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Upper Akaroa Harbour Seabed Bathymetry & Soft Sediments: A Baseline Mapping Study

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A Baseline Mapping Study

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Executive Summary

- This study was commissioned by Environment Canterbury to examine the soft-sediment seabed of upper Akaroa Harbour including areas north of Cape Three Points and The Kaik, to the upper harbour shoreline.
- Detailed information was gathered on the seabed surface sediment characteristics and intertidal bathymetry of the upper harbour, and combined with subtidal bathymetry data from LINZ (2008a) in order to form a baseline against which future changes could be assessed.
- Along central areas the seabed was very gently sloping, descending to -10 m AMSL between Akaroa Inlet and Wainui Bay. The nearshore bathymetry inside the bays appeared more gently sloping north of Takamatua Hill, particularly in the French Farm and Barrys Bay Inlet, steepening towards the shores of Akaroa Inlet and, in particular, Wainui Bay.
- Compared to the 1952 survey, the central axis of the upper harbour appears to have remained at approximately the same level, with the exceptions of east of Onawae, where the bed has shallowed by up to 1.25 m, and adjacent to northern Wainui Bay, where the bed has shallowed by 0.5 m. Bathymetry changes observed within the bays was more variable: inner Takamatua Bay appears to have undergone significant sedimentation since 1952, while the Akaroa Inlet may have been in a slightly erosion phase. Wainui Bay appears to be relatively high-energy, with sediment unable to infill the bay and shallow its profile to the same degree as has occurred in bays to the north.
- Silts and clays dominated most of the upper harbour, with clay dominating the central area between Akaroa Inlet and Robinsons Bay and possibly indicating a sediment sink zone. Sands dominated the shorelines and nearshore zones of much of Tikao, Petit Carenage, Duvauchelle, Robinsons, Takamatua and Childrens Bays, as well as intertidal patches in French Farm and Barrys Bays. Sands were most extensive in Duvauchelle, Robinsons and Takamatua. Gravel was absent from all but five samples.
- Bathymetry and sediment findings suggest that Akaroa Harbour has a slightly-more energetic zone south of Takamatua Hill; low-energy sheltered environments in areas adjacent and north of Takamatua Hill, and in the western upper harbour bays; and slightly-more energetic bays on the northern and eastern reaches of the upper harbour.
- The key recommendations for additional future research arise from this report:
 1. In order to improve knowledge of upper harbour sedimentation processes, a hydrodynamic field and modelling study should be conducted to establish circulation and wave energy patterns within the upper Akaroa Harbour. This study would help to explain the sediment patterns and bathymetry trends found, and would assist in determining the relative influences of catchment versus up-harbour transport sources of sediment.
 2. We recommend that the possible erosion of the mid and outer bay areas of Akaroa Inlet is investigated further.
 3. A study should be conducted to quantify the catchment inputs of water and sediment into upper Akaroa Harbour. This would include a review of the monitoring data from the large number of recent development sites around the

harbour. This sediment input information could then be compared to surface sediment texture patterns found in the present study, and the textural associations with biota found by Bolton-Ritchie (2005), to better understand the effects of contemporary catchment change on the biological resources of the harbour.

4. We recommend that in future upper harbour sediment and bathymetry surveys are conducted in conjunction with biological surveys so that the results are directly comparable. A biological sampling project that is more detailed than Fenwick (2004) and more extensive than Bolton-Ritchie (2005) is needed to describe the full range of biological community patterns of the upper harbour.

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List of Acronyms

AMSL – Above Mean Sea Level

CD – Chart Datum

DTM – Digital Terrain Model

ECan – Environment Canterbury

ESRI – Environmental Systems Research Institute

GIS – Geographic Information System

GNSS – Global Navigation Satellite System

GPS – Global Positioning System

LINZ – Land Information New Zealand

MSL – Mean Sea Level

MLWS – Mean Low Water Spring Tide

NIWA – National Institute of Water and Atmospheric Research

NZGD – New Zealand Geodetic Datum

1. Introduction and objectives

This report documents a study undertaken to map the soft-sediment seabed of upper Akaroa Harbour (Figures 1-2). It was commissioned by Environment Canterbury (ECan) in order to establish a baseline against which future changes in sediment and bathymetric patterns could be assessed in 10 to 15 years time. It complements Fenwick (2004), a NIWA report conducted for ECan, detailing the marine ecology of Akaroa Harbour's rocky shores and sub-tidal soft-sediment seabed. Hart *et al.* (2008) undertook a similar upper-harbour study for the adjacent Lyttelton Harbour, examining bathymetry, sediments and soft-sediment seabed biological communities.

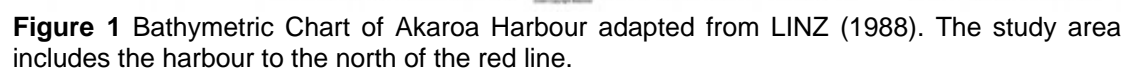
The objectives of this study were:

1. to map the bathymetry of the upper Akaroa Harbour, and
2. to characterise the spatial distribution of soft-sediment textures within the upper Akaroa Harbour.

In order to achieve Objective 1 it was necessary to survey the intertidal areas of the upper harbour bays not covered by the LINZ (2008a) survey: Barrys Bay, Duvauchelle Bay, Robinsons Bay, Takamatua Bay, Akaroa Inlet (including French, Childrens and Glen Bays), Wainui Bay, Tikao Bay, Petit Carenage Bay and French Farm Bay. Bathymetry maps were then produced using the data gathered in the field and by LINZ (2008a) and showing the seabed elevation contours of the intertidal and sub-tidal areas. In order to achieve Objective 2, seabed sediments were sampled at 89 intertidal and subtidal locations throughout the upper harbour, analyzed for size distribution, classified into types and mapped.

This report describes the field and analysis methodology employed to the level of detail required to make them repeatable. It also presents summaries and a discussion of the results, including an interpretation of changes in bathymetry since the last survey in 1952. A review was also conducted of previous research on the sediments, bathymetry and, briefly, of the biological communities of the harbour as a first step towards providing the baseline study.

All bathymetry and sediment maps produced from the results of the surveys are presented at the back of the report, with place names referred to in the report being shown on Maps 1 and 2. Transects along the central axis of harbour and in each bay extrapolated from the survey data are presented after the maps. A CD of the spatial and attribute data in digital form is also provided to allow the sampling and survey methodology to be replicated in the future. A list of the information contained on this CD is given in Appendix 1.



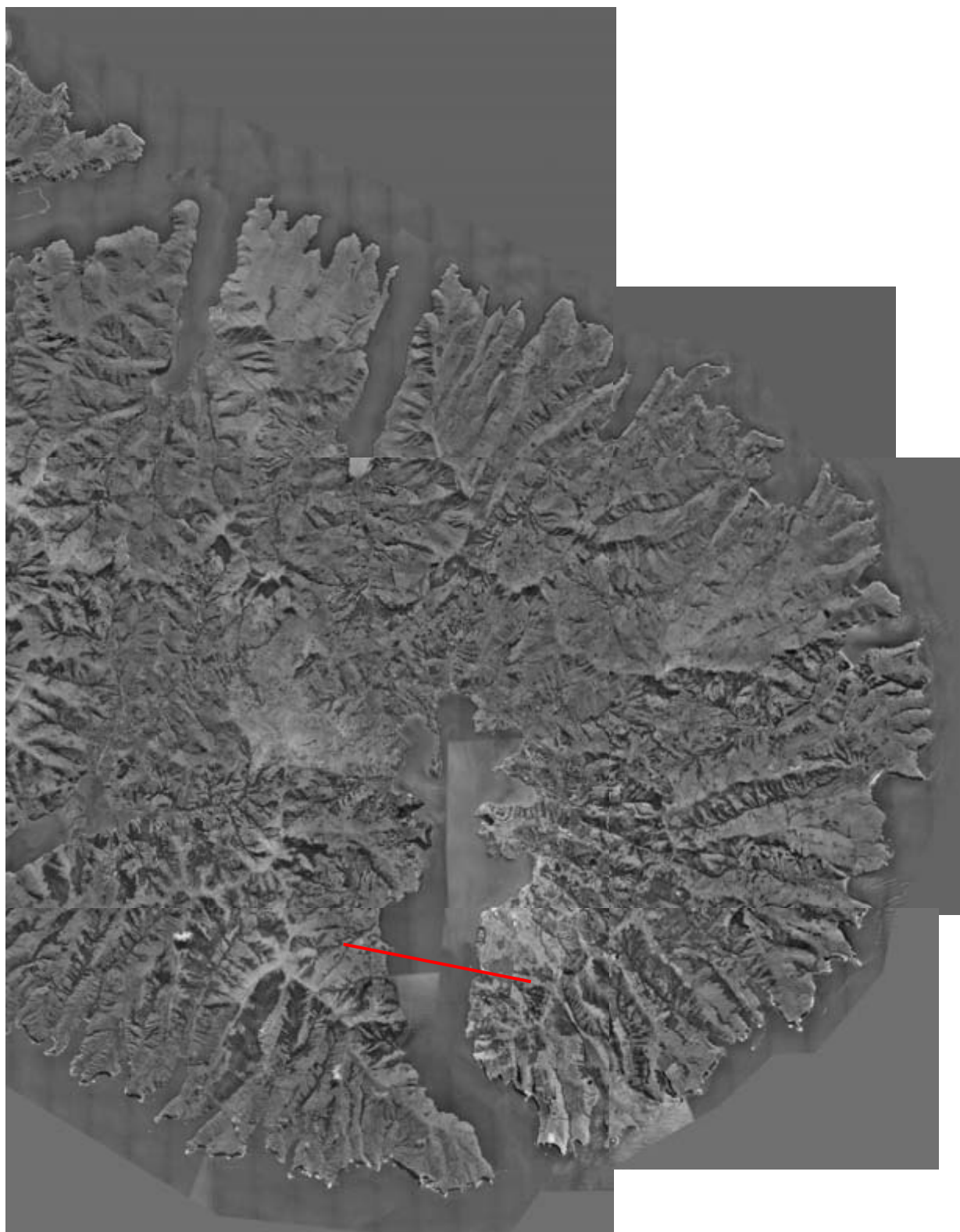


Figure 2 Aerial view of Akaroa Harbour with the southern boundary of the upper harbour study area delimited by a red-line (LINZ 2009a).

2. Previous research

2.1 Catchment geology and historical landuse

Banks Peninsula comprises the eroded and partially flooded cones of the composite Akaroa and Lyttelton Volcanoes (Liggett and Gregg 1965; Neumayr 1998; Porteous 1987). These two basaltic shield volcanoes, 30 km in diameter, erupted and coalesced to form an island 11 to 6 million years ago during the Miocene epoch. Basalt is a dark, fine-grained rock rich in magnesium and iron, which in the form of lava is thin and fluid. Basaltic lava quickly spreads to produce gently sloping (5°) shield volcanoes, so called because from a distance they look like giant shields lying on the ground.

The present day Akaroa and Lyttelton harbour morphologies are the product of weathering and marine incision of the crater remnants over millions of years. In Akaroa, the Onawe promontory forms the most visible remnants of the volcanic origins of the harbour, protruding nearly a mile southward between Duvauchelle and Barry's Bays (LINZ 2008a).

During subsequent glacial periods the volcanic rocks of the Peninsula were overlain by thick deposits of loess and loess colluvium, in places up to 20 m thick (Raeside 1964). Both harbour seabeds were gradually infilled with the predominantly fine-grained loess and volcanic sediment runoff from their surrounding peninsula catchments.

Since human occupation, the peninsula has undergone dramatic land cover changes, including the burning, felling and clearance of up to 90% of its native forest cover and the development of extensive introduced-species pasture grasslands (Figure 3). Under this pastoral regime the fine loess sediments of the harbour catchments were readily eroded and transported off the hill slopes into the marine environment.

Other landuse changes included the development of settlements, viticulture and native reserve land. Akaroa Harbour today has a number of growing residential settlements, occupying French Farm, Barry's, Duvauchelle, Robinsons, Takamatua and Wainui Bays, as well as Akaroa township. In addition, the harbour waters are a popular recreational boating and tourist resource used by local and international vessels of a range of sizes, including the occasional large cruise liner.

The 1988 whole harbour bathymetric chart was based on a survey conducted in 1952 (LINZ 1988). Increased vessel usage, particularly by large tourist vessels, and questions regarding the existing seabed topography from chart users, resulted in LINZ commissioning a survey of the subtidal area in 2008. Tourism and suburban development of the upper harbour bays has also resulted in concerns regarding sedimentation of the intertidal mudflats. This study provides the baseline data needed to start to examine the latter issue.

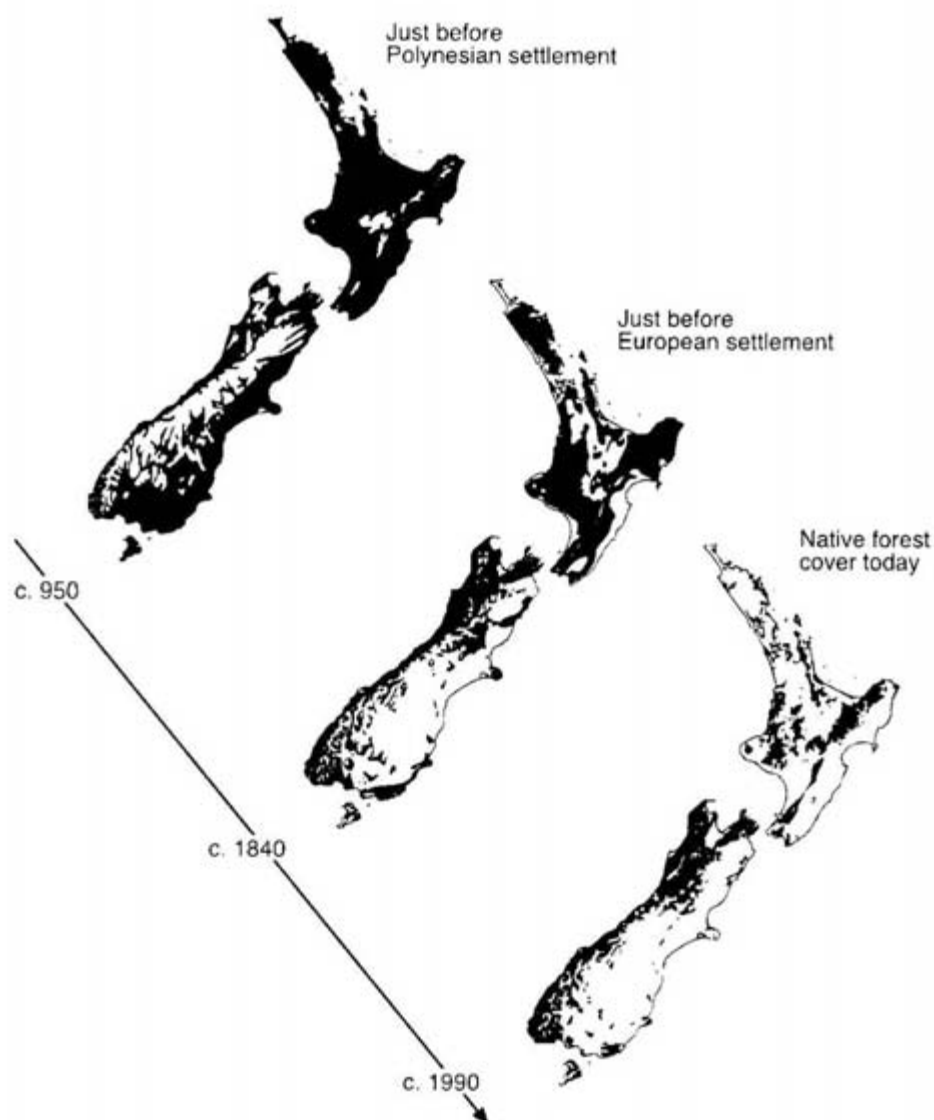


Figure 3 The shrinking forest cover of New Zealand (Holland 2001, 393). Note the major change in Banks Peninsula forest cover after 1840

Previous information on bathymetry and sedimentation patterns in upper Akaroa Harbour is temporally and spatially limited. This include 1952 and 2008 seabed bathymetry surveys (LINZ 1988, 2008a), a ten-site sediment and macrobenthos survey of Barrys, Duvauchelle, Robinsons and Takamatua Bays by Bolton-Ritchie (2005), and a brief study of harbour sediments as part of a larger biological investigation by Fenwick (2004). The only area of detailed study is around the intertidal and shallow subtidal areas of the various embayments within Akaroa Inlet, where Hicks and Marra (1988) collected 70 samples as part of investigations for a potential marina site. Therefore in general, there is a paucity of historical data for Akaroa Harbour. As described, the harbour does, however, share commonalities with the Lyttelton area as part of the wider Banks Peninsula region and in terms of forest clearance and catchment landuse change. Accordingly, broad patterns of sediment and bathymetry change in Lyttelton are reviewed alongside information concerning Akaroa.

2.2 Bathymetry

The bathymetry of Akaroa Harbour as surveyed in 1952 is displayed on the New Zealand Hydrographic Chart NZ 6324 (LINZ 1988) as shown in Figure 1. Chart depths are recorded in relation to chart datum (CD), a level similar to that of the Lowest Astronomical Tide (see Table 1 for tide levels), and 1.5 m below Mean Sea Level (MSL). This chart, which presents depth contours at 5 m intervals and spot heights at around 500 m intervals, shows seabed depths ranging from 25 m (CD) at the harbour entrance, to 10 m CD depth half-way up the harbour (southern limit of our study area), and to 5 m CD depth in outer areas of the upper harbour bays. Inside these bays, depths are shown to gently decrease towards chart datum (i.e. 1.5 m below MSL) at varying widths from the shore. However, there are limited spot heights given across the intertidal mudflats above chart datum to the shoreline.

Table 1 Tidal levels for Akaroa Harbour (43° 48' N, 172° 55' E) in relation to Chart Datum and to levels Above Mean Sea Level, AMSL (LINZ 2008c).

Level	Elevation (m above Chart Datum)	Elevation (m AMSL)
Mean High Water Spring (MHWS)	2.4	0.9
Mean High Water Neap (MHWN)	2.2	0.7
Mean Low Water Neap (MLWN)	0.7	-0.8
Mean Low Water Spring (MLWS)	0.5	-1.0
Mean Sea Level (MSL)	1.5	0
	Range (m)	
Spring tide	1.9	
Neap tide	1.5	

LINZ (2008a) conducted a detailed bathymetric survey of Akaroa Harbour over 14 square nautical miles from the upper harbour intertidal areas down to approximately the 20 m depth contour. Line spacing was set at 100 m, except in Akaroa Inlet where it was 50 m, consistent with the survey scales of 1:20,000 and 1:10,000 respectively. The southern limit of this LINZ survey occurred inside the harbour entrance in a line across the harbour adjacent to Lucas Peak. The results of this survey are presented in the updated New Zealand Hydrographic Chart NZ 6324 (LINZ 2009b), which has the same depth contour and spot height intervals as the 1988 chart.

The accompanying, LINZ (2008a) survey report describes the seabed topography as almost uniformly flat and featureless from the head of the harbour along its central axis, with the only exceptions occurring close to shore where localised tidal flows have scoured trenches near a number of headlands. They report this process to be particularly prevalent near Lushington Bay and Green Point. The northern part of the harbour is described as predominantly shallow and of low gradient, with extensive mudflats exposed at low water. South of Tikao Bay depths increase and mudflats are replaced by a rocky coastline consisting of steep hillsides and cliff faces with large rock shelves at their base. In contrast to the generally gentle gradients of the rest of the harbour, seafloor depths increase rapidly close to shore at the southern extent of the LINZ survey area, where the sheltered confines of the harbour become increasingly exposed to the open ocean (LINZ 2008a).

The general pattern of harbour depths revealed by the LINZ (2008a) survey is broadly similar to that recorded on Chart NZ 6324, with some differences in the depths of upper harbour areas. The details of seabed changes between 1952 and 2008 as indicated by the comparison of these two surveys are outlined in the results section of this report.

2.3 Sediments

Akaroa Harbour

As noted, there is a paucity of previous research on the sediments within Akaroa Harbour. The LINZ (1988) bathymetric chart indicates that the body of the upper harbour is dominated by mud, with sand pockets being present at the heads of all the major bays except Wainui, where no sediment type is indicated. The chart indicates that the lower harbour, outside of the study area for the current investigation, is dominated by fine sands and shell. The LINZ (2008a, report p12) survey report comments that the Akaroa Harbour “seabed texture is mainly of a muddy disposition, consistent with a sediment filled harbour”.

Within Akaroa Inlet, Hicks and Marra (1988) described the main features of the Childrens Bay sediment from their 70 samples as being: a broad bank of very fine and relatively mud-free sand on the tidal flats, with increasing mud content towards the NW corner of the bay, and low relief shell banks near the edge of the intertidal shelf towards the eastern end of the bay. The main features of sediments in the inlet to the south of Childrens Bay were described as being: a semi-continuous narrow belt of boulders and cobbles in the upper tidal zone with broader deltas at the stream mouths; a few short and narrow patches of mud-free sand overlying the gravel on the mid to low tide zone in the shallow embayments; a relatively broad but discontinuous belt of muddy sand just below the low water mark; followed by a transition into a continuous, wide belt of sandy mud and then into mud over the majority of inlet seabed. Hicks and Marra (1988) concluded that these sediment distributions reflected the degree of wave exposure and water depth, with the coarsest materials occurring in the intertidal zones where there is usually sufficient turbulence generated from breaking waves to prevent fine mud and silt materials from settling.

Hicks and Marra (1988) also examined the mineral composition and sources of the gravels and sands. The boulders and cobbles along the shore were found to be comprised of volcanic rock locally sourced from shore or catchment erosion. The relatively mud-free, well-sorted sands of the intertidal zone were divided into populations: very fine grey-tan quartz sand found primarily at the main swimming beach, which had been imported from Le Bons Bay for recreation purposes; brown and generally fine to medium sands composed almost entirely of fragmented rock supplied by local streams and found at Redhouse and Sailing Club Bays and in the NW corner of Childrens Bay; and light-coloured coarse sands composed predominantly of shell fragments, found in patches at The Glen, and derived from the rock oyster communities growing on nearby reefs.

Fenwick (2004) gives details of the sediment textures and organic content in samples taken along this study’s biological-sample transects. He found that the seabed

sediments transitioned from almost-completely mud in the shallow northern-most reaches, to fine sands towards the harbour entrance in the south. Organic content, total nitrogen and trace metal content also decreased as mud fractions decreased with increasing depth. He explained the pattern of increasing grain size with depth and distance from the upper harbour as the product of increasing hydrodynamic energy towards the harbour entrance.

Bolton-Ritchie (2005) also examined the sediments and macrobiota of the intertidal flats of upper Akaroa Harbour. Along with the biota, sediment textures, total nitrogen and total phosphorous and organic matter content was determined in samples from ten sites across Barrys, Duvauchelle, Robinsons and Takamatua Bays. Analyses revealed distinct differences in the sediment characteristics between bays. Seabed sediments in Barrys Bay, for example, comprised 93 to 98% mud, while those in Duvauchelle, Robinsons and Takamatua Bays comprised 73 to 96.5% sand. Organic matter content ranged from 0.5 to 4.6%, with no correlation occurring between organic matter content and sediment texture or with seagrass cover. Total nitrogen and total phosphorous content ranged from 800 to 2600 mg kg⁻¹ and from 390 to 830 mg kg⁻¹, respectively. A strong correlation between total nitrogen and total phosphorous, along with a lack of correlation between them and sediment texture indicated a common external nutrient source such as the harbour's catchment streams and/or the waterfowl that feed on the flats (Bolton-Ritchie 2005).

Comparisons with Lyttelton Harbour

In contrast to Akaroa Harbour, there have been a number of studies of the seabed sediments of Lyttelton Harbour, the most recent bathymetric and surface sediment maps of which are included in Appendix 2 for comparative purposes.

Previous research indicates that Lyttelton Harbour underwent a period of scour during the late nineteenth to early twentieth century, followed by a period of rapid deposition in response to peninsula forest clearance during the early to mid twentieth century. A period of slower deposition associated with pasture land cover occurred next, up to the late twentieth century, when there was another increase in sedimentation rates to the present day (Curtis 1985, Goff 2005). For the last 50 years, Hart *et al.* (2008) found that Lyttelton Harbour has experienced a reduction in depth of around 0.2 m at the mouth of each of the upper bays, with an average sediment deposition rate around 0.35 cm/yr. They observed shallowing along the north-western upper harbour from Rapaki Bay to Governors Bay, with possibly even-greater deposition rates here. Importantly, sedimentation rates were found to vary between the upper Lyttelton Harbour bays, a pattern which is likely to be replicated in Akaroa Harbour, and which has been taken into account in designing the sediment investigations in the present study.

Silts and clays dominate the upper Lyttelton Harbour seabed surface, with sediments becoming finer from east to west, and clay increasing south to north. Sands and gravels dominate south of the dredged channel and in pockets within the upper harbour, respectively (Appendix 2). Hart *et al.* (2008) attributed the distribution of sand and finer sediments in the upper Lyttelton Harbour to a combination of tidal and wave sediment transport processes, fine sediment catchment inputs, and lower-harbour continental-shelf sand inputs. In contrast, almost all of the upper harbour gravels were described as biogenic - the result of shell production. Comparisons

between the sediment patterns found for Akaroa Harbour in this study and those described for Lyttelton Harbour are made in the discussion section of this report.

A consistent finding of the Lyttelton Harbour studies is that the main source of material for sedimentation in this harbour is catchment erosion of loess and loess colluvium, with Curtis (1985) estimating the supply rate in the order of $44,300 \text{ t yr}^{-1}$. Hart (2004) noted that catchment erosion rates are an order of magnitude greater in the upper harbour (e.g. west and south of Cass Bay), with fluvial inputs also being concentrated in this area. The Lyttelton Harbour literature acknowledges that rates of sedimentation have accelerated since pre-European times, primarily due to modification of the catchment land cover, first through forest clearance and pasture conversion, and more-recently by increased residential development. This finding may also be expected for Akaroa Harbour given the similarities that exist in the two catchments land cover histories.

In addition to sediments and bathymetry, Curtis (1985) measured tidal circulation in Lyttelton Harbour, with mean current velocities varying between 0.15 m s^{-1} west of the port, up to 0.23 m s^{-1} in the central harbour, and to 0.27 m s^{-1} near the harbour entrance. He postulated that the interaction of these currents with harbour topography sometimes led to the development of a large clockwise gyre in the central to lower harbour on the flood tide and a comparable anti-clockwise gyre on the ebb tide, although the findings of Hart *et al.* (2008) suggest that this northward flux of fine sediments may not be as strong as originally thought. However, the south-to-north orientation and Canterbury-Bight entrance of Akaroa Harbour is very different to the east-to-west central axis and Pegasus-Bay entrance of Lyttelton Harbour so that patterns of hydrodynamic circulation within these two inlets may be expected to differ significantly.

2.4 Hydrodynamic Processes

Heuff *et al.* (2005) noted that there is a paucity of data on the hydrodynamics and associated physical properties of Akaroa Harbour. While this is true of the harbour in general, the report by Hicks and Marra (1988) does provide some detailed data on currents and waves in Akaroa Inlet.

Heuff *et al.* (2005) found that strong winds induced water circulation within the harbour, with a significant surface current directed into and out of the harbour during southerly and northerly winds respectively. Accompanying the surface current was a weaker return flow that extended the entire length of the harbour, along the seabed. During periods of light wind, tidally driven flow was observed to be the dominant forcing mechanism in the harbour.

LINZ (2008a) noted that afternoon sea breezes were common during the February 2008 field period and describe these as being funnelled along the central harbour axis, producing 'chop' in central axis areas with only the eastern and western bays remaining calm enough to survey. They also noted that the harbour water was particularly energetic during and after southerly wind conditions, which were effectively funnelled south to north along the harbour.

In terms of tidal currents, LINZ (2008a) noted evidence of scouring along the eastern coastline between Lushington Bay and Green Point, which they suggested were likely to be caused by stronger tidal streams in those areas.

Hicks and Marra (1988) measured current speed and direction over spring and neap tidal cycles at six stations within Akaroa Inlet. Off Green Point, they measured peak flood and ebb tide currents of 18 cm s^{-1} and 20 cm s^{-1} respectively, 7 to 8 cm s^{-1} higher than theoretical speeds calculated using tide levels. Observations indicated that flow convergence at this site was, in part, responsible for the higher than expected current speed findings.

Hicks and Marra also note the presence of a scour channel along the northern flank of the Green Point reef. Kingett Mitchell Limited (2006) reported that maximum tidal currents in the vicinity of Green Point were in the order of 10 cm s^{-1} , fluctuating in direction and magnitude near the shore. Hicks and Marra (1988) found that flow speeds within Akaroa Inlet itself were generally less than 10 cm s^{-1} , with ebb tide flows being slightly quicker than those of the flood tide. They also noted convergence of the flow on flood tides flowing past the headland at the southwest corner of Childrens Bay and off the mud flats into the channel past the boat ramp at the southeast corner of Childrens Bay.

The wave environment in Akaroa Harbour consists of a combination of swell waves, generated in deepwater and propagated into the harbour, and near-field wind waves generated within the harbour confines (Taylor 2003). As swell waves propagate from deepwater into the shallow water of Akaroa Harbour, friction with the seabed causes both shoaling and refraction.

Although there are no data from direct wave measurements within Akaroa Harbour, Dingwall (1966) showed that very little wave energy is transmitted into the harbour under most deepwater wave conditions. Significant transmission of wave energy up the harbour was found to only occur when the deepwater swell was approaching from the southeast (135°). Taylor (2003) concluded that refraction of these deepwater waves within Akaroa Harbour is significant.

Hicks and Marra (1988) derived the local extreme wind-wave heights for Akaroa Inlet from 10 years of New Zealand Meteorological Service wind observations at Akaroa township, plus local observations. Observations were of extreme south to south-westerly wave heights of 2 to 3 m at the main Akaroa wharf. The wave height maxima calculated for Childrens Bay from wind records were 0.87 m for SW wind speeds up to 15 m s^{-1} .

DTec (2008) used wind data from the same Meteorological Service site over 23 years to calculate the theoretical extreme heights of waves generated by winds blowing directly into each of bays in the upper harbour versus those generated by northerly and southerly winds blowing up and down the harbour and then refracted into the bays. The resulting wave heights are presented in Appendix 3, which shows that for all bays, the wind waves travelling directly into the bays were found to be fetch limited, except for Duvauchelle Bay (depth limited), with the most limited waves occurring in bays facing east and west (e.g. French Farm and Takamatua). In all of the bays, except Duvauchelle and Barrys Bays, the theoretical maximum refracted wind

waves were calculated to be larger than the direct wind waves. Maximum theoretical heights were depth limited to 1.5 m in Duvauchelle Bay for southerly winds above 27 m s^{-1} .

2.5 Biological Communities

Fenwick (2004) presented baseline data on the ecological state of the marine environment of Akaroa Harbour, including intertidal rocky shore fauna and subtidal soft bottom fauna as well as exploring relationships between abiotic and biotic patterns for these communities. The biota found in Akaroa Harbour comprised species of mollusc, polychaete, crustacean and other animals that are widely distributed around Banks Peninsula and along the wider South Island east coast. A total of 136 benthic species were found in the 30 measured samples (Figure 4) with 33% of species present in only 1 to 2 samples while 25% occurred frequently.

Amongst the soft bottom samples, species diversity was found to increase along the central axis of the harbour, towards the open-ocean entrance (southward). Mean faunal densities also increased southwards, with gastropods decreasing relative to polychaetes, crustaceans and bivalves.

Of the rocky shore samples, two species of barnacle dominated the mid/low-shore biota at the outer harbour Lucas Bay site, with species diversity higher lower down the shore. At sites half-way along the harbour, at Cape Three Points and in Tikao Bay, barnacles dominated mid-shore while several species co-dominated at the low-shore. The biota was consistently more-diverse, and dominance was less at low-shore levels and at higher wave exposures, throughout these three sampling areas.

Fenwick (2004) reports that the general subtidal species distribution patterns found were strongly-correlated with levels of wave exposure (which increase towards the harbour entrance), the organic, zinc and copper content of sediments, and with water depth. Intertidal distributions appeared to be largely controlled by wave exposure, with shading also a likely influence in Tikao Bay. It was not possible to detect any human impacts on the intertidal biota, perhaps due to the lack of historical data and sampling design.

Along with the sediment analyses described above, Bolton-Ritchie (2005) also examined the macrobiota of the intertidal flats of upper Akaroa Harbour, including faunal distributions and seagrass (*Zostera* spp.). She identified 104 taxa, which were dominated by molluscs, polychaetes and crustaceans and which represent species typical of enclosed harbour flats and estuaries in New Zealand. Communities were more similar within, than between, bays, reflecting differences in the suite of natural physical and biological factors affecting each bay's mud flats, with the flats of Robinsons Bay exhibited the richest biological communities.

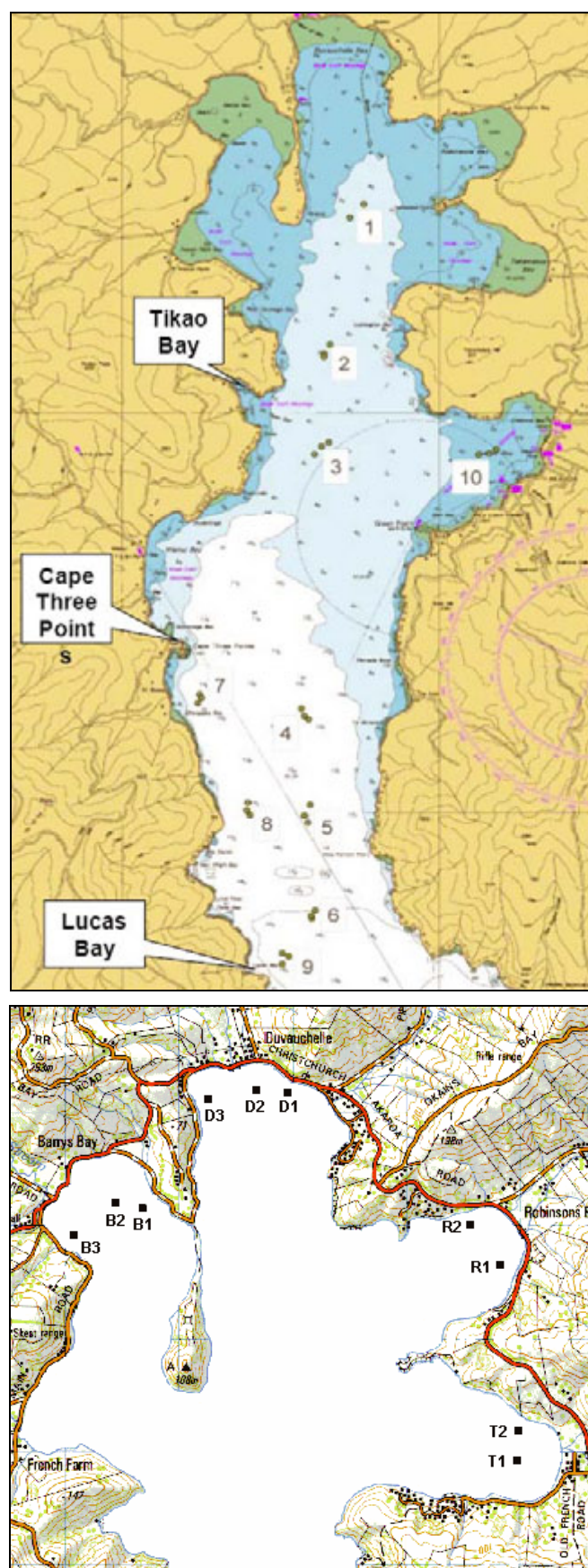


Figure 4 Location of biotic sampling sites used in previous research: above from Fenwick (2004, p3) and below from Bolton-Ritchie (2005, p5)

Cockles (*Austrovenus stutchburyi*) and wedge shells (*Macomona liliana*) contributed most of the biomass found. These species are important mahinga kai and as food for wading birds, flounders and predatory molluscs. Patterns of abundance and size of the cockles found was perhaps, in part, due to human harvesting and not just the product of abiotic and biotic influences. Seagrass was an important component of the biological community on each flat and functioned to stabilise sediments. This plant provides habitat and food for a range of organisms including gastropods and crustaceans (Bolton-Ritchie 2005).

Bolton-Ritchie (2005) commented that her findings support the classification of the upper Akaroa Harbour intertidal mudflats as 'Areas of Significant Natural Value' (ECan 2005, Schedule 1). This is in addition to the part of the outer harbour that has been a proposed marine reserve since 1996 (Figure 5; DOC 2009a). Bolton-Ritchie (2005) goes on to note that in order to ensure the sediments and macrobiota of these flats remain healthy, any proposed developments such as suburban subdivisions or catchment landuse changes should be thoroughly assessed with respect to likely impacts on associated intertidal flats, with consideration given to the conditions of any consents granted to include relevant seabed sediment and macrobiota monitoring. Where possible in this report we will compare the biotic patterns found by Bolton-Ritchie (2005) and others with patterns emerging from our abiotic (sediment and bathymetry) findings.

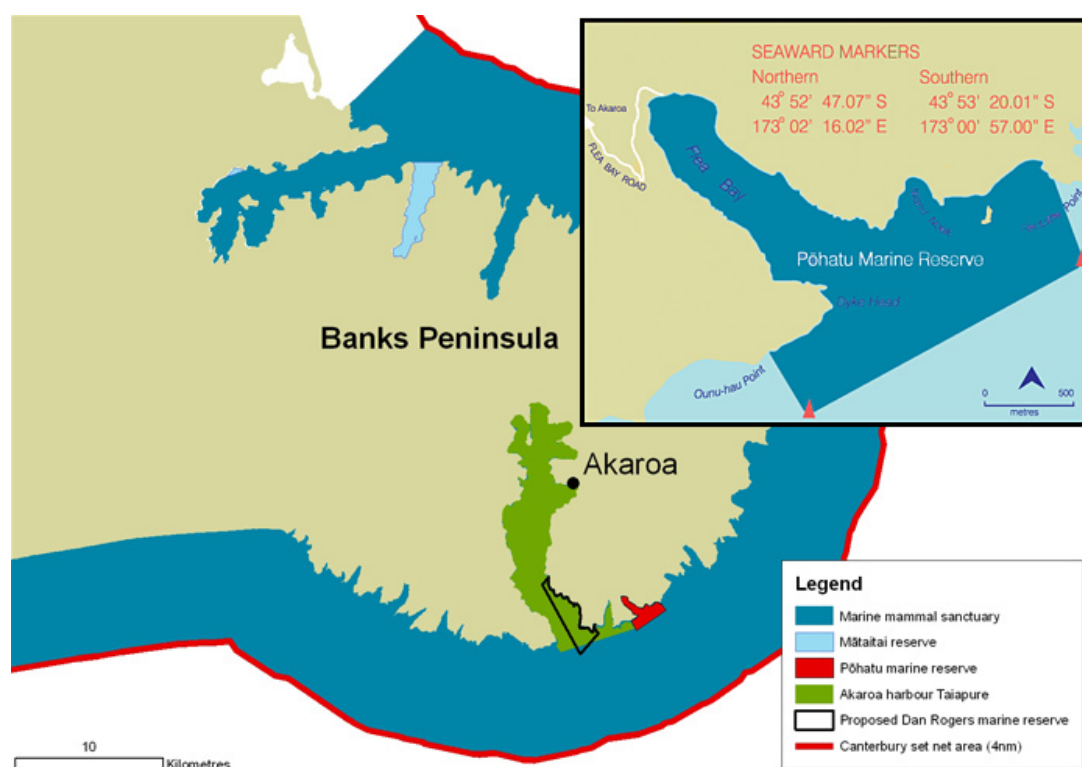


Figure 5 Map of proposed 'Dan Rogers' marine reserve and other management designations in and near Akaroa Harbour (DOC 2009b)

Another biotic study of Akaroa Harbour, Pirker (2002), focussed on the kelp forests. He described them as generally highly productive, with maximum giant kelp, *Macrocystis pyrifera* (Linnaeus), growth rates comparable to other southern hemisphere populations but considerably lower than northern hemisphere populations. He found physical factors affecting kelp growth and recruitment in Akaroa Harbour included seasonal changes in water turbidity, sedimentation and the deterioration of the surface canopy during summer (and, as a comparison, these factors were not found to be important in Tory Channel). Kelp recruitment in Akaroa Harbour also appeared to be nutrient limited, even at moderately low temperatures, meaning that significant changes in the harbour's nutrient regime could have flow-on effects for the kelp forests.

Daly (2004) conducted a desktop inventory of instream values for the rivers draining into Akaroa Harbour, amongst other Canterbury sites. In Akaroa Harbour's catchment he identified the presence of a diverse invertebrate fauna, a number of native and other fish species including longfinned and shortfinned eels, inanga, banded kokopu, perch, goldfish and brown trout. Overall he described the harbour streams as an important recreational and mahinga kai resource, with values classed as high for swimming; moderate for walking, eeling and other fishing; and low for bird-watching, trout angling and waterfowl hunting. This inventory shows evidence of human impacts on the fauna of the harbour catchments. It also reminds us of the importance of links between the harbour and its adjacent freshwater and terrestrial environments given that several species and abiotic processes transition across these three environments.

3. Methodology

3.1 Bathymetric surveying

All the intertidal surveys and fixing of sediment sample locations were undertaken using the New Zealand Geodetic Datum (NZGD 2000) coordinates. A *Trimble R8 Dual-Frequency GNSS* (Global Navigation Satellite System) was employed for surveys and location fixing, with sediment sample locations and the LINZ (2008a) survey points pre-programmed. A *Trimble* base station set up at Geodetic benchmark Akaroa Primary TGRM code A5N0 order 5 (LINZ 2008b) located in Barrys Bay for position and elevation control and real-time kinematic corrections (Figure 6a):. A radio-signal repeater was mounted on top of Takamatua Hill near the geodetic benchmark Akaroa Primary TGRM code B410 order 5 (Figure 6c) or in the *Beagle* (boat) as required to get a signal from the base station to the southern extent of the survey area.

Bathymetric surveys of the intertidal portions of Barrys Bay, Duvauchelle Bay, Robinsons Bay, Takamatua Bay, Akaroa Inlet, Wainui Bay, Tikao Bay, Petit Carenage Bay and French Farm Bay were conducted on foot using the GNSS-system backpack-mounted set-up and a point-recording interval of 5 s (Figures 6b and d). The pre-programmed LINZ data allowed for accurate navigation to, and overlap with, their subtidal survey areas.

Within each bay, the surveyors walked in lines approximately parallel to the shore and representative of contours, and spaced at or less than 250 m, depending on bay size, from the shore out to the limit of wading depth. This intertidal fieldwork was carried out around low tide to ensure that each bay could be surveyed as far offshore as possible. The accuracy of the intertidal bathymetric survey data is 20 mm horizontally and 50 mm vertically, a level deemed acceptable to fulfil the mapping and repeatability objectives of this study.

The intertidal bathymetric data were combined with the LINZ (2008a) subtidal data into a Digital Terrain Model (DTM) using the software programme *Golden Software Surfer 8* to interpolate the bathymetric contours. The shoreline position was derived from the 1:50,000 New Zealand topographic map (LINZ 1998).

Using the Environmental Systems Research Institute's *ESRI ArcView* software programme, bathymetric maps were produced at 1:10,000 for the 6 main surveyed bays (Table 2), with contours at 0.25 m or 0.5 m intervals depending on the steepness of each bay's seabed. A bathymetric map of the whole upper harbour was produced at a scale of 1:30,000 with contours mapped at 1 m intervals (Table 2). These maps provide considerably more detail than the updated New Zealand Hydrographic Chart NZ 6324 (LINZ 2009b), which has subtidal contours at 5 m intervals and spot heights at 500 m spacings, with very limited intertidal spot heights. All contour elevations on the maps provided in this report are relative to MSL.



Figure 6 The GNSS survey set-up including a trig-mounted base station (top left), intertidal contour mapping (top right), a radio repeater overlooking Akaroa Harbour (bottom left) and the Trimble GNSS backpack (bottom right). Photographs by Justin Harrison.

Table 2 List of bay contour maps and corresponding scales produced.

Bay name	Map number	Map scale	Contour interval (m)
Akaroa Harbour	2	1:30,000	1
Wainui Bay	3	1:10,000	0.5
French Farm Bay	4	1:10,000	0.25
Barrys Bay	5	1:10,000	0.25
Duvauchelle Bay	6	1:10,000	0.25
Robinsons Bay	7	1:10,000	0.25
Takamatua Bay	8	1:10,000	0.25
Akaroa Inlet (incl. Childrens, French and Glen Bays)	9	1:10,000	0.25



Figure 7 The 2.4 litre volume *Wildco Petite Ponar* grab sampler used to collect subtidal sediments from the *Beagle*. This grab has a sample area of 152 x 152 mm (Photograph by Nicholas Key).

In addition to the contour maps, longitudinal transects were extracted from the gridded survey data running along the central axes of the whole upper harbour, and of the main upper harbour bays: Barrys, Duvauchelle, Robinsons, Takamatua, French Farm and Wainui Bays, with two in Akaroa Inlet (from Childrens and French Bays). The same transects were located on the 1988 Hydrographic Chart (LINZ 1988), and comparisons made with the 1952 survey data presented on this chart. It is recognised that any changes detected via these comparisons can only be considered indicative due to the coarse nature of the 1952 data presented on the 1988 Hydrographic Chart.

3.2 Surface sediment sampling and analysis

A total of 89 sediment samples were collected using a sample grid of approximately 500 m spacing within the bays and 1 km spacing in central harbour areas, using the GNSS system to accurately locate sample sites. Sample locations are shown on Map 1 while the coordinates and sampling depths are on the CD accompanying this report (see Appendix 2 for a file list) and in the sediment results tables in Appendix 4. No samples were collected from the narrow beaches above the high tide line. In many of the bays of the harbour the sediment in this location is gravel, cobbles and boulders, with much of the larger material having been placed as shoreline protection works against erosion of the road network. This sediment does not form part of the sub- and inter-tidal soft sediment environment.

Subtidal sediments (AKA samples 001 to 010, 012 to 013, 017 to 036, 038, 040 to 049, 059 to 066, 069 tot 072, 077 to 081 and 085 to 088) were sampled from onboard the anchored *Beagle*, the University of Canterbury Department of Geography boat, using a spring-loaded grab sampler (Figure 7). Intertidal sediments (AKA samples 037, 039, 050, 056 to 058, 067, 068, 073 to 076, 082 to 084, and sample TIKAUZ2) were sampled using a hand trowel to a depth no greater than 0.2 m below the sediment surface, a depth which was comparable to that from the subtidal technique. Sample retrieval was repeated at all sites until at least 500 to 800 ml of sediment was retrieved.

Comprehensive particle-size analysis was performed on all samples including wet sieving, dry sieving and pipette analysis according to the standard guidelines of Lewis and McConchie (1994), to obtain the percentages in each size class (Table 3). Samples were coned and quartered until the final volume contained an estimated fine fraction (silts and clays) less than 20 g, 20 ml of Calgon solution (sodium hexametaphosphate) was added to each to decrease flocculation and samples were wet sieved through a 62.5 μm mesh (0.0625 mm or 4 Φ). The fine fraction (smaller than 62.5 μm) was placed in a measuring cylinder for pipette analysis and the remaining coarse fraction placed in an oven to dry for dry sieving.

The analysis involved determining the percentage of each sample in each of the sediment size classes given in Table 3, determining the sediment texture class of each sample as per the modified Folk (1965) classification presented in Figure 8, and calculating mean and medium grain size, and sorting of each of the samples. Maps were then produced of the percentage concentration of gravel, sand, mud and clay across the harbour at 1:70,000 scale (Map 10), and of the spatial distributions of the sediment texture classes, with and without bathymetry at 1:30,000 scales (Maps 11 and 12), and of the. The boundaries between the textural classes in Map 11 and 12 were determined by mean distance between samples, so should be taken as indicative rather than absolute locations.

Table 3 Udden-Wentworth grain size scale used in describing results.

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

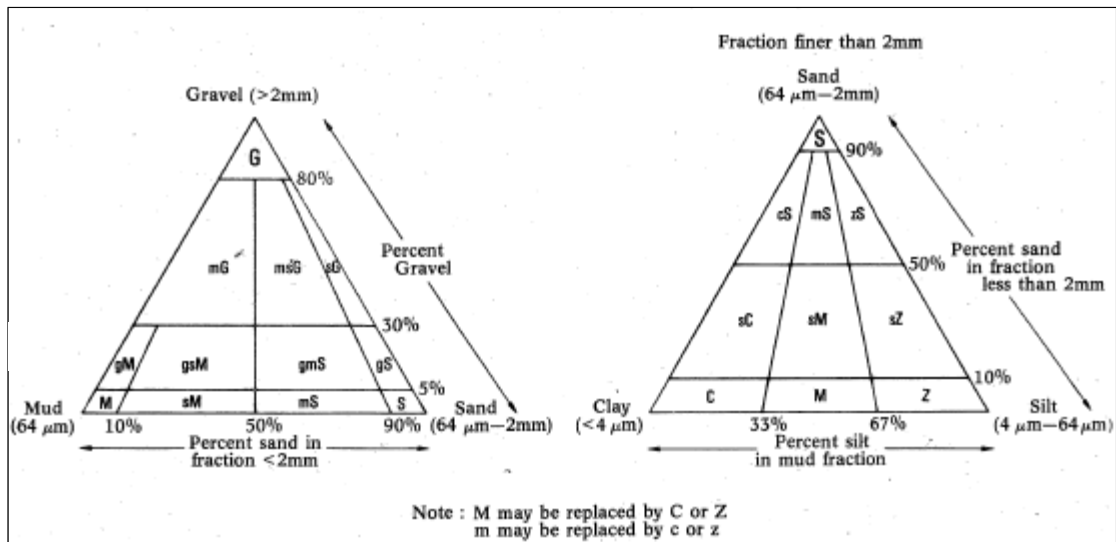


Figure 8 Textural sediment classification modified from Folk (1965) by Carter and Herzer (1986). Classes include gravel (G, g), sand (S, s), silt (Z, z), clay (C, c) and mud (a mixed silt and clay class: M, m). Capitals indicate the dominant constituent.

4. Results and Interpretation

The following sections describe the main findings from the bathymetry and sediment surveys of Akaroa Harbour and its intertidal bays. The maps and transects produced from the surveys are presented at the back of the report and on the CD supplied to ECan with this report. A digital copy of the raw data from the surveys and the Geographic Information System (GIS) shape files used to construct the maps are also included on the accompanying CD (see Appendix 1 for a list of the digital data on the CD).

4.1 Bathymetry

Map 2 illustrates the bathymetry of the whole Akaroa Harbour survey area at a scale of 1:30,000 while Maps 3 to 9 illustrate the bathymetry of each of the main harbour bays individually at scales of 1:10,000. Transect Plot 1 presents a long section of the harbour floor bathymetry along the central axis of the upper harbour from Duvauchelle to the southern limit of the survey area. Transect Plot 2 compares cross-sectional transects for each of the upper harbour bays derived from the shape files on the accompanying CD.

Note that on the bathymetric maps and transects all elevations are in terms of MSL, with the areas between the +1 m and -1 m MSL contours representing the intertidal foreshore zone based on (Table 1). All harbour areas deeper than the low water level are considered to comprise the nearshore zone since even short period waves are able to interact with the sea bed at all harbour depths over the survey area.

General patterns

Maps 2 and Plot 1 show that elevation of the upper harbour bed within the study area ranged from a maximum level of around +1 m MSL at the shores of all of the major bays to a minimum level more than -13 m MSL towards the centre of the southernmost study-area boundary between Cape Three Points and The Kaik.

As shown in Transect Plot 1, the central harbour axis bathymetry is gently sloping outside the bays of the upper harbour, descending at a slope of 1:1200 from -6.5 m MSL opposite the entrance of Robinsons Bay in the north to around -11.5 m MSL opposite the entrance to Wainui Bay. Thereafter the seabed slopes slightly more steeply (1:800 to 1:600) towards the southern limit of the study area, but at slopes still less than found inside the upper harbour bays.

As shown on Map 2, the alignment of the contours along the central axis of the harbour is generally north to south in areas north of the constriction caused by Takamatua Hill. South of this constriction the contours run more northwest to southeast, across the orientation of the central harbour axis. Map 2 also shows two troughs or low points located close to the shore on either side of Lushington Bay. The larger of these troughs reaches a depth of -14 m MSL, which is in the order of 6 m below the general elevation of the seabed in this area. The smaller trough reaches -11 m MSL, around 2 m below that of the surrounding bed in this area. A third trough

reaches -10 m MSL at Green Point, around the southern part of the entrance to Akaroa Inlet.

It is assumed that these troughs are the locations that the LINZ (2008a) report suggests are caused by scour induced by the stronger tidal streams found in these areas. However, the deeper of the Lushington Point troughs appears to be too deep to be formed by scour from tidal current velocities. Maximum measured tidal velocities at Green Point, for example, were around 20 cm s^{-1} in this area (Hicks and Marra 1988). The morphology of the three troughs also appears inconsistent with tidal current scour formation, this mechanism being more likely to produce channels than depressions defined by a central low point. Apart from a small reef at Green Point, the survey identified no significant high points or ridges on the bed of the harbour (in contrast to Lyttelton Harbour as reported in Hart *et al.* 2008).

In conjunction with the wider upper harbour views shown in Maps 2 and Transect Plot 1 the detailed individual bay bathymetry surveys illustrated on Maps 3 to 9 and Transect Plot 2 reveal differing bathymetric patterns between the more-gently sloping inner, and steeply sloping outer nearshore environments of upper Akaroa Harbour.

Wainui Bay

As shown by the dense contours of Map 3 and the steep transect on Transect Plot 2, Wainui Bay exhibits a very steep foreshore and nearshore morphology, which descends at an average nearshore slope of 1:33 to the -10 m contour towards the bay entrance. A small ridge, around 0.5 m high, is present around this depth across the southern half of the entrance to the bay. Slopes on the seaward side of the ridge fall steeply, at 1:40, to the -12.5 m contour, after which slopes become relatively flat across the central axis of the harbour. Across the northern half of bay entrance, the seabed below the -10 m contour slopes more gradually, at 1:200, out towards the relatively flat central axis area, which begins at around the -12 m contour.

Map 3 also indicates that mudflat development is absent in Wainui Bay, with the steep morphology contrasting with the gently sloping foreshores and nearshore areas of the upper harbour bays. This morphology is indicative of an outer harbour environment exposed to relatively-high wave energies and/or one in which a limited depth of unconsolidated sediment overlies a steep bedrock substrate.

French Farm, Barrys, Duvauchelle, Robinsons and Takamatua Bays

French Farm, Barrys, Duvauchelle, Robinsons and Takamatua Bays are all characterised by gently sloping intertidal mudflats and outer bay environments, reaching -4 to -5 m MSL at their entrances (Maps 4 to 8). The slopes of these bays from the shore to their entrance range between 1:500 and 1:250 (Transect Plot 2).

Barrys Bay has the gentlest sloping foreshore and nearshore of the upper harbour bays (Transect Plot 2). It is characterised by 600 m-wide intertidal mudflats between the +1 m and -1 m contours (Map 5), with no distinctive break in slope across the inner nearshore to a depth of -4 m MSL opposite the entrance to French Farm Bay. The bay's central axis runs north to south, parallel with the main axis of the upper harbour. The bay is somewhat sheltered from the latter by the flanks of Rocky Peak, which form a significant shoreline protrusion into the harbour between Wainui and Farm Bay (Map 2). Southerly waves moving up the harbour are refracted and

diffracted around this promontory, a process whereby they lose some of their energy via friction, then spread out across the shallow entrance to the French Farm and Barrys Bay Inlet. They are then refracted and diffracted again around the Onawe promontory, before funnelling up Barrys Bay with considerably reduced energy. This low energy environment allows the development of the extensive mudflats in Barrys Bay.

French Farm Bay is sheltered by the same large protrusion from Rocky Peak. The result is a typically sheltered headland lee wave environment as reflected in the shape of the seabed contours entering French Farm Bay. The foreshore and nearshore mudflats slope towards the northeast-facing entrance of the bay to join with the shallow water (e.g. -3.5 m MSL) in the middle of the central axis of Barrys Bay (Map 4). The French Farm Bay transect on Transect Plot 2 shows that the intertidal mudflat is around 400 m wide, with slopes in the order of 1:200. Beyond this mudflat area a distinct break in slope occurs over a short (150 m), relatively steep (1:100) section up to the -2.5 m contour. Thereafter the seabed flattens to slopes of around 1:250 towards the middle of the central axis of Barrys Bay.

Directly across the upper harbour, Robinsons Bay faces west-southwest while Takamatua Bay faces west (Map 2). Robinsons Bay is slightly steeper, with 400 m-wide intertidal mudflats and slopes in the order of 1:200 (Map 7). As in French Farm Bay, the intertidal mudflats give way to a distinct, short and relatively steep inner nearshore section up to the -3 m contour, beyond which the seabed slopes more gently (1:260) towards the -6 m contour at the entrance to the bay (Transect Plot 2).

In contrast, Takamatua Bay is more similar to Barrys Bay, having a 500 m wide intertidal mudflat and little variation in slope across the inner nearshore and out to the -5 m contour towards the bay entrance (Map 8). Slopes across the whole bay are in the order of 1:300 (Transect Plot 2).

The slightly gentler slopes of the Takamatua Bay foreshore and upper nearshore mudflats may be explained by the bay's west-facing entrance, which is sheltered by the protrusion of the lower slopes of Takamatua Hill to the south. Its aspect means that southerly waves travelling up the harbour have to refract more around this promontory to enter the bay, losing energy in the process (Map 2). Also of relevance, at the Akaroa climate station on Rue Lavaud the maximum recorded westerly winds are less than the maximum recorded south-westerly winds (DTec 2008). This suggests that the size of locally-generated wind waves moving directly into Takamatua Bay will be less than those moving directly into Robinsons Bay.

Another possible contributor to the differences in foreshore and nearshore slopes found between Takamatua and Robinsons Bays could be differing rates of sediment supply from the surrounding catchments. However, the catchments of both Robinsons and Takamatua Bay have similar elevations and catchment areas, the same aspect, and are exposed to the same weather. It is also noted that the two catchments have undergone different levels of development with more housing in Takamatua Bay. Never-the-less it is concluded that differences in exposure to hydrodynamic energy within the bays have a major influence on the observed differences in bathymetry.

Unlike the other upper harbour bays, Duvauchelle Bay faces south, along the central axis of Akaroa Harbour (Map 2). It has the narrowest and, thus, steepest intertidal mudflat area of the upper harbour bays: 300 m wide with an average slope of 1:150 (Maps 6 and Transect Plot 2). This bay also exhibits the widest inner-nearshore steep section, which extends 400 m to the -4 m contour. Beyond this section the bed of the bay is very flat, descending only 1.5 m over 800 m to the entrance of the bay. This bay's steeper foreshore and inner nearshore environment reflects its relatively high level of exposure to waves moving south to north along the central axis of the harbour. The passage of waves from central harbour areas towards Duvauchelle Bay is relatively unobstructed, except that the throat of the harbour narrows between the Takamatua Hill and Rocky Peak promontories, and to the extent that the increasingly shallow bed would progressively reduce wave energy via shoaling. Waves travelling up the harbour would undergo relatively little refraction until passing through the bay's entrance to the north of the Onawe promontory and Hammond Point (Map 2).

Tikao Bay and Petit Carenage Bay

Tikao Bay and Petit Carenage Bay exhibit narrow mudflats, with foreshore and nearshore slopes intermediate between those of Robinsons and Wainui Bays (Map 2). The small areas and narrow widths of these mudflats are clearly a product of the small size of the two inlets.

Akaroa Inlet

The bathymetry of Akaroa Inlet approximates, but is slightly steeper than, the five large and shallow upper harbour bays described above, with average foreshore slopes of 1:200 along cross-sections from both Childrens Bay and French Bay (Maps 9 and Transect Plot 2). This bathymetry is perhaps reflective of the position of the inlet within the harbour: north of the exposed Wainui Bay but south of the relatively-sheltered upper harbour, the latter of which is situated north of the constriction caused by the Takamatua Hill and Rocky Peak promontories.

The intertidal mudflats of Akaroa Inlet are also narrower than those of the upper harbour bays but wider than those of Wainui, ranging from around 200 m in width in Childrens Bay towards the north of the inlet, to around 50 m in French Bay. The latter includes a swimming beach constructed with imported sand. Intertidal mudflats are absent in Glen Bay at the south end of Akaroa Inlet (Map 9). It is considered that this pattern of mudflat development reflects the orientation, shape and hydrodynamics of the inlet.

Map 9 also indicates a couple of small irregularities in the seabed topography: a small exposed rock outcrop at the low tide level towards the northern end of French Bay; and a small trench running perpendicular to the shore between French Bay and Glen Bay at a depth of 4 m and 5 m below MSL.

4.2 Surface sediments

Detailed size analysis results for each of the intertidal and subtidal bed sediment samples, located on Map 1, are presented in Appendix 4 as well as on the accompanying CD while their spatial distributions are illustrated in Maps 10 to 12.

Note that the mapped distributions do not include the narrow beaches above the high tide line, as no samples were collected from this area in any of the bays.

Map 10 illustrates the distribution of gravel ($>2000\ \mu\text{m}$ or 2 mm), sand (2000 to $62.5\ \mu\text{m}$), silt (62.5 to $4\ \mu\text{m}$) and clay ($<4\ \mu\text{m}$) fractions in upper Akaroa Harbour according to their percentage composition of the bed samples (see Table 3 for textural class details). Map 12 illustrates the bed sediment textures of each sample classified according to a modified Folk (1965) scheme (refer to Figure 8 for details). In this map the textural classes overlie a colour-coded areal representation of the sediment textures according to their primary ($>50\%$) and secondary (25-49%) constituents. Map 13 illustrates the distribution of these primary and secondary textures against 1 m-interval bathymetry contours in relation to MSL.

The sediment distributions illustrated in Map 10 reveal the following general patterns:

- High gravel concentrations were only found in three isolated areas of the harbour: the steep intertidal and inner nearshore parts of central Wainui Bay (samples 14-16, Appendix 4); at -5.7 m MSL off the headland at the northern side of the entrance to Akaroa Inlet (Sample 33); and at -3.8 m MSL close to the south facing headland between Duvauchelle and Robinsons Bays (sample 65). The gravels from Wainui Bay were not biogenic while those from near Akaroa comprised 50% shell and those from near Robinsons Bay were 100% shell. As already indicated, gravel is also present in varying concentrations along many of the upper harbour shorelines, areas not represented by the sampling framework used in this study.
- Sand was predominantly found in the intertidal zone, between +1 and -1 m MSL, of the upper harbour bays except in Wainui. Sand concentrations rapidly decreased towards the bay entrances and were largely absent from the central harbour axis seabed. From Appendix 3 it can be seen that the majority of sand sized material comprised fine to very fine sand, with coarser sand present in significant quantities (e.g. $> 30\%$ of sample weight) only in the intertidal areas of the western corners of French Bay (sample 50) and Duvauchelle bay (Sample 84), and in inner nearshore areas of northern Wainui Bay (sample 13) and Tikao Bay (sample 37), and in central Takamatua Bay (sample 55). Since only the Wainui sample contained significant concentrations of sand derived from shell, it is suggested that these coarse sand gains were predominantly from rock origin, consistent with their location near the stream outlets into the bays.
- Silt was found in all harbour environments, except close to the gravelly shore at Wainui and in the sandy shore of Tikao Bay. In all of the bays silt concentrations generally increased away from the shore, becoming the dominant sediment class in outer bay areas. Outside of the bays silt concentrations decreased slightly, occurring in nearly equal proportions to clay on the bed of the central harbour axis.
- Clay was largely absent from the intertidal areas of all of the upper harbour bays except in the western corner of Barrys Bay. Clay concentrations increased across the inner-nearshore and outer parts of the bays, but remained a secondary mode to the dominant silt-sized material. Concentrations increased further across the central harbour seabed to reach similar levels as the silt-sized material.

The distribution of sediment textures in Map 11 shows that there is a lot of mixing of sediment classes and very few areas characterised by only one sediment size class. Only four samples of pure sand (>90% according to the modified Folk 1965 classification) were collected. These were from the intertidal and inner nearshore areas of Tikao Bay (samples Z2 and 37); the inner nearshore zone at north Wainui Bay (Sample 17); and the intertidal area at the northwest end of Takamatua Bay (sample 60). In none of these four samples was shell a significant contributor to the volume of sand-sized material collected. All were predominantly well-sorted fine to very-fine sands, except for the Tikao Bay inner nearshore sample, which comprised poorly-sorted coarse sand. In intertidal and inner nearshore zones, from +1 to -3.5 m MSL, the majority of sand found was mixed with silt and, thus, classed as silty-sand or sandy-silt according to the modified Folk (1965) texture classification (Figure 8). These samples were typically poorly or very poorly sorted, with mean and medium grain sizes in the very-fine sand or coarse silt classes (Appendix 4).

There were also very few samples with pure (>90%) silt classifications. As shown on Map 11 these were limited to: seven inner nearshore (+1 to -3.5 m MSL) samples from Barrys Bay (samples 71 and 72), French Bay in Akaroa Inlet (samples 22 and 23), the south side of Takamatua (sample 54), French Farm (sample 51) and Petit Carenage (sample 41) Bays; plus four samples from the outer parts of Duvauchelle Bay (samples 79 to 81 and 87); and one central axis sample (sample 2) opposite the south end of Wainui Bay. All of these samples except one from Duvauchelle Bay (sample 79), contained 20 to 32% clay, were poorly sorted and had mean grain sizes in the fine silt class (Appendix 3). Sample 79 only contained 6.5 % clay but also contained 4.5% sand, making it poorly sorted with a mean grain size in the coarse-silt class.

As illustrated on Map 11, only four samples (35, 43, 44, 46), from the central axis at the throat of the upper harbour and across the front of Takamatua Bay, had greater than 50% clay concentrations. All four contained less than 60% clay. Therefore, no samples were classified as pure (>90%) clay under the modified Folk (1965) texture classification.

Of the twenty samples collected from the central axis of the harbour, eighteen contained silt to clay ratios less than 2:1, so were classified as mud. Of the other two samples, one (sample 2) had a ratio very close to 2:1, while the other (sample 3, southern of Akaroa Inlet) had a silt to clay ratio close to 1:1 and was classified as sandy mud due to its 30% sand concentration. This sandy material was almost totally shell.

Sediment classified as mud was also found in deeper areas, below -6 m MSL, of Akaroa Inlet (samples 20 and 28 to 30), along the central channel of the French Farm-Barrys Bay Inlet (samples 48, 52, 53 and 86), and at the south side of the entrance to Takamatua Bay (sample 45). The seabed sediments at these locations appear to be a function of depth (i.e. lack of stirring by waves) and low energy. Surprisingly no mud was found in Robinsons or Duvauchelle Bays, suggesting that settlement of clay-sized material is limited in these bays due to more regular stirring of the bed by their higher-energy wave climates. The only place where sediment classified as mud was found in the intertidal zone was the very sheltered western corner of Barrys Bay (sample 76).

Table 4 summarises the minimum, maximum, average and standard deviations of concentrations of the four major sediment textures and shell in the sampled Akaroa Harbour sediments. The average values should be interpreted cautiously, not as ‘upper harbour averages’, since they are simply averages of our sample population (i.e. not spatially-weighted according to the area of each surface sediment zone). These values are, however, demonstrative of the overall dominance of silt in samples (making up over 50% of the total), with sand and clay comprising almost a quarter of the remaining sediment, clay content being more consistent. Gravel, as indicated above, occurred in only a few samples. Small concentrations of shell were present in many of the samples, averaging 4.7% overall.

Table 4 Summary of the percentage of shell and different size classes in sampled sediments (see Appendix 4 for more detail)

	Shell (%)	Gravel (%)	Sand (%)	Silt (%)	Clay (%)
Min	0	0	0	0	0
Max	100	100	100	89.2	55.1
Average	4.7	5.7	25.6	46.6	22.4
Standard deviation	13.3	23.3	31.1	22.8	17.5

4.3 Relationships between bathymetry and surface sediment textures

The above results indicate that the distribution of sediment textures in samples from upper Akaroa Harbour appears to be related to a combination of three key factors: depth; distance from the shoreline; and distance along the central axis of the harbour (see Map 12 and Transect Plot 1). That is, sediment textures generally became finer with increasing depth, from the shorelines of the bays towards the central axis of the harbour. For all of the bays except Wainui Bay, the general trend away from the shore is the same as shown on Transect Plot 1 for the harbour central axis; going from silty sands in the intertidal zone, to sandy silts in the inner nearshore, to silts in the outer reaches of the bays, to mud at depths of 6 m or more. At Wainui Bay, there is a fining with depth but the texture of the bed changes quickly from gravel to silty sand at the bay entrance, which at -12 m MSL is relatively deep, to mud along the central axis of the harbour.

However, the trend of increasingly fine sediment with depth does not continue down the central harbour axis south of Akaroa Inlet (see Maps 11 and 12, and Transect Plot 1). From this location the percentage of clay in the sample decreases from around 50% to 30%. This is considered most likely due to the increasing exposure of the outer study area to hydrodynamic energies moving up the harbour.

The relationship between bathymetry and the concentrations of the different sediment size classes in the samples is shown in Table 5. As can clearly be seen, the concentration of sand-sized sediment decreases with depth, while the concentrations of silt- and clay-sized sediments increase with depth. The table also identifies the dominant size class in each zone as: sand in the intertidal zone; silt in the inner

nearshore and outer bays zones (regardless of depth); and silt and clay co-dominating the central axis zone.

Table 5 Summary of the percentage of shell and different size classes in sampled sediments from each sub-environment of upper Akaroa Harbour (see Appendix 4 for details)

from each sub-environment of upper Akaroa Harbour (see Appendix 4 for details)						
	Shell (%)	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	Notes
	Intertidal sites: +1 to -1 contour (18 samples)					
Min	0	0	13.6	0.6	0	Does not include any samples from gravel intertidal area at Wainui
Max	17.5	0	99.2	67.6	35.0	
Average	3.2	0	57.8	34.8	7.4	
	Inner nearshore zone: -1 to -3.5 m contour (28 samples)					
Min	0	0	0	0	0	Includes 4 gravel and sand samples from Wainui
Max	43.7	100	99.9	73.9	41.7	
Average	4.8	10.7	31.5	42.4	15.5	
	Outer limits of bays zone: -3.5 m to -6 m contour (15 samples)					
Min	0	0	0	0	0	Includes 2 gravel samples dominated by shell
Max	100	100	23.4	89.2	37.6	
Average	11.9	13.3	8.1	57.2	21.7	
	Deep outer deep zone: Wainui and Akaroa Inlet (7 samples)					
Min	0.1	0	1.5	47.7	4.6	Includes 3 samples in Wainui and 4 in Akaroa
Max	4.9	0	37.0	57.8	45.9	
Average	1.6	0	20.9	53.9	25.3	
	Harbour central axis zone: Deeper than 6 m (20 samples)					
Min	0	0	0.5	37.0	32.7	Includes one sample with shell/sand contribution
Max	26.9	0	30.1	65.9	55.1	
Average	1.8	0	3.4	52.2	44.4	

The trend of increasingly fine sediment away from the shoreline towards the harbour centre line is consistent with two, related phenomena. Firstly, greater hydrodynamic energies are exerted on the seabed in shallow environments due to the interaction of the wave base, which is proportionate to wave length. As a result, coarser sediments remain on the foreshore and in the surf zone while fine sediments are transported out of such areas. Secondly, fine sediments may be transport for greater distances away from the shore before dropping out of the water column to settle in deeper, calmer environments (i.e. the null point hypothesis).

The latter concept relates to fines sourced from catchment runoff to the shoreline while the former concept can lead to the redistribution of sediments at a range of depths within the harbour depending on the length of waves reaching the upper harbour and is not necessarily a function of catchment sources. The observed trend of increasingly fine sediment with depth could be slightly blurred by the small amounts of shell found in surface sediments since shell is not delivered from the catchment but, rather, can be produced across the harbour.

Overall the sediment and bathymetry patterns found in Upper Akaroa Harbour are suggestive of a relatively sheltered environment, with hydrodynamic energies

increasing at the shore and to the south of Akaroa Inlet. There is no indication of sediment texture gradients across the harbour width, as was found for Lyttelton by Hart *et al.* (2008).

4.4 Comparison of 2008/2009 and 1952 bathymetric surveys

Comparisons between the 1952 survey as shown on New Zealand Hydrographic Chart NZ6324 (LINZ 1988) and the recent 2008/2009 bathymetry represented in Maps 2 to 9 give an indication of changes in the harbour seabed over the last 50 years. These comparisons involved reconstructing the 2008/9 (e.g. Transect Plots 1 and 2) from the 1952 bathymetric contours and spot depths shown on the 1988 chart, the results of which are illustrated in Transect Plots 3 to 5. The level of comparison is, however, subject to limitations concerning differences in the sounding methodologies and the sparseness of sounding points in the upper harbour bays shown on the earlier hydrographic chart, particularly in the intertidal zone. Differences in tidal level datum between the chart and Map 2 have been taken into account as explained in Table 1 above.

Despite the above limitations, Transect Plot 3 appears to show that the level of the central axis of the upper Akaroa Harbour has stayed relatively constant since 1952. The only areas of potential shallowing appear to be between Onawae Peninsula and the entrances to Robinsons and Takamatua Bays, where the bed appears to have shallowed by around 0.5 m, and between the entrance to Akaroa Inlet and Wainui Bay, where the bed has apparently shallowed by around 0.25 m. These two areas are separated by the narrowest part of the upper harbour, the throat between the flanks of Rocky Peak and Takamatua Hill. Here tidal currents travelling up and down the harbour become constricted, potentially increasing their velocities and limiting sediment deposition. It is noteworthy that the first of these potential deposition areas is in the location of the highest clay concentrations in the harbour.

The bathymetric changes along the Duvauchelle Bay transect are shown on Transect Plot 3, while the changes along transects within the four other shallow upper harbour bays (French Farm, Barrys, Robinsons, Takamatua) are presented in Transect Plot 4. All of these transects indicate that there has been a general lowering of the bed across the inner nearshore, above the -4 m contour, in each of the bays. However, for all these bays it is considered that this pattern is more likely to be a function of the spatial limitations of the 1952 sounding data, and errors in the contour locations in on the former chart (LINZ 1988) in these shallow areas, rather than actual erosion of the seabed. It is, however, likely that the deposition shown towards the outer limits of Takamatua Bay is real as this corresponds with the potential deposition on the harbour central axis in this location.

The differences in the seabed transects for the steeper Akaroa Inlet and Wainui Bay are shown in Transect Plot 5. These show a similar pattern of the 2008/2009 surveyed seabed being lower than the 1952 seabed, except that the differences between transects are greater and they occur at greater depths. Again this is considered most likely to be a function of the sparseness of 1952 sounding points, particularly at Wainui Bay, although the mapped changes in Akaroa Inlet warrant more detailed investigation. The 2008/2009 survey data sets a baseline against which future and more robust

comparisons may be made given the use of a similar level of technology and survey density.

4.5 Comparison of sediment textures with previous sediment and biotic research

The broad textural patterns found in the present study vary slightly from those described by Fenwick (2004) while approximating those described by Bolton-Ritchie (2005). The differences found are likely a function of the greater spatial distribution of sampling sites in the present study (Map 1) compared to this earlier research (Figure 4), leading to more a complex (but not inconsistent) picture of upper harbour textures.

As detailed in section 2.3, Fenwick (2004) found that surface sediment transitioned from mud in the outer reaches of Duvauchelle Bay to fine sands towards the harbour entrance. Our study did not include the lower harbour areas where Fenwick's (2004) sampling was concentrated.

For the upper harbour central axis we found a more complex pattern. Seabed sediment transitions from sandy-silts away from the shoreline of Duvauchelle Bay, to increasingly bimodal clay and silt mud in central areas adjacent to Takamatua Bay and Hill, before coarsening slightly to silt-dominated mud adjacent to Akaroa Inlet and Wainui Bay. There is some indication of the southward coarsening of sediments reported by Fenwick (2004) towards the limit of our study area, but the transition to fine sands does not appear to occur within this area.

Further comparisons between the Fenwick (2004) biological community findings and the sediment and bathymetry patterns found in this report are not particularly useful given the significant differences in sampling strategies.

Bolton-Ritchie (2005) found distinct differences in the sediment characteristics between the upper harbour bays, with Barrys Bay samples comprising up 98% mud versus Duvauchelle, Robinsons and Takamatua samples comprising up to 96.5% sand. Our results also show that the French Farm and Barrys Bay Inlet contain more extensive coverage of silts and muds while Duvauchelle, Robinsons and Takamatua exhibit more extensive areas of sandy sediments (Map 11).

However, we also found patches of silty-sand around the shorelines of French Farm and Barrys Bays, and extensive areas of silt dominated sediments in the central to outer reaches of Duvauchelle, Robinsons and Takamatua Bays (Map 11). That is, at a local level, the sample site textural results of this study and that of Bolton-Ritchie (2005) are in agreement, but the present study reveals more variable patterns within each of the upper harbour bays due to the greater sampling distribution and density.

The differences in the sediment textures found by Bolton-Ritchie (2005) between the western and eastern upper harbour bays were reflected in the biotic results, with communities being more similar within, than between, bays. This is consistent with the detailed variations in sediment textures illustrated on Map 11 as well as with the

variety of bathymetric trends described in section 5.1 above, suggested that the upper harbour bays are under a varying set of catchment and hydrodynamic conditions.

Within Akaroa Inlet, our results vary from those of Hicks and Marra (1988). That is, we found silty-sand sediments rather than mud-free sand in Childrens Bay. This difference is likely due to Hicks and Marra's (1988) sediments being sampled from higher elevations on the foreshore than those of this study. However, our results do support the general conclusion of Hicks and Marra (1988). They concluded that the distribution of textures reflected the degree of wave exposure and water depth, with the coarsest material being found in the intertidal zones where there is usually sufficient turbulence from wave breaking to prevent clay- and silt-sized materials from settling.

Comparisons with the upper Lyttelton Harbour results reported in Hart *et al.* (2008) reveal that upper Akaroa Harbour has a greater concentration of sand around the bay shorelines, particularly in the east and south of Takamatua Hill. Away from the bay shorelines both upper harbours were found to be dominated by muds, although Lyttelton exhibits greater subordinate proportions of sand and more extensive and numerous pockets of biogenic gravel in the upper Akaroa Harbour nearshore areas.

4.6 General interpretation of findings

The detailed interpretation of the combined bathymetry and sediment results is somewhat hampered by the lack of hydrodynamic and catchment runoff data for upper Akaroa Harbour. At a general level, however, the patterns found indicate that the area of high clay concentration in the central upper harbour operates as a sink for sediment that is transported and settles out of the upper harbour bays, and/ or for suspended fines swept northward along the central harbour axis to settle in this relatively sheltered area.

The bathymetry and sediment findings of this study suggest that Akaroa Harbour has a slightly more energetic zone south of Takamatua Hill; low energy sheltered environments in mid-harbour areas adjacent and north of Takamatua Hill, and in the western upper harbour bays; and slightly more energetic bays on the northern and eastern reaches of the upper harbour. These patterns are consistent with the narrowing of the harbour between Akaroa Inlet and Takamatua Bay and with the sheltering of the French Farm and Barrys Bay Inlet by the Onawae promontory.

5. Recommendations

The objectives of this study were to establish a baseline against which future changes in sediment patterns and bathymetry within the upper Akaroa Harbour could be assessed. Three key recommendations arise out of this study for additional future research as follows.

1. In order to improve knowledge of upper harbour sedimentation processes, a hydrodynamic field and modelling study should be conducted to establish circulation and wave energy patterns within the upper Akaroa Harbour. This study would help to explain the sediment patterns and bathymetry trends found, and would assist in determining the relative influences of catchment versus up-harbour transport sources of sediment.
2. We recommend that the possible erosion of the mid and outer bay areas of Akaroa Inlet is investigated further.
3. A study should be conducted to quantify the catchment inputs of water and sediment into upper Akaroa Harbour. This would include a review of the monitoring data from the large number of recent development sites around the harbour. This sediment input information could then be compared to surface sediment texture patterns found in the present study, and the textural associations with biota found by Bolton-Ritchie (2005), to better understand the effects of contemporary catchment change on the biological resources of the harbour.
4. We recommend that in future upper harbour sediment and bathymetry surveys are conducted in conjunction with biological surveys so that the results are directly comparable. A biological sampling project that is more detailed than Fenwick (2004) and more extensive than Bolton-Ritchie (2005) is needed to describe the full range of biological community patterns of the upper harbour.

6. Acknowledgements

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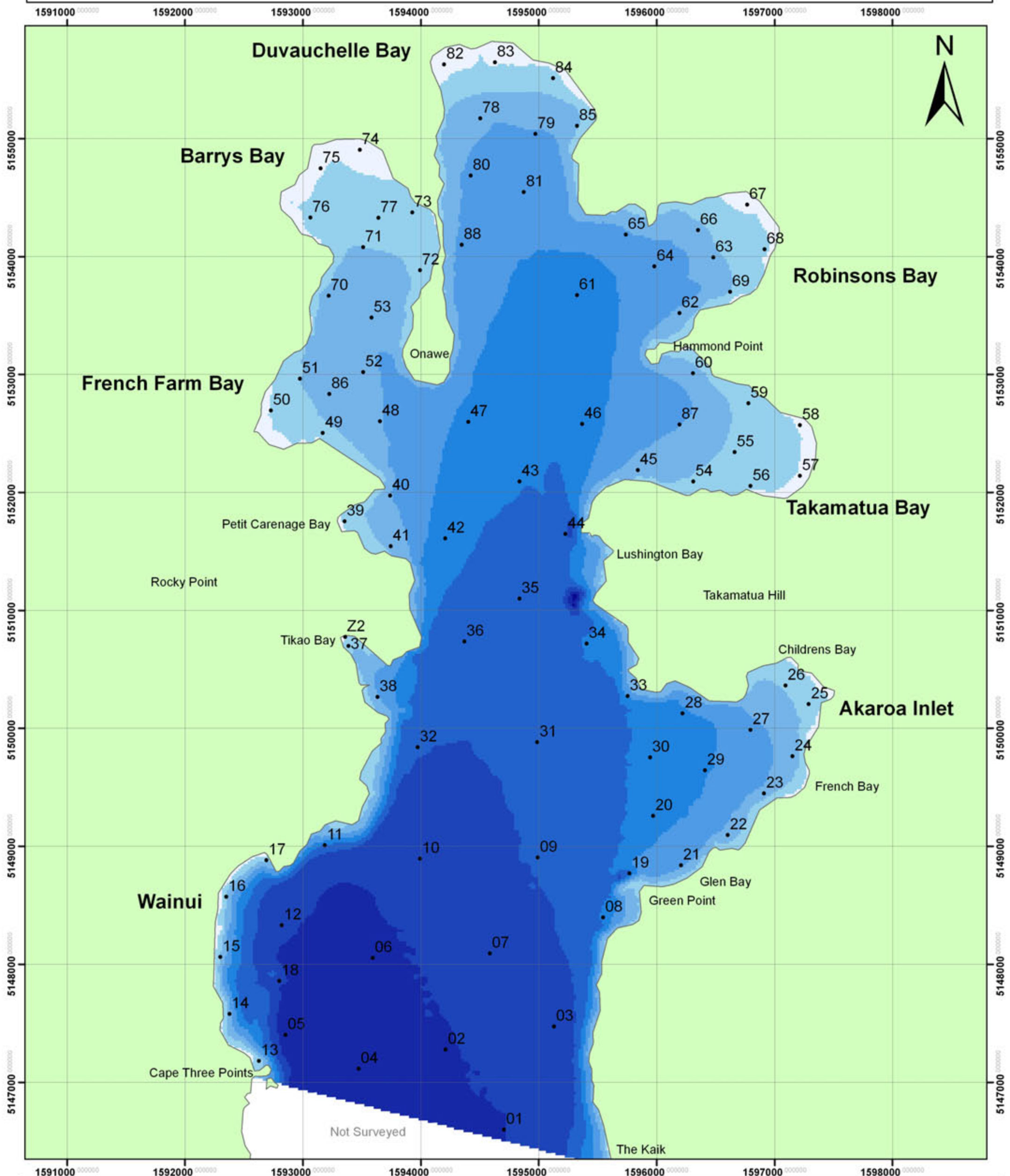
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MAPS

Map1: Akaroa Harbour Sediment Sample Sites

Scale 1:30,000

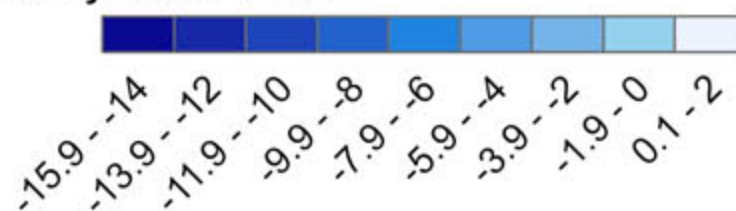


• Sediment sample points

Bathymetry is measured relative to mean sea level in Akaroa Harbour

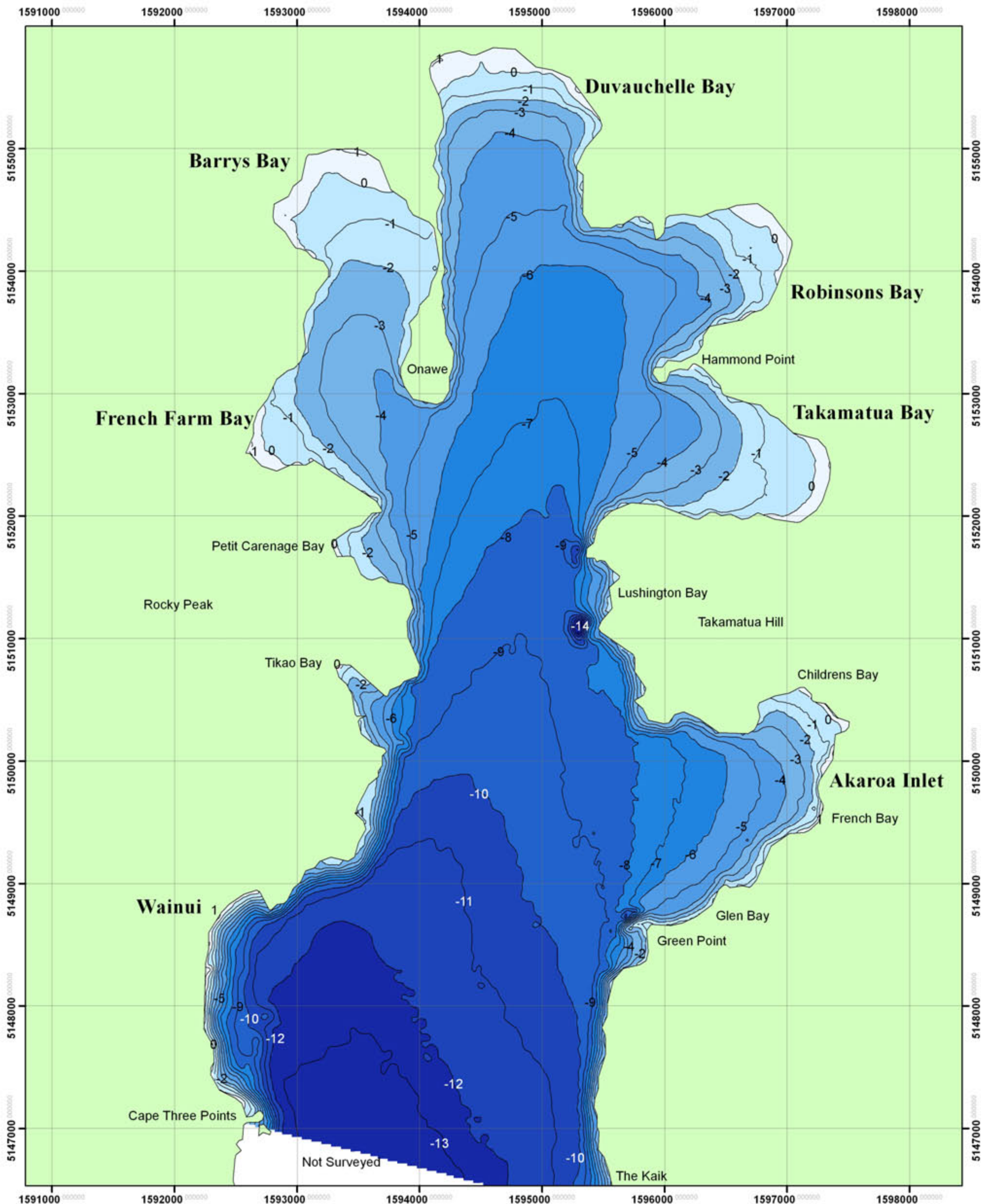
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Bathymetric Tints



Map 2: Akaroa Harbour Bathymetry

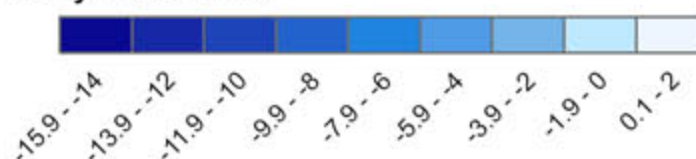
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Bathymetry is measured relative to mean sea level in Akaroa Harbour

Map Projection:
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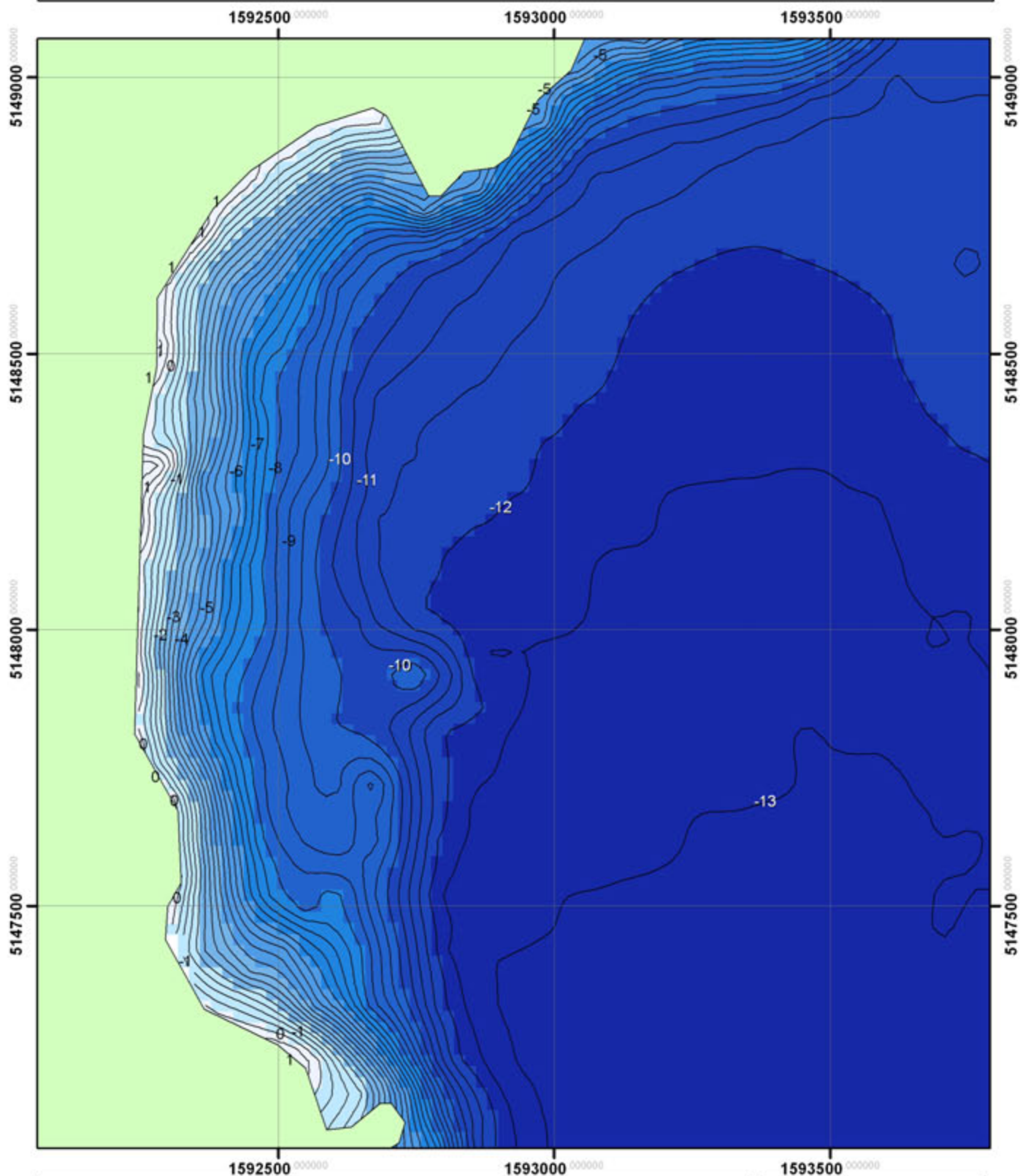
Bathymetric Tints



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Map 3: Wainui Bathymetry

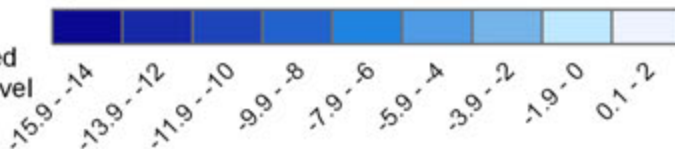
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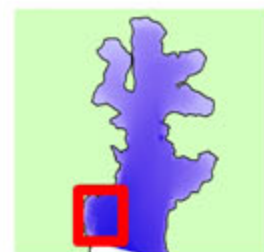
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Bathymetric Tints

Bathymetry is measured relative to mean sea level in Akaroa Harbour

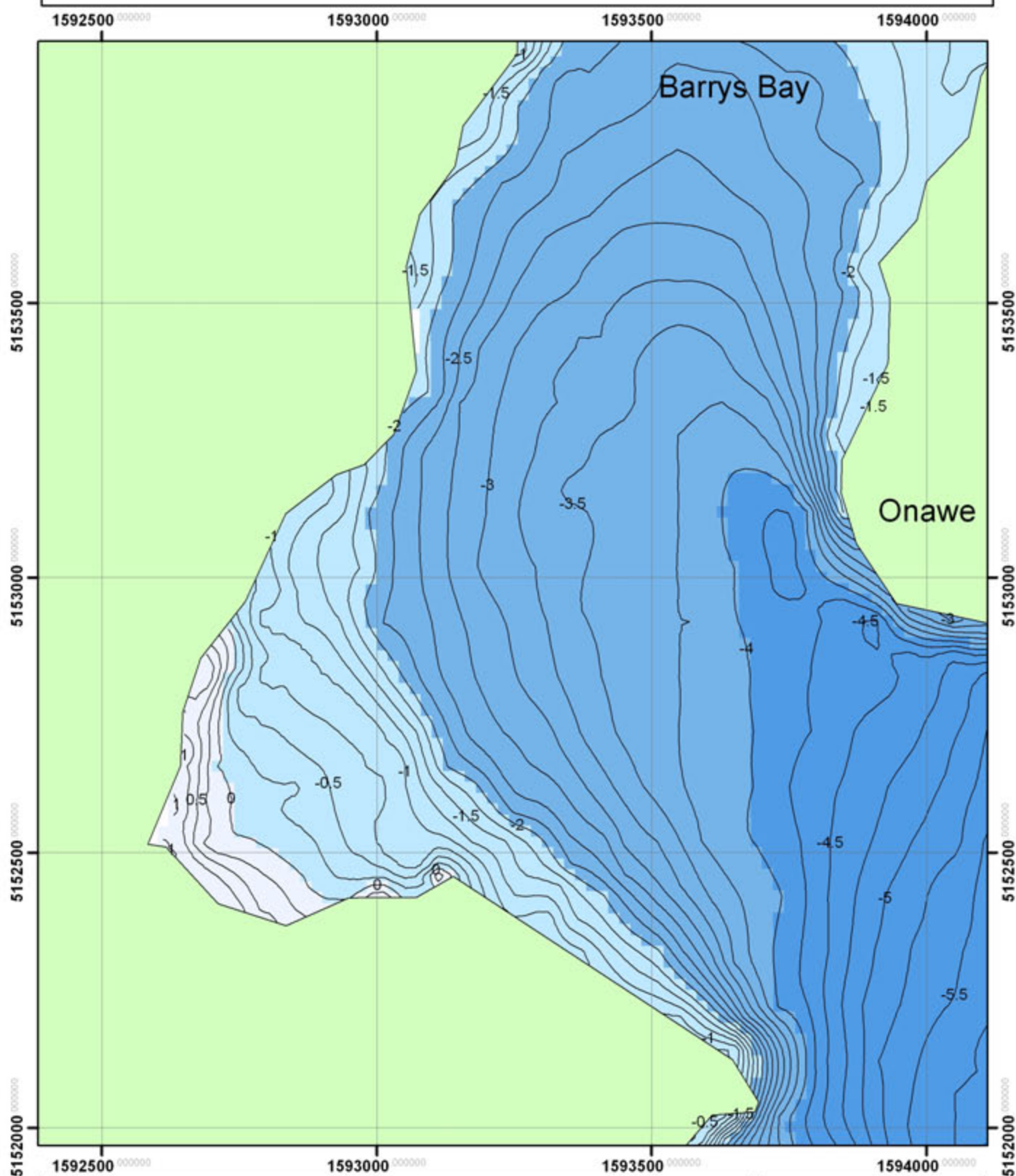


Map Projection:
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Map 4: French Farm Bay Bathymetry

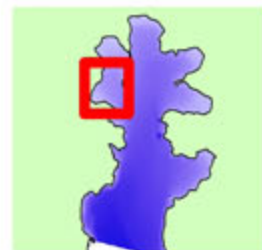
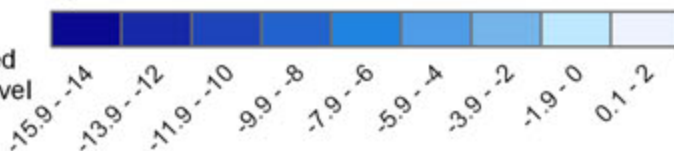
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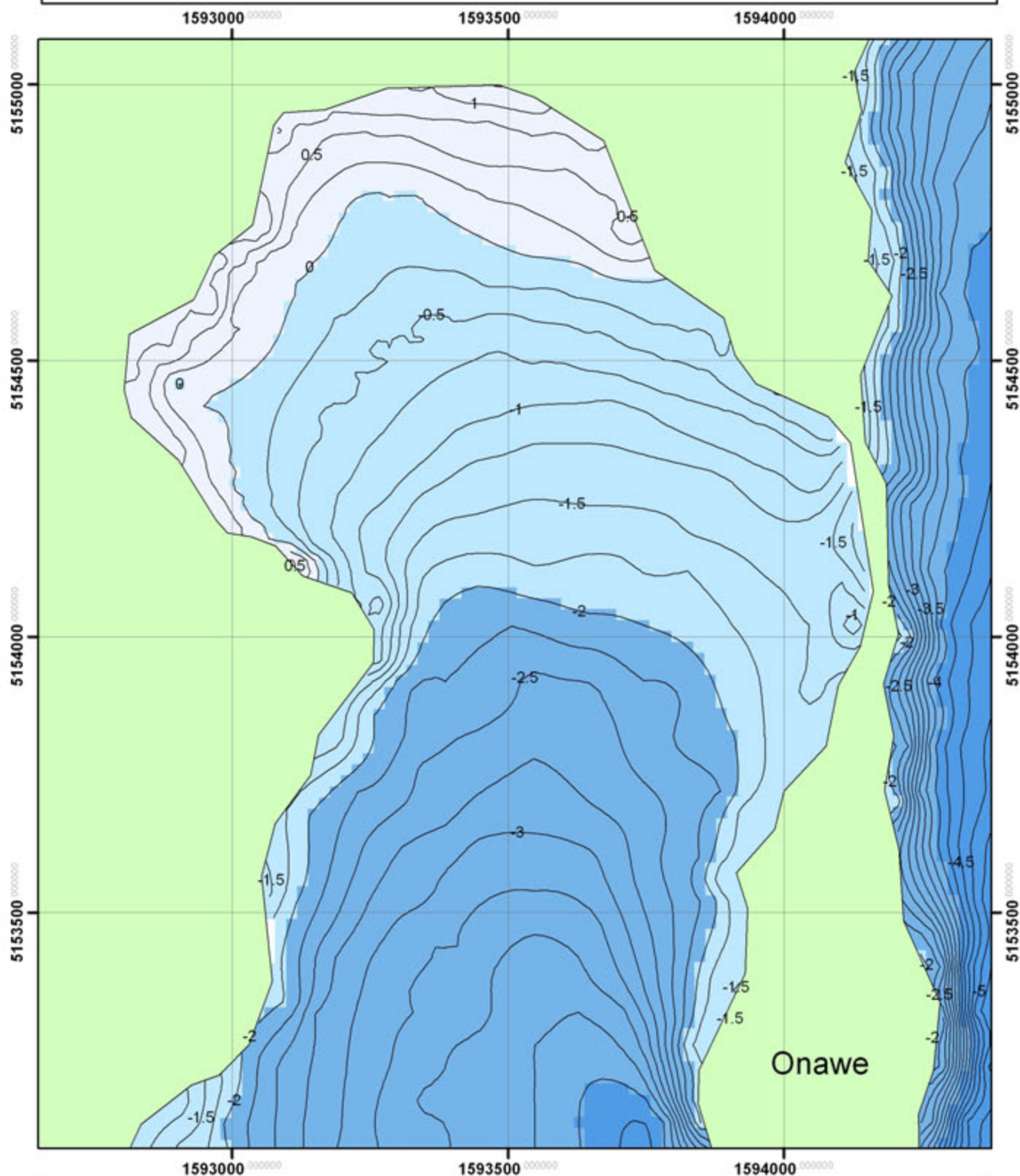
Bathymetry is measured
relative to mean sea level
in Akaroa Harbour

Map Projection:
New Zealand Transverse Mercator



Map 5: Barrys Bay Bathymetry

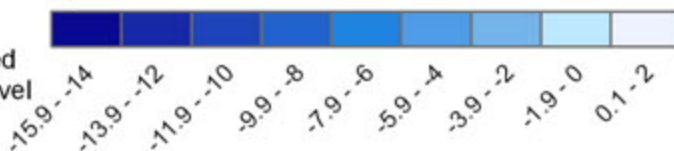
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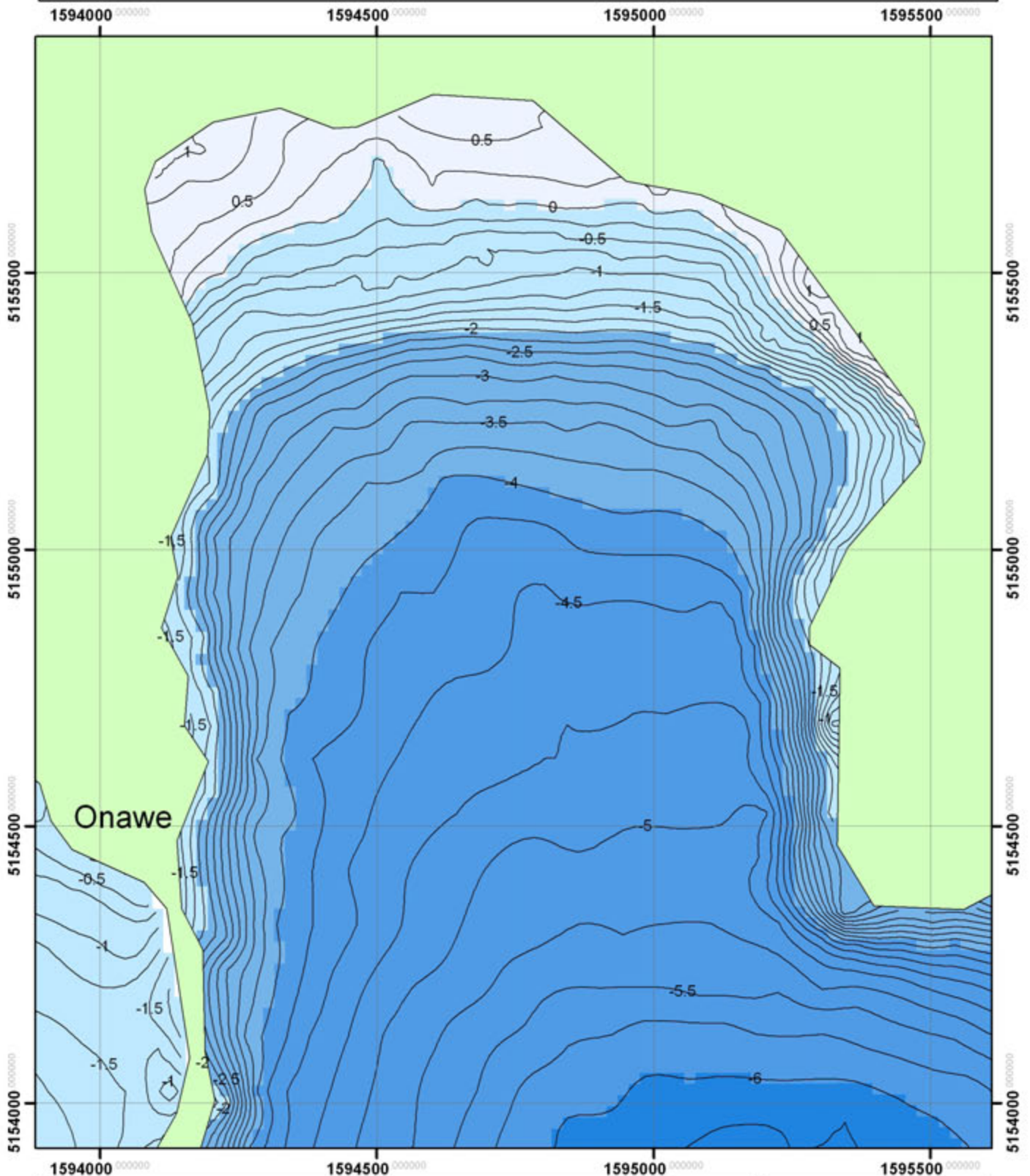
Bathymetry is measured
relative to mean sea level
in Akaroa Harbour

Map Projection:
New Zealand Transverse Mercator



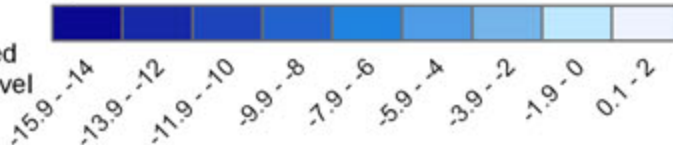
Map 6: Duvauchelle Bay Bathymetry

1:10,000



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Bathymetry is measured
relative to mean sea level
in Akaroa Harbour

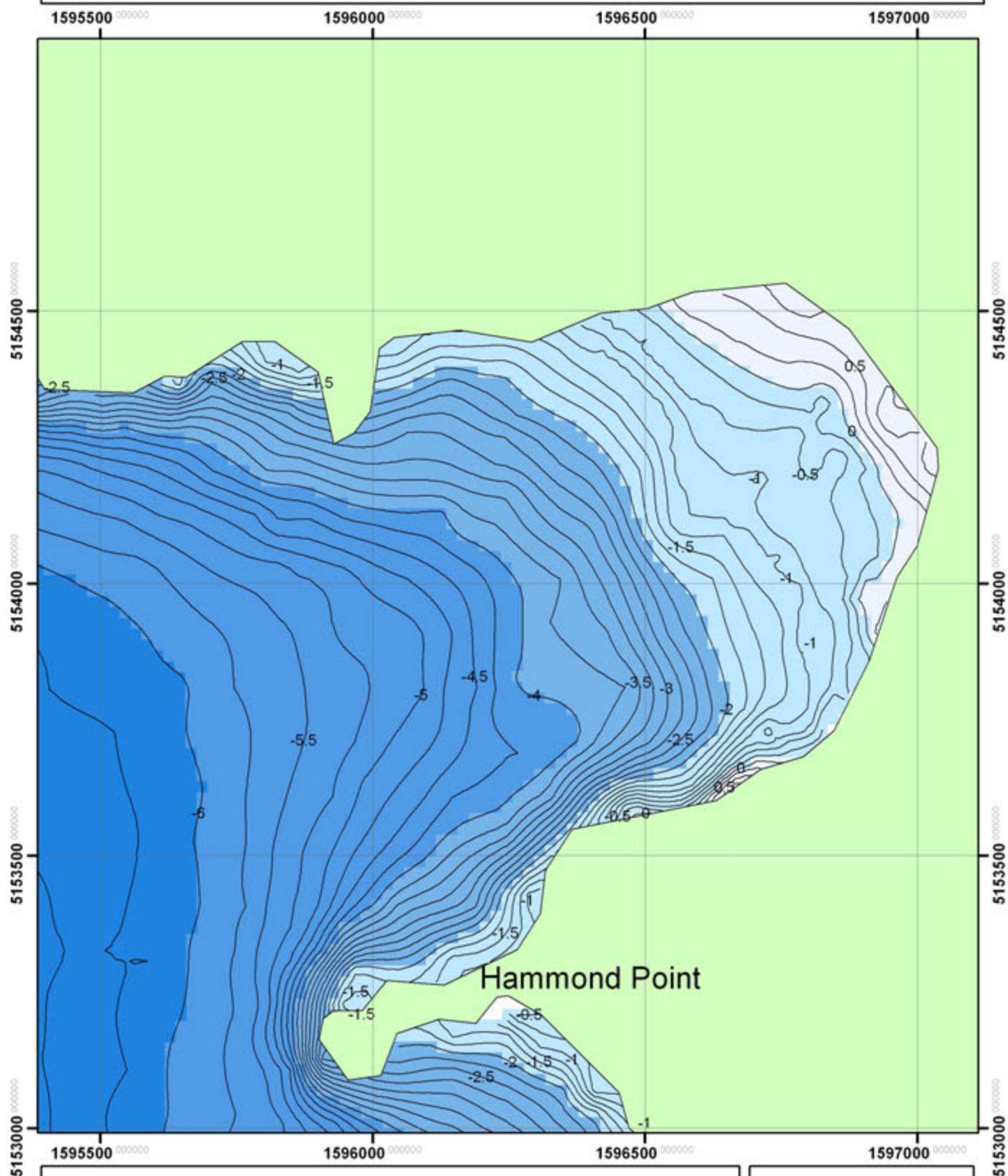


Map Projection:
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Map 7: Robinsons Bay Bathymetry

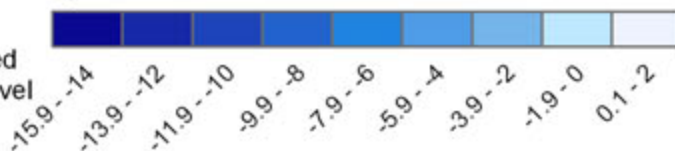
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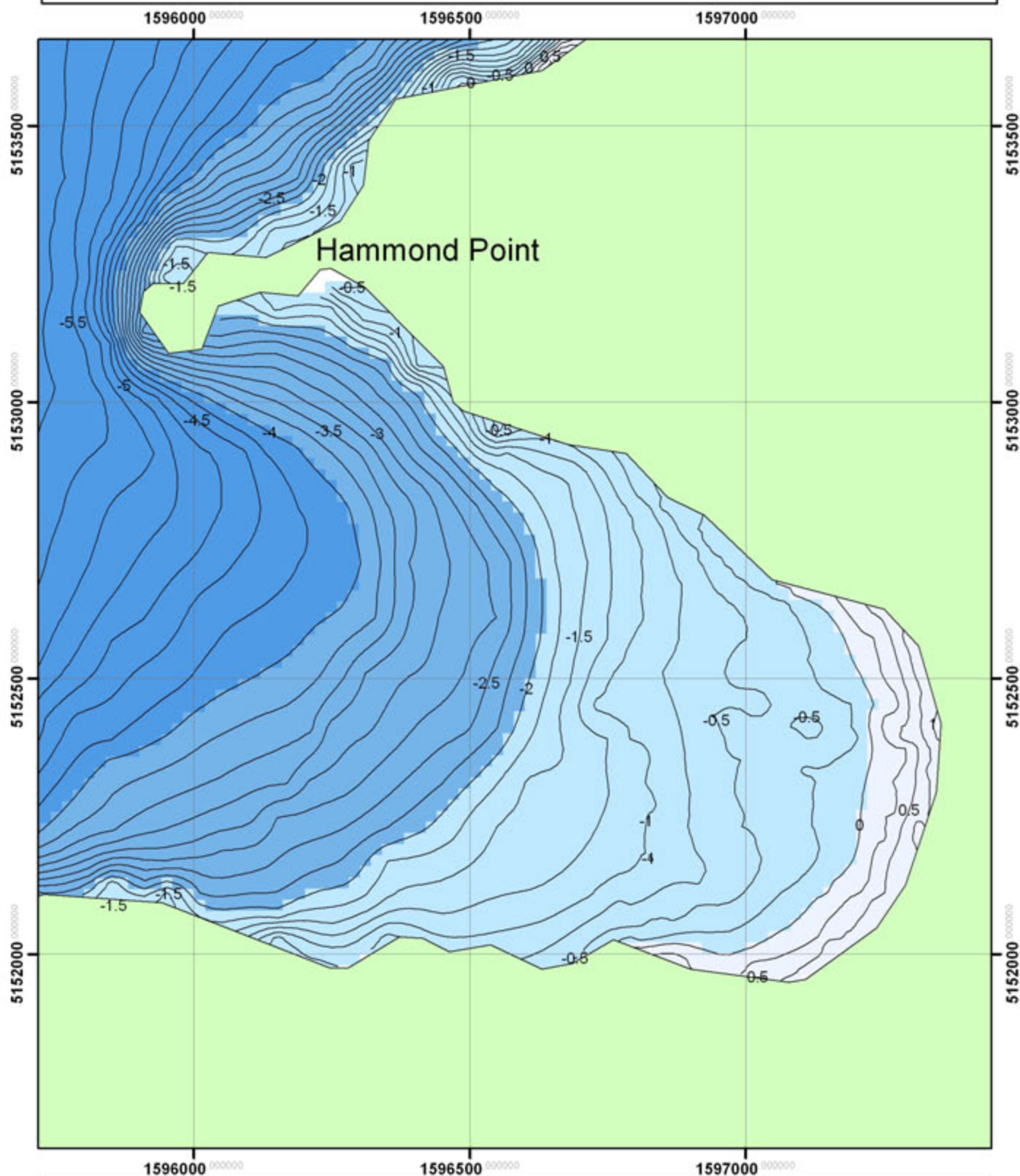
Bathymetry is measured
relative to mean sea level
in Akaroa Harbour

Map Projection:
New Zealand Transverse Mercator



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CANTERBURY
In White Wings & Words
CONSTRUCTION TEAM

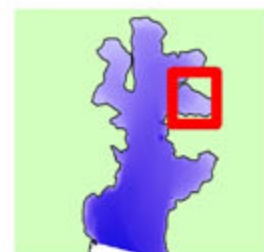


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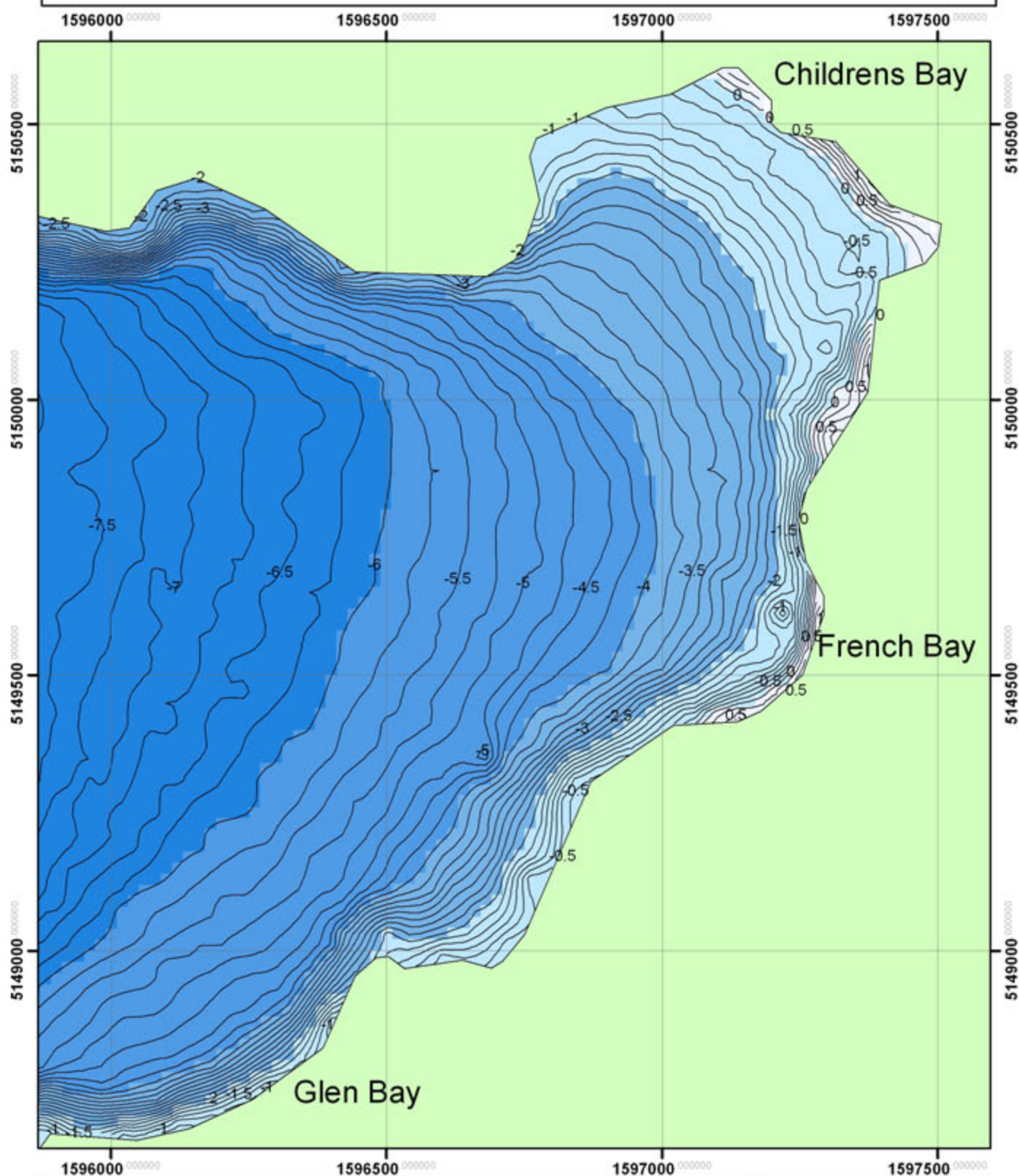
Bathymetry is measured relative to mean sea level in Akaroa Harbour

Map Projection:
New Zealand Transverse Mercator



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CANNON-CHANCE, 1200 16th Ave. S.W.



—— Contour 0.25m **Bathymetric Tints**

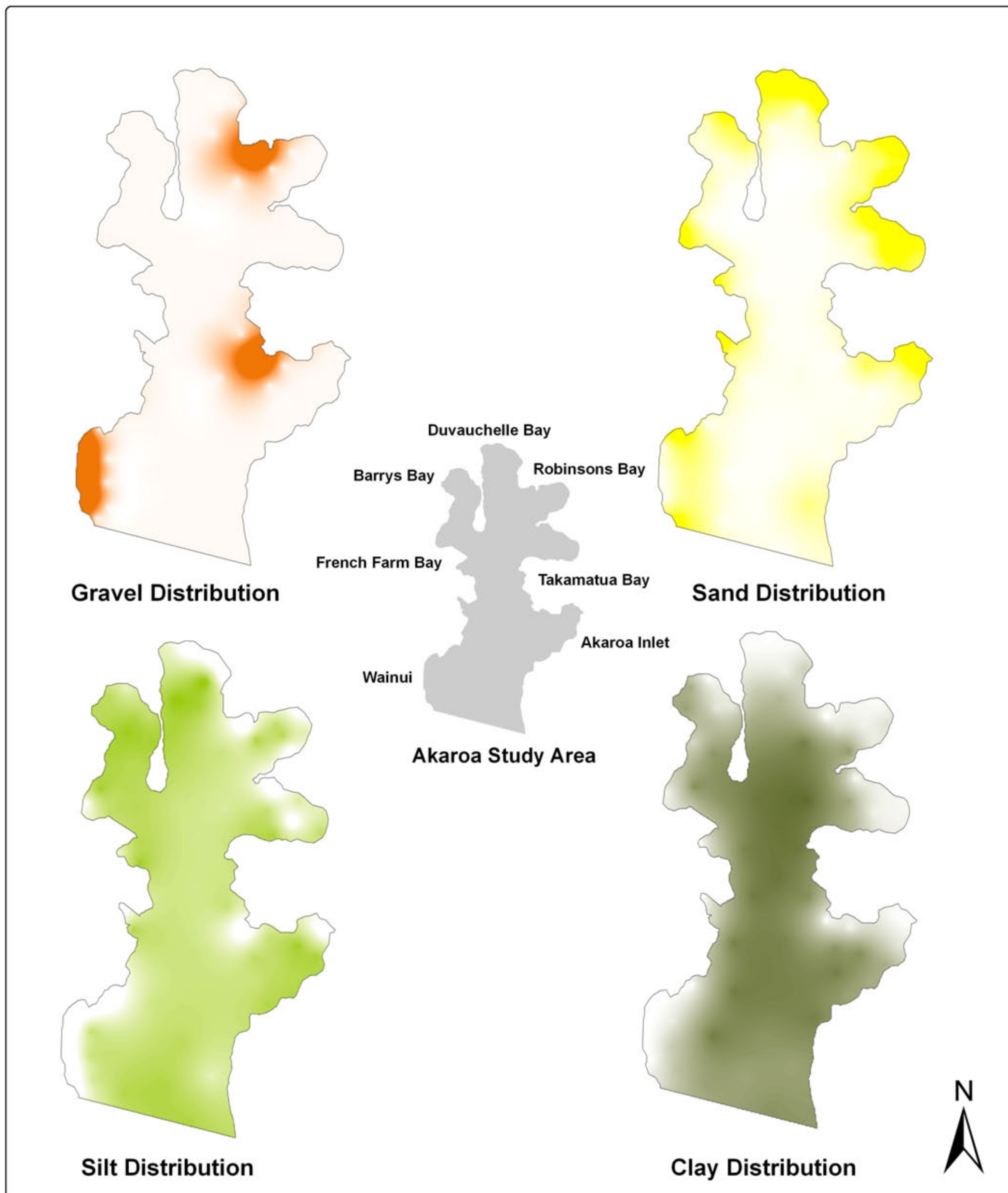



Bathymetry is measured relative to mean sea level in Akaroa Harbour

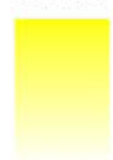
Map Projection:
New Zealand Transverse Mercator



Map 10: Akaroa Harbour Sediment Distributions



Gravel %
 High : 100
 Low : 0

Sand %
 High : 100
 Low : 0

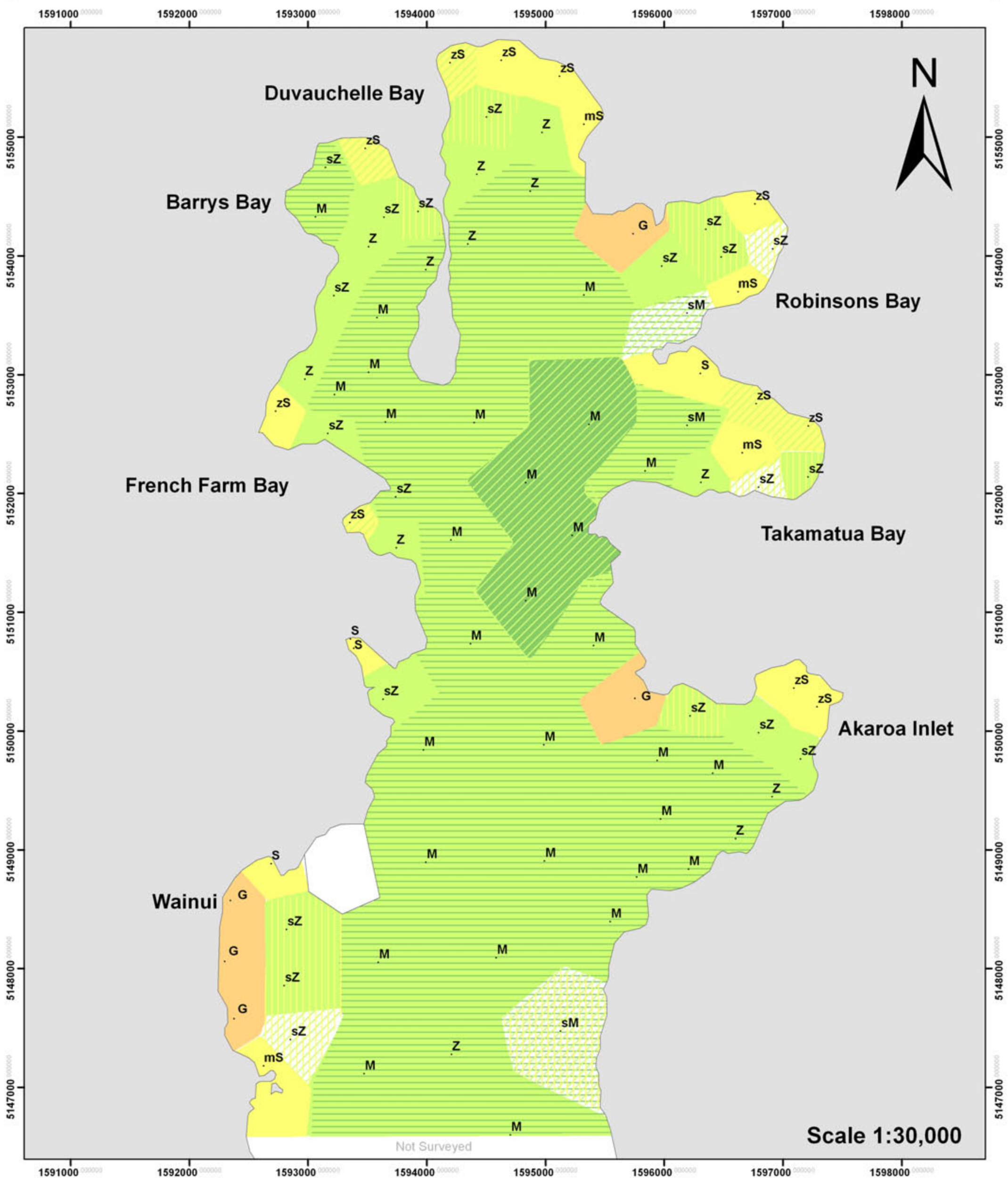
Silt %
 High : 86
 Low : 0

Clay %
 High : 55
 Low : 0

Sediment size class distribution is represented as a percentage of the total sediment at a specific point

Scale of coloured maps 1:70,000

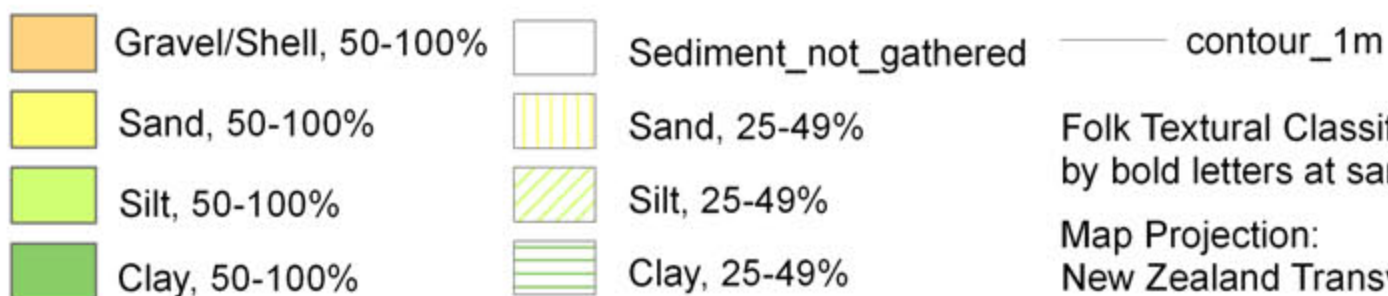
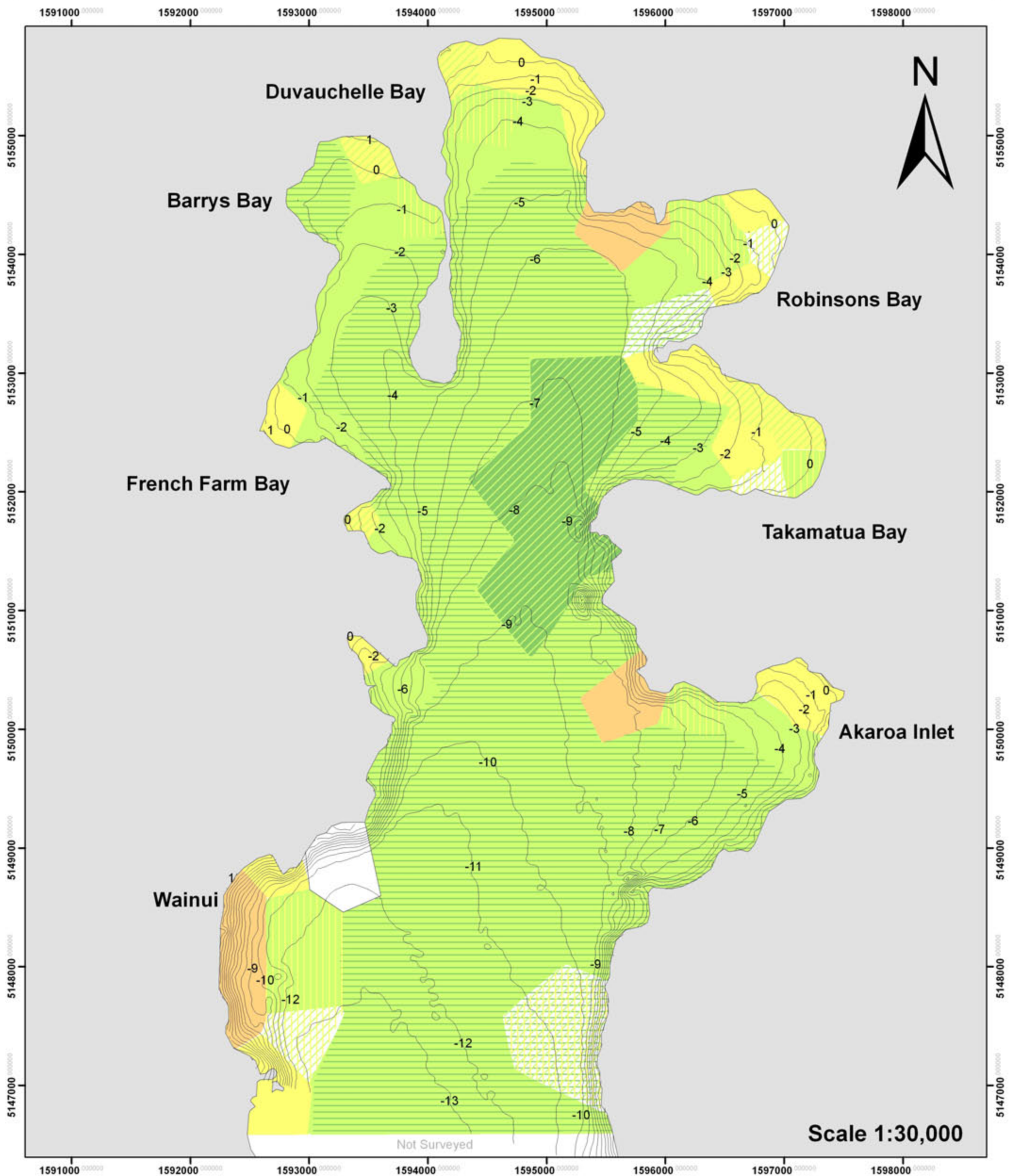
Map 11: Folk Textural Classification of Akaroa Harbour Sediments



Folk Textural Classification indicated by bold letters at sample sites

Map Projection:
New Zealand Transverse Mercator

Map 12: Akaroa Harbour Sediments and Bathymetry

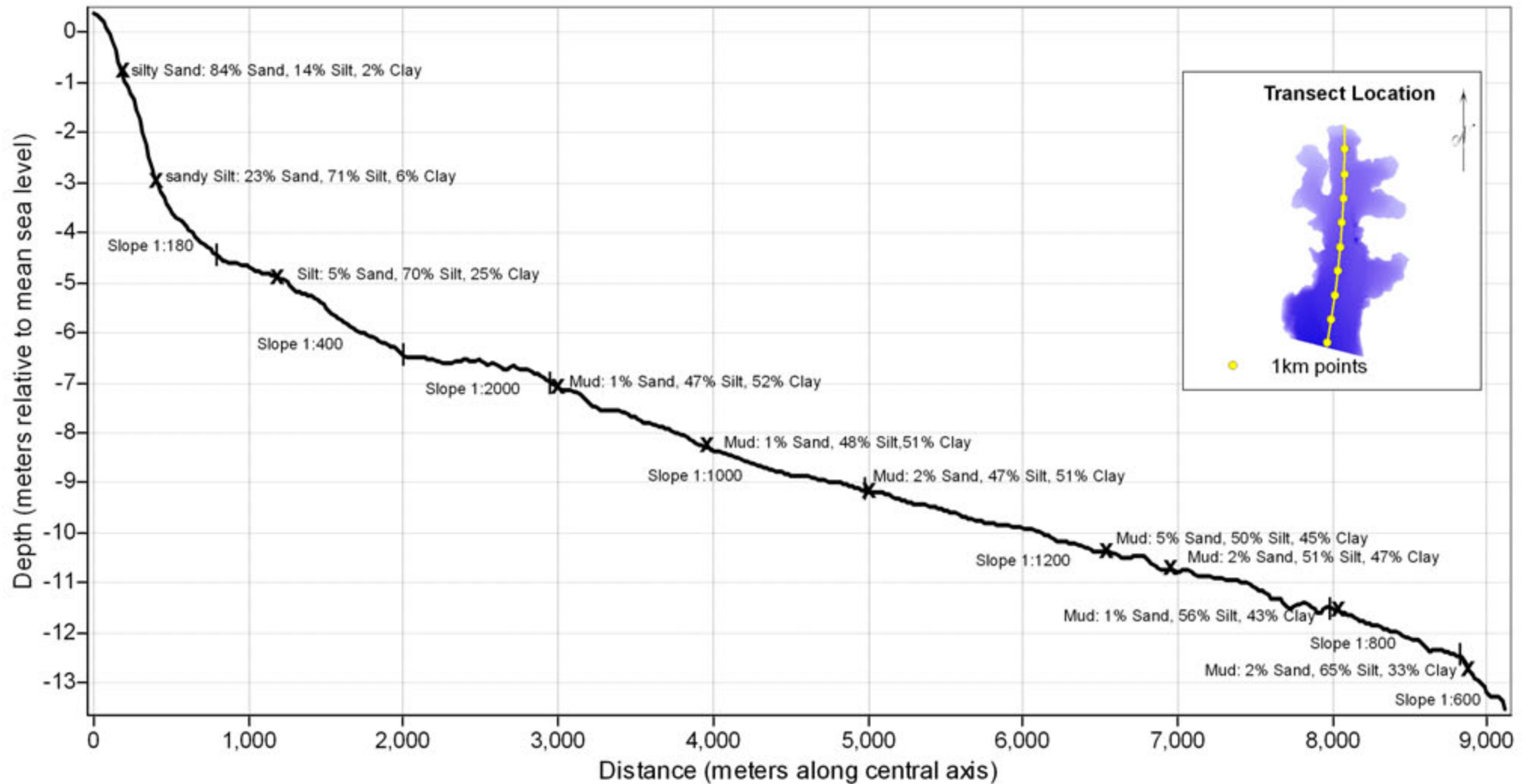


Folk Textural Classification indicated by bold letters at sample sites

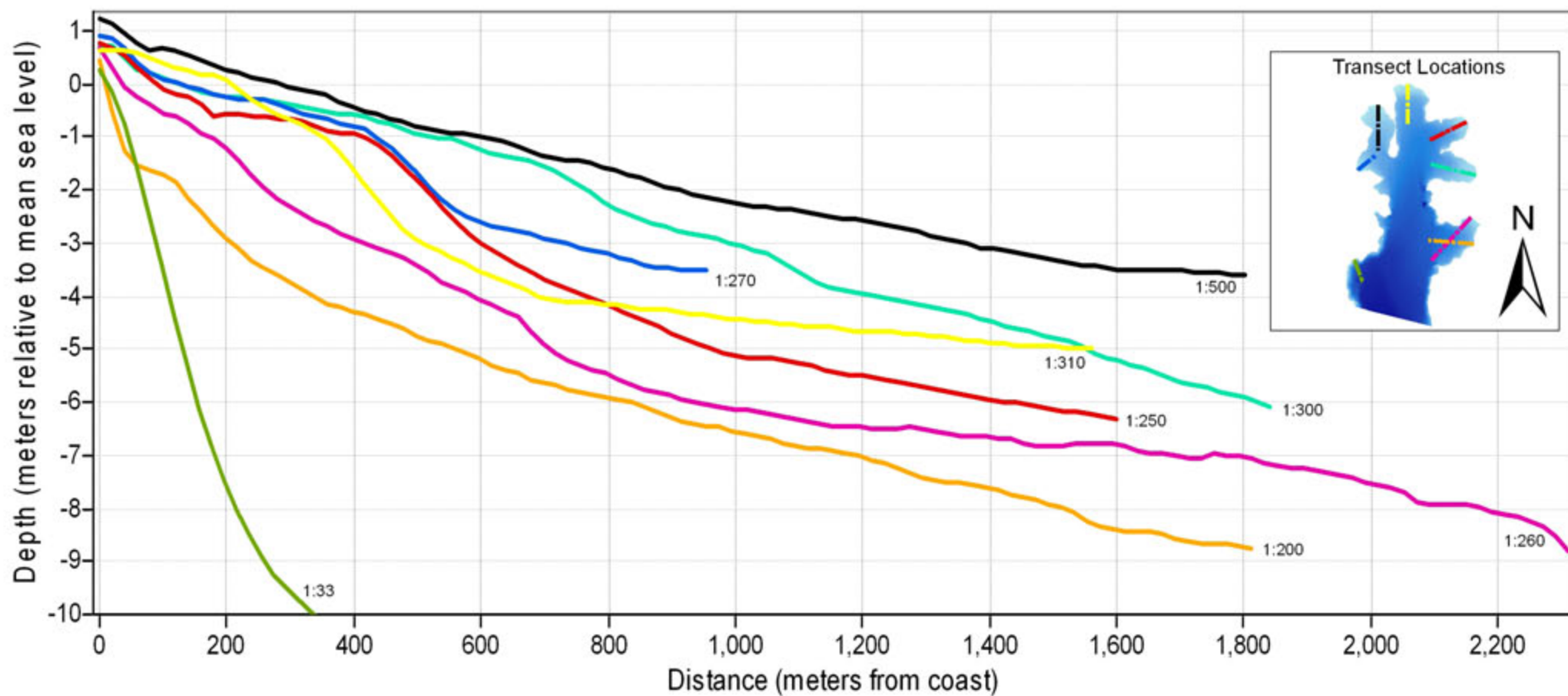
Map Projection:
New Zealand Transverse Mercator

TRANSECT PLOTS

Transect Plot 1

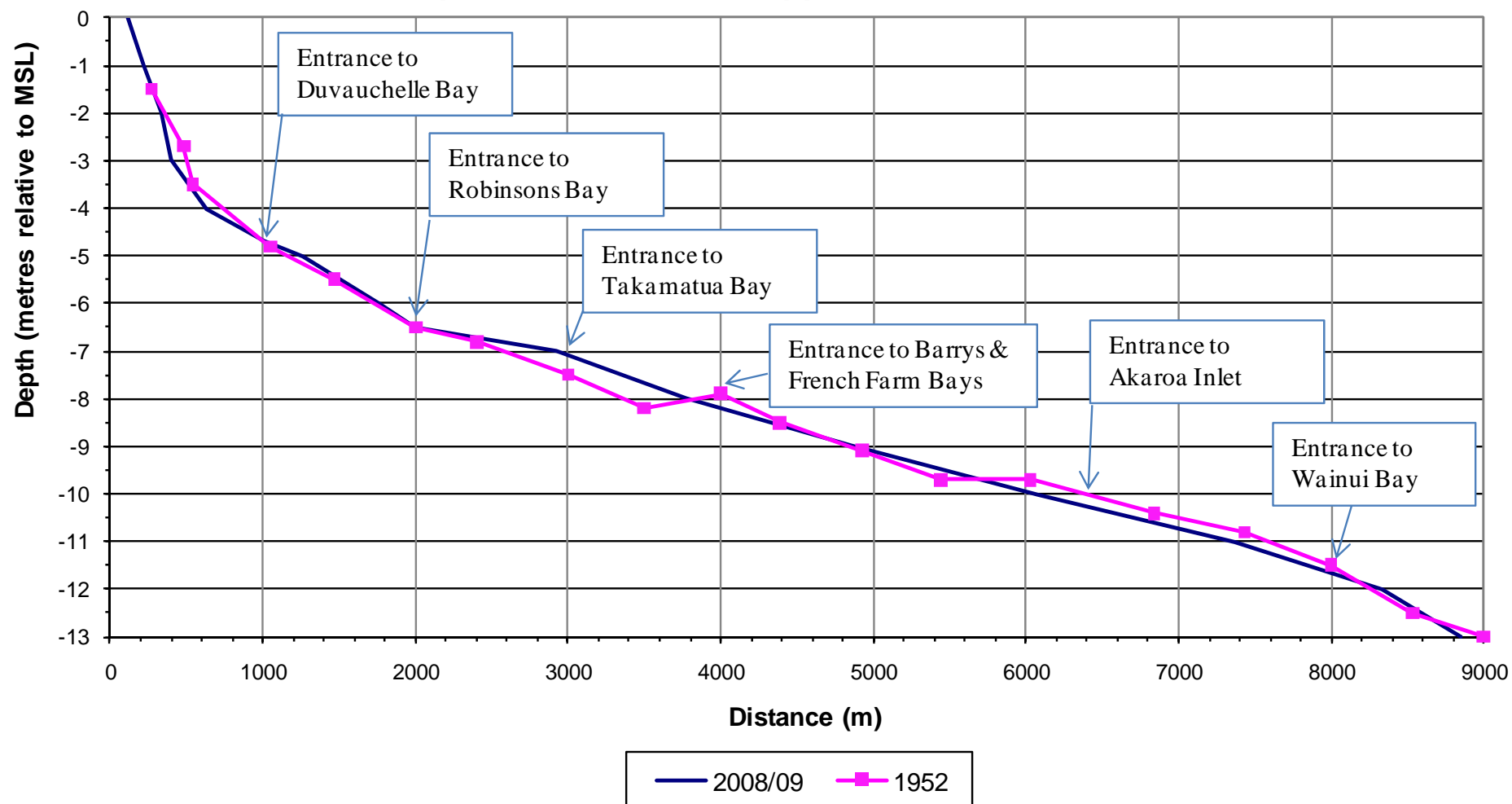


Transect Plot 2

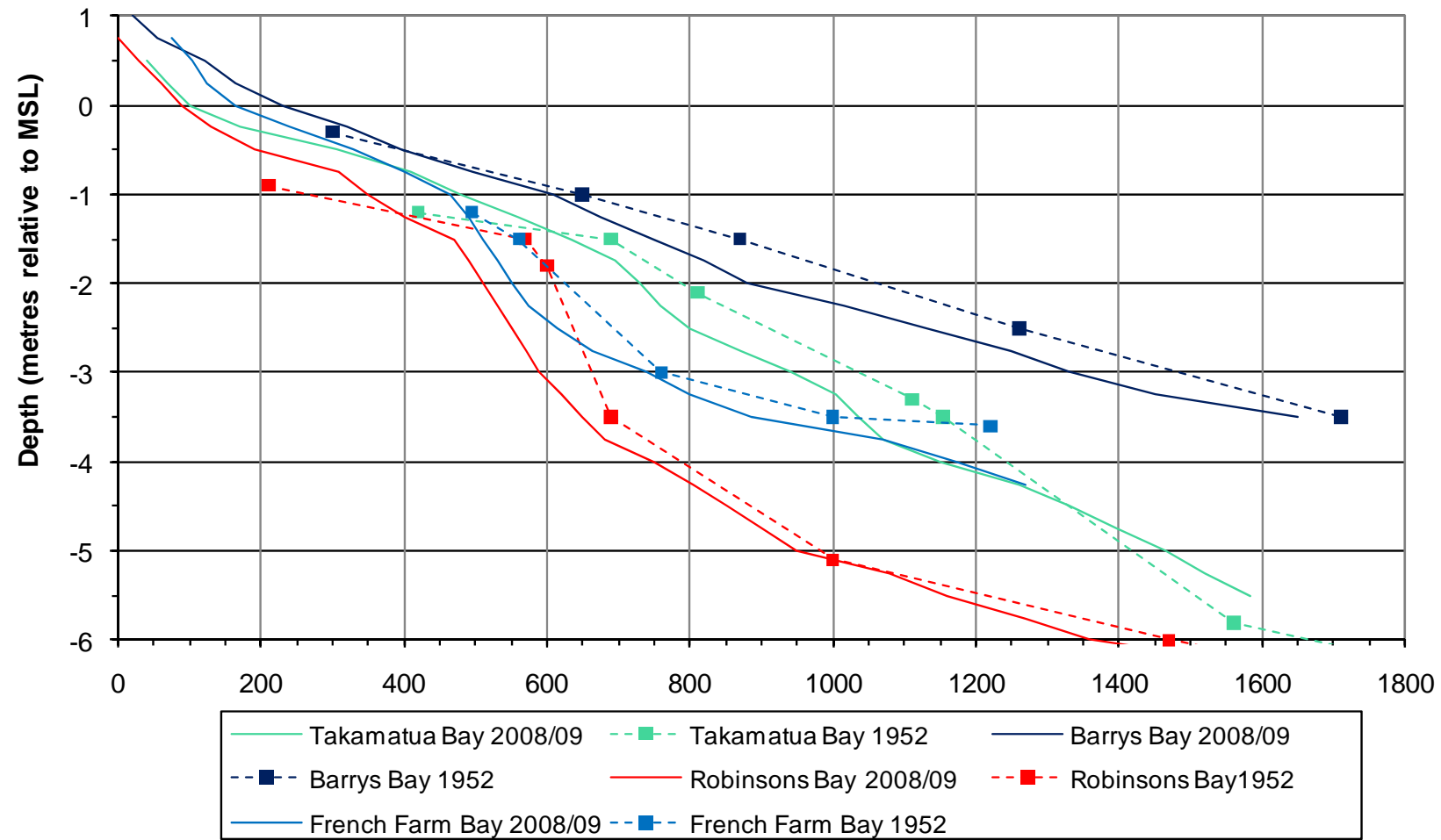


- | | | | |
|---|---|--|---|
| — Akaroa (French Bay) | — Takamatua Bay | — Barrys Bay | — Akaroa (Childrens Bay) |
| — Wainui | — French Farm Bay | — Robinsons Bay | — Duvauchelle Bay |

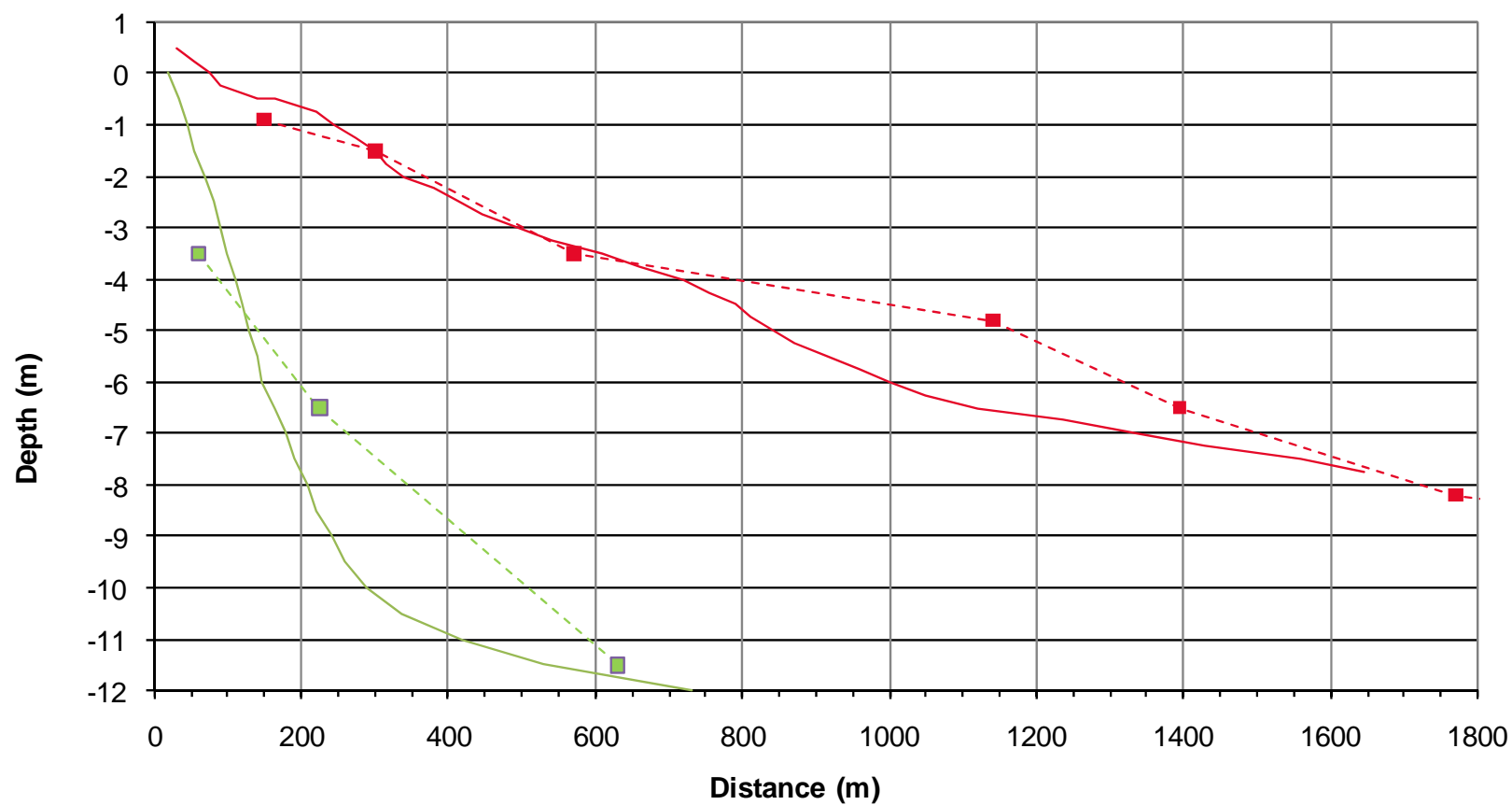
Transect Plot 3: Comparison Over Time of Upper Akaroa Harbour Central Axis



Transect Plot 4: Comparison Over Time of Shallow Upper Akaroa Harbour Bays Transects



Transect Plot 5: Comparison Over Time of Akaroa Inlet & Wainui Bay Transects



APPENDICES

Appendix 1: List of electronic files provided with this report

A1.1 Raw data

- Bathymetric GPS Data
- Upper Bays Transect Data
- Sediment Sample Data 1
- Sediment Sample Data 2
- Sediment Summary of Results (Appendix 4, includes sample site coordinates)

A1.2 Shape files

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

A1.3 Map JPEGs

Map 1: Akaroa Harbour Sediment Sample Sites

Map 2: Akaroa Harbour Bathymetry

Map 3: Wainui Bathymetry

Map 4: French Farm Bay Bathymetry

Map 5: Barrys Bay Bathymetry

Map 6: Duvauchelle Bay Bathymetry

Map 7: Robinsons Bay Bathymetry

Map 8: Takamatua Bay Bathymetry

Map 9: Akaroa Inlet Bathymetry

Map 10: Akaroa Harbour Sediment Distributions

Map 11: Folk Textural Classification of Akaroa Harbour Sediments

Map 12: Akaroa Harbour Sediments and Bathymetry

A1.4 Transect Plots

Transect Plot 1: Upper Akaroa Harbour Central Axis Transect (JPG file)

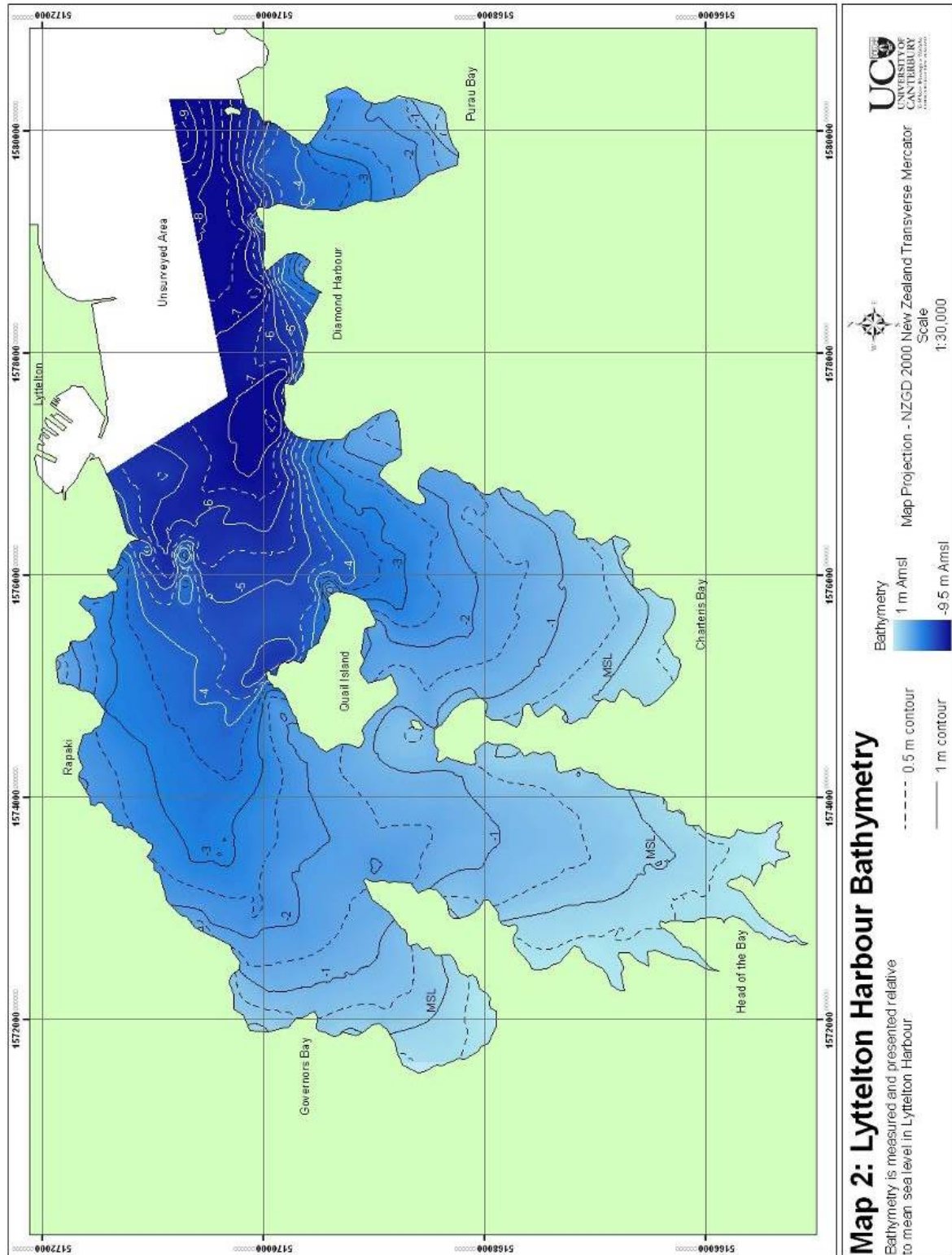
Transect Plot 2: Upper Akaroa Harbour Bay Transects (JPG file)

Transect Plot 3: Comparison over time of Upper Akaroa Harbour Central Axis Transect (xls file)

Transect Plot 4: Comparison over time of Shallow Upper Akaroa Harbour Bay Transects (xls file)

Transect Plot 5: Comparison over time of Akaroa Inlet and Wainui Bay Transects (xls file)

Appendix 2: Lyttelton Harbour Bathymetry and Sediments (by de Vries, in Hart et al. 2008)



Appendix 3: Theoretical maximum wave heights in the bays of Akaroa Harbour (from DTec 2008)

Table 1: Calculated Wind Waves Generated Directly into Bays Using Maximum of Daily Winds Recorded at Akaroa 1997-2001

Bay	Wind Direction	Max Wind speed (m/s)	Fetch Length (km)	Fetch or Depth ^(*) limited wave Height (m)	Fetch limited wave period (sec)
Wainui	East	12.4	3.0	0.41	1.68
	North-East	19.0	4.3	0.75	2.18
	South-East	19.0	3.9	0.72	2.11
Tikao Bay	South-East	19.0	3	0.63	1.93
French Farm	East	12.4	3.9	0.47	1.83
Barrys Bay	SSE	19.0	6.3	0.91	2.47
Duvauchelle	South-East	19.0	4.2	0.74	2.16
	South	26.8	14.55	1.50 ^(*)	3.65
Robinsons Bay	South-west	22.6	3.3	0.78	2.11
Takamatua	West	12.4	3.3	0.43	1.73
Akaroa	North-West	22.6	5.1	0.98	2.44
	West	12.4	3.6	0.45	1.78
	South-West	22.6	6.3	1.08	2.62

Table 3: Calculated Refracted Wave Heights (H_s) and Direction into the Bays from North and South winds Blowing up and down Akaroa Harbour

Wind speeds	Wind Speed: 26.8 m/s		Wind Speed: 43.2 m/s	
Bay	Southerly wind	Northerly Wind	Southerly wind	Northerly Wind
Wainui: North end	1.02 South	N/A	1.52 South/SSE	NA
Central & South end	0.82 SSE	0.45 East	1.21 SSE	0.73 East
Tikao Bay	0.91 SSE	0.46 NE/ENE	1.10 SE	0.78 ENE
French Farm	0.81 SE	NA	1.32 SE	NA
Barrys Bay	0.91 SSE	NA	1.46 SSE	NA
Duvauchelle	1.50 South	NA	1.50 South/SSE	NA
Robinsons Bay	1.10 SSW	NA	1.41 SSW/SW	NA
Takamatua	0.60 West	NA	0.92 West	NA
Akaroa: South end	NA	0.88 NNW/North	N/A	1.35 NNW/North
Central & North end	0.83 SSW	0.46 NW	1.04 SSW/SW	0.78 NW
<div>....</div> Wave Heights greater than for waves generated by from winds blowing directly into the bays				
<div>....</div> Depth limited waves				

Appendix 4: Summary of Akaroa Harbour sediment results

Site No.	Northing	Easting	Depth (m AMSL)	Shell (%)	Sediment Texture (% by weight)					Modified Folk (1965)		Mean Grain Size		Median Grain Size		Sorting Class	Skewness Class	Kurtosis Class
					Gravel	Coarse and med sand	Fine and v. fine sand	Silt	Clay	Class	Code	(mm)	Class	(mm)	Size Class			
AKA001	2504713.04147	5708193.27147	-12.1	0.05	0	0.2	0.7	66	39	mud	M	0.01	v fn silt	0.01	v fn silt	poorly	coarse	platy
AKA002	2504218.77253	5708872.21232	-12.2	0.92	0	1	0.9	65.9	32.7	silt	Z	0.01	v fn silt	0.01	v fn silt	poorly	coarse	platy
AKA003	2505136.70056	5709067.74729	-10.7	26.92	0	26.8	3.3	37	32.9	sandy mud	sM	0.03	md silt	0.01	fn silt	v poorly	st course	v platy
AKA004	2503480.08488	5708709.26652	-13.4	0.56	0	0.8	1.8	63.7	33.7	mud	M	0.01	v fn silt	0.01	v fn silt	poorly	near symm	v platy
AKA005	2502860.89082	5708997.13744	-12.8	1.41	0	3.2	28.6	47.7	20.6	sandy silt	sZ	0.02	md silt	0.03	cs silt	v poorly	fine	v platy
AKA006	2503599.57847	5709648.92066	-12.8	0.1	0	0.1	0.4	51.7	47.8	mud	M	0	v fn silt	0	v fn silt	poorly	course	v platy
AKA007	2504593.54788	5709686.94135	-11.2	0.92	0	1.1	0.7	60	38.2	mud	M	0	v fn silt	0	v fn silt	poorly	course	v platy
AKA008	2505554.92813	5709991.10685	-7.5	0	0	0.2	2.2	51.4	46.2	mud	M	0.01	v fn silt	0	v fn silt	poorly	st course	platy
AKA009	2505000.91239	5710501.67037	-9.9	0.41	0	0.6	1.3	52.5	45.6	mud	M	0.01	v fn silt	0	v fn silt	poorly	st course	platy
AKA010	2504001.51145	5710490.80732	-11.5	1.33	0	1.4	0.3	50.4	47.9	mud	M	0	v fn silt	0	v fn silt	poorly	st course	platy
AKA011	2503192.21395	5710604.86938	-7.4		Not Collected													
AKA012	2502828.30166	5709925.92853	-11.7	0.12	0	0.5	36.5	55.7	7.3	sandy silt	sZ	0.04	cs silt	0.04	cs silt	poorly	fine	v lepto
AKA013	2502633.64190	5708775.62312	-1.7	43.67	0	50.2	20.4	17.7	11.6	muddy sand	mS	0.12	v fn sand	0.25	md sand	v poorly	st fine	platy
AKA014	2502385.50615	5709172.89733	-2.7	0	100	0	0	0	0	gravel	G							
AKA015	2502307.50253	5709656.49148	-2.3	0	100	0	0	0	0	gravel	G							
AKA016	2502355.96799	5710168.16215	-1.7	0	100	0	0	0	0	gravel	G							
AKA017	2502697.18852	5710478.38359	-1.5	1.24	0	3	98.9	0.1	0	sand	S	0.14	fn sand	0.14	fn sand	well	near symm	lepto
AKA018	2502807.66185	5709453.38569	-11.2	3.02	0	3.6	25.8	52.6	18.1	sandy silt	sZ	0.02	md silt	0.03	cs silt	v poorly	st fine	platy
AKA019	2505778.70703	5710365.88220	-9	0.99	0	1.2	5.8	54	39	mud	M	0.01	fn silt	0.01	v fn silt	poorly	course	v platy
AKA020	2505979.67353	5710854.71962	-6.9	0.19	0	0.9	2	51.3	45.9	mud	M	0.01	v fn silt	0	v fn silt	poorly	st course	v platy
AKA021	2506214.94930	5710434.23442	-4.4	0.08	0	0.3	2.9	64.3	32.6	mud	M	0.01	fn silt	0.01	fn silt	poorly	near symm	v platy
AKA022	2506612.40231	5710690.63326	-3	0.02	0	0.4	6.6	63.6	29.4	silt	Z	0.01	fn silt	0.01	fn silt	poorly	fine	v platy
AKA023	2506918.75433	5711044.11166	-3.2	0.02	0	0.7	7.6	63.1	28.8	silt	Z	0.01	fn silt	0.02	md silt	poorly	fine	v platy
AKA024	2507159.86715	5711359.68837	-3	0.02	0	1.1	19.6	69.2	10.1	sandy silt	sZ	0.03	md silt	0.04	cs silt	poorly	st fine	v lepto

Site No.	Northing	Easting	Depth (m AMSL)	Shell (%)	Sediment Texture (% by weight)					Modified Folk (1965)		Mean Grain Size		Median Grain Size		Sorting Class	Skewness Class	Kurtosis Class
					Gravel	Coarse and med sand	Fine and v. fine sand	Silt	Clay	Class	Code	(mm)	Class	(mm)	Size Class			
AKA025	2507299.51732	5711801.08433	-0.7	0.15	0	0.4	84.3	13.4	2	silty sand	zS	0.08	v fn sand	0.08	v fn sand	mod well	near symm	lepto
AKA026	2507046.82419	5712075.89589	-0.7	1.72	0	2.9	72.5	22.5	2.1	silty sand	zS	0.07	v fn sand	0.08	v fn sand	mod	fine	lepto
AKA027	2506805.26560	5711582.54421	-4.6	0.04	0	0.2	13.2	72.4	14.1	sandy silt	sZ	0.02	md silt	0.04	cs silt	poorly	st fine	v lepto
AKA028	2506229.52376	5711723.76391	-6.3	4.94	0	6.3	34.6	54.6	4.6	sandy silt	sZ	0.05	cs silt	0.04	cs silt	poorly	st course	v lepto
AKA029	2506419.62720	5711240.35802	-6.2	0.48	0	0.6	0.9	57.5	41	mud	M	0.01	v fn silt	0.01	v fn silt	poorly	course	v platy
AKA030	2505952.51589	5711348.98856	-7.6	0.98	0	1.1	1.6	57.8	39.5	mud	M	0.01	v fn silt	0.01	v fn silt	poorly	course	v platy
AKA031	2504996.56717	5711479.34520	-9.4	3.3	0	4	1.1	50	44.8	mud	M	0.01	v fn silt	0	v fn silt	poorly	st course	platy
AKA032	2503980.87165	5711435.89299	-9.7	0.32	0	0.4	2	51.9	45.7	mud	M	0.01	v fn silt	0	v fn silt	poorly	course	v platy
AKA033	2505762.41245	5711870.41513	-5.7	50	100	0	0	0	0	gravel	G							
AKA034	2505414.79473	5712315.80033	-7.9	0.16	0	0.3	3.3	54.7	41.7	mud	M	0.01	v fn silt	0.01	v fn silt	poorly	st course	v platy
AKA035	2504844.48442	5712696.00721	-8.9	1.46	0	1.5	0.5	47.4	50.6	mud	M	0.01	v fn silt	0	clay	poorly	st course	platy
AKA036	2504377.37311	5712332.09491	-8.7	0.61	0	0.8	0.6	50.3	48.4	mud	M	0.001	v fn silt	0.01	v fn silt	poorly	st course	platy
AKA037	2503394.26675	5712294.07423	-1.4	10.58	0	80.7	18.2	2.2	0	sand	S	0.62	cs sand	1.09	v cs sand	poorly	st fine	meso
AKA038	2503682.13767	5712027.92941	-4.6	0.04	0	0.2	23.1	65.9	16.3	sandy silt	sZ	0.02	md silt	0.04	cs silt	poorly	st fine	meso
AKA039	2503361.67759	5713353.22196	-0.4	0.31	0	0.6	63.8	33.4	2.3	silty sand	zS	0.06	cs silt	0.07	v fn sand	mod well	st fine	v platy
AKA040	2503747.31600	5713570.48303	-3.8	0.03	0	0.4	10.3	62.6	26.5	sandy silt	sZ	0.01	fn silt	0.02	md silt	poorly	st fine	v platy
AKA041	2503752.74752	5713141.39241	-2.3	0.04	0	0	5.1	73.3	21.6	silt	Z	0.01	fn silt	0.03	md silt	poorly	st fine	platy
AKA042	2504214.42730	5713206.57073	-7.2	0.01	0	0.1	0.6	53.8	45.6	mud	M	0.01	v fn silt	0	v fn silt	poorly	st coarse	v platy
AKA043	2504844.48442	5713689.97662	-7.8	0.33	0	0.4	0.4	47.5	51.7	mud	M	0	v fn silt	0	clay	poorly	st coarse	platy
AKA044	2505235.55435	5713244.59142	-9.7	0.02	0	0.1	2	47.9	50	mud	M	0.01	v fn silt	0	clay	poorly	st coarse	platy
AKA045	2505849.31688	5713787.74411	-3	0.02	0	0	3.8	61	35.1	mud	M	0.01	fn silt	0.01	fn silt	poorly	near symm	v platy
AKA046	2505376.77405	5714178.81404	-6.7	0.01	0	0.1	0.7	44	55.1	mud	M	0.01	fn silt	0.01	fn silt	v well	coarse	v lepto
AKA047	2504409.96227	5714195.10862	-6.3	0.22	0	0.3	0.4	50.3	49.1	mud	M	0.01	v fn silt	0	v fn silt	poorly	st coarse	platy
AKA048	2503660.41157	5714200.54015	-4	0.06	0	0.1	0.4	61.9	37.6	mud	M	0.01	v fn silt	0.01	v fn silt	poorly	coarse	v platy
AKA049	2503177.00568	5714102.77266	-1.2	10.75	0	11	9.3	58.2	21.5	sandy silt	sZ	0.02	md silt	0.03	md silt	v poorly	fine	lepto

Site No.	Northing	Easting	Depth (m AMSL)	Shell (%)	Sediment Texture (% by weight)					Modified Folk (1965)		Mean Grain Size		Median Grain Size		Sorting Class	Skewness Class	Kurtosis Class
					Gravel	Coarse and med sand	Fine and v. fine sand	Silt	Clay	Class	Code	(mm)	Class	(mm)	Size Class			
AKA050	2502736.63869	5714292.11293	-0.2	10.53	0	33.1	40.7	21	5.3	silty sand	zS	0.13	fn sand	0.11	v fn sand	v poorly	near symm	meso
AKA051	2502935.72943	5714711.53042	-1.4	0	0	0.1	8	71.6	20.3	silt	Z	0.01	fn silt	0.03	md silt	poorly	st fine	platy
AKA052	2503519.19187	5714618.76771	-3.7	0.12	0	0.2	0.4	62	37.4	mud	M	0.01	v fn silt	0.01	v fn silt	poorly	coarse	v platy
AKA053	2503589.80172	5715080.44749	-3.4	0.05	0	0.2	0.4	61.8	37.6	mud	M	0.01	fn silt	0.01	fn silt	poorly	near symm	v platy
AKA054	2506319.35828	5713690.87393	-1.6	0	0	1.6	5.9	68.4	24.1	silt	Z	0.01	fn silt	0.03	md silt	poorly	st fine	v platy
AKA055	2506669.47743	5713939.82686	-1.5	20.21	0	50.4	35.1	8.7	5.8	muddy silt	mS	0.27	md sand	0.26	md sand	v poorly	fine	meso
AKA056	2506805.26560	5713651.95593	-0.5	2.73	0	3.3	46.5	42.9	7.4	sandy silt	sZ	0.05	cs silt	0.04	cs silt	poorly	near symm	v lepto
AKA057	2507223.68022	5713737.32121	0.1	0.66	0	2.9	34.9	57	5.2	sandy silt	sZ	0.05	cs silt	0.04	cs silt	poorly	near symm	v lepto
AKA058	2507224.11427	5714167.55204	0.2	0.07	0	1	56	39	4.1	silty sand	zS	0.06	cs silt	0.07	v fn sand	mod	st fine	lepto
AKA059	2506786.37619	5714354.33616	-1.1	6.13	0	7.4	42.6	44.3	5.7	silty sand	zS	0.06	cs silt	0.06	v fn sand	poorly	near symm	v lepto
AKA060	2506316.42819	5714607.90466	-2.7	1.95	0	4	90.3	3.9	1.8	Sand	S	0.1	v fn sand	0.1	v fn sand	mod well	fine	v lepto
AKA061	2505333.32183	5715270.55093	-6.5	0.08	0	0.3	0.9	51.1	47.7	mud	M	0.01	v fn silt	0	v fn silt	poorly	st coarse	v platy
AKA062	2506202.36613	5715118.46818	-3.7	17.69	0	20.7	2.7	39.4	37.3	sandy mud	sM	0.03	md silt	0.01	fn silt	v poorly	st coarse	platy
AKA063	2506490.23705	5715591.01101	-2.7	0	0	1	29.1	63	5.9	sandy silt	sZ	0.05	cs silt	0.04	cs silt	poorly	near symm	v lepto
AKA064	2505990.53658	5715514.96964	-5.1	2.37	0	4.5	17.2	66.7	11.7	sandy silt	sZ	0.02	md silt	0.04	cs silt	poorly	st fine	lepto
AKA065	2505680.93955	5715889.74499	-3.8	100	100	0	0	0	0	gravel	G							
AKA066	2506300.21961	5715948.90495	-2	3.2	0	3.6	34.5	56.9	5.3	sandy silt	sZ	0.05	cs silt	0.04	cs silt	poorly	near symm	v lepto
AKA067	2506776.59140	5716038.07308	0.4	0.2	0	0.8	78.8	18.1	2.3	silty sand	zS	0.07	v fn sand	0.08	v fn sand	mod	st fine	lepto
AKA068	2506924.18503	5715659.11594	-0.4	2.7	0	14.1	33.7	40.8	11.5	sandy silt	sZ	0.04	cs silt	0.04	cs silt	v poorly	near symm	lepto
AKA069	2506631.80089	5715298.11222	-1.9	17.02	0	30.5	49.8	12.1	7.7	muddy sand	mS	0.17	fn sand	0.14	fn sand	v poorly	near symm	v lepto
AKA070	2503225.88942	5715265.11940	-2.3	0.02	0	0.3	17.7	68.3	13.7	sandy silt	sZ	0.03	md silt	0.04	cs silt	poorly	st fine	v lepto
AKA071	2503519.19187	5715677.91544	-2	0.01	0	0.1	2.3	73.9	23.6	silt	Z	0.01	fn silt	0.02	md silt	poorly	st fine	v platy

Site No.	Northing	Easting	Depth (m AMSL)	Shell (%)	Sediment Texture (% by weight)					Modified Folk (1965)		Mean Grain Size		Median Grain Size		Sorting Class	Skewness Class	Kurtosis Class
					Gravel	Coarse and med sand	Fine and v. fine sand	Silt	Clay	Class	Code	(mm)	Class	(mm)	Size Class			
AKA072	2504002.59776	5715482.38048	-1.7	0.04	0	0.3	3.6	69.8	26.3	silt	Z	0.01	fn silt	0.02	md silt	poorly	st fine	v platy
AKA073	2503935.04717	5715973.04075	-0.8	17.46	0	18.5	20.8	52.5	8.3	sandy silt	sZ	0.1	v fn sand	0.04	cs silt	v poorly	st coarse	v leptot
AKA074	2503491.56284	5716505.03910	-0.7	0	0	0.2	61.8	35.6	2.3	silty sand	zS	0.06	cs silt	0.07	v fn sand	mod well	st fine	v platy
AKA075	2503157.03932	5716345.07269	0.1	0	0	0.5	10.4	60	29.2	sandy silt	sZ	0.01	fn silt	0.02	md silt	poorly	fine	v platy
AKA076	2503072.20020	5715929.18913	-0.2	0	0	0.6	3.4	61.1	35	mud	M	0.01	fn silt	0.01	fn silt	poorly	near symm	v platy
AKA077	2503531.14123	5716096.14301	-0.8	5.1	0	5.3	17.7	67.6	9.4	sandy silt	sZ	0.04	cs silt	0.04	cs silt	poorly	near symm	ext leptot
AKA078	2504513.16128	5716769.65234	-3.5	0.03	0	0.5	41.4	52	6.1	sandy silt	sZ	0.05	cs silt	0.04	cs silt	poorly	near symm	v leptot
AKA079	2504980.27259	5716639.29569	-4.1	0.02	0	0.2	4.1	89.2	6.5	silt	Z	0.04	cs silt	0.04	cs silt	poorly	st fine	ext leptot
AKA080	2504431.68838	5716286.24645	-4.2	0.03	0	0.8	0.9	79.1	19.1	silt	Z	0.01	fn silt	0.02	md silt	poorly	st fine	platy
AKA081	2504882.50511	5716145.02675	-4.9	2.62	0	3.2	1.5	69.9	25.4	silt	Z	0.01	fn silt	0.02	md silt	poorly	st fine	v platy
AKA082	2504206.32963	5717227.90031	0.7	0.02	0	0.3	58.8	38.7	2.2	silty sand	zS	0.06	cs silt	0.07	v fn sand	mod well	fine	v platy
AKA083	2504637.73089	5717246.25426	0.2	1.92	0	2.1	81.6	14.5	1.7	silty sand	zS	0.07	v fn sand	0.09	v fn sand	mod	st fine	leptot
AKA084	2505129.57299	5717112.12400	-0.7	12.88	0	66.7	21.7	8.2	3.3	silty sand	zS	0.36	md sand	0.44	md sand	poorly	st fine	meso
AKA085	2505368.21712	5716795.27018	-1.8	15.2	0	15.9	56.5	10.6	17	muddy sand	mS	0.08	v fn sand	0.08	v fn sand	v poorly	near symm	v leptot
AKA086	2503232.40725	5714431.92319	-2.9	0	0	0.2	0.4	57.6	41.7	mud	M	0.01	v fn silt	0	v fn silt	poorly	st coarse	v leptot
AKA087	2506202.36613	5714172.29621	-4	5.2	0	9.1	2.4	56.4	32.1	sandy mud	sM	0.01	fn silt	0.01	fn silt	v poorly	coarse	meso
AKA088	2504355.64700	5715698.55525	-4.3	0.15	0	0.4	1.8	68.2	29.6	silt	Z	0.01	fn silt	0.01	fn silt	poorly	fine	v platy
TIKAU22				0.29	0	3.4	95.8	2.3	0	sand	S	0.12	v fn sand	0.12	v fn sand	well	near symm	meso

Notes: Northings and Eastings are given in New Zealand Geodetic Datum NZGD 2000, AMSL denotes above mean sea level, the modified Folk (1965) classification scheme is detailed in Figure 8, where: classes include gravel (G, g), sand (S, s), silt (Z, z), clay (C, c) and mud (M, m), and capitals indicate the dominant constituent. Sorting was calculated using Folk and Ward's (1957) Inclusive graphic Standard Deviation where values $<0.35\phi$ = very well sorted; 0.35 to 0.5ϕ = well sorted, 0.5 to 0.71ϕ = moderately well sorted, 0.71 to 1.0ϕ = moderately sorted, 1.0 to 2.0ϕ = poorly sorted, 2.0 to 4.0ϕ = very poorly sorted, and $>4.0\phi$ = extremely poorly sorted. Skewness was calculated using Folk and Ward's (1957) Inclusive Graphic Skewness, where values of $+1.0$ to $+0.3$ = strongly fine-skewed, $+0.3$ to $+0.1$ = fine skewed, $+0.1$ to -0.1 = near symmetrical, -0.1 to -0.3 = coarse skewed, -0.3 to -1 = strongly coarse skewed. Kurtosis was calculated using Folk and Ward's (1957) Graphic Kurtosis where values <0.67 = very platykurtic, 0.67 to 0.90 = platykurtic, 0.9 to 1.11 = mesokurtic, 1.11 to 1.5 = leptokurtic, 1.5 to 3.0 = very leptokurtic, >3.0 = extremely leptokurtic.