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Department of Geography
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Mapping of the Bathymetry, Soft Sediments, and Biota of the Seabed of Upper Lyttelton Harbour

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Executive Summary

- This study examines the soft-sediment seabed of Lyttelton Harbour, from east of Purau Bay to the upper harbour shoreline and was commissioned by Environment Canterbury in response to community concerns regarding the potential effects of on-going sedimentation on marine ecosystems, and in particular, shellfish beds.
- Detailed information was gathered on the bathymetry, surface sediment characteristics and extent of biological communities in the upper harbour in order to form a baseline against which future changes could be assessed.
- The measured bathymetry closely reflected the 1951 Upper Lyttelton Harbour surveys shown on the current Hydrographic Chart except that there appears to have been shallowing of up to 0.2 m at the mouth of the three major upper harbour bays, and possibly more along the northwest side of the harbour from Rapaki Bay to Governors Bay.
- Silts and clays were found to dominate the surface of the upper harbour sea bed, with sediments becoming finer from east to west, and clay increasing south to north. Gravels and sands dominated south of the dredged channel and in pockets within the upper harbour.
- The distribution of sand and finer sediments in the upper harbour is likely the combined product of tidal and wave sediment-transport processes; fine-sediment catchment inputs; and lower-harbour continental-shelf sand inputs. In contrast, almost all of the upper harbour gravels were biogenic, the result of shell production.
- The sediment-distribution patterns found in the upper harbour are more-complex than revealed previously, possibly due to the more-detailed sampling regime employed in the present study and/or due to changes in sedimentation. Recent suburban development around the upper harbour catchment, for example, may have played a role in the shoreward increase in silts observed. Findings indicate that the northward flux of fine sediments suggested previously may not be as strong as originally thought.
- A continuum of overlapping benthic communities was found across the expansive intertidal sand and mudflats of the inner harbour in association with different environmental (water-level and sediment) conditions and including mud crabs, cockles, bivalves and gastropods. The only significant shellfish beds found were dominated by the cockle *Austovenus stutchburyi*, extending from mid intertidal levels down to 2 m below mean sea level. Other estuarine shellfish species occurred in samples infrequently, mostly as juveniles in low densities.
- The benthic biota comprised 48 species, including some represented as taxonomic groupings. Polychaetes were the largest group (17 species/families) followed by bivalves (11 species). The most widely distributed macrofaunal species was the stalk-eyed mud crab *Macrophthalmus hirtipes*, which was found at 11 of the 12 sites. The faunal diversity was highest at Charteris Bay (Site 43) and lowest off Rapaki (Site 19) and close to Quail Island (Site 14).
- The community analysis and intertidal sampling identified two main communities within Lyttelton harbour, these are the *Macrophthalmus/ Virgularia* (mud crab/sea pen) community and the *Austrovenus* (cockle) community found predominantly in intertidal areas but extending also into some sandy subtidal habitats.

- No evidence was found of extensive subtidal shellfish beds within the harbour, most samples containing juvenile shellfish. These shellfish are likely to be more-widely distributed than adults given the closeness of Lyttelton Harbour to Pegasus Bay, which may function as a dispersal area.
- Biological community and environmental-variable patterns indicate that the potential for cockle habitat is high in the inner harbour, where they are likely to occur on most intertidal mudflats and sandflats and extend down to shallow subtidal areas, except in areas dominated by coarse shell fragments or gravel.
- From previous studies it might have been predicted that adult shellfish of some species would have been collected in higher numbers. The use of a suction dredge or diving surveys where sediment is sampled to depths of more than 0.2 m depth, or a larger number of replicates, might have collected these larger individuals.
- Three key recommendations for additional future research arise from this report:
    (1) A hydrodynamic study be conducted to establish circulation and wave-energy patterns within the upper harbour and to determine the influence of different sediment sources on the observed deposits and associated benthic communities.

    (2) A study to quantify harbour catchment inputs of water and sediment to better understand the effects of contemporary catchment change on the sedimentation and biological patterns found in the harbour.

    (3) A larger-scale sampling project to describe the full range of biological communities present inside the harbour. The study would need to focus on sediment fractions containing high proportions of sand and gravel, with specialised suction equipment used to sample for deep burrowing bivalves.

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List of acronyms

DTM - Digital Terrain Model

ECan – Environment Canterbury

ESRI - Environmental Systems Research Institute

GIS - Geographic Information System

GNSS - Global Navigation Satellite System

GPS - Global Positioning System

MSL - Mean Sea Level

MLWS – Mean Low Water Spring Tide

NIWA - National Institute of Water and Atmospheric Research

NZGD - New Zealand Geodetic Datum

NZMG - New Zealand Map Grid

SE – Standard Error

2D – Two Dimensional

1. Introduction and Objectives

This report documents a study undertaken to map the soft sediment seabed of Upper Lyttelton Harbour (Figure 1). This study was conducted for Environment Canterbury (ECan) in response to community perceptions that sedimentation is on-going in the upper harbour and has the potential to impact on the marine ecosystems, in particular, the shellfish beds of this area. To investigate the environmental aspects of these concerns, detailed information was required on the bathymetry, surface sediment distributions and characteristics, and extent of biological communities in the upper harbour in order to form a baseline against which future changes in sediment patterns and biological communities could be assessed. Accordingly, the objectives of this study were:

1. To produce a bathymetric map of upper Lyttelton Harbour
2. To map the spatial extent of different soft sediment types within the upper harbour
3. To characterise the sediment grain size distribution at numerous upper harbour sites
4. To map the spatial extent of shellfish beds within the upper harbour
5. To describe the biological communities associated with different sediment types within the harbour

This report documents in detail the data collection and sampling methodology employed, and presents summaries and a discussion of the results, plus detailed results in the form of digital appendices. A review was conducted of previous research on the sediments, bathymetry and biological communities of the harbour as a first step towards providing a baseline for sediment and biological community information.

2. Previous Research

2.1 Sediments and bathymetry

Previous information on sedimentation patterns in Upper Lyttelton Harbour are largely derived from Curtis (1985), Hart (2004), Goff (2005) and de Vries (2007), with Curtis (1985) and Hunt (1991) also contributing some information regarding upper harbour circulation.

Curtis (1985, p44) made comparisons of the bathymetry from charts dated between 1849 (Admiralty Chart 1999 by HMS Acheron 1849) and 1976 (New Zealand Hydrographic Chart NZ6321 1976), noting analysis problems with changes in datum and sounding techniques over this period. His findings for the upper harbour were that a period of scour had occurred between 1849 and 1903, followed by rapid deposition until 1951, followed by a period of slower deposition.

Core sample analysis by Goff (2005) determined a slightly-different temporal pattern for the Head of the Bay. That is, sedimentation rates peaked between the years 1868 and 1900, followed by a decrease in rates to around 1953, then another increase to the present day. Goff (2005) also found that the sediment accumulation rates varied

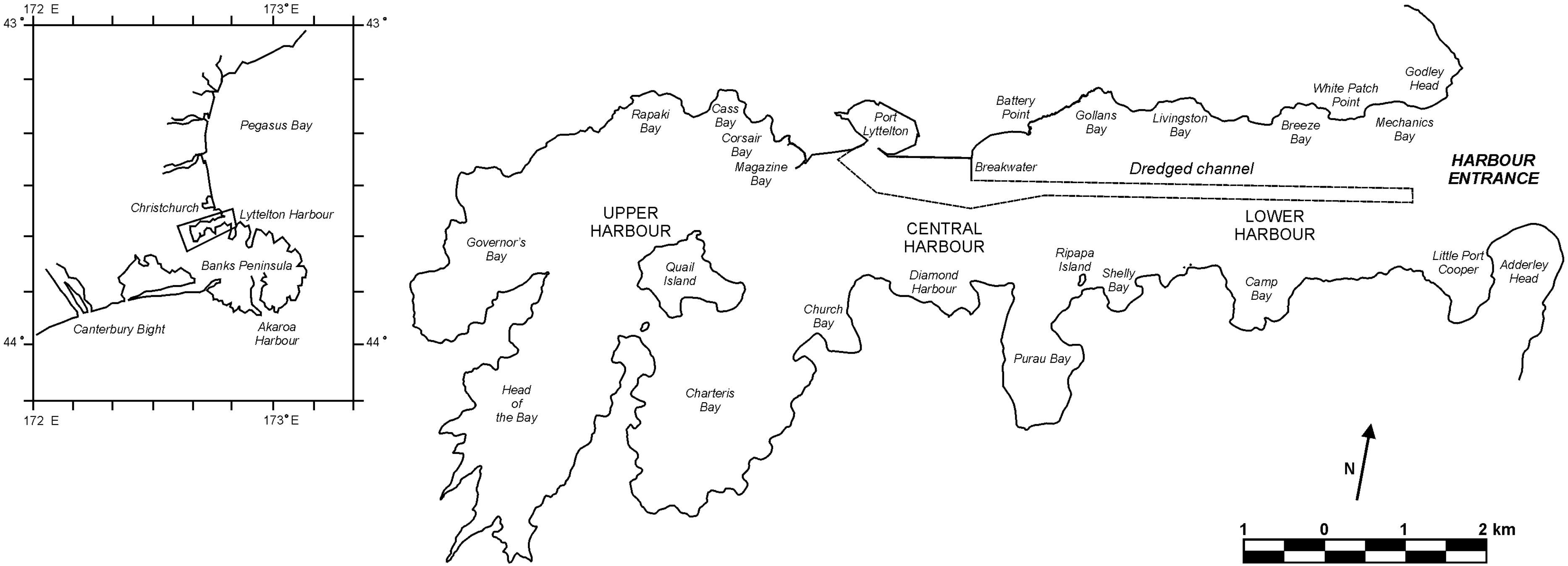


Figure 1 Map of Lyttelton Harbour including places mentioned in the text. The study area included all areas from the upper Harbour shoreline to just east of Purau Bay, except areas north of the dredged channel boundary.

between the upper harbour bays, a factor that was taken into account in designing the sedimentation investigations in the present study.

According to de Vries (2007), the mudflats at the Head of the Bay exhibit highly variable patterns of sediment and sediment disturbance. de Vries described a division across the mudflats between a relatively-stable upper intertidal zone characterised by fine silts and clays, and a much more-dynamic lower-intertidal zone dominated by sandier sediments and shell hash. During his winter-time field period, he found that the profile across the Head of the Bay mudflats, from the shoreline to their seaward limits, was characterised by an erosional concave-up shape, suggesting that, although the mudflats are accreting over the long-term, erosional processes may dominate for short periods.

Analyses of auger samples from the Head of the Bay revealed a substantial increase in the intertidal width from the shoreline to Mean Low Water Springs (MLWS), from 700 m in during the period 1860 to 1900, to 2000 m in 2007 (de Vries 2007). Mean yearly sedimentation rates were found to have been substantially lower in the upper intertidal zone than in the mid to lower intertidal zone, with core samples indicating that the average gradient of the mudflats has decreased over time as they have extended seaward. de Vries concluded that it is likely the intertidal area of the mudflats will continue to increase into the future under current landuse conditions and harbour systems.

Apart from detailed Port of Lyttelton surveys in relation to the dredge channel and spoil dumping grounds, the bathymetry of the upper harbour had not been updated since Royal New Zealand Navy surveys in 1951 by the HMNZS Lachlan (New Zealand Hydrographic chart NZ6321, 2000). The sounding grid in the upper harbour appears to have been at 400 m spacings, but was very limited or non-existent at the heads of the bays.

A consistent finding in previous research is that the main source of material for sedimentation in the upper Lyttelton Harbour is catchment erosion of loess and loess colluvium, with Curtis (1985) estimating the supply rate in the order of 44,300 $t.yr^{-1}$. Hart (2004) noted that catchment erosion rates are an order of magnitude greater in the upper harbour (e.g. west and south of Cass Bay), with fluvial inputs also being concentrated in this area.

In order to understand the transport pathways of harbour inputs and seabed deposits once suspended within the water column, Curtis (1985) measured tidal circulation in the central to lower harbour, and inferred upper-harbour circulation based on sediment texture patterns. He found that mean tidal velocities were greater towards the harbour entrance, varying between 0.15 ms^{-1} west of the port, up to 0.23 ms^{-1} in the central harbour, and to 0.27 ms^{-1} near the harbour entrance. He postulated that the interaction of these currents with harbour topography sometimes led to the development of a large clockwise gyre in the central to lower harbour on the flood tide and a comparable anti-clockwise gyre on the ebb tide. Using an early modelling approach, Hunt (1991) investigated a two-dimensional finite element hydrodynamic model to characterise circulation within the whole of Lyttelton Harbour and Port Levy. His model failed to accurately predict harbour circulation due to boundary condition problems, in particular, underestimating circulation across the extensive shallow mudflat environments.

The limited literature that exists suggests that due to the harbour current patterns, and the lower harbour and dredged channel being an efficient sediment sink, little sediment entering the harbour from Pegasus Bay, or re-circulated from dredge spoil deposition in the northern bays of the lower harbour, is transported into the upper harbour. This literature also acknowledges that rates of sedimentation have accelerated since pre-European times, primarily due to modification of the catchment land cover, first though forest clearance and pasture conversion, and more-recently by increased residential development.

Curtis (1985) presented sediment distribution patterns within the harbour based on 86 samples, including 40 from the upper harbour. Figure 2 is a summary of the sediment distribution obtained from this sampling, with the sample locations and more detailed maps of the results reproduced from Curtis (1985) being presented in Appendix 2. As can be seen from Figure 2, the resulting sediment distribution patterns revealed a north/south division in sediment texture along most of the harbour, with mud sediments dominating the northern flanks and sandier sediments increasing in concentration along the southern flanks of the harbour. These patterns were similar to those identified by Brodie (1955) in an earlier study. The Head of the Harbour was found to be dominated by sandy-mud with small areas of mud in the upper reaches of Governors and Charteris Bays. Curtis (1985) presented in appendices the standard percentiles and Folk parameters for sediment gain size for each of the samples but the sample locations, which were fixed by sextant and compass bearing, were not given other than in the map reproduced in Appendix 2, so the sample locations could not be replicated with any degree of accuracy.

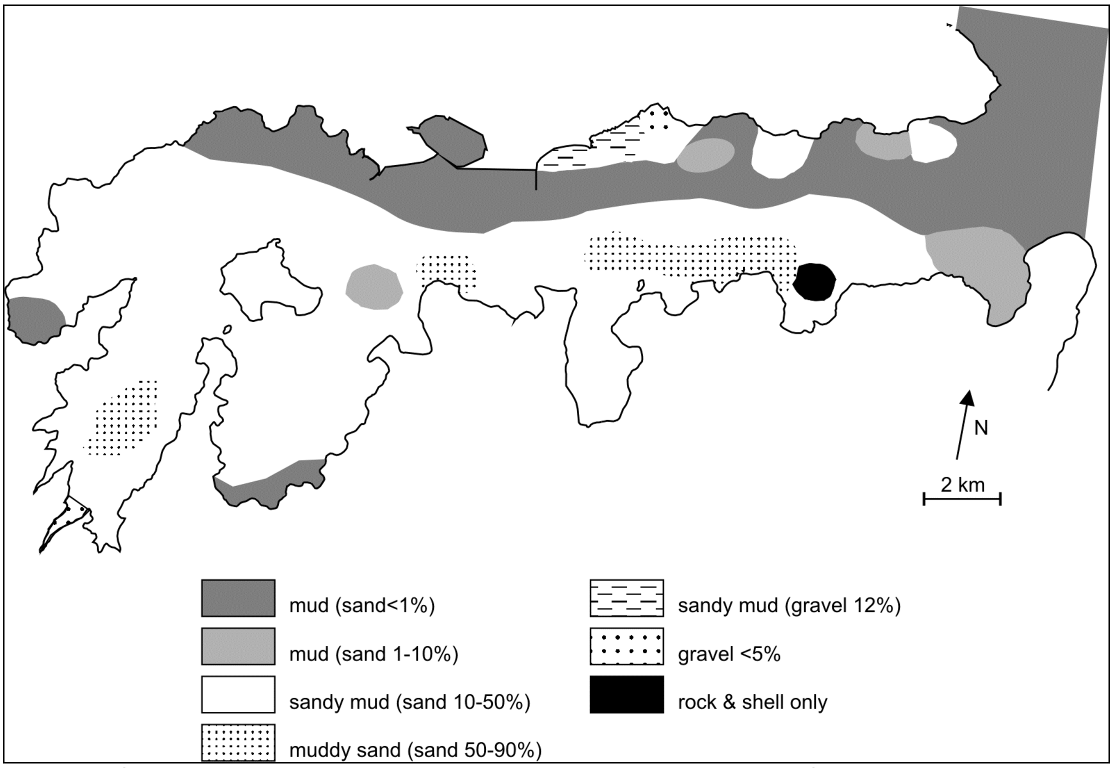


Figure 2 Spatial distribution of harbour sediment textures found by Curtis (1985, 58, modified from Hart 2004).

From textual and rollability analyses, Curtis (1985) concluded that the sand transport systems along either side of the harbour operate independently, with no transfer of sand laterally across the inlet. The analyses also showed that that along-harbour transport of sand was bi-directional, but in the long-term the flood-tide currents and wave induced currents combined to produce a net transport of fine sand along the south side of the harbour towards the head to be deposited in the three upper harbour bays.

2.2 Biological communities

The benchmark reference for defining the structure of the benthic communities in the upper regions of Lyttelton Harbour is Knight (1974). Knight defined the benthic communities from 71 samples taken by orange-peel grab, box dredge and epibenthic sledge, and undertook statistical analysis using Fager's recurrent species analysis technique. Unfortunately these sample locations are not given other than on a map so that they could not be accurately replicated. Four benthic communities were identified:

1. A crab and sea pen community associated with muddy regions of the upper harbour, particularly to the north of Quail Island,
2. A gastropod and polychaete community found in sandy substrates,
3. A New Zealand cockle *Austrovenus stutchburyi* community found in pure sand deposits, and
4. An oyster and gastropod community found on firm substrate.

In addition, eleven other species were found in varying concentrations over the area of bottom designated as sandy mud.

Since the work of Knight (1974) the National Institute of Water and Atmospheric Research (NIWA) have undertaken two biological surveys of the Port of Lyttelton (Handley *et al*. 2000; Fenwick 2003), which included thirteen samples taken by box dredge from the harbour channel between the port and Sticking Point. The location of the samples was recorded by Global Positioning System (GPS), so that identical sampling is able to be replicated in the future (the port is outside of the present study area). The majority of the samples contained large volumes of muddy sediment, with fauna dominated by crabs and polychaete worms.

A recent Biological Sciences postgraduate thesis (Johnston 2005) from the University of Canterbury involved a comparative seasonal study of the biota between the port and the general harbour. The benthic sampling included five sites in muddy sediments to the west of the port entrance, including subtidal sites at Rapaki, Cass and Corsair Bays. The fauna in the harbour was found to be dominated by polychaetes, small bivalves and crustaceans.

3. Methodology

3.1 Surveying

All surveys and the fixing of sediment sample location were undertaken using the New Zealand Map Grid (NZMG) Mt Pleasant Circuit, and then converted for presentation into New Zealand Geodetic Datum (NZGD 2000) coordinates. In order to provide a basis for the sampling regimes and to fulfil objective 1, a survey framework was designed covering both intertidal and subtidal zones of the upper harbour. The sediment accumulations and biological communities of interest occur in both these zones.

As illustrated in Map 1, the survey grid consisted of 16 transects running north-northwest to south-southeast across the harbour, spaced at 500 m intervals. In addition, four longitudinal transects were used, three running southwest to northeast from the major bays at the head of the harbour towards the port, and the other running west-southwest to east-northeast from Quail Island to the eastern end of the study area south of the dredged harbour channel. As shown on Map 1 the area of the port entrance channel was not included in the survey due to this area regularly being modified by the dredging of the channel to maintain suitable depths for shipping. All survey lines and sample sites were pre-programmed into a GPS system, a *Trimble R8 Dual-Frequency GNSS* (Global Navigation Satellite System), allowing accurate navigation along lines and to sites via boat or on foot.

Bathymetric surveys of the subtidal portions of the transects were conducted from the University of Canterbury Department of Geography boat, the Beagle, using an *Odom Hydrotrac Precision Echo Sounder* interfaced with the *Trimble R8 GNSS* system, using real-time kinematic corrections from a *Trimble* base station set up at Lyttelton Geodetic benchmark: Lyttelton Primary TGRM, code DJMF, order 1V (Land Information New Zealand 2008), and using a radio signal repeater mounted on top of Quail Island. Correction was performed in the hydrographic survey software *Trimble Hydropro* using 10 hz frequency sampling for heave compensation, and water-level records acquired from the Port of Lyttelton tide gauge to compensate for tidal and water level changes (Table 1). Accuracy of the survey transect data was estimated as 20 mm horizontally and 50 mm vertically, a level which was deemed acceptable for the mapping required.

Table 1 Tidal levels for Lyttelton Port in relation to Chart Datum and in relation to Mean Sea Level (MSL) (LINZ, 2008b).

Level	Elevation (m above Chart Datum)	Elevation (m above MSL)
Mean High Water Spring (MHWS)	2.44	1.07
Mean High Water Neap (MHWN)	2.04	0.67
Mean Low Water Neap (MLWN)	0.66	-0.71
Mean Low Water Spring (MLWS)	0.3	-1.07
MSL	1.37	0
Highest Astronomical Tide (HAT)	2.68	1.31
Lowest Astronomical Tide (LAT)	0.1	-1.27
	Range (m)	Range (m)
Spring tide	2.14	2.14
Neap tide	1.38	1.38

Surveys of the intertidal portions of the upper harbour transects were conducted on foot, using the same type of *Trimble R8 GNSS* system, this time backpack-mounted and with points recorded at 5 s intervals. An additional survey of the shoreline was conducted on foot to provide an accurate boundary for the final bathymetry grid.

All survey data were combined into a Digital Terrain Model (DTM) using *Golden Software Surfer 8* and contours were interpreted at 1 m intervals using the kriging method. The bathymetry was then mapped using the Environmental Systems Research Institute's Geographic Information System (GIS) software *ESRI ArcView*.

3.2 Sediment sampling and analysis

A sediment sample framework was designed to address objectives 2 and 3 of this study, following the broad spatial distribution used by Curtis (1985) and supplemented by additional samples to improve representation of the upper harbour bays (the area where sediment accumulation is perceived to be greatest). A total of 48 sediment-only samples were taken as illustrated in Map 1. These samples are in addition to the 14 taken for biological analysis, all of which were also analysed for particle size characteristics, but which are discussed separately in the biological sections of this report.

Sediment samples from the subtidal areas (samples 2-3, 10-37 and 40-45) were collected from the boat anchored in position. In areas with water depths between 1.5-3 m, a box scoop (Figure 3a) was used on the end of a telescopic pole. At sites deeper than 3 m, a 0.15 x 0.15 x 0.19 m spring-loaded grab sampler was employed. The depth of sediment sampled by both methods was similar, but during grab sampling, trace amounts of sediment could be lost through the narrow gap in the bottom of the instrument, when not fully closed, as it was pulled up through the water column. This may have resulted in a slightly-lower percentage of fine sediment being retained in samples from water depths greater than 3 m. Samples from intertidal sites (samples 0-1, 4, 5-9, 46-48) were collected via hand trowel to a depth no greater than 0.2 m below the sediment surface, so were comparable to the sediment depth from the subtidal areas. Sample retrieval was repeated at all sites until at least 500-800 ml of sediment was retrieved.

Comprehensive particle-size analysis was performed on all samples including wet sieving, dry sieving and pipette analysis according to the standard guidelines of Lewis and McConchie (1994), to obtain the percentages in each size class (Table 2). Samples were coned and quartered until the final volume contained an estimated fine fraction (silts and clays) less than 20 g, 20 ml of Calgon solution (sodium hexametaphosphate) was added to each to decrease flocculation and samples were wet sieved through a 62.5 μm mesh (0.0625 mm or 4 Φ). The fine fraction (smaller than 62.5 μm) was placed in a measuring cylinder for pipette analysis and the remaining coarse fraction placed in an oven to dry for dry sieving.

The analysis involved determined the percentage of each sample in each of the sediment size classes given in Table 2, determining the sediment texture class of each sample as per the Modified Folk (1965) classification presented in Figure 9, and calculating mean & medium grain size, and sorting (where possible) of each of the samples. Sorting was not calculated for samples with high percentages of silt due to the lack of a 95 percentile grain size required for this calculation.

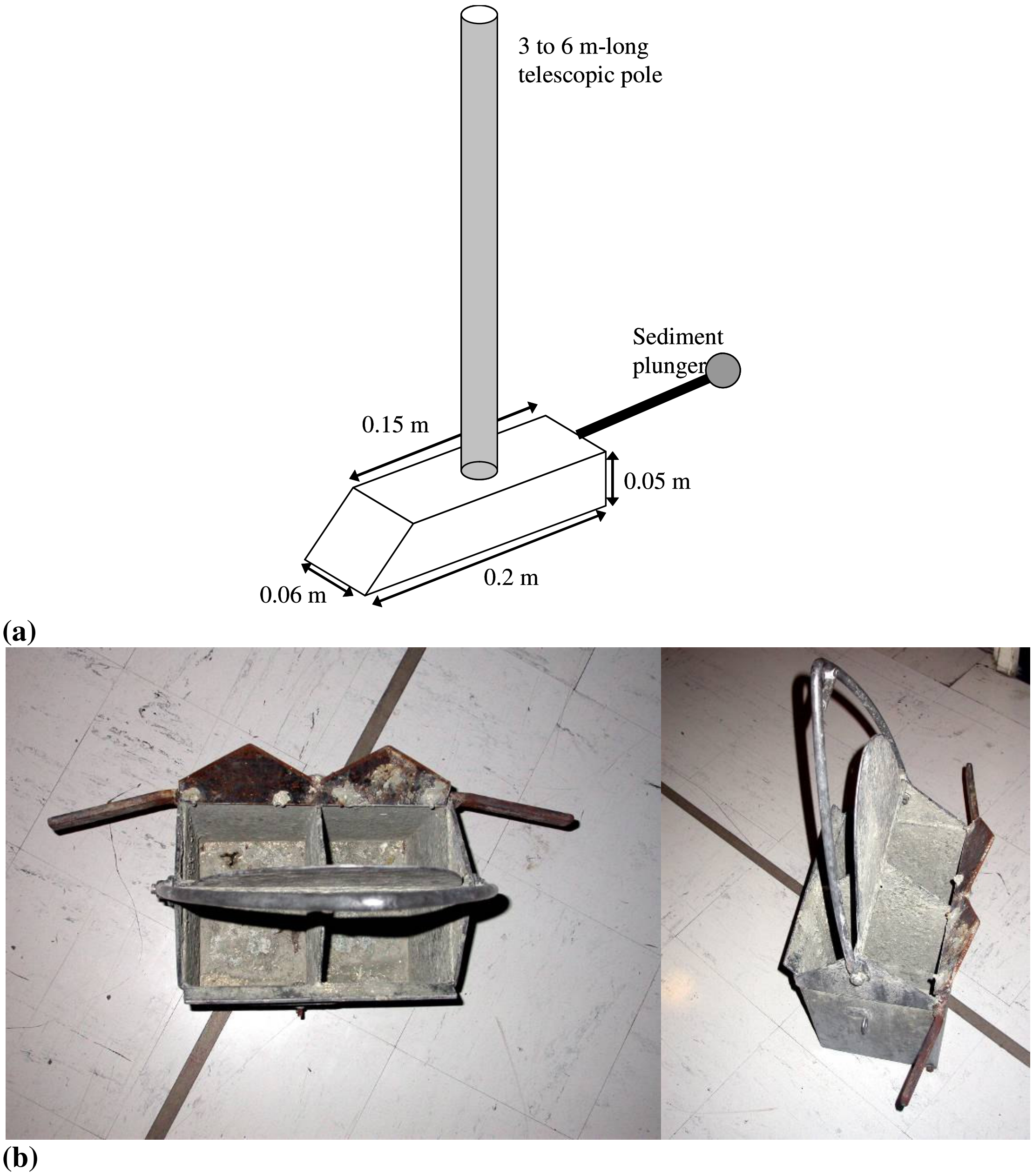


Figure 3 The box scoop used to collect sediment samples between 1.5 to 3 m below MSL (a) and the 0.3 m-wide, 0.2 m-tall and 0.3 m-long box dredge used to collect biological samples (b). Diagram by Justin Harrison and photo by G. Murphy.

Table 2 Udden-Wentworth grain size scale used in describing results.

Textural class	Size (µm)	(mm)	(Φ)
Gravel	>2000	>2	>-1
Very coarse sand	2000 to 1000	2 to 1	-1 to 0
Coarse sand	1000 to 500	1 to 0.5	0 to 1
Medium sand	500 to 250	0.5 to 0.25	1 to 2
Fine sand	250 to 125	0.25 to 0.125	2 to 3
Very fine sand	125 to 62.5	0.125 to 0.0625	3 to 4
Silt	62.5 to 4	0.0625 to 0.004	4 to 8
Clay	<4	<0.004	>8

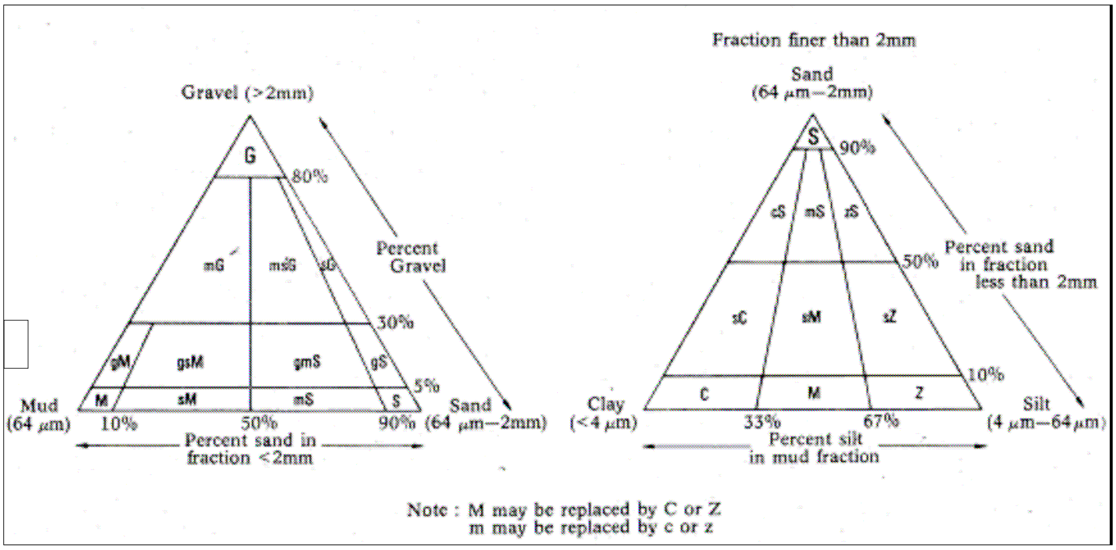


Figure 4 Textural sediment classification modified from Folk (1965) by Carter and Herzer (1986). Classes include gravel (G, g), sand (S, s), silt (Z, z), clay (C, c) and mud (a mixed silt and clay class: M, m). Capitals indicate the dominant constituent.

3.3 Biological communities

Along intertidal portions of the transects illustrated in Map 1 biological sampling was undertaken at 500 m-intervals, using the *TrimbleR8 Rover GPS* and base station for positioning. At each sample point, the location was recorded and fauna investigated within a 2.5 m radius using a small hand trowel to excavate the surface sediments to a depth of approximately 0.15 m in two to three randomly-selected places per site. The presence or absence of key indicator species was recorded, including the shellfish mussels, oysters, pipis and cockles. A total of 28 intertidal sampling sites were investigated.

For subtidal biological sampling, twelve sites were selected in consultation with ECan staff based on the sediment texture results to represent a range of substrates with different compositions including those with large fractions of clay, silt, sand and gravel size classes. The School of Biological Sciences boat was used for collecting samples using a box dredge (Figure 8b), a smaller version of that used by NIWA when investigating the subtidal soft bottoms of Akaroa Harbour (Fenwick 2004). The dredge was fitted with extensions to stop it tipping over and was able to retrieve approximately 10 L of undisturbed sediment when dragged over the sea bed for a distance of between 20 and 100 m around each sample site. This contrasted the sediment-only grab sampling described above, which was performed while the boat was anchored in a stationary position. Replicates were also sampled at each of the predetermined biological sampling sites, all within approximately 100 m of the sediment site location point and of each other, as confirmed using GPS (Map 1).

Because the biological sampling was undertaken using a different sampling device to that used for the sediment-only sampling, sediment analysis was also performed on one biological sample from each of the biological sites and comparisons where made between the sediment and biological site samples. Preliminary sampling was also undertaken to assess the effectiveness of the dredge, the number of replicates required for representative sampling, and to provide an indication of the diversity of organisms present. For this, the mud sample from each dredge sample was put into pre-labelled plastic buckets and the volume recorded. The buckets were transported back to the laboratory and the mud sieved gently through a 1 mm mesh using sea water. The collected organisms were separated and preserved in 10% formalin. The shell fraction was placed in separate containers and later checked to see if it contained living organisms.

A few replicate samples (from Sites 19 and 25) were sieved through a 500 µm mesh and this proved exceptionally time-consuming. Using the 1 mm mesh resulted in an underestimate of small polychaetes but allowed 3 L of sediment to be processed effectively. The results from the preliminary samples showed that 3 replicates were likely to be representative of the sites selected.

In the laboratory the samples were washed in formalin in seawater to reduce the amount of silt and mud present, the polychaetes were separated for counting and identification by ECan staff and the remaining animals transferred into 70% alcohol prior to identification and counting. Where possible, identifications were made to the genus and species levels, and polychaetes to the family level. Results were standardised per 3 L replicate because calculations using a standard conversion for the dredge have not been calculated for the different substrate types sampled.

3.4 Bio-statistical analyses

The biological data from each site were entered as a matrix into an Excel spreadsheet to calculate average densities for each species and the various taxonomic groups for each site. The multivariate statistical package programme *Primer* was used to compare faunal assemblages between sites and to identify the species that contributed to the main site groupings. The data were square root transformed, similarity dendrograms were prepared, and multidimensional scaling was used to generate ordination (MDS) plots. This process was also used to group the sites based on their sediment and depth characteristics. A further application of this programme, *BioEnv*, was used to determine which abiotic features of the site correlated with the faunal distributions.

4. Results

The following sections describe the main findings from the bathymetry, sediment and biological surveys. The resulting maps are from the surveys are presented at the end of the report. A digital copy of the raw data from the surveys and the GIS shape files used to construct the maps are included in the CD supplied to ECan with this report. Appendix 1 provides a list of the digital data contained on this CD.

4.1 Bathymetry

Map 2 illustrates the bathymetry of the central to upper Lyttelton Harbour study area with depth contours at 0.5 m intervals in relation to MSL (refer to electronic material supplied to ECan for the shape files used to create this map). Over the entire study area elevation of the harbour bed ranged from >0.5 m above MSL towards the shorelines of Governors Bay, Head of the Bay and Charteris Bay, to 9.5 m below MSL along the southern boundary of the Lyttelton Port dredged channel to the east of Purau Bay.

Along the central axis of the harbour to the east of Quail Island there is a gradual shallowing from 9.5 m below MSL east of the entrance to Purau Bay to 4 m below MSL along the north-eastern side of Quail Island. This gives a general gradient of the seabed in the order of 1:850. However, this slope is interrupted by several depressions, up to 7.5 m below MSL to the south of the dredged channel and off Magazine Bay, and several high points, up to intertidal elevations between the Port and Quail Island. The most prominent of these highpoints is Shag Reef, an intertidal rock reef complex shown in Figure 5.

The sub and intertidal slopes of the seabed along a central transect of three major bays of the upper harbour are presented in Figure 6(a), with the locations of the transects presented in Figure 6(b). These results show that the steepest seabed slopes over the total transect length are found in Chartertis Bay, at around 1:700, followed by Governors Bay at around 1:750, and the Head of the Bay in the western lee of Quail Island being considerably flatter at 1:1,500. In all three bays there appears to be a step in the slopes at around at elevation of 0.5 m below MSL, with the intertidal seabed slopes about this elevation being considerably steeper, at 1:400 for Chartertis Bay, 1:650 for Governors Bay, and 1: 1,100 for Head of Bay, than the subtidal slopes. Despite these steeper intertidal slopes, there are still extensive intertidal flats in all three bays, with the 1 m below MSL contour being located in the order of 900 m from the shore in Chartertis Bay, in the order of 1200 m from the shore in Governors Bay, and in the order of 1650 m from the shore in the Head of the Bay. Hence at low spring tide conditions around half of the area of Charteris Bay and two thirds of Governors Bay and Head of the Bay are exposed intertidal mud flats.

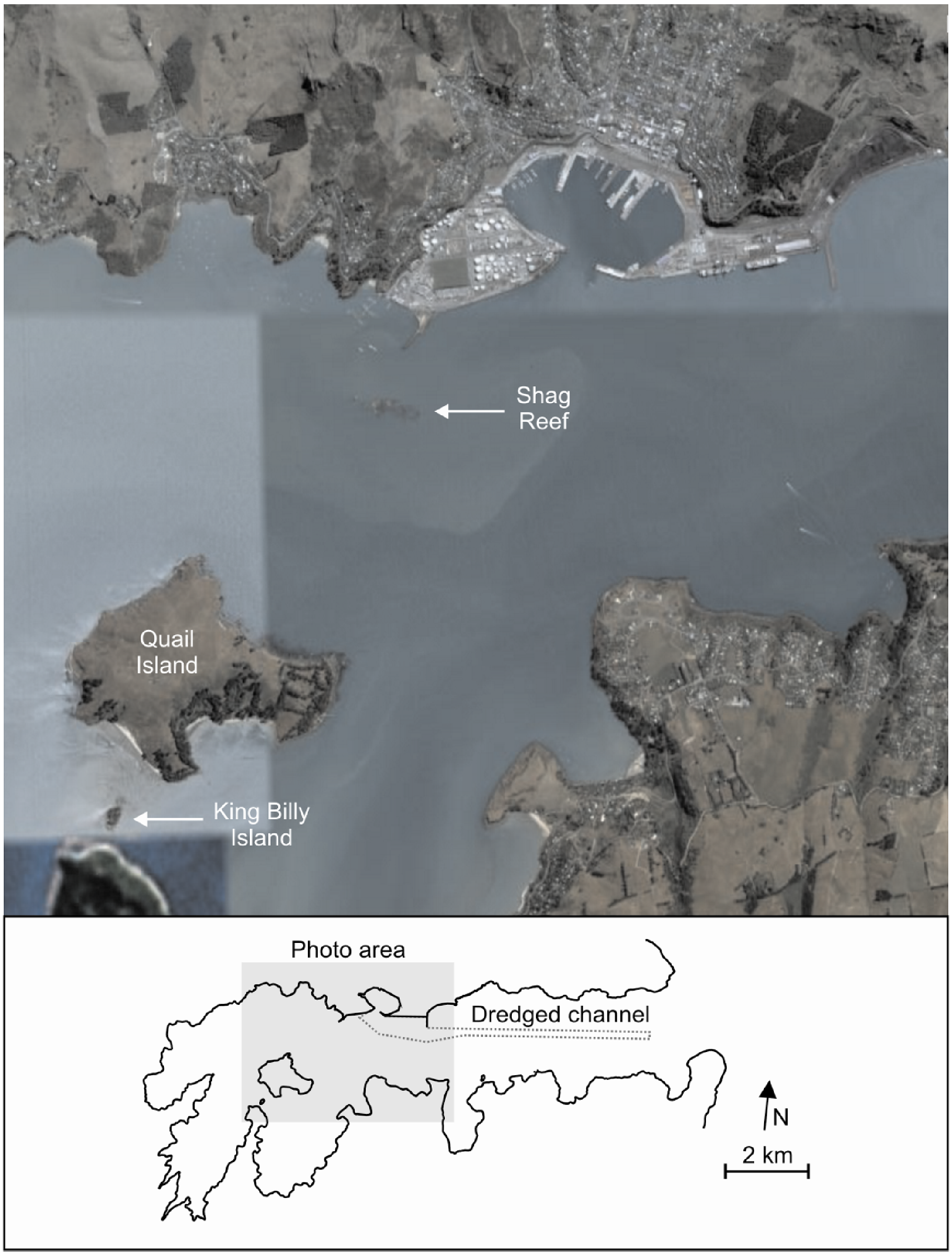


Figure 5 Aerial view of central Lyttelton Harbour showing the intertidal rock reef exposed at low tide.

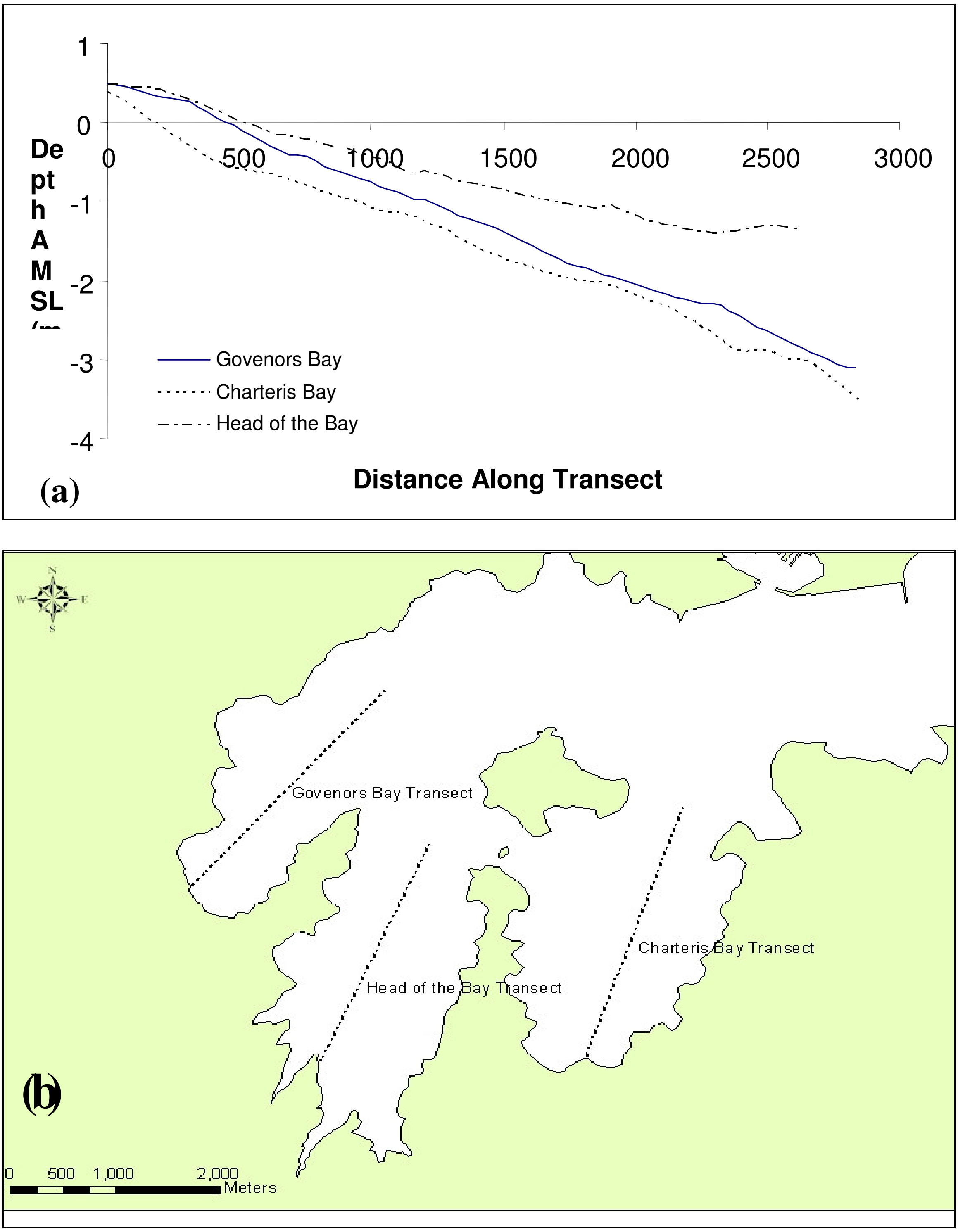


Figure 6 **(a)** Cross-sectional bathymetric profiles and **6(b)** locations of profiles along the central axes of Governors and Charteris Bays and Head of the Bay mudflats. AMSL means above mean sea level.

4.2 Sediments

Detailed size analysis results for each bed sediment sample are presented in Appendix 3, and the spatial distributions are presented in maps 3 to 5. Map 3 illustrates the distribution of gravel (>2000 µm), sand (2000 to 62.5 µm), silt (62.5 to 4 µm) and clay (<4 μm) fractions in upper Lyttelton Harbour according to their percentage composition of bed samples (see Table 2 for textural class details). Map 4 illustrates the bed sediment textures of each sample classified according to a modified Folk (1965) scheme (refer to Figure 4 for details). In this map the textural classes are overlie a colour-coded areal representation of the sediment textures according to their primary (>50%) and secondary (25-49%) constituents. Map 5 illustrates the distribution of these primary and secondary textures against the 0.5 m-interval bathymetry contours in relation to MSL.

In general, the sediment texture analysis showed that fine sediments (silt and clay) dominated most of the study area, with sediments becoming finer from east to west along the central axis of the harbour towards its upper reaches while clays also increased in concentration south to north across the harbour. Coarse sediments (gravel and sand) dominated the harbour 'neck' area south of the dredged channel and in pockets within the upper harbour and around Quail Island.

Maps 3-4 show that high concentrations of gravel (>50%) were confined to pockets at the head of Purau Bay, between Magazine Bay and Shag Reef, and north of Church Bay, while moderate gravel concentrations (25-50%) were found in central Purau and north-eastern Charteris Bays, in Diamond Harbour, north-west of Quail Island and around the periphery of areas with high-gravel concentrations. 100% of the gravel fractions found were biogenic shell hash except in sample 39 from the head of Purau Bay, which comprised 73% mineral and 27% shell-hash gravel, and in sample 48 from south-east Charteris Bay, which contained 10% mineral and 90% shell-hash gravel (Appendix 3). No live shells were counted amongst the shell-hash gravel and this hash was almost-entirely made up of small fragments, with few grains comprising more than ¾ of the original shell test.

High concentrations of sand (>50%) were found along the neck of the harbour south of the dredged channel and into Purau Bay and in a pocket in the central-western Head of the Bay. Moderate concentrations of sand (25-50%) were found across the western Head of the Bay, around all but the south-eastern periphery of Quail Island, in eastern and southern Charteris Bay, from east of Church Bay through Diamond Harbour and in central Purau Bay (Maps 3-4).

High concentrations of silt (>50%) were found throughout Governors Bay and in southern areas of the Head of the Bay and Charteris Bay while high concentrations of clay (>50%) were found in northern areas of the upper harbour including in Rapaki, Cass and Corsair Bays (Map 3). The distributions of silts and clays were combined into the textural class 'mud' for Map 4, which shows that mud dominated almost all of the upper harbour east of the port.

In terms of the modified Folk classifications, a spatial division was found between sites west and east of a line running approximately from the boundary of the port dredged channel to half-way between Church Bay and Diamond Harbour – those in the west were generally dominated by mud (M) while those in the east were generally dominated by sand (S) (Map 4 and Appendix 3). That is, 54% of the sediment sample sites were found to be dominated by mud (M), with another 15% having mud as their secondary class (m). All of the sites dominated by mud (M) occurred in the central to upper harbour area west of the port division line. Five sites (10%) dominated by sand (S) occurred east of the port.

A further 19% of sites, all west of the port, were dominated by silts (Z). Six sites (13%) were dominated by gravel (G). These occurred in isolated pockets throughout the study area, except in the upper reaches of the upper harbour. Overall, the modified Folk classifications confirm the pattern of increasing fine sediments from east to west along the harbour length, except for gravels, which occurred in pockets throughout the harbour, except in the upper reaches of the upper mudflats.

Analysis of mean and median grain sizes for the sediment sample sites is presented in Appendix 3. Of the 48 samples studied, 43 have a mean grain size in the silt to fine sand range (250 to 3.9 µm or 2 to 8 Φ), 3 have granule mean sizes (greater than 200 µm or - 1 Φ) and two have medium to coarse sand (1000 to 500 µm, or 0 to 2 Φ). It should be noted that these mean sizes represent the average of multimodal population distributions for most samples, a point that is supported by the differences between the mean and median sizes for most samples, and the poor to very poor sorting of all samples where this parameter was able to be calculated (Appendix 3).

Spatially, the three upper harbour bays are characterised by a pattern of increasingly fine mean grain sizes, from coarse silt (62.5 to 31 µm, or 5 to 4 Φ) in the outer reaches, towards medium silts (15.6 µm, 6 Φ) at the head of each bay. This pattern also occurs from south to north across the upper harbour between Quail Island and Rapaki, with the northern shoreline from Rapaki to the port characterised by fine silts (7.8 µm, 7 Φ). Moving west to east along the inner harbour there is an extensive tract of fine sand in the lee of Quail Island (250 to 125 µm, 2 to 3 Φ), a central tract of medium to fine silts north of Quail Island, and sandy areas along the neck of the harbour south of the main dredged channel to east of Purau Bay. Within Purau Bay mean grain sizes, which range from fine sand to granules (125 to 2000 µm, 3 to -1 Φ), reflect the shoreward increase in gravel. These are mineral-based gravels, which are in contrast to the pockets of biogenic gravel that occur adjacent to Shag Reef and are reflected in two localised granule mean grain size hotspots.

In addition to the textural and mean grain size analysis, observations from the field programme shed light on the nature of the harbour substrate. At sites 28 and 30 (Map 1) it was very difficult to capture sediment. Instead, the grab sampler returned a small amount of shell material, some algae, starfish and, at site 30, a live rock oyster. Combined with the proximity of site 30 to Shag Reef, these observations indicate the occurrence of rocky substrate at this site and also site 28.

Also, during intertidal surveying it was observed that the bed sediments of Governors Bay were very soft, with walkers commonly sinking 0.15 to 0.3 m into the mud. From Governors Bay, across Head of the Bay and into Charteris Bay, the bed sediments became progressively firmer, with walkers sinking as little as 0.05 to 0.1 m into the mud. These observations reflect the textural findings that concentrations of clay were greatest in Governors Bay while sand concentrations were higher in Head of the Bay and Charteris Bay.

4.3 Relationships between sediment textures and bathymetry

No single, unifying relationship was found between bed sediment texture and bathymetry, although according to the percentage texture data there was a general fining of sediments with decreasing depth from east to west along the harbour length. This pattern was interrupted by the occurrence of pockets of shell-hash gravel between Church and Magazine Bays, and both sand and shell hash around Quail Island. The increase in clay from south to north across the harbour does not correspond to a decrease in bathymetry, instead possibly relating to patterns of harbour circulation.

Sites dominated by the modified Folk class of gravel (G) occurred at depths ranging from 1 to 7 m below MSL, while sand-dominated sites (S) occurred at depths from 0 to 9.5 m below MSL, and mud-dominated sites (M) occurred at depths from 0.25 to 7.25 m below MSL (Map 5 & Appendix 2).

Overall the sediment versus bathymetry data patterns indicate that distribution of sand and finer sediments in the upper harbour is likely the combined product of (1) sediment transport processes (i.e. tidal and wave currents), (2) fine sediment inputs from the harbour catchment, and (3) lower-harbour sand inputs from the continental shelf. In contrast, almost all of the gravel distribution appears unrelated to catchment sources and sediment transport. Given its biogenic nature (Appendix 3), these gravel pockets are more-likely the result of *in situ* shell production. This poses the question as to whether this source is contemporary or relic in nature.

4.4 Intertidal communities and shellfish beds

Across the expansive intertidal sand and mudflats of inner Lyttelton Harbour several types of biological community were found, including a number of dominant invertebrates associated with the tidal and sediment conditions of each area. The dominant invertebrates included mud crabs, cockles and other bivalves, and gastropods such as topshells and whelks (Appendix 4).

The mud snail *Amphibola crenata* was the most frequently found species in the intertidal survey, occurring in 82% of sites sampled, at elevations from +0.25 to -0.5 m above MSL and in sediments dominated by up to 75% silt (Figure 7).

The mud crab *Helice crassa* occurred in 54% of the intertidal sites, generally closer to the high-tide mark, and absent from more central regions of the mudflats. These were generally areas between 0 and -0.5 m below MSL and where the sediments consisted of 20 to >60% sand (Figure 7).

The cockle *Austrovenus stutchburyi* was found in 46% of the sites sampled during the intertidal survey, in areas close to the shoreline and in the central mudflat areas (Figure 8). It was found at tidal elevations from 0.5 m below MSL to above MSL, where the sediment contained up to 70% silt and 66% sand.

Often found in similar habitats to the cockle, the stalk eyed mud crab *Macrophthalmus hirtipes* was found at 36% of the intertidal sites, in more central areas of the mudflats than the *Helice crassa* mud crab. *Macrophthalmus hirtipes* (Figure 8) was found in a wide range of substrate types, dominated by both sand and silt and at elevations to 0.5 m below MSL in the intertidal.

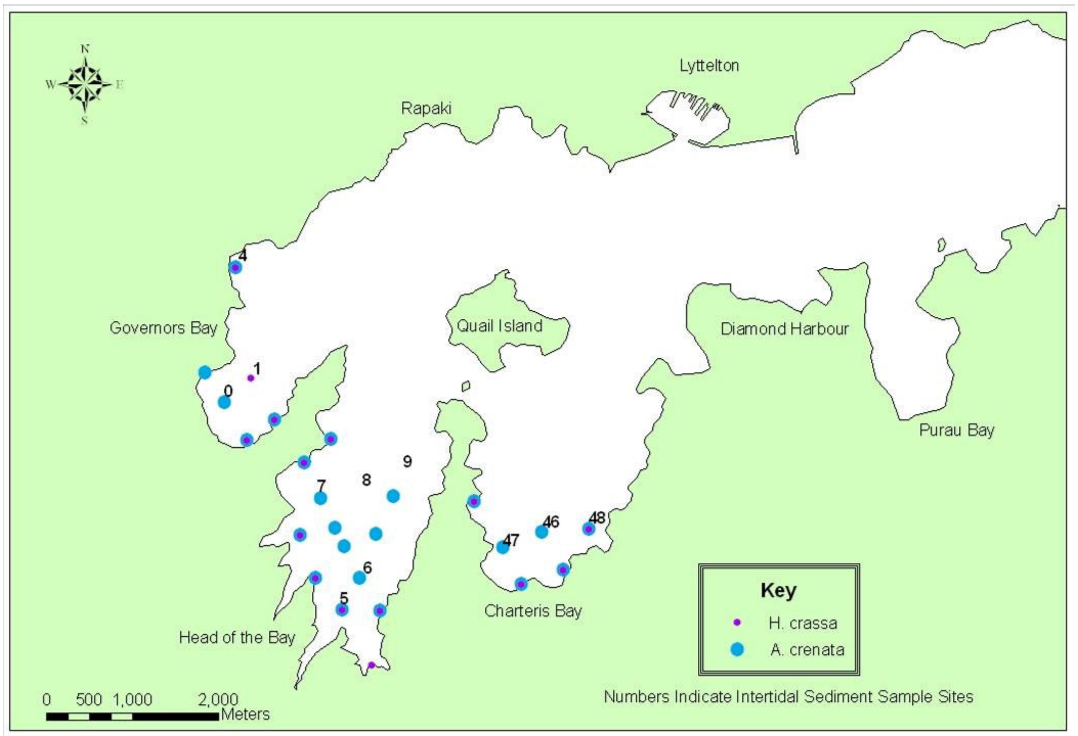


Figure 7 Occurrence of the mud snail *Amphibola crenata* and the mud crab *Helice crassa* on intertidal sandflats within Lyttelton Harbour.

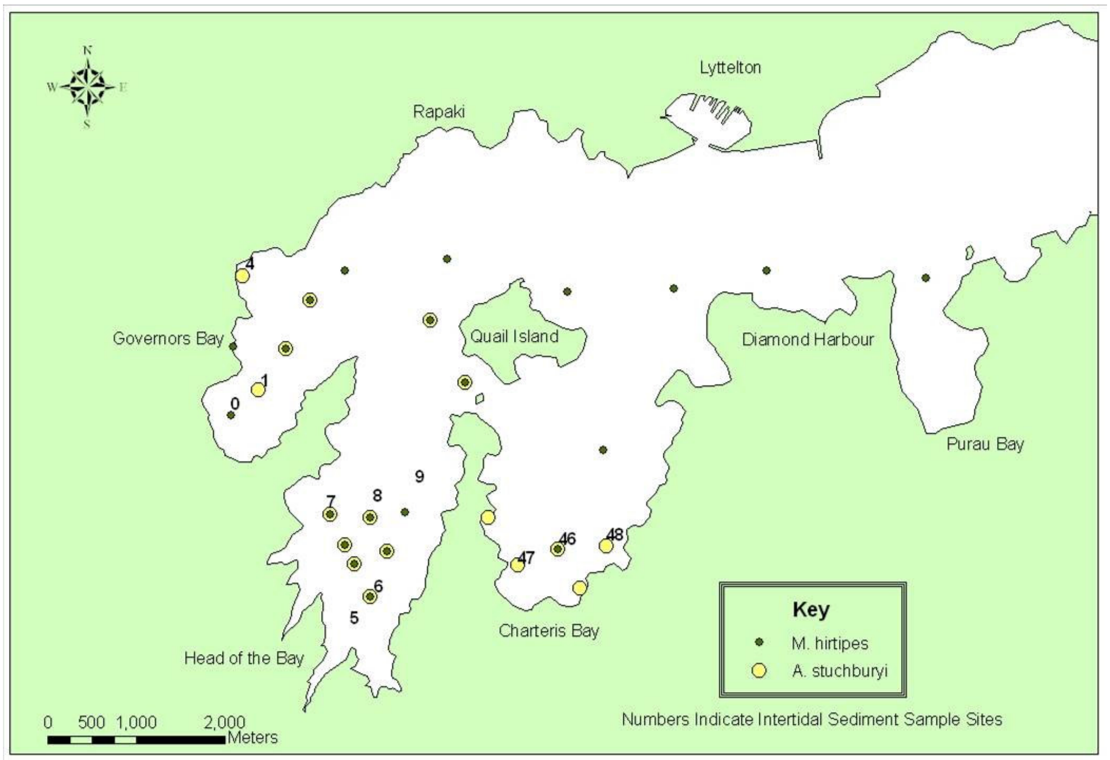


Figure 8 Occurrence of the cockle *Austrovenus stutchburyi* and the stalk eyed mud crab *Macrophthalmus hirtipes* in intertidal sandflats and at benthic sampling sites within Lyttelton Harbour.

Other species recorded during the intertidal survey included the top shell *Diloma subrostrata,* which occurred at 36% of the sites, where it was commonly found with cockles and mud snails. The crab *Hemigrapsus crenulatus* occurred in 18% of the sites that also included *Amphibola.* The whelk, *Cominella glandiformis* was also found in 14% of similar sites. Some other bivalves were found irregularly, and in areas containing hard substrate the fauna included mussels.

As part of the survey the presence of an anoxic layer was recorded in 18% of the sites (Appendix 4). At these locations, macrofauna including mud snails and mud crabs occurred on the sediment surface.

4.5 Site and faunal descriptions for subtidal biological sites

Following are individual descriptions for the biological sites shown on Map 1 and as detailed in Appendix 5.

Site 2 (43.630°S, 172.659°E)

The innermost biological sampling site in Lyttelton Harbour was Site 2, in the central region of Governors Bay at an approximate depth of 1 m below MSL. Silt and clay made up more than 80% of the sediment at this site, plus small amounts organic detritus, some mollusc shells (including bivalves and turret shells) but shell volume was generally less than 65% of samples. The community consisted of 15 species, dominated by bivalves and 8 species of polychaete worms. Cockles (*A. stutchburyi*) of an average shell length 24.4 mm, a few trough shells (largest shell length 32 mm), the glass shell, *Theora lubrica* and numerous specimens of the minute bivalve *Arthritica bifurca* (average 23 per sample).The polychaetes included *Nicon* and *Pectinaria* sp. as well as capitellids and spionids. The stalk eyed mud crab was present and an unusual find was individuals of the sphaeromatid isopod, *Exosphaeroma chilensis.*

Site 3 (43.626°S, 177.662°E)

Located some 500 m distance from the shoreline, at a depth of 2.5 m below MSL, Site 3 contained the largest proportion of fine sediments of all the biological study sites, comprising more than 96% silt and clay fractions. There were few shell fragments and those that were present were small. In all, 14 species were recorded but the fauna was dominated by small bivalves and polychaetes. *Arthritica bifurca* was found at an average density of 9 individuals per replicate and the main polychaetes were maldanids, *Nicon* sp. and terebellids. Apart from the small bivalve *Theora lubrica* and juvenile surf clams (less than 6mm shell length), the remaining fauna comprised oysters, *Tiostrea chilensis*, a single cockle, a stalk eyed mud crab and a sea squirt.

Site 11 (43.622°S, 172.667°E)

Seawards of Site 3 but at a similar distance from the shoreline, Site 11 was located at an approximate depth of 3.5 m below MSL where the sediment consisted of approximately 72% silt and clay and 21% sand. There were high proportions of shell fragments of all sizes, including empty turret shells (*Maoriocolpus rosea)* and gastropods. Of the 10 species recorded the most abundant species was the stalk eyed mud crab *Macrophthalmus hirtipes*. Small numbers of bivalves, between 14 and 20 mm shell length included wedge shell, *Macomona liliana* and the venus shell, *Ruditapes largillierti.* The polychaetes included spionid, terebellid and maldanid worms. A single orange starfish, *Coscinasterias muricata*, was an unexpected find.

Site 14 (43.633°S, 177.684°E)

Nestled behind Quail Island close to the entrance to the Head of the Bay, Site 14 was located in the intertidal zone at a depth of about 1.5 m below MSL. The sediments, made up of mixed particle sizes, were dominated by approximately 30% of both sand and silt and about 15% each of clay and gravel. There was a high shell volume, made up of a wide size range of fragments from gastropods and bivalves. The fauna at this site had a low species richness, 5 species in total, and was dominated by bivalves, mostly cockles *Austrovenus stutchburyi* (mean density of 6 per replicate, average shell length of 22.28 mm, SE=1.23), *Macomona lilliana* and *Ruditapes largllierti.* Few polychaetes were present at this site.

Site 15 (43.607°S, 172.679°E)

In the central channel behind Quail Island, Site 15 is approximately 2.5 m below MSL. The sediments were dominated by silt (58%) and just over 30% sand and shell fragments of a medium size range (including cockles), some detritus and seaweed. There were 12 species present, with the fauna dominated by bivalve molluscs, gastropods and mud crabs. The cockle *Austrovenus stutchburyi* was relatively abundant (mean density of 6.33 per replicate, shell length of 31.68 mm, SE=0.93), as was the wedge shell (mean density of 3.0 per replicate, shell length 15 mm, SE=2.63) and rock oysters, *Tiostrea lutaria.* There were gastropods *Sigapatella novaezelandiae,* two species of chitons, stalk eyed mud crabs, *Macrophthalmus hirtipes,* an ophiuroid, the starfish *Astrostole scabra* and a few polychaetes.

Site 18 (43.601°S, 172.681°E)

Situated approximately half way between Quail Island and the northern coastline, Site 18 at a depth of 3.5 m below MSL was characterised by sediment consisting of almost 60% silt and sand and 25% larger fractions made up of empty turret shells, bivalves and gastropods. There were 10 species recorded here, mainly bivalves, crustaceans and a range of other species. There were wedge shells, *Macomona liliana* and venus shells, *Ruditapes largillierti,* including adults (one with a shell length of 35 mm) and juveniles less than 4 mm shell length. Also found was the small invasive bivalve, *Theora lubrica.* The dominant crustacean was the stalk eyed mud crab, *Macrophthalmus hirtipes* which occurred with hymenosomatid crabs, starfish and seasquirts.

Site 19 (43.612°S, 172.683°E)

Off Rapaki, Site 19 at a depth of 2.8 m below MSL, was characterised by fine sediments comprising 39% clay and 60% silt. There were few shell fragments and very little detritus. The community present here was quite restricted, with only 3 species, the dominant ones being sea pens *Virgularia gracillima* at densities of 3.3 indivduals per sample. Other members of the fauna included maldanid and nereid polychaete worms.

Site 25 (43.624°S, 172.798°E)

In the central channel, 500 m seaward of Quail Island, Site 25 was approximately 4.8 m below MSL. The sediment was dominated by silt (62%) and sand (22%). There were few shell fragments in the sediment and those that were present were small. The community consisted of 9 species. Two larger invertebrate species were dominant, the sea pen *Virgularia gracillima* (1.67 individuals per sample), and the mud crab, *Macrophthalmus hirtipes*; these occurred at similar densities. Also, the polychaetes were quite diverse consisting of *Pectinaria* sp., high densities of terebellids, maldanids and nepthyds.

Site 28 (43.624°S, 172.713°E)

To the north of Charteris Bay, Site 28 was one of the deeper biological-survey sites at a depth of 6.5 m below MSL. It was dominated by coarse sediments, sand (59%) and shell hash (14%), made up of a combination of turret shells, gastropods and bivalves. The sediment also contained organic detritus including seaweed. There were 10 species present, including 4 species of polychaete worms. The mud crab *Macrophthalmus hirtipes* was the dominant crustacean and the most abundant polychaete was *Owenia* sp. Other members of the community included hymenosomatid crabs, small juvenile bivalves and the gastropod *Sigapatella novaezelandiae.*

Site 33 (43.622°S, 172.726°E)

Close to Diamond Harbour, Site 33 was a deeper biological-survey site, at a depth of -6.5 m below MSL. The sand content here was 59%, there was little shell gravel and the silt/clay content exceeded 40%. The community (12 species) was dominated by sea pens *Virgularia gracillima* (3.3individuals per sample) and the mud crab *Macrophthalmus hirtipes.* Small juveniles of three species of bivalves, pipi, tuatua and venus shells were found with polychaetes from three families, Sigalionidae, Nepthydae and Goniadidae.

Site 36 (43.623°S, 172.748°E)

Within the central part of Purau Bay, Site 36 was sampled at a depth of 4 m below MSL. The sediment here comprised 66% sand and 30% silt with some shell fragments of medium and small sizes. The community was made up of 10 species, chitons, bivalves, mud crabs and polychaetes. Juvenile bivalves included tuatua, *Paphies donacina,* surf clams, *Dosinia subrosea*, *Cyclomactra ovata* and unidentified sunset shells. Other species present were the mud crab *Macrophthalmus hirtipes* and the gastropod *Sigapatella novaezelandiae.* The polychaetes were from families Maldanidae, Nepthydae and Oweniidae.

Site 43 (43.640°S, 172.703°E)

Within Charteris Bay Site 43 at a depth of 2 m below MSL the sediments were predominantly sand (41%), silt (28%) and shell gravel (24%). The sediment contained a high shell volume of mixed shell sizes and attached red seaweed. The community contained some large macroinvertebrates (14 species) including crustaceans, molluscs, echinoderms and sea aquirts. There were conspicuous camouflage crabs, a shrimp, and the gastropod *Sigapatella novaezelandiae.* Starfish were relatively common and included *Astrostole scabra*, *Patiriella regularis* and the brittle star *Ophiomyxa* *brevirima*. There were intermediate-sized venus shells, *Ruditapes largillierti* (shell lengths up to 2 2mm) and juvenile *Cyclomactra ovata*. However within the coarser sediments there were no polychaetes collected.

4.6 Biological site sediment compositions

The sediments analysed from the biological samples spanned a wide range particle sizes (Map 1, Figure 9). At all of these sites, silt was present in varying amounts from 21% at Site 28 to 68% at sites 2 and 3. The sand content was also variable, ranging from less than 2% at Site 19 to 66% at Site 6. Shell fragments generally made up less than 10% of each sample, but reached close to 25% of sample weight at sites 18 and 43. Where shell fragments comprised a high volume of the sediment there was a mixed range of sizes (Table 3). Some samples also contained small proportions of detritus, and a few had seaweed. At Site 43, benthos contained a high percentage of seaweed that had been attached to the shells.

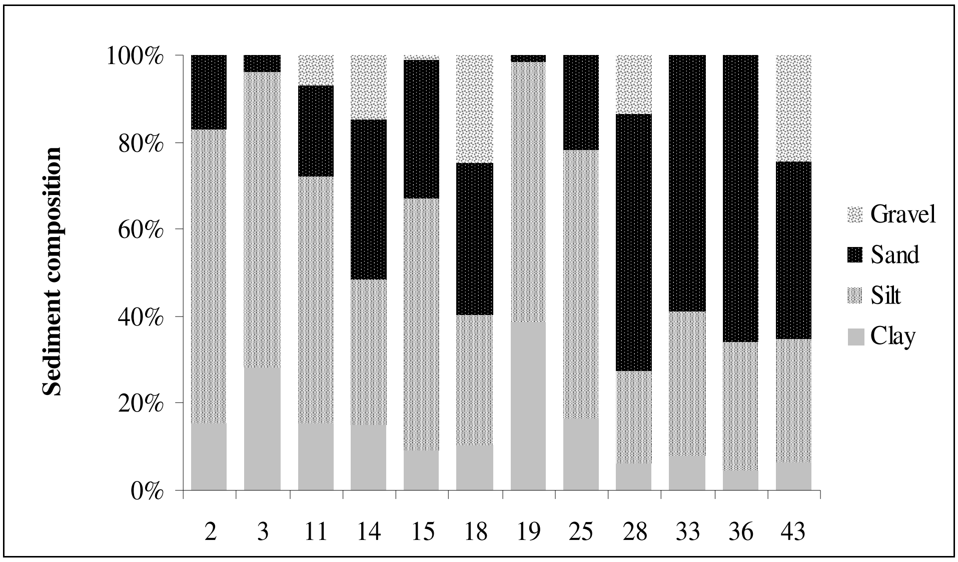


Figure 9 Percentage of gravel, sand, silt and clay sediment textures found in the biological samples.

Table 3 Relative abundance, shell volume, fragment size, detritus and seaweed from biological sample sites 2-3, 11, 14-15, 18-19, 25, 28, 33, 36 and 43 in Lyttelton Harbour. Percentage categories include Low (<33%), Med (33-65%), High (>65%), and sizes include Sml (<5 mm), Med (5-10 mm) and Lge (>10 mm).

	Shells Volume (%)			Shell Fragment (mm)			Detritus			Seaweed (%)		
Site	Low	Med	High	Sml	Med	Lge	Low	Med	High	Low	Med	High
2		X		X			X					
3	X			X								
11			X	X	X	X	X			X		
14			X	X	X	X	X					
15		X			X		X			X		
18		X	X	X	X	X	X			X		
19	X				X		X					
25	X			X								
28			X	X	X	X						
33	X			X								
36		X		X	X		X					
43		X	X	X	X	X	X				X	X

Comparisons between the sediment compositions found in the biological and sediment-only samples are presented in Appendix 6. This comparison shows that the results are largely similar, especially those dominated by fine sediments. The only significant difference was at site 28, where there was a much larger gravel-shell size percentage in the sediment only sample. We suggest that this difference may be due to the high local variability in shell-hash distributions.

4.7 Biological site water depths

The biological samples were selected based on sediment characteristics and locations within the upper harbour (Maps 1 and 5). Some samples were selected close to the shoreline and Quail Island, while others were selected at greater depths towards the mouth of the harbour. The depth range extended from 0.75 m below MSL (Site 14) to 6.5 m below MSL (Sites 28 and 33) (Figure 10). On spring tides the sandflats at Site 14 are exposed at low tide.

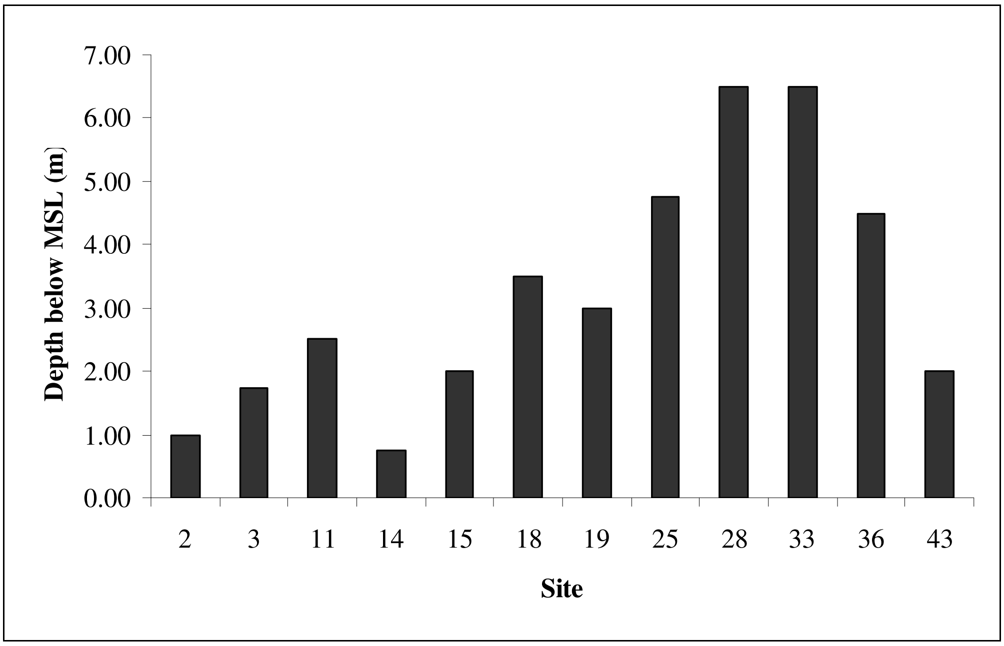


Figure 10 Water depth at each biological site sampled in Lyttelton Harbour (refer to Map 1 for site locations).

Based on sediment and depth information the biological sample sites were divided into three main groupings (Figure 11):

- A large group of sites characterised by the large proportions of silt and clay (Sites 2, 3, 11, 15, 19, 25)
- A group dominated by large shell fragments (Sites 14, 18 and 43)
- A group of sites characterised by deeper water and sandy sediments (Sites 28, 33, 36).

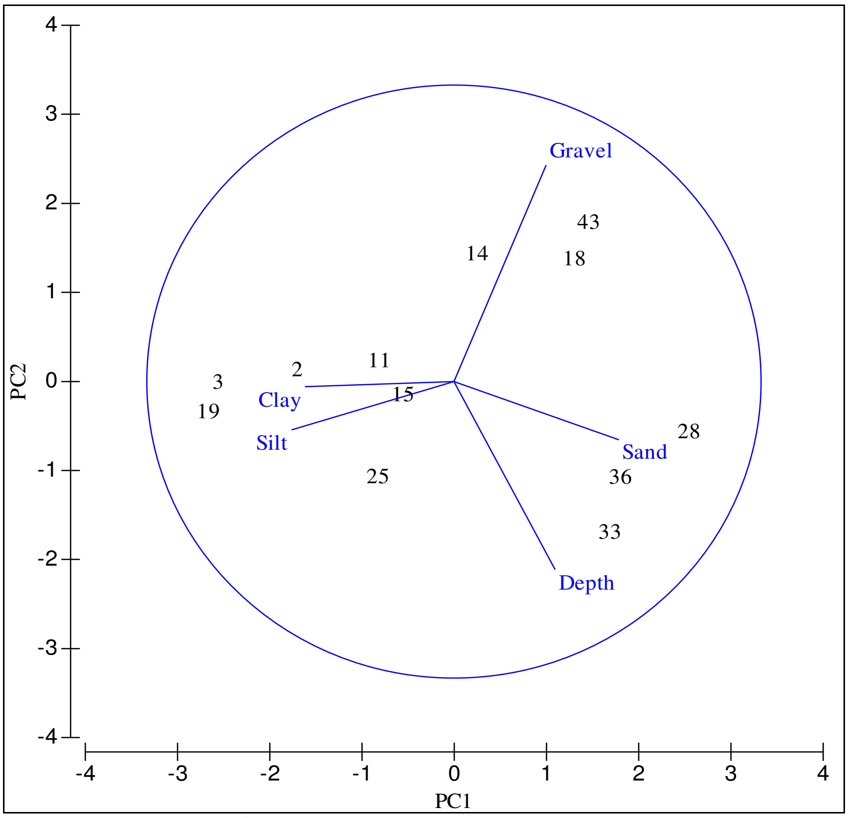


Figure 11 Two-dimensional PCA ordination of physico-chemical variables (clay, silt, sand, gravel and depth) for the 12 biological sample sites in Lyttelton Harbour. PC1 and PC2 together account for 85.9% of the total sample variability.

4.8 Species assemblages and patterns

Species richness

Macrofaunal diversity was generally quite low with a total of 48 species recorded (Table 4). The mean species richness for the 12 sites ranged between 3 and 15 with mean species richness between 2.67 and 8.33 (Table 5). At 6 sites the dominant species were bivalves, while the mud crab *Macrophthalmus hirtipes* was dominant or subdominant at 6 sites. Sea pens were dominant at sites 19 and 33. Bivalves were present at all sites except Site 19 where sea pens were abundant. Although there was quite a range in the mean number of species per site, the variation was quite similar (Figure 12). Mean densities of macrofauna were up to 39 individuals per sample at Site 2 to less than 10 individuals per sample at sites 11,14,19 and 36 (Figure 13).

Table 4 Total number of species and individuals found for each major taxonomic group.

Class	Species	Individuals
Polychaeta	17	139
Bivalvia	11	238
Decapoda	4	72
Asteroidea	4	12
Gastropoda	2	16
Polyplacophora	2	14
Isopoda	2	7
Pennatulacea	1	27
Ascidacea	1	19
Ophiuroidea	1	5
Holothuroidea	1	2
Phoronida	1	2
Malacostraca	1	1
Total	48	554

Table 5 Total species richness and mean species richness for each biological sample site. The Berger-Parker Dominance Index of the two or three main species from each site was calculated as: total number of each species/total individuals from that site.

Site	Total species richness	Mean species richness	Berger-Parker Dominance Index		
2	15	8	*Arithritica bifurca* 0.585	*Nicon* sp. 0.127	
3	14	8	*Arithritica bifurca* 0.354	*Asychis* sp. 0.266	
11	10	4.33	*Macrophthalmus hiripes* 0.273	*Streblosoma* sp. 0.182	
14	5	3	*Austrovenus stutchburyi* 0.692	*Macomona liliana* 0.192	
15	12	7	*Austrovenus stutchburyi* 0.311	*Macomona liliana* 0.164	*Macrophthalmus hiripes* 0.164
18	10	5.33	*Ruditapes lagillierti* 0.333	*Macrophthalmus hiripes* 0.314	*Macomona liliana* 0.137
19	3	2.67	*Virgularia gracillima* 0.455	*Asychis* sp. 0.364	
25	9	5	*Macrophthalmus hiripes* 0.452	*Virgularia gracillima* 0.161	
28	10	4.67	*Owenia sp.* 0.5	*Macrophthalmus hiripes* 0.188	
33	12	5.33	*Virgularia gracillima* 0.313	*Macrophthalmus hiripes* 0.125	
36	10	5.33	*Macrophthalmus hiripes* 0.222	*Paphies donacina* 0.222	
43	14	8.33	Tunicates/Ascidians 0.222	*Ruditapes lagillierti* 0.130	*Ischnochiton maorianus* 0.130

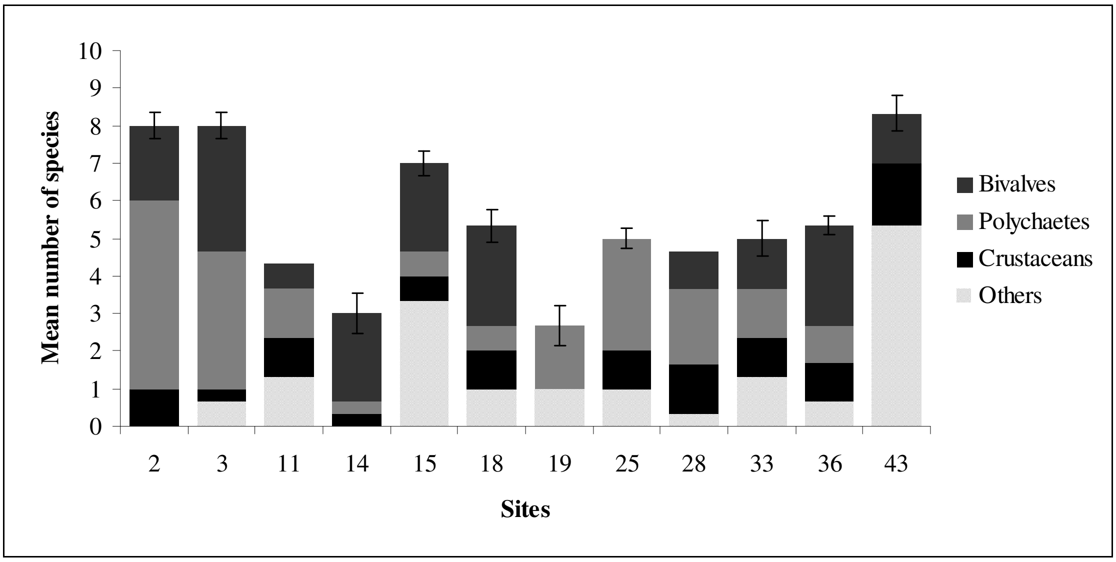


Figure 12 Mean number of species (±S.E.) in major taxonomic groups at each site.

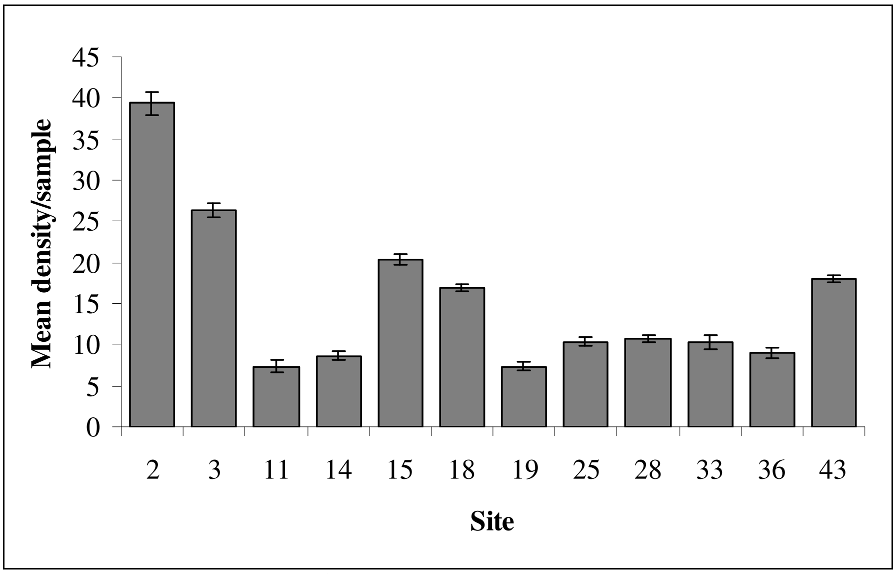
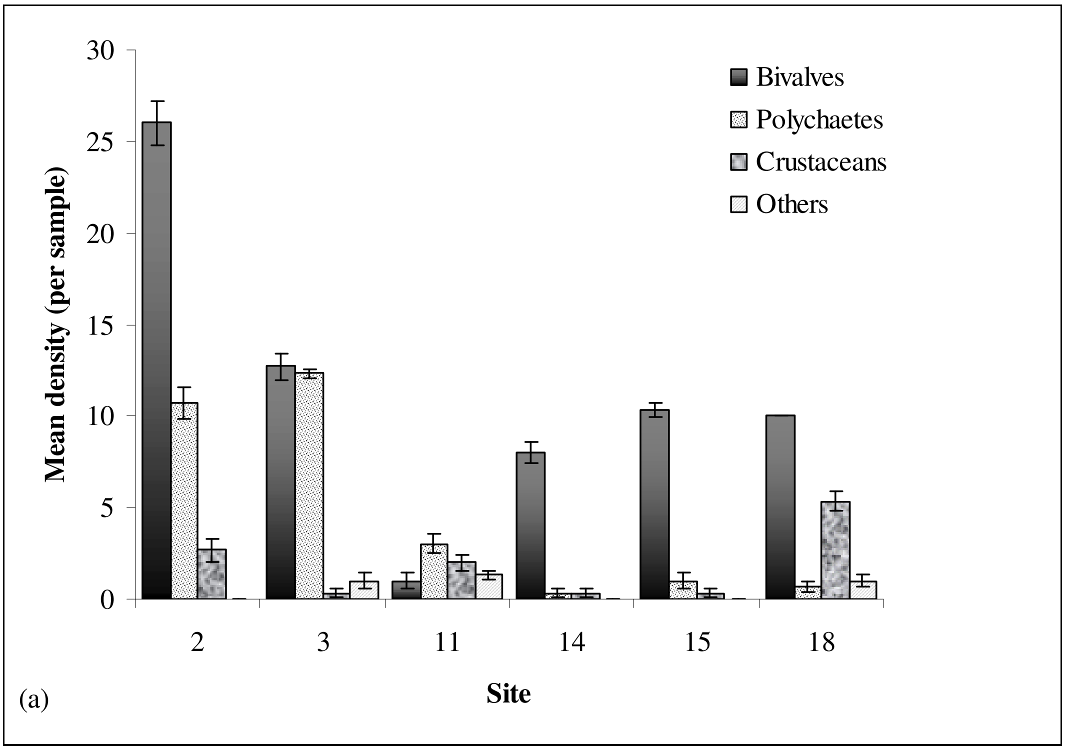


Figure 13 Mean density (±S.E.) of total fauna at each site.

Taxonomic groupings

Overall bivalves were found to be the dominant taxonomic group at half of the sites, including Sites 2, 3, 14, 15, 18 and 36, while other groups, including polychaetes, were important at Sites 2, 3, 11, 19, 25, 28 and 33. At site 43, as well as bivalves, there were tunicates, echinoderms and crustaceans (Figure 14).



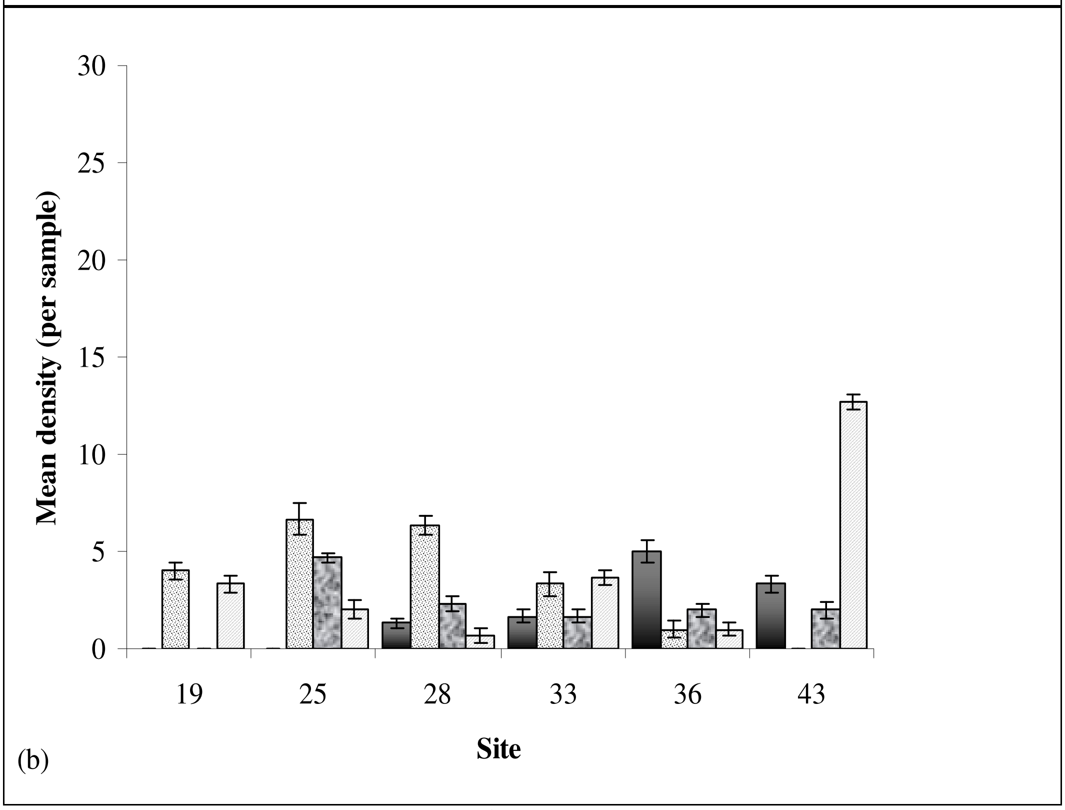


Figure 14 Mean density of individuals (±S.E.) of each major taxonomic group from (a) sites 2, 3, 11, 14, 15 and 18, and (b) 19, 25, 28, 33, 36 and 43.

Site classifications

The cluster analysis of sites based on average density data divided the sites into three groups (Figures 15 and 16) based on their similarity. The largest group of 6 sites was made up of two subgroups, sites 33, 25 and 19 from the central part of the harbour and

Sites 28, 11 and 36 from inner and more outer regions of the harbour. The second group was sites 14 and 15 from the western side of Quail Island, and these were clustered with sites 18 and 43 to the north and south of Quail Island The third group was made up of Sites 2 and 3, the innermost harbour samples.

Comparison of the fauna between sites revealed a low level of similarity (21.3%), with the stalk eyed mud crab responsible for 36% of the variation. This crab was the dominant species from the largest site grouping where it contributed to 38% of the variation, with the other contributor being the sea pen *Virgularia*, 14.9%. The second grouping (Sites 14, 15, 18, 43) was also characterised by the mud crab (24.2%) and the wedge shell, *Macomona liliana* (20.8%), cockles, *Austrovenus stutchburyi* (12.8%) and *Ruditapes largillierti* (12.4%).

The faunal patterns were examined in relation to the sediment and depth information recorded as part of the study using the Primer BIOENV procedure. This indicated relatively poor correlations for each of the variables when considered on their own, with sand showing the best correlation (0.32). Combinations of two or more of the variables (clay, silt, sand, gravel and depth) in all combinations improved the correlation but the highest correlation value for two variables was for %clay and water depth (0.53). When water depth, clay and sand were considered together the correlation was 0.50.

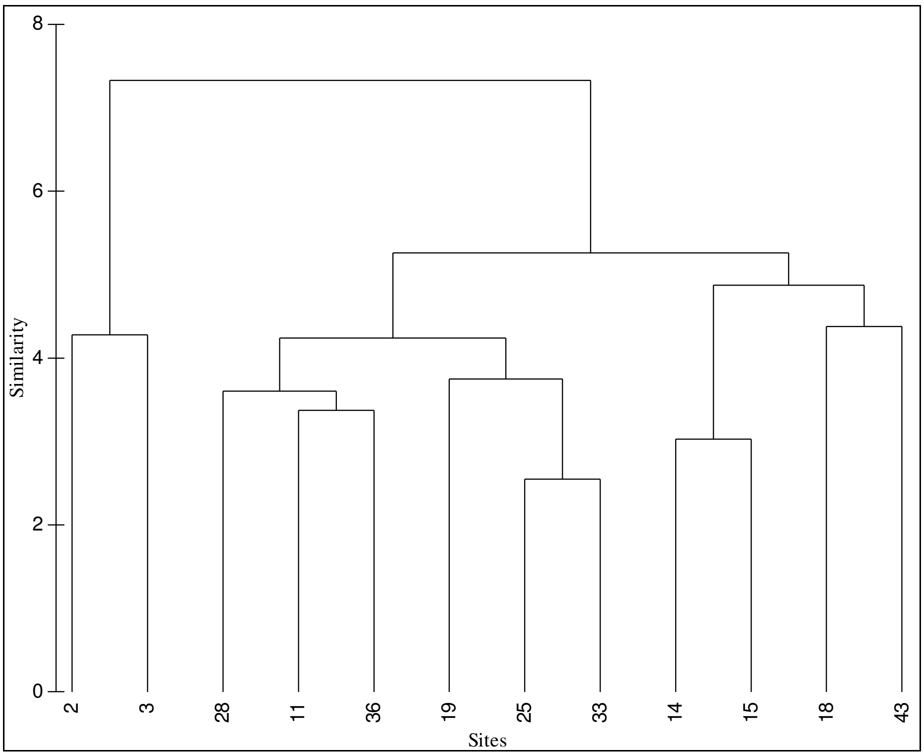


Figure 15 Dendrogram based on similarity by euclidian distance.

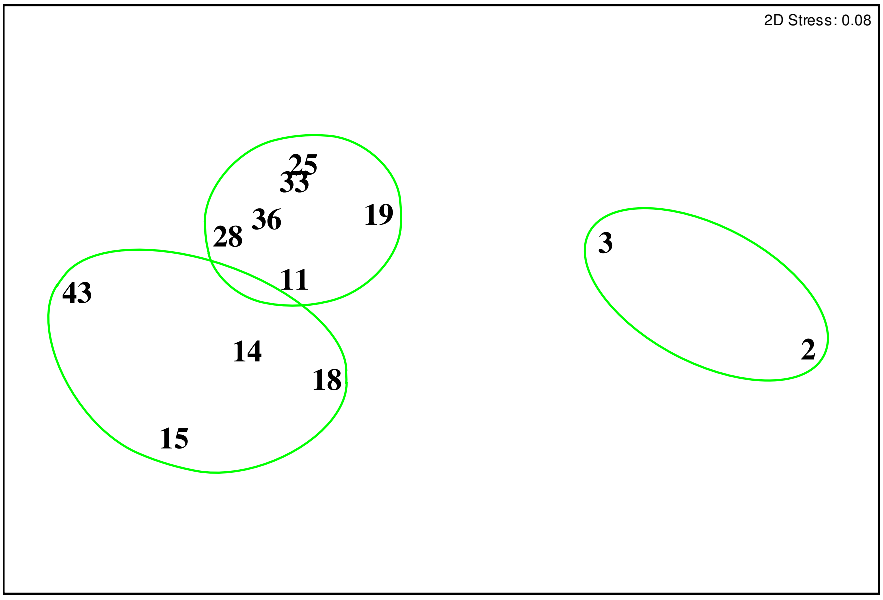


Figure 16 MDS ordination showing differences between the mean community composition from sites in Lyttelton Harbour. The two dimensional (2D) stress of 0.08 indicates a high level of accuracy of the graphical representation by MDS.

5. Discussion

5.1 Comparison of surveyed bathymetry with previous records

Comparisons with the New Zealand Hydrographic Chart NZ6321 (2000) are difficult due differences in the sounding methodologies and the sparseness of sounding points in the upper harbour bays on the Hydrographic Chart. It is also noted that the chart datum's for the various tide levels (e.g. MHWS, MHWM MLWN, MLWS), are different on the chart from those given on LINZ website, which are presented in Table 1 (p6). However, at the mouth of the three upper harbour bays the position of the 0 m chart datum contour on the Hydrographic Chart is very similar to the position of the 1 m below MSL contour shown on Map 2. This suggests that there has been a reduction in depth of around 0.2 m at the mouth of each of the upper harbour bays, with a sediment deposition rate in the order of 0.35 cm/yr over the last 50 years. This is in line with the contemporary sedimentation rate obtained by Goff (2005) from coring undertaken further into the Head of Bay. Based on the relative positions of the contours on the Hydrographic Chart and Map 1, there would also appear to be shallowing along the northwestern side of the Upper Harbour from Rapaki Bay to Governors Bay, with deposition rates possibility being higher than those in the three larger bays at the head of the harbour.

No comparisons with Curtis (1985) can be made as he did not provide a bathymetry map.

5.2 Comparison of sediment texture results with Curtis (1985)

The broad textural patterns found in the present study compare reasonably well with those of Curtis (1985) which are presented in Appendix 2, but the greater spatial distribution of sites within the upper harbour in the present study revealed more complex local distributions of textures. The high concentrations of sand found along the neck of the harbour south of the dredged channel, and the moderately-high concentrations of sand found around all but the south-eastern sides of Quail Island in the present study reflected Curtis' findings (compare Figures in Appendix 2 with Maps 3-4). However, the pocket of high-sand and moderate-gravel concentrations found in western Charteris Bay was not identified by Curtis. The difference in findings may be a product of the more-detailed sampling regime employed in the current study and/or due to a change in sediment textures between 1985 and 2008.

The finding of the present study that clay concentrations increase from south to north across the harbour agrees, at least superficially, with the broad north/south coarse/fine sediment division identified by Curtis. However, the distribution of silt concentrations found in the present study does not reflect this division, with increases in silt found towards the northern, western and southern shorelines in the upper harbour in our study.

Comparison of the mean grain size results given in Appendix 3 with those from Curtis (1985) (Figure in Appendix 2) reveals some similarities and differences. The dominance of silt mean sizes along the northern and western upper harbour mudflats was recorded in both studies. However, areas characterised by mean sand sizes were found in the western lee of Quail Island, in north-eastern Charteris Bay, and along the neck of the harbour south of the dredged channel were identified in the present study but not by Curtis (1985). Similarly, the present study identified pockets of shell-hash gravels with mean granule sizes between Magazine and Church Bays, not identified by Curtis. These results reinforce that there is a general increase in clay sediments south to north across the harbour as suggested by Curtis. However, the patterns of silt (which increase towards the upper harbour bays' shorelines), of sand (which dominates along parts of the harbour central axis), and the pockets of shell-hash gravel found, demonstrate that the sediment distributions are more-complex than originally thought and are less indicative of a strong south to north fine transport system, instead indicating that silt sources are important in the upper bay catchment and that the harbour neck, and perhaps the port, may be relatively strong transport pathways for sands and clays.

Overall results reveal that the patterns of sediment distribution in the upper harbour are presently more-complex than revealed by Curtis (1985), with increasing silts towards the shorelines and, conversely, an increased occurrence of pockets of shell-hash gravels with increasing depth. It is impossible to conclude definitively the degree to which the differences found are due to changes in sediment composition over time versus an artefact of the sampling regimes, but the latter factor is likely to have played a significant role. Recent suburban development around Governors Bay and other parts of the upper harbour catchment may also have played a role in the shoreward increase in silts observed in this study. An examination of catchment sources of sediment, needed to confirm this suggestion, was beyond the scope of this investigation. These findings indicate that, at the very least, the hydrodynamic current patterns operating with the upper harbour should be re-examined as the northward flux of fine sediments suggested by Curtis, based on his sediment texture results, may not be as strong as originally thought.

5.3 Intertidal and subtidal shellfish beds

The only significant shellfish beds found during the present survey were of the cockle, *Austovenus stutchburyi.* These beds extended from the mid intertidal down to 2 m below MSL at Site 15 (Maps 1-2). At Site 14 (0.75 m below MSL), close to Quail Island, and which is exposed on spring tides, cockles were of medium shell length and at densities similar to those from intertidal populations. Cockles were absent from the deeper subtidal sites and at Site 43, which had a high proportion of shell-hash gravel. Overall these patterns indicate that the potential for cockle habitat is high in the inner harbour, where they are likely to occur on most intertidal mudflats and sandflats and extend down to shallow subtidal areas. It is unlikely that they occur in areas dominated by coarse shell fragments or gravel.

Other estuarine shellfish species were found infrequently, for example, the wedge shell (*Macomona liliana)* was found at Sites 11, 14, 14, 18, pipi (*Paphies australis)* at sites 3, 18, 28 and 33 and *Cyclomactra ovata* at Sites 2, 36 and 43 (Map 1). The sunset shell (*Ruditapes largiillierti)* was found in half of the samples, occurring across a wide range of substrates including some of the deeper sites (up to 6 m below MSL) and those dominated by coarse shell fragments. It is suggested that potentially this species is widely distributed throughout the harbour but that densities may not be as high as cockles.

Juvenile shellfish in low densities were recorded from many of the sites and these included juveniles of the estuarine species, cockles, wedge shells and *Cyclomactra.* Also found were pipi (*Paphies australis)* and juvenile surf clams including tuatua, *Paphies donacina* and *Dosinia subrosea.* Other irregular shellfish finds were oysters at sites 3 and 15 (Map 1).

The present study did not find evidence of extensive subtidal shellfish beds within Lyttelton Harbour. In a previous study (Knight 1974) recorded several shellfish species but the size of the individuals was not given. In the present survey mostly juvenile shellfish (including surf clams) were found and these are likely to be more widely distributed than adults given the closeness of Lyttelton Harbour to Pegasus Bay, which has extensive surf clam beds and may function as a dispersal area from which juveniles are likely transported into the harbour.

From previous studies it might have been predicted that some adult shellfish species would have been collected in higher numbers. One such species, *Cyclomactra ovata*, has been previously found at sites along the northern part of Lyttelton Harbour just outside the port (Johnston, 2005). One large individual was collected from Site 19 as part of preliminary sampling but this species was not recorded as part of the main sampling programme at that site. It is possible that other sampling techniques or a larger number of replicates would have identified further individuals. Although there was no evidence to suggest that there were adult surf clams within the harbour, the box-dredge sampling programme used in this survey would not be expected to collect such species because they are characteristic of exposed sand beaches. These are difficult species to sample, requiring a suction dredge or diving surveys with samples exceeding 0.2 m depth.

5.4 Biological communities associated with different sediment types

The benthic communities of Lyttelton Harbour have been investigated previously, from early studies by Knight (1974) to more recent studies by Johnston (2005), Handley *et al*. (2000) and Fenwick (2003), where the main focus was on the fauna of the Port of Lyttelton. Knight's (1974) study, undertaken in 1970-71, was the most extensive, sampling 40 sites using three collection devices - an orange-peel grab, a box dredge, and an epibenthic sled, and sieved the faunal samples using a mesh size of 400 µm. More than 117 species were recorded, with the fauna dominated by polychaetes (26 species), bivalves (19 species) and gastropods (19 species).

The present survey sampled 12 stations using a box dredge, samples were selected on the basis of the sediment characteristics and the sediment from each biological site sieved through a 1 mm (1000 µm) mesh. The species list comprised 48 species, with polychaetes being the most diverse (17 species) and the only other dominant group being bivalves (11 species). Although only six of the sites selected for the present study appear to have been close to locations sampled by Knight (1974), differences in the number of species found are most likely explained by the different collection and separating techniques. Examination of preliminary samples that were sieved through a 500 µm mesh suggests that the number of species and densities of polychaetes were significantly reduced because of sieving through a coarser mesh size.

While subtidal surveys in Akaroa (Fenwick 2004) yielded 136 species, this is high compared with some other locations in Banks Peninsula and within the port of

Lyttelton. Similar numbers of species to the present survey were recorded from Little Akaloa (Davidson 1989) and species diversity within the Port of Lyttelton was reported as 29 taxa by Fenwick (2004).

It is difficult to compare the densities of selected species between studies because of the different collection techniques. Fenwick (2003) used an anchor-box dredge that was larger than the one used in the present survey but that study investigated a greater range of water depths. However, densities of dominant organisms appear considerably lower in Lyttelton Harbour than they are within Akaroa Harbour. Some of these differences, especially for polychaete worms, can be explained by the larger sieve mesh size used to separate animals in the current study.

In his study Knight (1974) identified 117 species using three very different collection techniques to the box-dredge device used for biological sampling in the present survey. We have previously used corers to sample the benthos and an epibenthic sled. These sampling devices are particularly efficient at catching shallow surface dwelling organisms and those living in the surface sediment. They sample a much larger surface area and therefore it would be expected that a greater selection of species would be collected. It is, therefore, not surprising that small crustaceans such as mysids and small cephlaopods were not collected in the present study. However, despite the limited number of sites sampled in the present study, many large invertebrates were collected, including camouflage crabs, starfish and brittle stars.

Three main community types were identified by Knight (1974): a crab/sea pen community found in muddy regions, a turret shell/*Pectinaria* community from sandier substrates, and a cockle community in restricted sandy areas. The present study identified *Macrophthalmus hirtipes/Virgularia* as the dominant community type. Living turret shells were not collected in this survey, although they were often present as shell in the substrate. This deposit-feeding snail is known to inhabit coarse shelly deposits down to a depth of 100 m and, elsewhere in New Zealand, forms a distinct community type. Its absence from the present survey does not mean that it does not occur - it occurs commonly elsewhere on Banks Peninsula, and probably suitable substrate was not sampled in the present study. The polychaete species *Pectinaria* was found by Knight (1974) to occur in conjunction with the turret shell community – in the present study this polychaete was found at Sites 2, 18, 25 and 28. This species, however, did not feature as a dominant species in any of the site groupings, and was found in deposits of varying particle size. From both the intertidal and shallow subtidal sampling, the cockle *A. stutchburyi* was identified as part of an identifiable community type, co-occurring with the mud crab and other bivalves.

The findings discussed here suggest that within Lyttelton Harbour there is a continuum of overlapping communities associated with the mud crab *Macrophthalmus hirtipes*. This community type has been described elsewhere in New Zealand. Overall, it is concluded that the Lyttelton Harbour communities are related to substrate sediment texture composition and that there is a characteristic fauna associated with fine sediments. The low similarity values for the species recorded from the 12 biological sites sampled in this survey suggests that there are likely to be more distinct communities present within the harbour. Sandier and coarse sediments from shallow subtidal areas potentially have a varied fauna and this is worthy of further investigation.

6. Recommendations

Although the objectives of this study were to establish a baseline against which future changes in sediment patterns and biological communities in the Upper Lyttelton Harbour could be assessed, there are three key recommendations for additional future research that arise from this report. These are as follows:

1. Curtis' (1985) Lyttelton Harbour circulation study was based primarily on measurements in the central and lower harbour, with conclusions regarding upper harbour circulation drawn based primarily on sediment texture patterns. The latter texture patterns contrast those found using a more-detailed sampling regime in this study. In light of our new findings, and to improve knowledge of upper harbour sedimentation processes, a hydrodynamic field and modelling study should be conducted to establish circulation and wave energy patterns within the upper harbour, in order to determine the influence of different sediment sources on the observed sediment deposits.

2. A study should be conducted to quantify the catchment inputs of water and sediment from the Upper Lyttelton Harbour catchment. This would include a review of the monitoring data from the large number of recent development sites (particularly in Governors and Cass Bays) and those in the process of development. This sediment input information could then be compared to surface sediment texture patterns, and textural associations with biota found in the present study, to better understand the effects of contemporary catchment change on the biological resources of the harbour.

3. Initiate a larger-scale biological sampling project to describe the full range of biological communities present inside the harbour. The focus of this study needs to be on sediment fractions containing a higher proportion of sand and gravel, with specialised suction equipment used to sample for deeper burrowing bivalves. This will clarify whether the shell hash deposits are contemporary or relic in nature.

7. Acknowledgements

Wybren de Vries is credited with production of Maps 1-5. Enormous thanks are due to the following people: Gerry Murphy – for biological sampling and laboratory analysis Renny Bishop – for biological sampling; Russell Taylor – for biological sampling and as the Biology boat master; Justin Harrison – for intertidal surveying, sediment and biological sampling, and GPS expertise; Paul Bealing – for subtidal surveying and sediment sampling, and GPS expertise; and Nicholas Key – for subtidal surveying and sediment sampling, and as the Beagle boat master.

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New Zealand Hydrographic Chart NZ6321. 1976.

MAPS

APPENDICES

Appendix 1: List of electronic files provided to ECan with this report

Raw Data

- Bathymetric GPS Data
- Upper Bays Transect Data
- Sample Site Co-ordinates
- Sediment Sample Size Analysis
- Sediment Sampling Summary of Results (Appendix 3)
- Biological Site Sediment Sample Analysis
- Biological Intertidal Species Presence (Appendix 4)
- Biological Subtidal Species Counts
- Biological Subtidal Species Presence (Appendix 5)

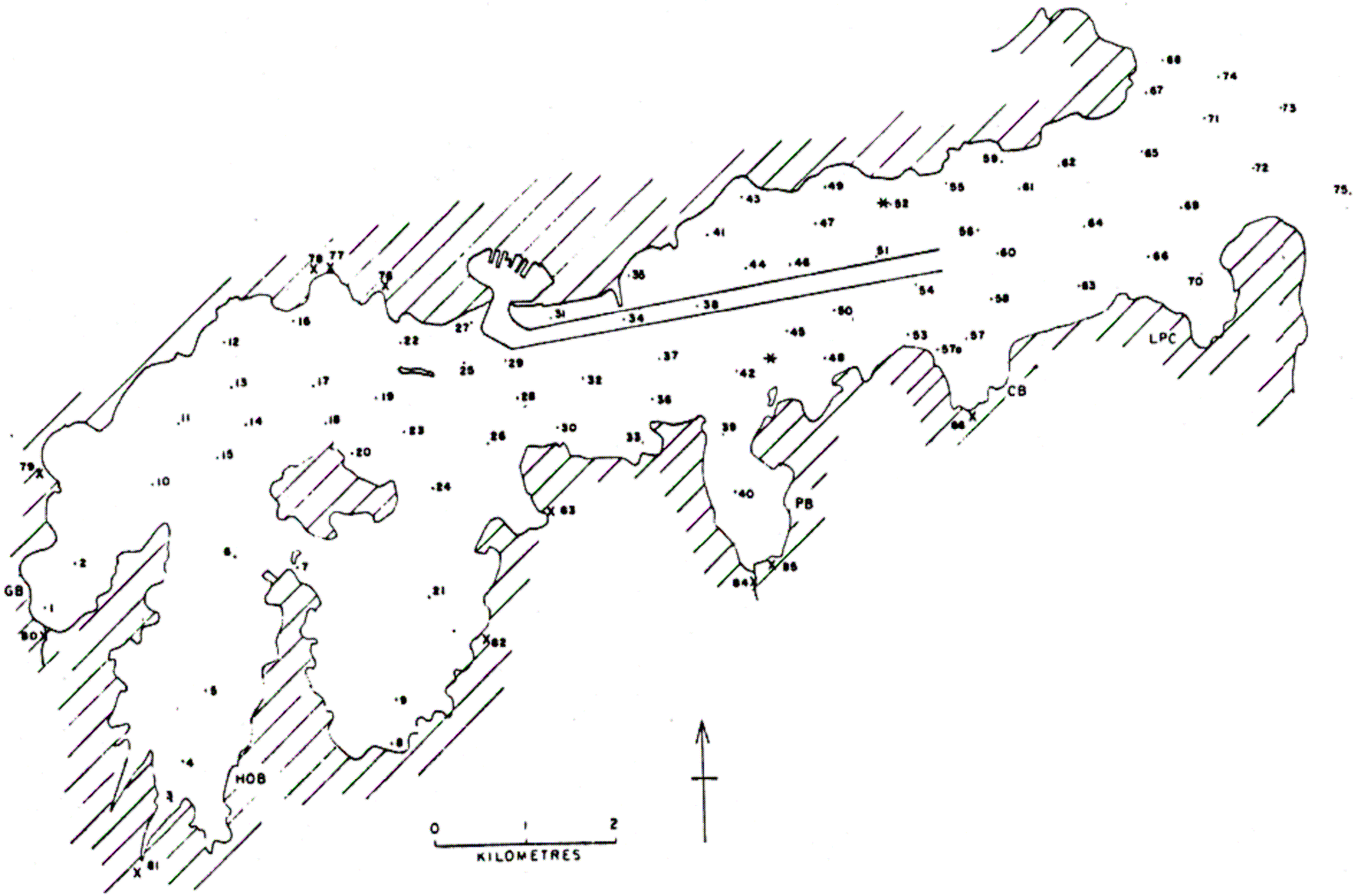
Shapefiles

- Gravel Distribution Shapefiles
- Sand Distribution Shapefiles
- Silt Distribution Shapefiles
- Clay Distribution Shapefiles
- Mud (silt plus clay) Distribution Shapefiles
- Bathymetry Shapefiles

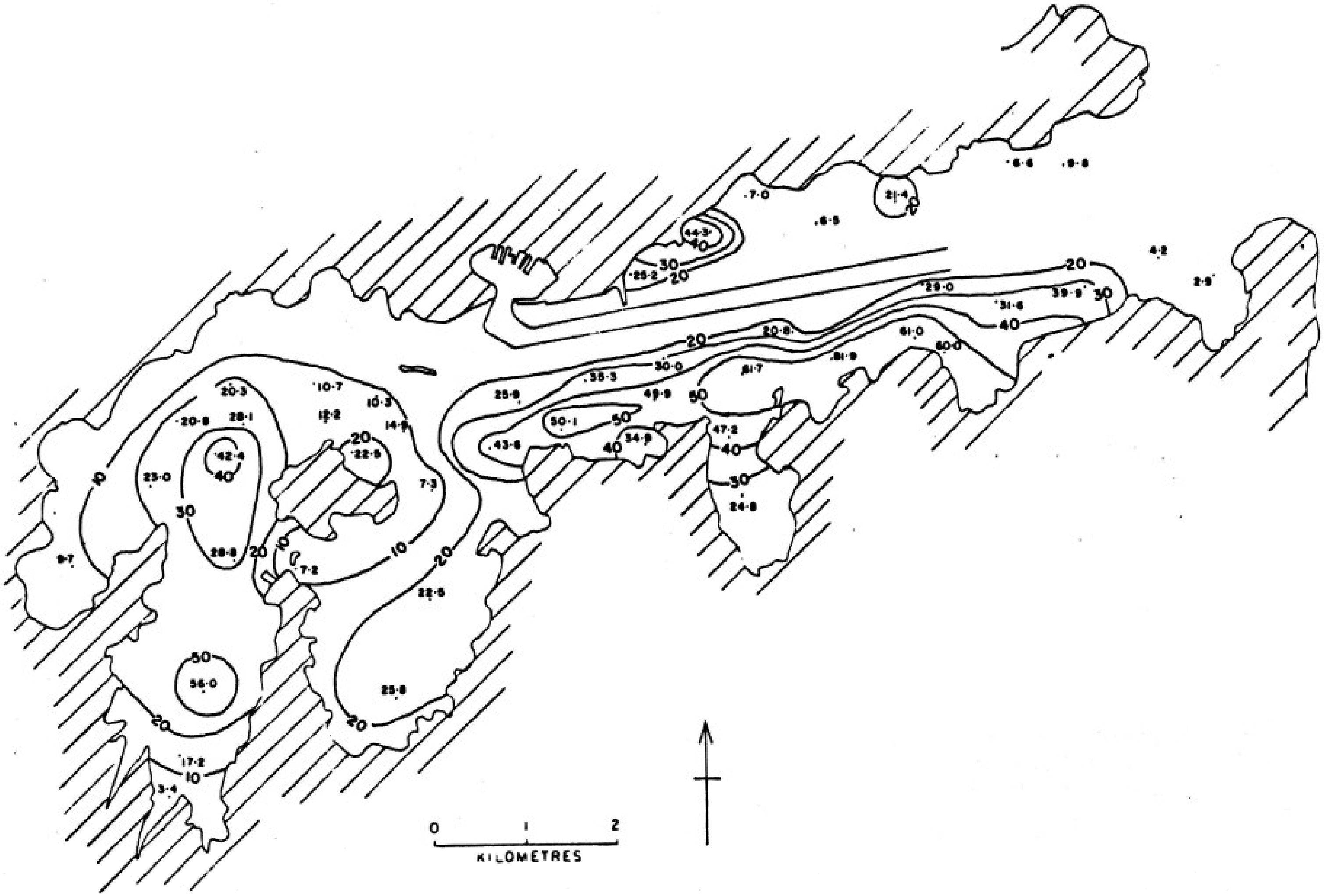
Map JPGs

- Map 1: Lyttelton Harbour Bathymetric Survey Transects and Sample Sites
- Map 2: Lyttelton Harbour Bathymetry
- Map 3: Lyttelton Harbour Sediment Distributions
- Map 4: Lyttelton Harbour Sediments with Folk Classifications
- Map 5: Lyttelton Harbour Sediments and Bathymetry
- Figure 6b: Location of Transects Along Axis of Upper Harbour Bays
- Figure 7: Occurrence of the mud snail *Amphibola crenata* and the mud crab *Helice crassa* on intertidal sandflats
- Figure 12: Occurrence of the cockle *Austrovenus stutchburyi* and the stalk eyed mud crab *Macrophthalmus hirtipes* in intertidal sandflats

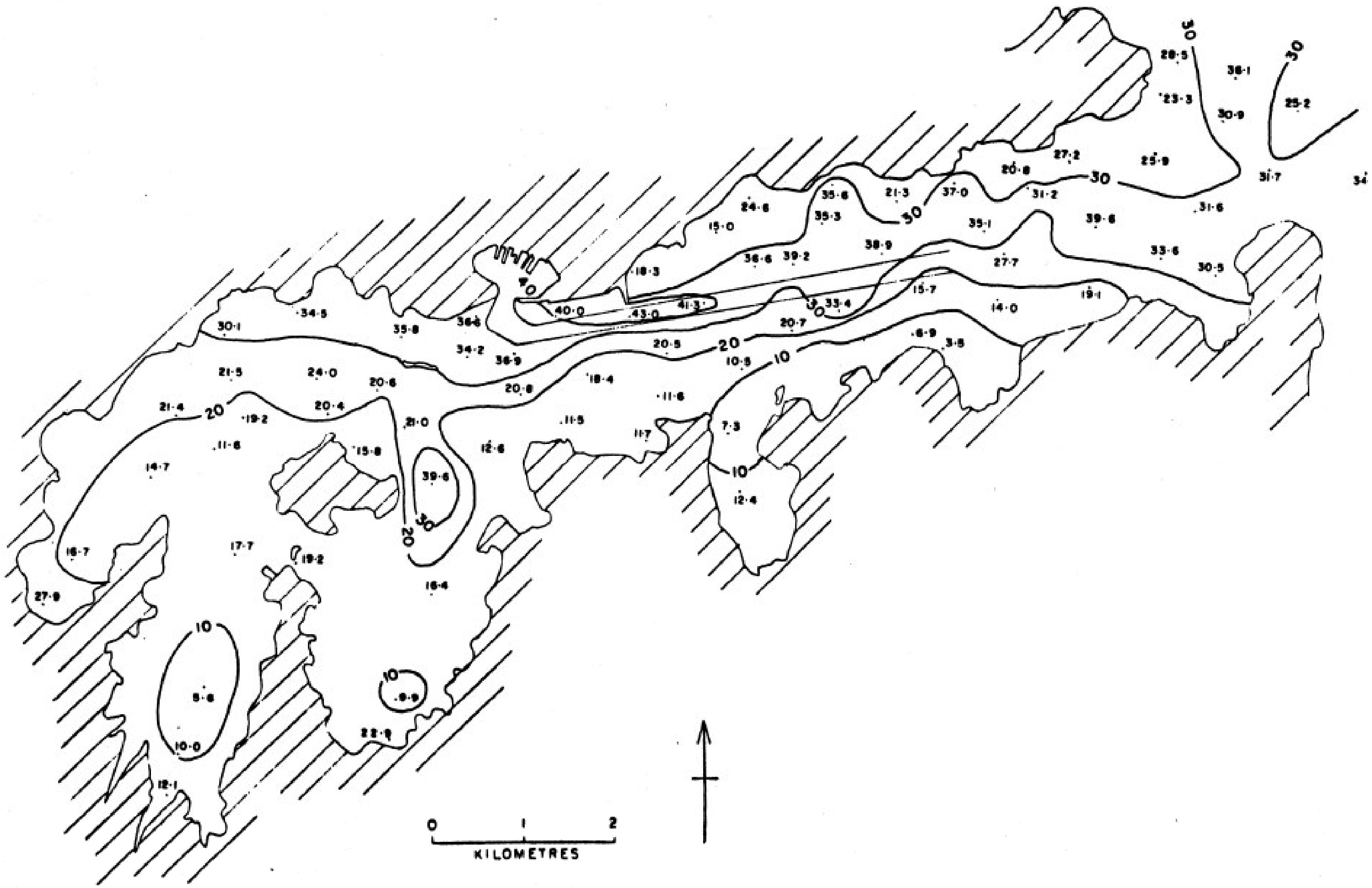
Appendix 2: Sediment Distribution Figures from Curtis (1985)



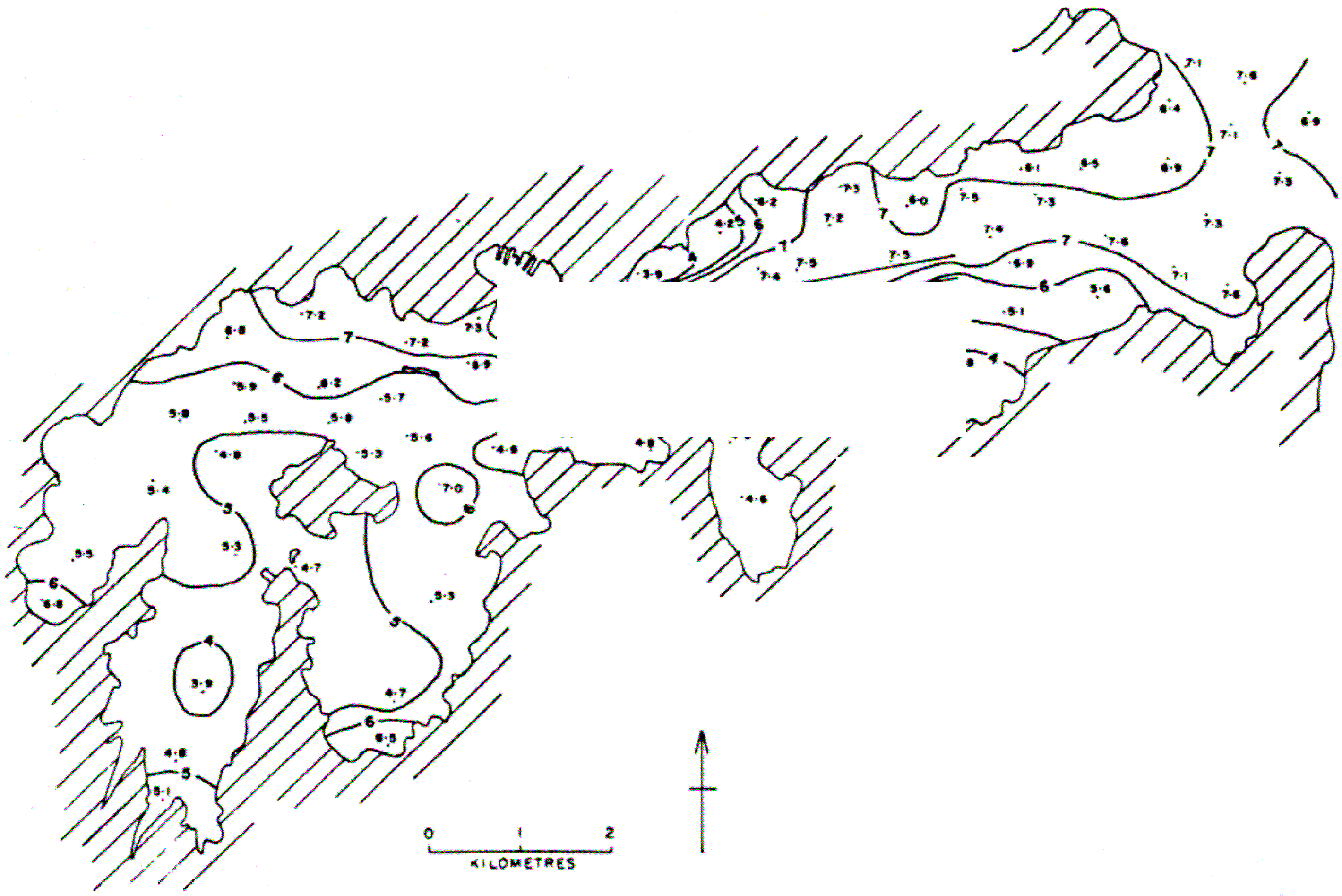
Sediment sample sites used by Curtis (1985, p54). GB is Governors Bay, HOB is Head of the Bay, PB is Purau Bay, CB is Camp Bay, and LPC is Little Port Cooper. Note the limited spatial coverage of sediment sample sites in Governors and Charteris Bays and in the Head of the Bay.



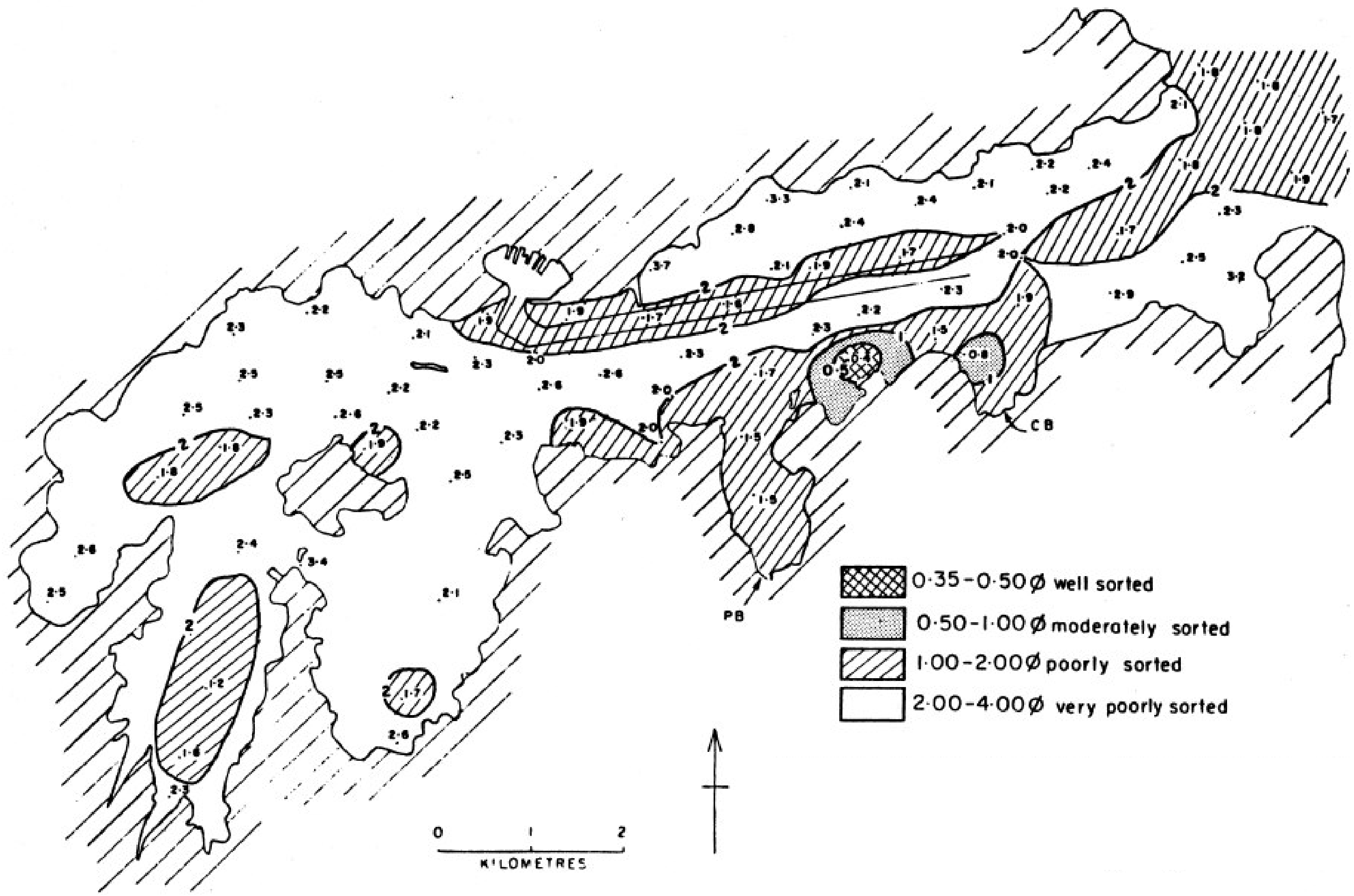
Contour map of percentage fine to very fine sand (2 to 4 φ) found in bed-sediments by Curtis (1985, p60).



Contour map of percentage clay (<8 φ) found in bed-sediments by Curtis (1985, p61).



Mean grain size contour map from Curtis (1985, p63). (Note contours are in Φ units)



Spatial distribution of sediment texture sorting found in bed-sediments by Curtis (1985, p66).

Appendix 3: Summary of Lyttelton Harbour sediment sample locations and analysis results

Site No.	Northing	Easting	Depth (m above MSL)	Gravel composition (% shell or mineral)	Sediment Type (% by weight) Gravel	Sand	Silt	Clay	Modified Folk (1965)	Mean Grain Size (mm)	Size Class	Medium Grain Size (mm)	Size Class
0	5168428	1571837	0.25		0	4	75	20	Z	0.0137	Fn Silt	0.0185	Md Silt
1	5168686	1572165	-0.5	100% shell	1	9	72	18	Z	0.0179	Md Silt	0.0309	Md Silt
2	5169178	1572457	-1		0	12	71	16	sZ	0.0195	Md Silt	0.0337	Cs Silt
3	5169718	1572731	-1.75		0	4	69	27	Z	0.0110	Fn Silt	0.0135	Fn Silt
4	5170008	1571999	-0.25		0	18	64	18	sM	0.0203	Md Silt	0.0344	Cs Silt
5	5166016	1573183	-0.5	100% shell	1	20	67	12	sZ	0.0270	Md Silt	0.0385	Cs Silt
6	5166366	1573454	0		0	21	70	9	sZ	0.0370	Cs Silt	0.0424	Cs Silt
7	5167317	1572926	0	100% shell	3	66	26	5	mS	0.0912	V Fn Sand	0.0961	V Fn Sand
8	5167394	1573442	-0.5		0	20	67	13	sZ	0.0264	Md Silt	0.0376	Cs Silt
9	5167614	1573925	-0.5	100% shell	15	29	45	11	gsM	0.0741	V Fn Sand	0.0540	Cs Silt
10	5168444	1573454	-1.5	100% shell	15	22	51	11	gsM	0.0739	V Fn Sand	0.0480	Cs Silt
11	5170056	1573121	-2.5		0	14	63	23	sM	0.0157	Md Silt	0.0265	Md Silt
12	5169246	1573595	-1.75	100% shell	16	40	37	7	gsM	0.1750	Fn Sand	0.0782	V Fn sand
13	5168336	1574128	-1	100% shell	37	15	36	12	mG	0.1134	V Fn Sand	0.0785	V Fn sand
14	5168801	1574485	-0.75	100% shell	19	28	38	16	gsM	0.0804	V Fn Sand	0.0558	Cs Silt
15	5169496	1574094	-2		0	50	50	0	mS	0.0703	V Fn Sand	0.0633	V Fn Sand
16	5170283	1573651	-3	100% shell	2	37	49	12	sM	0.0359	Cs Silt	0.0483	Cs Silt
17	5170886	1573886	-3		0	8	61	31	M	0.0101	Fn Silt	0.0113	Fn Silt
18	5170188	1574277	-3.5	100% shell	45	19	27	9	mG	0.1850	Fn Sand	0.1882	Fn Sand
19	5171128	1574396	-3		0	3	59	38	M	0.0066	V Fn Silt	0.0062	V Fn Silt
20	5171563	1574163	-2		0	9	60	31	M	0.0088	Fn Silt	0.0077	V Fn Silt
21	5170311	1574833	-4.25	100% shell	2	33	49	17	sM	0.0276	Md Silt	0.0421	Cs Silt
22	5171062	1574991	-3.5		0	1	61	37	M	0.0072	V Fn Silt	0.0065	V Fn Silt
23	5171280	1575507	-3.5		0	2	60	38	M	0.0066	V Fn Silt	0.0061	V Fn Silt
24	5170252	1576043	-5.25		0	29	53	18	sM	0.0240	Md Silt	0.0385	Cs Silt
25	5169829	1575636	-4.75	100% shell	1	37	54	7	sM	0.0535	Cs Silt	0.0515	Cs Silt
26	5168979	1576106	-3.5		0	10	61	26	sM	0.0119	Fn Silt	0.0136	Fn silt
27	5169374	1576500	-3.5	100% shell	27	29	28	15	gsM	0.0998	V Fn Sand	0.0867	V Fn Sand
28	5169865	1576837	-6.5	100% shell	87	7	3	3	G	2.6799	Granule	2.6799	Granule
29	5170506	1576504	-6		0	13	61	27	sM	0.0123	Fn Silt	0.0155	Fn Silt
30	5170970	1576262	-6	100% shell	88	6	2	4	G	2.6927	Granule	2.6970	Granule
31	5171147	1576773	-5.5		0	3	57	39	M	0.0060	V Fn Silt	0.0058	V Fn Silt

Site No.	Northing	Easting	Depth (m above MSL)	Gravel composition (% shell or mineral)	Sediment Type (% by weight) Gravel	Sand	Silt	Clay	Modified Folk (1965)	Mean Grain Size (mm)	Size Class	Medium Grain Size (mm)	Size Class
32	5170100	1577280	-7.25		0	43	42	15	sM	0.0329	Cs Silt	0.0514	Cs Silt
33	5170075	1577891	-6.5		0	65	30	5	cS	0.0819	V Fn Sand	0.0865	V Fn Sand
34	5169985	1578583	-7	100% shell	45	32	14	8	mG	0.4905	Md Sand	1.2102	V Cs Sand
35	5170242	1579051	-7.5		0	88	10	2	cS	0.1152	V Fn Sand	0.1152	V Fn Sand
36	5169995	1579685	-4.5	100% shell	1	63	31	5	cS	0.0831	V Fn Sand	0.0847	V Fn Sand
37	5170737	1580021	-9.5		0	57	30	13	cS	0.0408	Cs Silt	0.0748	V Fn Sand
38	5168941	1579717	-2.5		0	54	40	7	mS	0.0708	V Fn Sand	0.0689	V Fn Sand
39	5168467	1579960	-1	73% mineral, 27% shell	84	15	1	1	G	2.6480	Granule	2.6480	Granule
40	5168397	1576418	-2.25	100% shell	26	35	31	8	gsM	0.1895	Fn Sand	0.1079	V Fn Sand
41	5168912	1577333	-1.25		0	10	66	24	sM	0.0125	Fn Silt	0.0157	Md Silt
42	5167446	1576365	-1		0	32	56	12	sM	0.0330	Cs Silt	0.0439	Cs Silt
43	5168042	1576047	-2	100% shell	56	25	14	5	mG	0.7163	Cs Sand	2.1617	Granule
44	5168674	1575709	-3		0	17	57	26	sM	0.0153	Fn Silt	0.0271	Md Silt
45	5167629	1575145	-1		0	10	75	15	sZ	0.0211	Md Silt	0.0347	Cs Silt
46	5166918	1575546	-0.5	100% shell	2	33	63	2	sM	0.0462	Cs Silt	0.0493	Cs Silt
47	5166693	1575090	0		0	26	67	7	sZ	0.0473	Cs Silt	0.0456	Cs Silt
48	5166963	1576082	-0.5	90% shell, 10% mineral	2	32	60	6	sM	0.0413	Cs Silt	0.0468	Cs Silt

Notes: Northings and Eastings are given in New Zealand Geodetic Datum NZGD 2000, MSL denotes mean sea level, the modified Folk (1965) classification scheme is detailed in Figure 4, where: classes include gravel (G, g), sand (S, s), silt (Z, z), clay (C, c) and mud (M, m), and capitals indicate the dominant constituent

Appendix 4: Presence of benthic faunal species and anoxic layer at intertidal sites

Intertidal Site	Location		Species present											Anoxic Layer present
	Northing	Easting	A. crenata	D. subrostrata	H. crassa	H. crenulatus	M. hirtipes	M. liliana	P. australis	A. stuchburyi	M. galloprovincialis	X. pulex	C. glandiformis	
i	5166963	1576082	X		X									
ii	5166963	1576082			X									
iii	5166963	1576082	X		X	X								
iv	5166963	1576082	X	X			X			X				
v	5166963	1576082	X	X			X			X			X	
vi	5166963	1576082	X	X			X			X			X	
vii	5166963	1576082		X			X			X			X	
viii	5166963	1576082	X	X	X									X
ix	5166963	1576082	X		X									
x	5166963	1576082	X		X									
xi	5166963	1576082	X		X								X	X
xii	5166963	1576082	X				X			X				
xiii	5166963	1576082	X				X			X				
xiv	5166963	1576082	X				X		X					
xv	5166963	1576082		X		X					X			
xvi	5166963	1576082	X	X	X					X				
xvii	5166963	1576082		X			X				X	X		X
xviii	5166963	1576082	X			X								
xix	5166963	1576082	X				X							
xx	5166963	1576082	X		X	X								
xxi	5166963	1576082			X					X				
xxii	5166963	1576082	X		X									
xxiii	5166963	1576082	X		X									X
xxiv	5166963	1576082	X	X						X				
xxv	5166963	1576082	X	X	X	X				X				X
xxvi	5166963	1576082	X		X					X				
xxvii	5166963	1576082	X				X			X				
xxviii	5166963	1576082	X		X					X				
N			23	10	15	5	10	0	1	13	2	1	4	5
%			82.1	35.7	53.6	17.9	35.7	0	3.6	46.4	7.1	3.6	14.3	17.9

Notes: X indicates presence, N the number of sites where species were found and % the percent occurrence in total sites. Coordinates given in New Zealand Geodetic Datum NZGD 2000

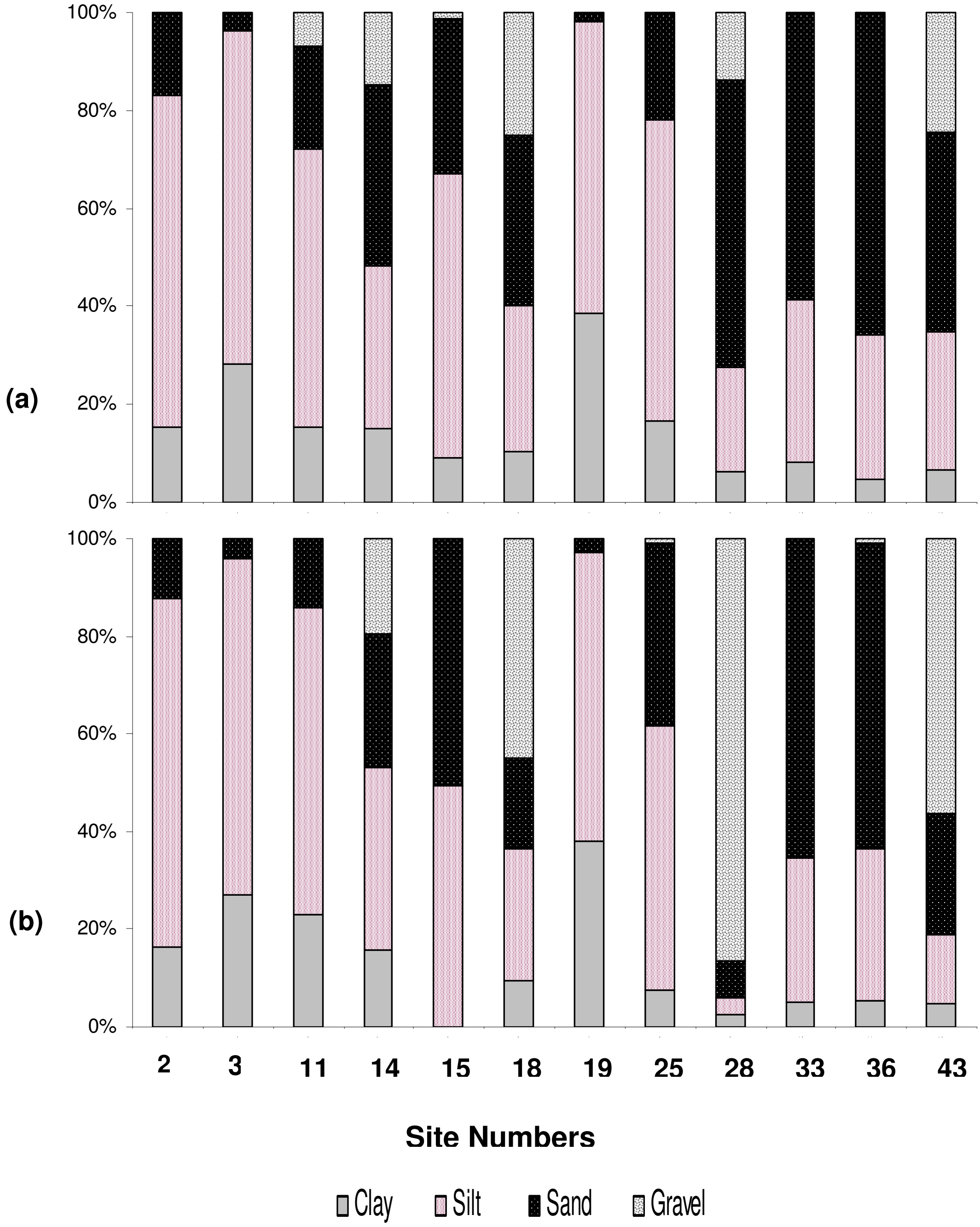
Appendix 5: Presence of benthic faunal species at subtidal biological sample sites

Phylum	**Species**	**Presence at each biological sample site**											
		2	**3**	**11**	**14**	**15**	**18**	**19**	**25**	**28**	**33**	**36**	**43**
Annelida	*Heteromastus* sp.	X											
Annelida	*Glycinde* sp.	X									X		
Annelida	*Scoletoma* sp.									X			
Annelida	*Magelona* sp.	X											
Annelida	*Asychis* sp.	X	X	X				X	X			X	
Annelida	*Aglaophamus* sp.								X		X	X	
Annelida	*Nicon* sp.	X	X					X					
Annelida	*Platynereis* sp.				X	X							
Annelida	*Owenia* sp.								X	X		X	
Annelida	*Pectinaria* sp.	X					X		X	X			
Annelida	*Lepidonotinae* sp. 1	X											
Annelida	*Lepidonotinae* sp. 2		X										
Annelida	*Boccardia sytrtis*	X	X	X		X							
Annelida	unidentified sp.		X										
Annelida	*Streblosoma* sp.			X									
Annelida	*Terebellides* sp.	X	X				X		X		X		
Annelida	*Sthenolepis* sp.								X	X	X		
Arthropoda	unidentified shrimp									X			
Chordata	*Tunicates/Ascidians*		X			X	X						X
Cnidaria	*Virgularia gracillima*		X					X	X		X		
Crustacea	*Halicarcinus whitei*									X			
Crustacea	*Notomithrax ursus*												X
Crustacea	unidentified majid												X
Crustacea	*Macrophthalmus hirtipes*	X	X	X	X	X	X		X	X	X	X	X
Crustacea	*Cymodopsis montis*												X
Crustacea	*Exosphaeroma chilensis*	X											
Echinodermata	*Allostichaster insignis*						X						X
Echinodermata	*Astrostole scabra*					X							X

Phylum	**Species**	**Presence at each biological sample site**											
		2	**3**	**11**	**14**	**15**	**18**	**19**	**25**	**28**	**33**	**36**	**43**
Echinodermata	*Coscinasterias muricata*			X									
Echinodermata	*Patiriella vulgaris*											X	X
Echinodermata	Holothurian								X		X		
Echinodermata	*Ophiomyxa brevirima*					X							X
Lophophorata	Phoronid			X									
Mollusca	*Arithritica bifurca*	X	X				X			X			
Mollusca	*Cyclomactra ovata*	X										X	X
Mollusca	*Paphies australis*		X				X			X	X		
Mollusca	*Paphies donacina*		X								X	X	
Mollusca	*Tiostrea chilensis*		X			X							
Mollusca	Sunset shell											X	
Mollusca	*Theora lubrica*	X	X				X					X	
Mollusca	*Macomona liliana*			X	X	X	X						
Mollusca	*Austrovenus stutchburyi*	X	X		X	X							
Mollusca	*Dosinia subrosea*											X	
Mollusca	*Ruditapes largillierti*			X	X		X			X	X		X
Mollusca	*Sigapatella novaezelandiae*			X		X				X			X
Mollusca	*Acanthochitona zelandica*					X							X
Mollusca	*Ischnochiton maorianus*					X						X	X

Notes: X indicates presence.

Appendix 6: Comparison Between Sediment Composition in Biological and Sediment Only Samples



Percentage of gravel, sand, silt and clay sediment textures found in the biological (a) versus the sediment-only (b) site samples