Foraminifera species distribution and geochemistry of Lyttelton Harbour, Canterbury, NZ

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I. Abstract

Benthic foraminifera species and populations provide a powerful tool for ecological and paleoclimatological assessment. This study was conducted to assess the suitability of Lyttelton Harbour in Canterbury, NZ for foraminiferal analysis by characterizing the presence, abundance, and species diversity of the local foraminifera communities. Foraminifera were collected from the modern intertidal zone in in four bays in Lyttelton Harbour. Foraminifera abundance and diversity, sediment trace element chemistry, and percent organic sediment component were analysed for each sample site. We found that foraminiferal abundance and sediment geochemistry were controlled by sedimentary processes. This project demonstrated that foraminifera are abundant in the Lyttelton Harbour, and thus provided the foundation for future investigations into the local biogeochemistry. Such work can be used to assess the extent to which anthropogenic development and port activity have impacted the water quality, sediment chemistry, and biota in the harbour.

II. Introduction

Benthic foraminifera species and populations are valuable indicators of past and present marine conditions. They are readily accessible, diverse and often abundant in modern marine sediments (Frontalini et al., 2009), well preserved in sedimentary record (Southall et al., 2006; Hayward et al., 2007) and detectably responsive to physical and chemical stresses in the environment (Yanko et al., 1994; Frontalini et al., 2009; Coccioni et al., 2009). Modern abundance, diversity, and distribution of foraminifera species can be used to evaluate the health of an ecosystem and potential anthropogenic impacts on the environment (Frontalini et al., 2009; Coccioni et al., 2009). The foraminiferal biogeography also reflects species' associations with conditions such as tidal exposure, salinity, and ecological setting (Figs 1, 2). These relationships can be synthesized with fossil foraminifera collected from cores to detect temporal changes in local ecosystems.

The foraminifera species of coastal New Zealand are generally well documented: numerous studies have characterized the benthic foraminifera populations in deep water (>100m; Hayward et al., 2003; Buzas et al., 2007; Hayward et al., 2010) and shallow environments (Hayward and Hollis, 1994; Hayward et al., 1999; Hayward et al., 2007) in locations on the North and South Islands. These projects have analysed foraminifera communities for a variety of paleoclimatological purposes: records were used to characterize changes in tidal influence (Gehrels et al., 2008), changes in local sea level (Southall et al., 2006), and vertical earthquake displacement recorded by rapid local sea level change (Hayward et al., 2004; Hayward et al., 2007).

Analysis of the modern and historical foraminifera records in the Lyttelton Harbour in Canterbury, NZ would likewise provide insight into the changing condition of the harbour in response to activity at the Port of Lyttelton, but no such project has been conducted thus far. This study set out to assess the suitability of Lyttelton Harbour for foraminiferal analysis, based on the presence, abundance, and species diversity of foraminifera in various bays around the harbour. Physical and chemical characteristics of the sediment were also collected to identify any potential causes of variation between foraminifera communities. These results can be used as a basis for more detailed, site-specific surface studies and examination of fossil foraminifera records.

III. Geologic setting

Lyttelton Harbour is a large tidal inlet in northern Banks Peninsula in Canterbury, NZ. It is the location of the Port of Lyttelton, the most active seaport on the South Island (Inglis et al., 2008). The harbour is 14 km long from its opening in the east to the Head of the Bay in the west, and ranges from 2km wide in the east to 5 km wide in its western reaches (Fig 3). The cliffs surrounding the harbour are composed of Miocene volcanic deposits (Sewall, 1988), and draped with greywacke-derived loess deposits from the late Pleistocene (Raeside, 1964). In addition to erosion-fed inputs from the surrounding landscape (Curtis, 1985), recent (past 180 years) sediment accumulation rates in these tidal flats have increased in response to catchment land parcel development and harbour activity that flourished after European arrival (Goff, 2005). The changing sedimentation rates and dynamics resulting from dredging practices are examined in detail by Bushell and Teear (1975) and Curtis (1985).

IV. Methods

4.1 Sample collection

Nine samples were collected from four bays in the Lyttelton Harbour. Sediment was collected from the surface (top 2-3cm) and stored. Sampling locations were chosen from tidal heights of mean high water (MHW) to mean sea level (MSL).

4.2 Grain size analysis

For each sample, qualitative sediment texture estimations were made in the field and during the sampling process in the laboratory. These were then assigned quantitative grain size values following the classification regime of Wentworth (1922).

4.3 Foraminiferal analysis

Samples were soaked in Rose Bengal (1g/L) for 24 hours following the methods of Walton (1952) to stain foraminiferal protoplasm and provide a mechanism by which we could differentiate between live and dead foraminifera. The sediment was then washed through a 63µm sieve to remove silt and clay, dried at 50ºC and dry sieved at 355µm to remove the coarse sand component. The remaining sample was separated to isolate a portion containing approximately 100 foraminifera and floated in LST (SG = 1.59) to separate foraminifera from denser material. The floated material was dried at 50ºC. In each sample, ≤100 foraminifera were picked, mounted on slides, identified, and counted.

Foraminifera species diversity was analysed using PAST software. A two-way Bray-Curtis cluster analysis was conducted to determine similarity between the species identified at each site. Diversity index analysis was conducted to determine the dominance and evenness of the species found within each sampling site.

4.4 Geochemical analysis

Whole samples were dried at 50ºC and pulverized. To analyse the sediment organic component, the sample was combusted using an Elemental Combustion System 4010 by Costech Instruments, and total C and N contents were analysed using a Delta V Plus Ion Ratio Mass Spectrometer by ThermoScientific. To analyse the sediment for the presence trace elements, samples were digested in solutions of HNO_3 and HCl and analysed using Inductively Coupled Plasma Mass Spectrometry following the methods of Parry (2012).

V. Results

5.1 Grain size analysis

Sediment was mainly clayey to sandy silt, except in Corsair Bay, where bottom sediment was composed of medium to coarse sand (Fig 4). Sediments sampled at all locations included a shelly component (5-30%).

5.2 Foraminifera species and abundance

Fourteen species of live foraminifera were identified from nine sample sites around Lyttelton Harbour (Fig 5). The maximum number of species found in a single sample was eight. The most common species found were *Ammonia parkinsoniana f. tepida* (29-92%) and *Haynesina depressula* (0-63%) (Fig 6). The cluster analysis conducted produced no strong species clusters and two possible site clusters: LYT-07, 08, and 02 (Cluster 1), and LYT-04, 09, 05, 06, and 10 (Cluster 2) (Fig 7). Foraminifera were abundant in all samples except for LYT-02 (Table 1). Foraminifera were typically more abundant at sites with more fine-grained sediment (Fig 8).

5.3 Geochemical analysis

Figure 9 shows the percent organic C and N by mass in the sediment at five sites; Table 2 shows the concentration of trace elements (ppm) measured at six sites. Sediments at remaining sites were unsuitable for geochemical analysis. It appears that the organic C and N components are higher at mean sea level (MSL) than at mean high water (MHW) in both Governors Bay and Charteris Bay (Fig 9), and trace element concentrations appear to be higher in finer-grained samples (Fig 10).

VI. Discussion

6.1 Sedimentary processes and the biogeochemistry of Lyttelton Harbour

To complete this survey, a small number of samples were collected over a large and diverse intertidal area in order to identify broad chemical and biological trends. The results indicate that both foraminiferal abundance and sediment geochemistry are closely related to sedimentary processes across the harbour. Foraminifera and trace elements were found to be more abundant in finer grained sediments (Figs 8, 10), as they were most likely washed out of the coarser and thus more porous areas by tidal currents (Incera et al., 2003). The exception in the case of foraminifera abundance was at the relatively sparsely populated LYT-02 site, where it is possible that sedimentation rates and dynamics have been altered by the major dredging and dumping of sediment into the harbour as part of maintenance at the Port of Lyttelton (Curtis, 1985). The percent organic sediment component was higher near mean sea level than mean high water (Fig 9), possibly due to the lower-energy conditions in the moderate tidal geography that allowed for the development of vegetative communities and the accumulation of sedimentary organic material (Incera et al., 2003).

While it appears that natural sedimentary processes control the distribution of trace elements in the harbour, it is possible that this chemistry is influenced by anthropogenic activity. Trace elements found in these sediments such as V and Cu that have also been identified in the lithology surrounding the harbour (Price and Taylor, 1980) could be present due to erosional processes in the catchment. The occurrence of other elements such as Mn, Pb, and Zn, however, has sometimes been attributed to industrial activities (Coccioni et al., 2009; Frontalini et al., 2009). Even in environments with an identified point source of pollution, such as in Santa Gilla lagoon in Italy, it is possible to find higher concentrations of trace elements accumulated in finer sediments that are distant from the source of contamination (Frontalini et al., 2009), as they are in Lyttelton Harbour. Thus, it is possible that some of the trace elements found in the harbour are related to the activities at the Port of Lyttelton, but have been redistributed away from the port itself by sedimentary processes. Indeed, concentrations of Mn and Zn appear elevated compared to pre-industrial levels measured in the nearby Avon-Heathcote Estuary (Table 2; Vettoretti, 2014 unpublished data). Close chemical analysis of Lyttelton Harbour's pre-industrial sediments should be conducted to determine the extent to which industrialization has impacted harbour chemistry.

Additionally, concentrations of trace elements that are legally below contamination levels could potentially place stresses the local microbiological communities. Trace element pollution has disturbed diversity and abundance and caused morphological abnormalities in foraminifera populations in heavily polluted environments (Frontalini et al., 2009; Coccioni et al., 2009). Further investigation can be completed in Lyttelton Harbour to identify foraminiferal dwarfism and structural abnormalities in individuals or significant disturbances to population diversity, which could be indicators of the influence even of low levels of trace elements.

6.2 Statistical analysis

The results of the statistical analysis do not clearly indicate that relationships between samples or species are influenced by any factor or group of factors, either physical, chemical, or geographical. This is most likely a result of the low number of samples taken over a large geographic area (Fig 5) and the fact that the number of foraminifera collected from each sample varied widely (Table 2). Based on cluster analysis results (Fig 7), the samples in Cluster 1 appear to be linked by geographic similarity, as both were sampled from sites in Governors Bay. Within Cluster 2, LYT-04 and LYT-09 are most similar, which indicates that this cluster's similarity may be influenced by tidal height, as both are from mean high water zones. This is not a particularly robust association, however, as this cluster contains extensive nesting. Additionally, it is difficult to determine associations between species and ecological zones because not all samples are dominated by one species: the dominance value exceeds 0.5 in only five of nine samples (Fig 5).

Due to these statistical limitations, it is not possible to design species associations based on the dataset presented in this study. This project has demonstrated, however, that the bays of Lyttelton Harbour are suitable localities in which to conduct a thorough investigation that could produce such associations. Paired with chemical investigations of pre-industrial sediments, such work could also be used to assess the changing conditions in the harbour due to anthropogenic activities and determine to what extent these have placed stresses on the microbiological community. Such insight could inform decisions related to water quality management and harbour maintenance practices.

VII. Conclusion

This study has demonstrated that a wide variety of species of foraminifera are abundant in Lyttelton Harbour, making it a good candidate for future foraminferal analysis. The harbour biochemistry examined is closely related to physical sedimentation processes, reflected in the organic, trace element, and foraminiferal abundance in the sediments. This study was a broad survey of the biogeochemistry of Lyttelton Harbour; future work should more thoroughly sample each bay to confidently characterise foraminifera communities and their correlations with the physical and chemical characteristics of each study site.

VIII. Acknowledgements

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IX. References

Bushell, J.B., and Teear, G.C., 1975. Lyttelton Harbour -Dredging and regime improvement. 2nd AustralianConf. Coastal and Ocean Eng., Queensland. Inst. Engs., Australia Natl. Conf. Publ.**75**, 53-68.

Buzas, M.A., Hayek, L.-A.C., Hayward, B.W., Grenfell, H.R., and Sabaa, A.T., 2007. Biodiversity and community structure of deep-sea foraminifera around New Zealand: Deep Sea Research Part I: Oceanographic Research Papers **54**, doi: 10.1016/j.dsr.2007.05.008.

Coccioni, R., Frontalini, F., Marsili, A., and Mana, D., 2009. Benthic foraminifera and trace element distribution: A case-study from the heavily polluted lagoon of Venice (Italy). Marine Pollution Bulletin **59**, 257-267.

Curtis, R.J., 1985. Sedimentation in a rock-walled inlet, Lyttelton Harbour, New Zealand. PhD, Univeresity of Canterbury: Christchurch, NZ.

Frontalini, F., Buosi, C., Da Pelo, S., Coccioni, R., Cherchi, A., and Bucci, C., 2009. Benthic foraminifera as bio-indicators of trace element pollution in heavily contaminated Santa Gilla lagoon (Calgary, Italy). Marine Pollution Bulletin **58**, 858-877.

Gehrels, W.R., Hayward, B.W., Newnham, R.M., and Southall, K.E., 2008. A 20th century acceleration of sea-level rise in New Zealand. Geophysical Research Letters **35**, doi: 10.1029/2007GL032632.

Goff, J., 2005. Preliminary core study – Upper Lyttelton Harbour. Prepared for Environment Canterbury. NIWA Project **ENC06501**: Christchurch, NZ.

Hayward, B.W., Cochran, U., Southall, K., Wiggins, E., Grenfell, H.R., Sabaa, A., Shane, P.R., and Gehrels, R., 2004. Micropalaeontological evidence for the Holocene earthquake history of the eastern Bay of Plenty, New Zealand, and a new index for determining the land elevation record. Quaternary Science Reviews **23**, doi: 10.1016/j.quascirev.2004.01.010.

Hayward, B.W., Grenfell, H.R., Reid, C.M., and Hayward, K.A., 1999. Recent New Zealand shallow-water benthic foraminifera: Taxonomy, ecologic distribution, biogeography, and use in paleoenvironmental assessment. New Zealand Geological Survey: GNS Science Monograph **21**: Lower Hutt, NZ.

Hayward, B.W., Grenfell, H.R., Sabaa, A., and Hayward, J.J., 2003. Recent benthic foraminifera from offshore Taranaki, New Zealand: New Zealand Journal of Geology and Geophysics **46**, doi: 10.1080/00288306.2003.9515024.

Hayward, B.W., Grenfell, H.R., Sabaa, A.T., Neil, H.L., and Buzas, M.A., 2010. Recent New Zealand deep-water benthic foraminifera: Taxonomy, ecologic distribution, biogeography, and use in paleoenvironmental assessment. New Zealand Geological Survey: GNS Science Monograph **26**: Lower Hutt, NZ.

Hayward, B.W., Grenfell H.R., Sabaa, A.T., Southall, K.E., and Gehrels, W.R., 2007. Foraminiferal evidence of Holocene subsidence and fault displacements, coastal South Otago, New Zealand. Journal of Foraminiferal Research **37,** doi:10.2113/gsjfr.37.4.344.

Hayward, B.W., and Hollis, C.J., 1994. Brackish foraminifera in New Zealand: A taxonomic and ecologic review. Micropaleontology **40**, doi:10.2307/1485816.

Incera, M., Cividanes, S.P., Lastra, M., and Lopez, J., 2003. Temporal and spatial variability of sedimentary organic matter. Estuarine, Coastal and Shelf Science 58S, 55-61.

Inglis, G., Gust, N., Fitridge, I., Floerl., O., Woods, C., Kospartov, M., Hayden, B., and Fenwick, G., 2008. Port of Lyttelton: Second baseline survey for non-indigenous marine species. Prepared for MAF Biosecurity New Zealand. MAFBNZ Technical Paper No **2008/02**: Wellington, NZ.

Parry, R., 2012. Trace elements in the sediments of Lake Forsyth/Wairewa. Prepared for Waterways centre for Freshwater Management. WCFM Report **2012-003**: Christchurch, NZ. Price, R.C., and Taylor, S.R., 1980. Petrology and geochemistry of the Banks Peninsula volcanoes, South Island, New Zealand. Contrib. Mineral. Petrol. **72**, 1-18.

Price, R.C., and Taylor, S.R., 1980. Petrology and geochemistry of the Banks Peninsula volcanoes, South Island, New Zealand. Contributions to Minerology and Petrology **72**, 1-18.

Raeside, J.D., 1964. Loess deposits of the South Island, New Zealand, and soils formed on them. New Zealand Journal of Geology and Geophysics **7**, 811-838.

Sewall, R.J., 1988. Late Miocene volcanic stratigraphy of central Banks Peninsula, Canterbury, New Zealand. New Zealand Journal of Geology and Geophysics **31**, 41-64.

Southall, K.E., Gehrels, W.R., and Hayward, B.W., 2006. Foraminifera in a New Zealand salt marsh and their suitability as sea-level indicators. Marine Micropaleontology **60**, doi:10.1016/j.marmicro

Vettoretti, G.J., 2014. Intertidal foraminifera of the Avon-Heathcote Estuary; response to coseismic deformation and potential to record local historic events. MSc thesis in preparation, Department of Geological Sciences, UC.

Walton, W.R., 1952. Techniquees for recognition of living Foraminifera. Cushman Foundation of Foraminiferal Research Contributions **3**, 56-60.

Wentworth, C.K., 1922. A scale of grade and class terms for clastic sediment. The Journal of Geology **30**, 377-392.

Yanko, V., Kronfeld, J., and Flexer, A., 1994. Response of benthic foraminifera to various pollution sources: implications for pollution monitoring. Journal of Foraminiferal Research **24**, 1-17.

Tables

Table 1. Foraminifera species census from four bays in Lyttelton Harbour, Canterbury, NZ.

	Allandale		Charteris			Governors		Corsair	
	LYT-02	LYT-03	LYT-04	LYT-05	LYT-06	LYT-07	LYT-08	LYT-09	LYT-10
Ammonia parkinsoniana f. aoteana	2	21	71	59	82	23	24	24	34
Ammonia parkinsoniana f. tepida	2	0	0	0	0	0	0	0	
Elphidium advenum	0	6	4	6	2	4	0	5	18
Haplophragmoides wilberti	0	5	0	0	0	0	0	0	0
Haynesina depressula	2	0	10	14	4	50	50	5	10
Jadammina macrescends	0	1	0	0	0	0	0	0	0
Miliammina fusca	0	0	0	1	0	0	1	0	1
Notorotalia finlayi	0	0	0	0	0	0	0	1	0
Quinqueloculina incisa	0	0	0	0	0	0	0	0	1
Rosalina bradyi	0	0	0	0	1	2	0	0	
Rosalina irregularis	0	3	3	0	0	0	0	0	1
Trochammina inflata	1	20	4	2	0	1	0	0	0
Zeaflorilus parri	0	1	0	0	0	0	0	0	0
Total	**7**	**57**	**92**	**82**	**89**	**80**	**75**	**35**	**65**

Table 2.Trace element chemistry from bottom sediment collected from three bays in Lyttelton Harbour, Canterbury, NZ. Concentration noted in ppm.

	Allandale	Charteris			Governors	
	LYT-02	LYT-04	LYT-05	LYT-06	LYT-07	LYT-08
V	29.33	25.54	39.04	34.86	27.07	32.95
Cr	16.83	10.75	19.90	17.13	13.74	19.16
Mn	374.75	238.79	407.75	320.74	288.54	354.39
Co	6.70	6.01	8.27	7.95	5.83	7.24
Ni	11.50	9.40	13.97	13.45	9.03	12.78
Cu	6.89	5.16	9.38	7.23	7.20	7.90
Zn	58.70	40.23	68.59	59.70	52.61	68.40
As	5.42	5.48	6.66	7.34	5.30	5.54
Pb	15.30	12.32	18.06	17.67	15.68	18.51

Figures

Figure 1

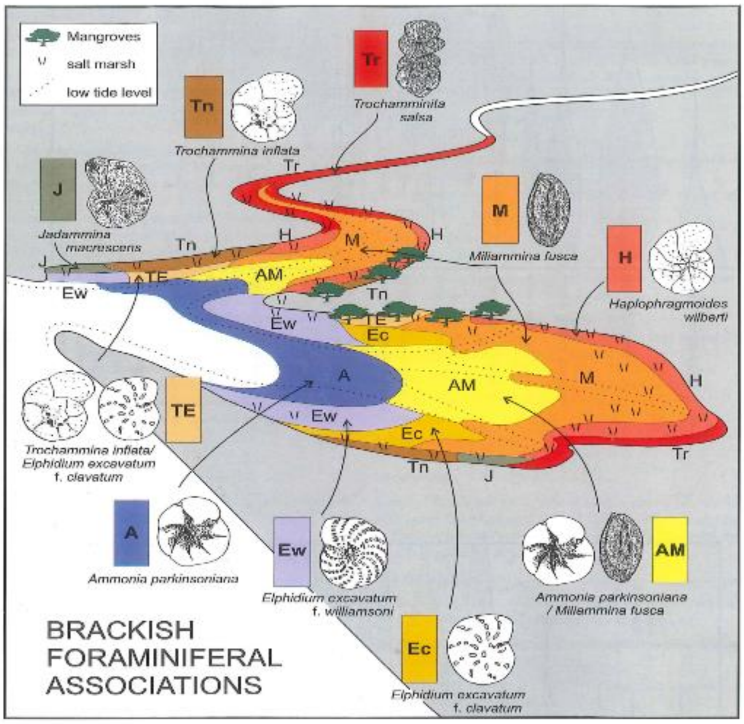
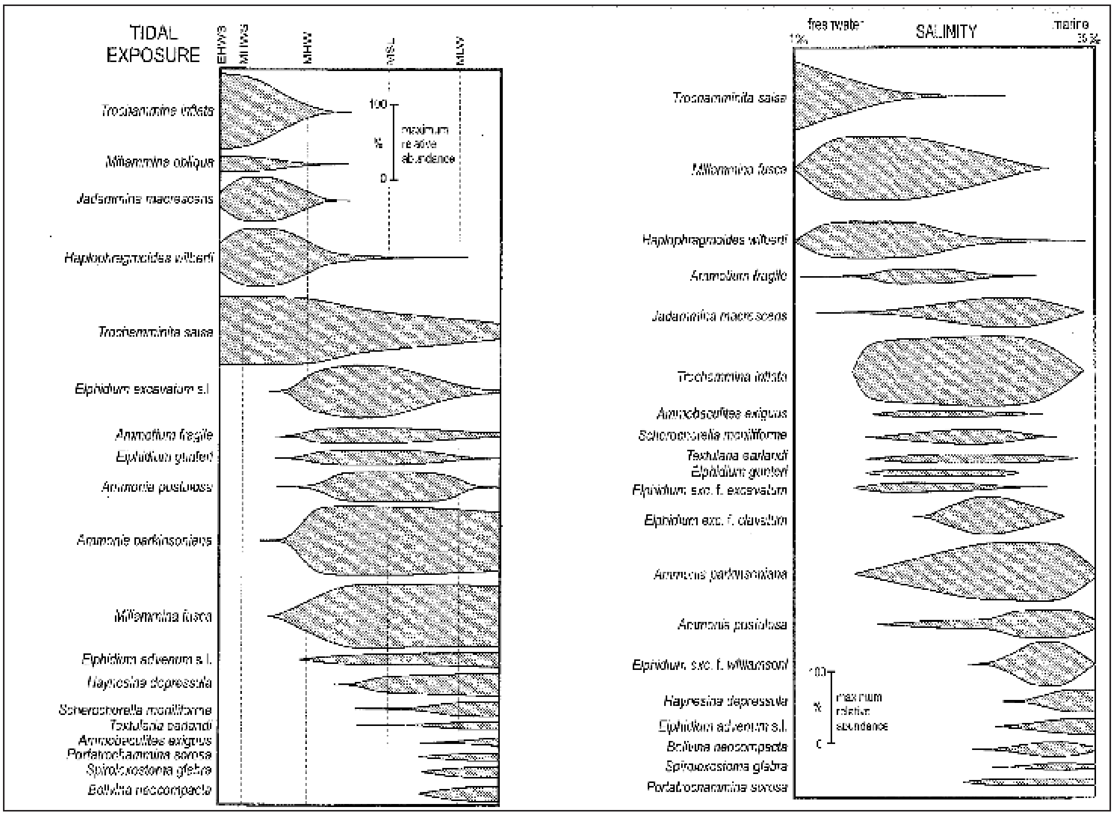


Figure 2



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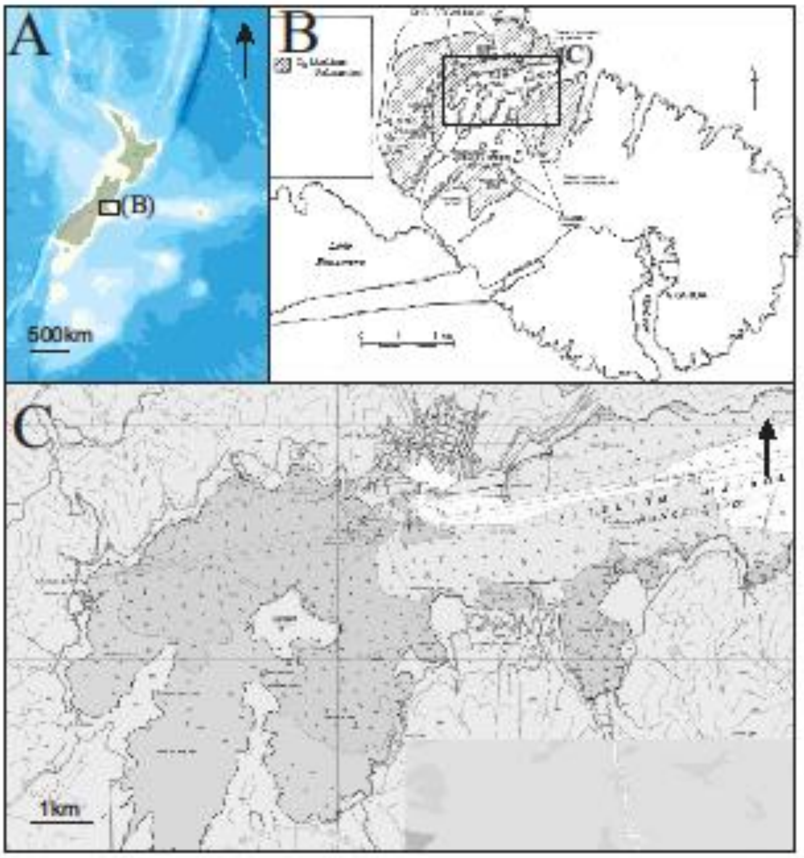


Figure 4

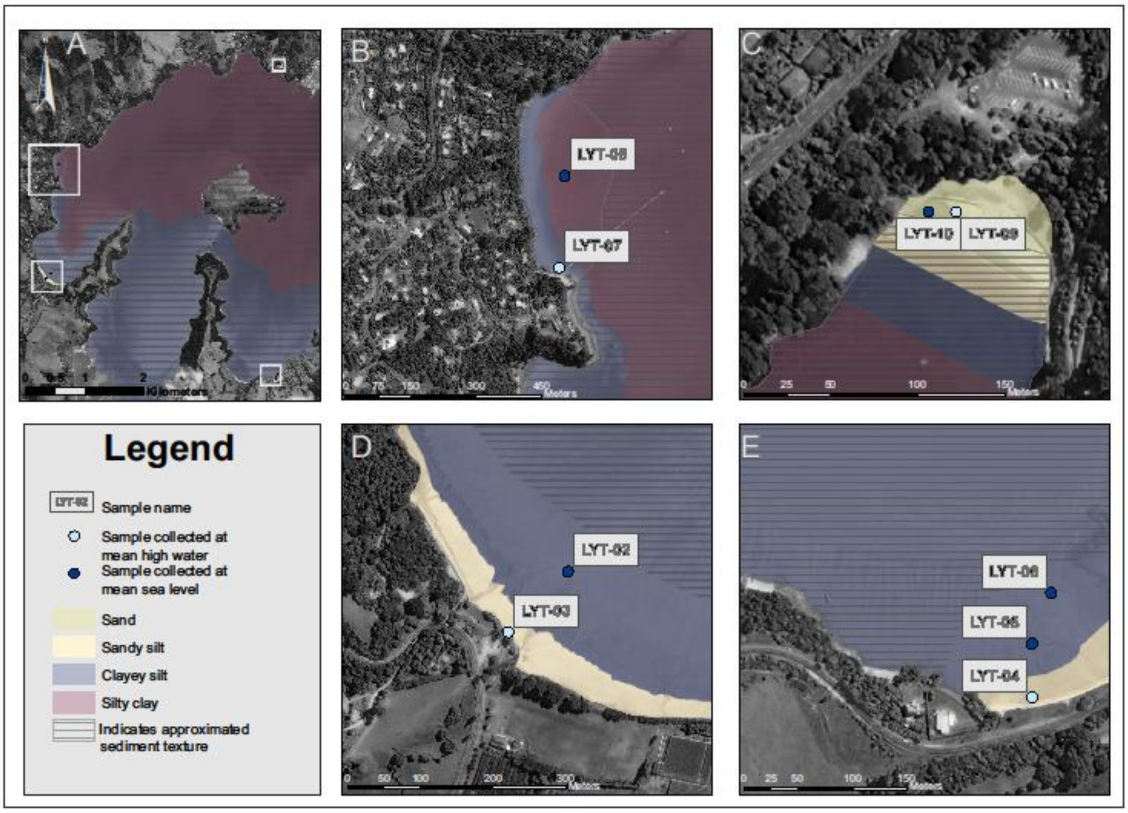


Figure 5

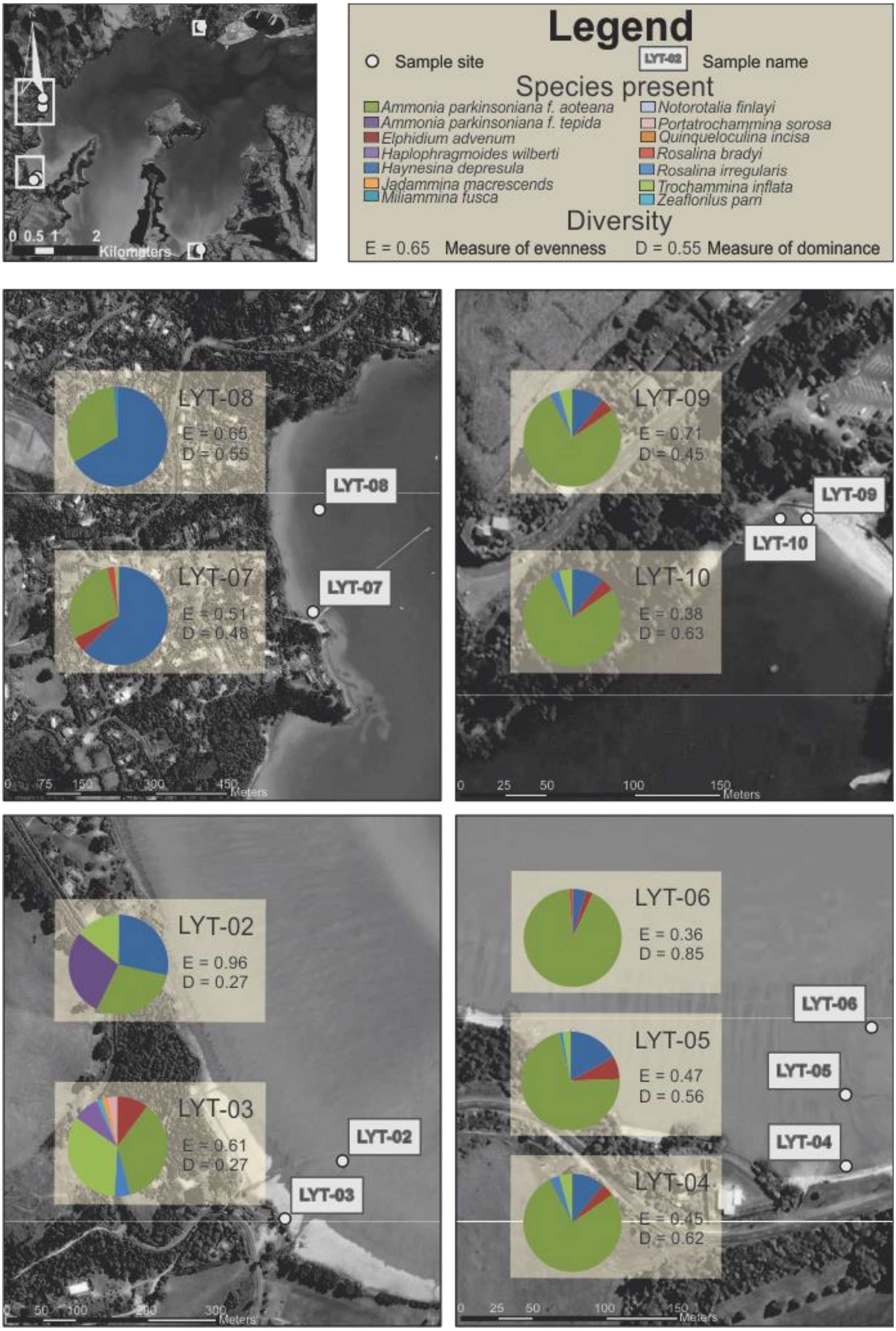

0 0.5 1 2 Kilometers
Legend
Sample site
LYT-02 Sample name
Species present
Ammonia parkinsoniana f. aoteana
Ammonia parkinsoniana f. tepida
Elphidium advenum
Haplophragmoides wilberti
Haynesina depresula
Jadammina macrescends
Miliammina fusca
Notorotalia finlayi
Portatrochammina sorosa
Quinqueloculina incisa
Rosalina bradyi
Rosalina irregularis
Trochammina inflata
Zeaflorilus parri
Diversity
E = 0.65 Measure of evenness
D = 0.55 Measure of dominance
LYT-08
E = 0.65
D = 0.55
LYT-07
E = 0.51
D = 0.48
0 75 150 300 450 Meters
LYT-09
E = 0.71
D = 0.45
LYT-10
E = 0.38
D = 0.63
0 25 50 100 150 Meters
LYT-02
E = 0.96
D = 0.27
LYT-03
E = 0.61
D = 0.27
0 50 100 200 300 Meters
LYT-06
E = 0.36
D = 0.85
LYT-05
E = 0.47
D = 0.56
LYT-04
E = 0.45
D = 0.62
0 25 50 100 150 Meters

Figure 6

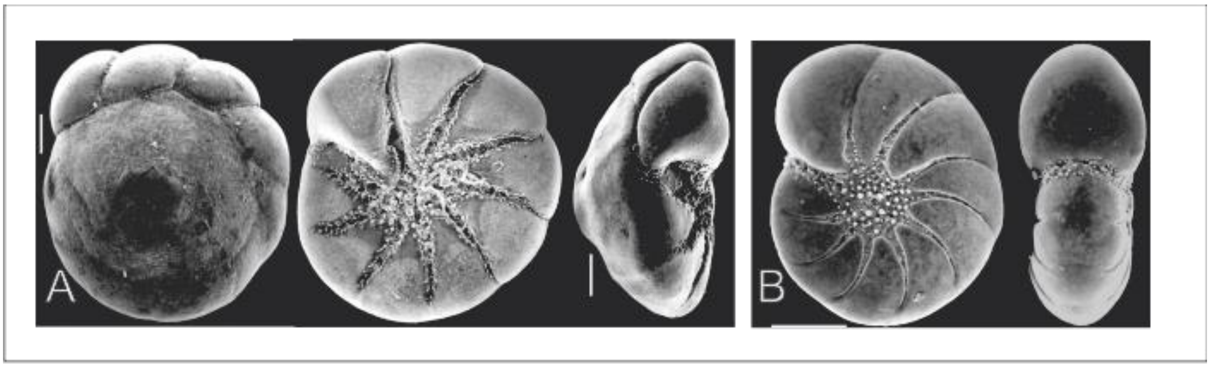
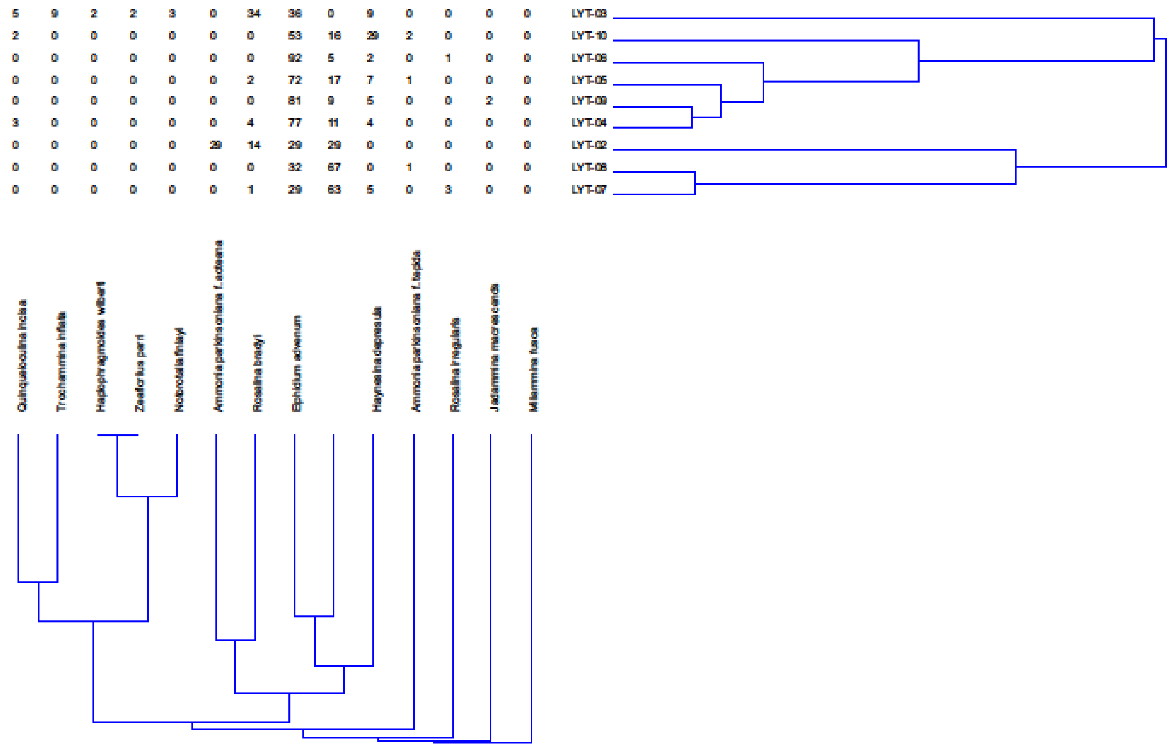


Figure 7



Quinqueloculina incisa	Trochammina inflata	Haplophragmoides wilberti	Zeaflorilus parri	Notorotalia finlayi	Ammonia parkinsoniana f. aoteana	Rosalina bradyi	Elphidium advenum		Haynesina depressula	Ammonia parkinsoniana f. tepida	Rosalina irregularis	Jadammina macrescens	Miliammina fusca	
5	9	2	2	3	0	34	36	0	9	0	0	0	0	LYT-03
2	0	0	0	0	0	0	53	16	29	2	0	0	0	LYT-10
0	0	0	0	0	0	0	92	5	2	0	1	0	0	LYT-06
0	0	0	0	0	0	2	72	17	7	1	0	0	0	LYT-05
0	0	0	0	0	0	0	81	9	5	0	0	2	0	LYT-09
3	0	0	0	0	0	4	77	11	4	0	0	0	0	LYT-04
0	0	0	0	0	29	14	29	29	0	0	0	0	0	LYT-02
0	0	0	0	0	0	0	32	67	0	1	0	0	0	LYT-08
0	0	0	0	0	0	1	29	63	5	0	3	0	0	LYT-07

Figure 8

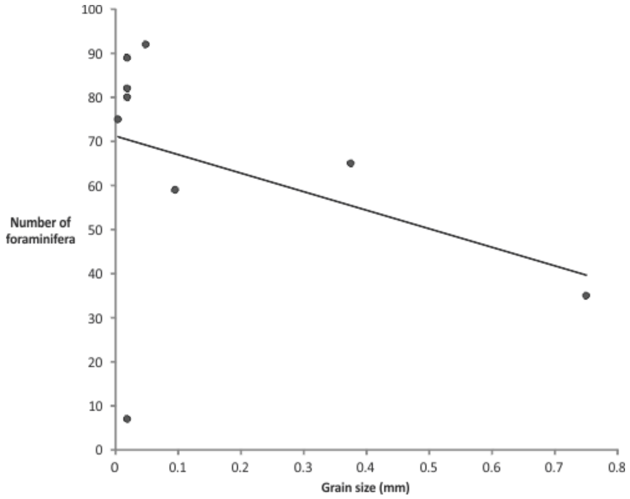


Figure 9

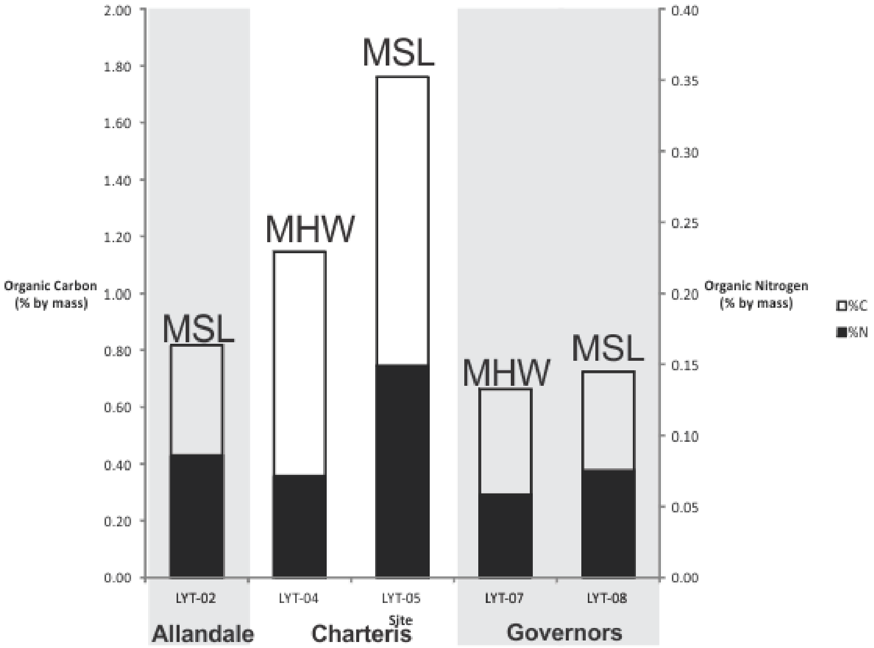
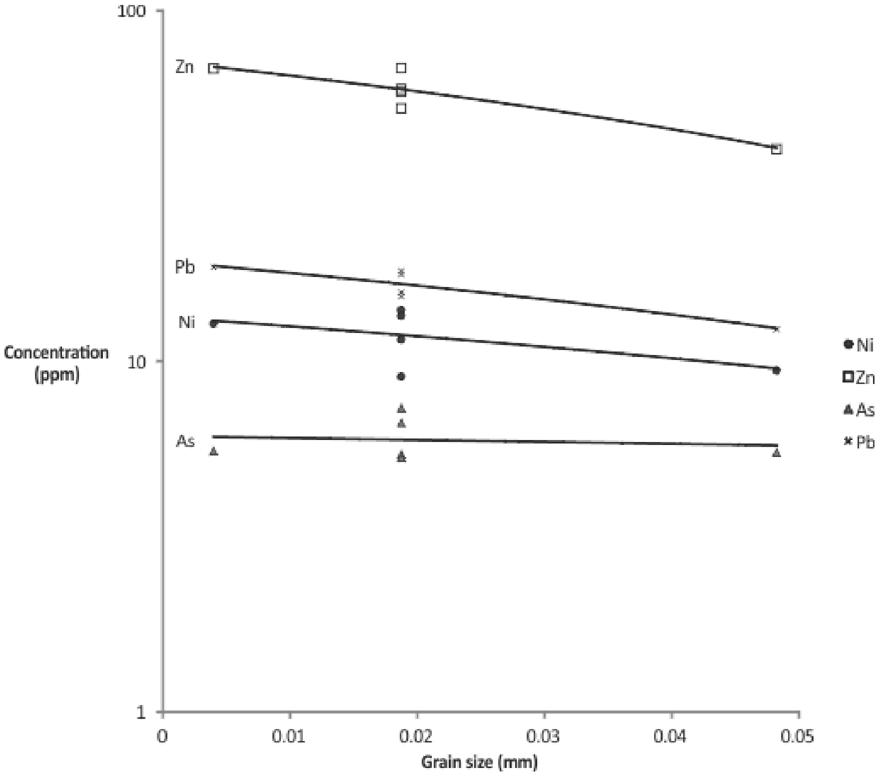


Figure 10



Captions

Figure 1 Schematic diagram of formaminiferal estuarine associations in a typical brackish-water environment (from Hayward et al., 1999). Associations are derived from shallow marine environments in New Zealand.

Figure 2 Impact of tidal exposure and salinity on foraminifera species abundance. Histogram models relative species abundance of benthic foraminifera samples collected from shallow, brackish locations on the North and South Islands of New Zealand (from Hayward et al, 1999).

Figure 3 Map of study area. (A) Bathymetry map of New Zealand; image courtesy of the NIWA 2013. (B) Simplified geologic map of Banks Peninsula (from Sewall, 1985). (C) Map of Lyttelton Harbour; image courtesy of LINZ 2013.

Figure 4 Survey of sediment texture in four bays in Lyttelton Harbour, Canterbury, NZ. Study areas are marked on a map of Lyttelton Harbour (A). Grain size classifications are based on qualitative analysis conducted on samples collected from sites in Governors Bay (B), Corsair Bay (C), Allandale Reserve (D), and Charteris Bay (E).

Figure 5 Foraminifera species distribution in four bays in Lyttelton Harbour, Canterbury, NZ. Study sites are marked on a map of Lyttelton Harbour (A). Foraminfera were collected and identified in Governors Bay (B), Corsair Bay (C), Allandale Reserve (D), and Charteris Bay (E). Relative species abundace charts and results of statistical analysis (species evenness and dominance; maximum value = 1) are provided for each sample.

Figure 6 SEM images of two common foraminifera species found in Lyttelton Harbour, Canterbury, NZ: *Ammonia parkinsoniana f. aoteana* (A) and *Haynesina depressula* (B). Scale bar = 100µm (from Hayward et al., 1999).

Figure 7 Dendrogram of cluster analysis conducted on foraminifera species collected in Lyttelton Harbour, NZ. Bray-curtis cluster analysis variation was conducted using PAST software.

Figure 8 Impact of grain size on foraminifera species abundance. Total number of foraminifera collected in Lyttelton Harbour is plotted against each sample’s quantitative value given to qualitative grain size classification, based on the Wentworth (1922) classifcation regime.

Figure 9 Impact of tidal exposure on the organic component of sediment samples. Chart shows percent organic matter (C,N) by mass measured in the sediment, with annotations indicating the tidal geography of each sample. A higher percentage of organic matter by mass can be found at mean sea level than at mean high water at both Charteris Bay and Governors bay.

Figure 10 Trace element chemistry of sediment samples collected in Lyttelton Harbour. Trace element concentrations (ppm) from six sites are plotted against each sample's quantitative value given to qualitative grain size classification, based on the Wentworth (1922) classification regime.