Mudflat Morphodynamics and Sedimentation Rates:

A Case Study of the Intertidal Mudflats at the Head of the Bay, Lyttelton Harbour

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Figure 1.1, The mudflats at the Head of the Bay; looking west across the intertidal embayment, this photo was taken 1700 m seaward of the benchmark used in this project. (W. de Vries $7^{th}/9^{th}/2007$)

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Abstract

Intertidal mudflats are a unique feature of low energy coastal environments. The mudflats at the Head of the Bay in Lyttelton Harbour cover an extensive intertidal area of over 4 km^2 and are a prominent feature of the region. There has been a vacuum in the knowledge regarding the sedimentation processes operating on the harbour mudflats compared to knowledge of the adjacent open-cast sandy beaches of Pegasus Bay. In this study, the current morphology of the mudflats at the Head of the Bay is examined using a number of survey transects. These transects also provide insight into the extent to which accretion and erosion processes operate on short times scales (weeks to months), and the spatial distribution of these process across the mudflat. The role of tidal flows on sediment disturbance is assessed along with sediment size distributions across the intertidal area of the mudflat. Knowledge of historical changes in environmental and catchment conditions is used to date stratigraphic layers from a number of auger samples taken from the mudflats. An increased knowledge of local systems acquired from field work and existing literature is used to increase the understanding of the processes occurring on the mudflats, and the nature of sediment accretion across the mudflat.

The mudflats at the Head of the Bay show a highly variable distribution of short term sediment disturbance. A relatively stable zone in the upper intertidal area is associated with finer silt and clay sized particles, and a much more dynamic zone in the lower intertidal area dominated by sandier sediments and shell hash. A concave up seaward profile suggests that the mudflats were dominated by erosional processes over the study period. Analyses of auger samples show a substantial increase in the intertidal area from 700 m in 1860-1900, to 2000 m in 2007. Mean yearly sedimentation rates have been substantially lower in the upper intertidal area than in the mid to lower intertidal area, with the average gradient of the mudflats decreasing over time as they extended seaward. It is likely that the intertidal are of the mudflats will continue to increase in the future under current landuse conditions and harbour systems.

Contents

1.0 Introduction

Background

The mudflats at the Head of the Bay, Lyttelton Harbour (Figure 1.1), extend out to the east headland of Governors Bay and Quail Island to the north of Charteris Bay. This area of the harbour has been identified as a sink for eroded sediments from both within the harbour and the surrounding catchment (Curtis, 1985). A core taken from near the high water mark at the Head of the Bay by Goff (2005) uncovered the presence of a stratigraphic layer of charcoal and a rapid change in pollen composition at about 66cm depth. This layer is indicative of rapid land use change and associated vegetation change cause by European settlement about 130 years ago (Goff, 2005). The findings of this core study as well as local observations suggest that the mudflats have been prograding under current land use and environmental conditions. There is some concern about the extent to which the mudflats will advance for a number of reasons:

The first reason is that the passage between Quail Island and the headland between Charteris Bay and The Head of the Bay is seen as important for mixing the waters in the harbour and avoiding such problems as stagnation and algal blooms. This passage is currently passable by foot at low tide. Further sedimentation of the mudflats may result in the blocking up of this passage way. This may also result in reduced water quality and reduce the attractiveness and safety of water sports in this area.

Secondly, recreational activities such as boating may be limited by the extent of the mudflats and the resulting water depth.

Thirdly, some of the local residents feel the mudflats are not visually and aesthetically pleasing and would prefer not to have area of ocean visible reduced by mudflats. These are concerns that have been passed on from members of the public to the Lyttelton Harbour Issues Group and Environment Canterbury (Kate McKeowen, Resource Care, Environment Canterbury, *pers.comm.* 17/5/2007)

1.2 Aims and Thesis

This project aims to investigate the effects that land use changes have had on the sedimentation rates of the mudflats at The Head of the Bay, Lyttelton Harbour. Knowledge of historical changes in environmental and catchment conditions is used to analyse and date stratigraphic layers from a number of auger samples taken from the mudflats. An increased knowledge of local systems acquired from field work and existing literature is used to increase the understanding of the processes occurring on the mudflats at the Head of the Bay, and the nature of sediment accretion across the mudflat. This knowledge is used to investigate the extent to which the intertidal area of the mudflats has increased over the last century. The results of this study may be useful in making predictions of future changes to the mudflats and surrounding processes as well as providing a basis for future management of the area. This data will also have the potential to be helpful in addressing some of the issues mentioned above.

1.3 Current mudflat knowledge

Literature from study sites around the world was selected in order to understand the processes operating on mudflats and their effects on morphology. Mudflats support a diverse range of organisms over a wide range of trophic levels (Quresma et al., 2007). Intertidal flats act as natural protection against erosion from wave action by dissipating their energy (Black et al., 1998)

Mudflats are generally found in low energy environments where tidal currents are the main force causing sediment disturbance (Dyer et al. 2000; Woodroffe 2003; Wood and Widows 2003). Suspended sediment concentrations are often correlated to current flow speed and wave activity (Christie et al., 1999). As for coarser grained coastal environments, calm wave conditions are associated with periods of deposition and stormy higher energy events with erosion (Stelder 1999; Dyer et al. 2000; Kirby 2002). Studies on intertidal mudflats in the Netherlands found that accreting mudflats have a convex up cross-shore profile whereas eroding mudflats have a concave up profile (Dyer et al. 2000; Kirby 2002). Further it is suggested that accreting convex up mudflats are dominated by tidal processes whilst mudflats with concave up profiles are dominated by wind wave processes. Tidal asymmetry of dominant ebb or flood tides leads to steeper flats whilst ebb dominance can force the mudflat to retreat landward (Pritchard 2001).

One of the main biological characteristics of mudflats is the presence of benthic algal films which exist in the upper layer of the mud as a slimy film (microphytobenthos) often increasing the cohesion of the mudflat (Widdows et al. 2000; Woodroffe 2003; Amos et al. 2004; Orvain et al. 2004; Le Hir et al. 2007). The benthic algal film is clearly visible on the mudflats at the Head of the Bay and also on the other mudflats of Lyttelton Harbour. Sediment stability is also increased by epifaunal bivalves and prolonged exposure of sediments to air (Widdows et al. 2000). Bioturbation caused by burrowing and deposit feeding bivalves can lead to increased sediment destabilization and erosion (Widdows et al. 2000; Orvain et al. 2004). Seasonal variations in the erosion threshold of mudflats have been identified as causing notable changes in mudflat profiles in a number of studies. The erosion threshold can increase in warmer seasons when the presence of the algal film is more pronounced (Le Hir et al. 2007; Widdows et al. 2000). The seasonal increase of bioturbating bivalve species however, has been shown to decrease mudflat stability (Widdows et al., 2000). Sediment cohesion and size can have a notable effect on mudflat morphology: the presence of sediments with lower cohesion results in higher accretion rates on the upper levels of the mudflat and in a steeper profile (Widdows et al., 2001). Another effect is that increased cohesion results in increased accretion on the intertidal area of the mudflat (Widdows et al., 2001). The intertidal mudflats at Governors Bay, Head of the Bay and Charteris Bay cover an area of approximately 11 km^2 (at low tide), and have a tidal range of about 2 m (Curtis 1985, Brown 1976). The mudflats are predominantly made up of loess eroded from the hills of Banks Peninsula. They consist predominantly of fine, silt sized sediments at the mid to upper tidal limits, with slightly-larger sandy sediments in the lower intertidal zone (Curtis, 1985).

It is clear that mudflat profile, sediment size and sediment stability are important parameters in assessing the stability and operative processes on mudflats. The nature and extent of these three parameters on the mudflats at the Head of the Bay, Lyttelton Harbour, are researched in this project.

1.4 Similar Studies in New Zealand

There is a reasonable amount of previous research on the effects of land use on sedimentation rates in New Zealand harbours and estuaries (Hume 1983; Sheffield et al. 1995; Swales et al. 2002; Mead and Moores 2005). These examples concentrate on specific areas such as Aucklands harbours and estuaries (Hume 1983; Swales et al. 2002), Port Waikato (Mead and Moores 2005) and Whangamata in the Coromandel (Sheffield et al., 1995). These studies have analysed cores of varying depths and analysed the content of stratigraphic layers for pollen, charcoal, sediment type, and composition. Using these observations and some basic dating techniques a picture is created of the effects of varying land use on the sedimentation rates in each catchment. Mead and Moores (2005) and Sheffield (1995) found that sedimentation rates in harbours and estuaries from Waikato and the Coromandel were consistently higher for post European settlement than for Polynesian settlement. However no in-depth studies of this sort have been carried out in Lyttelton Harbour. Land use changes associated with European settlement were similar in the above mentioned study sites suggesting that similar observations may be expected in Lyttelton Harbour.

1.5 Sedimentation and land use on Lyttelton Harbour and Banks Peninsula

The core taken from the Head of The Head of the Bay by Goff (2005) indicated that at the current high water mark the mudflats were, at the time of European colonisation (1830), at a level 66cm below that which they are today. At the time of Maori colonisation (1250) the level of the mudflats at the core site is estimated to have been 91 cm below the present level. Mean yearly sedimentation rates of 0.07 cm a year before human settlement, 0.043 cm a year during Maori settlement and 0.37 cm a year during European settlement can be calculated from Goffs (2005) core study. The origin of the majority of sediments on the mudflats and the nature of currents limiting the introduction of sediments to the harbour from external sources suggest the main sediment source to be from the surrounding catchments (Curtis 1985). The rapid increase in sedimentation rates of over eight times that during Maori settlement suggests that European colonisation, and the associated intense change in land use is the most probable cause of increased sedimentation rates.

Historic changes in vegetation (as described by Petrie 1963; Ogilvie 1990; and 1992) have been observed in pollen records by various studies looking at land use change as a result of European colonization (Dunbar et al. 1997, Woodward and Shulmeister 2005, Sheffield et al.1995) and the effects on sedimentation rates of water bodies in surrounding catchments (Hume 1983,). Woodward and Shulmeister (2005) show that deforestation on Banks Peninsula is marked by a rapid decline in the pollen record of Matai and Totara pollen from 1840 to 1895, after which levels remain consistently low, and the appearance and increase of exotic grass species from about 1895 onwards. Changes in charcoal concentration have also provided a good time indicator in various studies around New Zealand (Dunbar et al. 1997, Woodward and Shulmeister 2005) as large areas of bush were burnt during European settlement. Woodward and Shulmeister (2005) found that charcoal concentrations increase rapidly from 1840 onwards peaking shortly after 1895 as a direct result of burning native bush to free up farm land on Banks Peninsula. In this study sedimentation rates in the Head of the Bay will be explored using charcoal analysis of stratigraphic samples to date layers.

1.6 Thesis Structure

The Methodology which leads on from the introduction is broken up in to two parts, firstly the geography of the study site relevant to analyzing the results is explored and secondly the processes undertaken to gather information and the methods by which these are analysed is presented. A number of scale figures created in ArcGIS are presented showing the location of the study site as well as specifics for survey transects used. This is followed up by the results sections in which the data obtained from field work is presented and interpreted. The discussion section takes the results from this study and interprets them in the context of both local environmental conditions and processes as well as a wider knowledge of mudflat processes and sedimentation patterns. This section also investigates the limitations of material gathered in this study identifying shortcomings as well as providing some suggestions as to how knowledge of the mudflats at the Head of the Bay may be enhanced through further studies. The conclusion provides a brief overview on the findings and limitations of the study. Acknowledgements of people who have offered academic and technical support are made. The report ends with a list of literature cited.

2. Methodology

2.1 Background of Study Area

2.1.2 Lyttelton Harbour Geology

Lyttelton Harbour is located on the northern side of Banks Peninsula, which is on the east coast of the South Island, New Zealand. The harbour entrance faces northeast (Figure 1.1). The harbour is about 14 km in length and has an average width of approximately 2 km. Lyttelton Harbour is the eroded remnant of the smaller of the two volcanoes that formed Banks Peninsula, becoming dormant about 8.5 million years ago (Weaver et al. 1985). Most of the hills surrounding the harbour are between 300-450 m in height and have a base layer of volcanic rock types which protrude around the ridges (Weaver et al., 1985). On the lower slopes aeolian loess that is wind swept silt blown of the Canterbury Plains during the Pleistocene, is present to a depth of 10 m (Bushell and Teear 1975). The above-mentioned loess is regarded as the main source of sedimentation in the Lyttelton Harbour basin, reaching depths of up to 47 m in the harbour basin (Bushell and Teear 1975). The bed of the Harbour can be described as flat with a depth of 15.5 m at the Harbour entrance, gently grading towards extensive intertidal flats at the head of the harbour in Governors Bay, Head of the Bay and Charteris Bay (Curtis 1985). Although not well quantified, evidence indicates that the main fluvial inputs to the harbour occur in these three bays, with freshwater inputs from streams being small (Curtis 1985).

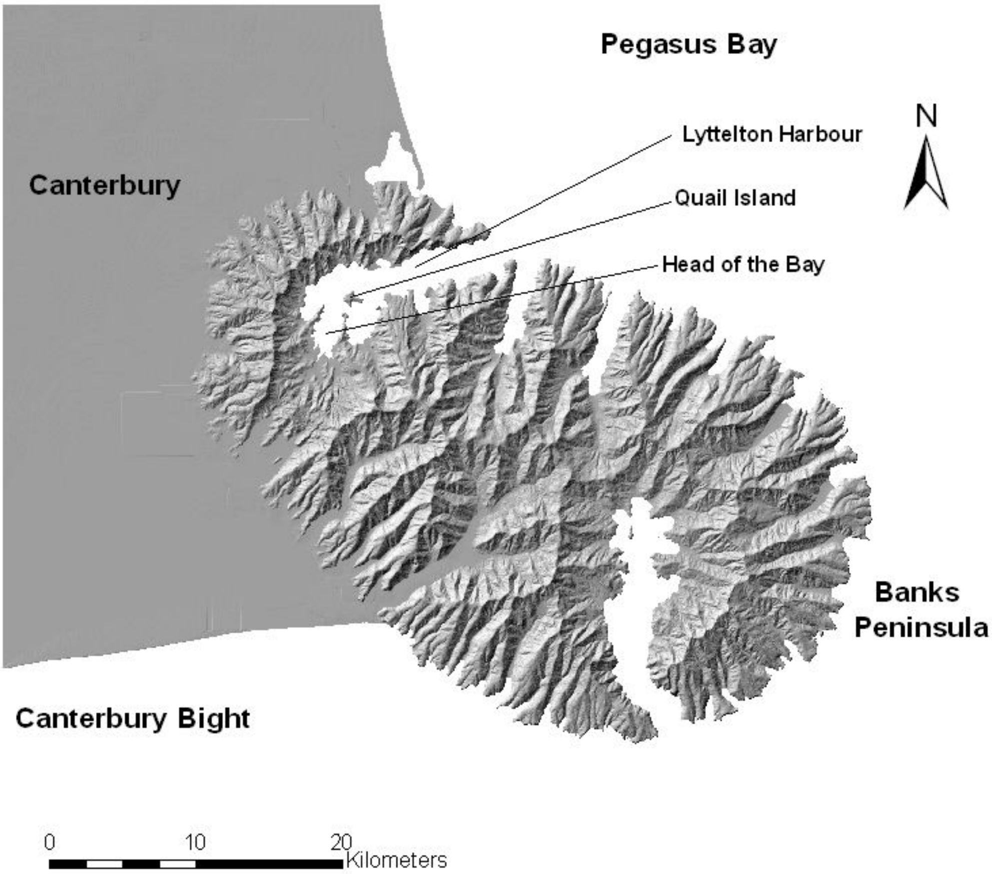

Figure 2.1. Location map showing the study site at the Head of The Bay, Quail Island and surrounding topography.

2.1.2 Coastal/marine processes in Lyttelton Harbour and the Canterbury region

The Canterbury coastline is dominated by the Southland Current which flows to the north along the Canterbury Bight before bending around Banks Peninsula and splitting into two currents in Pegasus Bay, one flowing south along the southern bay and the other flowing north along the northern bay. (Campbell 1974). The Southland Current carries fine fluvial sediment brought to the coast by braided rivers such as the Rakia and depositis a quantity of this of the north eastern coast of Banks Peninsula (Campbell 1974). Tides are semi-diurnal, with a tidal range of 2.16 m between mean high water spring and mean low water spring (Goring 1991). Dredging in Lyttelton Harbour occurs to the northeast of Lyttelton Port. It is suggested by Curtis (1985) that dredging is one of the main sources of sediment redistribution and deposition within the Harbour. The flood tide generally flows down the southern side of the Harbour and into the Head of the Bay, with some circulation occurring to the north east of the Port. During the ebb tide water from the Head of the Bay is mixed in with that on the southern side of the harbour through the gap between the western Charteris Bay headland and Quail Island (Figure 2) (Curtis 1985). Due to its straight profile Lyttelton Harbour is open to waves of unlimited fetch from the north east (Curtis 1985), resulting in highly-variable wave conditions within the harbour. Due to wave refraction in the outer harbour waves have often lost much of there energy by the time they approach the mudflats at the southern end (Bushell and Tear 1975; Curtis 1986). Predominant swells in the region are south westerly with a relatively low occurrence of north easterly swells (Gorman et al. 2003) this results in Lyttelton Harbour generally being a low energy environment.

Sedimentation from coastal erosion and sediment deposition from surrounding catchments has been estimated by Curtis (1985) to be less then 45 000 t y^{-1}. The amount of sediment entering the harbour from Pegasus Bay and the Southland Current is unknown, it is suggested by Curtis (1985), however that the lower harbour and dredged channel will be a sufficient sink for this material preventing it from being transported to the southern end of the harbour. The process of dredging in Lyttelton Harbour involves the redistribution of sediments, although a large portion (approximately 80%) of dredged sediment is re-circulated into, and refills the dredged channel (Curtis 1985, Barter 2000). The head of the harbour (Head of the Bay, Governors and Charteris Bay) has also been identified as a sink for some of this material (Curtis 1985).

2.1.3 History and Deforestation

The first Europeans settled the Peninsula in the 1830s but it was not until the arrival of the Canterbury Association settlers in the 1950s that the timber industry began to grow with increased housing demand in Lyttelton and Christchurch (Ogilvie 1992, Ogilvie 1990). Prior to human settlement the valleys and tops of Lyttelton Harbour were covered in podocarp forest and native bush with headlands and the dryer areas with native tussock, much of this vegetation remained during Maori colonisation (Petrie 1963). Major deforestation occurred on Banks Peninsula between 1860 and 1890.

This resulted in the rapid decline of native forest species giving succession to a range of introduced grasses and pine at various stages of colonisation (Petrie 1963). A period of forest clearance likely resulted in a pulse of sedimentation rates to the harbour. Whilst a change from forest in to pasture is expected to increase annual sedimentation rates (Fahey and Marden 2000) which in the case of Lyttelton Harbour may have led to an increase in sedimentation rates.

2.2 Methods

This section presents the methods that were used to obtain data from field work to address the aims of this project. Transect profiles and sediment samples provide useful indicators of the state of the mudflats in terms of typical mudflat characteristics as described by literature discussed in the introduction. Survey transects taken at different times through out the study period are used to provide an idea of the distribution and magnitude of "short term" erosion and accretion processes operational on the mudflat. A knowledge of the distribution of vertical mixing and sediment disturbance across the intertidal mudflat is useful in understanding the processes driving morphological shifts on the mudflats and provide a basis for the positioning of auger samples as well as providing an indication of their accuracy. Auger sampling and sediment processing can be analysed for the identification of stratigraphic layers which can be traced across the mudflat to provide an idea of past sedimentation patterns and rates.

2.2.1 Mudflat Profiles

The mudflats were surveyed across the tidal gradient at different periods in time. This was done in order to assess their dynamics in response to variations in short term climatic variables. A bench mark, from which surveys would be taken, was created by driving a long peg, (peg 1, Figure 2.2) with a cross marked on top, 60 cm in to the ground. As there are no animals grazing this area and given the short term stability of the coastal land and the relatively short study term it was felt that this depth would be sufficient to prevent against any disturbance to the bench mark from animals or subsidence/erosion. Peg 1 was used as a bench mark in terms of height and location to remain constant for the duration of the surveys. Two hundred meters landward of the benchmark (peg 1) another marker peg (peg2) was driven in to a similar depth (Figure 2.2). A Sokia 530R3 (theodolite) was setup to be centered over the initial peg (Sokia Surveying Instruments, 2002). A bearing was then taken of the eastern side of peg 2 and the total station rotated 180 degrees and then locked in position. This allowed for the bearing of transect line A to remain the same for each of the surveys taken. Three surveys were taken along transect line A at approximately one month intervals throughout the winter of 2007. Surveys were taken across the tidal mudflats from maximum high water to mean low water.

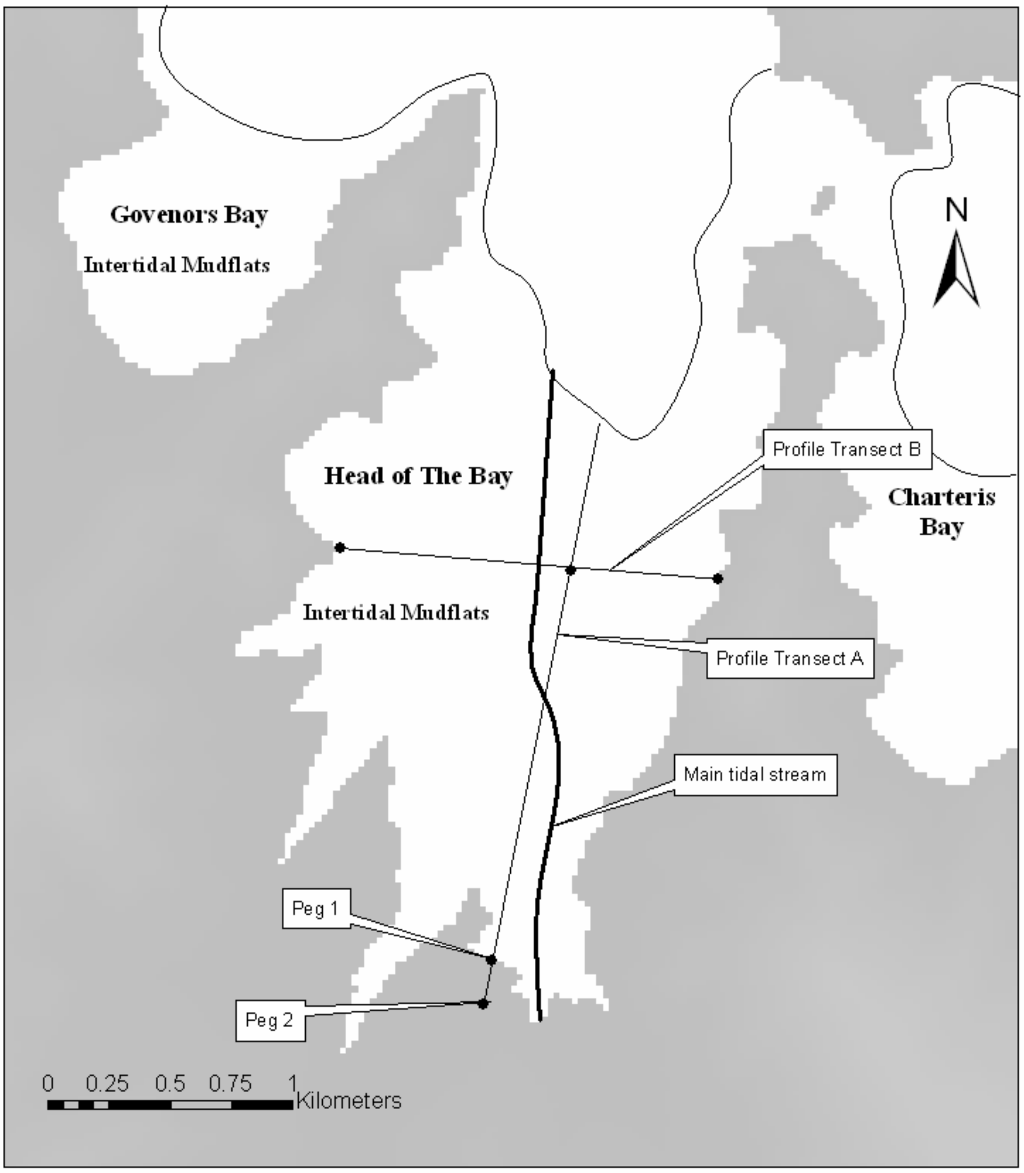

Figure 2.2. survey transect locations at the Head of The Bay Lyttelton Harbour, Peg 1 represents the temporary bench mark and Peg 2 was used to maintain a constant bearing on the transect line throughout the study period.

2.2.2 Horizontal Sediment Disturbance

The extent of tidal driven vertical mixing of the surface sediment was assessed in order to establish the best methodology for quantifying this amount. Two methods were used to identify the extent of sedimentation, Firstly, stakes were driven in to the sediment at regular intervals across the intertidal transect. Using these as a fixed elevation, changes in sediment depth could be observed by placing a 1 m rod across the base of the stake and measuring the distance to the top of the stake. The use of a 1 m rod insured any effects of the stake on sedimentation patterns would be minimized. This method would be effective in identifying any substantial changes (over 10mm) of accretion or deposition. Secondly filter papers on paper clips as described by Brown (1985) were used to asses for more subtle sediment disturbances.

Filter paper sediment traps were adapted from those described by Brown (1998). A 90 mm circumference mesh stainless steal disk, with 1 mm holes in it was attached to the top of a 200 mm by 3 mm stainless steel rod. A 90 mm circumference (1.2 µm) glass fiber filter paper was attached to the disk (Figure 2.3). Prior to deployment filter papers were weighed. Individual filter papers were attached to their stands and their location on the transect relative to their weight recorded. Four "sediment traps" were located at even intervals across the tidal mudflat by pushing the 200 mm rod in to the sediment until the disk was at an even elevation with the substrate. Sediment traps were left on the mudflats for two tidal cycles before being retrieved. Sediment and papers were taken back to the lab and dehydrated in the oven before recording their final combined weight. The difference in weight of the filter paper, and the resulting dried filter paper and sediment was then used to record the amount of horizontal sediment displacement at each site over the two tidal cycles.

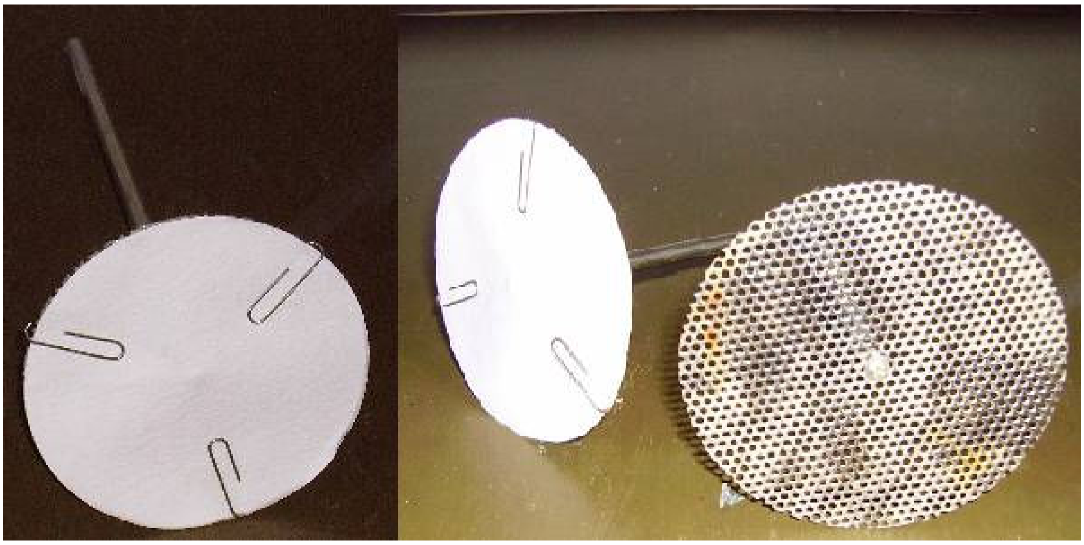

Figure 2.3. Photos of filter paper sediment “traps” before deployment, note filter papers attached to the gauze top with only three paper clips to minimize disturbance to current flows.

2.2.3 Mudflat Sediment Stratigraphy

Attempts at coring were made using a vibra corer, a D corer, impact corer and the barrel and mallet method, major problems were experienced in terms of core retention within the barrel, and with core compaction and bi passing of sediments at the head of the barrel. This resulted in the use of an auger, 100 mm diameter by 200 mm deep, to obtain a profile of the different sediment layers and their thicknesses. Auger samples were taken at two locations to a depth of around 1700 mm below the mudflat surface, near the high tide mark and 680 m from the benchmark where the mudflat was assessed to be relatively stable. The use of auger samples over core samples decreased accuracy as samples could only be taken in 100-150 mm sections due to the viscous nature of sediments and the retention of sediments in the auger head. Consequently any observations in sediment composition and relative aging will fall with in the 100-150 mm segments rather then being pinpointed at an exact depth as with a core sample.

It was initially intended to carry out pollen analysis on substrate samples, using knowledge of local vegetation changes to date certain depths and to explore how sedimentation rates were effected by vegetation changes as in (Woodward and Shulmeister 2005, Hume 1983). However due to time constraints and limited access to phylogeny equipment this procedure was unable to be carried out for this project.

2.2.4 Sediment Analysis, Dating Layers

Sediment samples were coned and quartered in the lab in order to reduce the sample size for processing and to get a smaller sample representative of the depth range covered. Special care was taken to ensure all equipment for coning and quartering was cleaned thoroughly between samples in order to minimize the risk of contamination. Samples were analysed for charcoal and processesed in accordance with the methods outlined by Rhodes (1998). This involved the bleaching of any organic material in the sediment using various concentrations of hydrogen peroxide in order to be able to positively identify charcoal fragments (the coloration of which is unaffected by the bleaching procedure). Using the knowledge of historic forest burning on Banks Peninsula and its representation in cores (Woodward and Shulmeister 2005; Goff 2005; Petrie 1963; Ogilvie 1990 and 1992) an approximate age of a sediment layer can be calculated.

2.2.5 Sediment Size Distribution

Surface sediment samples of about 30 g were taken at 200 m intervals along transect line A. Individual samples were analysed in the lab for the relative content of different sized particles including shells, using sediment sieves. Shifts in dominant sediments are calculated as a percentage of fines (silts and clays) versus coarse (sands and shell fragments). This data will provide an understanding of the sediment size distribution throughout the intertidal transect. Sediment size data may also be able to be linked to shifts in the predominant wave conditions experienced at various tidal levels, as well as providing an insight in to the stability of sediments.

3.0. Results

The results section focuses on data obtained from field work and is broken up into three sections presenting material that addresses the following questions;

1. What is the current morphology of the mudflats? What is the stability of sediments on the mudflats?
2. What indicators may explain or be related to, decreasing stability of the mudflats seaward along the profile?
3. To what extent has sedimentation occurred on the mudflats in the last 130 years or so? How may sedimentation have affected the intertidal area and morphology of the mudflats?

3.1. Mudflat morphology

Mudflat profiles taken along transect one (Figure 2.1) on the 11/6/07, 20/7/2007 and the 1/9/07 indicate that the mudflats currently have a horizontal intertidal area of around 2 km (Figure 3.1.A.). There is a substantial amount of vertical variation in the level of the mudflat, particularly in the lower tidal range, from 1100-1200 m onwards. A large vertical lowering was observed in the lower intertidal area from 11/6th till the 20/7th; with a maximum profile change of 0.77 m observed at 1650 m over the six week period. The profile taken on the 1/9th shows an increase in sedimentation following the earlier erosion period, raising the mudflats back up to a level of about half that eroded over the previous six weeks (Figure 3.1.A). Horizontal sediment displacements of 632 m^2 for the 11/6th – 20/7th and 315 m^2 for the period 11/7th – 1/9th can be calculated (using Arc info and Arc map).

The X at 1613 m on Figure 3.1.A. indicates where the long shore profile in Figure 3.1.B. (transect 2) intersects transect 1. The vertical variation in the profile surrounding the intersection point (X) on Figure 3.1.B. suggests that the vertical variation of the three profiles observed in Figure 3.1.A. can not be attributed to erroneous variation between the three intertidal profiles created by differences the observation angle. An exploration of the potential for surveying errors to have influenced the vertical variation observed between profile transects on “transect A” (Figure 2.2) with only 1.3 cm of horizontal variation at 1600 m caused by slight (0.355°) changes in the observation angle. The margin of error for the recordings taken by the Sokia theodelite is negligible (Sokia Surveying Instruments, 2002).

In the longshore profile it is interesting to note the gentle gradient from the west to the tidal stream at the centre of the profile, whilst on the eastern side of the tidal stream the mudflats maintain a much gentler profile until within a 200 m of the eastern shore, before assuming a much steeper profile towards the mean high water spring level. These differences in morphology suggest that different processes may be operating on either side of the mudflats. Throughout the survey period the mudflats maintain a gentle concave up profile (Figure 3.1.A.).

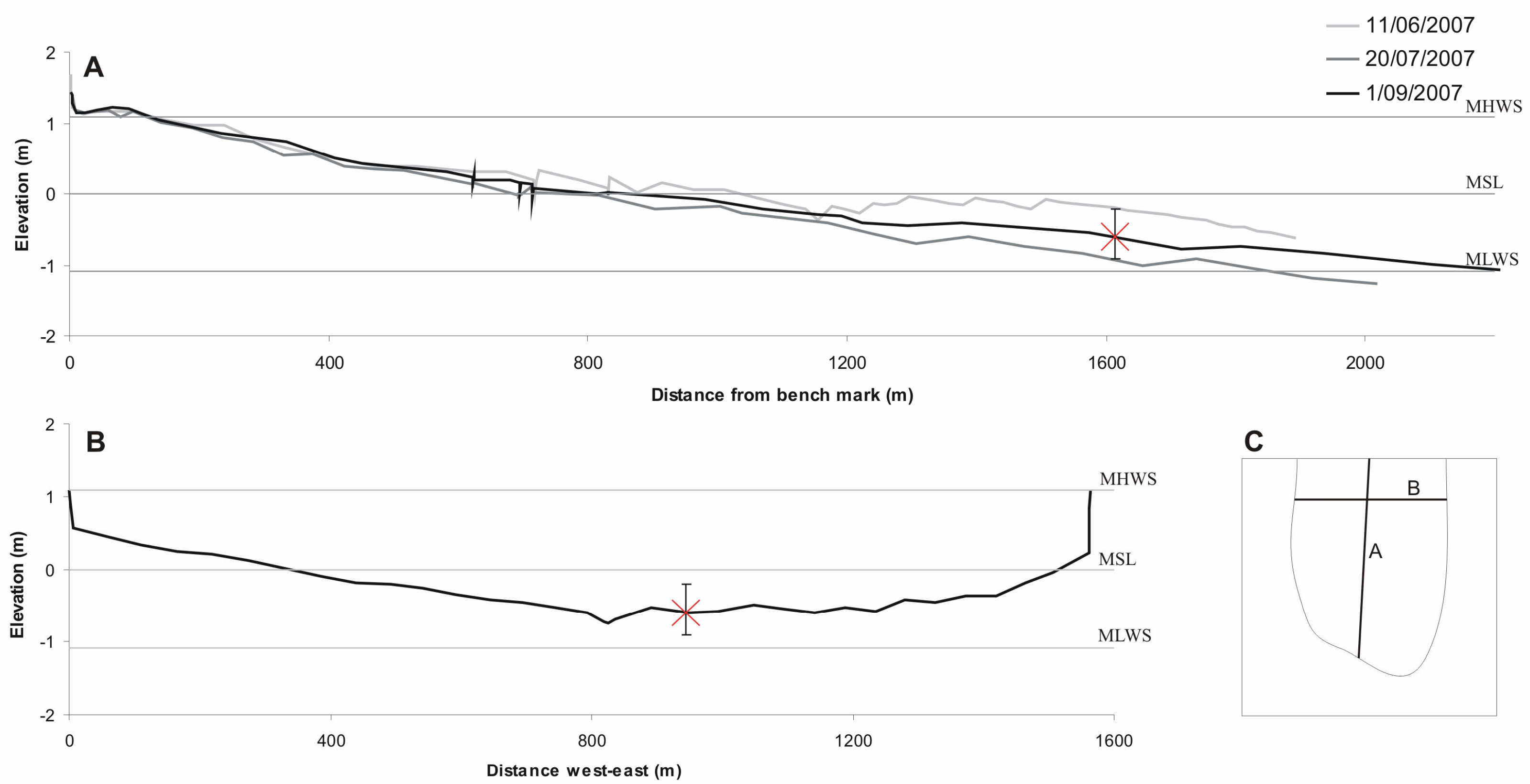

Figure 3.1 A Profile of the intertidal mudflats as observed across the Head of the Bay along transect A. The profiles show the morphology of the mudflats at approximately six week intervals, with changes (from 11/06/07 - 1/09/07) indicated by variations observed between the transect lines. The cross at 1613 m marks the location where this profile crosses transect B, with the horizontal bars indicating the range of change at this location. Mean High Water Spring (MHWS), Mean Sea Level and M.S.L, Mean Low Water Spring (MLWS), are shown as grey lines. **B,** Profile graph of the intertidal mudflats as observed along transect B on the 8/9/07. The cross at 943 m marks the location where this profile intersects transect A. Note the tidal stream is located at 822 m from the western. The transect was taken from west (0 m) to east (1600 m). The cross at 1613 m marks the location where this profile crosses transect B. Mean High Water Spring (MHWS), Mean Sea Level (MSL), and Mean Low Water Spring (MLWS), are shown as grey lines. **C,** basic overview figure showing the approximate locations of transects A and B in the embayment at The Head of the Bay.

3.2 Mudflat sediments and stability

The stability of the mudflats at the Head of the Bay decreases in the lower intertidal zone with the envelope of change increasing with decreasing elevation of the mudflats (Figure 3.2.A.). The sediments on the lower mudflats are composed mainly of coarser sediments such as sands with an increase in broken particles of bivalve and mollusc shells in the sediments. The percentage of fine silts and clays is much higher in the upper intertidal area accounting for about three quarters of the total sediment from the bench mark at 0 m to about 800 m seaward (Figure 3.2.B.). This pattern of increased coarseness of sediments along transect 1 appears to closely follow the trend of decreased stability at lower levels on the intertidal flat. A filter paper assessment of tidal driven mixing over two tidal cycles gave similar values of sediment disturbance across the flats; 0.051-0.055 g/cm^2 from 98-1472 m along transect 1 (Table 3.1). These values suggest that variability in the stability of the mudflats as observed in Figure 3.1.A. is driven by process other than the tides, or alternatively that tidal-driven sediment disturbance is difficult to observe.

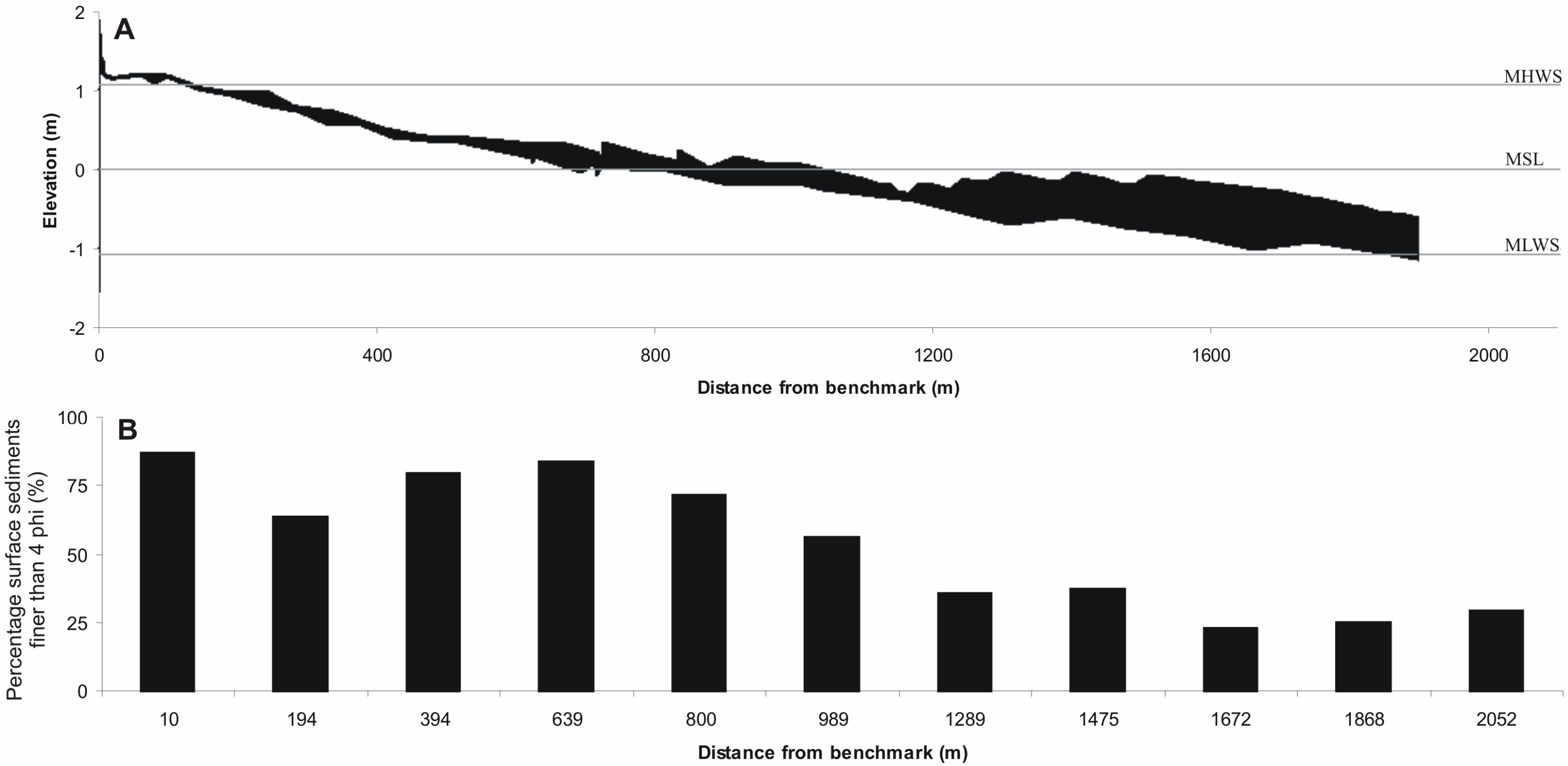

Figure 3.2 A. The envelope of morphological change observed along transect 1 between the 11/06/07 and the 1/09/07. **B.** Percentage of fine sediments (<4) phi as a component of total sediment along transect 1 on 9/9/07, the remaining, coarser, sediment were generally 2-4 phi, with a few larger shell fragments. Samples were taken along transect 1 at approximately 200 metre intervals.

Table 3.1: Tidal driven horizontal sediment disturbance values as calculated from dry weight variations in filter papers, bags, and sediment derived from the sediment traps. Values represent the amount of sediment disturbed over two tidal cycles. Note that the sediment trap at 902 m was lost during fieldwork, resulting in no values at that location.

Distance From Peg 1, (m)	98	515	902	1472
Suspended Sediment, (g/cm²)	0.051	0.051	-	0.055

3.3. Sedimentation rates and changes in mudflat morphology

There is a notable range in the observations of charcoal counts taken from auger samples. Auger location A shows relatively high charcoal counts up until a depth of 42.5 cm, after which charcoal levels remain consistently lower (Figure 3.3). Auger and core depths are represented as depths from the surface of the mudflat at the time of observation. The decrease in charcoal counts is accompanied by a shift in sediment composition, with a notable increase in red-brown material in sediments below the 42.5 cm sample. In a core which was retrieved from within 1 m of auger hole location A, there was a clear transition from grey dominated sediments to sediments containing large clusters of red-brown material at 30 cm. The transition in sediment composition described above was consequently located at a depth of 29-30 cm. Given that some compression of the core is likely, this depth matches well with the depth of observed decreases in charcoal counts. This suggests that the increase in charcoal concentrations occurred at a time of changing sedimentation conditions. The observations of charcoal counts taken from auger hole B are much less decisive than those from auger hole A, with three large spikes in charcoal counts (Figure 3.3). At this point it is important to mention that tests of the accuracy of the method used for counting charcoal densities produced low standard deviations of 2.309 at auger hole A and 1.528 at auger hole B, suggesting that charcoal counts are accurate to within 5 % per count. A notable increase in red-brown material was observed from processed sediments used for charcoal analysis at a depth of 136.25 cm, where the third spike in charcoal counts was observed. There are two pieces of evidence suggesting that the spike in charcoal counts at 136.25 cm is representative of the same stratigraphic layer observed at 42.5 cm at the location of auger hole A; firstly, the change in sediment composition in auger hole A at a similar depth to the shift in charcoal counts is also observed in auger hole B at a depth similar to the third spike in charcoal counts. Secondly, the analysis of a core by Woodward and Shulmeister (2005) taken from a nearby lake uncovered three spikes in charcoal concentrations, the third (deepest) being dated to the late 1800s. It is possible that the three spikes did not appear in the analysis of auger samples from location A given the comparatively lower number of samples representing a similar sedimentation period. For the purpose of analysis of results in this

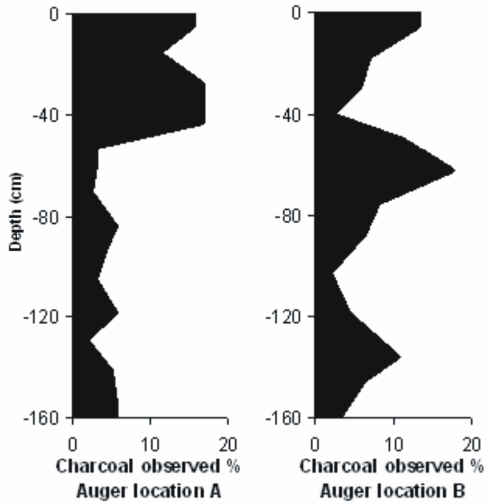

Table 3.2. Duplicates of charcoal particle counts from one depth sample at auger sites A and B. Counts are of the number of charcoal particles larger then 4 phi observed in 0.2 g of sediment from the sample. Note that these samples were processed individually from those used to establish relative charcoal percentages at different depths.

Sample	1	2	3	Mean	Standard Deviation
A,10-20 (cm)	*13*	*17*	*17*	*15.667*	*2.309*
B,10-25 (cm)	*11*	*13*	*14*	*12.667*	*1.528*

Figure 3.3. Left, Component percentage of total observed charcoal in 0.2g samples of sediment retrieved from auger holes. Sediment samples fall between two depths intervals and percentages for individual depths samples have been graphed against the mean depth of the sample. Note that 0 m depth represents the current mean surface level of the mudflats at that location (A or B).

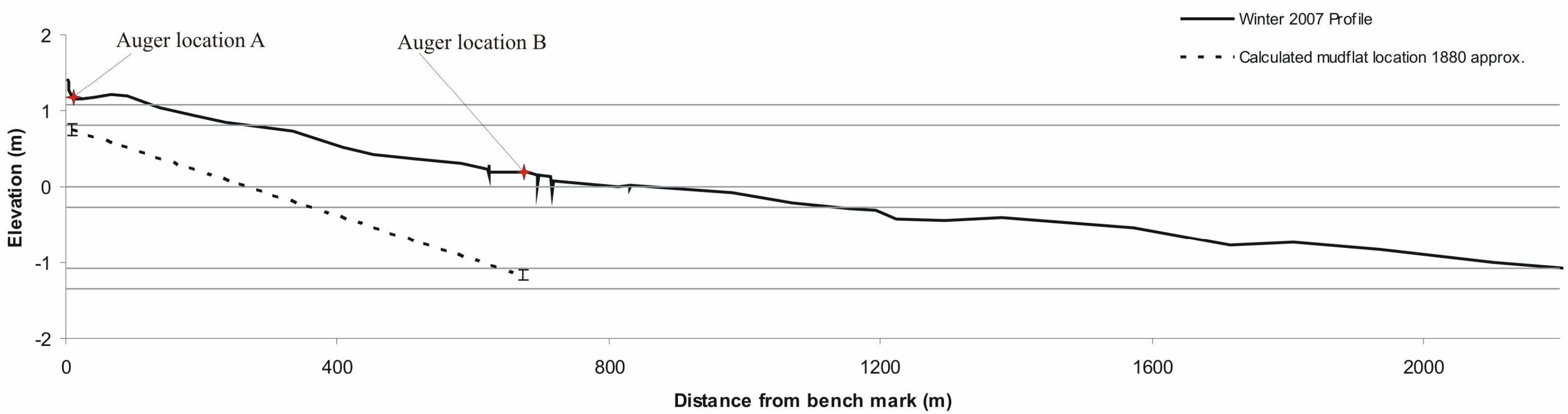

Figure 3.4. Representative current mudflat profile and tidal ranges, compared to calculated mudflat level and intertidal extent in the period 1860-1900, mean sea level (MSL), Mean low water spring, (MLWS) and mean highwater spring (MHWS) have been calculated for 1880 from values of sea level rise as presented by Hannah 2004. Note the locations of auger sample sites A and B.

study, these two depths are used as an indicative stratigraphic layer of the time of land use change associated with European settlement. With increased concentrations of charcoal in stratigraphic layers related to the clearance and burning of native forest to clear the land for pastoral farm land. The transect taken on the 1/9th is used as a representative line of the level of the mudflats at present as it falls in between the other two observed transects in terms of vertical stability. The calculated level of the mudflats in the 1880s shows an intertidal area of a little over 700 m. This suggests substantial accretion over the past 127 years with the mudflats having an intertidal profile three times greater than that of the mid to late 1800s (Figure 3.4), with a horizontal area displacement of 597 m^2 between the 2007 profile and that dated 1860-1900 (note that this value only covers the sedimentation between the two auger sample sites).

Although it is not possible to obtain a detailed picture of the form of the mudflats with only two auger sample locations, given the tendency of mudflats to maintain a gentle gradient a straight line between the two auger sample sites should provide a good proxy for past predictions of the morphology of the mudflats. The average gradient of the mudflats in this landward section has decreased substantially over the past 127 years, with observations of mudflat levels in the 1860s-1900s showing an average gradient of 0.0028 m compared to 0.001 m today (Figure 3.4).

3.4. Overview of results

The mudflats have a consistent concave up profile during the study period with a cross-shore intertidal width of 2000 m, and an average gradient of 0.0028. A large amount of short-term (6 week) variability in mudflat morphology is observed on the lower half of the mudflats with up to 70 cm of vertical change. A higher proportion of fine silt and clay sized surface sediments are found in the upper more-stable reaches of the mudflat. From 1000 m seaward sediments are coarser with an increase in sand sized particles and shell fragments. Over the last centaury sedimentation has increased the level and area of the mudflats, with a threefold increase in the cross-shore intertidal distance. In the upper reaches of the mudflat sedimentation rates increase shoreward leading to a decrease in the gradient of the mudflats.

4.0 Discussion

The objectives of this research topic were to;

1. Asses the current morphological state of the mudflats
2. To investigate the extent to which the mudflats are in a state of "dynamic" equilibrium
3. Investigate the nature and extent of sedimentation on the mudflats at the Head of the Bay after the change in catchment vegetation associated with European settlement

The results produced a number of interesting findings which will help address these questions. This chapter investigates the findings presented in chapter 3 in the context of wider processes in the study site and in light of relevant literature from other study sites.

4.1 Mudflat morphology

A consistently concave up profile is observed on the mudflats at the Head of the Bay over the study period (Figure 3.1 A). The concave up profile suggests that the mudflats are currently in a state of erosion (Dyer et al., 2000; Kirby 2002). Stormy high energy events are associated with mudflat erosion (Stelder 1999; Dyer et al. 2000; Kirby 2002). The association between mudflat profile and erosion is supported by the findings of Pritchard (2001), who found that concave up mudflats are dominated by wind wave processes. An assessment of the three profiles reveals an erosion period occurring between the first two transect profiles observed (11/06/07-20/7/07) followed by an accretion period over the following six weeks (20/7/07-1/9/07). This would suggest that that the mudflats were exposed to a higher level of wave activity in the initial observation period. A higher number of swells from the north east and east were recorded by the Canterbury wave buoy from 11/6/07-20/7/07 than for the following six weeks, with swell heights of 2-4 m. Lyttelton Harbour opens to the northeast and is most exposed to waves approaching from this angle. This is likely to have resulted in higher wave activity on the mudflats over the first six weeks of observation. It is also interesting to note the occurrence of a period of very high southerly swells from the 23rd-27th of June peaking at 13 m on the 25th, this is event is of substantially larger magnitude then those observed over the depositional period from the 20/7/07-1/9/07 with maximum southerly wave heights of 10 m and the majority of swells <6 m (ECan A, 2007, ECan B, 2007).

Given that the observed erosion is wave dominated it is likely that erosion of a similar scale to that observed along the transect is operative across a large proportion of the lower intertidal zone, which has a surface area of over 4 km^2. Keeping this in mind, the maximum intertidal horizontal sediment displacement of 632 m^2 observed on the lower half of the mudflats suggests that a shift in sediments of a magnitude of 100 000s of cubic metres within the coastal system may be a relatively frequent occurrence. The magnitude of accretion and erosion events in the lower half of the mudflats clearly indicates a shift from a relatively stable zone in the higher intertidal area to a much more dynamic zone in the lower intertidal area.

The cross-shore profile (Figure 3.1 B) shows a gentler gradient on the western side of the mudflats and assumes a straight line. On the contrary the eastern side of the mudflat assumes a much shorter steeper profile with a concave up profile. An onshore sediment flux is associated with flood tides whilst a dominance of ebb tides causes an offshore sediment flux, contributing to intertidal mudflat accretion and erosion respectively (Christie et al. 1999). The dominance of ebb tides can lead to the landward retreat of the shoreline (Pritchard 2001); this may explain the more landward reach of the mudflats on the eastern side proportionally to the shoreline and aspect of the embayment (Figure 2.2). The predominant tidal currents associated with the flood tide move up the north western side of the harbour whilst the ebb tide flows seaward along the south-eastern side. In the Head of the Bay the ebb tidal currents flow seaward through the gap between Quail Island and the headland separating the Head of the Bay and Charteris Bay (Curtis 1985). The dominance of ebb tides on the western side of the mudflat is a likely cause for the steeper mudflat profile and the concave up profile suggesting a greater importance of erosion processes on this side of the mudflat.

Tidal streams are clearly visible in the upper reaches of the mudflat profiles as sharp downward spikes located at 600-700 m (Figure 3.1 A). It is interesting to note that the locations of tidal streams remain relatively constant over the three month study period despite horizontal variations in the profiles. At 695 m along transect A the earlier transect associated with the main observed erosional period (20/7/07) shows a very gentle gradient to the stream bed. The transect taken six weeks later at a level 15 cm above that observed on the earlier transect at the same point has the stream bed in the same location but with steeper banks.

4.2 Mudflat sediments and stability

Sediments on the intertidal mudflats at the Head of the Bay are finer in the upper tidal regions; this is typical of mudflats environments (Woodroffe 2003). There is a decrease in sediment stability in the lower half of the intertidal mudflat at the Head of the Bay, this shift is closely associated with the shift in proportion of fine muds and silts compared to sands (Figures 3.2 A and B). The current distribution of sediments on the mudflats is similar to that observed by Curtis (1985), indicating that there has been little spatial shift in sediment distributions and suggesting that the energy distribution across the flats has remained similar. Widdows (1999) found that sediment cohesion and size can have a notable effect on stability, with larger less cohesive sediments generally representing a less stable environment. Sedimentary processes are different for mud and sand, sand moves primarily as saltation or bedload where as mud is transported in suspension and can continue to be shifted when water flows drop below threshold levels for sand transportation (Woodroffe 2003). When suspended mud sediments have settled they also have a higher erosion threshold (Woodroffe 2003). This provides part of the explanation for increased erosion in the lower half of the tidal flats as coarser sediments are more prone to erosion. The distribution of fine sediments on the mudflats further also suggests that water flows are weaker in the upper tidal reaches resulting in the deposition of finer sediments in this region. In comparison, flows in the lower tidal flats are stronger and waves, which are limited by water depth (Woodroffe 2003), would be larger in this deeper area, resulting in both increased erosion and deposition processes in this region.

Analysis of tidally driven suspended sediment showed a relatively constant disturbance across the tidal range. There are two possible explanations for this; either flow speeds associated with tidal currents are relatively constant across the mudflat. However as mudflat processes are dominated by tidal currents (Dyer et al. 200; Woodroffe 2003; Wood and Widows 2003) and given the distribution of fine sediments across the mudflats this is unlikely. Secondly the sediment traps may not have given an accurate representation of the amount of sediment suspended during the tidal cycles, this may have been due to the feet on the filter paper sediment traps (Figure 2.3) maintaining the traps at a fixed level and so limiting the amount of sediment that will settle on the trap to the level of the mudflat. A much more in-depth analysis of the processes associated with sediment disturbance, accretion and erosion is required in order to understand the extent to which different parameters influence the profile changes observed.

4.3 Sedimentation rates and changes in mudflat morphology

In order to be able to interpret the results from auger sampling and charcoal analysis it is important to discuss the basis for dating the charcoal layer associated with native forest clearance on Banks Peninsula as well as identifying the associated margin of error. The main period of deforestation on Banks Peninsula falls between 1860 and 1890 (Petrie 1663; Ogilvie 1990, 1992). A core taken from a nearby lake on Banks Peninsula (Lake Forsyth) showed a concentration of charcoal related to the clearance of forest dated to 1895 (Woodward and Shulmeister 2005). Furthermore, a core taken by Goff 2005 in Charteris Bay found a charcoal layer at 50 cm. This layer is located 3 cm above that dated to 1830. If mean yearly sedimentation rates are extrapolated for the period from 1250 AD-1830 AD to the late 1800s a predicted level similar to that of the observed charcoal layer is observed. The findings presented by Woodward and Shulmeister (2005) and Goff (2005) suggest that it was not until the mid to late 1800s that charcoal began to appear in stratigraphic sedimentation of water bodies. These observations correlate well with historical reports of forest clearance (Petrie 1663; Ogilvie 1990, 1992) in the mid to late 1800s. Based on this evidence the charcoal layers interpreted from fieldwork will be dated between 1860 and 1900. Although this is a rather large window from which to calculate sedimentation rates it will provide a general idea of the patterns of sedimentation across the mudflat and as well as a good indication of how sedimentation has changed the mudflats over the last 100-150 years.

Sedimentation rates appear to have increased at higher rates in the lower tidal reaches of the mudflat then in the upper tidal reaches, calculations reveal a mean yearly accretion rate of 2.9-4.0 mm at 10 m along transect 1 and 9.3-12.7 mm 672 m along transect 1. In the mid to late 1800's the mudflats had an intertidal seaward extent of around 700m with a much steeper gradient then they currently have. Shifts in the level of the mudflats show a threefold increase in sedimentation rates across the landward third of the intertidal flat. These results show similar results to those of Goff (2005) who observed post European settlement mean yearly sedimentation rates of 3.7 mm from a core in the high intertidal zone.

The observed sedimentation rates are substantially higher then pre European mean yearly sedimentation rates of 0.43 mm (Goff 2005). The accuracy of these figures would be likely to increase substantially were cores retrieved and relevant layers dated. These findings are similar to other studies looking at New Zealand harbours and estuaries with substantial increases in sedimentation rates caused by deforestation and land use change associated with European settlement (Mead and Moores 2005; Sheffield et al. 1995). There is likely to be more variation in the accuracy of the observations of charcoal counts observed at 672 m as this area is likely to have been exposed to more intense sediment disturbance. This may be related to the lower standard deviation of the charcoal counts at Auger location B which could indicate a higher amount of mixing throughout the auger sample resulting in less concentrated stratigraphic layers. Higher sediment stabilities at auger sample location A can be expected to cause more concentrated stratigraphic layering which would lead to decreased accuracy with increased auger sample depth size.

It is important to explore the possibility of a pulse of sediment entering the harbour system during the main period of deforestation in the region as it will help determine the extent to which the sedimentation rates are representative of the actual yearly sedimentation rate. Sedimentation rates have been found to vary substantially over time with shifts in land use (Sheffield et al. 1995). Increased sedimentation rates of harbours and inlets are often a direct result of periods of deforestation both today and in the past (Sheffield et al. 1995; Hume and Dahm 1992). Sedimentation rates on the mudflats at the Head of the Bay were more then double what they are today in the period 1868-1890 (Goff 2005). This suggests that more then 36% of sedimentation observed on the mudflat took place between the 1860-1900 margin set for this project, indicating that the current mean yearly sedimentation rates fall in the lower range of the observed 2.9-4.0 mm at 10 m and 9.3-12.7 mm at 672 m along transect 1. Although a pulse in sediments entering the marine system is likely to have contributed substantially to sedimentation rates, current land use (mixed grazing and forest) in the catchments is likely to contribute higher yearly sediment yields to the marine environment then the forested catchments in pre European times (Fahey and Marden

2000). This is supported at the Head of the Bay by the findings of Goff (2005); with yearly sedimentation rates sustained over the last 100 years at a rate substantially higher then that for pre European settlement, and at other locations around New Zealand (Sheffield et al. 1995; Mead and Moores 2005; Swales et al. 2002).

The variation in sedimentation rates between the two auger sample locations in this study and the core analysed by Goff (2005) indicates the variability of sedimentation rates across the mudflats; this variation is likely a direct response to the spatial variation in environmental conditions and the equilibrium processes operating on the mudflats.

4.4 Predictions and future studies

The mean intertidal area of the mudflats appears to have increased threefold over the last 110-150 years from 1860-1900 (Figure 3.4). A mean yearly advance of 9-12 m seaward can be estimated from the results. Given the likely occurrence of a pulse of sediment associated with the forest clearance (Sheffield et al. 1995; Hume and Dahm 1992; Goff 2005) it is likely that the mudflats advanced at an accelerated rate in the mid to late 1800s. It is therefore likely that the current advance of the mudflats is some what lower then the figure mentioned above. Given that catchment cover and landuse and, thus, sedimentation systems are likely to remain similar in the near future to that of the recent past it is highly likely the intertidal area of the mudflats will continue to expand in the future.

Calculations of actual volumes of sediment that have accumulated on the mudflat at the Head of the Bay as a response to land-use change in the catchments are difficult to make given the large number of assumptions required. The retrieval of a number of cores from the intertidal mudflats at a wider distribution than the auger samples in this study would provide a more accurate representation of the state of the mudflats 127 years ago. The use of more accurate dating techniques (i.e. radio carbon dating rather than proxy studies) would enable more accurate calculations of sedimentation rates as well as an indication of how the pulse of sediment associated with European forest clearance affected sedimentation rates across the mudflats and thus the intertidal area. These values could be used in conjunction with a topographic survey of the intertidal mudflat area (Using a Global Navigation Satellite System such as the Trimble R8) to calculate the volume of sediment that has accumulated on the mudflats. More accurate calculations of mean yearly sedimentation rates, an in-depth understanding of the upper harbour bathymetry and harbour flows should allow for reasonably accurate predictions of future mudflat progradation.

5.0 Conclusions

The mudflats at the Head of the Bay show a highly variable distribution of short term sediment disturbance with a relatively stable zone in the upper intertidal area associated with finer silt and clay sized particles, and a much more dynamic zone in the lower intertidal area dominated by sandier sediments and shell hash. The distribution of sediments and short term erosional activity observed is typical of that observed on mudflats around the world. A concave up seaward profile suggests that the mudflats were dominated by erosional processes over the study period.

The intertidal area of the mudflats at the Head of the Bay in Lyttelton Harbour have shown a substantial increase in area under current land use conditions, with a seaward growth from 700 m in the mid-late 1800s to 2000 m observed in the winter of 2007. The seaward gradient of the intertidal mudflats has decreased over time with higher mean yearly sedimentation rates of 2.9-4.0 mm at 10 m and 9.3-12.7 mm at 672 m along the surveyed transect line. The occurrence of a pulse of the sediments entering the mudflat environment as a result of forest clearance associated with European settlement is highly likely; suggesting that mean yearly sedimentation and mudflat advance values will be lower today than the calculated mean yearly values. It is likely that the intertidal area of the mudflats will continue to increase in the near future. The analysis of core or auger samples using more accurate dating methods then those used in this study will likely provide a more accurate value for current sedimentation and intertidal advance rates of the mudflats. Results from cores taken at various points through out the upper intertidal area as well as an investigation of harbour bathymetry and coastal processes near the study site should allow for the formulation of reasonably accurate predictions of future mudflat growth.

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