high positive correlation coefficients with absolute abundance of benthic foraminiferal shells; Table 1). On the floor of the New Caledonia Basin, the increasing absolute abundance with increasing water depth within the calcareous pelagic mud substrate probably reflects decreasing terrigenous mud supply with increasing distance from land.

The absolute abundance of coarser benthic foraminiferal tests ( $>150 \mu\text{m}$ ) per gram of sand strongly reflects terrigenous sediment supply, generally with much lower abundance values on the Taranaki shelf than farther offshore (Fig. 8). Regions of higher absolute abundance of these coarser faunas along the foot of the slope west of Auckland and in the southwest of the study area are not readily explained in terms of lower terrigenous sediment supply, and may reflect enhanced productivity. The higher absolute abundance values in the southwest, on the northeast margin of the Challenger



**Fig. 8** Contoured maps of number of benthic foraminiferal tests  $>63 \mu\text{m}$  per gram of sediment (left) and number of foraminiferal tests  $>150 \mu\text{m}$  per gram of sand (right) in the offshore Taranaki study area.

Plateau, coincide with similar higher values in the fine fraction, and may result from nutrient upwelling along the West Coast of the South Island (e.g., Foster & Battaerd 1985).

The relative abundance of agglutinated taxa is low and the four orders of agglutinated taxa are treated together here for simplicity (Fig. 9).

**RELATIVE ABUNDANCE OF FORAMINIFERAL ORDERS**

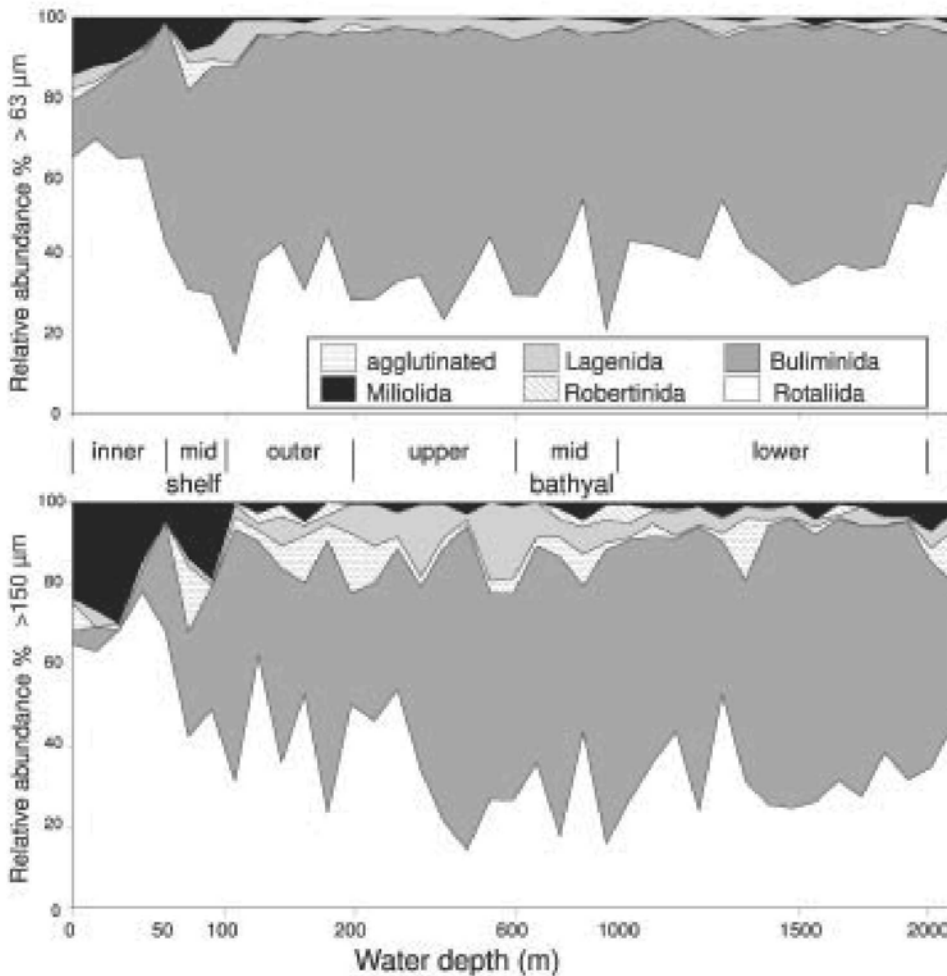
Eight of the 14 orders of Foraminifera currently recognised (Loeblich & Tappan 1992) are present in our census data.

Bathymetric trends in the relative abundance of the different orders are similar in both the fine and coarse fraction faunas, but there are some significant differences in actual relative abundances. Miliolids, robertinids, lagenids, and agglutinated orders all have considerably higher relative abundances in >150 µm faunas than in the finer >63 µm faunas (Fig. 9). Small buliminids (>63 µm) have higher

**Table 1** Correlation coefficients between relative percentage abundance of the common benthic foraminiferal species and a selection of the environmental proxies. More significant coefficients (>0.5) are bolded. Coefficients relating to the small (>63 µm) faunas are italicised. The categories of environmental proxy data used in this study are listed at the end.

	Abbr.	Depth	Depth	%mcs	%mcs	%vfs	%vfs	%mud	%mud	FRAG	FRAG	n/gsa	n/gsa	n/gsed	n/gsed	Jz	Jz
% mud		<b>0.70</b>	<b>0.70</b>														
% very fine sand	%vfs	<b>-0.53</b>	<b>-0.53</b>					<b>-0.54</b>	<b>-0.54</b>								
% medium-coarse sand	%mcs	<i>-0.36</i>	<i>-0.36</i>			<i>0.14</i>	<i>0.14</i>	<b>-0.56</b>	<b>-0.56</b>								
% planktic foraminifera	plank%	<b>0.84</b>	<b>0.78</b>	<i>-0.46</i>	<i>-0.45</i>	<b>-0.50</b>	<b>-0.44</b>	<b>0.86</b>	<b>0.85</b>								
Fragmentation Index	FRAG	<i>-0.22</i>	<i>-0.22</i>	<i>0.41</i>	<i>0.41</i>	<i>0.01</i>	<i>0.01</i>	<i>-0.36</i>	<i>-0.36</i>								
n per g sediment	n/gsed	<i>-0.27</i>	<i>-0.27</i>	<i>0.00</i>	<i>0.00</i>	<b>0.74</b>	<b>0.74</b>	<i>-0.25</i>	<i>-0.25</i>	<i>-0.10</i>	<i>-0.10</i>						
n per g sand	n/gsand	<i>0.00</i>	<i>0.00</i>	<i>-0.33</i>	<i>-0.33</i>	<i>-0.07</i>	<i>-0.07</i>	<i>0.39</i>	<i>0.39</i>	<i>-0.19</i>	<i>-0.19</i>			<i>0.31</i>	<i>0.31</i>		
Carbon flux to seafloor	Jz	<b>-0.90</b>	<b>-0.90</b>	<i>0.21</i>	<i>0.21</i>	<b>0.70</b>	<b>0.70</b>	<b>-0.71</b>	<b>-0.71</b>	<i>-0.26</i>	<i>-0.26</i>	<i>0.26</i>	<i>0.26</i>	<b>0.54</b>	<b>0.54</b>		
<i>Abditodentrix pseudothalmanni</i>	Abd	<i>0.31</i>	<i>-0.23</i>			<i>-0.24</i>		<i>0.35</i>		<i>-0.08</i>		<i>-0.02</i>		<i>-0.14</i>		<i>-0.18</i>	
<i>Alabaminella weddellensis</i>	Alab	<b>0.85</b>	<i>-0.22</i>			<i>-0.37</i>		<b>0.59</b>		<i>-0.23</i>		<i>-0.01</i>		<i>-0.16</i>		<b>-0.74</b>	
<i>Astrononion novozealandicum</i>	Asn	<i>-0.16</i>	<i>-0.30</i>	<i>-0.13</i>	<i>-0.13</i>	<i>-0.12</i>	<i>0.25</i>	<i>0.18</i>	<i>0.00</i>	<i>-0.16</i>	<i>-0.07</i>	<b>0.64</b>	<b>0.58</b>	<i>-0.02</i>	<i>0.26</i>	<i>0.19</i>	<b>0.70</b>
<i>Bolivina cacozela</i>		<i>-0.57</i>		<i>0.22</i>		<b>0.63</b>		<i>-0.43</i>		<i>0.10</i>		<i>0.28</i>		<b>0.64</b>		<b>0.75</b>	
<i>Bolivina subspinescens</i>		<i>-0.34</i>		<i>0.46</i>		<b>0.52</b>		<i>-0.28</i>		<i>-0.06</i>		<i>-0.04</i>		<i>0.33</i>		<b>0.64</b>	
<i>Bulimina marginata</i> f. <i>acanthia</i>		<i>-0.43</i>	<i>-0.49</i>	<b>0.50</b>	<i>0.49</i>	<i>0.11</i>	<i>0.19</i>	<b>-0.57</b>	<b>-0.64</b>	<b>0.63</b>	<i>0.27</i>	<i>-0.26</i>	<i>-0.21</i>	<i>-0.11</i>	<i>0.04</i>	<i>0.42</i>	<b>0.58</b>
<i>Bulimina marginata</i> f. <i>aculeata</i>	Bual	<b>0.75</b>	<b>0.81</b>	<i>-0.34</i>	<i>-0.34</i>	<i>-0.36</i>	<i>-0.40</i>	<i>0.46</i>	<b>0.53</b>	<i>-0.08</i>	<i>-0.16</i>	<i>-0.06</i>	<i>-0.03</i>	<i>-0.22</i>	<i>-0.22</i>	<b>-0.58</b>	<b>-0.62</b>
<i>Bulimina marginata</i> s.s.	Bum	<b>-0.54</b>	<b>-0.57</b>	<i>0.19</i>	<i>0.25</i>	<i>0.32</i>	<i>0.51</i>	<i>-0.50</i>	<i>-0.45</i>	<i>-0.03</i>	<i>-0.05</i>	<i>0.02</i>	<i>-0.05</i>	<i>0.06</i>	<i>0.19</i>	<b>0.70</b>	<b>0.75</b>
<i>Bulimina striata</i>	Bust		<i>0.29</i>		<i>-0.25</i>		<i>-0.35</i>		<i>0.45</i>		<i>-0.11</i>	<i>0.07</i>		<i>-0.21</i>		<i>-0.10</i>	
<i>Bulimina truncana</i>	But	<b>0.54</b>		<i>-0.35</i>		<i>-0.44</i>		<i>0.53</i>		<i>-0.12</i>		<i>0.00</i>		<i>-0.26</i>		<i>-0.47</i>	
<i>Cassidulina carinata</i>	Cac	<b>-0.52</b>		<i>0.31</i>		<i>0.33</i>		<i>-0.43</i>		<i>0.17</i>		<i>0.02</i>		<i>0.41</i>		<b>0.62</b>	
<i>Cibicides dispar</i>	Cidi	<i>-0.39</i>	<b>-0.57</b>	<b>0.59</b>	<b>0.62</b>	<i>0.06</i>	<i>0.39</i>	<b>-0.70</b>	<b>-0.71</b>	<b>0.69</b>	<i>0.41</i>	<i>-0.32</i>	<i>-0.02</i>	<i>-0.08</i>	<i>0.34</i>	<i>0.18</i>	<b>0.78</b>
<i>Cibicides wuellerstorfi</i>	Ciw		<b>0.62</b>		<i>-0.17</i>		<i>-0.37</i>		<i>0.45</i>		<i>-0.20</i>		<i>0.07</i>		<i>-0.17</i>		
<i>Discorbinaella bertheloti</i>	Disb	<b>-0.56</b>	<b>-0.57</b>	<i>0.42</i>	<i>0.48</i>	<b>0.59</b>	<i>0.49</i>	<b>-0.63</b>	<b>-0.69</b>	<i>0.17</i>	<i>0.29</i>	<i>-0.11</i>	<i>-0.17</i>	<i>0.41</i>	<b>0.51</b>	<b>0.77</b>	<i>0.47</i>
<i>Elphidium charlottense</i>	Elc	<i>-0.32</i>		<i>0.14</i>		<i>0.18</i>		<b>-0.52</b>		<b>0.83</b>		<i>-0.22</i>		<i>-0.10</i>			
<i>Epistominella exigua</i>	Epx	<b>0.64</b>		<i>-0.13</i>		<i>-0.21</i>		<i>0.31</i>		<i>-0.16</i>		<i>-0.06</i>		<i>-0.11</i>		<i>-0.41</i>	
<i>Gavelinopsis praegeri</i>	Gavp	<b>-0.58</b>		<b>0.61</b>		<i>0.45</i>		<i>-0.59</i>		<i>0.17</i>		<i>-0.18</i>		<i>0.32</i>		<i>0.49</i>	
<i>Globocassidulina subglobosa</i>	Gcsu	<b>0.70</b>	<b>0.71</b>	<i>-0.11</i>	<i>-0.12</i>	<i>-0.26</i>	<i>-0.24</i>	<i>0.31</i>	<i>0.29</i>	<i>-0.06</i>	<i>-0.06</i>	<i>0.06</i>	<i>-0.04</i>	<i>-0.13</i>	<i>-0.13</i>	<b>-0.50</b>	<b>-0.50</b>
<i>Gyroidinoides soldanii</i>	Gys	<b>0.56</b>	<b>0.54</b>	<i>-0.29</i>	<i>-0.29</i>	<i>-0.38</i>	<i>-0.41</i>	<i>0.48</i>	<i>0.49</i>	<i>-0.14</i>	<i>-0.18</i>	<i>-0.04</i>	<i>0.03</i>	<i>-0.20</i>	<i>-0.21</i>	<i>-0.45</i>	<i>-0.44</i>
<i>Haynesina depressula</i>		<i>-0.42</i>	<i>-0.35</i>	<i>0.20</i>	<i>0.12</i>	<i>0.17</i>	<i>0.13</i>	<b>-0.54</b>	<b>-0.51</b>	<b>0.64</b>	<b>0.60</b>	<i>-0.27</i>	<i>-0.26</i>	<i>-0.07</i>	<i>-0.10</i>	<i>0.20</i>	
<i>Miliolinella subrotunda</i>	Mils	<i>-0.26</i>	<i>-0.22</i>	<i>-0.07</i>		<i>0.10</i>		<i>-0.40</i>		<i>-0.05</i>	<i>-0.05</i>	<i>-0.19</i>		<i>-0.12</i>		<i>-0.17</i>	
<i>Neouvirgerina proboscidea</i>	Nep	<i>-0.48</i>		<i>0.28</i>		<b>0.51</b>		<i>-0.28</i>		<i>-0.07</i>		<i>0.14</i>		<i>0.20</i>		<b>0.81</b>	
<i>Nonionellina flemingi</i>	Nonf	<i>-0.32</i>		<i>0.03</i>		<i>0.35</i>		<i>-0.12</i>		<i>0.11</i>		<i>-0.18</i>		<i>0.00</i>		<i>0.48</i>	
<i>Notorotalia depressa</i>	Notd		<i>-0.39</i>		<i>0.47</i>		<i>0.05</i>	<i>-0.45</i>		<b>0.78</b>		<i>-0.24</i>		<i>-0.01</i>		<i>0.37</i>	
<i>Oridorsalis umbonatus</i>	Ori	<i>0.38</i>	<b>0.77</b>	<i>-0.16</i>	<i>-0.07</i>	<i>-0.13</i>	<i>-0.22</i>	<i>0.24</i>	<i>0.38</i>	<i>-0.14</i>	<i>-0.21</i>	<i>0.38</i>	<i>-0.09</i>	<i>0.04</i>	<i>-0.14</i>	<i>-0.24</i>	<b>-0.54</b>
<i>Osangularia bengalensis</i>	Os	<i>0.40</i>	<i>0.47</i>	<i>-0.27</i>	<i>-0.31</i>	<i>-0.38</i>	<i>-0.38</i>	<i>0.46</i>	<i>0.45</i>	<i>-0.13</i>	<i>-0.09</i>	<i>0.21</i>	<i>0.04</i>	<i>-0.17</i>	<i>-0.21</i>	<i>-0.29</i>	<i>-0.41</i>
<i>Pullenia bulloides</i>	Pub	<b>0.61</b>	<b>0.85</b>	<i>-0.30</i>	<i>-0.33</i>	<i>-0.37</i>	<i>-0.49</i>	<i>0.46</i>	<b>0.59</b>	<i>-0.05</i>	<i>-0.13</i>	<i>0.01</i>	<i>-0.04</i>	<i>-0.19</i>	<i>-0.28</i>	<i>-0.46</i>	<b>-0.75</b>
<i>Quinqueloculina seminula</i>	Qs	<i>-0.41</i>	<i>-0.39</i>	<i>0.38</i>	<i>0.40</i>	<i>0.00</i>	<i>0.05</i>	<b>-0.72</b>	<b>-0.75</b>	<i>0.33</i>	<i>0.43</i>	<i>-0.31</i>	<i>-0.34</i>	<i>-0.15</i>	<i>-0.15</i>		
<i>Siphotextularia fretensis</i>	Stxf		<i>-0.38</i>		<i>-0.02</i>		<i>0.27</i>		<i>-0.09</i>		<i>-0.04</i>		<i>0.47</i>		<i>0.28</i>		
<i>Trifarina angulosa</i>		<i>-0.38</i>		<i>-0.08</i>		<i>0.51</i>		<i>-0.07</i>		<i>-0.12</i>		<i>0.21</i>		<i>0.42</i>		<b>0.84</b>	<i>0.15</i>
<i>Uvigerina peregrina</i>	Uvp	<i>0.27</i>	<i>0.17</i>	<i>-0.38</i>	<i>-0.38</i>	<i>-0.34</i>	<i>-0.16</i>	<i>0.49</i>	<i>0.46</i>	<i>-0.17</i>	<i>-0.23</i>	<i>0.10</i>	<i>0.15</i>	<i>-0.22</i>	<i>-0.05</i>	<i>-0.14</i>	<i>0.06</i>
<i>Virgulopsis turris</i>	Virt	<i>-0.22</i>		<i>-0.01</i>		<b>0.51</b>		<i>-0.49</i>		<i>0.17</i>		<i>-0.08</i>		<i>0.45</i>		<i>0.48</i>	
<i>Zeaflorilus parri</i>	Zeap	<i>-0.34</i>	<i>-0.30</i>	<i>0.10</i>	<i>0.28</i>	<i>0.18</i>	<i>0.07</i>	<b>-0.51</b>	<i>-0.41</i>	<b>0.92</b>	<b>0.70</b>	<i>-0.23</i>	<i>-0.24</i>	<i>-0.10</i>	<i>-0.06</i>		

- depth – water depth below mean sea level (in metres); proxy for numerous depth-related factors.
- lat – latitude.
- % mud – percentage of sediment composed of mud fraction (<63 µm); proxy for bottom current strength, oxygenation of bottom waters.
- % vfs – percentage of sediment composed of very fine sand fraction (63–125 µm); proxy for bottom current strength.
- % mcs – percentage of sediment composed of medium and coarse sand fraction (>250 µm); proxy for bottom current strength.
- FRAG – planktic foraminiferal fragmentation index; proxy for high energy bottom waters, and maybe organic carbon flux (bathyal depths).
- Jz – proxy for organic carbon flux to the seafloor, a function of primary productivity and water depth, using the empirical relationship of Berger & Wefer (1990) and surface chlorophyll *a* values (NODC 1998); calculated for water depths >200 m.
- n/gsed – number of benthic foraminiferal tests per gram of sediment; proxy for productivity.
- n/gsa – number of benthic foraminiferal tests per gram of sand.
- plank>63 – percentage of the >63 µm foraminiferal fauna composed of planktic tests; proxy for oceanicity and surface water productivity.
- plank>150 – percentage of the >150 µm foraminiferal fauna composed of planktic tests; proxy for oceanicity and surface water productivity.



**Fig. 9** Bathymetric distribution of the relative abundance of specimens of each order as a percentage of the total benthic foraminiferal fauna  $>63 \mu\text{m}$  (above) and  $>150 \mu\text{m}$  (below). The four orders of agglutinated foraminifera (Astrorhizida, Lituolida, Trochamminida, Textulariida) have been combined.

relative abundances than large buliminids ( $>150 \mu\text{m}$ ) at shelf and upper bathyal depths, and lower relative abundances than large specimens at middle and lower bathyal depths ( $>600 \text{ m}$ ). Small and large rotaliids exhibit exactly the opposite pattern to the buliminids (Fig. 9).

Miliolids have their greatest relative abundances (up to 30%) at inner shelf depths, with slightly lower values on the mid-shelf, and consistently low values (0–5%) at depths  $>100 \text{ m}$ . Lagenids have their greatest relative abundance at outer shelf and upper bathyal depths in faunas  $>63 \mu\text{m}$ , and particularly at upper bathyal depths (200–600 m) in faunas  $>150 \mu\text{m}$  (Fig. 9). The only robertinid is *Hoeglundina elegans* and its distribution (0–5% relative abundance) is confined to the outer shelf and bathyal. There is no apparent correlation between the relative abundance of agglutinated foraminifera and bathymetry in this study, with irregular peaks of abundance in the coarse fraction up to 15–16% (Fig. 9).

The Buliminida and Rotaliida exhibit complementary patterns of relative abundance (Fig. 8). The buliminids are least abundant (0–25%) at inner shelf depths, but increase to become the dominant order at outer shelf and bathyal depths (100–2000 m) with relative abundances ranging between 30 and 80% (mean 55%). The rotaliids are most abundant (63–78%) at inner shelf depths and decrease to become the second most abundant order (15–60%, mean 35%) at depths  $>100 \text{ m}$ .

Within the bathymetric range of this study (0–2100 m), the major trends in the relative abundance of foraminiferal orders that are consistent and strong enough (Fig. 9) to be

utilised in the estimation of paleobathymetry are those that are likely to distinguish inner, and maybe mid-shelf, faunas from those occurring at outer shelf and bathyal depths ( $>100 \text{ m}$ ). These trends involve the rapid decrease in abundance of miliolids (mostly *Quinqueloculina* and *Miliolinella*) and rotaliids (mostly *Elphidium*, *Rosalina*, *Zaeflorilus*), and the increase in abundance of buliminids (mostly *Bulimina*, *Cassidulina*, and *Uvigerina*).

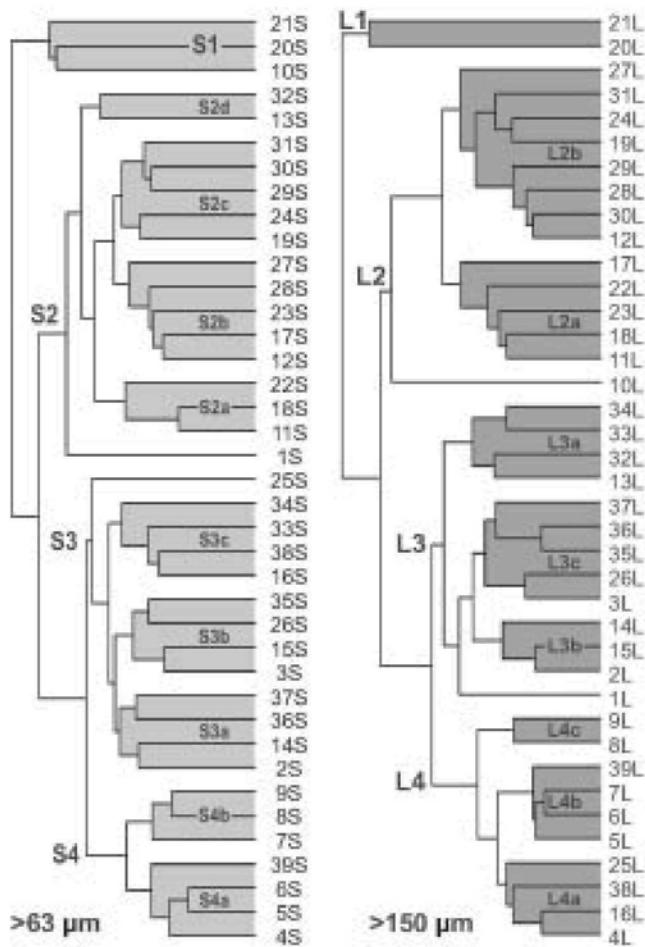
## SPECIES ASSOCIATIONS AND THEIR BATHYMETRIC DISTRIBUTION

### Computer methods

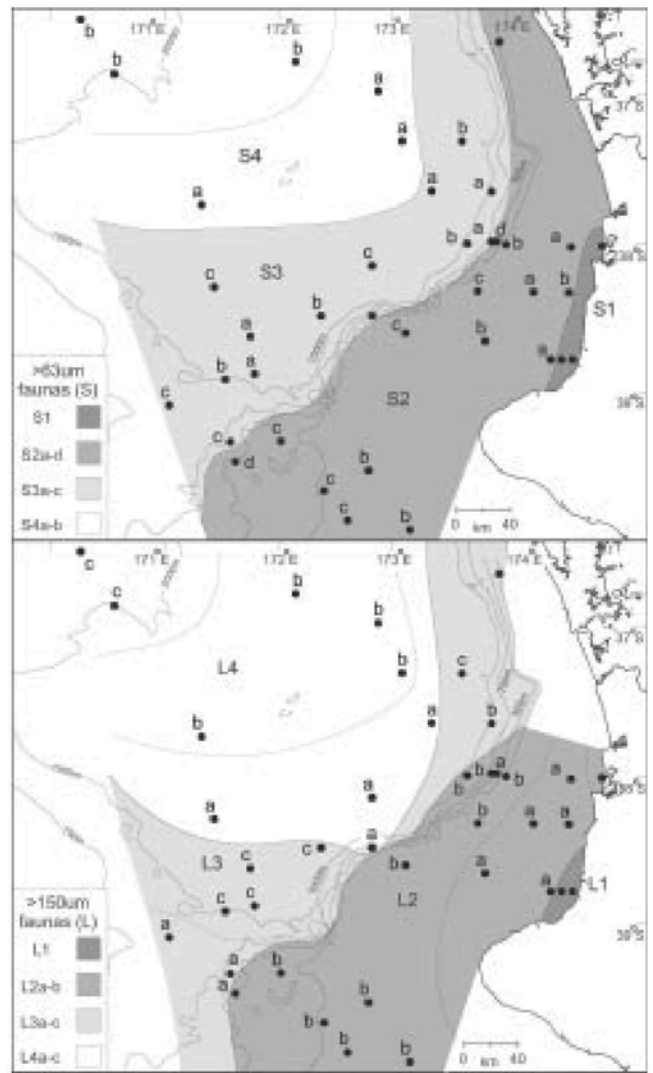
The faunal data consist of 2 sets of census counts ( $>63$ ,  $>150 \mu\text{m}$ ) of 231 foraminiferal species in 39 samples. The data matrices were standardised by converting counts to percentages of sample totals. Unweighted pair group Q-mode cluster analysis using arithmetic averages of a Bray-Curtis distance matrix was used to produce a dendrogram classification for each dataset from which sample associations were selected. The mathematical definition of the Bray-Curtis coefficient is given in Sneath & Sokal (1973).

### Results

The Q-mode cluster analysis dendrograms (Fig. 9) produce four major sample groups in both the fine and coarse datasets, although the group 1 samples in both dendrograms are clearly



**Fig. 10** Dendrogram classifications of benthic foraminiferal faunas >63 µm (S, left) and >150 µm (L, right) produced by cluster analysis using Bray-Curtis distance. The sample groups (1, 2, 3) and associations (a, b, c, d) were selected by inspection of the dendrograms. The relative abundance (%) of the common species in each group and association is summarised in Table 2.



**Fig. 11** Mapped distribution of benthic foraminiferal associations (Fig. 10, Table 2) from the offshore Taranaki study area, west of New Zealand.

more disparate than those in groups 2–4. At a lower level, 10 and 9 associations are discernible in the >63 and >150 µm datasets, respectively, and we have chosen these as sample associations. Several samples (1S, 1L, 10L, 25S) cluster with the higher level groups, but are ungrouped at lower levels of the dendrograms (Fig. 10). Each association consists of two or more samples that are grouped together because of the similarity of their foraminiferal faunas and particularly their dominant taxa. The geographic and bathymetric distributions of these groups and associations are mapped in Fig. 11 and summarised together with their taxonomic composition in Fig. 12, 13 and Tables 2–4.

**>63 µm faunal associations, S (Tables 2–3)**

*S1* *Elphidium charlottense*-*Rosalina irregularis*-*Virgulopsis turris* group, inner shelf

As indicated by the cluster analysis dendrogram (Fig. 10) and the ordination (Fig. 14), the three faunas in group S1 are significantly different in their compositions, and could each

be treated as a separate association. The shallowest fauna (20S, 6 m) comprises 44% *Rosalina irregularis* with subordinate *Miliolinella subrotunda*, *Quinqueloculina seminula*, and *Elphidium charlottense*. At 18 m depth, 10S is more even in its composition with co-dominant *Elphidium charlottense* (16%) and *Zeaflorilus parri* (14%), and a string of subordinate species (4–7%)—*Ammonia aoteana*, *Haynesina depressula*, *Bulimina marginata*, and *Rosalina irregularis*. This fauna is similar to the *Zeaflorilus parri* association that occurs right around New Zealand in clean sand on exposed coasts at innermost shelf depths (Hayward et al. 1999). The deepest of the three (21S, 22 m) is distinctly different, dominated by *Virgulopsis turris* (21%), with subordinate (7–9%) *Bolivina cacozela*, *B. subexcavata*, *Gavelinopsis praegeri*, and *Quinqueloculina seminula*. This faunal group is most similar to the *Elphidium charlottense*-*Virgulopsis turris* association that occurs at innermost shelf depths along the east coast of Northland (Hayward et al. 1999).

S2 *Cassidulina carinata*-*Bulimina marginata* s.s. group, mid-shelf to upper bathyal

This group is characterised by a dominance of *C. carinata* and *B. marginata* s.s., and these are the only two taxa that occur in every sample within it. The shallowest of the associations S2a, occurring at mid-shelf depths off the coast of North Taranaki (Fig. 11), has *Cibicides dispars* as a co-dominant along with *C. carinata* and *B. marginata* s.s.

The mid-shelf to uppermost bathyal associations S2b and S2c, both have *Discorbinella bertheloti* as a co-dominant along with *C. carinata* and *B. marginata* s.s., and have peak abundances of *Gavelinopsis praegeri*, *Neouvigerina proboscidea*, and *Trifarina angulosa*. The two associations are largely discriminated on the relative abundance of *C. carinata* (>25% in S2b, <17% in S2c). Both occur on the northern and southern parts of the continental shelf in the study region, with S2c located seaward of S2b (Fig. 11). These two associations are similar to the *Cassidulina carinata* association present at mid-shelf depths in the Wanganui Bight, east of the study area (Hayward et al. 1997).

The two samples in upper bathyal association S2d, occur around the top of the continental slope (500–550 m depth). They are dominated by *C. carinata*, with peak abundances of *Eilohedra levicula* (24% in 13S) and *Trifarina occidentalis* (13% in 32S).

The four S2 associations can be mapped as depth-related belts across the shelf and into the upper bathyal (Fig. 11) and exhibit generally increasing species diversity with

increasing depth— $\alpha$  8 (S2a) to 14 (S2d), H 2.4 (S2a) to 3.0 (S2d).

S3 *Cassidulina carinata*-*Alabaminella weddellensis* group, middle–lower bathyal

This group is characterised by the dominance of *C. carinata*, *A. weddellensis*, *Abditodentrix pseudothalmanni*, and *Bulimina truncana*. The only persistent species to occur in all 13 samples are *A. weddellensis*, *Bulimina marginata* f. *aculeata*, and *Uvigerina peregrina*. The group occurs at middle–lower bathyal depths (500–1500 m), with three associations recognised from the cluster analysis (Fig. 10). There is a general, but not consistent, deepening trend from association S3a to S3c (Table 2).

Association S3a is co-dominated by subequal numbers (means 8–9%) of *A. weddellensis*, *U. peregrina*, and *C. carinata*, with subordinate (means 7–8%) *Cassidulina nørvangi*, *Eilohedra levicula*, and *Bulimina truncana*. Having their peak abundances (mean 5%) in S3a are *Cibicidoides bradyi* and *Osangularia bengalensis*. Association S3b differs in having fewer *C. carinata*, *E. levicula*, and *C. nørvangi*, and is dominated by *A. pseudothalmanni* (mean 18%) and subdominant (11–13%) *B. truncana* and *A. weddellensis*. *Gyroidinoides soldanii* has its peak abundance (mean 5%) in this association. Association S3c is dominated by *C. carinata* (mean 18%) with subdominant (mean 10–12%) *B. marginata* f. *aculeata* and *A. weddellensis*.

The S3 group is similar in composition to the bathyal *C.*

**Table 2** Characterising species, depth range, and diversity of benthic foraminiferal sample groups and associations.

Faunal associations >63 $\mu$ m							
Sample assoc.	Characterising species	No. of stns	Depth range	Mean depth	Mean diversity		
					$\alpha$	H	J
S1	<i>Elphidium charlottense</i> - <i>Rosalina irregularis</i> - <i>Virgulopsis turris</i> - <i>Zeaflorilus parri</i> - <i>Haynesina depressula</i>	3	6–22	15 m	11	2.7	0.78
S2	<i>Cassidulina carinata</i> - <i>Bulimina marginata</i> s.s.	16	46–541	206 m	10	2.7	0.78
S2a	<i>C. carinata</i> - <i>Cibicides dispars</i> - <i>B. marginata</i> s.s.	3	46–91	66 m	8	2.4	0.76
S2b	<i>C. carinata</i> - <i>B. marginata</i> s.s.- <i>Discorbinella bertheloti</i>	5	49–328	134 m	8	2.4	0.74
S2c	<i>B. marginata</i> s.s.- <i>C. carinata</i> - <i>Discorbinella bertheloti</i>	5	137–276	199 m	12	3.0	0.82
S2d	<i>C. carinata</i> - <i>Eilohedra levicula</i> - <i>Trifarina occidentalis</i>	2	506–541	524 m	14	3.0	0.81
S3	<i>Cassidulina carinata</i> - <i>Alabaminella weddellensis</i>	13	498–1518	1050 m	10	2.8	0.82
S3a	<i>A. weddellensis</i> - <i>Uvigerina peregrina</i> - <i>C. carinata</i>	4	794–1233	1040 m	10	2.7	0.80
S3b	<i>Abditodentrix pseudothalmanni</i> - <i>Bulimina truncana</i> - <i>A. weddellensis</i>	4	974–1244	1117 m	11	2.9	0.83
S3c	<i>C. carinata</i> - <i>A. weddellensis</i> - <i>A. pseudothalmanni</i>	4	746–1518	1133 m	10	2.8	0.82
S4	<i>Bulimina marginata</i> f. <i>aculeata</i> - <i>Alabaminella weddellensis</i>	7	1419–2150	1765 m	10	2.7	0.78
S4a	<i>B. m. f. aculeata</i> - <i>A. weddellensis</i> - <i>Globocassidulina subglobosa</i>	4	1419–1748	1596 m	9	2.7	0.80
S4b	<i>A. weddellensis</i> - <i>B. m. f. aculeata</i> - <i>Epistominella exigua</i>	3	1825–2159	1992 m	10	2.7	0.79
Faunal associations >150 $\mu$ m							
Sample assoc.	Characterising species	No. of stns	Depth range	Mean depth	Mean diversity		
					$\alpha$	H	J
L1	<i>Zeaflorilus parri</i> - <i>Rosalina irregularis</i>	2	6–22	14 m	8	1.9	0.65
L2	<i>Cibicides dispars</i> - <i>Bulimina marginata</i> s.s.	14	18–276	134 m	7	2.2	0.73
L2a	<i>C. dispars</i> - <i>B. marginata</i> s.s.- <i>Discorbinella bertheloti</i>	5	46–121	73 m	6	2.2	0.72
L2b	<i>C. dispars</i> - <i>B. marginata</i> s.s.- <i>Uvigerina peregrina</i>	8	109–276	187 m	7	2.3	0.72
L3	<i>Uvigerina peregrina</i> - <i>Bulimina marginata</i> f. <i>aculeata</i>	13	379–1244	896 m	10	2.5	0.75
L3a	<i>U. peregrina</i> - <i>Bulimina m. f. aculeata</i> - <i>B. marginata</i> s.s.	4	506–850	661 m	11	2.8	0.83
L3b	<i>U. peregrina</i>	3	794–1011	926 m	8	2.0	0.61
L3c	<i>U. peregrina</i> - <i>B. m. f. aculeata</i> - <i>Gyroidinoides soldanii</i>	5	1025–1244	1170 m	9	2.6	0.77
L4	<i>Bulimina marginata</i> f. <i>aculeata</i> - <i>Uvigerina peregrina</i>	10	498–2150	1579 m	8	2.2	0.70
L4a	<i>B. m. f. aculeata</i> - <i>U. peregrina</i>	4	498–1518	1213 m	7	2.2	0.69
L4b	<i>B. m. f. aculeata</i> - <i>Pullenia bulloides</i> - <i>Oridorsalis umbonatus</i>	4	1545–1825	1697 m	6	2.0	0.66
L4c	<i>B. m. f. aculeata</i> - <i>O. umbonatus</i> - <i>Globocassidulina subglobosa</i>	2	2000–2150	2075 m	10	2.6	0.77

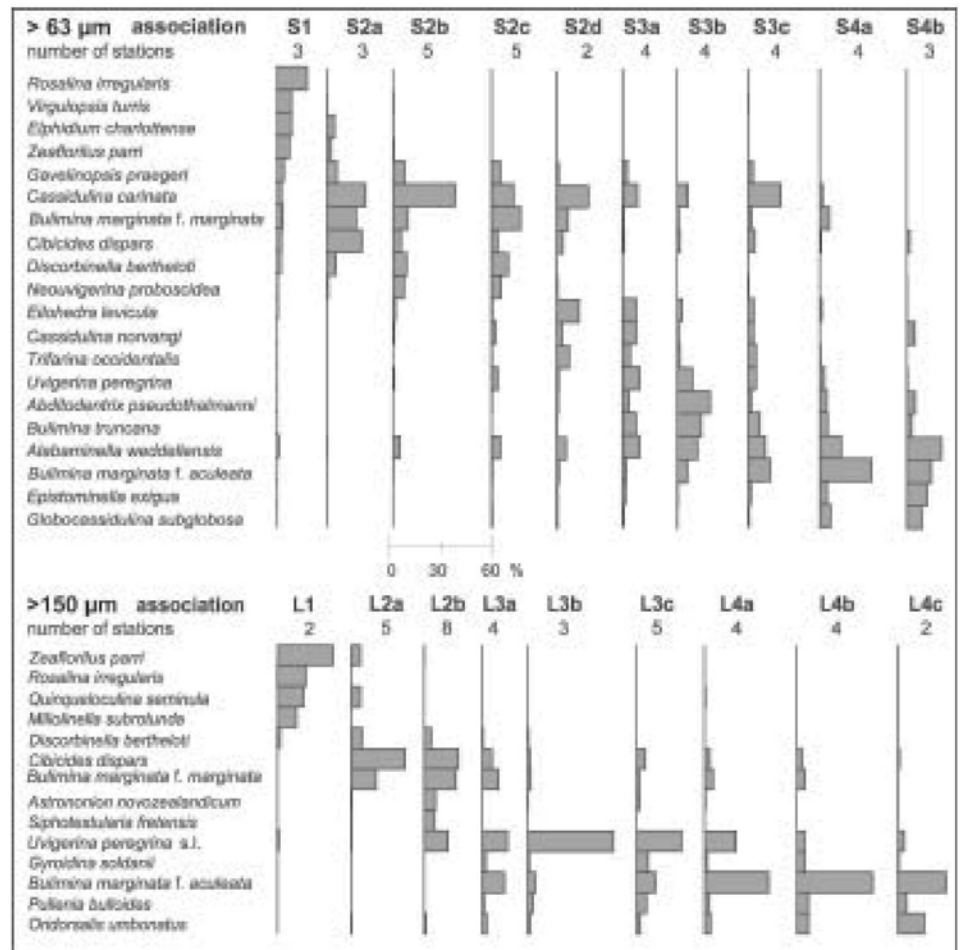
**Table 3** Mean relative percentage abundance (range in brackets) for the dominant benthic foraminiferal species in each sample association from the faunas >63 µm.

Associations	S1	S2a	S2b	S2c	S2d	S2	S3a	S3b	S3c	S3	S4a	S4b	S4
Number of stations	3	3	5	5	2	16	4	4	4	13	4	3	7
<i>Rosalina irregularis</i>	16 (0–44)	0	0	0	0	0	0	0	0	0	0	0	0
<i>Virgulopsis turris</i>	7.7 (0–21)	0.2 (0–0.5)	0.5 (0–2)	0.1 (0–0.5)	0	0.2 (0–2)	0	0	0.2 (0–1)	0 (0–1)	0	0	0
<i>Elphidium charlottense</i>	7.6 (3–16)	3.8 (0–12)	0.2 (0–1)	0.1 (0–0.5)	0	0.8 (0–12)	0	0	0	0	0	0	0
<i>Zeaflorilus parri</i>	6.4 (1–14)	2.1 (0–6)	0.7 (0–3)	0.1 (0–0.5)	0	0.7 (0–6)	0	0	0	0	0	0	0
<i>Haynesina depressula</i>	5.4 (4–7)	1.7 (0–5)	0.8 (0–3)	0	0	0.7 (0–5)	0	0	0	0	0.3 (0–1)	0	0.2 (0–1)
<i>Nonionellina flemingi</i>	4.3 (1–12)	0.2 (0–0.5)	1.4 (0–4)	1.6 (0–8)	0	1.1 (0–8)	0	0	0	0	0	0	0
<i>Quinqueloculina seminula</i>	4.3 (1–7)	2.7 (2–3)	0.2 (0–1)	0	0.2 (0–0.5)	0.6 (0–3)	0	0	0.3 (0–1)	0.1 (0–1)	0	0	0
<i>Bolivina subexcavata</i>	3.4 (0–8)	0	1.7 (0–4)	3.1 (1–7)	2.5 (2–3)	1.8 (0–7)	0.4 (0–2)	0.5 (0–2)	0.2 (0–1)	0.4 (0–2)	0	0	0
<i>Miliolinella subrotunda</i>	3.4 (1–7)	0.2 (0–0.5)	0	0	0	0	0	0	0	0	0.1 (0–0.6)	0	0.1 (0–0.6)
<i>Bolivina cacozela</i>	3.4 (1–9)	1 (0–2)	3.2 (1–5)	2.8 (2–4)	0.9 (0–2)	2.2 (0–5)	0.1 (0–0.5)	0	0.3 (0–1)	0.2 (0–1)	0	0	0
<i>Quinqueloculina oblonga</i>	3 (0–9)	0.3 (0–1)	0.1 (0–0.5)	0	0	0.1 (0–1)	0	0	0	0	0	0	0
<i>Ammonia aoteana</i>	2.4 (0–7)	0	0	0	0	0	0	0	0	0	0	0	0
<i>Gavelinopsis praegeri</i>	3.6 (0–9)	5.5 (4–7)	6.4 (3–12)	4.7 (1–9)	0.8 (0–2)	4.6 (0–12)	2.6 (0–5)	0	2.5 (0–10)	1.6 (0–10)	0	0	0
<i>Cassidulina carinata</i>	2.2 (1–3)	21 (15–26)	34 (25–43)	12 (5–17)	17 (14–21)	21 (5–43)	8.5 (5–14)	5.7 (0–12)	18 (10–22)	10 (0–22)	1.7 (0–4)	0	0.9 (0–4)
<i>Bulimina marginata</i> s.s.	2.9 (1–6)	16 (4–25)	8.2 (5–14)	16 (9–24)	6 (5–7)	12 (4–25)	0.5 (0–2)	0.8 (0–2)	1.7 (0–5)	1.1 (0–5)	5.8 (0–11)	0	3.3 (0–11)
<i>Cibicides dispars</i>	2 (1–4)	19 (13–26)	4.3 (0–9)	3.3 (1–6)	3.4 (2–5)	6.4 (0–26)	0.8 (0–2)	1.7 (0–4)	3.4 (2–5)	1.9 (0–5)	0.9 (0–3)	1.7 (1–2)	1.3 (0–3)
<i>Discorbinella bertheloti</i>	1.9 (1–4)	4.8 (3–6)	7.5 (2–12)	8.8 (4–20)	0	6 (0–20)	0	0	0	0 (0–0.5)	0	0	0
<i>Neowigerina proboscidea</i>	0.5 (0–1)	0.5 (0–1)	6.1 (0–13)	5.2 (3–10)	0.4 (0.4)	4 (0–13)	0	0.1 (0–0.5)	0.3 (0–1)	0.2 (0–1)	0	0.2 (0–0.5)	0.1 (0–0.5)
<i>Eilohedra levicula</i>	0.6 (0–2)	0	1.3 (0–5)	0.3 (0–1)	12 (0–24)	2 (0–24)	7.8 (6–10)	2.8 (0–6)	3.0 (2–4)	4.2 (0–10)	1.4 (0–3)	0.3 (0–1)	0.9 (0–3)
<i>Trifarina angulosa</i>	0.2 (0–0.5)	0.3 (0–1)	1.4 (0–4)	3.4 (2–6)	1.3 (0–3)	1.8 (0–6)	1.1 (0–3)	0.2 (0–1)	0	0.7 (0–4)	0.4 (0–1)	0	0.2 (0–1)
<i>Cassidulina norvangi</i>	0	0	0.8 (0–3)	2.2 (0–7)	2.8 (1–5)	1.8 (0–9)	7.8 (0–28)	0.9 (0–4)	2.6 (0–5)	4.1 (0–28)	0	4.6 (2–8)	2 (0–8)
<i>Oridorsalis umbonatus</i>	0	0.2 (0–0.5)	0.7 (0–2)	2.4 (0–6)	0.4 (0–1)	1.1 (0–6)	0.4 (0–1)	0.5 (0–2)	0.6 (0–2)	0.5 (0–2)	2.4 (0–4)	3.3 (1–6)	2.8 (0–6)
<i>Trifarina occidentalis</i>	0	0	0.1 (0–0.5)	0.2 (0–1)	6.8 (0–13)	1 (0–13)	4.4 (3–8)	1.6 (1–3)	4.0 (0–10)	3.4 (0–10)	0.5 (0.5)	0	0.3 (0–0.5)
<i>Osangularia bengalensis</i>	0	0	0	0	3.1 (2–4)	0.4 (0–4)	5.5 (0–13)	4 (2–6)	2.0 (1–3)	3.6 (0–13)	1.5 (1–2)	1.8 (1–2)	1.6 (1–2)
<i>Gyroidinoides soldanii</i>	0.2 (0–0.5)	0	0.2 (0–1)	0.2 (0–1)	2.2 (0–4)	0.4 (0–4)	1.7 (0–4)	5.4 (2–9)	3.3 (1–9)	3.3 (0–9)	3.8 (2–7)	2.6 (1–5)	3.3 (1–7)
<i>Cibicides bradyi</i>	0	0	1.8 (0–4)	3.3 (0–6)	1.5 (0–3)	1.8 (0–6)	5.3 (0–8)	2.8 (0–7)	2.3 (0–4)	3.4 (0–8)	3.1 (0–6)	1.8 (0–5)	2.5 (0–6)
<i>Uvigerina peregrina</i>	0	0	0.8 (0–2)	3.3 (1–6)	0.8 (0.5–1)	1.5 (0–6)	9.2 (5–16)	8.1 (5–12)	4.0 (3–7)	6.8 (3–16)	2.7 (1–4)	0.5 (0–1)	1.8 (0–4)
<i>Abditodentrix pseudothalmanni</i>	0	0	0	0.2 (0–1)	0.6 (0–1)	0.1 (0–1)	3.8 (2–6)	18 (10–23)	1.4 (0–4)	9.3 (0–28)	4.2 (1–10)	4.9 (2–9)	4.5 (1–10)
<i>Bulimina truncana</i>	0	0	0	0	0.2 (0–0.5)	0 (0–0.5)	7.5 (4–10)	13.3 (9–23)	6.4 (4–12)	8.3 (0–23)	4.7 (3–6)	3.1 (3–4)	4.1 (3–6)
<i>Alabaminella weddellensis</i>	1.2 (0–4)	0.2 (0–0.5)	3.8 (0–9)	4.8 (1–11)	5.2 (5.2)	3.4 (0–11)	9.4 (7–11)	11 (4–14)	9.5 (8–12)	9.7 (4–14)	12 (8–15)	20 (18–24)	15 (8–24)
<i>Bulimina marginata</i> f. <i>aculeata</i>	0	0	0.2 (0–1)	0.4 (0–1)	1.1 (0–2)	0.3 (0–2)	1.9 (1–3)	5.4 (1–10)	12 (5–15)	6.3 (1–15)	29 (27–31)	14 (5–23)	22 (5–31)
<i>Epistominella exigua</i>	0	0	0	0.2 (0–0.5)	0.4 (0–1)	0.1 (0–1)	1.6 (0–5)	0.4 (0–0.5)	1.2 (0–3)	1.9 (0–12)	4.4 (4–6)	12 (10–14)	7.5 (4–14)
<i>Globocassidulina subglobosa</i>	0	0	0	0.4 (0–2)	0.4 (0–1)	0.2 (0–2)	0.5 (0–1)	0.3 (0–1)	0.5 (0–2)	0.4 (0–2)	6.4 (0–13)	8.5 (5–11)	7.3 (0–13)

**Table 4** Mean relative percentage abundance (range in brackets) for the dominant benthic foraminiferal species in each sample association from the faunas >150 µm.

Association	L1a	L1b	L1	L2a	L2b	L2	L3a	L3b	L3c	L3	L4a	L4b	L4c	L4
Number of stations			2	5	8	14	4	3	5	13	4	4	2	10
<i>Zeaflorilus parri</i>	2.6	60	31 (3–60)	5.8 (0–19)	0.2 (0–2)	2.9 (0–19)	0	0	0	0.1 (0–2)	0	0	0	0
<i>Rosalina irregularis</i>	33.9	0	17 (0–34)	0	0	0	0	0	0	0	0	0	0	0
<i>Quinqueloculina seminula</i>	3.7	24.3	14 (4–24)	5.9 (1–12)	0	2.6 (0–12)	0	0	0	0	0.4 (0–2)	0	0	0.2 (0–2)
<i>Miliolinella subrotunda</i>	14.8	2.9	9 (3–15)	0	0	0	0	0	0	0	0	0	0	0
<i>Spiroplectinella proxispira</i>	4.8	1.4	3.1 (1–5)	3.1 (0–14)	0	1.1 (0–14)	0	0	0	0	0	0	0	0
<i>Notorotalia depressa</i>	1.1	2.9	2 (1–3)	5.7 (1–13)	0.3 (0–1)	2.2 (0–13)	0	0	0	0	0.7 (0–2)	0	0	0.3 (0–2)
<i>Ammonia aoteana</i>	0.5	1.4	1 (0.5–1.5)	0.1 (0–1)	0	0.8 (0–10)	0	0	0	0	0	0	0	0
<i>Bulimina marginata</i> f. <i>acanthia</i>	0	0	0	4 (2–9)	1.5 (1–4)	2.3 (0–9)	0.8 (0–2)	0	0	0.3 (0–2)	0.1 (0–0.5)	0	0	0
<i>Discorbinella bertheloti</i>	3.2	0	1.6 (0–3)	6.7 (4–12)	4.2 (0–10)	5 (0–12)	0.7 (0–2)	0.5 (0–2)	0	0.3 (0–2)	0	0	0	0
<i>Cibicides dispars</i>	0	0	0	34 (14–46)	22 (3–35)	26 (3–46)	6 (5–9)	1.7 (0–4)	5.2 (0–13)	4.3 (0–13)	3.2 (0–5)	3.1 (0–5)	0.9 (0.9)	2.7 (0–5)
<i>Bulimina marginata</i> f. <i>marginata</i>	0.5	0	0.3 (0–0.5)	16 (3–26)	20 (12–37)	17 (0–37)	10 (7–17)	2.2 (0–5)	1.3 (0–5)	5.3 (0–17)	5.2 (0–9)	5 (0–12)	0	4.1 (0–12)
<i>Astrononion novozealandicum</i>	0	0	0	0.7 (0–3)	7 (1–21)	4.3 (0–21)	0	0.4 (0–1)	1.6 (1–3)	0.9 (0–3)	0.5 (0.5)	0	0	0.2 (0–0.5)
<i>Siphotextularia fretensis</i>	0	0	0	0.4 (0–2)	6.5 (2–15)	3.8 (0–15)	0	0	0	0.1 (0–2)	0	0	0	0
<i>Globocassidulina canalisuturata</i>	0	0	0	0.7 (0–4)	5.2 (0–18)	3.5 (0–18)	0	0	0	0	0	0	0	0
<i>Uvigerina peregrina</i> s.l.	1.1	0	0.5 (0–1)	0.4 (0–2)	15 (8–22)	8.7 (0–22)	16 (12–18)	54 (44–64)	28 (21–35)	31 (12–64)	19 (15–25)	4.6 (4–5)	3.8 (2–6)	10 (2–25)
<i>Gyroidinoides soldanii</i>	0	0	0	0	0	0	2.6 (1–6)	1.2 (0–3)	7.2 (4–11)	3.9 (0–11)	1.6 (1–3)	4.9 (2–8)	0.6 (0–1)	2.7 (0–8)
<i>Ehrenbergina trigona</i>	0	0	0	0	0	0	0.1 (0–0.5)	0	5.5 (0–17)	2.1 (0–17)	1.3 (0–5)	0	0.6 (0–1)	0.6 (0–5)
<i>Nodosaria hispida</i>	0	0	0	0.1 (0–0.5)	1.7 (0–8)	1 (0–8)	3.3 (0–6)	0.2 (0–0.5)	0	1.1 (0–6)	0	0	0	0
<i>Bulimina striata</i>	0	0	0	0	0.3 (0–2)	0.2 (0–2)	2.9 (0–11)	4.7 (3–7)	5 (2–9)	4.3 (0–11)	2	0.8 (0–1)	1.5 (1–2)	1.4 (0–2)
<i>Cibicides wuellerstorfi</i>	0	0	0	0	0.1 (0–0.5)	0	1.9 (0–4)	0	2.9 (1–6)	1.8 (0–6)	0.4 (0–1)	2.4 (1–4)	3.8 (3–5)	1.9 (0–5)
<i>Bulimina marginata</i> f. <i>aculeata</i>	0	0	0	0	0.1 (0–0.5)	0	14 (9–19)	5.2 (2–10)	12 (5–22)	10 (2–22)	39 (35–42)	47 (41–53)	29 (23–35)	40 (23–53)
<i>Pullenia bulloides</i>	0	0	0	0	0	0	1.4 (0–3)	3.5 (1–5)	6 (4–10)	3.6 (0–10)	3.1 (0–6)	7.3 (6–10)	5.5 (3–8)	5.3 (0–10)
<i>Oridorsalis umbonatus</i>	0	0	0	0.4 (0–2)	1.4 (0–4)	1 (0–4)	3.1 (0–5)	1.9 (1–3)	2.1 (1–4)	2.3 (0–5)	3.8 (1–9)	7.3 (5–10)	16 (14–18)	7.7 (1–18)
<i>Globocassidulina subglobosa</i>	0	0	0	0	0	0	0	0	0	0	0.6 (0–1)	5.2 (3–8)	5.8 (5.8)	3.5 (0–8)

**Fig. 12** Histograms showing the mean relative abundance (%) of the more common benthic foraminiferal species in each of the faunal associations.



*carinata*-*A. weddellensis*-*A. pseudothalmanni* group that occurs at similar depths east of New Zealand (Hayward et al. 2001). The main difference is the greater evenness in species distributions in the S3 group and also the greater abundance of *U. peregina*.

**S4** *Bulimina marginata* f. *aculeata*-*Alabaminella weddellensis* group, lower bathyal to uppermost abyssal

The lower bathyal to upper abyssal S4 group differs from the shallower S3 by the virtual disappearance of *C. carinata* and the greater dominance of *B. marginata* f. *aculeata* (mean 22%), and *A. weddellensis* (mean 15%). Two associations are recognisable from the cluster analysis (Fig. 10), with S4a occurring at shallower depths (1400–1750 m) than S4b (1800–2200 m).

Association S4a has *B. m. f. aculeata* strongly dominant (mean 29%), with subdominant *A. weddellensis* (14%) and subordinate (6%) *B. marginata* s.s. and *Globocassidulina subglobosa*. Association S4b has *A. weddellensis* (mean 20%) more dominant than *B. m. f. aculeata* (14%), *Epistominella exigua* (12%), and *G. subglobosa* (9%). S4b has a similar composition to the *E. exigua*-*B. m. f. aculeata*-*A. weddellensis* association that occurs at similar lower bathyal to upper abyssal depths in the Bounty Trough, east of New Zealand (Hayward et al. 2001), although *G. subglobosa* is more abundant here in S4b.

**>150 µm faunal associations, L** (Tables 2, 4)

**L1** *Zeaflorilus parri*-*Rosalina irregularis* group, inner shelf

As shown in the cluster analysis dendrogram (Fig. 10) and ordination (Fig. 14), the two faunas in group L1 are vastly different and could be recognised as two separate associations. The shallower sample (20L, 6 m) is co-dominated by *Rosalina irregularis* (34%) and *Miliolinella subrotunda* (15%), whereas the deeper (21L, 22 m) is dominated by *Zeaflorilus parri* (60%) and *Quinqueloculina seminula* (24%).

**L2** *Cibicides dispars*-*Bulimina marginata* s.s. group, shelf to uppermost bathyal

Two associations are recognised from the cluster analysis (Fig. 10) in this group, which is characterised by the co-dominance of *C. dispars* and *B. marginata* s.s. In addition to these two species, the shallower, mid-shelf (50–120 m depth) association, L2a, has subordinate (mean 5–7%) *Discorbinella bertheloti*, *Q. seminula*, and *Z. parri*. The deeper, outer shelf to uppermost bathyal (100–300 m depth) association, L2b, has the same two dominant species, but with subdominant *Uvigerina peregina* (mean 15%) and subordinate (mean 6%) *Q. seminula*, *Z. parri*, and *Notorotalia depressa*.



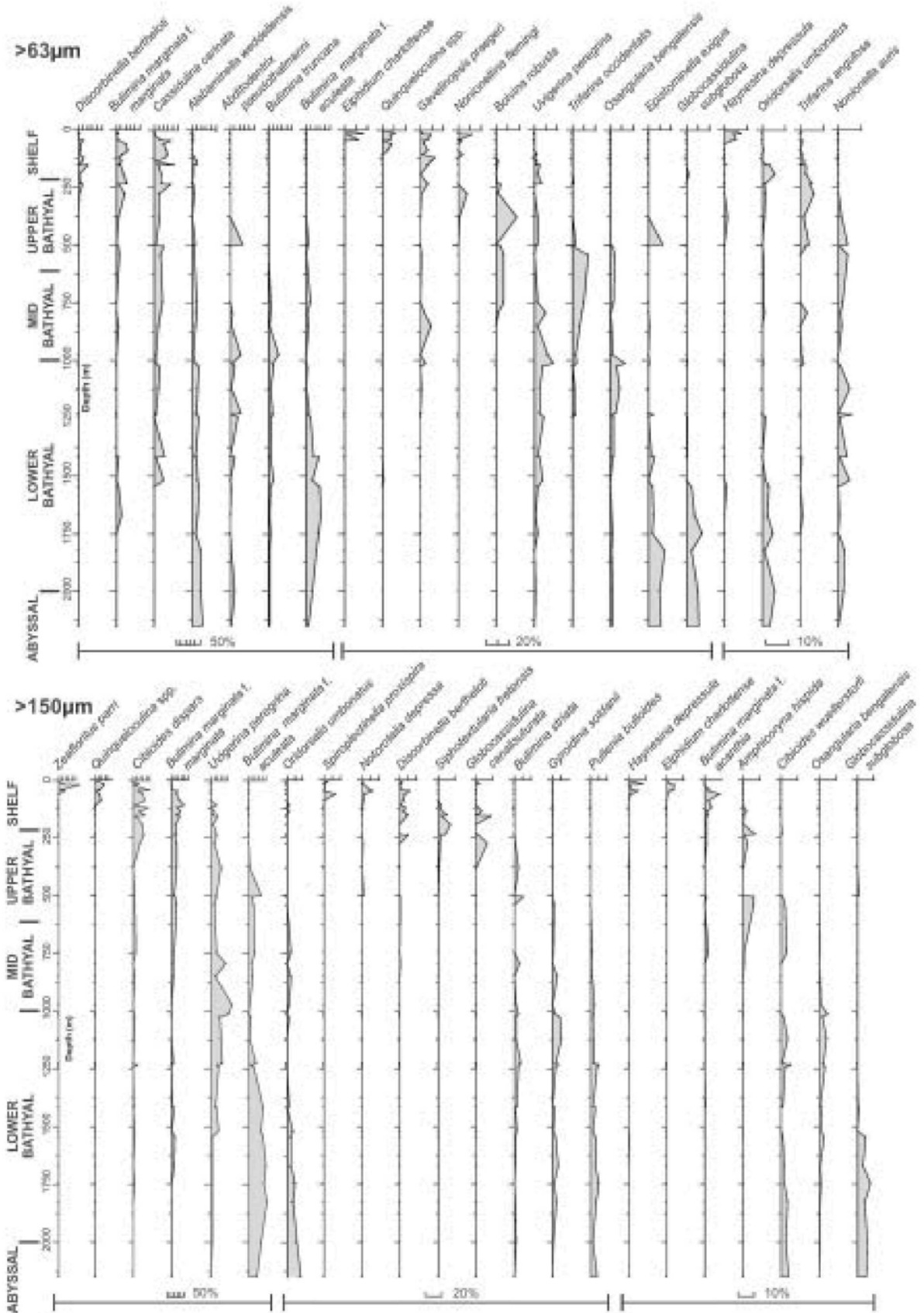
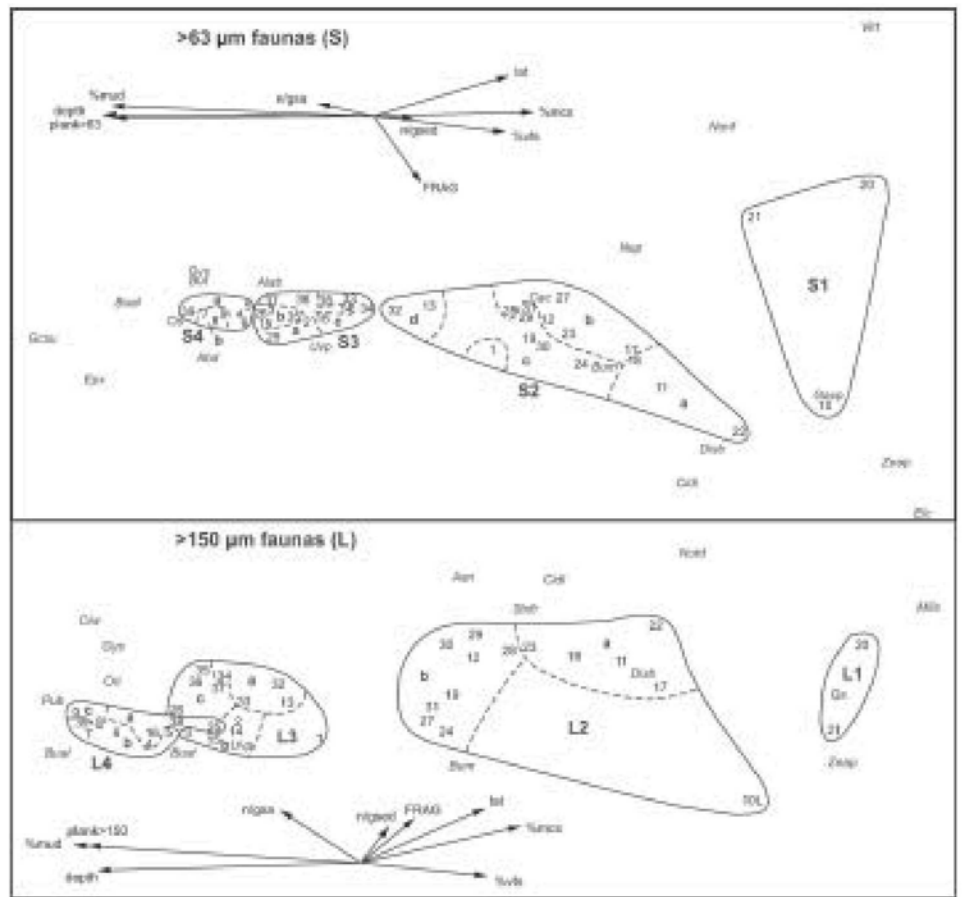


Fig. 13 Depth distribution of the relative abundance of common benthic foraminifera in surface sediment samples in the offshore Taranaki region for faunas >63 µm (S) and >150 µm (L).

**Fig. 14** 2D configurations of foraminiferal faunas and common species  $>63 \mu\text{m}$  (S, upper) and  $>150 \mu\text{m}$  (L, lower) produced by Detrended Canonical Correspondence Analysis (DCCA). Vector axes (arrows) show the correlation of faunal distribution patterns with proxies for some environmental factors. The faunal groups and associations used are those identified from the cluster analysis (Fig. 10). For explanation of abbreviations see Table 1.



**L3** *Uvigerina peregrina*-*Bulimina marginata* f. *aculeata* group, upper-mid bathyal

Three associations are recognised in this group and all three are dominated by *U. peregrina*. The greatest abundance of *U. peregrina* (mean 54%) occurs in the lower mid-bathyal (800–1000 m) L3b association, with subordinate (mean 5%) *Bulimina striata*, and *B. m. f. aculeata*. *U. peregrina* is least abundant (mean 16%) in the mid-bathyal (500–850 m) L3a association, where *Bulimina marginata* s.s. and f. *aculeata* are subordinate (10–14%). In the deepest, shallow lower bathyal (1000–1250 m) association, L3c, *U. peregrina* comprised 21–35% (mean 28%) of faunas, with subordinate *B. m. f. aculeata* (mean 12%) and numerous subordinate (5–7%) species—*Gyroidinoides soldanii*, *Pullenia bulloides*, *Ehrenbergina trigona*, *Cibicides dispars*, and *B. striata*.

**L4** *Bulimina marginata* f. *aculeata*-*Uvigerina peregrina* group, mid-bathyal to uppermost abyssal

The three associations recognised in the deepest group, L4, are all dominated by *B. m. f. aculeata*. The shallowest (500–1500 m) of the associations, L4a, is co-dominated by *B. m. f. aculeata* (mean 39%) and *U. peregrina* (mean 19%). *B. m. f. aculeata* has its greatest abundance (mean 47%) in the deep lower bathyal (1500–1800 m) association, L4b, where it occurs together with subordinate (5–7%) *Oridorsalis umbonatus*, *Pullenia bulloides*, *Globocassidulina subglobosa*, *B. marginata* s.s., *Gyroidinoides soldanii*, and *U. peregrina*. The deepest association is restricted to the

upper abyssal (2000–2200 m) and is dominated by *B. m. f. aculeata* (mean 29%) with subordinate *O. umbonatus* (16%), and subordinate (6%) *G. subglobosa* and *P. bulloides*.

## DISCUSSION

Most previous quantitative studies of Recent New Zealand benthic foraminifera have examined faunas in the size fraction  $>63 \mu\text{m}$ , and thus comparisons are most readily made with our smaller-sized foraminiferal associations (S1–4). Our inner shelf S1 (and to a lesser extent L1) group is similar to the *Elphidium charlottense*-*Virgulopsis turris* and *Zeaflorilus parri* associations previously recognised in clean sand at similar depths off exposed to moderately exposed coasts around New Zealand (Hayward et al. 1999). The high abundance (44%) of *Rosalina irregularis* in the shallowest S1 sample (station 20, 6 m) is unusual. These inner shelf groups are restricted to the New Zealand region, because the dominant species are endemic.

The mid-shelf to uppermost bathyal Taranaki group S2 (and L2) corresponds well with the *Cassidulina carinata* association recognised below 55 m in Wanganui Bight (Hayward et al. 1997) and the *C. carinata*-*Cibicides dispars*-*Gavelinopsis praegeri* association from similar depths east of New Zealand (Hayward et al. 2002). The bathyal Taranaki group S3 is equivalent in taxonomic composition of the dominants to the bathyal *C. carinata*-*Alabaminella weddellensis*-*Abditodentrix pseudothalmani* association east of New Zealand (Hayward et al. 2002). The lower bathyal to

uppermost abyssal Taranaki group S4 has similarities to the *Epistominella exigua*-*Alabaminella weddellensis* association which occurs at similar and greater depths east of New Zealand (Hayward et al. 2002). The main differences at lower bathyal and abyssal depths relate to the greater relative abundance of *Bulimina marginata* f. *aculeata* west of New Zealand, and the greater relative abundance of *E. exigua* and *Cassidulina nørvangi* to the east.

The dominant taxa at bathyal depths off Taranaki are prominent members of deep-sea benthic foraminiferal associations elsewhere in the world, often in combination with other species (e.g., Resig 1981; Corliss 1983; Murray 1991).

## FACTORS INFLUENCING BENTHIC FORAMINIFERA DISTRIBUTIONAL PATTERNS

### Computer methods

The ordination technique of detrended canonical correspondence analysis (DCCA, Ter Braak 1985) was used to summarise the faunal data (limited to the 56 most common species with >6% relative abundance in at least one sample) and relate them to a set of 10 measured environmental proxies (Table 1). Representations of the samples and species in 4D space were produced. The co-ordinates of a sample in each of the four dimensions are weighted averages of all the species percentages, and similarly the co-ordinates of a species in each dimension are weighted averages of all the sample percentages. These representations are plotted on the first two DCCA axes for both the small (S) and large (L) faunal samples and species (Fig. 14). The DCCA vector arrows show the axis and direction of increasing values of each environmental proxy. The length of each vector arrow is a measure of the correlation between that factor and the faunal pattern—the longer the arrow, the stronger the correlation. Ranking of species or samples with respect to each environmental proxy may be determined by projecting their plotted positions perpendicularly onto the appropriate vector arrow.

Correlation coefficients between common species and the measured environmental proxies were determined (Table 1) to help decipher the factors most important in determining the benthic foraminiferal distribution patterns.

### Results and discussion

The ordination plots of all samples (Fig. 14) roughly reproduce their seafloor distribution in terms of their depths. The four cluster analysis groups in both the small and large specimen datasets largely plot in separate discrete regions. The longest vector arrows in both DCCA analyses are planktic percentage, percent mud, and depth, and all three are closely aligned in direction and length. Correlation coefficients show that all three are strongly positively correlated and could be taken jointly as a strong proxy for water depth, suggesting that factors that have a relationship with depth are the most significant in influencing the foraminiferal faunal distribution. Proxies having a negative correlation with water depth, and having vector arrows pointing towards the shallow samples, are: very fine sand, medium-coarse sand, and to a lesser extent, latitude. Proxies recording the absolute abundance of benthic foraminifera and fragmentation index have short vector arrows and therefore weak correlation with the overall faunal pattern. In summary, the benthic foraminiferal faunal pattern

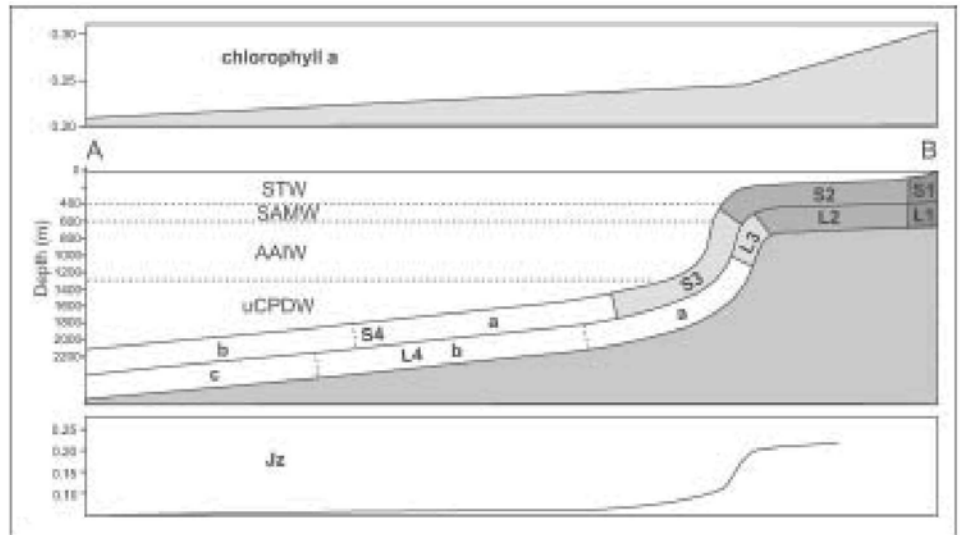
correlates most strongly with water depth and related proxies.

After many years of studies of deep-sea benthic foraminifera around the world, most workers have concluded that the observed distributional patterns are regulated by the interplay of organic carbon flux (food supply), dissolved oxygen concentration, and biological interactions (Van der Zwaan et al. 1999). Studies indicate that sinking organic matter derived from plankton productivity in the photic zone is the primary source of food for deep-sea benthic foraminifera (e.g., Altenbach & Sarthein 1989; Hermelin & Shimmield 1995; Gooday & Hughes 2002). The abundance and assemblage composition of benthic foraminiferal faunas are reportedly related to this carbon flux (e.g., Gooday 1988; Graf 1992; Loubere & Fariduddin 1999). Two groups of taxa have been identified that reportedly abound in relatively high carbon flux conditions. The first group are opportunistic, largely epifaunal species, with small, thin-walled shells and few chambers (e.g., *Alabaminella weddellensis*, *Epistominella exigua*, and *Ioanella tumidula*). These flourish where there is an intermittent, seasonal, phytodetrital carbon flux (e.g., Gooday & Turley 1990; Smart et al. 1994). The second group has larger shells with more chambers and are predominantly infaunal (e.g., *Uvigerina peregrina*, *Bulimina* spp., *Cassidulina* spp.). These are reportedly abundant where organic carbon flux is high throughout the year (e.g., Rathburn & Corliss 1994; Mackensen et al. 1995).

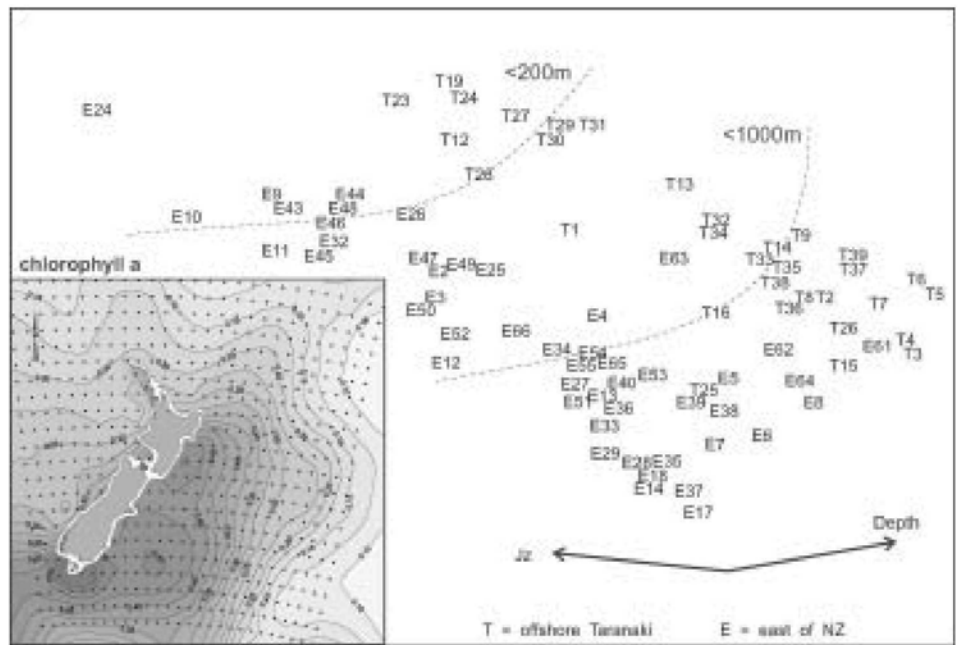
The faunas at mid-shelf and greater depths off Taranaki are dominated by *Bulimina*, *Cassidulina*, and *Uvigerina* (Tables 2–4) and suggest moderately high organic carbon flux levels throughout the year, although some workers have inferred that *Cassidulina* are opportunistic detritivores reflecting pulsed food supply (e.g., Nees 1997; Nees & Struck 1999). The increasing abundance of *Alabaminella* at lower bathyal and upper abyssal depths (below 1000 m) off Taranaki (associations S3c, S4) suggest some seasonal phytodetritus pulses (Gooday 1993) over the New Caledonia Basin in the northwest. Organic carbon is consumed as it sinks through the water column and thus the amount reaching the seafloor decreases with increasing water depth. This may provide an explanation for the observed depth-related distributional pattern of the deep-sea benthic foraminifera (see below). For example, off Taranaki, the deepest associations (L4b, L4c; >1500 m) have increasing relative abundances of *Oridorsalis umbonatus* and *Globocassidulina subglobosa* (Table 4), which may relate to decreasing food supply, tending towards oligotrophic conditions. This is supported by the strong negative correlation coefficients with the proxy for organic flux to the seafloor, Jz (Table 1).

Other studies from beyond the Southwest Pacific have shown a close relationship between some benthic foraminifera and the level of oxygenation of the bottom waters (Schnitker 1994; Murray 1995; Kaiho 1999; Bernhard & Sen Gupta 1999). Often low oxygen levels are triggered by high organic carbon flux, so that these benthic assemblages may also reflect a relationship with increased food supply (e.g., Pederson et al. 1988; Rathburn & Corliss 1994; Fontanier et al. 2002). Taxa identified as dominating oxygen-deficient substrates include *Bulimina*, *Globocassidulina*, *Uvigerina*, *Nonionella*, and smooth *Bolivina* (Verhallen 1991; Hermelin 1992; Sen Gupta & Machain-Castillo 1993). The first three of these are dominant members here of groups S4 and L4 (Table 2) which underlie upper CPDW, which has a regional oxygen minimum zone, but no dysoxic or anoxic conditions are present in this study.

**Fig. 15** Generalised transect through the offshore west Taranaki study area (located on Fig. 1) summarising the distribution of water masses, proxies for primary productivity (chlorophyll *a*) and carbon flux to the seafloor (*Jz*), and their relationship to the benthic foraminiferal sample associations (S1–4, >63  $\mu\text{m}$ ; L1–4, >150  $\mu\text{m}$ ). STW = Subtropical Surface Water; SAMW = Subantarctic Mode Water; AAIW = Antarctic Intermediate Water; uCPDW = upper Circumpolar Deep Water.



**Fig. 16** 2D ordination of outer shelf to upper abyssal (100–3000 m) foraminiferal faunas (>63  $\mu\text{m}$ ) from offshore Taranaki (T prefix) and offshore east New Zealand (E prefix, Hayward et al. 2001, 2002) produced by Detrended Canonical Correspondence Analysis (DCCA). Vector axes (arrows) show the correlation of the faunal distribution patterns with water depth and a proxy (*Jz*) for organic carbon flux to the seafloor, a function of primary productivity and water depth, using the empirical relationship of Berger & Wefer (1990). *Inset*: Contoured annual surface water chlorophyll *a* values around New Zealand for 1998 (from the NOAA, NODC World Ocean Atlas 1998 Annual analysed chlorophyll in  $\mu\text{mol/L}$ ).



Early work on deep-sea benthic foraminifera in the North Atlantic indicated that distribution patterns were largely related to the thermohaline properties of different deep-water masses (e.g., Streeter 1973; Weston & Murray 1984; Murray et al. 1986; Schnitker 1994). For example, an *Oridorsalis umbonatus*-*Globocassidulina subglobosa* association was thought to be typical of North Atlantic Deep Water (Murray 1988) and an *Epistominella umbonifera* association typical of Antarctic Bottom Water (Weston & Murray 1984). More recently, the relationship between benthic foraminifera and deep-water masses has been questioned. Some researchers reject it out of hand (e.g., Van der Zwaan et al. 1999), whereas others still argue that where productivity is uniform or low, deep-sea epifaunal benthic foraminiferal faunas carry a strong imprint of the structure of the deep water masses that directly overlie them (Gooday 1994; Schnitker 1994; Mackensen et al. 1995; Murray 1995; Thomas & Gooday 1996; Schmiedl et al. 1997). This latter view could be supported by our

observations off west New Zealand, where the faunal associations match well with the documented bathymetric distributions of the overlying water masses (Fig. 15). Groups S1, S2, L1, and L2 (0–400 m) are overlain by Subtropical Surface Water (STW); S3, L3, and L4a (500–1500 m) are overlain by Mode and Antarctic Intermediate Water (SAMW and AAIW); and S4, L4b, and L4c (>1500 m) are overlain by Circumpolar Deep Water (CPDW). The most significant faunal changes (that result in the recognition of the separate associations) generally coincide with the deep water mass boundaries, and could explain the strong depth-related foraminiferal distributional patterns.

**Comparison with eastern New Zealand**

Cluster analysis and correspondence analysis ordinations (e.g., Fig. 16) show that the benthic foraminiferal faunas at outer shelf-abyssal depths (>100 m) on either side of New Zealand are significantly different and do not overlap in their

overall composition. Nineteen common species exhibit major differences in relative abundance between the west (Taranaki, this study) and east (Hayward et al. 2001, 2002) coasts (Table 5). These differences may provide an insight into the underlying environmental factors responsible for the observed depth-related distributional pattern.

The water masses that flow above the outer shelf to upper abyssal seafloor west of New Zealand (i.e., STW, AAIW, CPDW, Fig. 1) are essentially the same as those over the northern half of the east New Zealand study area (north of the STF). The main difference with southeast of New Zealand is the presence of colder Subantarctic Surface Water, which forms the uppermost layer south of the STF. East of New Zealand, environmental differences north and south of the STF (inferred to be differences in primary productivity, Hayward et al. 2002) are manifest in slight differences in the composition of deep-sea benthic foraminiferal associations (particularly the relative abundance of *Epistominella exigua*; Hayward et al. 2002). These faunal differences off east New Zealand, which may relate to surface water mass productivity differences, are minor when compared to the faunal differences between opposite sides of New Zealand (Fig. 16, 17).

A possible clue to the causes of the west–east foraminiferal differences comes from surface chlorophyll *a* values, calculated from satellite data for the New Zealand region (NODC 1998). These indicate that in 1998, mean annual surface chlorophyll was significantly higher east of New Zealand (0.35–0.45  $\mu\text{mol/L}$ ) than to the west (0.20–0.30  $\mu\text{mol/L}$ , Fig. 16). Although there is some debate about the exact translation of satellite colour data into phytoplankton productivity values, it seems clear that primary productivity east of New Zealand is significantly greater than to the west (e.g., Murphy et al. 2001). Is this responsible for the observed foraminiferal differences? Many of the species with observed greater relative abundance east of New Zealand (e.g., *C. carinata*, *E. exigua*, *T. angulosa*) are reported elsewhere as flourishing in regions of enhanced food supply, but other reportedly eutrophic species (e.g., *A. weddellensis*, *B. marginata*, *U. peregrina*) show little difference in their relative abundances between west and east.

Studies in the Mediterranean Sea show that the depth ranges of most eutrophic and oligotrophic bathyal and upper abyssal benthic foraminifera become shallower coincident with a west–east decrease in surface water primary

productivity (de Rijk et al. 2000). Is a similar pattern observable around New Zealand? Examination of the depth ranges and relative abundances of the more common benthic foraminifera west and east of New Zealand allows the recognition of three groups:

Group 1—taxa with shallower lower limits of high relative abundance in the west than the east (e.g., Fig. 17). These taxa include *Bolivina robusta*, *B. subexcavata*, *Cassidulina carinata*, *Discorbinella bertheloti*, *Globocassidulina minuta*, *Nonionella auris*, *Notorotalia profunda*, *Trifarina angulosa*, and *T. occidentalis*. Most of these have strong positive correlation coefficients with the proxy (Jz) for organic flux to the seafloor in this study off Taranaki (Table 1) and clearly prefer more eutrophic (shallower) conditions.

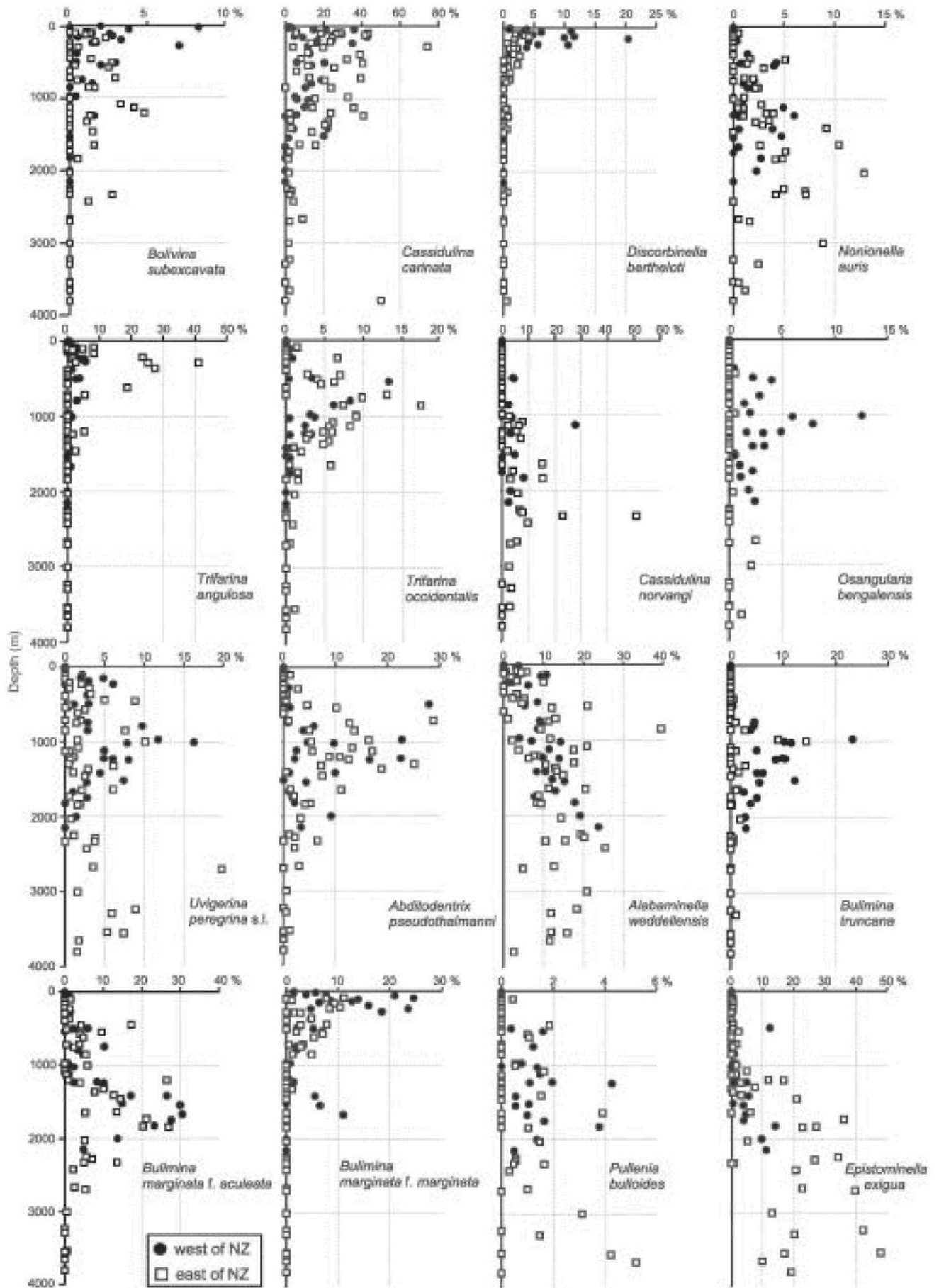
Group 2—taxa with shallower upper limits of high relative abundance in the west than the east (Fig. 17). These taxa include *Cassidulina nørvangi*, *Osangularia bengalensis*, and *Uvigerina peregrina*, all of which have low negative correlation coefficients with Jz off Taranaki (Table 1) and prefer less eutrophic conditions than group 1.

Group 3—taxa with similar relative abundances and depth ranges off both sides of New Zealand, e.g., *Abditodentrix pseudothalmanni*, *Alabaminella weddellensis*, *Astronionion novozealandicum*, smooth-walled *Bolivina*, *Bulimina marginata* s.s., *Bulimina marginata* f. *aculeata*, *Cibicides dispars*, *Gavelinopsis praeegeri*, *Nonionellina flemingi*, *Oridorsalis umbonatus*, and *Pullenia bulloides*. This group includes species with high positive, high negative, and low correlation coefficients with Jz.

The lower depth limits of the more eutrophic taxa in group 1 appear to be controlled by the decreasing level of food supply (flux) with increasing depth, in that they have shallower depth limits where primary productivity is lower (west), and deeper limits where it is higher (east). Similarly, the upper depth limits of the more oligotrophic taxa in group 2 are probably influenced by the higher food supply at shallower depths, possibly in conjunction with competition from more eutrophic taxa. The above observations suggest that while some taxa appear to be unaffected by the differences in carbon flux between west and east New Zealand, many others exhibit patterns consistent with the hypothesis that the bathymetric distribution of most of the dominant benthic foraminifera is controlled by the level of the organic flux to the seafloor (Carney 1989; Altenbach et al. 1999).

**Table 5** Common benthic foraminiferal species that exhibit significantly greater relative abundance on the west (this study) or east (Hayward et al. 2001, 2002) sides of New Zealand.

More abundant off the west (Taranaki) side of New Zealand	More abundant off the east (Chatham Rise) side of New Zealand
<i>Bulimina truncana</i>	<i>Anomalinoidea spherica</i>
<i>Discorbinella bertheloti</i>	<i>Cassidulina carinata</i>
<i>Globocassidulina canalisuturata</i>	<i>Epistominella exigua</i>
<i>Gyroidinoides soldanii</i>	<i>Evolocassidulina orientalis</i>
<i>Melonis affinis</i>	<i>Globocassidulina minuta</i>
<i>Neouvigerina proboscidea</i>	<i>Globocassidulina subglobosa</i>
<i>Osangularia bengalensis</i>	<i>Ioanella tumidula</i>
<i>Trifarina bradyi</i>	<i>Notorotalia profunda</i>
	<i>Siphonotextularia rolshauseni</i>
	<i>Sphaeroidina bulloides</i>
	<i>Trifarina angulosa</i>



**Fig. 17** Plots showing the percentage relative abundance distribution of common benthic foraminifera (>63 μm) with water depth off the west (this study) and east (Hayward et al. 2001, 2002) coasts of New Zealand. Note that the depth range of the study off the west coast only extends down to 2150 m.

### BATHYMETRIC RANGES OF COMMON SPECIES

The depth ranges of the peak relative abundances of common benthic species (Table 6) may be helpful in a general way in reconstructing the paleobathymetry from fossil faunas. For example, high relative abundances (>5–10%) of *Elphidium charlottense*, *Zeaflorilus parri*, and/or *Quinqueloculina* spp. are indicative of inner–mid-shelf depths. High percentages of: *Discorbinella bertheloti* suggests mid-outer shelf depths; *Trifarina angulosa*—outer shelf to upper bathyal; *Cibicides dispars*—shelf to uppermost bathyal; *Siphotextularia fretensis* and *Bolivina robusta*—upper bathyal; *Abditodentrix pseudothalmanni*, *Alabaminella weddellensis*, and/or *Bulimina truncana*—middle–lower bathyal. Less useful because of their broader or inconsistent abundance depth ranges are *Gavelinopsis praegeri*, *Uvigerina peregrina*, and *Cassidulina carinata*. The two common forms of *Bulimina marginata* (Jorissen 1988; Hayward et al. 1999) have potentially useful depth ranges for their peak abundance levels (>10%), with the shallower f. *marginata* (with undercut chamber margins) present at mid-shelf to upper bathyal depths, and the more spinose f. *aculeata* (with more rounded chamber profiles) at lower bathyal to upper abyssal depths.

The depth ranges for the peak abundances of these common species (Table 6) can only be used as a guide to the likely paleobathymetry, because their differing bathymetric distribution patterns west and east of New Zealand suggest that they are influenced by changes in primary productivity.

### UPPER DEPTH LIMITS OF KEY BENTHIC SPECIES

The extreme upper depth limits of deep-sea benthic foraminifera have considerable potential to refine paleodepth determinations estimated from total benthic foraminiferal assemblages (e.g., Hayward 1986b, 1990; Crundwell et al.

1994; Hayward et al. 1999). This is particularly true in hydrocarbon exploration drillholes, where all microfossil faunas are derived from cuttings samples, with potential for downhole cavings contamination.

Table 7 lists the upper depth limits of a number of relatively common deep-sea benthic species from west of New Zealand, as determined in this study. These depth values exhibit a similar, but by no means identical, pattern to the upper depth limits obtained from our previous study east of New Zealand (Hayward et al. 2001). Approximately 50% of taxa have similar depth ranges, but some species have significantly shallower upper depth limits in the west compared to the east (e.g., *Cassidella bradyi*, *Gyroidinoides pulisukensis*, *Bolivina pusilla*, *Pullenia salisburyi*, *Cassidulina nørvangi*, *Cibicoides bradyi*), whereas others have significantly deeper upper depth limits in the west (e.g., *Abditodentrix pseudothalmanni*, *Bolivinita quadrilatera*, *Fursenkoina complanata*, *Rutherfordoides rotundata*, *Melonis pompilioides*). These differences in upper depth limits are presumably related, at least in part, to the differences in primary productivity and consequently food supply to the seafloor on either side of New Zealand.

Previous studies in the Neogene benthic foraminiferal faunas in the prograding Giant Foresets strata of Taranaki Basin have identified a number of taxa with potentially useful upper depth limits (Hayward 1990; Crundwell et al. 1994). Five of these (or their apparent descendants) are present in this Taranaki study. Their upper depth limits determined from the Neogene record are fairly similar to those on the modern seafloor for *eggerella ihungia/bradyi*, *Melonis barleeaanum/affinis*, and *Sigmoilopsis schlumbergeri*. The modern upper depth range for both *Cibicides wuellerstorfi* (250 m) and *Osangularia* (400 m) are somewhat shallower than determined from the fossil record (500, 700 m, Hayward et al. 1999), possibly a result of productivity changes. Many of the species listed in Table 7 have potential to assist in estimating paleobathymetry.

**Table 6** Bathymetric ranges of the peaks of relative abundance of common benthic foraminifera in the study region (Fig. 13) that have potential for paleobathymetric subdivision of the bathyal and abyssal in the New Zealand region. Comparative depth ranges for east of New Zealand are given in square brackets (Hayward et al. 2001).

Species	Depth range for relative abundances of
<i>Elphidium charlottense</i>	>5% 0–40 m (fine & crs)
<i>Zeaflorilus parri</i>	>10% 0–40 m (crs)
<i>Quinqueloculina</i> spp.	>5% 0–80 m (fine & crs)
<i>Cibicides dispars</i>	>20% 0–300 m (crs)
<i>Gavelinopsis praegeri</i>	>5% 0–900 m (fine) [5–750 m]
<i>Discorbinella bertheloti</i>	>5% 40–250 m (fine & crs) [50–500 m]
<i>Bulimina marginata</i> s.s.	>10% 50–750 m (crs), 50–300 m (fine) [20–600 m]
<i>Cassidulina carinata</i>	>10% 50–1550 m (fine) [20–2800 m]
<i>Trifarina angulosa</i>	>2% 100–500 m (fine) [10–650 m]
<i>Siphotextularia fretensis</i>	>5% 250–500 m (crs)
<i>Bolivina robusta</i>	>5% 300–750 m (fine) [200–650 m]
<i>Abditodentrix pseudothalmanni</i>	>10% 400–1300 m (fine) [500–2800 m]
<i>Trifarina occidentalis</i>	>5% 500–900 m (fine) [200–1600 m]
<i>Alabaminella weddellensis</i>	>12% 1000–2100+ m (fine) [500–3500 m]
<i>Uvigerina peregrina</i>	>5% 750–1550 m (fine), 100–1550 m (crs)
<i>Bulimina truncana</i>	>5% 850–1500 m (fine)
<i>Pullenia bulloides</i>	>5% 950–2100+ m (crs)
<i>Bulimina marginata</i> f. <i>aculeata</i>	>10% 1250–2100+ m (fine) [400–3000 m] >400 m (crs)
<i>Globocassidulina subglobosa</i>	>5% 1500–2100+ m (fine & crs)
<i>Oridorsalis umbonatus</i>	>10% 1700–2100+ m (crs)
<i>Epistominella exigua</i>	>10% 1750+ m (fine) [1000–4700 m]

## DISCUSSION

## Influence of shell size on census data and bathymetric trends

This study confirms suspicions that faunal composition differs dramatically between samples studied at  $>63\ \mu\text{m}$  and  $>150\ \mu\text{m}$  shell size. Taxa having a predominance of large shells (e.g., *Cibicides dispars*, *Gyroidinoides soldanii*, *Oridorsalis umbonatus*, *Pullenia bulloides*, *Uvigerina peregrina*) have enhanced census counts in the  $>150\ \mu\text{m}$  samples, and taxa having a predominance of small sized tests (e.g., *Abditodentrix pseudothalmanni*, *Alabaminella weddellensis*, *Bulimina truncana*, *Cassidulina carinata*, *Eilohedra levicula*, *Epistominella exigua*, *Virgulopsis turris*) have reduced (or even zero) census counts in the  $>150\ \mu\text{m}$  samples. Thus, the dominant species in the faunal associations are considerably different, although some common taxa (e.g., *Bulimina marginata* s.s., *B. marginata* f. *aculeata*, *Discorbinella bertheloti*, *Zeaflorilus parri*) characterise both faunas with small and large sized tests. The differences are sufficiently significant that paleobathymetric estimates of fossil faunas  $>150\ \mu\text{m}$ , potentially will be far less precise if based on  $>63\ \mu\text{m}$  modern samples than those based upon faunas with similar large shell size.

Both small and large shell-size faunal associations show similar depth-related distributional patterns however (Fig. 11), with a similar level of discrimination possible (4 groups, 9–10 associations). There is not a 1:1 correspondence between the small and large shell-size faunas from the same samples and their assignment to faunal groups and

associations. There is, however, a similar depth-related subdivision with an inner shelf, a mid-shelf to uppermost bathyal, a bathyal, and a lower bathyal to upper abyssal group recognised from both shell-size datasets. Thus, it is likely that studies using either shell size have the potential to provide paleobathymetric estimates of similar resolution.

Many of the dominantly small taxa are thin-shelled, opportunistic, eutrophic species, and thus fossil studies using just larger shell sizes are more likely to have a less complete proxy record of changes in primary production.

## Reliability of deep-sea benthic foraminifera for paleodepth assessments

The benthic foraminiferal species and associations off west Taranaki (both  $>63\ \mu\text{m}$  and  $>150\ \mu\text{m}$ ) have distribution patterns that correlate most strongly with water depth, resulting in their usefulness in estimating the paleobathymetry at which fossil Neogene foraminiferal faunas accumulated.

Examination of the bathymetric distribution of the outer shelf to upper abyssal groups off west Taranaki shows considerable correlation with the major depth-stratified water masses (Fig. 15):

- (1) Subtropical Surface Water (STW)—underlain by groups S2 and L2, dominated by *Cassidulina carinata*, *Discorbinella bertheloti*, *Cibicides dispars*, and *Bulimina marginata* s.s.;
- (2) Antarctic Intermediate Water (AAIW) and Subantarctic Mode Water (SAMW)—underlain by groups S3, and L3–

**Table 7** Upper depth limits of key benthic foraminiferal species from offshore Taranaki, west of New Zealand, compared with previously determined limits from east of New Zealand (Hayward et al. 2001), and for identical or similar species in the late Neogene of Taranaki Basin that have been calibrated using reflector geometry (from Hayward 1990; Crundwell et al. 1994; Hayward et al. 1999).

Key species	West of NZ (m)	East of NZ (m)	North Taranaki late Neogene key species and upper depth limits	
<i>Notorotalia profunda</i>	150	90		
<i>Epistominella exigua</i>	150	100		
<i>Gyroidinoides soldanii</i>	150	200		
<i>Laticarinina altocamerata</i>	150	200		
<i>Cassidella bradyi</i>	200	1600		
<i>Abditodentrix pseudothalmanni</i>	250	100		
<i>Cibicides wuellerstorfi</i>	250	350	<i>Cibicides wuellerstorfi</i>	500 ± 150 m
<i>Gyroidinoides pulisukensis</i>	250	600		
<i>Nonionella auris</i>	375	400		
<i>Osangularia bengalensis</i>	400	500	<i>Osangularia culter</i>	700 ± 200 m
<i>Bolivinita quadrilatera</i>	500	250		
<i>Fursenkoina complanata</i>	500	200		
<i>Rutherfordoides rotundata</i>	500	300		
<i>Martinotiella communis</i>	500	400		
<i>Pyrgo murrhina</i>	500	400		
<i>Bulimina truncana</i>	500	450		
<i>Pullenia salisburyi</i>	500	950		
<i>Cassidulina norvangi</i>	500	1000		
<i>Melonis affinis</i>	550	500	<i>Melonis barleeaanum</i>	400 ± 100 m
<i>Bolivina pusilla</i>	550	1700		
<i>Eggerella bradyi</i>	750	625	<i>Eggerella ihungia</i>	600 ± 150 m
<i>Sigmoilopsis schlumbergeri</i>	750	750	<i>Sigmoilopsis schlumbergeri</i>	600 ± 150 m
<i>Cibicoides bradyi</i>	750	1200		
<i>Cibicides robertsonianus</i>	800	1000		
<i>Epistominella umbonifera</i>	—	1200		
<i>Siphotextularia rolshauseni</i>	—	1300		
<i>Laticarinina pauperata</i>	2000	2000		
<i>Melonis pompilioides</i>	2150	1000		



L4a, dominated by *C. carinata*, *Abditodentrix pseudothalmanni*, *Bulimina truncana*, *Uvigerina peregrina*, *Alabaminella weddellensis*, and *Bulimina marginata* f. *aculeata*;

- (3) upper Circumpolar Deep Water (uCPDW)—underlain by groups S4, and L4b,c dominated by *B. marginata* f. *aculeata*, *Oridorsalis umbonatus*, *Globocassidulina subglobosa*, and *A. weddellensis*.

East of New Zealand there is a similar correspondence between the recognised benthic foraminiferal associations and the same overlying, depth-stratified water masses, but some of the dominant taxa differ from those in the west:

- (1) STW—underlain by associations S1–S3 of Hayward et al. (2002), dominated by *Trifarina angulosa*, *C. carinata*, *C. dispersa*, and *Gavelinopsis praegeri*;
- (2) AAIW—underlain by associations B1 and B2 of Hayward et al. (2002), dominated by *C. carinata*, *A. weddellensis*, *A. pseudothalmanni*, and *Trifarina occidentalis*;
- (3) uCPDW—underlain by associations A1–A2 of Hayward et al. (2002), dominated by *Cassidulina nørvangi*, *E. exigua*, *A. weddellensis*, *B. marginata* f. *aculeata*, and *Nonionella auris*.

Closer examination of the distribution patterns of New Zealand's common deep-sea (100–2200 m) benthic foraminifera also shows significant differences exist between those off the west and east coasts:

- (1) 11 common, mostly eutrophic species are significantly more abundant on the east than west (e.g., *C. carinata*, *E. exigua*, *Evolvocassidulina orientalis*, *Trifarina angulosa*, Table 5);
- (2) eight common, more oligotrophic species are more abundant on the west than east (e.g., *Bulimina truncana*, *Melonis affinis*, *Trifarina bradyi*, Table 5);
- (3) nine common eutrophic species have shallower lower limits of abundance in the west than east (e.g., *Bolivina*, *C. carinata*, *Nonionella auris*, *T. angulosa*, Fig. 17);
- (4) three common more oligotrophic species have shallower upper limits of abundance in the west than east (e.g., *Cassidulina nørvangi*, *Osangularia bengalensis*, *Uvigerina peregrina*, Fig. 17).

These differences between west and east coast faunas cannot easily be explained as resulting from the physical properties of the water masses (e.g., salinity and temperature), as there is no significant difference from one side to the other. The main observed difference from west to east appears to be in annual phytoplankton productivity as indicated by satellite imaging of surface water chlorophyll *a* (Fig. 16). Thus, food supply (organic carbon flux to the seafloor) is likely the main factor producing these observed differences in faunal composition and depth range. The decreasing carbon flux resulting from increasing depth to the seafloor is probably also the main factor producing the observed depth-related distributional patterns of deep-sea benthic foraminifera off New Zealand, as concluded by a number of recent studies elsewhere (e.g., Jian et al. 1999; Van der Zwaan et al. 1999; De Rijk et al. 2000; Murray 2000).

If this is true, then the observed modern depth ranges of deep-sea benthic foraminifera cannot be expected to provide consistent values that can be reliably applied to high-

resolution determinations of the paleobathymetry of fossil faunas, unless food supply has remained relatively constant through time, which is unlikely. It would seem that more accurate paleodepth determinations will be obtained from western New Zealand sedimentary basins by using western modern analogues and from eastern basins using eastern analogues.

#### Use of benthic foraminifera for determining paleobathymetry

We have highlighted the differences between the deep-sea benthic foraminiferal distribution patterns west and east of New Zealand, but there are also many similarities in their depth-related distributions that appear to be less affected by differences in primary productivity and can be used to provide less-precise paleobathymetric estimates. These are, in order of decreasing potential accuracy:

- (1) associations that appear to be reliable indicators of shallow water (<100 m), marine environments (e.g., dominated by *Elphidium*, *Zeaflorilus*, *Quinqueloculina*, *Virgulopsis*, glabratellids);
- (2) upper water depth limits of many individual deep-sea benthic species (Table 7, e.g., *Cibicides wuellerstorfi*, *Osangularia bengalensis*, *Martinotiella communis*, *Bulimina truncana*, *Melonis affinis*, *Sigmoilopsis schlumbergeri*);
- (3) associations of deeper water benthic foraminifera, with a trend from eutrophic (e.g., *Cassidulina carinata*, *Trifarina angulosa*, *Gavelinopsis praegeri*) to more oligotrophic assemblages (e.g., *Oridorsalis umbonatus*, *Globocassidulina subglobosa*) with increasing water depth and decreasing carbon flux;
- (4) planktic foraminiferal percentage (Fig. 5);
- (5) depth distributions of maximum relative abundance peaks of selected individual species (Table 6, e.g., *Bolivina robusta*, *Trifarina angulosa*).

Features of the foraminiferal faunas that appear to be of little value for paleobathymetric estimates at these depths are:

- (1) benthic species diversity measures;
- (2) absolute abundance of benthic foraminifera; and
- (3) planktic fragmentation index values.

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**APPENDIX 1** Station location, depth, faunal association, planktic foraminiferal percent, and benthic foraminiferal diversity values. S = species richness (raw number of species present);  $\alpha$  = Fisher Alpha Index; H = Information Function; J = Evenness.

Stn. no.	NIWA stn.	IGNS cat. no.	Depth (m)	Latitude	Longitude	Faunal assoc.	Planktics (%)	FRAG index	S	$\alpha$	H	J
1L	E887	F202415	379	36° 40' 00" S	173° 53' 00" E	L3	54		44	18	2.8	0.74
1S	E887	F202415	379	36° 40' 00" S	173° 53' 00" E	S2	42	2	42	16	3	0.81
2L	E469	F202416	1011	37° 40' 00" S	173° 50' 00" E	L3b	79		26	8	2	0.6
2S	E469	F202416	1011	37° 40' 00" S	173° 50' 00" E	S3a	86	9	27	8	2.8	0.84
3L	E892	F202417	1226	37° 20' 00" S	173° 35' 00" E	L3c	64		21	6	2.2	0.72
3S	E892	F20417	1226	37° 20' 00" S	173° 35' 00" E	S3b	63	17	25	7	2.7	0.83
4L	E465	F202418	1419	37° 40' 00" S	173° 20' 00" E	L4a	74		20	6	2	0.68
4S	E465	F202418	1419	37° 40' 00" S	173° 20' 00" E	S4a	87	8	29	10	2.7	0.79
5L	E473	F202419	1545	37° 20' 00" S	173° 05' 00" E	L4b	67		21	6	2.2	0.72
5S	E473	F202419	1545	37° 20' 00" S	173° 05' 00" E	S4a	84	12	27	9	2.6	0.78
6L	E476	F202420	1670	37° 00' 00" S	172° 53' 00" E	L4b	86		20	6	2	0.67
6S	E476	F202420	1670	37° 00' 00" S	172° 53' 00" E	S4a	88	8	29	9	2.6	0.76
7L	B94	F202421	1825	36° 48' 12" S	172° 12' 00" E	L4b	85		23	7	1.9	0.6
7S	B94	F202421	1825	36° 48' 12" S	172° 12' 00" E	S4b	91	12	21	6	2.4	0.8
8L	J51	F202422	2000	36° 52' 00" S	170° 42' 00" E	L4c	95		28	10	2.4	0.73
8S	J51	F202422	2000	36° 52' 00" S	170° 42' 00" E	S4b	96	6	33	11	2.8	0.8
9L	J48	F202423	2150	36° 30' 00" S	170° 26' 00" E	L4c	95		30	10	2.7	0.8
9S	J48	F202423	2150	36° 30' 00" S	170° 26' 00" E	S4b	96	7	32	11	2.8	0.81
10L	C279	F202424	18	38° 1' 12" S	174° 46' 12" E	L2	7		16	8	2.5	0.9
10S	C279	F202424	18	38° 1' 12" S	174° 46' 12" E	S1	9		34	11	3	0.84
11L	C288	F202425	60	38° 1' 48" S	174° 30' 24" E	L2a	28		21	5	2.3	0.75
11S	C288	F202425	60	38° 1' 48" S	174° 30' 24" E	S2a	20	12	24	7	2.4	0.76
12L	C293	F202426	238	38° 1' 12" S	173° 57' 36" E	L2b	35		20	6	2.2	0.73
12S	C293	F202426	238	38° 1' 12" S	173° 57' 36" E	S2b	22	6	31	9	2.5	0.74
13L	E898	F202427	506	38° 00' 00" S	173° 53' 00" E	L3a	55		30	11	2.9	0.84
13S	E898	F202427	506	38° 00' 00" S	173° 53' 00" E	S2d	53	8	38	12	2.8	0.76
14L	E453	F202428	794	38° 00' 00" S	173° 50' 00" E	L3b	80		30	10	2.3	0.69
14S	E453	F202428	794	38° 00' 00" S	173° 50' 00" E	S3a	82	12	30	10	2.9	0.86
15L	E900	F202429	974	38° 01' 00" S	173° 38' 00" E	L3b	67		20	6	1.6	0.54
15S	E900	F202429	974	38° 01' 00" S	173° 38' 00" E	S3b	73	13	36	11	2.6	0.72
16L	E446	F202430	1417	38° 10' 00" S	172° 50' 00" E	L4a	88		34	11	2.4	0.68
16S	E446	F202430	1417	38° 10' 00" S	172° 50' 00" E	S3a	83	19	29	10	2.7	0.81
17L	C266	F202431	49	38° 20' 00" S	174° 29' 48" E	L2a	16		16	4	2.3	0.82
17S	C266	F202431	49	38° 20' 00" S	174° 29' 48" E	S2b	12	43	24	6	2.4	0.75
18L	C271	F202432	91	38° 20' 00" S	174° 11' 48" E	L2a	16		26	7	2.1	0.64
18S	C271	F202432	91	38° 20' 00" S	174° 11' 48" E	S2a	13	3	30	10	2.4	0.7
19L	C275	F202433	137	38° 20' 00" S	173° 43' 30" E	L2b	48		22	6	2.4	0.78
19S	C275	F202433	137	38° 20' 00" S	173° 43' 30" E	S2c	51	10	37	12	3	0.84
20L	L24025	F202434	6	38° 59' 08" S	174° 23' 31" E	L1a	1		33	12	2.6	0.74
20S	L24025	F202434	6	38° 59' 08" S	174° 23' 31" E	S1	4	8	36	13	2.5	0.69
21L	L24022	F202435	22	38° 56' 20" S	174° 22' 10" E	L1b	0		9	3	1.2	0.56
21S	L24022	F202435	22	38° 56' 20" S	174° 22' 10" E	S1	16		27	8	2.7	0.81
22L	I878	F202436	46	38° 47' 00" S	174° 21' 06" E	L2a	8		16	4	2	0.72
22S	I878	F202436	46	38° 47' 00" S	174° 21' 06" E	S2a	2	80	21	6	2.5	0.81
23L	C358	F202437	121	38° 40' 00" S	173° 47' 30" E	L2a	36		25	8	2.1	0.65
23S	C358	F202437	121	38° 40' 00" S	173° 47' 30" E	S2b	37	16	26	7	2.5	0.75
24L	B657	F202438	155	38° 37' 00" S	173° 07' 00" E	L2b	48		20	6	2.2	0.73
24S	B657	F202438	155	38° 37' 00" S	173° 07' 00" E	S2c	48	8	30	10	2.9	0.85
25L	E441	F202439	498	38° 30' 00" S	172° 50' 00" E	L4a	85		25	7	2.2	0.68
25S	E441	F202439	498	38° 30' 00" S	172° 50' 00" E	S3	83	3	31	10	2.6	0.76
26L	E904	F202440	1244	38° 30' 00" S	172° 24' 00" E	L3c	76		34	11	2.8	0.79
26S	E904	F202440	1244	38° 30' 00" S	172° 24' 00" E	S3b	76	18	33	12	2.8	0.81
27L	Q248	F202441	109	39° 55' 48" S	173° 09' 24" E	L2b	42		22	7	2.2	0.71
27S	Q248	F202441	109	39° 55' 48" S	173° 09' 24" E	S2b	39		27	8	2.5	0.76
28L	G20	F202442	154	39° 32' 00" S	172° 48' 00" E	L2b	23		21	6	2.1	0.7
28S	G20	F202442	154	39° 32' 00" S	172° 48' 00" E	S2b	26	12	29	9	2.3	0.69
29L	H112	F202443	194	39° 52' 00" S	172° 37' 12" E	L2b	49		24	7	2.1	0.67
29S	H112	F202443	194	39° 52' 00" S	172° 37' 12" E	S2c	42	13	35	11	2.9	0.82
30L	C169	F202444	234	39° 40' 00" S	172° 25' 00" E	L2b	65		22	6	2.1	0.69

## APPENDIX 1 (continued)

Stn. no.	NIWA stn.	IGNS cat. no.	Depth (m)	Latitude	Longitude	Faunal assoc.	Planktics (%)	FRAG index	S	$\alpha$	H	J
30S	C169	F202444	234	39° 40' 00" S	172° 25' 00" E	S2c	54	8	39	13	2.9	0.78
31L	C625	F202445	276	39° 20' 00" S	172° 03' 00" E	L2b	76		33	12	2.7	0.77
31S	C625	F202445	276	39° 20' 00" S	172° 03' 00" E	S2c	58	12	39	14	3.1	0.83
32L	B306	F202446	541	39° 28' 00" S	171° 39' 30" E	L3a	88		29	10	2.8	0.83
32S	B306	F202446	541	39° 28' 00" S	171° 39' 30" E	S2d	84	3	44	16	3.2	0.85
33L	F736	F202447	746	39° 20' 00" S	171° 37' 00" E	L3a	88		30	10	2.7	0.8
33S	F736	F202447	746	39° 20' 00" S	171° 37' 00" E	S3c	88	5	41	14	3	0.81
34L	F840	F202448	850	39° 05' 00" S	171° 06' 00" E	L3a	87		32	11	2.9	0.84
34S	F840	F202448	850	39° 05' 00" S	171° 06' 00" E	S3c	92	2	34	11	3.1	0.88
35L	F730	F202449	1025	38° 55' 00" S	171° 35' 00" E	L3c	92		27	9	2.5	0.76
35S	F730	F202449	1025	38° 55' 00" S	171° 35' 00" E	S3b	89	7	26	8	2.8	0.85
36L	F733	F202450	1120	38° 53' 00" S	171° 50' 00" E	L3c	89		24	8	2.5	0.8
36S	F733	F202450	1120	38° 53' 00" S	171° 50' 00" E	S3a	89	9	26	8	2.6	0.79
37L	F728	F202451	1233	38° 38' 00" S	171° 48' 00" E	L3c	94		34	12	2.8	0.79
37S	F728	F202451	1233	38° 38' 00" S	171° 48' 00" E	S3a	96	4	37	14	3.2	0.88
38L	F6	F202452	1518	38° 18' 00" S	171° 30' 00" E	L4a	96		23	7	2.2	0.69
38S	F6	F202452	1518	38° 18' 00" S	171° 30' 00" E	S3c	96	2	26	8	2.6	0.79
39L	G831	F202453	1748	37° 45' 00" S	171° 24' 18" E	L4a	86		18	5	2.1	0.72
39S	G831	F202453	1748	37° 45' 00" S	171° 24' 18" E	S4a	93	14	32	11	2.7	0.78

**APPENDIX 2** Taxonomic reference list for common species. All offshore Taranaki taxa cited in the paper are included, together with citations of figured specimens that reflect the taxonomic concept followed here. Some of the more common species are illustrated in Fig. 4 (figure numbers cited below in bold). Generic classification largely follows Loeblich & Tappan (1987), with the ordinal classification after Loeblich & Tappan (1992). The original descriptions of these species can be found in the Ellis and Messina world catalogue of foraminiferal species on www.micropress.org The observed depth range of these species in this study is given in brackets.

**Order Textulariida**

- Eggerella bradyi* (Cushman). Loeblich & Tappan 1987, pl. 189, fig. 1, 2. (746–2150 m)  
*Martinotiella communis* (d'Orbigny). Jones 1994, pl. 48, fig. 1, 2, 4–8. (506–1244 m)  
*Siphotextularia fretensis* Vella. Loeblich & Tappan 1994, pl. 41, fig. 1–4. (18–379 m)  
*Siphotextularia rolshauseni* Phleger & Parker. Hayward et al. 2001, fig. 14H,I (not present off Taranaki). **Fig. 4A**  
*Spiroplectinella proxispira* (Vella). Hayward et al. 1999, pl. 2, fig. 9–11. (6–109 m)

**Order Miliolida**

- Miliolinella subrotunda* (Montagu). Hayward et al. 1999, pl. 3, fig. 24. (6–1748 m) **Fig. 4B**  
*Pyrgo murrhina* (Schwager). Jones 1994, pl. 2, fig. 10, 11, 15. (498–2150 m)  
*Quinqueloculina oblonga* (Montagu). Hayward et al. 1999, pl. 4, fig. 27, 28. (18–121 m)  
*Quinqueloculina seninula* (Linnaeus). Hayward et al. 1999, pl. 5, fig. 9, 10. (6–1518 m) **Fig. 4C**  
*Sigmoilopsis schlumbergeri* (Silvestri). Jones 1994, pl. 8, fig. 1–4. (22–2150 m)

**Order Nodosariida**

- Nodosaria hispida* d'Orbigny. Loeblich & Tappan 1994, pl. 16, fig. 7, 8. (18–794 m)

**Order Robertinida**

- Hoeglundina elegans* (d'Orbigny). Hayward et al. 1999, pl. 8, fig. 5–7. (91–1825 m)

**Order Buliminida**

- Abditodentrix pseudothalmanni* (Boltovskoy & Guissani de Kahn). Hayward et al. 2001, fig. 14J,K. (276–2150 m) **Fig. 4D**  
*Bolivina cacozela* Vella. Hayward et al. 2001, fig. 14L,M. (6–850 m)  
*Bolivina pusilla* Schwager. Kurihara & Kennett 1986, pl. 2, fig. 7, 8. (541–2150 m)  
*Bolivina robusta* Brady. Hayward et al. 2001, fig. 14P,Q. (18–1545 m)  
*Bolivina subexcavata* Cushman & Wickenden. Hayward et al. 2001, fig. 14T,U. (6–1244 m)  
*Bolivina subspinescens* (Cushman). Hayward et al. 2001, fig. 14V,W. (22–2150 m)  
*Bolivinita quadrilatera* (Schwager). Jones 1994, pl. 42, fig. 8–12. (498–1825 m)  
*Bulimina marginata* f. *acanthia* Costa. Hayward et al. 1999, pl. 9, fig. 16, 17. (6–1417 m)  
*Bulimina marginata* f. *aculeata* d'Orbigny. Hayward et al. 1999, pl. 9, fig. 10–12. (49–2150 m) **Fig. 4E**  
*Bulimina marginata* f. *marginata* d'Orbigny. Hayward et al. 1999, pl. 9, fig. 13–15. (6–1670 m) **Fig. 4F**  
*Bulimina striata* d'Orbigny. Jones 1994, pl. 51, fig. 10–13 (as *B. mexicana*). (194–2150 m)  
*Bulimina truncana* Gumbel. Hayward et al. 2001, fig. 14DD,EE. (155–2150 m) **Fig. 4G**  
*Cassidella bradyi* (Cushman). Jones 1994, pl. 52, fig. 9 (as *Fursenkoina*). (194–1748 m)  
*Cassidulina carinata* Silvestri. Hayward et al. 1999, pl. 8, fig. 23, 24. (6–1748 m) **Fig. 4H**  
*Cassidulina nørvangi* Thalman. Hayward et al. 2001, fig. 14GG. (121–2150 m) **Fig. 4I**  
*Ehrenbergina trigona* Goes. Eade 1967, fig. 8, no. 8. (498–2000 m)  
*Evolvocassidulina orientalis* (Cushman). Hayward et al. 1999, pl. 8, fig. 28. (46–1417 m)  
*Fursenkoina complanata* (Egger). Hayward et al. 2001, fig. 14LL. (498–1545 m)

## APPENDIX 2 (continued)

- Globocassidulina canalisuturata* Eade. Hayward et al. 1999, pl. 8, fig. 29, 30. (18–2000 m)  
*Globocassidulina minuta* (Cushman). Hayward et al. 2001, fig. 14OO,PP. (155–2000 m)  
*Globocassidulina subglobosa* (Brady). Hayward et al. 2001, fig.14QQ. (194–2150 m) **Fig. 4J**  
*Neouvirgerina proboscidea* (Schwager). Hayward et al. 2001, fig. 14RR. (18–1825 m) **Fig. 4K**  
*Rutherfordoides rotundata* (Parr). Jones 1994, pl. 52, fig. 10, 11 (as *Fursenkoina*). (500–1670 m)  
*Trifarina angulosa* (Williamson) s.l. Hayward et al. 1999, pl. 9, fig. 23, 24. (6–1670 m)  
*Trifarina bradyi* Cushman. Loeblich & Tappan 1994, pl. 251, fig. 6–16. (137–1025 m)  
*Trifarina occidentalis* (Cushman). Hayward et al. 2001, fig. 14UU,VV. (109–1748 m) **Fig. 4L**  
*Uvirgerina peregrina* Cushman s.l. Hayward et al. 2001, fig. WW, XX. (6–2150 m) **Fig. 4M**  
*Virgulopsis turris* (Heron-Allen & Earland). Hayward et al. 1999, pl. 8, fig. 33. (18–1417 m) **Fig. 4N**

**Order Rotaliida**

- Alabaninella weddellensis* (Earland). Hayward et al. 2001, fig. 15U–W. (22–2150 m) **Fig. 4O–Q**  
*Anmonia aoteana* (Finlay). Hayward et al. 1999, pl. 16, fig. 7–9. (6–49 m)  
*Anomalinoides spherica* (Finlay). Hayward et al. 1999, pl. 15, fig. 27–29. (6–1825 m)  
*Astrononion novozealandicum* Cushman & Edwards. Hayward et al. 1999, pl. 15, fig. 8, 9. (6–2150 m)  
*Cibicides dispars* (d'Orbigny). Hayward et al. 1999, pl. 14, fig. 22–24. (6–2150 m) **Fig. 4R–T**  
*Cibicides robertsonianus* (Brady). van Morkhoven et al. 1986, pl. 11. (794–1518 m)  
*Cibicides wuellerstorfi* (Schwager). Jones 1994, pl. 93, fig. 8, 9. (234–2150 m)  
*Cibicidoides bradyi* (Trauth). Van Morkhoven et al. 1986, pl. 30. (109–2150 m)  
*Discorbinella bertheloti* (d'Orbigny). Hayward et al. 1999, pl. 14, fig. 1–3. (6–794 m) **Fig. 4U–W**  
*Eilohedra levicula* (Resig). Loeblich & Tappan 1994, pl. 303, fig. 1–13. (22–2000 m) **Fig. 4X–Z**  
*Elphidium charlottense* (Vella). Hayward et al. 1999, pl. 9, fig. 187, 188. (6–137 m) **Fig. 4AA, BB**  
*Epistominella exigua* (Brady). Hayward et al. 2001, fig. 15Y–AA. (155–2150 m) **Fig. 4CC–EE**  
*Epistominella umbonifera* (Cushman). Jones 1994, pl. 95, fig. 9, 10 (not present off Taranaki).  
*Gavelinopsis praegeri* (Heron-Allen & Earland). Hayward et al. 1999, pl. 10, fig. 15–17. (18–541 m)  
*Gyroidinoides pulisukensis* (Saidova). Loeblich & Tappan 1994, pl. 363, fig. 1–7. (238–2150 m)  
*Gyroidinoides soldanii* (d'Orbigny). Hayward et al. 2001, fig. 15HH,II. (18–2150 m) **Fig. 4FF, GG**  
*Haynesina depressula* (Walker & Jacob). Hayward et al. 1999, pl. 15, fig. 10, 11. (6–1545 m) **Fig. 4HH, II**  
*Ioanella tumidula* (Brady 1884). Hayward et al. 2001, fig. 16D–F. (506–1545 m)  
*Laticarinina altocamerata* (Heron-Allen & Earland). Hayward & Buzas 1979, pl. 19, fig. 242, 243. (137–1825 m)  
*Laticarinina pauperata* (Parker & Jones). Jones 1994, pl. 104, fig. 3–11. (2000–2150 m)  
*Melonis affinis* (Reuss). Hayward et al. 2001, fig. 16G,H. (91–2150 m)  
*Melonis pompilioides* (Fichtel & Moll). Jones 1994, pl. 109, fig. 10, 11. (2150 m)  
*Nonionella auris* (d'Orbigny). Hayward et al. 2001, fig. 16I–K. (194–2000 m)  
*Nonionellina flemingi* (Vella). Hayward et al. 1999, pl. 15, fig. 14, 15. (6–379 m) **Fig. 4JJ, KK**  
*Notorotalia depressa* Vella. Hayward et al. 1999, pl. 16, fig. 16–18. (6–1417 m)  
*Notorotalia profunda* Vella. Hayward et al. 2001, fig. 16L–N. (155–234 m)  
*Oridorsalis umbonatus* (Reuss). Hayward et al. 2001, fig. 16R,S. (91–2150 m). **Fig. 4LL–NN**  
*Osangularia bengalensis* (Schwager). Jones 1994, pl. 96, fig. 3. (379–2150 m) **Fig. 4OO–QQ**  
*Pullenia bulloides* (d'Orbigny). Hayward et al. 2001, fig. 16T,U. (379–2150 m) **Fig. 4RR, SS**  
*Pullenia salisburyi* Stewart & Stewart. Hayward et al. 2001, fig. 16X,Y. (154–2150 m)  
*Rosalina irregularis* (Rhumbler). Hayward et al. 1999, pl. 11, fig. 4, 5. (6–18 m) **Fig. 4TT, UU**  
*Sphaeroidina bulloides* d'Orbigny. Hayward et al. 2001, fig. 16BB. (154 m)  
*Zeaflorilus parri* (Cushman). Hayward et al. 1997, fig. 5M–O. (6–379 m) **Fig. 4VV–XX**