Distinguishing erosional and accretional mudflats on Banks Peninsula.

Honours Dissertation

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Abstract

This research aimed to discover whether certain muddy environments within Banks Peninsula are in a state of erosion, accretion or stability according to theory proposed by Kirby (2002) where erosional profiles exhibit a concave up profile and accretional profiles exhibit a convex up profile. Repeated direct measurements by transect survey and sediment texture analysis of seabed surface sediment samples were conducted on a selection of bays in the Lyttelton and Akaroa region. These were Charteris Bay, Head of the Bay, Governors Bay, in Lyttelton Harbour, and Takamatua Bay and Barrys Bay in Akaroa Harbour. It was discovered that Governors Bay and Barrys Bay exhibit traits of a depositional environment, whereas Charteris Bay and Takamatua Bay exhibit traits of an erosional environment. Head of the Bay produced conflicting results and was therefore inconclusive. The theory for profile shape according to Kirby (2002) conforms well to the erosional profiles in the meso-tidal setting of Banks Peninsula. However, this rule is overly simplified for accretional environments that were studied on Banks Peninsula. Results showed that the effects of seismic activity on muddy environments due to recent earthquake events occurring in the Canterbury region. It was shown that uplift has occurred in Governors Bay and Charteris Bay in specific locations on the shore. Tilting of the mudflat occurred in Head of the Bay and Governors Bay, which can be attributed to uplift of the upper intertidal zone and slumping of the lower intertidal mudflat. Evidence of subsidence was documented in Charteris Bay.

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1. Introduction

The main controls on the dynamics of muddy coasts are; sediment supply, sediment size, tidal range, incident wave energy, cross-shore currents and tidal influence (Kirby, 2002). A simple approximation of their occurrence can be described as a coastal zone where the abundant fine grain sediment supply is deposited faster than the hydrodynamic conditions can remove these muddy deposits (Wang *et al.*, 2002a). Erosion occurs when the sediment budget is in deficit while accretion occurs where there is a surplus in the sediment budget. According to one theory proposed by Kirby (2002), accreting mudshores have a strong tendency to exhibit a high and convex profile due to bed flexing to attenuate wave induced shear, whereas eroding mudshores have a low and concave profile caused by a reduced elasticity from an over-consolidated foundation. In this study, this theory was tested to determine its applicability to Banks Peninsula and facilitate a profile classification for each mudflat and to understand the complex interactions between influencing variables on the mudflats of Governors Bay (Ohinetahi), Head of the Bay and Charteris Bay (Te Wharau) in Lyttelton Harbour (Whakaraupo), Barrys Bay (Taraouta) and Takamatua Bay in Akaroa Harbour. This was undertaken through repeated survey of transects and comparisons made with historical transect data from 2008 and 2009. A location map of the study area is provided in Figure 3.1.

Seabed surface sediment samples were taken from each bay and analysed to distinguish whether the morphodynamics were accurately represented in the profile shape and conformed to Kirby's (2002) rule. Analysis of sediment texture provides inference about cohesiveness, settling velocity and the ability of hydrodynamic forces to erode the seabed. Wang *et al.* (2002) discovered that on tidal flats silts and clays dominated the central parts of the intertidal zone and lower to subtidal areas were dominated by sandy silt and silty sand. The density of the seabed surface sediment samples was assessed to discover their energy absorbing potential because mud response to hydrodynamic forcing is an important control over profile stability (Mehta, 2002).

Due to the recent seismic activity in the Canterbury region, comparisons made with previous studies presented by Hart *et al.* (2008 and 2009) illustrated the influence of seismic activity on mudflat stability. Subsidence and lateral spread can occur during earthquake events as the ground movement causes unconsolidated sediment to lose its load bearing strength which leads to settling or slumping due to gravity (GNS, 2012). Therefore due to the low cohesion in sediments, sloping bathymetry and abundance of sea water associated with mudflats, the occurrence of subsidence, slumping or liquefaction can prevail during seismic activity. This study seeks to examine any slumping or subsidence on mudflats caused by seismic activity due to their fluid state expanding on the limited knowledge of the effects of seismic activity on mudflats in New Zealand.

Therefore the main objective of this research was to discover the current geomorphic state for mudflats through classification of the profile shape, sediment texture and density. Specifically the research questions were: What is the response of mudflats to seismic activity? What are the effects of hydrodynamic forcing on sediment composition, density, geomorphology and profile shape?

2. Literature review

This chapter looks at the various influences involved in the dynamic equilibrium of mudflats, in both a global and local context. It examines which variables affect the stability of a mudflat, what human impacts there are, and finally, a summary of the local environment in which these mudflats exist.

2.1 Stabilising and destabilising mudflat variables

Mudflat profile shape can tell us much about the environment to which they are exposed. Wind waves, tides, sediment cohesion and size, and density are some of the variables that influence the stability of a mudflat (Table 2.1) which in turn influences its profile shape. It is generally considered that tidal processes dominate accreting, convex mudshores and wind wave processes dominate an eroding, concave profile (Kirby, 2000, Pritchard *et al.,* 2002). Kirby (2000) illustrates varying profile shapes caused by different tidal ranges (Figure 2.1) which was applied during mudflat classification in this study. The role played by tides shows that a dominance of flood tides produces an onshore sediment flux whereas dominating ebb tides create an offshore sediment flux (Christie, Dyer, & Turner, 1999). Ebb tide dominance can lead to retreat of the shoreline in a landward direction (Pritchard, Hogg, & Roberts, 2002). This continuous hydrodynamic forcing in the intertidal zone leads to sediments becoming well sorted (Holland & Elmore, 2008) and can create a spatial zonation of sandier sediment in the lower intertidal zone and muds and clays closer to high tide because hydrodynamic forcing is reduced toward higher tide levels (Holland & Elmore, 2008) . However, waves and currents can also redistribute sediments into heterogeneous patches (Holland & Elmore, 2008) and sediment generally becomes less stable with larger less cohesive grain sizes (Widdows, Brown, Brinsley, Salkeld, & Elliott, 2000).

The density of the surficial and fluid mud is an important control on mudflat stability as it determines the ability of sediments to be entrained or deposited under hydrodynamic forcing (Dyer, Christie and Wright, 2000). The density (ρ) of a high energy absorbing slurry of fluid mud has been calculated to be between 1030 kg m^{-3} and 1300 kg m^{-3} (Mehta, 2002). Classification of mud density according to Dyer et al. (2000), describes a high density as $\rho > 1000$ kg m^{-3}, medium density as $1000 > \rho > 600$ kg m^{-3}, and a low density as $\rho < 600$ kg m^{-3}. Thus, in low energy environments, where deposition rates of fine grained materials are higher, there is a greater surplus of sediment that has a lower density (Mehta, 2002).

Table 2.1: *Factors that influence the stability of mudflats.*

Mudflat stabilising factors	**Mudflat destabilising factors**
Sediment supply (Kirby, 2000, Shi, 1996)	Wind waves (Kirby, 2000, Shi, 1996, Pritchard *et al.,* 2002)
Bottom hardness (Kirby, 2000)	Storm surges (Kirby, 2000)
Coastal structures (Kirby, 2000)	Coastal structures (Kirby, 2000)
Morphological control (Kirby, 2000, de Vires, 2007)	Tides (Kirby, 2000, Shi, 1996, Christie *et al.,* 1999, Pritchard *et al.,* 2002)
Sediment composition (Kirby, 2000, de Vries, 2007, Shi, 1996)	Bioturbation (Kirby, 2000)
Vegetative cover (Kirby, 2000)	
Biological processes (Kirby, 2000)	
Sediment stability (de Vries, 2007, Shi, 1996)	
Sediment cohesion (Widdows *et al.,* 2000)	
Density (Dyer *et al.* 2000)	

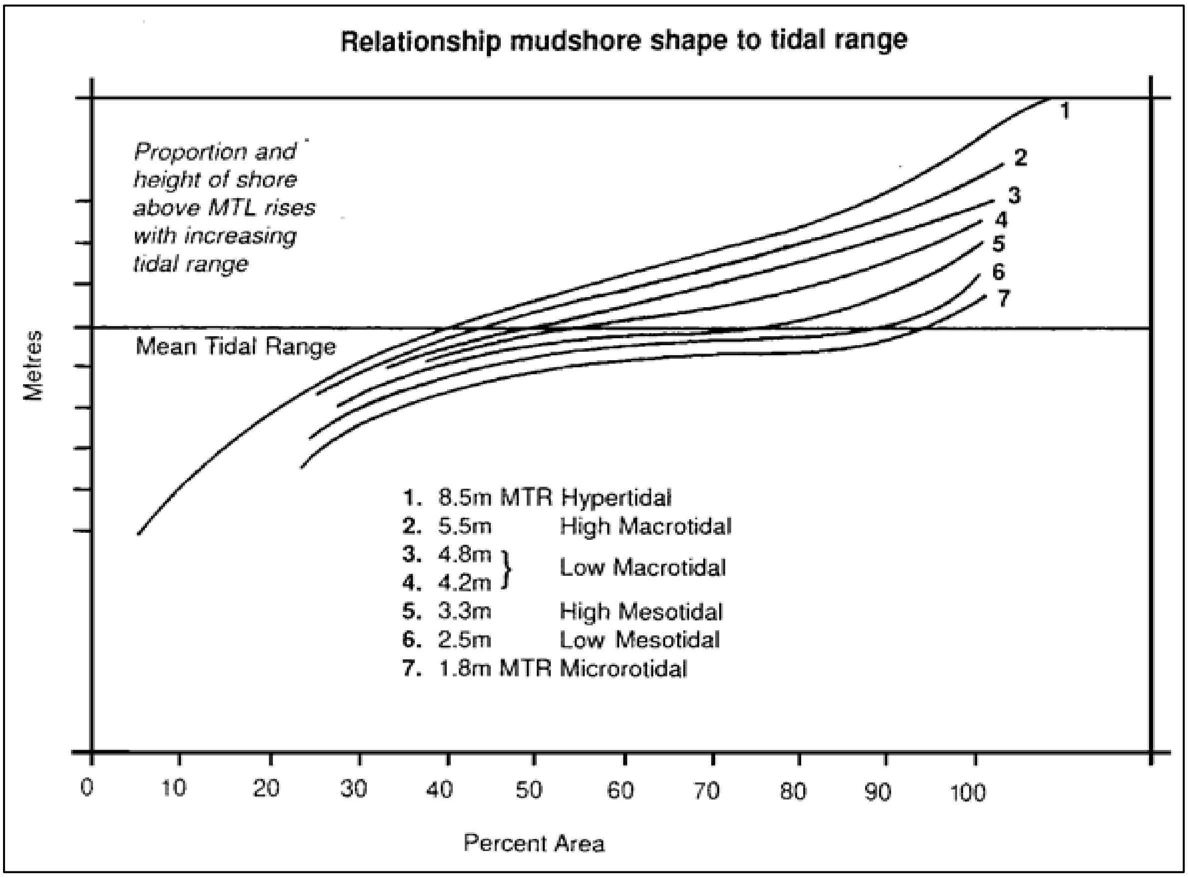


Figure 2.1: *The relationship between tidal range and profile shape, as theorised by Kirby (2002).*

2.2 Anthropogenic influences on mudflats

Humans have impacted and continue to impact on muddy environments globally for a range of reasons. Deforestation and urbanisation of catchments leads to an excess sediment supply to harbours (Oldman, Black, Swales, & Stroud, 2009). Dredging regimes cause the re-suspension of fine sediments into the water column for deposition in calmer environments (Suedel, Kim, Clarke, & Linkov, 2008). Permanent structures have been placed within the intertidal zone which initiates scour of the adjacent bathymetry and sea level rise will see continual coastal squeeze (Hughes & Paramor, 2004).

European colonisation has caused acceleration of sedimentation in Lyttelton and Akaroa Harbours. Sedimentation peaked at around 0.85 cm a^{-1} during 1830 to 1900 in Lyttelton Harbour (Goff, 2005), which was primarily due to catchment clearance of native forest cover for conversion to pasture and timber for industry. Catchment modification resulted in transport of the easily erodible fine-grained loess from the terrestrial environment into the marine environment (Goff, 2005, Curtis, 1985, Hart *et al.,* 2008, Hart *et al.,* 2009). After 1900 sedimentation slowed due to increased awareness of sedimentation and a hiatus was emplaced until 1953 on land clearance activities (Goff, 2005). More recently on-going suburban development has raised concerns about the effect of these activities on sedimentation processes on the intertidal mudflats (Hart *et al.,* 2009). Re-circulated spoil material created by dredging operations of the Lyttelton Port Company has also been cited as the primary internal source of sediment to the mudflats (Curtis, 1985).

Climate change, and its associated sea level rise and increased storminess are predicted to cause a migration of stable and slowly accreting mudflats to an erosive regime (Kirby, 2000, Cundy, 2000). Although a healthy saltmarsh fringe is an efficient attenuator of incoming waves (Kirby, 2000). The replacement of saltmarsh communities with housing, infrastructure and farmland, and the associated shoreline hardening through levees and revetments to protect the human use system, has led to coastal squeeze (Hughes & Paramor, 2004). Thus, sea level rise and coastal squeeze lead to waves of increasing magnitude reaching closer to coastal defences before breaking and therefore increasing the vulnerability of the low lying hinterland (Kirby, 2000).

2.3 The Banks Peninsula environment

Lyttelton and Akaroa Harbours are erosion calderas created by seawater inundation of the calderas of a large extinct shield volcano complex (Soons, 1968). Banks Peninsula was initially an offshore island which throughout history has been alternately linked to the mainland of the South Island depending on interglacial-glacial variations in sea level (Shulmeister et al., 1999). Alluvial fans have prograded out of the Southern Alps to meet up with the eastern flank of Banks Peninsula. The presence of shore platforms from the Last Interglacial age confirm that Banks Peninsula has been tectonically stable for the last 125,000 years (Shulmeister et al., 1999).

The mudflats of Banks Peninsula are comprised of fine loess sediment of greywacke origin that erodes out of its catchments. The geological composition of Banks Peninsula is primarily volcanic basalt (Shulmeister et al., 1999). The loess was created during glaciation of the

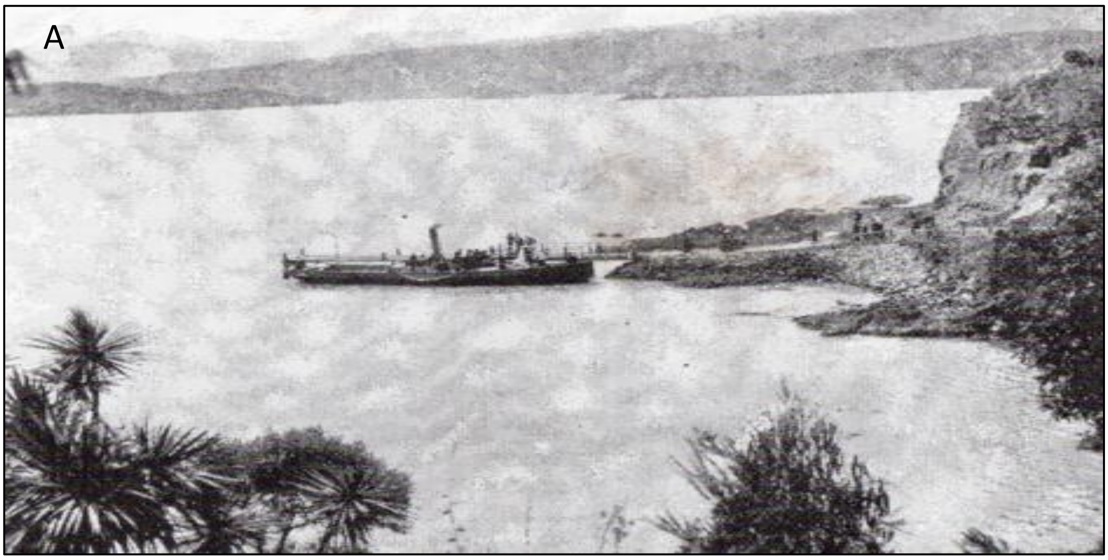
Southern Alps and was subsequently deposited aerially on Banks Peninsula (Soons, 1968). It consists of predominantly silt and sand sediment classes that are deposited throughout the intertidal zone (Curtis, 1985). Curtis (1985) also hypothesised that a significant amount of fine material can enter the harbour from offshore and settles out of suspension in these calm environments. Quantification of this phenomenon has been difficult to this point in time.

Banks Peninsula is exposed to the south to north Southland Current (Soons, Moar, Shulmeister, Wilson, & Carter, 2002) which travels up the east coast of the South Island, and exposure to this current is greater in Akaroa Harbour than Lyttelton Harbour. The wave climate of Akaroa Harbour is moderated by its shape, depth and length. The Akaroa Harbour headland are exposed to the full force of Southerly storm waves and swells that can penetrate at least a third of the way up the harbour (Fenwick, 2004). The inner half of the Akaroa Harbour is more sheltered because its orientation changes some 5 km inland (Fenwick, 2004). Tidal currents are considered the dominant hydrodynamic force in Lyttelton Harbour and wind waves and swells have unlimited fetch to the north east (Curtis, 1985). Curtis (1985) proposed that the interaction between tidal currents and topography led to a large clockwise gyre in the central to lower Lyttelton Harbour on the flood tide, and a counter clockwise gyre on the ebb tide.

The current state of bathymetric knowledge in Lyttelton Harbour has shown a shallowing during the twentieth century and a rate of sediment deposition of around 0.35 cm a^{-1} on average in the mouths of the upper bays over the past 50 years. Shallowing has been observed in the north western upper harbour in the vicinity of Governors Bay and Rapaki Bay (Hart *et al.,* 2008). Head of the Bay has had a dramatic increase in area, with a seaward migration in mudflat width from 700 m in the mid to late 1800s to 2000 m in 2007 (de Vries, 2007). There has also been a reduction in the gradient of the mudflat over time due to sedimentation (de Vries, 2007). Historic photographs of Governors Bay are included in Figure 2.2, showing the harbour and landuse in approximately 1915 with comparative contemporary photographs illustrating landuse and harbour changes. The central axis of Lyttelton Harbour has a maximum depth of 9.5 m below mean sea level (MSL) due to the

Lyttelton Port dredged channel, with an outer harbour gradient of 1:850. Charteris Bay, Head of the Bay and Governors Bay have intertidal slopes of 1:400, 1:1100, 1:650 respectively (Hart *et al.,* 2008).

The bathymetry of Akaroa Harbour is 30 m deep just beyond the headland, and the outer harbour has a slope of 1:600 to 1:800. The upper harbour has a slope of 1:1200, from -6.5 m MSL opposite Robinsons Bay along the central axis (Fenwick, 2004, Hart *et al.,* 2009). Less bathymetric information has historically been known about Akaroa Harbour and hence a baseline study was performed in 2009 by Hart *et al.* to document accurate bathymetric data for future comparison. Similar sedimentation processes as in Lyttelton Harbour would have likely occurred in Akaroa Harbour due to similar historic landuse change (Hart *et al.,* 2009).

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Governor's Bay. Christchurch. F.G.R. 6178.

Figure 2.2: *Historic and contemporary photographs of Governors Bay illustrating landuse and bathymetry changes. Historical photographs are courtesy of Jane Robertson and contemporary photographs are from Google Earth (2012), except Figure 2.2F which is taken from Sissistein (2012). (A) Photograph of Governors Bay pre 1915 with a launch at the short jetty. (B)Photograph of contemporary Governors Bay with the redundant long jetty. (C) Photograph of Lyttelton Harbour with Governors Bay in the fore ground. The entrance to Head of the Bay appears to have an extensive mudflat exposed which no longer exists. (D) Contemporary view of Lyttelton Harbour. Beige seawater demarcates the approximate MLWS mark in Governors Bay. (E) Photograph of Governors Bay in approximately 1912 illustrating a new subdivision and eroding loess visible in the background. (F) Contemporary view of Governors Bay and catchment landuse with Head of the Bay in the background.*

2.4 Earthquake effects

The cause of seismic changes to the mudflats was a magnitude 7.1 earthquake centred under Darfield 40km west of Christchurch occurred on the 4th of September 2010, followed by a significant aftershock of magnitude 6.3 under Lyttelton on the 22nd of February 2011. Many subsequent aftershocks have occurred, with one prior to the study period on the 23rd of December 2011, a 5.8 magnitude just off the coast of New Brighton (GNS, 2012). Figure 2.3 shows a map of the earthquake series. This resulted in the Lyttelton Harbour seabed being uplifted on average by ~ 0.1 m (New Zealand Hydrographic Society, 2012). Many effects of this earthquake series have been observed on the Avon-Heathcote Estuary which suffered extensive liquefaction, ~20-40% of its surface area, and a general tilting of the estuary that has seen subsidence to the northern extent and uplift at its southern extent (Measures *et al.*, 2011).

Earthquakes affect both the morphology and evolution of coastlines by introducing abrupt elevation changes of uplift, or subsidence, slumping or tsunami inundation (Cundy *et al.* 2000). The Napier earthquake of 1931, with a magnitude of 7.8, altered the coastal morphology of the region considerably due to fault movement occurring only 30 km north-west of Napier city, which itself straddles the coast (Komar, 2010). The along-coast land elevation changes at its greatest extent saw uplift of 2 m at Tongoio, 1.8 m in Napier, and 1 m subsidence at Haumoana, Te Awanga and Clifton. Interestingly the earthquake caused abrupt uplift of the Ahuriri lagoon, reducing its area by approximately 12.8 km^2, which has since become the site of the Napier Airport (Komar, 2010). Similarly, the Gulf of Atalanti, Greece endured significant coastal change during an earthquake series in 1894 which was dominated by a 6.2 magnitude event followed by a 6.9 magnitude event (Cundy *et al.* 2000). This earthquake series led to extensive coastal slumping, surface faulting, tsunami inundation and coastal subsidence by as much as 1 m (Cundy *et al.* 2000). Coastal subsidence was caused by the processes of localised slumping, liquefaction and tectonic down warping (Cundy *et al.* 2000). This earthquake was similar in magnitude, coastal proximity and effects to that of the Canterbury earthquake series, although tsunami inundation did not occur in Canterbury.

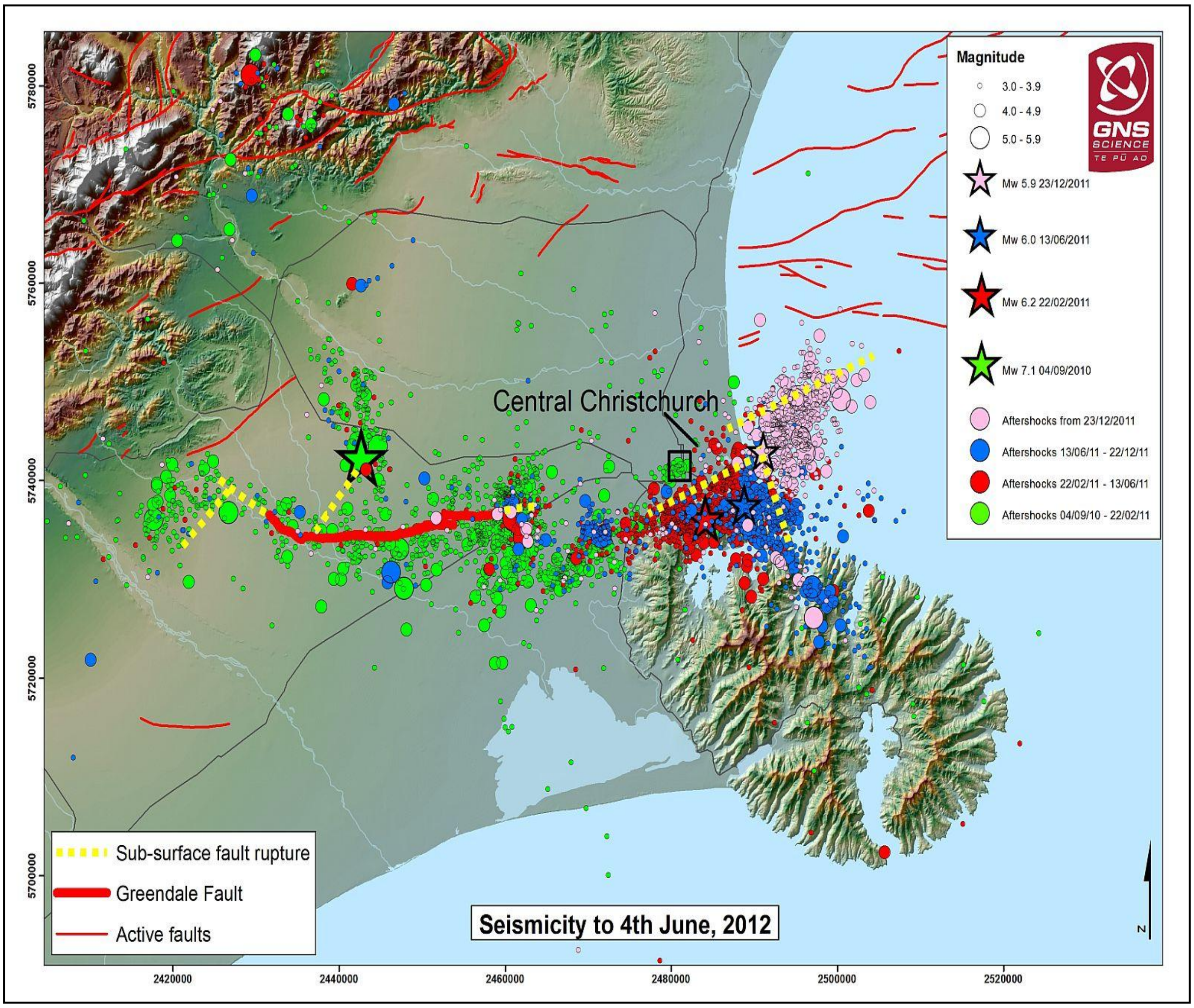


Figure 2.3: *Canterbury earthquake series from the initial Greendale quake on the 4th of September 2011to the 4th of June 2012. (GNS Science, 2012).*

3. Methods

A field and laboratory investigation was undertaken to test the theory proposed by Kirby (2002) that erosional mudflats have a concave profile and accretional mudflats have a convex profile. An examination of mudflat transects, seabed surface sediment texture and sediment density allowed classification of mudflat state, and whether Kirby's (2002) theory is applicable to the selected bays of Banks Peninsula.

The methods used were:

1. Survey and examination of intertidal mudflat transects over a six month study period and comparisons of these transects with previous bathymetric studies.
2. Analysis of seabed surface sediment sample textures, including grain sizes and distributions.
3. Analysis and comparison of sediment density.

3.1 Study area

The study area covers five bays in the two major harbours of Banks Peninsula. Figure 3.1 illustrates the location of the two harbours on Banks Peninsula, and the insets show each Harbour's layout in more detail. Figure 3.2 shows photographs of the specific bays where research was undertaken. Bays were selected based on previous research available.

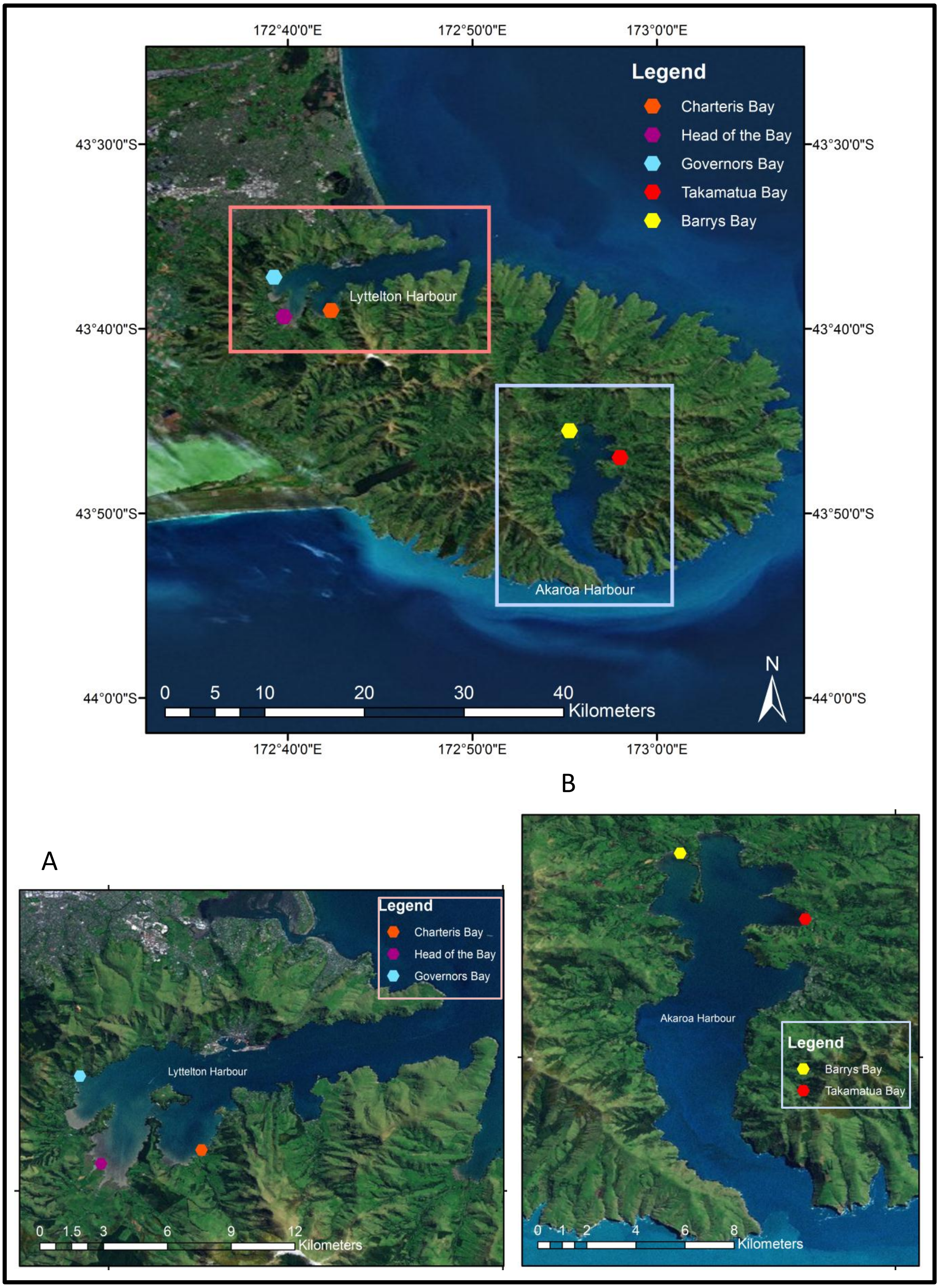


Figure 3.1: *Location map of Banks Peninsula showing the bays where surveying and sampling was undertaken. Inset A illustrates the bay locations in Lyttelton Harbour. Inset B illustrates the bay locations in Akaroa Harbour.*

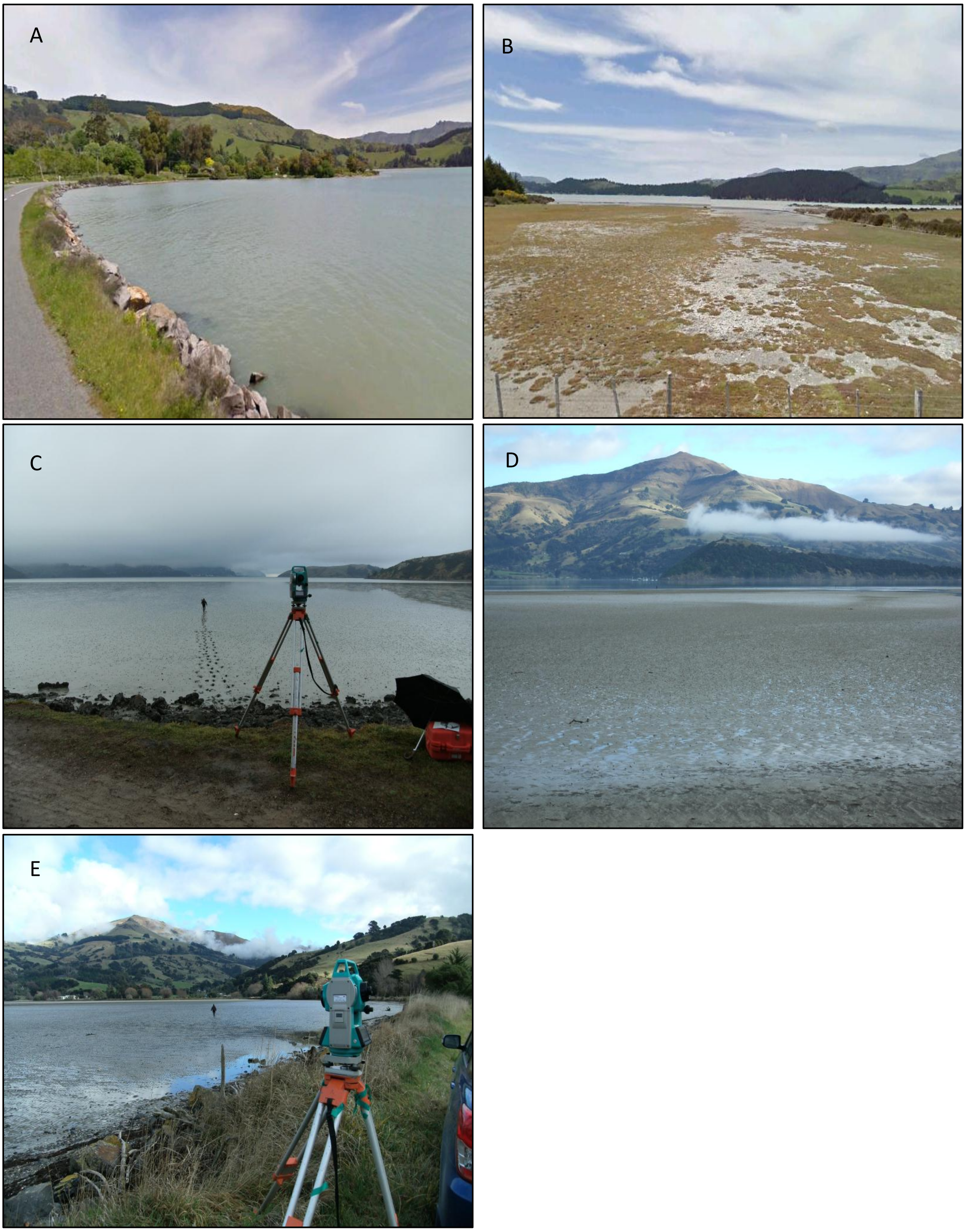


Figure 3.2: *Study site of (A) Charteris Bay, (Google Earth, 2012). (B) Head of the Bay, (Google Earth, 2012). (C) Governors Bay, photograph by Doug Eaves. (D) Takamatua Bay, photograph by Doug Eaves. (E) Barrys Bay, photograph by Doug Eaves.*

3.2 Surveying mudflat transect shapes

A central, shore normal axis was established for the centre of each bay by examining bathymetric studies from LINZ (2011) to determine a transect from the levels of approximately mean high water neap (MHWN) tide to mean low water neap (MLWN) tide producing a representative intertidal transect for comparison. Longitudinal transect survey measurements provided the data to produce a geomorphic shape for each bay, and assess the occurrence of a convex, concave or linear profile. A *Sokkia 50RX Total Station* was used to survey this central axis from existing field benchmarks created by Hastings (2011). Transect height data determined the transect shapes of each bay through the intertidal transect from +1 m above mean sea level (MSL) to -1 m below MSL. These vertical observations were recorded at horizontal intervals of approximately 20 m for Charteris Bay, Takamatua Bay and Barrys Bay, whereas Head of the Bay and Governors Bay used intervals of 50 m due to the longer extent of the topography. Table 3.2 shows the tidal information for Lyttelton Port from which the MSL and tidal range are compared for all surveys. Figure 3.1 shows the *Sokkia 50RX Total Station* in Takamatua Bay.

A *Trimble R8 dual-frequency Global Navigation Satellite System (GNSS) Global Positioning System (GPS)* was used to locate, create and measure benchmarks needed for the survey. To calibrate the change in height of the benchmarks disturbed by seismic activity, benchmark heights recorded by Hastings in 2010-2011 were subtracted from the benchmarks recorded in 2012. The *Trimble R8's* 'Ibase' function was used for 2012 measurements. The timeline shown in Figure 3.2 illustrates the timing of surveys and earthquakes that may have affected the study sites. Benchmarks are presented in New Zealand Map Grid (NZMG) Mount Pleasant 2000 coordinate format as used by Hastings (2011). A similar transect technique has been used by de Vries (2007) to discover sedimentation rates at Head of the Bay and Hart *et al.* (2008 and 2009) during their bathymetric surveys in Lyttelton and Akaroa Harbours.

Table 3.2: *Lyttelton Port tidal levels in relation to chart datum and mean sea level (LINZ, 2012).*

Level	Elevation (m above Chart Datum)	Elevation (m above MSL)
Mean High Water Spring (MHWS)	2.49	1.11
Mean High Water Neap (MHWN)	2.05	0.67
Mean Low Water Neap (MLWN)	0.65	-0.73
Mean Low Water Spring (MLWS)	0.27	-1.11
Mean Sea Level (MSL)	1.38	0
Highest Astronomical Tide (HAT)	2.72	1.34
Lowest Astronomical Tide (LAT)	0.07	-1.31
	Range (m)	**Range (m)**
Spring tide	2.22	2.22
Neap tide	1.4	1.4

Figure 3.3: *Sokkia 50RX Total Station set up in Takamatua Bay. Photograph by Doug Eaves.*

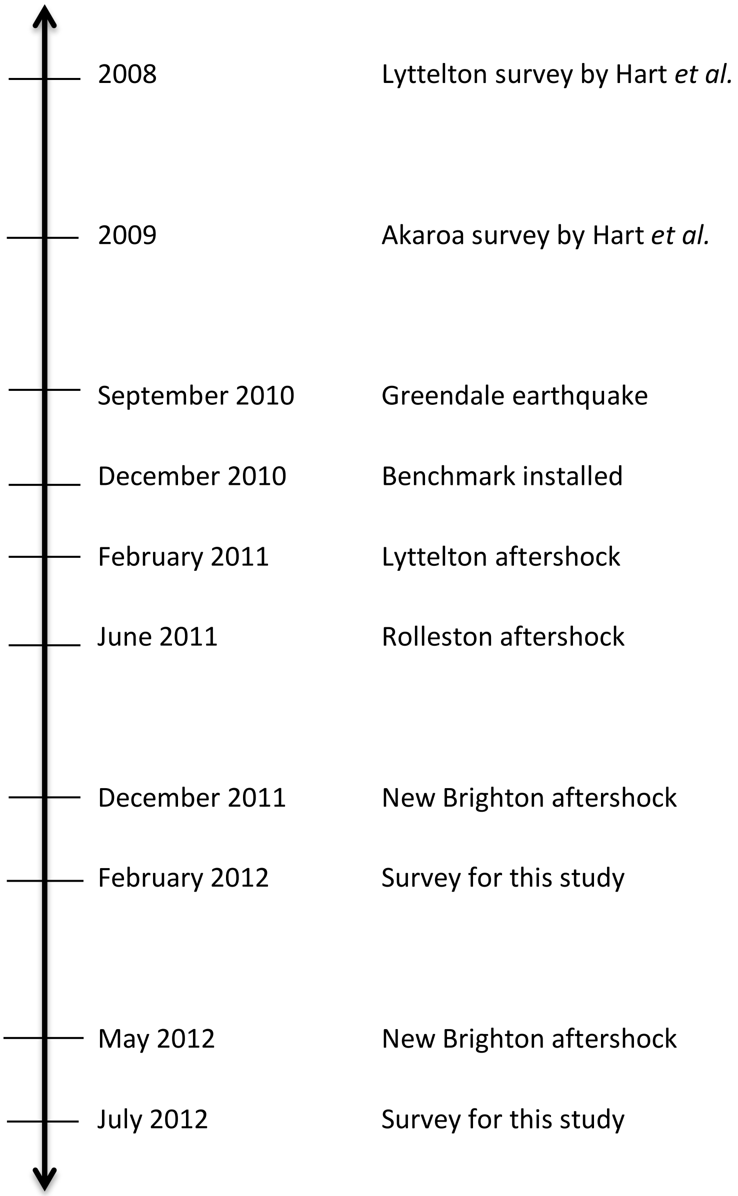


Figure 3.4: *Timeline of survey and earthquake events during the study.*

3.3 Examining mudflat transect shapes

Comparisons were made between the datasets provided courtesy of Hart *et al.* (2008) , Hart *et al.* (2009) and the recorded 2012 dataset. The 2008 Lyttelton dataset was compared with transects taken from Charteris Bay, Head of the Bay and Governors Bay in Lyttelton Harbour. Similarly, the 2009 Akaroa dataset was compared with transects taken from

Takamatua Bay and Barrys Bay. Temporal changes were analysed in Excel to determine the stability of each transect over time and the occurrence of any seismic activity.

3.4 Sediment texture analysis

Seabed surface sediment samples were removed from two transects for the bays selected; one longitudinal profile for each bay, providing information through the intertidal zone, and one perpendicular to the orientation of the bay, providing cross-shore information about the seabed at varying depths. Samples were removed at approximately 200m intervals using containers of either 200 ml or 80 ml. 12 samples were removed from Governors Bay, Takamatua Bay and Barrys Bay. 12 samples were removed from Head of the Bay, and 8 for Charteris Bay. However, only 8 samples were analysed from Head of the Bay and 3 from Charteris Bay due to processing time constraints. See Appendix 1 for sediment texture dataset and Appendices 2-5 for sample location maps.

Samples were analysed for their grain size distribution using sieve and pipette analysis to determine the sediment textural composition. The laboratory methods of analysis conform to those of Lewis and McConchie (1994) and the sediment size classification was that of the USGS (2000). The cone and quartering method reduced the sample size, as described by Schumacher *et al.* (1990) to determine samples of approximately 30 g. Methods of sieve and pipette analysis are similar to those of Hart *et al.* (2008 and 2009) to determine sediment size distribution.

Classification of sediment determined the percentage of sand, coarse silt, medium silt, fine silt and clay in each sample using the Udden-Wentworth phi (Φ) scale, shown in Table 3.3. This made it possible to make comparisons within each bay and between each bay. Wet sieving was conducted on samples at 2.3Φ (sand) and 4Φ (coarse silt) and the residual was examined through pipette analysis to determine the sediment sizes up to 9 Φ (clay). Mud was classified as grains smaller than 4 Φ by Carter and Herzer (1986). Each textural sediment was then classed using the modified Folk (1965) classification of Carter and Herzer (1986) to determine the prevalence of mud, this classification regime is illustrated in Figure 3.5. The grain size distribution was then graphed as a cumulative percentage to show the amount of sediment in each class, the quantity of mud in each sample and the sample variance within each bay.

Sorting, skewness and kurtosis allows inference into mudflat stability due to hydrodynamic forcing and settling velocity. The level of sorting, skewness and kurtosis within each sample was calculated using the criteria outlined by Lewis and McConchie (1994). The total number of different phi sizes in the range between the 16%, and 84% of the cumulative sediment distribution determines the level of sorting. Skewness and Kurtosis were derived statistically. The descriptions for sorting are outlined in Table 3.4, which also defines sorting classes according to Folk and Ward (1957), who derive sorting through a samples standard deviation. This has been added for literature comparison.

The amount of shell in the form of *Austrovenus Stutchburyi*, a bivalve cockle species, in each sample was quantified and subtracted from the samples in order to remove any skewness in the sediment distribution. The presence of this biota also allowed us to better understand the geomorphic state of the mudflat because bivalve organisms are not suited to rapidly eroding environments (Kirby, 2002).

Table 3.3: *the Udden-Wentworth phi scale for sediment size classification.*

Phi	Description	µm
-1	Very Coarse sand	2000
0	Sand	1000
1	Medium sand	500
2	Fine sand	250
3	Very fine sand	125
4	Coarse silt	625
5	Medium silt	313
6	Fine silt	156
7	Very fine silt	78
8	Clay	39
9	Clay	20

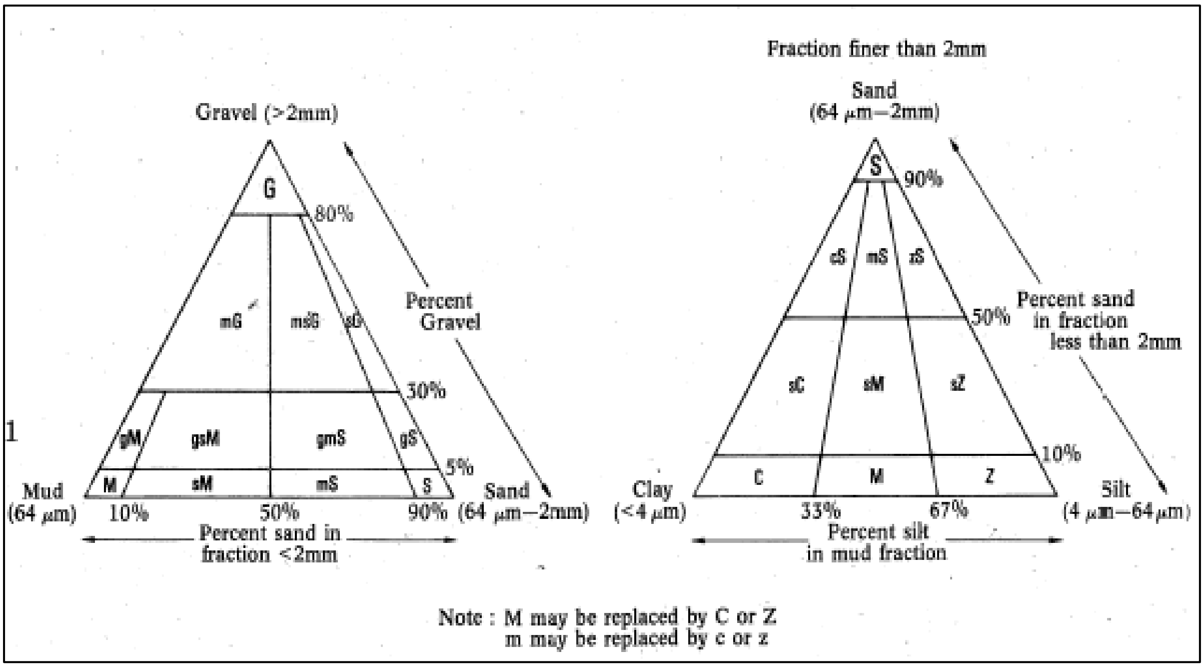


Figure 3.5: *Sediment texture classification used modified from Folk (1965) by Carter and Herzer (1986). Capitals indicate the dominant parameter.*

Table 3.4: *Classification of the sorting mechanism derived by Lewis and McConchie (1994) and Folk and Ward (1957).*

Sorting description	84-16 phi value (Lewis and McConchie, 1994)	Standard deviation, σ (Folk and Ward, 1957)
Very well sorted	0.5	σ < 0.35
Well sorted	1.0	0.35 > σ < 0.5
Moderately sorted	1.0-2.0	0.5 > σ < 1.0
Poorly sorted	2.0-3.0	1.0 > σ < 2.0
Very poorly sorted	>3.0	2.0 > σ < 4.0

3.5 Sediment density analysis

The density of seabed surface sediment samples was investigated to discover a relationship between it, sorting and mudflat stability. Seabed surface sediment samples described above were initially weighed to discover their wet density. Using equation 1, an approach also taken by Balco (2003), density was determined by:

$$\rho = 1000 / \text{Volume (ml)} * \text{Sample (g)} \qquad (1)$$

$$\rho = n\ (\text{kg m}^{-3})$$

These values were then compared with the classification given by Mehta (2002) for fluid mud which has a density ranging from 1,030 kg m^{-3} to 1,300 kg m^{-3}. Samples were then dried for over 72 hours to calculate their dry density and classified according to Dyer *et al.* (2000).

3.6 Statistical analysis

The results of the grain size analysis and density analysis were compared using the statistical software suite SPSS by IBM, and the Microsoft Excel add-on Multibase, to facilitate classifications and relationships. A multivariate statistical test was used to test the hypothesis that each bay is significantly different from one another. It compared seabed surface sediment samples between each bay simultaneously to determine which bays are significantly different from one another based on density, sediment texture and sorting. An IBM SPSS multivariate test (MANOVA) tested the variance between each bay and a post hoc Tukey test was performed where variance was statistically significant to discover the strength and direction of these relationships. Tukey was used as it reduces type 1 errors in hypothesis testing, type 1 errors are where the null hypothesis is rejected when it is true (Fausset, 2009).

Due to the limited number of samples, an analysis of variance (ANOVA) test could not be performed within each bay. Analysis within each bay is, however, shown by graphical representation of the cumulative percentage of each sediment size. Correlation coefficients (r^2) and regression analysis were performed between variables to identify any relationships.

Multibase was used to discover any clustering of particular samples, or any disparity in close proximity samples through cluster analysis. Multibase was also used to perform principle component analysis to determine the weighting of the variables being tested. This has been shown in Appendix 7 and 8.

4. Results

The results have been divided into four sections. The first section gives an overview of the broad patterns of profile shape and surface sediment character for each bay. The second section compares and classifies the survey transects. The third section analyses the results of sediment texture analysis. The fourth section classifies the density of each sample and examines and derives relationships between sediment textures, sorting and density.

4.1 Overview of the profile and surface sediments for each bay

4.1.1 Charteris Bay

Charteris Bay is located on the south side of Lyttelton Harbour and has greater exposure to tidal currents, and its depth increases more rapidly than the other bays assessed in Lyttelton Harbour (Figure 3.1). Charteris Bay has experienced uplift of its benchmark over the period from 2010 to 2012, whereas the mudflat has subsided over the same period. Charteris Bay exhibited a concave profile from 2008 to 2012 (Figure 4.1). The seabed surface sediment samples at Charteris Bay are a mix of coarse silt and sand (Appendix 1). The samples were predominantly poorly sorted (Figure 4.10) and tended to be platykurtic (Figure 4.11). The densities of samples vary from highly-to moderately-dense (Figure 4.12). 70 % or more of its composition was sand and coarse silt, with at least 22% mud (Figure 4.7A). The seabed surface sediment samples show a similar trend in sediment texture distribution with a small variance between samples (Figure 4.7A). However the representativeness of these descriptions for the entire surface of Charteris Bay is limited by the small number of samples.

4.1.2 Head of the Bay

Head of the Bay, as its name suggests, is situated at the head of the Lyttelton Harbour (Figure 3.1). It has a long thin shape and a very gradual gradient, therefore tidal movement is fast. Head of the Bay benchmark movement was less than the surveying margin of error between 2010 to 2012. The mudflat itself appears to have tilted, increasing its gradient over the period from 2008 to 2012. Head of the Bay has maintained a linear profile throughout the assessment period, as shown in Figure 4.2. Head of the Bay seabed surface sediment samples infer a dense substrate (Figure 4.12) of dominant coarse silt. This bay exhibits a seaward coarsening in surface sediment texture, probably due to the presence of increasing shell hash toward the low tide mark. Chenier ridges are present in the lower intertidal zone created from disinterred gastropod and bivalve shells. Samples were moderately to well sorted throughout (Figure 4.10) and display a very leptokurtic distribution (Figure 4.11), with a mud content of at least 16 % (Figure 4.7B). These samples show a similar trend in sediment texture distribution with a small variance between samples (Figure 4.7B). Salt marsh is prevalent toward the landward side of the mudflat.

4.1.3 Governors Bay

Governors Bay is also located at the Head of Lyttelton Harbour, adjacent to the north of Head of the Bay (Figure 3.1). Governors Bay exhibited uplift in its benchmark from 2010 to 2012. The mudflat itself appears to have tilted increasing its gradient over the period from 2008 to 2012. Governors Bay had a convex profile in 2008, but changed to a slightly concave profile after 2010 (Figure 4.3). Seabed surface sediment samples showed poor to very poor sorting throughout this bay (Figure 4.10), with a mesokurtic to very platykurtic sample distributions (Figure 4.11) and density ranging from high to medium (Figure 4.12).The finer sediment classes of fine silt and clay found on the northern flank of the bay represent unconsolidated sticky mud (Appendix 1). There was one sample (GB12) on the south side of the bay with a dominant sediment type of coarse silt, where the substrate was denser and firmer. Density and grain size increased in a cross shore direction within the bay from a northern to southern direction (Appendix 1). Excluding the outlier of GB12, the mudflat comprised at least 60 % mud in samples (Figure 4.7C), and displayed a variety of sediment texture distributions, with variance between samples.

4.1.4 Takamatua Bay

Takamatua Bay is located on the eastern side of the main axis of Akaroa Harbour (Figure 3.1). Adjacent to the mudflat are houses and a significant hill stream catchment. The benchmark has remained relatively unchanged throughout the 2010 to 2012 period (Figure 4.4). The transect changed very little throughout the period from 2009 to 2012, remaining in a state of concavity. The seabed surface sediment samples were comprised of mainly coarse silt and sand (Appendix 1). The majority of the substrate had high density sediments with pockets of low density sediments (Figure 4.12). Samples were predominantly well to moderately sorted (Figure 4.10), becoming less sorted, and coarser in a seaward direction, from coarse silt to sand, with an increase in shell hash toward the low tide mark. The mudflat comprised at least 65 % sand and coarse silt with at least 8 % mud (Figure 4.7D). The seabed surface sediment samples showed a similar trend in sediment texture distribution between each other with a low standard deviation between samples (Figure 4.7D). The sediment distribution varied from very leptokurtic at higher intertidal levels to very platykurtic at lower intertidal levels.

4.1.5 Barrys Bay

Barrys Bay is located at the head of Akaroa, adjacent to Onawe promontory (Figure 3.1). The benchmark remained relatively unchanged throughout the period from 2010 to 2012. However, transects changed from a concave shape in 2009, to concave on the upper mudflat and convex on the lower mudflat in 2012 (Figure 4.5). There was an abundance of the *Zostera* species of sea grass throughout the soft and sticky mud of this transect, biomass fluctuations have created the micro scale perturbations shown in the July transect (Figure 4.5). The density of the seabed surface sediment samples was significantly lower on the upper flat than the lower flat, with a range from high to low density throughout this mudflat

(Figure 4.12). Samples ranged from well sorted to poorly sorted (Figure 4.10) and kurtosis ranged from very platykurtic in the upper intertidal zone to very leptokurtic in the lower intertidal zone (Figure 4.11). Firm substrates showed a dominance of either coarse silt or sand whereas soft substrates contained poorly sorted sediment classes or an abundance of fine silt (Appendix 1). Samples from the upper intertidal western flank of the bay exhibited low density and poorly sorted mud, with samples 6 and 7 containing black anoxic mud. The eastern flank consisted of moderately sorted coarse silt, with a higher density. At least 32% of the mudflat consists of sand and coarse silt and at least 17% mud (Figure 4.7E). Samples showed a variety of trends in sediment texture distribution with a high standard deviation between samples (Figure 4.7E).

4.2 *Survey results for bay transects*

Survey results for the bay transects are divided into mudflat changes that were recorded by the *Sokkia 50RX Total Station* and benchmark movement recorded by the *Trimble R8 dual frequency GNSS GPS.* Continual changes in benchmark and topography from seismic activity reduced precision throughout the survey period, so error bars were added to all affected transects in Lyttelton Harbour. The margin of error applied to the transects was; 30mm of epoch movement (natural annular variation) and 70mm of Trimble vertical error, totalling an error of 100mm. Error bars were not added to transects in Akaroa Harbour due to reduced seismic movement.

The 2008 and 2009 surveys performed by Hart *et al.* were undertaken using different benchmarks from those used in this study. However, changes can be estimated in mudflat shape throughout the period when results are compared using mean sea level as a vertical benchmark proxy. Thus all transect measurements are relative to mean sea level. Associated change in response to the Greendale fault movement on the 4th of September 2010 could not be estimated against the benchmarks in this study as they were installed after the event (Figure 3.2).

4.2.1 The transects

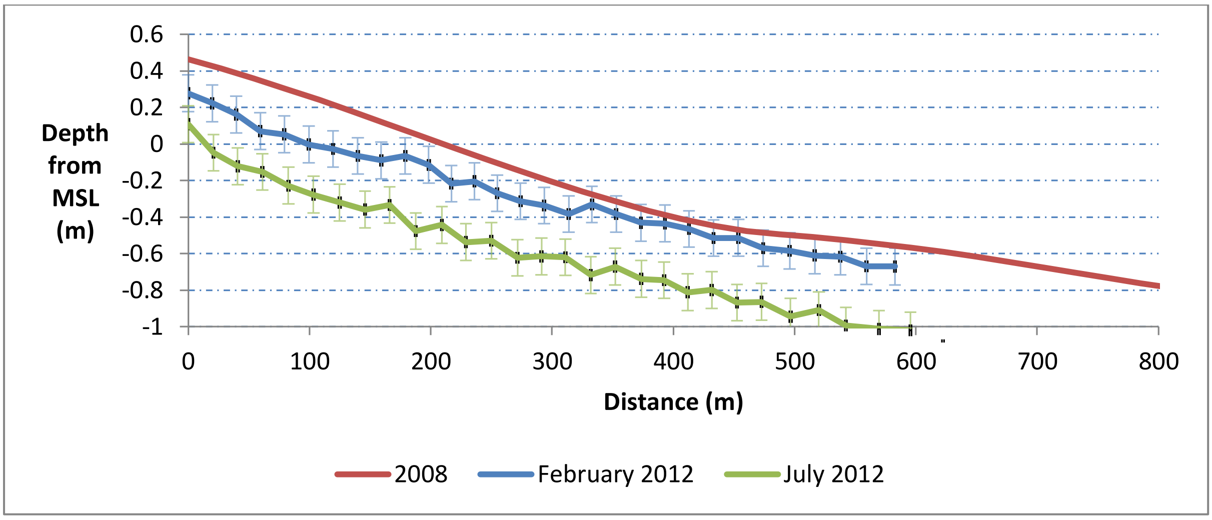


Figure 4.1: *Change in the Charteris Bay survey transects over the period 2008-2012.*

Charteris Bay exhibited uplift of the benchmark over the period from 2010 to 2012, whereas the mudflat has subsided over this period. Charteris Bay has exhibited a concave profile from 2008 to 2012 when analysing the three profiles (Figure 4.1).

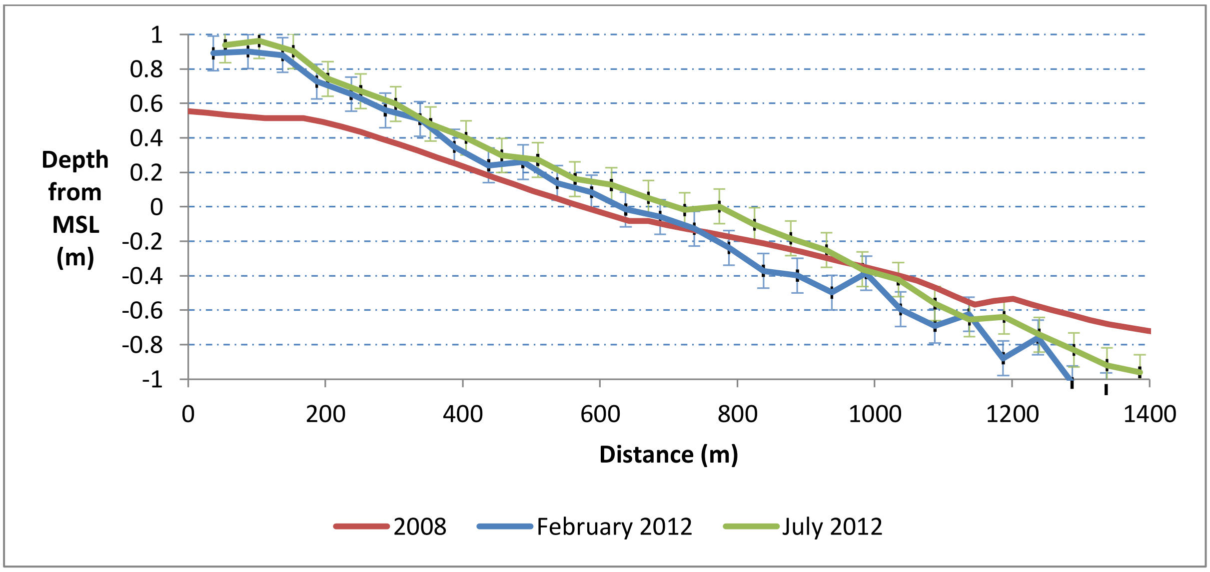


Figure 4.2: *Change in the Head of the Bay survey transects over the period 2008-2012.*

Head of the Bay exhibited no significant change in the benchmark from 2010 to 2012, with total movement falling below the error threshold. The mudflat itself appears to have been uplifted and tilted, increasing its gradient over the period from 2008 to 2012. Head of the Bay has maintained a linear profile throughout the assessment period (Figure 4.2).

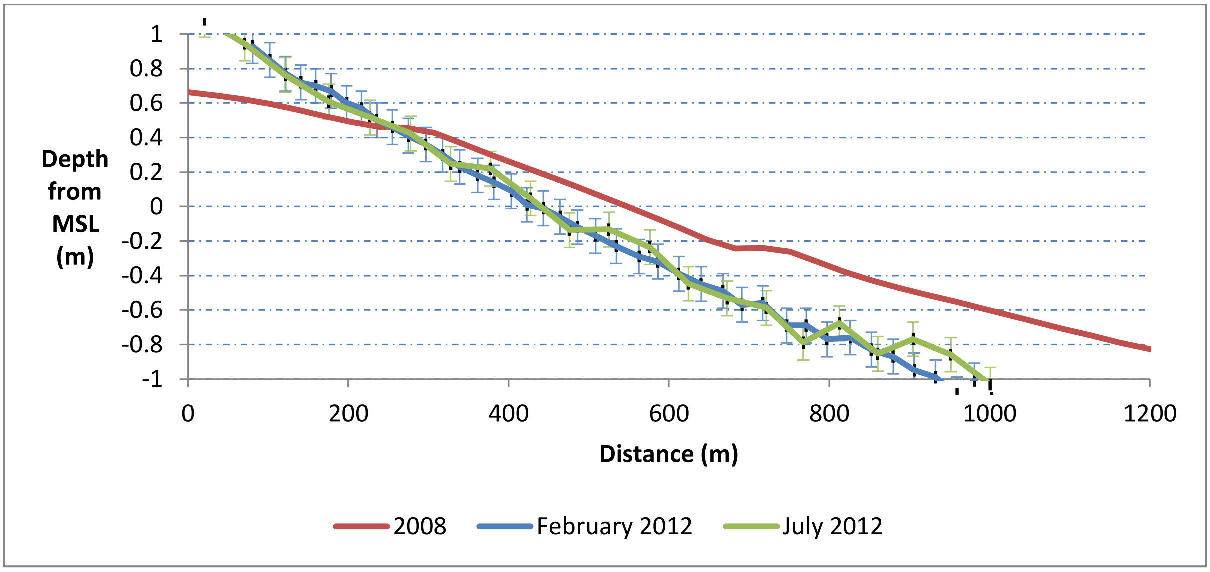


Figure 4.3: *Change in the Governors Bay survey transects over the period 2008-2012.*

Governors Bay exhibited an uplift in the benchmark from 2010 to 2012. The mudflat itself appears to have tilted increasing its gradient over the period from 2008 to 2012. Governors Bay had an accretional profile in 2008, yet has changed to a slightly concave profile in 2012 (Figure 4.3).

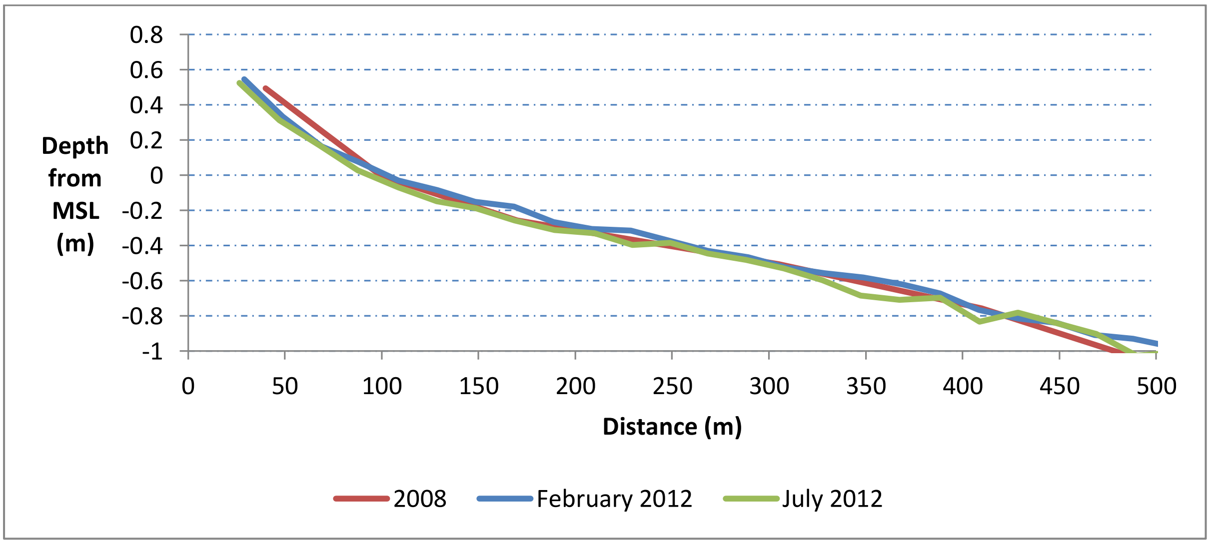


Figure 4.4: *Change in the Takamatua Bay survey transects over the period 2009-2012.*

The benchmark at Takamatua Bay remained relatively unchanged throughout the 2010 to 2012 period (Figure 4.6). The transect has changed very little throughout the period from 2009 to 2012, where it has remained in a state of concavity (Figure 4.4).

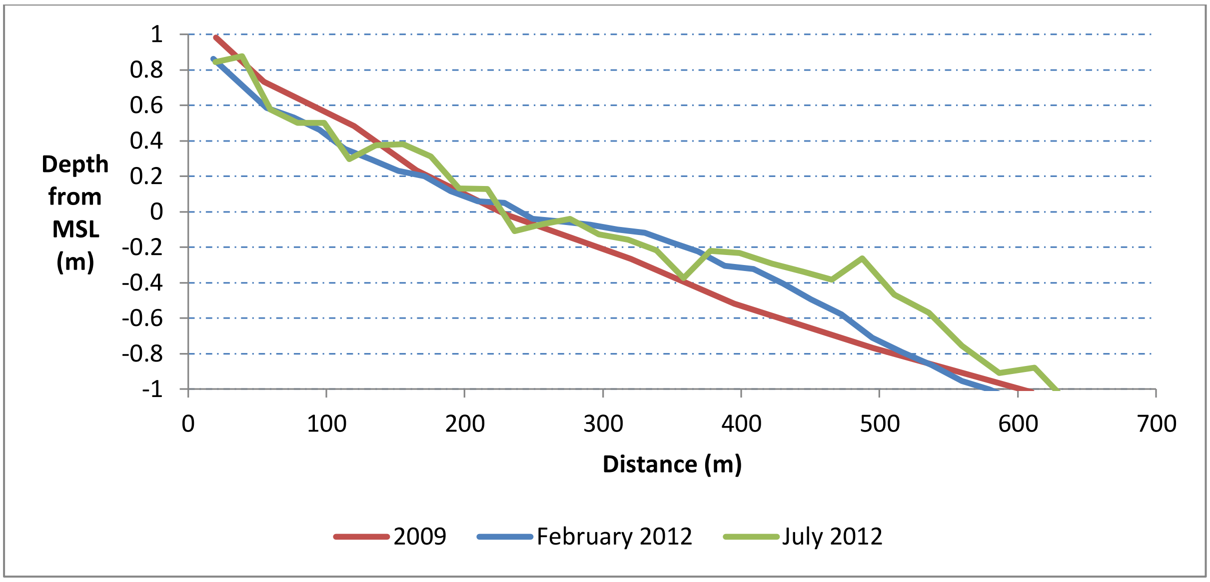


Figure 4.5: *Change in the Barrys Bay survey transects over the period 2009-2012.*

The Barrys Bay benchmark remained relatively unchanged throughout the period from 2010 to 2012. The transect, however, changed from a concave shape in 2009, to being concave on the upper mudflat and convex on the lower mudflat in 2012 (Figure 4.5). There was an abundance of *Zostera* sea grass throughout the soft and sticky mud of this transect, biomass fluctuations may have created the microscale hummocks shown in the July transect.

4.2.2 Benchmark movement

The change in height of each benchmark was recorded during transect measurement and then compared with the original measurements recorded by Hastings (2010). Figure 4.6 shows the movement recorded due to the Canterbury earthquake series in Lyttelton Harbour between December 2010 and July 2012. Governors Bay benchmark 2 (GB2) migrated the most over the period with 161 mm of uplift, and 102 mm of uplift at GB4. The benchmark at Charteris Bay (CH2) uplifted 129 mm. Head of the Bay (HOB1), Barrys Bay (B1) and Takamatua Bay (T1) had insignificant movement. CH2, GB2, GB4, B1 and T1 are located on consolidated material; HOB1 is located on a levee built on unconsolidated marshland. Little change has occurred in Akaroa Harbour beyond epoch changes.

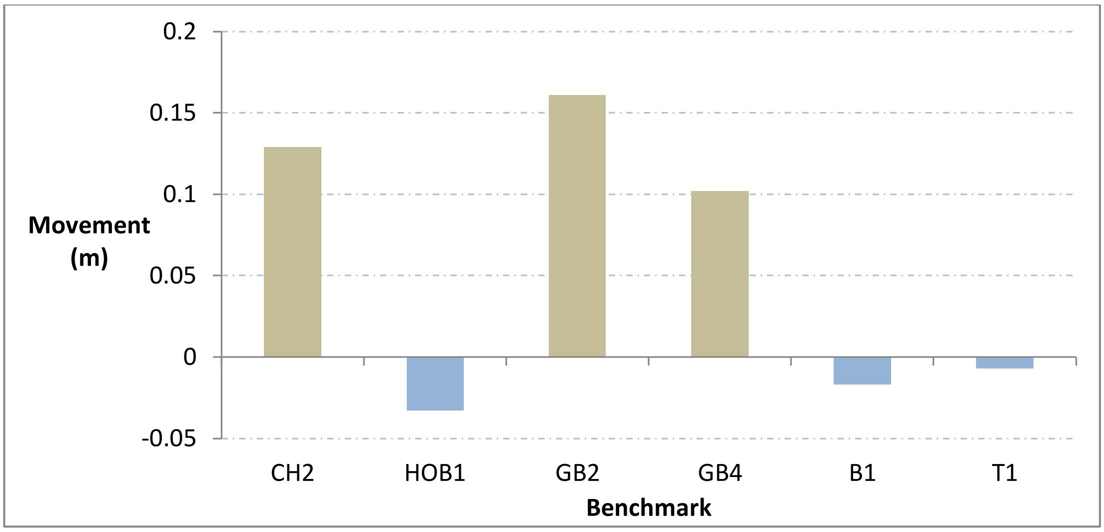


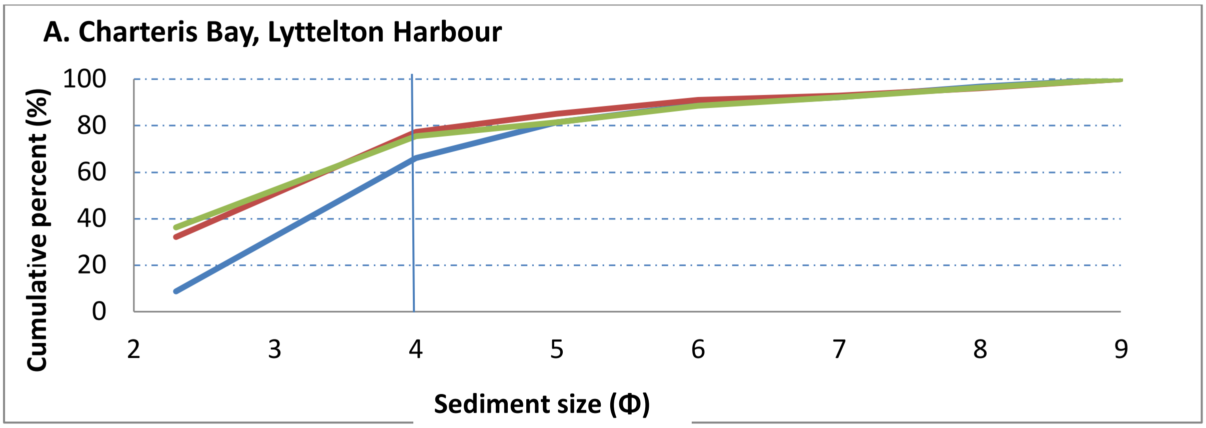
Figure 4.6: *Vertical measured benchmark movement between 2010 and 2012 in Lyttelton Harbour and Akaroa Harbour.*

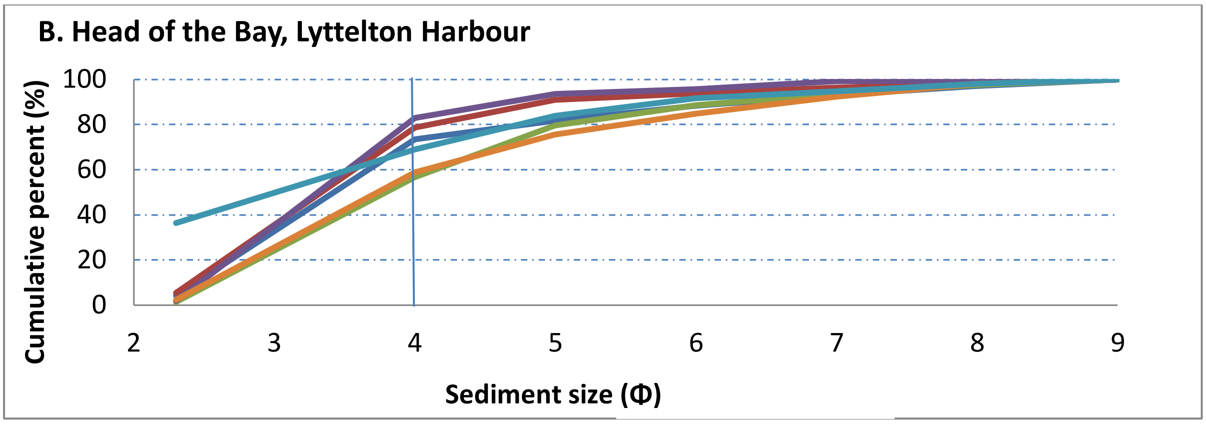
4.3 Results of the sediment texture analysis

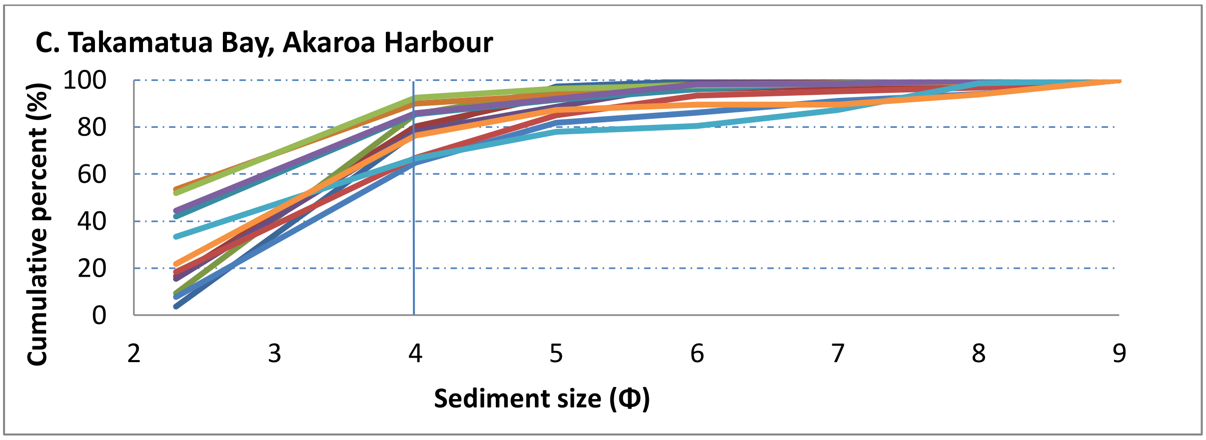
The results of sediment texture analysis have been divided into comparisons within each bay and then between bays.

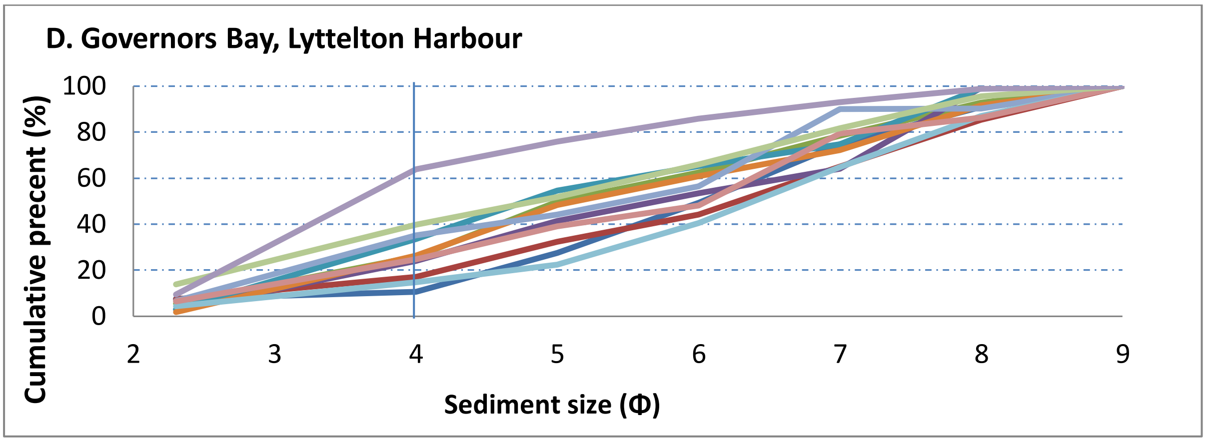
4.3.1 Within bay analysis of variance

Charteris, Head and Takamatua Bay show a relatively homogeneous trend in size distribution between the three, eight and twelve samples analysed respectively (Figure 4.7A, 4.7B and 4.7C). Governors and Barrys Bay samples show a more heterogeneous trend in sediment size distribution between the eleven and twelve samples analysed respectively (Figure 4.7D, 4.7E). Sediment smaller than 4Φ is classified as mud by Folk (1965), shown by the blue line. Charteris Bay, Head of the Bay, Takamatua Bay, Barrys Bay consisted of at least 22%, 16%, 8%, 17% mud respectively, and Governors Bay consists of at least 60% mud when excluding outlier GB12.


A. Charteris Bay, Lyttelton Harbour
Cumulative percent (%)
100
80
60
40
20
0
2
3
4
5
6
7
8
9
Sediment size (Φ)


B. Head of the Bay, Lyttelton Harbour
Cumulative percent (%)
100
80
60
40
20
0
2
3
4
5
6
7
8
9
Sediment size (Φ)


C. Takamatua Bay, Akaroa Harbour
Cumulative percent (%)
100
80
60
40
20
0
2
3
4
5
6
7
8
9
Sediment size (Φ)


D. Governors Bay, Lyttelton Harbour
Cumulative precent (%)
100
80
60
40
20
0
2
3
4
5
6
7
8
9
Sediment size (Φ)

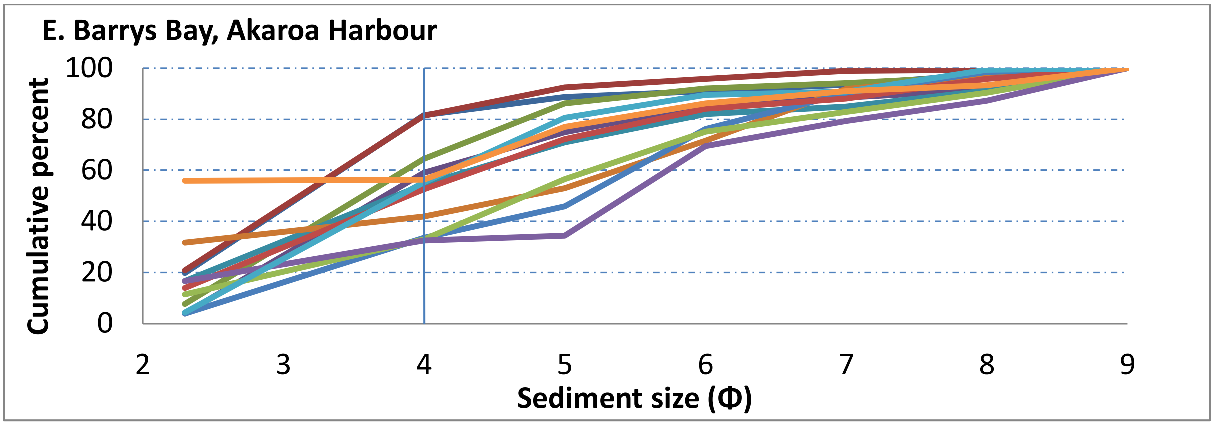


***Figure 4.7:** Cumulative sediment size distribution for Charteris Bay (A), Head of the Bay (B), Takamatua Bay (C), Governors Bay (D), Barrys Bay (E). The 4 Φ boundary represents the cut off for mud size sediments and is represented by the blue line (i.e. 4 Φ and higher).*

4.3.2 Between bays analysis of variance

The main findings from multivariate analysis of variance was that there is a clear distinction between the firm sand and coarse silt substrates of Takamatua Bay and Head of the Bay and the softer fine silt and clay substrates of Barrys and Governors Bay (Table 4.1). A similar pattern emerges with the inter bay comparison of density and sorting; Barrys and Governors Bay are significantly different from Head of the Bay and Takamatua in terms of their densities, and Governors Bay and Barrys Bay are significantly different from Head and Takamatua as well as each other in regards to sediment sorting in the seabed surface sediment samples. The limited number of samples taken from Charteris Bay excluded it from statistical significance in the clay and sorting categories.

Table 4.1: *A MANOVA multivariate test for bay category performed using Tukey equal variances in post hoc test based on logged sediment type, density and sorting. Results show statistically significant differences in the means between bay 1 and bay 2 with respect to the dependent variable being examined.*

Dependent variable	Bay (1)	Mean difference (bay 2)	Significance ($p < 0.05$)
Sand	Takamatua	Governors	0.004
	Takamatua	Head of the Bay	0.004
Coarse silt	Takamatua	Governors	0.037
Medium silt	Nil		
Fine silt	Barrys	Takamatua	0.000
	Governors	Charteris	0.033
	Governors	Head of the Bay	0.004
	Governors	Takamatua	0.000
Clay	Barrys	Takamatua	0.002
	Governors	Head of the Bay	0.004
	Governors	Takamatua	0.000
Density	Barrys	Head of the Bay	0.000
	Barrys	Takamatua	0.014
	Governors	Head of the Bay	0.000
	Governors	Takamatua	0.027
Sorting	Barrys	Governors	0.005
	Barrys	Head of the Bay	0.011
	Barrys	Takamatua	0.007
	Governors	Head of the Bay	0.000
	Governors	Takamatua	0.000

4.3.3 Between bays analysis of mean grain size

Comparing the mean grain size and the standard deviation of each sample shows clustering for each bay by these two moments of measure (Figure 4.8). The standard deviation (σ) can show how well sorted a sample is; the higher σ, the better sorted the sample is. Governors Bay exhibits a tight clustering of mean grain size values of medium to fine silt, with a large range in the standard deviation of the samples. Barrys and Takamatua Bay have a larger range of sediment texture, but a smaller standard deviation (Figure 4.8). Therefore the apparent poor sorting in Governors Bay is due to a high standard deviation from the mean within each sample, whereas poor sorting in Barrys Bay is related to a large range of sediment sizes between samples.

Sorting has also been classified according to Lewis and McConchie (1994) and represented graphically from MHWN to MLWN (Figure 4.10). There appears to be no trend within each bay from MHWN to MLWN with regard to sorting. However, expanses of poorly sorted sediment were located in sheltered aspects of Barrys and Governors Bay illustrating a tendency for deposition to be related to a lack of wind wave forcing.

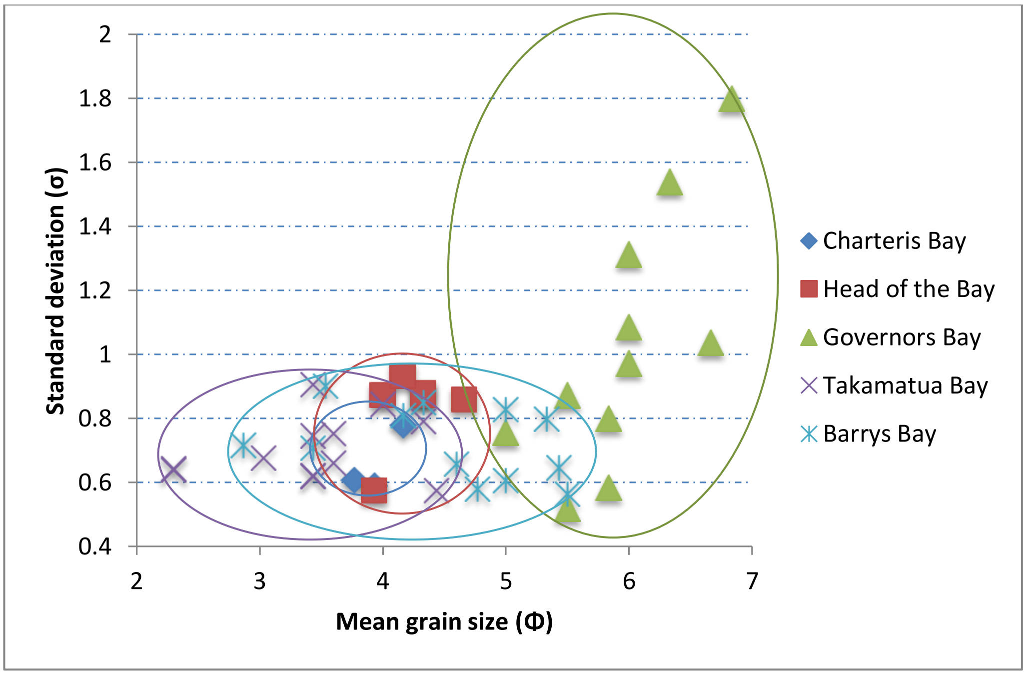


Figure 4.8: *Distribution of seabed surface sediment samples comparing the mean grain size and standard deviation.*

4.3.4 Kurtosis

Figure 4.11 shows the classification of kurtosis for each bay. Takamatua and Head of the Bay both show a trend in kurtosis. Samples nearer MHWN appear to have a tendency to be leptokurtic, whereas samples nearer MLWN appear to have a tendency toward platykurtosis. Takamatua Bay showed a tendency for samples to be very leptokurtic to leptokurtic at higher tide marks and in sheltered areas of the bay, and platykurtic to very platykurtic in deeper, more exposed regions of the bay. Head of the Bay showed a majority of very leptokurtic samples, with a platykurtic distribution near MLWN.

4.4 Analysis of density

Analysis of density was divided into a density classification and also its relationship with the sorting mechanism by way of correlation and regression analysis.

Figure 4.12 illustrates the density classification for each bay, based on seabed surface sediment samples. Each seabed surface sediment sample has been classified according to Dyer *et al.* (2000) into three categories of high, medium and low density. Samples were predominantly of high density except for regions of Barrys Bay and Governors Bay which were of medium density. One sample had a low density (B10), located in Barrys Bay. There appears to be no trend within each bay across the different tidal levels with regard to density.

In order to determine if there is a relationship between density and sorting, correlation and regression analysis were undertaken on these two variables. The standard deviation of a sample was used to measure the sorting variable, where a low standard deviation reflects a well sorted sample. Density and sorting had a weak positive correlation of 0.591 ($p < 0.01$). Therefore samples that are well sorted have a higher density than those that are poorly sorted. The results of the regression analysis between density and sorting also confirm this weak positive relationship, with $R^2 = 0.35$ (Figure 4.9). Therefore there is a strong positive trend in slope, although the low R^2 value illustrates a large scattering of samples.

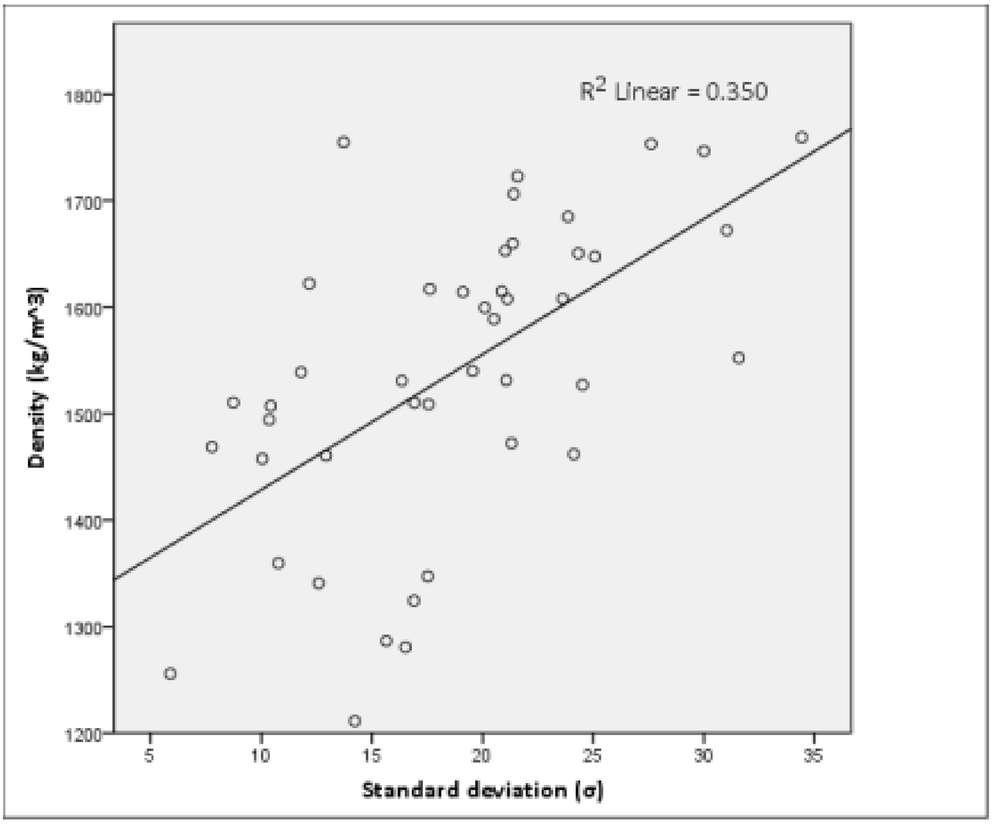


Figure 4.9: *Scatterplot showing a regression between density in kg m^3, and standard deviation, σ. (R^2 = 0.35, y = 11.25x + 1350).*

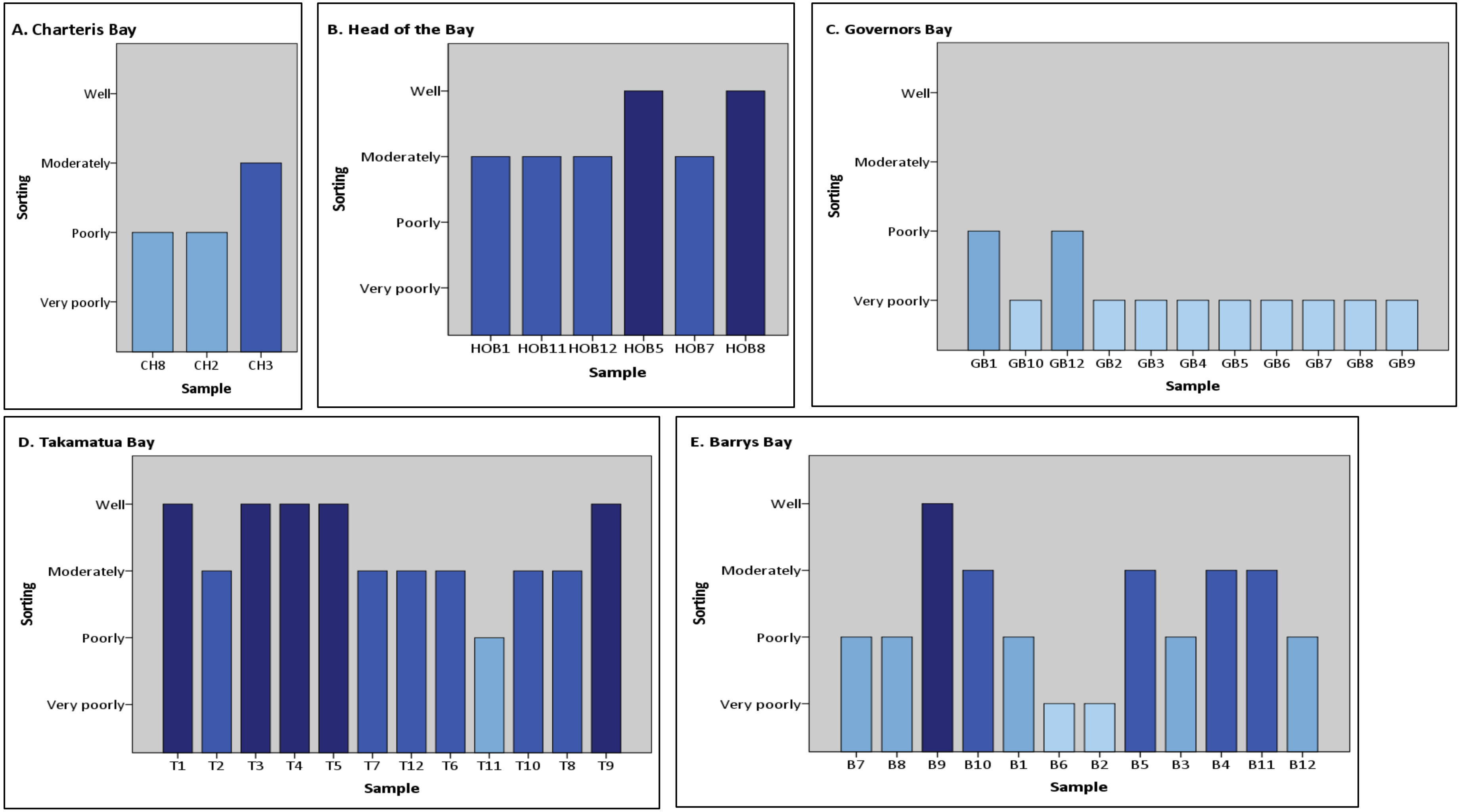


Figure 4.10: *Sorting values for samples illustrated by bay from MHWN on the left to MLWN on the right. Classification was according to Lewis and McConchie (1994). Blue shading represents the level of sorting; darker shades illustrate a tendency towards being a well sorted sample.*

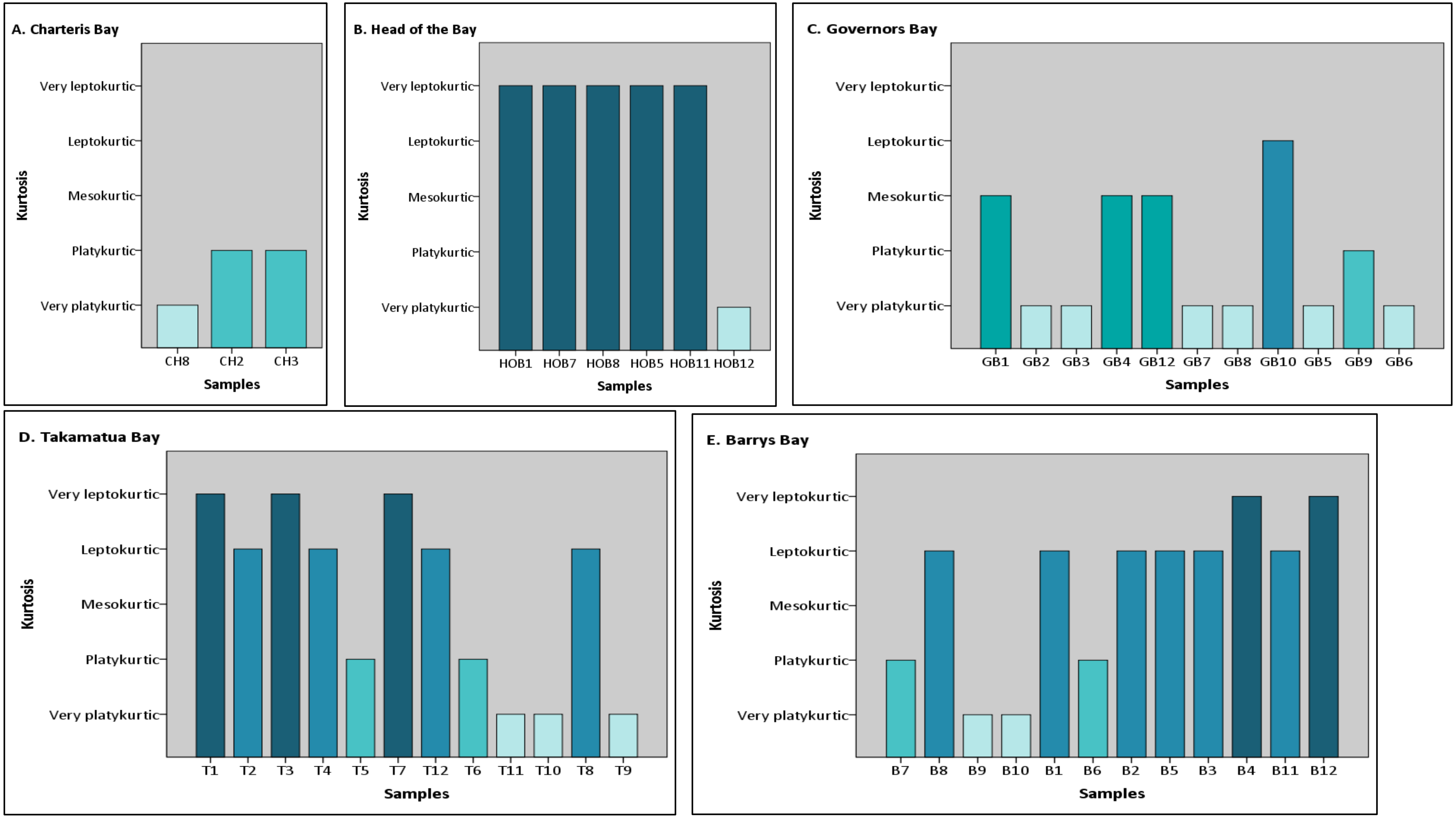


Figure 4.11: *Kurtosis values for samples illustrated by bay from MHWN on the left to MLWN on the right. Classification was according to Lewis and McConchie (1994). Marine shading represents the level of kurtosis; darker shades illustrate a tendency towards a leptokurtic sample whereas lighter shades are more platykurtic.*

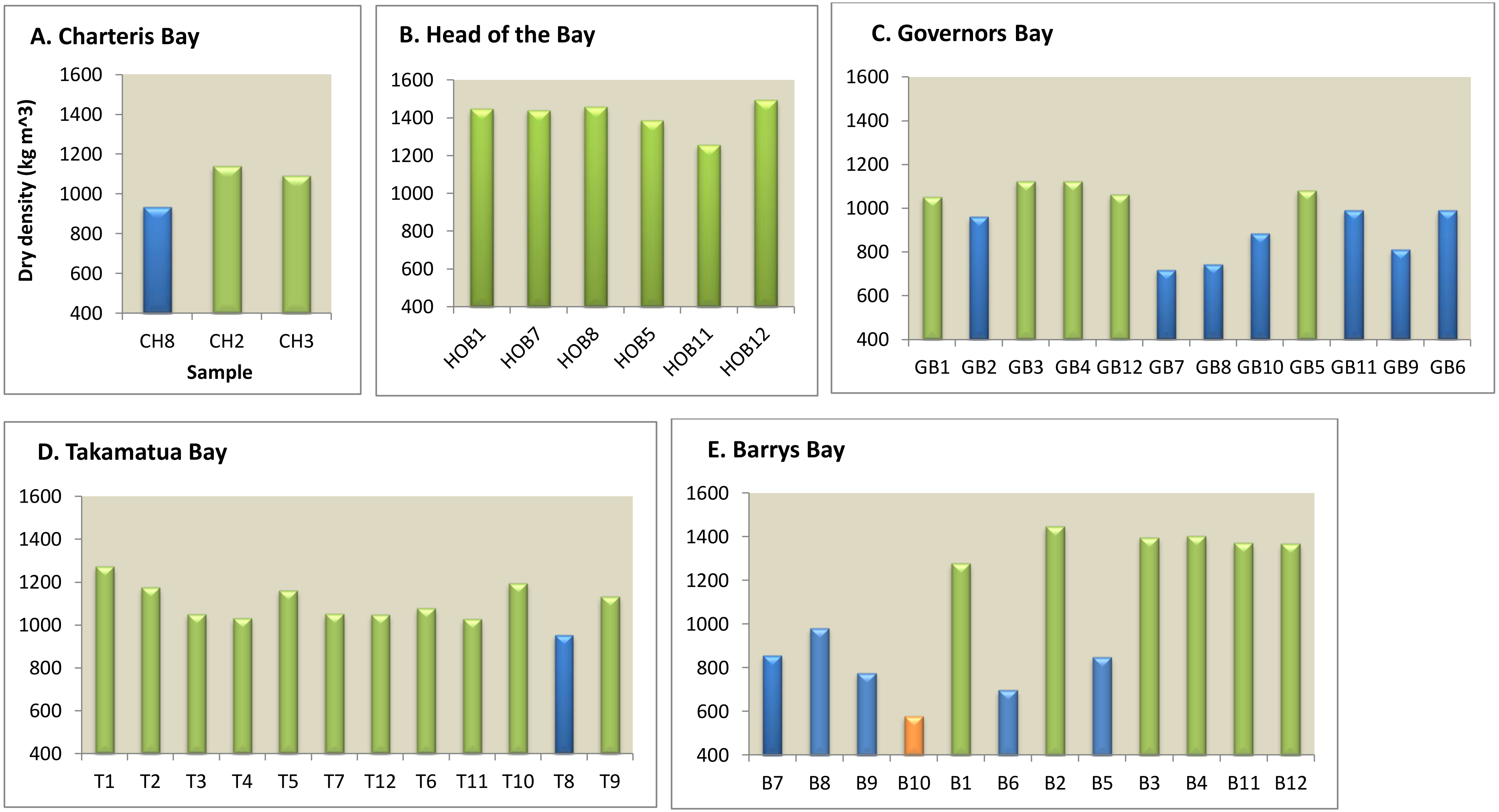


Figure 4.12: *Dry density values for samples illustrated by bay from MHWN on the left of the x axis to MLWN on the right of the x axis. Classification was according to Dyer et al. (2000). Green bars represent high density ($\rho > 1000$ kg m^{-3}), blue bars represent medium density ($1000 > \rho > 600$ kg m^{-3}), and orange bars represent low density ($\rho < 600$ kg m^{-3}).*

5 Discussion

The results are initially discussed in a setting for each bay and then the bays have been discussed altogether. This is followed by a discussion of; the relationship between sorting and density, comparison with the wider mudflat research, anthropogenic impacts on mudflats, and finally, limitations of the study.

5.1 Charteris Bay

Charteris Bay exhibits a concave profile throughout the period from 2008 to 2012 when analysing transects taken. When we consider the theory proposed by Kirby (2002) this would be interpreted as an erosional state. If the classification of erosional is correct, this might have occurred for three reasons. First, this bay is limited in retreat by being backed by road infrastructure and houses, which lead to scouring from hydrodynamic forcing that would create this profile shape. Second, the meso tidal range associated with Banks Peninsula will cause a tendency for this type of profile shape to develop according to Kirby (2002). Third, tidal currents proposed by Curtis (1985) in Lyttelton Harbour create a clockwise gyre which may scour between Quail Island and Charteris Bay on the incoming tide.

The Charteris Bay benchmark is located adjacent to the road on a consolidated rock revetment which can exacerbate erosion (Masselink *et al.* 2011), and is backed by undulating topography. Benchmark uplift due to seismic events from 2010 to 2012 is consistent in magnitude and direction with LINZ (2012) changes at Lyttelton Port. The mudflat itself has subsided over the period from the repeated disturbance, which was also shown to occur in the study of earthquake deposits by Cundy *et al.* (2000).

Recent (2011-2012) seabed surface sediment samples were poorly sorted and platykurtic with a medium to high density of coarse silt and sand. These findings are similar to those of Hart *et al.* (2008). The prevalence of a nearby catchment and active hydrodynamic forcing could explain this sediment grain size mixing with varying density.

Charteris Bay will continue to exhibit an erosional profile because of the current hydrodynamic regime, particularly because tidal forcing manages to outweigh any deposition that may occur. However, this mudflat may aggrade slightly near the high tide mark and in sheltered areas of the bay that are not backed by the revetment. This would be due to the uplift that has occurred, and the abundant sediment supply from its main catchment which is driven onshore by harbour currents as described by Curtis (1985). Sample CH8 shows this recently deposited sediment.

5.2 Head of the Bay

Head of the Bay has a linear profile when analysing transects throughout the period from 2008 to 2012. Applying the classification by Kirby (2002), this is a mudflat in a stable state. However, geomorphology suggests that this bay is in an erosional state due to the presence of a retreating salt marsh cliff and Chenier shell banks, which are traits of an erosion dominated regime (Kirby, 2002). Kirby (2002) describes accreting mudshores as having a conformable junction, or little change in slope between the mudflat and saltmarsh whereas eroding mudshores exhibit a disconformity, or cliff. De Vries (2007) found that the upper intertidal area was relatively stable, with sedimentation rates higher in the lower intertidal zone than the upper inter tidal zone. Although de Vries' profile proved to be concave upward which he describes as dominated by erosional processes, the gradient was decreasing and the mudflat migrating seaward (de Vries, 2007). Hart *et al.* (2008) discovered that the mouth of Head of the Bay has been accreting by 0.35 cm yr^{-1} over the past 50 years. Thus it appears that minimal erosion is occurring within the upper intertidal zone and deposition is occurring in the lower intertidal zone.

The benchmark movement at Head of the Bay is within the margin of error so is therefore inconclusive. The mudflat has tilted increasing its gradient over the period from 2008 to 2012. The tilting of the mudflat however can be explained by uplift in the upper intertidal zone and slumping in the inherently unstable lower intertidal zone, where instability regularly occurs due to the increased hydrodynamic forcing (Mehta, 2002).

The seabed surface sediment analysis shows moderately to well sorted, leptokurtic, dense samples consisting primarily of coarse silt. Thus deposition has not occurred recently and hydrodynamic forcing has been able to rework sediments. Similarly to de Vries (2007), this study found that sandier sediments and shell hash dominated the dynamic lower intertidal zone. De Vries (2007) describes this lower intertidal zone as having decreased stability compared to the rest of mudflat.

Previous research provides evidence of erosion and accretion of the lower intertidal zone. Sediment analysis and geomorphology portray an erosional environment, although current profiles appear stable. We can therefore not assume that this is a stable environment based on profile shape described by Kirby (2002). Once seismic perturbations have been accommodated by hydrodynamic forcing further examination of geomorphology and profile shape is recommended in order to discover the state of Head of the Bay.

5.3 Governors Bay

Governors Bay was observed to have an accretional (convex) profile in 2008 according to Kirby’s (2002) classification. However it has migrated to a slightly erosional (concave) profile during the 2012 survey observations. This change in profile shape could be attributed to the uplift of the shoreline evident by the increase in benchmark height. This explains the tilting of the mudflat which was observed over the 2008 to 2012 period as the gradient increases with uplift. Slumping caused through seismic activity would explain this shift in profile shape from convex to concave due to the unconsolidated nature of mudflats. Similarly, NIWA (2011) discovered that the Avon-Heathcote Estuary has risen by 0.14 m on average relative to MSL yet the northern end of the estuary has subsided by 0.2 m to 0.5 m and the southern end has risen by 0.3 m to 0.5 m.

The sediment texture and density analysis of seabed surface sediment samples exhibited that of a depositional environment over the majority of the mudflat. Masselink *et al.* (2011) and Holland *et al.* (2008) describe poorly sorted sediment as being rapidly or recently deposited. Poor sorting is evident throughout Governors Bay, with a mesokurtic to platykurtic distribution that decreases in density toward the low tide mark. The mudflat comprises at least 60% mud and these finer sediment classes of fine silt and clay exist over the northern half of the bay. These findings are similar to those of Hart *et al.* (2008).

This deposition occurs due to the ebb tidal current being insufficient to erode and transport sediment offshore, as higher velocities are required to erode than to deposit sediment (Curtis, 1985, Holland *et al.* 2008). Curtis (1985) discovered that due to this effect that sediment moved less distance seaward on the ebb tide than sediment moves landward on the flood tide for the mudflats of Lyttelton Harbour. Suspended sediment will also preferentially settle into unconsolidated sticky mud in these calmer environments such as the northern half of Governors Bay where protection from wind waves is offered by Cashin Quay.

An investigation is needed in order to quantify the effect of resuspended sediment from shipping channel dredging and ship propeller wake, because finer material such as clays can remain suspended for long periods to be transported to the upper harbour. Catchment erosion near landuse changes such as new subdivisions and deforestation have been described as possible causes of harbour sedimentation by Hart *et al.* (2008). Quantification of these variables should also be undertaken to determine their significance.

5.4 Takamatua Bay

Takamatua Bay exhibits a concave profile throughout the period from 2009 to 2012 when analysing transects taken. Considering the theory proposed by Kirby (2002) this would be interpreted as an erosional state. The transect shapes conform very well to the proposed mudflat profile by Kirby (2002) for a meso tidal scale mudflat illustrated in Figure 2.1. The earthquake series has had little effect on this mudflat and its benchmark due to the greater distance between epicenters and Takamatua Bay.

The seabed surface sediment samples were comprised of mainly coarse silt and sand, which are moderately to well sorted with a predominantly high density. Tidal forcing is evident on this mudflat because samples become less sorted in a seaward direction and also becoming coarser in a seaward direction from coarse silt to sand. There is also an increase in shell hash toward the low tide mark. The sediment distribution varies from very leptokurtic at higher intertidal levels to very platykurtic at lower intertidal levels. Masselink *et al.* (2011) and Holland *et al.* (2008) describe well sorted sediment as being frequently reworked by hydrodynamic forcing with larger grain sizes, which is also evident by the composition of the mudflat being at least 65% sand and coarse silt. Bolton-Ritchie (2005) also found a large proportion of sand sediment in this bay. This abundance of larger grain sizes explains the steeper gradient of Takamatua Bay, because a higher angle of internal friction of the stacked grains leads to a steeper gradient (Masselink *et al.,* 2011). Bolton-Ritchie (2005), however, explains that this predominance of sandy sediments is due to a higher exposure to wind generated waves and, thus, the higher energy levels characteristic of this bay.

Geomorphology of this bay yields conflicting results to this being an actively eroding mudflat. Firstly, there is a high abundance of the bivalve species *Austrovenus Stutchburyi* (cockles), which were detected in many samples taken from Takamatua Bay. Bivalves tend to not form habitats in highly erosive environments (Kirby, 2002). However, this mudflat is limited in retreat by housing and shoreline hardening in the form of seawalls. This limitation could explain its sudden increase in concavity in the upper intertidal zone through the inability to retreat with ongoing sea level rise of 1.7 ± 0.4 mm per year in New Zealand (Bell, 2001). Furthermore, there is a significant hill catchment flowing into this mudflat that could provide adequate sediment to meet the demands of the mudflats dynamic equilibrium.

This mudflat satisfies the requirements according to Kirby (2002) of being an erosional profile in a meso tidal setting. Although with the abundance of bivalves and possibly an adequate sediment supply, erosion of this mudflat would be slow.

5.5 Barrys Bay

The Barrys Bay benchmark has remained relatively unchanged throughout the period from 2010 to 2012 due to a greater distance to earthquake epicenters. The transects however have migrated from that of an erosional (concave) shape in 2009, to being erosional (concave) on the upper mudflat and accretional (convex) on the lower mudflat in 2012, when the classification by Kirby (2002) is applied. This is explained by a large mass of deposited mud entering the intertidal zone. The 2012 transects pass through an outwash fan from a significant nearby catchment entering from the north west of Barrys Bay. This gently sloping mudflat has developed due to the low hydrodynamic energy environment provided by its surrounding topography (Hart *et al.*, 2009).

The seabed surface sediment samples are heterogeneous due to the partial cover of this mudflat by deposited mud. Therefore density values are significantly lower on the upper flat than the lower flat, which is a contradiction to the trend of decreasing stability toward low tide proposed by Kirby (2002) and de Vries (2007). Similarly a reverse trend is visible in kurtosis; ranging from very platykurtic in the upper intertidal zone to very leptokurtic in the lower intertidal zone. Firm and dense substrates show a dominance of either coarse silt or sand, whereas soft substrates contain poorly sorted sediment classes or an abundance of fine silts and clays. Firm substrates are evident at lower intertidal levels and on the eastern flank of the mudflat where hydrodynamic forcing is more prevalent. Wind waves and funneled tidal currents scour the eastern flank of this bay as they refract off the seawall that is protecting the road, this scouring process created by a seawall is also explicated by (Han, 2002). The upper intertidal western flank of Barrys Bay is more sheltered than other aspects of the bay (Bolton-Ritchie, 2005) and exhibits low density and poorly sorted mud consisting of more fine silts and clays. Hart *et al.* (2009) and Bolton-Ritchie (2005) also found clay in abundance within this region of the mudflat. These unconsolidated sediments, some of which are anoxic due to nutrient cycling in the photic zone, appear to have accumulated out of the adjacent main catchment, suggesting a highly depositional environment.

There is an abundance of the *Zostera* species of sea grass throughout the soft and sticky mud of this bay which functions to stabilise sediment (Hart *et al.* 2009). Zostera made surveying considerably more difficult to replicate due to the trapping of tidal water by it. Zostera is not new to the area of Barrys Bay, Bolton-Ritchie (2005) found variable quantities throughout Barrys Bay. Bolton-Ritchie (2005) reported higher organic content in Barrys Bay and attributes it to the catchment, the dense Zostera beds, or a combination of these two sources.

The mudflat of Barrys Bay does not appear to simply conform to one single profile type provided by Kirby (2002). There appears to be a slightly erosive environment on the eastern side of this bay, which is flanked by a seawall and is exposed to greater hydrodynamic forcing. An accreting depositional environment is visible on the western side of this bay, where unconsolidated mud is accumulating near a significant catchment in a calmer hydrodynamic environment.

5.6 Between bays analysis

Multivariate analysis show a distinct divide between the accretional bays of Governors and Barrys and the erosional bays of Charteris, Head and Takamatua. Density, sorting, and grain size are the main variables by which this distinction was made between deposition and erosion, followed up by geomorphic observation. Concentrations of fine silts and clays were generally poorly sorted with low density which was present in Governors and Barrys Bay. Takamatua and Head of the Bay had predominantly high density and well sorted seabed surface sediment samples reminiscent of hydrodynamic forcing. These two bays also exhibited a pattern in the kurtosis of samples showing the effect of hydrodynamic forcing which causes samples to shift from leptokurtic to platykurtic through the intertidal range from high tide to low tide respectively. More samples were needed to statistically analyse variance within each bay.

Similarly to the sediment texture analysis of this report Hart *et al.* (2008) found sediment fining toward the upper intertidal zone from sands to fine silts in Lyttelton Harbour and Curtis (1985) and Hart *et al.* (2008) also found concentrations of clay in the upper intertidal zone of Governors Bay. Hart *et al.* (2008) claim that sediment distribution patterns are caused by tidal and wave currents and catchment erosion. Further investigation is needed into incoming tidal forcing which may form a clockwise gyre around Quail Island in Lyttelton Harbour. This could explain erosion of sediments occurring at Charteris Bay which are then deposited in the northern reaches of Governors Bay, or from an environment with a higher tidal flux to a calmer depositional environment.

Within Akaroa Harbour Hart *et al.* (2009) discovered a pattern of increasing grain size with depth from the upper intertidal zone to the center of the harbour due to increasing hydrodynamic energy toward the center of the harbour. Although samples did not extend as far in this study, a pattern emerged of seaward coarsening occurring at Takamatua Bay. Thus the upper reaches of the intertidal zone of Takamatua Bay are not exposed to as higher energy wind waves as the lower intertidal zone due to the refraction that needs to occur around Takamatua Hill.

Classification of profile shape according to the definition provided by Kirby (2002) given the recent seismic activity has made conclusive evidence based on shape alone difficult in Lyttelton Harbour. However, this has provided good insight into how seismic activity affects mudflats. It has been shown that uplift, slumping and subsidence have occurred at spatially varying degrees throughout Lyttelton Harbour. Liquefaction, lateral spread and horizontal displacement may have also occurred but were not documented due to time constraints.

5.7 The density and sorting relationship

A positive correlation between the densities of seabed surface sediment samples and the sorting mechanism was to be expected. Recently deposited sediments have a higher porosity, more water content and particles lack alignment (Allen, 1985) and therefore should have a lower density. Tidal cycles tend to align particles and fill pore spaces whereas wind waves tend to preferentially sort particles according to grain size (Masselink *et al.* 2011). Thus the reason for the weak relationship between density and sorting is that poorly sorted samples can still have a relatively high density due to minimal pore space from effective packing.

It was thought that density could act as a proxy measure for sorting as processing times would be substantially reduced; however, this relationship was too weak to draw this conclusion.

5.8 Mudshore comparisons

The fundamental difference between the embayment mudflats of Banks Peninsula and the majority of mudflats around the world is tidal range. Mudflats suit a macro tidal range because the greater surface area of the mudflat can dissipate hydrodynamic energy across this greater surface area, which in combination with the cohesiveness of muddy sediment, leads to greater deposition and inhibited erosion provided there is an abundant sediment supply (Wang *et al.,* 2002a and Hang, 2002). Although mudflats can occur wherever there is sustained net onshore sediment movement and due to the fluidity of mud it will create a near horizontal plane (Wang *et al.,* 2002a).

Zhejiang and Fujian provinces of China exhibit many coastal embayment mudflats of which some are similar to those of Banks Peninsula, although tidal range in this region can exceed 4 m on average favouring mudflat development through sediment deposition (Wang *et al.,* 2002b). Within Xiamen Bay, Fujian Province, seabed surface sediments were relatively poorly sorted silty sands, clayey sands, sandy clays and clayey silts and the mineral content reflected that this sediment supply comes from a local catchment (Wang *et al.,* 2002b). Thus, Xiamen Bay exhibits an accreting environment similar to that of Barrys Bay.

When classifying the seabed surface sediment samples with the classification of fluid mud which ranges between 1,030 kg m^{-3} to 1,300 kg m^{-3} (Mehta, 2002). Barrys Bay has 4 samples that contain fluid mud and 3 samples in Governors Bay fall below 1,350 kg m^{-3}, or within 4% of this threshold. The Dyer *et al.* (2000) dry density classification used in this report was tested on 18 mudflats of Northern Europe. The findings of this study discovered that within depositional environments density acted as a dependent variable within a bay. However under an erosional regime where there is an over-consolidated bed, the density shifted to that of an independent variable (Dyer *et al.,* 2000). Therefore the dynamic response of mudflats to perturbations can be understood in part by its density characteristic.

5.9 Anthropogenic impacts

Much of the research into mudflat environments has been to assess the impact of human activity on these systems (Curtis, 1985, Han, 2002, Oldman, 2009, Suedel, 2008). Catchment landuse changes, urbanisation and dredging appear to be the main human impacts changing natural sediment processes in Lyttelton and Akaroa Harbour.

Changes in landuse, such as urbanisation and deforestation of the catchment lead to an increase in the sedimentation rate in the Mahurangi Estuary (Oldman et al., 2009). Similar anthropogenic events have been observed in Lyttelton Harbour (Curtis, 1985), and in Akaroa Harbour (Bolton-Ritchie, 2005). Human utilisation of muddy coasts are also increasingly impacting on salt marsh leading to a loss of biodiversity (Han, 2002). This utilisation is due to an increasing need for agricultural land which has seen the conversion of muddy coasts in Malaysia, Philippines, Thailand and China (Han, 2002). Farmland in Head of the Bay has been reclaimed from salt marsh, illustrating agricultural encroachment. With on-going sea level rise, coastal squeeze of the salt marsh will lead to a reduction of this natural environment. Unfortunately salt marsh has been minimised from all other bays assessed in this study due to housing, infrastructure and parkland.

Dredging has been an on-going permitted activity in Lyttelton harbour and dredge spoil recirculation represents the major harbour sediment supply (Curtis, 1985). The effects of dredging activities include increased turbidity, increased suspended sediment concentrations and disturbance of aquatic biota and water fowl (Suedel *et al.,* 2008). The repetitive dredging of Lyttelton Harbour is therefore partially responsible for the sedimentation rates in the upper harbour and more investigation is needed into suspended sediment concentrations associated with dredging.

5.10 Limitations of the study

The main limitations of this study are; a lack of survey control information, a limited number of seabed surface sediment samples, absent analysis of mineralogy of seabed surface samples and the short timeframe of the study period.

Due to the ongoing changes in datum in the Canterbury region caused by the 2010-2012 earthquake sequence, accurate survey control information was limited. NIWA (2011) also encountered this problem while surveying the Avon-Heathcote Estuary where systematic bias may have occurred. Once post-earthquake datum has been corrected by LINZ for the Canterbury region a repeat survey is needed to tune any systematic bias from survey control information. Due to the ongoing earthquake sequence occurring throughout this study period, future surveying of transects is required to expose any changes in the dynamic equilibrium of these mudflats to seismic activity.

More seabed surface sediment samples need to be examined in order to strengthen statistical comparisons, particularly from Charteris Bay. This would make analysis of processes within each bay more accurate. Geographic comparison of sample density has been made difficult by a lack of mineralogy analysis because different geologic structures will have different weights. The main geologic constituents of Banks Peninsula are loess, basalt, trachyte and rhyolite (Ogilvie, 2000). Varying levels of these minerals may be found in the samples examined here.

Despite these limitations sound results have been illustrated throughout this report and will prove useful to future analysis of the mudflats of Banks Peninsula.

6 Conclusion

The primary aim of this research was to discover whether certain muddy environments within Banks Peninsula are in a state of erosion, accretion or stability according to theory proposed by Kirby (2002) through repeated direct measurement and sediment texture analysis of seabed surface sediment samples. It was discovered that Governors Bay and Barrys Bay exhibit traits of a depositional environment, whereas Charteris Bay and Takamatua Bay exhibit traits of an erosional environment. Head of the Bay produced conflicting results and was therefore inconclusive. The theory for profile shape proposed by Kirby (2002) conforms well to the erosional profiles in this meso-tidal setting of Banks Peninsula. However, this rule is overly simplified for accretional environments that were studied on Banks Peninsula.

The secondary aim of this research project was to discover the effects of seismic activity on the muddy environments of Lyttelton and Akaroa Harbours. It was shown that uplift of the shoreline has occurred in Governors and Charteris Bay at specific locations. Tilting of the mudflat has occurred in Head of the Bay and Governors Bay, which can be attributed to uplift of the upper intertidal zone and slumping of the lower intertidal mudflat. Evidence of subsidence has been documented in Charteris Bay.

The tertiary aim was to discover the influences of hydrodynamic forcing. Prolonged exposure to tidal forcing on sediment composition leads to packing and consolidation of the substrate through the infilling of void spaces with the appropriate grain sizes and the alignment of grain size axes. This led to a denser, better sorted, more consolidated substrates evident from the seabed surface sediment samples taken from Takamatua Bay and Head of the Bay. Areas of Governors Bay and Barrys Bay were sheltered from the agitation of wind wave orbital motion and allowed sediment textures with a low settling velocity to fall out of suspension, creating low-density mud deposits that were poorly sorted. Lower bed shear stress on the ebb tide than the flood tide also led to deposition in these areas, as entrainment requires more energy than transport. Profile gradient can be determined by the intensity of hydrodynamic energy which acts to destabilize the environment and align the sediment grain size distribution to the grain's angle of internal friction, leading to steeper stacking and a steeper profile. Other geomorphologies associated with hydrodynamic forcing observed were salt marsh cliff and Chenier ridges in Head of the Bay.

Future surveying will be required once survey control has been re-established. This will provide further insight into the extent of seismic activity on these mudflats and their return to a dynamic equilibrium of accretion, erosion, or stability. A more comprehensive seabed surface sampling regime, including mineralogy, should consolidate the findings of this report and provide clarity to processes acting within the mudflat environment. Investigation into mudflat catchment erosion, marine suspended sediment and harbour currents would complement this research.

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8 Bibliography

Allen, J. (1985). *Principles of physical sedimentology*. London: George Allen and Unwin Ltd.

Balco, G. (2003). Measuring the density of rock, sand, till etc. Retrieved 12/11/2011, from http://depts.washington.edu/cosmolab/chem.html

Bell, R., Hume, T., Hicks, D. . (2001). Impacts on climate change on coastal margins in Canterbury: National Institute of Water and Atmospheric Research.

Bolton-Ritchie, L. (2005). Sediments and macrobiota of the intertidal flats of the inner Akaroa Harbour: Environment Canterbury.

Carter, L., Herzer, R. (1986). Pegasus sediments (2nd ed.). N.Z.: Oceanographic Institute Chart.

Christie, M. C., Dyer, K. R., & Turner, P. (1999). Sediment Flux and Bed Level Measurements from a Macro Tidal Mudflat. *Estuarine, Coastal and Shelf Science, 49*(5), 667-688. doi: 10.1006/ecss.1999.0525

Cundy, A., Kortekaas, S., Dewez, T., Stewart, I., Collins, P., Croudace, I., Maroukian, H., Papanastassiou, D., Gaki-Papanastassiou, P., Pavlopoulos, K., Dawson, A. (2000). Coastal wetlands as recorders of earthquake subsidence in the Aegean: a case study of the 1894 Gulf of Atalanti earthquakes, central Greece. *Marine Geology, 170*, 3-26.

Curtis, R. (1985). *Sedimentation in a rock walled inlet, Lyttelton Harbour, New Zealand*. Unpublished Phd thesis. Department of Geography. University of Canterbury.

de Vries, W. (2007). *Mudflat morphodynamics and sedimentation rates: A case study of the intertidal mudflats at the Head of the Bay, Lyttelton Harbour.* Honours, University of Canterbury.

Dyer, K., Christie, M., Wright, E. (2000). The classification of intertidal mudflats. *Continental Shelf Research, 20*, 1039-1060.

Fausset, C., Rogers, W., Fisk, A. (2009). Univariate and Multivariate Analysis of Variance: A Primer (S. o. P. H. F. a. A. Laboratory, Trans.). Atlanta, Georgia: Georgia Institute of Technology.

Fenwick, G. (2004). Marine ecology of Akaroa Harbour: rocky shores and subtidal soft bottoms. Christchurch: National Institute of Water and Atmospheric Research.

Folk, R., Ward, W. (1957). Brazos River bar: a study in the significance of grain size

parameters. *Journal of Sedimentary Petrology, 27*, 3-26.

GNS. (2012). Earthquake Hazards Retrieved 20/3/2012, from http://www.gns.cri.nz/Home/Learning/Science-Topics/Earthquakes/Earthquake-Hazards

Goff, J. (2005). Preliminary core study: Upper Lyttelton Harbour. Christchurch: National Institute of Water and Atmospheric Research.

Google Earth. (2012) Untitled image: U.S. Department of State Geographer. Retreived 5 October 2012, from www.earth.google.com.

Han, M. (2002). Human influences on muddy coasts. In T. W. Healy, Y. and Healy J. (Ed.), *Muddy coasts of the world: Processes, deposits and function* (pp. 293-316): Elsevier Science.

Hart, D., Marsden, I., Todd, D., de Vries, W. (2008). Mapping of the bathymetry, soft sediments and biota of the upper Lyttelton Harbour. Christchurch: University of Canterbury.

Hart, D., Todd, D., Nation, T., McWilliams, Z. (2009). Upper Akaroa Harbour seabed bathymetry and soft sediments: A baseline mapping study *Coastal Research Report* (Vol. 01). Christchurch: University of Canterbury.

Hastings, T. (2011). Station description: University of Canterbury Integrated Coastal Research Centre.

Holland, K., Elmore, P. (2008). A review of heterogeneous sediments in coastal environments. *Earth-Science Reviews, 89*(3–4), 116-134. doi: 10.1016/j.earscirev.2008.03.003

Hughes, R. G., & Paramor, O. A. L. (2004). On the loss of saltmarshes in south-east England and methods for their restoration. *Journal of Applied Ecology, 41*(3), 440-448. doi: 10.1111/j.0021-8901.2004.00915.x

Kirby, R. (2000). Practical implications of tidal flat shape. *Continental Shelf Research, 20*, 1061-1077.

Kirby, R. (2002). Distinguishing accretion from erosion-dominated muddy coasts. In T. W. Healy, Y. and Healy J. (Ed.), *Muddy coasts of the world:Processes, deposits and function* (pp. pp. 61-81): Elsevier.

Komar, P. (2010). Shoreline evolution and management of Hawke's Bay, New Zealand: Tectonics, coastal processes and human impacts. *Journal of Coastal Research, 26*(1), 143-156.

Lewis, D., McConchie, D. (1994). *Analytical sedimentology*. New York: Chapman and Hall.

LINZ. (2011). Official raster navigational charts Retrieved 11/12/2011, from http://www.linz.govt.nz/hydro/charts/digital-charts/nzmariner

LINZ. (2012). Tide level information for surveyors Retrieved 12/9/2012, from http://www.linz.govt.nz/geodetic/datums-projections-heights/vertical-datums/tidal-level-information-for-surveyors

Masselink, H., Knight,. (2011). Sediments, boundary layers and transport *Coastal processes and geomorphology* (2nd ed., pp. pp. 105-147). U.K.: Hodder Education.

Measures, R., Hicks, M., Shankar, U., Bind, J., Arnold, J., Zeldis, J. (2011). Mapping earthquake induced topographical change and liquefaction in the Avon-Heathcote Estuary: National Institute of Water and Atmospheric Research.

Mehta, A. (2002). Mudshore dynamics and controls. In T. W. Healy, Y. and Healy J. (Ed.), *Muddy coasts of the world: Processes, depositis and function* (pp. 19-60). Amsterdam: Elsevier.

New_Zealand_Hydrographic_Society. (2012). Lyttelton Chart Datum: Effects of earthquakes: Land Information New Zealand

Ogilvie, G. (2000). *Enjoying the Port Hills*. Christchurch: The Caxton Press.

Oldman, J. W., Black, K. P., Swales, A., & Stroud, M. J. (2009). Prediction of annual average sedimentation rates in an estuary using numerical models with verification against core data – Mahurangi Estuary, New Zealand. *Estuarine, Coastal and Shelf Science, 84*(4), 483-492. doi: 10.1016/j.ecss.2009.05.032

Pritchard, D., Hogg, A. J., & Roberts, W. (2002). Morphological modelling of intertidal mudflats: the role of cross-shore tidal currents. *Continental Shelf Research, 22*(11–13), 1887-1895. doi: 10.1016/s0278-4343(02)00044-4

Schumacher, B., Shines, K., Burton, J., Papp, M. (1990). A comparison of soil homogenisation techniques. Las Vegas: Environmental Protection Agency.

Shearer, M. (2011). *Soil erosion and intertidal sedimentation in Lyttelton Harbour/Whakaraupō: The ongoing legacy of land use change assessed using the Revised Universal Soil Loss Equation (RUSLE).* Honours Dissertation. Department of Geography. University of Canterbury.

Shi, Z., Chen, J. (1996). Morphodynamics and sediment dynamics on intertidal mudflats in China (1961-1994). *Continental Shelf Research, 16*(15), 1909-1926.

Shulmeister, J., Soons, J. M., Berger, G. W., Harper, M., Holt, S., Moar, N., & Carter, J. A. (1999). Environmental and sea-level changes on Banks Peninsula (Canterbury, New Zealand) through three glaciation–interglaciation cycles. *Palaeogeography, Palaeoclimatology, Palaeoecology, 152*(1–2), 101-127. doi: 10.1016/s0031-0182(99)00035-8

Sissistein. (2012). Untitled photograph. Retreived 10 October 2012, from www.sissitein.com

Soons, J. (1968). Raised submarine canyons: A discussion of some New Zealand examples. *Annals of the Association of American Geographers, 58*(3), 606-613.

Soons, J. M., Moar, N. T., Shulmeister, J., Wilson, H. D., & Carter, J. A. (2002). Quaternary vegetation and climate changes on Banks Peninsula, South Island, New Zealand. *Global and Planetary Change, 33*(3–4), 301-314. doi: 10.1016/s0921-8181(02)00084-x

Suedel, B. C., Kim, J., Clarke, D. G., & Linkov, I. (2008). A risk-informed decision framework for setting environmental windows for dredging projects. *Science of The Total Environment, 403*(1–3), 1-11. doi: 10.1016/j.scitotenv.2008.04.055

USGS. (2000). Grain size analysis of marine sediments: Methodology and data processing Retrieved 19/01/2012, from http://pubs.usgs.gov/of/2000/of00-358/text/chapter1.htm

Wang, Y., Healy, T., Augustinus, P., Baba, M., Bao, C., Flemming, B., Fortes, M., Han, M., Marone, E., Mehta, A., Ke, X., Kirby, R., Kjerfve, B., Schaeffer-Novelli, Y., Wolanski, E. (2002). Definition, properties, and classification of muddy coasts. In T. W. Healy, Y. and Healy J. (Ed.), *Muddy coasts of the world: Processes, Deposits and function* (pp. 9-18): Elsevier Science.

Wang, Y., Zhu, D., Wu X. (2002). Tidal flats and associated muddy coast of China. In T. W. Healy, Y. and Healy J. (Ed.), *Muddy coasts of the world: Processes, deposits and function* (pp. 319-345): Elsevier Science.

Widdows, J., Brown, S., Brinsley, M. D., Salkeld, P. N., & Elliott, M. (2000). Temporal changes in intertidal sediment erodability: influence of biological and climatic factors. *Continental Shelf Research, 20*(10–11), 1275-1289. doi: 10.1016/s0278-4343(00)00023-6

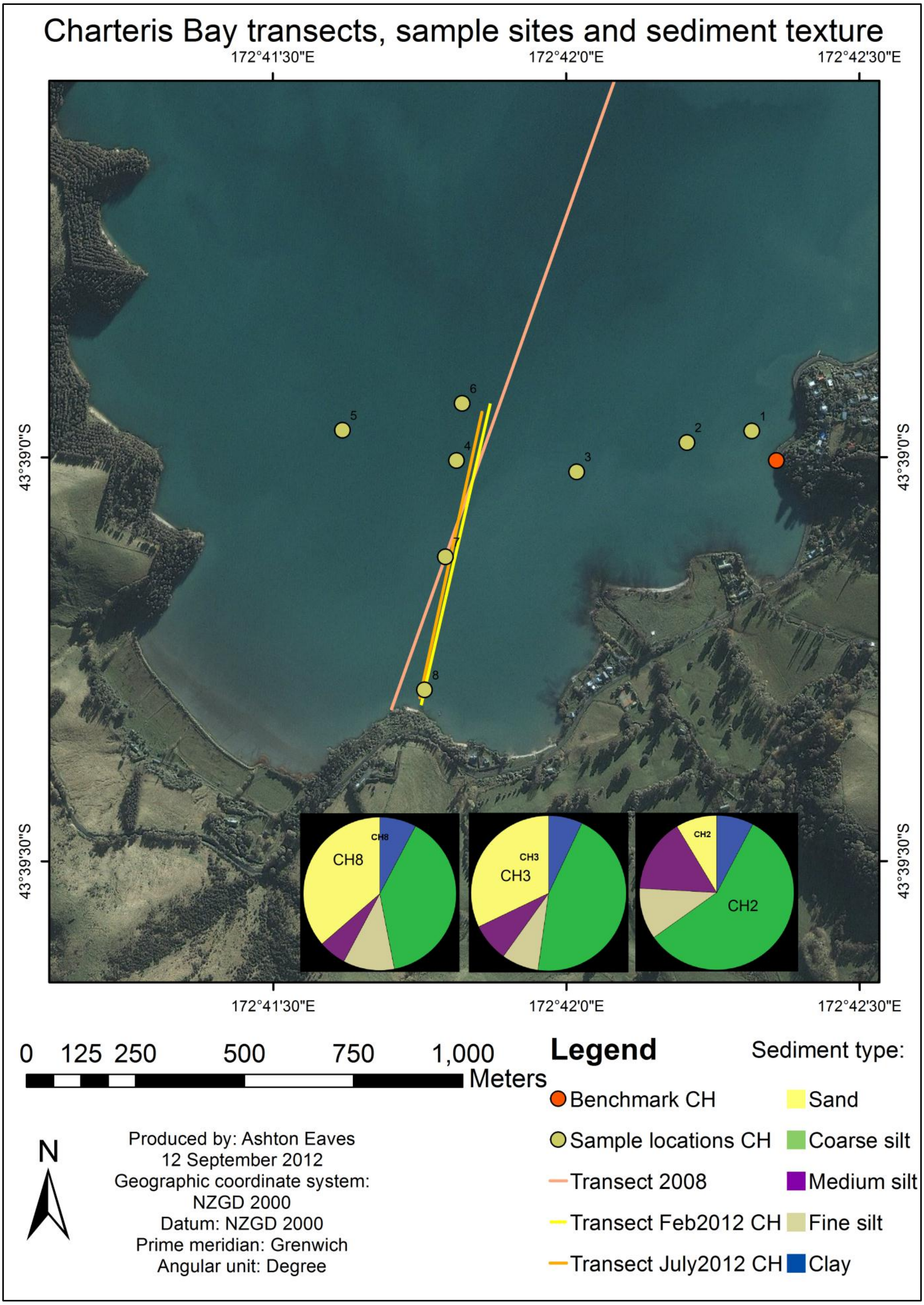
Appendix 1: Seabed surface sediment samples data

Site No.	**Northing**	**Easting**	**Depth**	**Wet density**	**Dry density**	**Dry density classification**	**% Shell**	**Sediment Type (% by weight)**						**Folk classification**	**Sorting Class**	**Skewness Class**	**Kurtosis Class**
			(m)	**(kg m^{-3})**	**(kg m^{-3})**	**Dyer et al. (2000)**	**(gm)**	**Sand**	**Coarse silt**	**Medium silt**	**Fine silt**	**Clay**	**Texture**	**(1965, modified)**			
CH2	793363	398250	-0.6	1608	1140	high	2.19	8.63	57.39	15.46	10.78	7.73	Coarse silt	Z	Poorly sorted	v coarse	v lepto
CH3	793430	397848	-0.6	1617	1092	high	4.57	32.11	45.15	7.96	7.73	7.05	Sandy silt	sZ	Moderately sorted	v coarse	platykurtic
CH8	792861	397500	0.3	1531	934	medium	0.00	36.35	39.20	5.85	10.87	7.73	silty sand	sZ	Poorly sorted	v coarse	v platy
HOB1	793081	395877	0	1753	1447	high	0.00	4.17	69.20	8.48	11.24	6.90	Coarse silt	Z	Moderately sorted	v coarse	v lepto
HOB5	793351	395308	-0.3	1747	1386	high	6.49	5.42	73.35	12.26	5.49	3.48	Coarse silt	Z	Well sorted	v coarse	v lepto
HOB7	792906	394857	0.5	1706	1440	high	0.00	1.34	55.43	22.81	14.08	6.35	Coarse silt	Z	Moderately sorted	v coarse	v lepto
HOB8	793128	394978	0.2	1759	1459	high	0.43	1.81	81.22	10.46	5.72	0.79	Coarse silt	Z	Well sorted	v coarse	v lepto
HOB11	793892	395322	-0.6	1660	1257	high	0.67	2.25	56.55	16.88	16.68	7.64	Coarse silt	Z	Moderately sorted	v coarse	v lepto
HOB12	794168	395418	-0.8	1755	1495	high	7.59	36.33	32.66	14.93	10.72	5.36	silty sand	sZ	Moderately sorted	v coarse	v platy
GB1	794870	393696	0.5	1509	1050	high	0.00	7.54	2.93	16.91	47.39	25.22	Fine silt	Z	Poorly sorted	v coarse	meso lepto
GB2	794978	393844	0.2	1460	960	medium	0.20	7.28	9.90	15.29	32.52	35.02	Silty clay	M	V Poorly sorted	coarse	v platy
GB3	795089	394018	-0.1	1510	1124	high	0.00	5.52	20.44	23.67	28.90	21.47	Medium to fine silt	Z	V Poorly sorted	coarse	v platy
GB4	795234	394187	-0.4	1539	1122	high	3.89	2.97	21.01	17.49	22.62	35.91	Clay	M	V Poorly sorted	v coarse	meso lepto
GB5	795266	394313	-0.6	1494	1080	high	4.24	2.98	30.55	20.94	20.30	25.22	Silty clay	Z	V Poorly sorted	coarse	v platy
GB6	795371	394414	-0.8	1507	989	medium	1.89	1.73	24.66	22.04	23.66	27.91	Silty clay	Z	V Poorly sorted	coarse	v platy

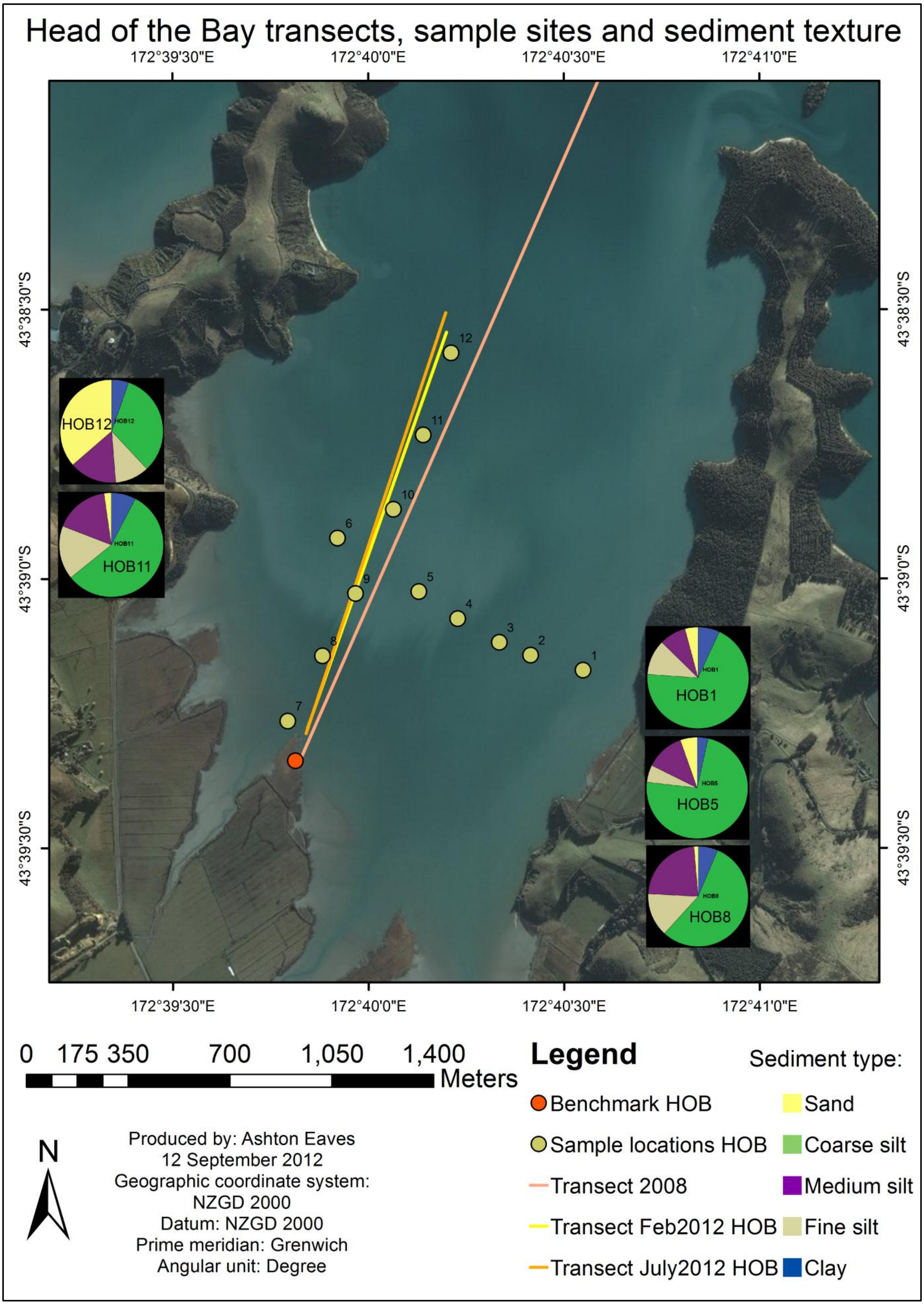
GB7	796358	394057	0.6	1324	719	medium	8.99	6.64	28.57	8.89	45.84	10.06	Fine silt	Z	Poorly sorted	v coarse	v platy
GB8	796239	394094	0.5	1347	744	medium	0.00	4.35	10.47	7.48	42.40	35.30	Clayey silt	M	V Poorly sorted	coarse	v platy
GB9	796105	394126	0.3	1341	809	medium	0.00	6.32	18.31	14.32	40.28	20.77	Clayey silt	Z	V Poorly sorted	v coarse	platykurtic
GB10	795653	394145	-0.5	1469	885	medium	8.41	13.85	25.96	11.89	29.97	18.33	Fine silt	sM	V Poorly sorted	coarse	leptokurtic
GB12	795052	394482	-0.4	1540	1062	high	5.45	9.45	54.31	12.14	17.14	6.96	Coarse silt	Z	Poorly sorted	v coarse	v lepto
T1	778662	419303	0.7	1672	1273	high	0.00	3.76	73.77	19.81	2.25	0.41	Coarse silt	Z	Well sorted	v coarse	v lepto
T2	778652	419261	0.2	1647	1174	high	4.50	16.56	63.60	13.23	3.97	2.65	Coarse silt	sZ	Moderately sorted	v coarse	leptokurtic
T3	778701	419147	-0.1	1552	1050	high	1.37	9.40	76.08	10.27	2.83	1.42	Coarse silt	Z	Well sorted	v coarse	v lepto
T4	778716	419065	-0.2	1527	1031	high	1.03	15.42	62.75	10.36	11.10	0.37	Coarse silt	sZ	Well sorted	v coarse	leptokurtic
T5	778756	418949	-0.4	1615	1161	high	17.38	42.05	43.38	6.18	7.29	1.11	Sandy silt	sZ	Well sorted	v coarse	platykurtic
T6	778766	418830	-0.5	1608	1076	high	27.42	53.43	36.56	3.62	5.00	1.38	Sand	zS	Moderately sorted	v coarse	platykurtic
T7	778412	418873	-0.4	1531	1051	high	2.03	7.73	57.14	16.86	9.45	8.82	Coarse silt	Z	Moderately sorted	v coarse	v lepto
T8	778502	418893	-0.8	1510	954	medium	6.45	18.45	48.49	18.10	10.16	4.80	Coarse silt	sZ	Moderately sorted	v coarse	leptokurtic
T9	418895	778582	-0.7	1651	1132	high	19.13	52.02	40.51	3.74	2.16	1.57	silty sand	zS	Well sorted	v coarse	v platy
T10	778810	418948	-0.6	1653	1195	high	8.36	44.53	41.27	6.29	6.29	1.61	silty sand	sZ	Moderately sorted	v coarse	v platy
T11	778910	418960	-0.5	1622	1027	high	24.53	33.28	33.28	11.32	9.48	12.64	Silty sand	sM	Poorly sorted	v coarse	v platy
T12	778996	418973	-0.4	1589	1046	high	16.54	21.82	54.53	11.01	2.23	10.41	Coarse silt	sM	Moderately sorted	v coarse	leptokurtic
B1	780932	415810	-0.2	1462	1278	high	0.75	19.77	61.83	7.05	4.89	6.46	Coarse silt	sZ	Moderately sorted	v coarse	leptokurtic
B2	780931	415682	-0.5	1685	1448	high	7.20	20.72	60.68	11.13	6.43	1.04	Coarse silt	sZ	Poorly sorted	v coarse	leptokurtic
B3	780891	415574	-0.7	1723	1394	high	5.68	7.56	56.89	21.73	7.90	5.93	Coarse silt	Z	Well sorted	v coarse	leptokurtic

B4	780827	415353	-0.8	1599	1402	high	0.00	3.94	55.04	15.84	13.62	11.55	Coarse silt	M	Moderately sorted	v coarse	v lepto
B5	780750	415202	-0.6	1458	849	medium	0.00	16.66	37.86	16.39	14.09	15.01	Coarse silt	sM	Poorly sorted	v coarse	leptokurtic
B6	780682	415036	-0.3	1211	698	medium	0.00	31.67	10.14	11.24	38.89	8.05	Sandy fine silt	sZ	V Poorly sorted	v coarse	platykurtic
B7	781305	415118	-0.8	1281	856	medium	0.00	3.91	29.54	12.50	44.16	9.88	Fine silt	Z	Poorly sorted	coarse	platykurtic
B8	781225	415154	0.3	1360	982	medium	0.00	13.98	38.57	19.66	15.93	11.86	Coarse silt	sM	V Poorly sorted	v coarse	leptokurtic
B9	781158	415202	-0.2	1256	776	medium	0.00	11.30	21.53	23.79	26.19	17.19	fine to medium silt	sM	Poorly sorted	symmetrical	v platy
B10	781019	415284	-0.2	1287	578	low	3.34	16.62	15.89	1.84	44.92	20.73	Clayey silt	sM	Moderately sorted	fine	v platy
B11	780816	415365	-0.8	1614	1371	high	0.00	4.19	51.16	25.26	10.14	9.25	Coarse silt	Z	Moderately sorted	v coarse	leptokurtic
B12	780812	415409	-0.9	1472	1369	high	0.00	55.80	0.57	20.62	13.96	9.05	sand	zS	Poorly sorted	v coarse	v lepto

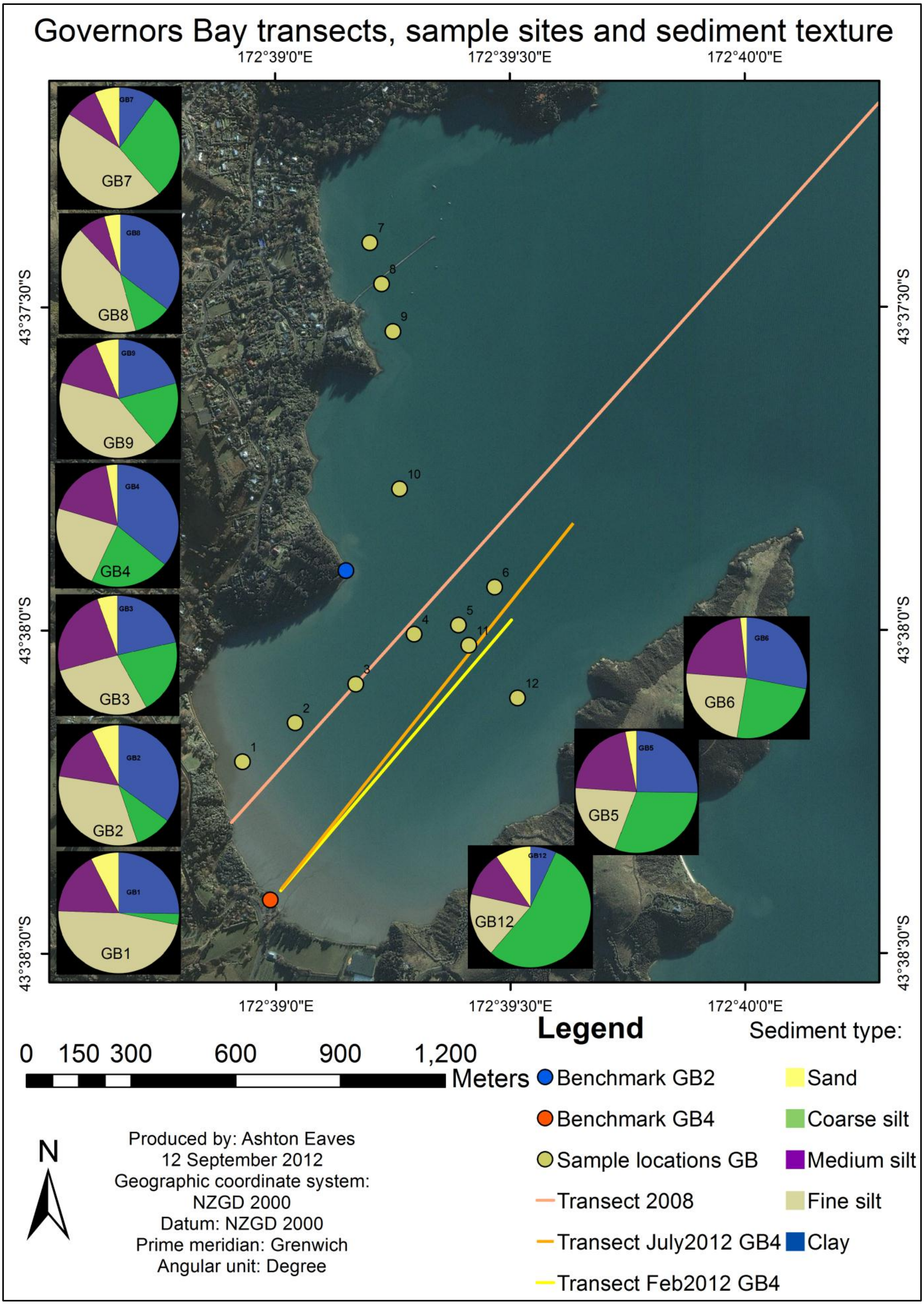
Appendix 2: Map of Charteris Bay



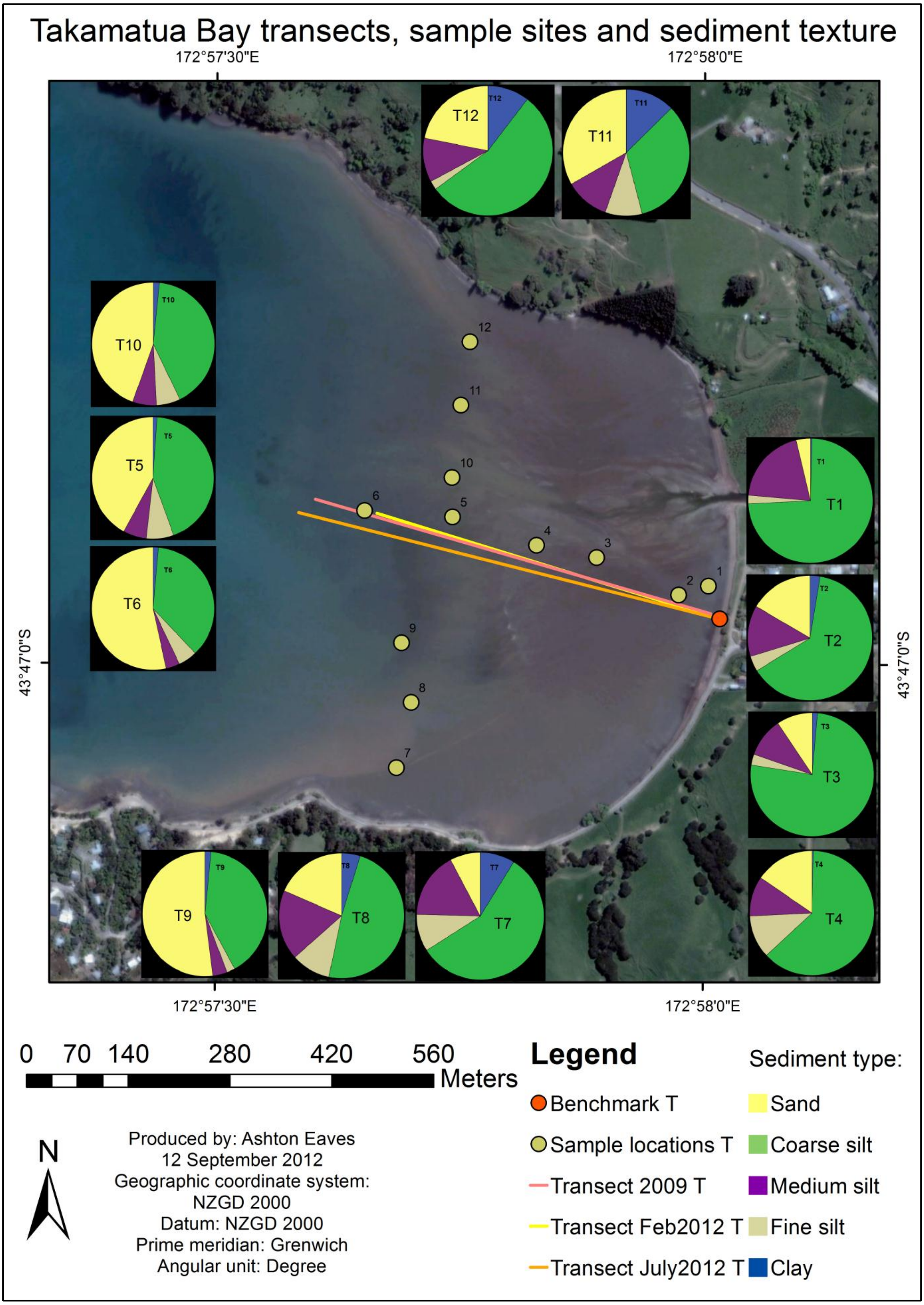
Appendix 3: Map of Head of the Bay



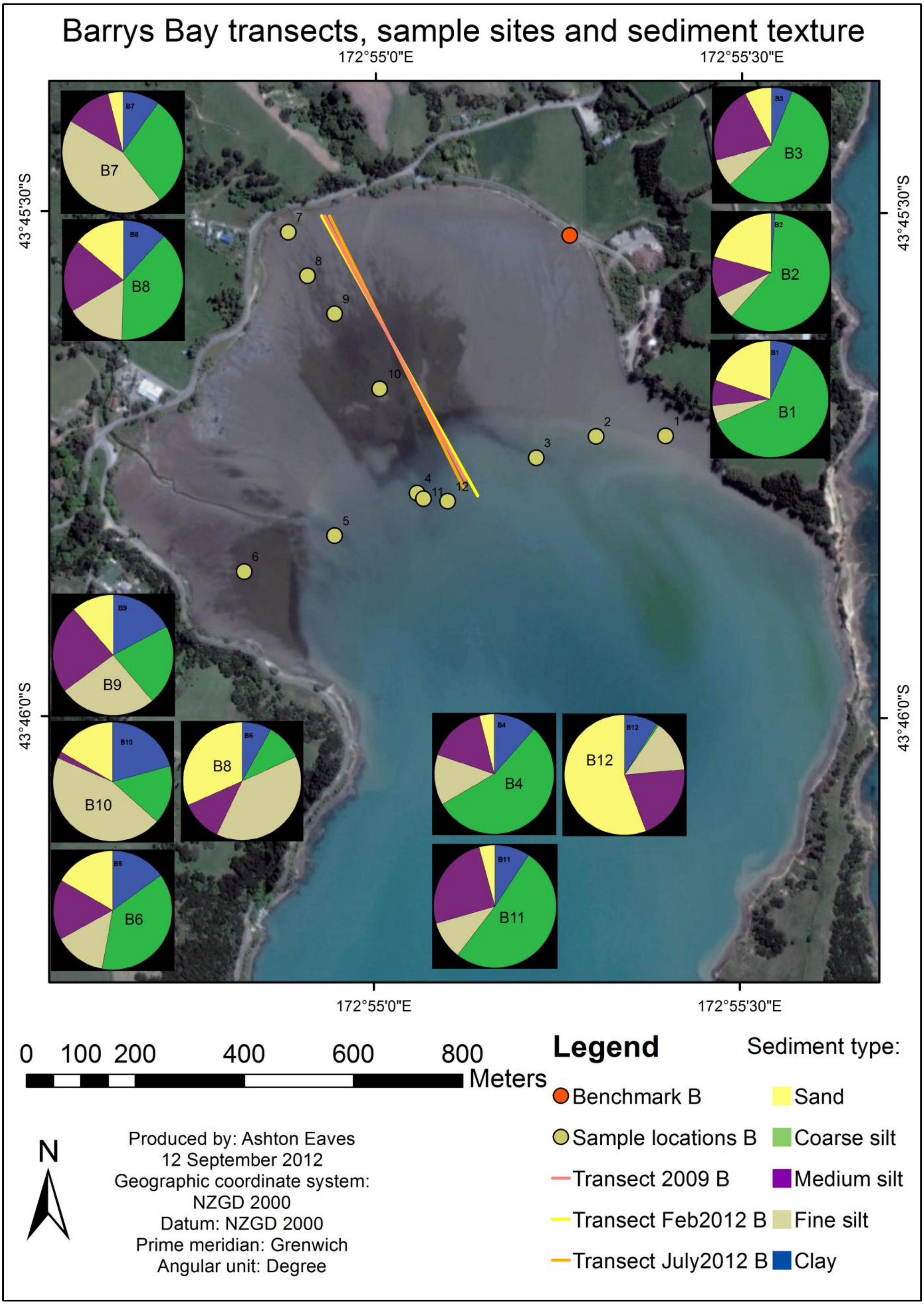
Appendix 4: Map of Governors Bay



Appendix 5: Map of Takamatua Bay

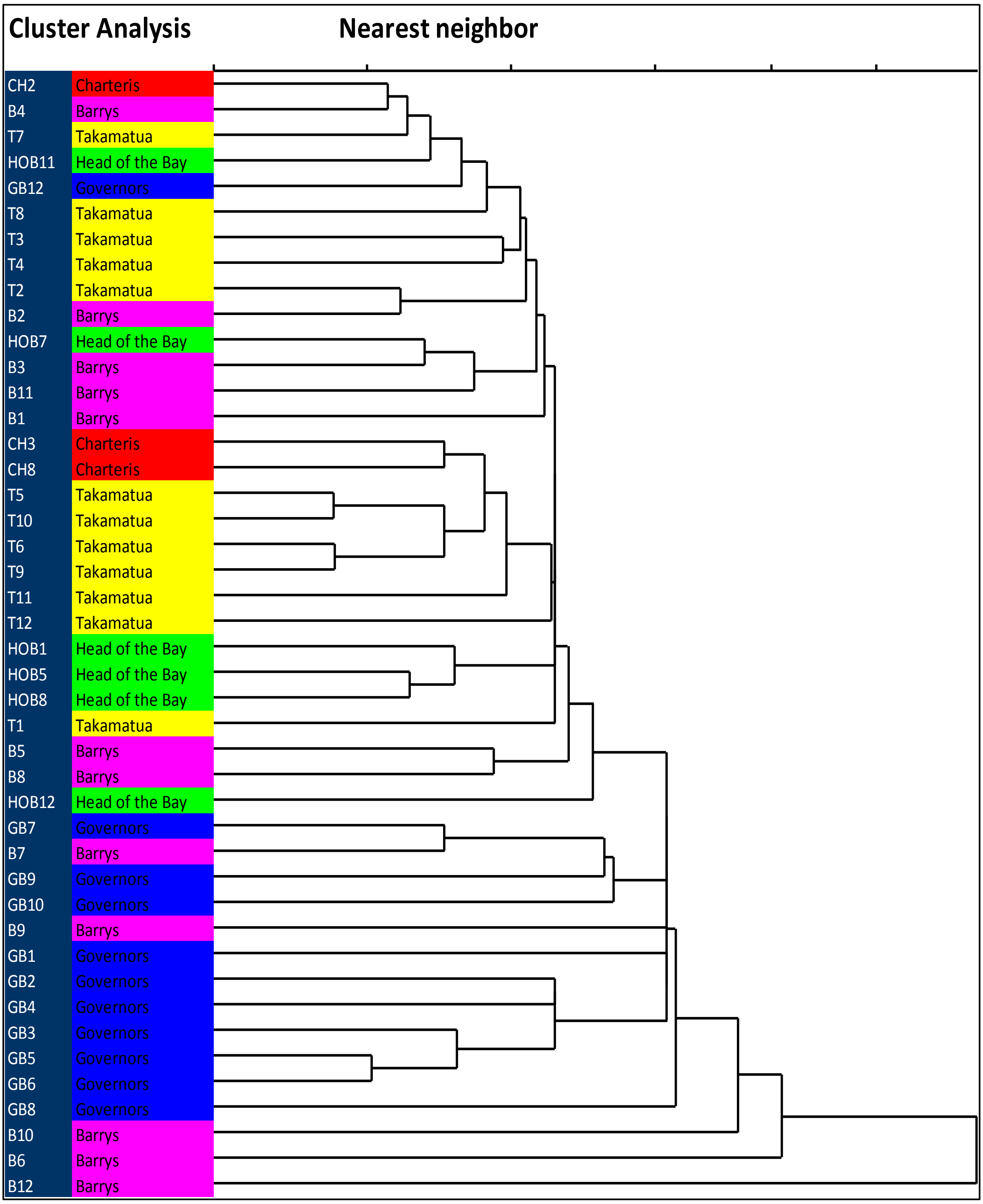


Appendix 6: Map of Barrys Bay



Appendix 7: Cluster Analysis

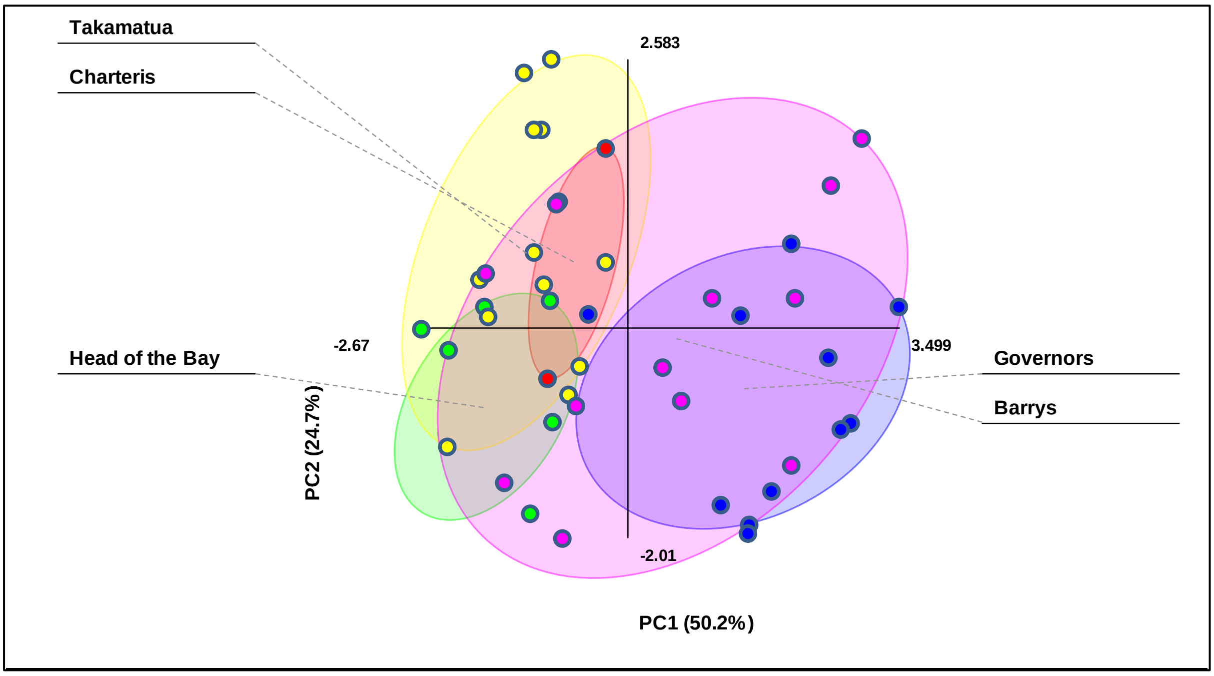
Cluster analysis for seabed surface sediment samples based on nearest neighbour. Variables assessed were density, sand, coarse silt, medium silt, fine silt and clay. The distribution shows a clustering of consolidated mudflat substrates at the top of the diagram and unconsolidated mudflat substrates at the bottom (data was normalised).



Appendix 8: Principle component analysis

Principle component analysis for density and grain size distributions (PC1 VS PC2). Samples from Barrys Bay have the largest distribution of sediment sizes and densities. Governors Bay samples have the highest concentration of fine silts and clays and Takamatua Bay samples have higher densities with proportionally more sand and coarse silt.

Samples:



Loadings: