GOLD MINING AND ESTUARINE EVOLUTION

A study of the accelerated sedimentation of Parapara Inlet,

Golden Bay, New Zealand.

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FRONTISPIECE



Parapara Inlet, Golden Bay, New Zealand

ABSTRACT

Estuaries are depositional environments formed within drowned river embayments which receive sediment from both marine and terrestrial sources. In many cases a beach-barrier sequence forms subaerially at the mouth of the flooded embayment and the area behind it is termed a barrier estuary. Such estuary types are found around the New Zealand coast especially in areas of relative tectonic stability and their sediments are often used to reconstruct Holocene sea level. Infill of these estuaries is initially dominated by marine flood tide delta sediments, with later infill occurring through fluvial processes. The final stages of infill within these estuaries is poorly understood.

Parapara Inlet in Golden Bay, New Zealand, is a Holocene barrier estuary influenced by hydraulic sluice mining within its river catchment. A study of Parapara Inlet was undertaken to discover how human disturbance within a river catchment can affect the evolution of a barrier estuary, by comparing previous models of barrier estuary evolution to the stratigraphy record within Parapara Inlet. 18 vibracores were sampled from Parapara Inlet in November 2009. Radiocarbon dating (AMS) within these cores provided a maximum age of 7090-6910 Cal BP. Deposition within the estuary has occurred in three stages; the first in Pre-Holocene marsh or lake environments; the second after inundation 6500-7500 years Cal BP, as fluvial sediments dominate the centre of the estuary; and thirdly in a series of quartz dominated gravels and sands within 1m of the surface. These units vary from the traditional models of evolution as the topography of the estuary has influenced the extent of deposition within the central mud basin. Mining sediment forced Parapara Inlet into a late stage of evolution, however the amount of sediment provided through sluice mining was not large enough to force the estuary into a supratidal stage.

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CHAPTER 1: INTRODUCTION

1.1 RESEARCH RATIONALE

The effect of human interference on coastal environments is a common topic in today's news media. Sea level has risen at a rate of approximately 0.2 mm per year over the past 1000 years, and the threat of further sea level rise and storm amplification, as consequences of a changing climate, causes concern among those owning coastal properties (Bell et al. 2001). These coastal changes often involve erosion and coastal retreat. The common response is to introduce large man-made structures which alter the natural environment (Bird 1993; Bird 2000). This action has been shown to have positive feedback effects on other sections of coastline, disturbing the natural coastal environment (Woodroffe 2002).

Interference with the natural coastal system can also occur much further inland. Storm amplification as a result of global warming may increase erosion and flood events within river catchments (Fowler & Hennessy 1995; Goudie 2006). Models of soil erosion, resulting from fluvial processes within warming temperature scenarios, suggest "the increases in rates of erosion could be on the order of 25-50%" (Goudie 2006, p391). Changing sediment budgets in fluvial environments can have positive feedback effects on estuarine evolution (Roy 1984; Woodroffe 2002). One such example of this interference occurred throughout New Zealand in the nineteenth century, with the introduction of gold mining. The first gold rush in New Zealand's history began in Collingwood, Golden Bay, after gold was discovered by Andrew Duncan in 1856 (Newport 1971; Nolan 1976). Parapara valley itself was mined from the 1870s to the 1930s due to its extensive mineral sources (Nolan 1976; Dawber & Win 2008). In 2009, students from Victoria University of Wellington analysed core samples taken at Parapara inlet, a barrier estuary in Golden Bay, New Zealand. The core samples showed a period of sedimentation which varied from modelled estuarine evolutionary deposition. The Roy (1984; 2001) and Woodroffe (1993; 2002) models of natural barrier estuary evolution show infill and evolution patterns for wave-dominated estuaries along the Australian coast. Their widely cited diagrams of simplified estuary stratification provide a process model for the evolutionary study of estuaries (Heap 2004; Wilson et al. 2007). These can be applied to individual estuaries to determine stages of estuarine evolution, from initial creation in transgressive coastal environments to the eventual stage of a river estuary after floodplain material is deposited over estuarine mud. Within the analysed cores from Parapara are believed to be depositional units formed as the result of sluice mining in Parapara valley. The overall aim of this study is to "Investigate the effects of mining on estuarine infill within Parapara Inlet". In order to complete this aim, the following objectives will be undertaken:

1) Assess the depositional record of Parapara Inlet in relation to sedimentological changes associated with 19th century mining

2) Compare the infill history at Parapara Inlet to established models of estuarine development.

This will provide an example of how estuaries react to rapid infill in a New Zealand setting, and in turn give further insight into estuarine evolution.

1.2 THESIS OUTLINE

Chapter 2 provides a literature review of classifying estuaries and their evolution, focussing on those in a New Zealand context. Studied effects of mining on estuarine evolution are also discussed. The history of mining within the chosen study site is described in Chapter 3, as well as geological setting of the area.

Chapter 4 includes the research methodologies of field surveying, vibracore sampling and laboratory procedures. The results of these methods are visible in Chapter 4, as the surface and subsurface environments within Parapara Inlet are described. Chapter 6 interprets these results with relation to known historical records as well as previous studies of depositional environments. A comparison is then made between commonly used models of estuarine evolution and the depositional record found within Parapara Inlet. Finally, the conclusions of this research are presented in Chapter 7, as well as a discussion of further research possibilities.

CHAPTER 2: LITERATURE REVIEW

2.1 INTRODUCTION

Estuaries are transitional areas between the river and sea (Bird 2000; Woodroffe 2002). The most cited definition is that of Cameron and Pritchard (1963, p306), where an estuary is "a semi-enclosed coastal body of water which has a free connection with the open sea, and within which seawater is measurably diluted with freshwater derived from land drainage". Despite its repeated use, this definition is too simplistic, ignoring key processes such as tides and enclosed environments such as coastal lagoons (Dalrymple et al. 1992; Kjerfve, 1994; Perillo 1995; Elliot & McLusky 2002). Defining an estuary is important both for scientific purposes and in order to clarify management policies and shore protection strategies (Allanson & Baird 1999; Elliot & McLusky 2002). Estuaries may be considered purely the extent of the waterline, allowing property development closer to the water's edge, or may encompass larger areas, extending boundaries for hazard mapping (Nordstrom 1992; Elliot & McLusky 2002). Other definitions use sediment transport and facies distribution as a basis for classification, stating estuaries can be defined as "the seaward portion of a drowned valley system which receives sediment from both fluvial and marine sources and which contains facies influenced by wave, tide and fluvial processes" (Dalrymple et al. 1992, p1132). When examining the evolution of an estuary, the definition used should focus on the sedimentary nature of the estuary, therefore Dalrymple's (1992) definition provides an accurate classification for this study.

Estuaries are classified by the relative dominance of tidal, wave and river processes within them (Fig 2.1) (Nordstrom 1992; Roy et al. 2001; Woodroffe 2002; Shepherd & Hesp



Figure 2.1: Estuary morphology relative to the dominance of a) Wave, b) Tide and c) River processes. (Adapted from Roy 1984 and Woodroffe 2002)



Figure 2.2: Diagram of the various zones which make up an estuary.

(Adapted from Woodroffe 2002)

2003). Many estuaries began their development as river valleys, cut during Quaternary glaciations when lower sea levels extended fluvial environments onto the continental shelf (Carter 1995). Coastal waters flooded these incised valleys in the early Holocene, as glaciers and ice sheets melted and sea level rose. This flooding adjusted fluvial and coastal processes within the valleys and they became basins for estuarine deposition (Bird 1993). Some remained open to the ocean with wide entrances while others developed sand or gravel barriers at their mouths (Hume & Herdendorf 1988). These variations in shape and dominant processes produce distinct sediment facies, which are described as being either wave, tide or river-dominated (Roy et al. 2001).

2.1.1 Wave-dominated estuaries

Wave-dominated estuaries are most commonly found on microtidal coasts, and despite the term 'wave-dominant', suggesting extensive wave activity, another term for these environments is wave 'influenced', as wave action is concentrated on the seaward barrier and does not extend far into the estuary (Fig 2.1) (Roy 1984; Woodroffe 2002). Tidal exchange is generally limited within the central (mud basin) parts of the system and is often greatest at the estuary mouth as water is forced through the narrow inlet formed through the barrier (Roy 1984; Woodroffe 2002). Regardless of these limitations, sedimentation in a wave-dominated estuary is influenced by tides and tidal exchange is increasingly important as the estuary fills with sediment (Roy 1984; Woodroffe 2002). The extent of fluvial influence within a wave-dominated estuary is kept to the alluvial plain and fluvial delta predominantly, both of which increase in area as the estuary infills (Roy 1984; Roy et al. 2001). Barrier estuaries are the most common example of a wavedominated estuary. Coastal lagoons and rias are other varieties of wave-dominated estuaries, the former having no connection to the sea and the latter no intertidal barrier (Roy 1984; Roy et al. 2001; Woodroffe 2002; Hume 2003).

2.1.2 Tide-dominated estuaries

Tide-dominated estuaries are most commonly found on macrotidal coastlines and are typically characterised by a funnel shaped planform (Fig 2.1) (Dalrymple et al. 1992; Roy et al. 2001). These estuaries have a large tidal prism, allowing for wide distribution of sediment through the different stages of tidal flux (Dalrymple et al. 1992; Carter 1995). The tide extends into the fluvial system and the shape of the estuary reflects this interaction, with a wide entrance which narrows to a tight fluvial channel through which the tide can propagate (Dalrymple et al. 1992; Roy et al. 2001). This fluvial channel develops a 'straight-meandering-straight' topography as fluvial incision occurs upstream maintaining a single channel while downstream the decreased flow gives the channel a more meandering shape (Dalrymple et al. 1992; D'Alpaos et al. 2007).

Sediment movement within tidal estuaries is active with the ebb and flow of the tidal waters (Dalrymple et al. 1992; Hume 2003). Deposition occurs at the fluvial delta, which forms where the estuary widens and deepens. Turbidity decreases in this delta, allowing finer sediment to settle from the water column (Dalrymple et al. 1992; Roy et al. 2001; Seminara et al. 2001; Woodroffe 2002). Sand bars also gradually move onshore at the delta, which temporally decreases its water depth, allowing for the transition of meandering channels further towards the coast (Dalrymple et al. 1992; Carter 1995). Eventually, tidal estuaries fill with sand bars, reducing accommodation space and decreasing the tidal influence on the estuary (Dalrymple et al 1992; Woodroffe et al 1993).

2.1.3 River-dominated estuaries

River-dominated estuaries possess a different shape than traditional wave-and tidedominated types as they often form at the very end stage of estuarine infill (Fig 2.1) (Roy 1984; Roy et al. 2001). With little accommodation space, these estuaries are shallow and salinity is usually limited due to the limited tidal range (Hume 2003; Kennedy in press). Fluvial processes dominate the infill and salinity of these estuaries, as floods and high energy flow can decrease salinity and increase erosive power, and droughts can decrease delivered sediment and increase salinity (Cooper 1993; Roy et al. 2001). Other variations of river-dominated estuaries include river mouth estuaries or hapua, which form thin barriers within river mouths (Hume 2003). These estuaries vary from traditional deltaic river environments as deltas may not form within them as a consequence of strong wave conditions at the mouth of river-dominated estuaries (Kennedy in press).

2.2 ESTUARINE ZONATION

Each form of estuary differs widely in shape, however, regardless of the many varieties of estuary shape, they generally consist of four main zones (Fig 2.2) (Roy et al. 2001). These are: (1) a marine tidal delta zone, (2) a central mud basin, (3) a fluvial delta and (4) a riverine channel and alluvial plain.

2.2.1 Marine Tidal Delta Zone

The marine tidal delta occurs at the mouth of the estuary and is shaped by tidal and storm processes (Hume 2003). This zone can be divided into two parts: the flood (internal) and ebb (external) tidal deltas, which occur at either end of the estuarine inlet channel (Carter 1995). The ebb delta acts as a large store of sediment, which can be reworked by waves in storm events, or through tidal action (Hume 2003). The size of an ebb delta varies in relation to the available sediment supply and the shape of the inlet. Wide tidal inlets allow space for growth, while narrow inlets found in wave-dominated estuaries produce smaller ebb deltas (FitzGerald 2005). The flood tidal delta may have a variety of shapes depending on estuarine morphology, fluvial flow, and sediment character, which is characterised by a mix of fine and coarse material (Roy 1984). The flood tidal delta zone also differs between wave- and tide-dominated estuaries, since in the former, seaward progradation occurs until reaching the barrier, rather than continuing seaward as in the latter (Roy 1984; Roy et al. 2001). Both the flood and ebb tide deltas have a similar morphology, in which flow is centred on a ramp of the delta, flowing over and eddying behind the delta (Carter 1995; Woodroffe 2002).

2.2.2 Central Mud Basin

In wave-dominated estuaries the central mud basin occurs in the deep internal section of the estuary. This depth creates a low energy environment in which fine sediment suspended within the water column settles (Roy et al. 2001; Woodroffe 2002). This deposition is illustrated in sediment cores by a thick layer of mud with high concentrations of estuarine shells and organic material (Roy et al. 2001). Infill rates in the central mud basin are directly related to the sediment supply (Roy et al. 2001). Material within the central mud basin is stirred by wind-waves only when the water is less than 2 metres (Roy et al. 2001). Fine sediment suppned within the central mud basin reduces light filtration, inhibiting photosynthesis within estuarine flora (Roy 1984; Roy et al. 2001).

2.2.3 Fluvial Delta

The fluvial delta is a turbid environment in which fluvial flow enters an estuary and deposits sediment (Roy et al. 2001). In tide-dominated estuaries, the mix of fluvial and tidal can extend upstream in one main channel, whereas wave-dominated estuaries concentrate this exchange at the bay-head delta (Dalrymple et al. 1992). Periods of high fluvial flow in wave-dominated estuaries can cause bifurcation in the delta, creating smaller channels (Hume 2003; Heap 2004). In dry seasons, reduced flow may return flow into one main channel, forming paleochannels across the delta (Woodroffe 2002). Also, as the fluvial delta extends into the estuary its gradient decreases, which can change the path of flow into the estuary (Dalrymple et al. 1992; Carter 1995).

2.2.4 Riverine Channel And Alluvial Plain

Behind the fluvial delta sits the alluvial plain and riverine channel. These features form as the fluvial delta extends into the central mud basin, and are defined by the limit of tidal exchange (Dalrymple et al. 1992; Roy et al. 2001; Woodroffe 2002). Tide-dominated estuaries have a 'straight-meandering-straight' morphology in their riverine channel, caused by the low energy environment of low gradient and an unconfined channel (Dalrymple et al. 1992). In wave-dominated estuaries, this riverine channel is generally confined by levees (Dalrymple et al. 1992; Roy et al. 2001). Sediment within riverine channels is sandy, although steeper catchments and flood events can produce coarser sediment (Roy et al. 2001; Woodroffe 2002). The alluvial plain is not estuarine, instead consisting of river levees, wetlands, relict channels and floodplains overlying pre-Holocene to mid-Holocene estuary deposits (Roy et al. 2001; Woodroffe 2002). Often these environments are well vegetated with both freshwater and saline tolerant flora, and are a source of freshwater flow (Woodroffe 2002).

2.3 WAVE ESTUARY CLASSIFICATION

Along the 11,000km coast of New Zealand, a range of estuary classes can be identified. These have been defined based on the primary processes of basin development; fluvial, marine/fluvial, tectonic, volcanic and glacial (Hume & Herdendorf 1988). These classes are then subdivided by their geomorphologic characteristics. New Zealand estuaries occur in a micro-mesotidal environment and can therefore be broadly classified as wavedominated. Typical funnel shaped macrotidal estuaries are not found in New Zealand. There are 3 broad types of microtidal estuaries: rias, saline coastal lagoons, and barrier estuaries, the latter being the focus of this study.

2.3.1 Rias

Rias (also known as drowned river valleys and incised valleys) are river valley systems drowned through sea level rise (Evans & Prego 2003; Hume 2003). Unlike typical funnel shaped estuaries, microtidal rias are often narrow and dendritic, shaped by the steep underlying bedrock topography (Woodroffe 2002). Despite their microtidal environment, these estuaries can be described as having a dominance of mixed processes, since tides dominate the lower marine zone while fluvial flow dominates the upper reaches of the drowned river valley (Roy et al. 2001; Evans & Prego 2003). Waves and tides are also attenuated within these estuaries due to a narrow inlet formed by rocky headlands (Hume 2003). Deposition within ria occur through tidal deltas and mud basin infill in the lower estuary and river deltas in the upper estuary. Tidal deltas are predominantly sandy with shell material, though finer particles may settle from suspension in the deep water of the inlet (Roy 1984). Mangrove wetlands and swamps are common in the river delta and

alluvial plains of the upper estuary, and accumulate sediment by disturbing flow (Roy 1984).

2.3.2 Barrier estuaries

Barrier estuaries are common globally and can be easily distinguished from other estuaries due to the development of sand or gravel barriers at their seaward end. A coastal barrier is defined as "an elongate accumulation of sand and/or gravel formed by waves, tides and wind, parallel to the shoreline, rising above present sea level, often impounding terrestrial drainage or blocking off a lagoon" (Woodroffe 2002, p298). This barrier decreases wave action within the estuary, creating a large section of still water in which sediment can settle from suspension (Roy et al. 2001). The inlet of barrier estuaries provides tidal exchange within the basin, which is also limited due to the narrow nature of barrier inlets (Roy 1984). Barrier estuary sedimentation ranges from coarse sands at the rivermouth, fine muds within the central mud basin and fine sands at the barrier and flood tide delta (Roy 1984; Carter 1995; Roy et al. 2001; Woodroffe 2002). Vegetation occurs on the barrier and at the rivermouth, as marsh and mangroves form in the mix of saline and freshwaters (Carter 1995). Seagrasses and marsh may also form in shallow back barrier environments (Carter 1995; Woodroffe 2002).

2.3.3 Coastal lagoons

Coastal lagoons form in locations where a sand and/or gravel barrier forms across the inlet and there is no free connection with the sea (Roy et al. 2001). This is often a result of reduced river discharge in small catchments or drought conditions (Roy et al. 2001). The barrier can be breached through flood or storm action, as well as mechanically by humans (Kjerfve 1994; Woodward & Shulmeister 2005). The waters within the coastal

lagoon are influenced by the relative balance of fluvial and marine activity, if fluvial input into the estuary is greater than marine, the lake decreases in salinity (Kjerfve 1994; Soons et al. 1997; Shepherd & Hesp 2003). Similarly, if the fluvial input is impeded by drought, hypersalinity may occur (Schumann & Pearce 1997). Exchange with marine environments may continue through the barrier, as gravel barriers are often permeable, and in storm events barrier overtopping by storm surge can transport saline waters and marine sediment into the lagoon (Carter 1995; Shepherd & Hesp 2003). Sedimentation within coastal lagoons is similar to that of barrier estuaries; however, the sediment supply is predominantly low due to low rates of fluvial flow (Roy et al. 2001). Sediment within coastal lagoons mostly consists of fine muds, with some coarse material provided by storm events from the seaward edge (Roy et al. 2001).

2.4 BARRIER ESTUARY INFILL

Estuarine evolution is essentially the process of sediment infilling (Roy 1984). The most commonly cited evolutionary model is that of Roy (1984; 2001) who described the evolution of estuaries on the coast of New South Wales, Australia. This evolution is described in four main stages – creation, barrier stabilisation, fluvial delta progradation, and finally swamp formation (Fig 2.3) (Roy 1984; Roy et al. 2001). Each stage of evolution occurs relative to changes in sea level (Woodroffe 2002).

2.4.1 Stage A (Youth)

Global Holocene coastal transgression occurred within the last 10 ka years, reaching current eustatic sea level at around 6 ka years ago (Gibb 1986; Roy et al. 2001). Within



Figure 2.3: The 4 stages of estuarine evolution A)Youth, B) Intermediate,C) Mature and D) River estuary. (Adapted from Roy 1984 & et al. 2001)

this time, barriers formed across the entrances of submerged valleys, creating the common barrier estuary morphology. This barrier formation can be attributed to two different processes: sea level rise and littoral drift. In the first process, barriers formed on the continental shelf as sea level rose, and moved landward in a process known as rollover (Thom 1983; Carter 1995). The second process formed barriers from littoral drift of sediment along the coast, which when reaching an abrupt change in shoreline, such as a drowned valley, caused sediment to accumulate across the entrance in the direction of drift (Roy 1984; Carter 1995; Roy et al. 2001; Hume 2003).

Once a barrier forms across the entrance of an estuary, the net movement of sediment is seaward (Roy 1984), resulting in increased deposition behind the barrier. Fluvial deposition occurs from the tidal limit in a bay-head delta, which is often exposed for much of the tidal cycle (Woodroffe 2002). As fluvial processes can often carry large material such as gravel or boulders, this sediment is deposited as a delta, since the river loses energy flowing into the estuary. The finer suspended sediment is then transported into the central mud basin where much of it settles from suspension in the deep and less turbulent waters (Roy 1984). Extensive accommodation space within the central mud basin should allow rapid deposition, contingent upon a consistently high rate of fluvial input (Roy et al. 2001). In many Australian and South African estuaries this is not the case, as dry seasons can inhibit fluvial input for months at a time (Schumann & Pearce 1997; Allanson & Baird 1999; Woodroffe 2002).

2.4.2 Stage B (intermediate stage)

As the estuary matures to the intermediate stage, the central mud basin becomes shallower as it fills with sediment. This filling allows the fluvial delta to extend further into the estuary, developing more defined channels and depositing coarser sediment in the estuary's centre (Roy 1984). The shallower nature of the central mud basin also means that high river discharge can flush sediment directly out to sea (Cooper et al. 1990; Woodroffe et al. 1993; Roy et al. 2001; Sloss et al. 2006). These high discharge events also decrease the salinity and increase erosion of riverine channels within the estuary.

Sedimentation within an estuary also occurs through intertidal vegetation in the bay-head delta and surrounds (Roy 1984). Salt marshes and mangroves disturb the flow of tidal waters and reduce the energy of wind-waves, allowing entrained sediment to fall out of suspension (Woodroffe et al. 1993; Carter 1995; Li & Lee 1997; Sanchez et al. 2001). Submerged aquatic vegetation cover also increases within the central mud basin as the estuary shallows, moving the sediment surface into the photic zone, contributing to photosynthesis (Roy 1984). This in turn increases the rate of deposition of sediment, as vegetation such as grasses and weeds may disturb suspension, decreasing the turbidity of the water and providing more light for photosynthesis (Koch 2001; D'Alpaos et al. 2007).

2.4.3 Stage C (semi-mature)

The processes which dominate infill change once the semi-mature stage of barrier estuary evolution is reached. At this point, the central mud basin is intertidal, reaching an almost supratidal level, which means waves and tides can now stir sediment in the basin, thereby moving sediment throughout the estuary through flood and ebb tidal flow. This sediment disturbance presents an interesting point, as disturbance decreases the rate of sedimentation within the estuary, which in turn would decrease the ability of an estuary to become supratidal. For an estuary to become supratidal there must be either be one rapid period of sedimentation which overcomes the tidal forcing and wind wave interaction, or a long and slow process that eventuates in supratidal shifts. Flood situations increase the strength of rivers, allowing larger material to be transported further within an estuary (Shepherd & Hesp 2003). Coarse loads of sediment deposited as floodwaters settle can create supratidal areas within the estuary, and deposition of flood sediment along tidal channels can form natural levees (Roy 1984). These levees may channel tidal flow, allowing less salt water to reach the fringes of the estuary (D'Alpaos et al. 2007). The presence of vegetation within fringes of estuaries provides a possible solution as to why similar estuaries may either remain intertidal or become supratidal, as vegetation disturbs flow, aiding the deposition of suspended sediment (Carter et al. 1987; Kennedy in press).

Towards the end of Stage C, as the supratidal surface area within the estuary increases, the fluvial system progrades fully through the estuary, adding to the supratidal surface area in the form of floodplains (Roy 1984; Roy et al. 2001; Woodroffe 2002). This process also forms 'cut-off-embayments', as levees formed along the riverine channel separate sections of the estuary from both fluvial and tidal environments (Roy 1984). In these sections, smaller tributaries may provide fluvial flow, creating marsh areas, which in turn are colonised and become either further floodplain or isolated coastal lakes (Roy et al. 2001).

2.4.4 Stage D (mature)

By the end stage of estuarine evolution, fluvial flow is confined to a riverine channel which bypasses the rest of the estuary which has become a floodplain. The estuary becomes fluvially-dominant and is then referred to as a river estuary (Roy 1984; Cooper 1993; Roy et al. 2001; Woodroffe 2002).

2.5 VARIATIONS OF ESTUARINE EVOLUTION

There are many reasons why an estuary may not follow this exact path of depositional evolution. These include natural variations such as sea level change, tectonism, fluvial erosion and mass movement, as well as anthropological variations such as urban sprawl, industrialisation and mining.

2.5.1 Natural Variations

Changes in sea level alter the stage of evolution of estuaries. This is due to the resulting increase or decrease in water depth and therefore accommodation space within the estuary. If eustatic sea level rises during stages B, C or D of evolution, the increased water depth provides further space for deposition, increasing the youthfulness of the estuary (Wilson et al 2007). Similarly, sea level fall within these stages decreases accommodation space and matures the estuary. Examples of this can be seen in the depositional record along coastlines of continents in the process of isostatic rebound, as variations in coastline elevation create sea level rise or fall on a regional scale (Lambeck 2009). This can also be seen in areas of active tectonism. Uplift or subduction caused by the shifting of faults lifts or submerges land in relation to sea level (Bird 1993). When this occurs, estuaries are altered, as by raising the land the estuaries become drained, reducing the accommodation space for sediment and drying the land (Rossetti 2004; Sloss 2006, Kennedy in press). Unlike a stable tectonic environment, varying uplift or subsidence rates cause the supply of coastal and fluvial sediment to increase or decrease in relation to the amount of tectonic movement. A tidal estuary which is uplifted may have a decreased tidal range as the tidal prism moves seaward with the coastline (Berryman et al. 1992; Woodroffe 2002). Uplift events can also cause estuaries to skip evolutionary stages, or to revert back to a predeveloped stage, with the introduction or removal of accommodation space (Kennedy in press).

Flood events can also vary the depositional record of an estuary, through both deposition and erosion. High fluvial flow has the ability to deliver a larger percentage of sediment from the rivers catchment into the estuary (Cooper 1990; Fowler & Hennessy 1995). Sediment becomes deposited as the influence of tides and accommodation space decrease the energy of the floodwaters as they flow to the sea (FitzGerald et al. 2005). This may be visible in depositional records as an abrupt change in sedimentology from mud and fine sand to coarse sediment, with fine sediment settling further throughout the estuary (Cooper et al. 1990). However, mature estuaries without deep accommodation space can also be affected by flood erosion. This can rework channels and increase the accommodation space within the estuary, returning it to an earlier stage of evolution (Cooper et al. 1990). The erosion of fluvial channels across an estuary may open closed embayments and introduce a rush of freshwater. The flow may also breach barriers of coastal lagoons, opening them to the tides (Hume 2003).

Mass movement of sediment can also alter depositional evolution within estuaries. Unstable slopes alongside rivers and high rainfall create a supply of unconsolidated sediment which flows to the estuarine system (Hayes 1978). The introduction of these large sediment 'slugs' to estuaries can cause rapid aging within areas near to the source, as well as smothering biota at the surface. Tidal exchange and fluvial flow can distribute this sediment throughout the estuary, and the distribution of these sediment deposits are thought to be a method of late stage deposition within estuaries (Kennedy in press). The source of these sediment 'slugs' is not necessary a natural one, as farming, urban sprawl and mining can produce similar sediment supplies.

2.5.2 Anthropological Variations

Land use variations along the periphery of waterways have an impact of the sedimentation of estuaries. Farming can increase overland transportation of silt to streams and rivers (Victor et al. 2004; Carter, 1995). The negative effect of this land use increases as pastoral land provides little stability for hillslopes, increasing the likelihood that storm events erode the hillside. This eroded sediment is transported into sediment sinks such as estuaries and lakes, and seasonal storm events can provide a depositional signature through sedimentation (Page et al. 1994). Other impacts of farming on estuarine deposition include increased nitrogen levels which can lead to an increase in estuarine vegetation, such as mangrove and salt marsh development . This is not necessarily limited to farming on land, as shrimp farms have been known to increase nitrogen within estuaries, which stimulate mangrove development (Rivera-Monroy 1999).

Urban sprawl can also increase sediment introduction into estuarine systems as the removal of vegetation to lay housing foundations exposes lower sediments. These can run into storm-water drains which often feed into estuaries before reaching the sea. Chemicals in the same runoff can bind with estuarine mud and remain within the estuary until disturbed later. Transportation routes often effect estuarine development as well, as causeways which cut through estuaries are common within the North Island. These causeways act as a barrier allowing a small inlet for tidal exchange, and are often applied on narrow arms of large drowned river valley estuaries.

Rapid erosion of a landscape through anthropogenic means also occurs through mining. Mining of mineral resources has become heavily controlled with regard to the unwanted sediment left after excavation, which is known as tailings (Pittams 1977). The current methods of ore mineral extraction involve pollutants and heavy chemicals such as arsenic, lead and zinc and which are hazardous to health (Conesa 2005; Moreno 2006; Arcega-Cabrera 2010). As a response to prior pollution of waterways, more strict disposal requirements are in place, such as tailings dams which separate polluted waters and sediment from natural systems. Unfortunately these methods are not always effective, and contamination can still occur.



2.6 NEW ZEALAND EUSTATIC SEA LEVEL

A knowledge of Holocene sea level fluctuations is required in order to correlate radiocarbon dating results to relative estuarine inundation. Gibb (1986) established a sea level curve using sites throughout New Zealand (Fig 2.4) . This corrects for tectonism, Radiocarbon dated shells were used to create a paleosea-level proxy. Gibb corrected for tectonism through comparisons between estuaries considered tectonically stable and other estuaries within New Zealand. Active estuaries in New Zealand formed within the last 10,000 years, with two stillstands at c9.2-8.4ka and reaching their current state of inundation c6500 years bp (Gibb, 1986).

2.7 NEW ZEALAND TECTONISM

Tectonism in New Zealand can alter depositional records through uplift and subduction. In 1931, Hawkes Bay, New Zealand, was struck by a magnitude 7.8 earthquake, which raised the Ahuriri estuary in the northern section and sunk the southern section as a response. This drained the north of the Ahuriri estuary, and this land has become a vegetated swamp area, with reclaimed land used for the local airport (Chague-Goff et al. 2000). This rapid aging of the estuary through the removal of accommodation space provides a national example of tectonism within estuarine records. Pakarae River estuary, Gisborne, New Zealand, provides an example of how tectonism in combination with sea level rise can produce records which vary from traditional models of deposition (Berryman et al. 1992; Wilson et al. 2007). Unlike the three model estuaries from Dalrymple (1992), Roy (1984) and Woodroffe (2002), this example shows the relative dominance of initial sea level rise followed by repeated uplift events.

2.8 MINING IN NEW ZEALAND

New Zealand became part of the global gold trend after mining booms in Australia and California. Officially, the first goldfield was in the Coromandel Peninsula in 1852, but the first New Zealand gold rush occurred in 1856 on the Aorere River, Collingwood, Golden Bay (Nolan 1980; Eldred-Grigg 2008). The rush was small, with approximately 2500 people working the fields at its height (Nolan 1976). Mining during the rush was predominantly worked as individual claims or small groups (Eldred-Grigg 2008). The Collingwood rush ended in 1858, and soon after, gold was discovered in Gabriel's Gully, Central Otago, drawing miners away from Nelson.

Gold mining occurs in two main processes: alluvial gold mining which utilises sediment already eroded from the underlying geology, and hard rock gold mining which requires excavation of ore (Jardine & Scobie 1988; Barker 1996). Before industrialised mining tools were developed, alluvial mining was the predominant method of gold retrieval. Alluvial sediment in riverbeds and dry terraces was processed with box sluice, long tom, cradle or pan (Salmon 1963; Pittams 1977). River sands were washed within a pan and cradle. These methods involved utilising fluvial flow to remove lighter sediment, leaving the valuable heavier mineral behind (Nolan 1980). Groups were able to process these faster using sluices, with which water diverted from rivers moved sediment along wooden flumes with riffles to catch the heavier gold. Alluvial sediment provided easy access to gold already eroded from quartz formations, however, accessing the quartz formations within hillslopes required heavy machinery.



Figure 2.5: Tailings along the Parapara River valley. (Dawber & Win 2008)



Figure 2.6: Sluice mining in Parapara. (Dawber & Win 2008)

Natural stream paths, or makeshift water races at the end of the sluice lines, collected the remaining tailings (Fig 2.5) (Dawber 2000; Black et al. 2004). Over time this material was transported towards the coast with the natural fluvial system, becoming trapped when it reached the deep water of an estuarine setting.

Once alluvial sediment had been worked, more intense mining in the form of hydraulic sluice mining was used. This involved the use of pressurised water aimed at rock faces in order to erode the rock, releasing the gold found in quartz veins (Newport 1971; Nolan 1976). This material was broken from boulders to small gravel and washed down sluice runs, which are long metal and wooden water races, with slats used to let lighter material pass and to trap heavier minerals (Fig 2.6) (Nolan 1976). The remaining trapped material is then extensively panned to remove further sediment, leaving the gold behind.

The final stage in the mining process is the deposition of sediment used in the mining process. Rocks and boulders discarded by miners quickly became a problem. If there was a large river the materials could often be carried fluvially from the mining site (Newport, 1979). Nearby valleys also provided a space to deposit sediment (Pittams, 1977). When the sediment became troublesome for those living downstream of the activity, litigation within New Zealand inspired the declaration that rivers and streams could be used as "sludge channels" by miners, with compensation paid to affected parties (Pittams, 1977 pp 160-161). In California (USA) policy regarding hydraulic sluice mining changed to prevent the practice in 1884, as "it was proved that waterways were becoming filled by material from sluicing" (Pittams, 1977 p161)

2.9 APPLICATIONS FOR EVOLUTIONARY KNOWLEDGE IN NEW ZEALAND

Models of estuarine evolution provide a common guideline for management of estuaries. The future of an estuary's natural development can be found through classifying the characteristics of an estuary with regard to its evolutionary stage, and noting the following stage of development. Estuarine end-stage evolution is considered a problem for two reasons. The first is due to aesthetic value. The decrease in water depth creates tidal mud flats. Gas from the decaying organic matter deposited in the mud is released during low tide, causing a pungent aroma (Nybakken & Bertness 2005). The New Zealand mangrove (Avicennia marina) colonises the fringes of aging estuaries in the upper North Island (Hicks & Silvester 1985). They propagate through seed and contribute to sediment deposition as their stems and leaves disturb flow, allowing sediment to settle from suspension Young & Harvey 1996). Mangroves are difficult to navigate and block access to the water, preventing boating recreation for example, and coastal properties no longer have direct access to the water. The second reason is an environmental one. Estuaries are considered sites of ecological importance as they act as a nursery for many species of fish and bird (Bird 2000; Woodroffe 2002). The shallow waters provide a safe environment for fish to mature, as they are sheltered and have a variety of food sources, such as insects and plants (Hume 2003; Nybakken & Bertness 2005). This is the same for wetland birds, who nest on the fringes of estuaries, or roost there as part of a migration cycle (Melville & Battley 2006). When an estuary becomes supratidal it is no longer capable of fulfilling the many requirements of these species (Hume 2003; Nybakken & Bertness 2005). This is a natural process, however as anthropological interference has removed many of the other nesting and breeding locations throughout the globe, it is important to attempt to maintain these locations to save endemic and rare species.

CHAPTER 3: REGIONAL SETTING

3.1 INTRODUCTION TO PARAPARA INLET

Parapara Inlet (40° 40' 0" S, 172° 50' 0" E) is located within Golden Bay in the northwest of the South Island, New Zealand (Fig 3.1 & 3.2). Parapara Inlet covers approximately 31 hectares and is one of 10 barrier estuary systems within Golden Bay (McLay 1976). It is predominantly surrounded by native bush, Pinus radiata forestry and farmland. Two settlements occur around the estuary, the town of Parapara situated on the barrier, and Milnthorpe, north of the estuary beside the inlet (Washbourn 1970; McLay 1976).

3.2 GEOLOGY

New Zealand was formed from both sea floor volcanism and sediment eroded from Gondwanaland, and deposited 500-380 million years ago (Thornton 2007). Tectonism compressed this sediment against Gondwanaland 370 million years ago, forming the oldest rocks in New Zealand. These can be found within the geology of northwest Nelson, as part of the Tuhua Orogeny, which, in the Devonian, metamorphosed Paleozoic sandstone and mudstone, creating Onekaka Schist and Waingaro Schist (Wilson 1999; Thornton 2007). While semi-submerged during the middle Permian, conglomerates and fossiliferous sandstones formed, and were then deformed and uplifted during the Rangitata Orogeny 140 million years ago, through metamorphosis and also through heat from nearby granite plutons (Wilson 1999; Thornton 2007). These are visible in the form of greenschist to amphibolite facies metamorphism within Golden Bay.






Figure 3.2: Map of Parapara Inlet

The main rock types within the Parapara catchment include sandstone, limestone, quartzite and talc schist (Fig 3.3) (Thornton, 1985). Waingaro Schist is found in the catchment of the Parapara River, while Onekaka Schist is found south of the estuary within the catchment for Washbourne and Limonite Creek. Mesothermal quartz deposits within Palaeozoic geology in northwest Nelson contain gold bearing veins (Christie & Brathwaite 2001). These are formed in metamorphic green schist, which is found in the Parapara River catchment.

The north-western corner of the South Island has an extensive geological history of fault movement; although it is not known to contain active faults (Fig 3.4). The lack of recent fault activity within the region suggests that tectonism has not altered the depositional record. This tectonic stability means that for Parapara estuary, stable estuarine models (such as the Roy model (1984; 2001)) can be used to compare records of depositional evolution.

3.2.1 Fluvial Setting

The Parapara River flows approximately 21 km between Parapara Peak (1249 m elevation) and Parapara Inlet (Fig 3.5 & 3.6). The river has a catchment of 4,478 ha originating at Parapara Peak and bordered by the Parapara and Queen Ridges. Seventy nine tributaries feed the Parapara River and eighteen streams flow directly into Parapara Inlet. Flow within the river has been previously measured as a mean annual of 2925L/sec (Lamb accessed 2011). Freshwater springs are also found in the northwest corner of Parapara Inlet within the intertidal zone of the estuary (Williams 1977).



Figure 3.3: Geology of Parapara, Golden Bay.



Figure 3.4: Fault presence or absence within Northwest

Nelson and Golden Bay



Figure 3.6: Aerial photograph showing Washbourne and Limonite Creeks in relation to the southern section of the estuary



Parapara River Catchment

Figure 3.5: Aerial photograph showing the Parapara River

catchment in relation to the estuary.

3.2.2 Marine Setting

Golden Bay is approximately 25km wide and 28km long and has a shallow offshore bathymetry of <40m (Fig 3.7) (Ridgway, 1977). A diurnal tide occurs within Golden Bay, with a tidal range up to 4m (Bye & Heath, 1975). As the D'Urville current enters Cook Strait at Farewell Spit, it separates into a clockwise gyre within Golden Bay and an anticlockwise gyre within Tasman Bay Bye & Heath, 1975; Ridgway 1977). Offshore sediment is predominantly mud, while the coast consists of well sorted medium to fine sands (Van der Linden 1969).



Figure 3.7: Offshore profile of Golden Bay, showing the gyre of the DÚrville current. (Adapted from University of Auckland 1975)

3.2.3 Climate

Golden Bay has approximately 2500 annual sunshine hours and a mean annual rainfall of 2400 mm (NIWA accessed 2009). Parapara Peak has a mean annual rainfall of 5500 mm per year (Lamb accessed 2011). Wind measurements taken from nearby Farewell Spit show prevailing westerly winds (Appendix 1), however Farewell spit is quite exposed and westerly winds are lessened within the bay by the influence of the Wakamarama and Burnett ranges within North West Nelson Conservation Park, as well as Kahurangi National Park, which shelter the bay (University of Auckland 1975).

3.3 HUMAN SETTLEMENT AND LAND USE

Golden Bay was originally named Moordenaer's Bay (Murderers Bay) after a confrontation between Maori and Abel Tasman, New Zealand's first European explorer, in 1642 (Newport 1971). In 1773 Captain Cook mapped the area and when D'Urville visited in 1837 he renamed it Massacre Bay. The area was renamed again once the gold rush occurred, and became known as Golden Bay (Newport 1971).

Historical knowledge of Maori in Golden Bay is limited due to the loss of oral history as a result of interactions with lower North Island tribes (Newport 1971). A pa is thought to be located at the hills behind the estuary and garden sites are present along the Parapara Spit (McFagden & Challis 1979). Maori mythology regarding Parapara tells of deaths related to high tidal ranges and variable river flow. A taniwha named Te Kai whakaruaki (the vomit eater) was believed to live in the Parapara River and eat those travelling across the river and inlet (Mitchell & Mitchell 2004). This myth may have been used by the Maori both explain the deaths associated with the swift currents from the river and tidal inlet, as well as providing a deterrent for those tempted to search for food and greenstone at Parapara (Mitchell & Mitchell 2004).

The first European settlement in Golden Bay occurred in the 1840s and this was associated with the removal of the native Nothofagus and Podocarp forest (Washbourn 1933; Washbourn 1970). This revegetated as Pakihi. A peak in population was reached in the 1850/60's during the gold rush (Washbourn 1970; Eldred-Grigg 2008).

3.4 MINING AT PARAPARA

Parapara valley itself was mined from the 1870s to the 1930s (Nolan 1976; Dawber & Win 2008). Gold, silver, copper, iron ore, galena, asbestos, tourmaline, molybdenite and sapphire have all been found in the Parapara Valley (Nolan 1976). Four companies worked at Parapara, either sluicing gold from the valley or dredging material from the Parapara River. Parapara Iron and Coal Company, est. 1873, was the first (Newport 1971). This developed into the Parapara Sluicing Company in the 1890s when pipes were able to provide enough water for hydraulic sluicing (Fig 3.8) (Newport 1971). In 1892 Sir James Hector published a survey of the Collingwood goldfield in order to determine whether mining would remain a feasible venture in Parapara valley and surrounding areas. This report, requested by Parapara Sluicing Company, indicates the geological extent of the quartz veins in which gold was found. It also describes the state of mining at Parapara in 1890: "At one time there was a considerable mining population in the district, but, owing to the difficulty of procuring a sufficient water supply for sluicing, the miners gradually abandoned the place" (Hector 1892, 13). Gold was not processed at Parapara, and was instead taken to Collingwood to the north, meaning that chemicals such as arsenic and lead were not introduced to the fluvial system (Newport, 1971).



Figure 3.8: Parapara Slucing Company

(The Nelson Provincial Museum: Tyree Studio Collection, 182351/3)



Figure 3.9: Dredge within the Parapara River (Dawber & Win, 2008)

The Parapara Hydraulic Sluicing and Mining Company was floated in 1892, and this merged with the Parapara Sluicing Company to become the Parapara Hydraulic Sluicing Company in 1894 (Pittams 1977; Dawber & Win 2008). A common trend throughout the history of mining in Parapara is closure due to insufficient funds and gold finds. Parapara Flat Gold Dredging Company dredged the river and mouth of the estuary within the 1900s (Fig 3.9). The dredge was only operated for one year, due to instability in the riverbed, sinking half of the dredge into the Parapara River during a flood (Dawber & Win 2008). Sluice mining at Parapara finally ended in the 1900s due to a lack of water pressure for working the fields (Newport 1971). By this point, a large extent of the valley was scoured from sluice activity (Dawber & Win 2008).

Additionally, mining also focused on iron ore found in the sections behind the estuary at Washbourn Creek (Washbourn 1970). This ore was used primarily for paint production within the New Zealand Hematite Paint Company (est. 1879). In order to process the ore a water race from a dam in Parapara Gorge was utilised, with water from the race used to wash the oxide powder and to turn a large 30 foot water wheel used to power the battery (Nolan 1976). Waste from the operations were sent through Washbourn Creek into Parapara Inlet (Washbourn 1970). This mining and processing operation ran under various owners until ceasing in 1922 (Walrond 2010).

CHAPTER 4: METHODOLOGY

4.1 FIELD WORK

Gold mining occurred throughout the fluvial systems of northwest Nelson and the estuaries at their seaward end potentially record this mining activity within their depositional record. Parapara Inlet was chosen for this study as mining occurred throughout its catchment and it is an example of a barrier estuary, an estuarine type where the broad natural rates of infill are well understood (Roy 1984). Field work took place in November 2009.

4.1.1 Sediment coring

Estuarine sediments were sampled using a vibracore technique involving a 20kg concrete vibrating head attached to aluminium pipe 74mm in diameter and approximately 5m in length (Fig 4.1). The core was extracted using an A-frame lever and prusik knot (Smith 1984). Vibracoring was chosen over other techniques such as percussion sampling, auger sampling and sediment probing as the technique is cost effective and produces an undisturbed continuous core sample (Smith 1984; Finkl & Khalil 2005). It also allows sediment to be easily sampled below the water table level and is the standard technique for geomorphic estuarine studies.

In order to provide a broad visual perspective of sedimentation within the estuary, core sampling locations were chosen in a range of surface environments. This included transects through the central mud basin and behind the causeway, but excluded the barrier and marine tidal delta. These latter areas were restricted due to the nesting of the Variable Oystercatcher (Haematopus unicolor) which is endemic to New Zealand and breeds between September and December (Dowding & Moore 2006; Melville & Battley 2006). Sampling at Parapara Inlet occurred at low tide, when the sediment surface was exposed above the water. A vibrating head was attached near the top of aluminium pipe, which was then manually held vertical. Gravity and vibration through the pipe liquified sediment, allowing for core penetration. Before removal, the compaction of sediment within the core was measured. A plumbers bung was placed within the pipe, providing a seal and also creating suction which assists accurate core extraction (Armour 2003). Once removed, both ends of the core were sealed for transport back to the laboratory. Later, these cores were divided into smaller pieces for ease of travel using a skill saw. In total eighteen cores were taken, with depths ranging from 0.4 - 4.19 metres. (Appendix 3) Core locations throughout the estuary were chosen in order to provide a broad visual perspective of the depositional record. In some cores the depth of core penetration was limited by coarse gravels. Where gravel impeded core penetration, a 1.5m steel sediment probe was used to quantify the extent of the gravel around the coring site.

The area of Parapara estuary was mapped using a Sokkia 3030R Total Station (Fig 4.2). Data was processed using Topocad software in order to create a topographical display of core site locations for schematic cross sections throughout the estuary. This surveying tool is accurate to a range of X mm + Y ppm for distance and seconds for angle (Huang 2002).



Figure 4.1: Coring within the northern section of the estuary.



Figure 4.2: Sokkia Total Station in use within Parapara

4.1.2 Historical Information collection

Aerial photography can be used to map visual changes in the surface landscape over long and short timescales. A greater difference in time between images is preferred, as this provides a more visible difference in the photographed environment (Shoshany & Degani 1992). High resolution imagery is also preferred, as the finer scale provides greater detail, subsequently increasing accuracy (Shoshany & Degani 1992). Examples of aerial photographic application include the mapping of seagrass coverage (Robbins 1997), shoreline variation (Smith & Zarillo 1990; Shoshany & Degani 1992) and river channel morphology (Winterbottom & Gilvear 1997). In the case of Parapara Estuary, aerial photography of the region was collected from 1938 onwards by New Zealand Aerial Mapping Ltd.

Aerial photography provides visual evidence of change to topography over time, and can therefore be useful when monitoring the change to coastlines over a decadal timescale (Smith & Zarillo 1990; Shoshany & Degani 1992). Changes in regional deposition and erosion are visible when using high resolution images over longer time periods in order to see significant changes within the environment (Shoshany & Degani 1992). Within Parapara Inlet, visible changes in aerial photography from the oldest and most recent records (1938 and 2009) have been mapped using Geographic Information Systems.

Possible error within aerial photography is based on distortion of images. Tilt of the camera can displace landscape features from their actual ground location (Crowell et al. 1991). Changes in scale due to altitude, relief displacement and radial lens distortion can also alter an image to give inaccurate results (Smith & Zarillo 1990; Crowell et al. 1991).

4.2 LABORATORY WORK

All cores were visually logged in order to determine stratigraphic deposition and correlation between these samples of stratigraphy. From this, characteristic cores were selected for more detailed analysis. Cores number 5, 12, 14, 16 and 18 were chosen, as the core log from each displayed different attributes of deposition which gave representation to a different section of the estuary. These cores were sampled for grain size, carbonate and organic content analysis. Grain mount thin section analysis was also selected for Core 18, as it contained the greatest depth of sediment and range of stratigraphy for analysis.

4.2.1 Grain size analysis

Samples were taken from the five main cores in 100mm increments from the surface downwards. Approximately five grams of sample were taken at each increment. These were first measured using a Beckman Coulter Laser Particle Sizer, wet sieved through 0.5 phi. If coarse grains remained in the sieve, a larger sample (up to 50 grams dependent on coarse fraction) was then dry sieved through 0.5, 0, -1, -2, -3 and -4 phi, and weighed to determine size fractions.

4.2.2 Inorganic Carbonate analysis

The percentage of inorganic carbonate (CaMgCO₃) within each sample was measured using gravimetric analysis. Approximately 10-20g of sample was used in an individual 200ml beaker. Each beaker was first dried overnight at 40°c and weighed. Sample was then added to each beaker and reweighed (weight A). Diluted (10%) hydrochloric acid (HCl) was then poured gradually into each beaker, and each sample was agitated in order to allow full reaction. Once the beaker contained 100ml of HCL, each beaker was placed in a water bath at 45°c in order to increase reaction rates. Samples were reacted for ~ 60 hours (or until reaction had ceased) to dissolve all inorganic carbonate from each sample. The supply of 10% HCl was refreshed regularly to assist reaction. Samples were then washed with distilled water into 250ml bottles and processed in a centrifuge at 3000rpm for 15 minutes. Supernatant from the bottle was then decanted using a 50ml pipette, in order to prevent loss of sample. This process was repeated twice more in order to remove all acid and dissolved calcium carbonate. The sample was then returned to its beaker and dried in a 40°c oven (weight B). The dry sample and beaker were then weighed, with the difference between weight C and weight B providing the percentage of carbonate in the sample.

Sample size varied between 5g and 55g, dependent on available sediment and accuracy of measurement (1cm) either side of the measurement was included in the sample, providing there not be an abrupt change of deposition within this range, which would alter the record). Sections of core which contained greater amounts of organic material (such as wood) weighed substantially less than those with a high amount of gravel.

This oxidation technique is based on the rationale that inorganic carbon in the form of calcium carbonate dissolves in HCl, which can be decanted to leave the remaining sediment (Kennedy & Woods in press). This can be weighed to determine the percentage of calcium carbonate in the sample. As the presence of calcium carbonate in this environment requires a marine environment, depositional sequences with a high percentage would be considered to be influenced by marine processes.

4.2.3 Organic carbon analysis

The amount of organic carbon within samples was determined using loss on ignition (LOI), in which heat is used to turn carbon from organic matter into CO_2 . This can be described using the equation $CH_2O + O_2 \rightarrow CO_2 + H_2O$ (Kennedy & Woods, in press). Crucibles were dried at 400°c over 2 hours, cooled in a dessicator and weighed. Samples weighing approximately 6 grams were then added, before drying for 24 hours in a 105°c oven. These were then weighed and baked for 16 hours in a 400°c furnace. The weight lost from the sample after ignition represents the amount of organic carbon within the sample.

This technique is less accurate than those utilising high frequency induction furnaces; however, baking the sample at 400°c over 16 hours in comparison to other methods of rapid high-heat combustion has less of an effect on the mineral components of the sample, increasing accuracy. Also, as clays are known to release water trapped in their lattice structure during ignition between 500-1000°c, ignition for a greater time period at 400°c prevents possible inaccuracies (Dean 1974; Kennedy & Woods in press).

4.3 XRF ANALYSIS

Five thin sections were taken from core 18 at various core depths for X-ray fluorescence (XRF) analysis. Samples were submitted to SpectraChem Analytical, Lower Hutt, New Zealand and the major oxides in the material were analysed. This method bombards the material with x-rays which causes the elements to ionize, dislodging an inner electron making the element unstable and thus causing an outer electron to replace it. This movement of electrons causes a release of radiation which is of a lower energy than the initial X-rays bombarding the sample and is therefore termed fluorescent radiation. The

energy emitted is different for each element and therefore fluorescent X-rays can be used to detect the abundance of an element within a sample (Tertian & Claisse 1982). The results of this analysis is represented in Fig 5.13 and Appendix 2.

4.4 RADIOCARBON DATING

Radiocarbon dating provides the main chronological control for the site. Samples were submitted to the Waikato Radiocarbon Dating laboratory, Hamilton, New Zealand for analysis by Accelerator Mass Spectrometer (AMS). A total of 12 radiocarbon samples from seven cores were analysed. Shell material from 10 *Austrovenus stutchburyi* samples, two *Amphibola crenata* one wood sample was used for dating. *A. crenata* have been known to produce unreliable ages due to their diet of surface mud which can contaminate a sample. This makes them prone to producing older ages than expected (Anderson, 1991). For this reason it was deemed necessary to exclude these samples from the chronology. The ages have been converted to calendar years using the calibration program OxCal V3.10 and the IntCal09 calibration curve (Reimer et al. 2009)

CHAPTER 5: RESULTS

5.1 CONTEMPORARY SURFACE ENVIRONMENTS

Parapara estuary currently covers an area of 184 hectares, and is found at elevations between MSL & MHWS. The surface environments can be subdivided into nine distinct facies; (i) river channel and alluvial plain, (ii) fluvial delta, (iii) tidal channels, (iv) intertidal sediment flats, (v) embayed mud flats, (vi) salt marsh, (vii) flood tide delta, (viii) inlet and (ix) barrier beach (Figs 5.1 & 5.2).

River channel and Alluvial Plain (Fig 5.2a)

The river is 46 m wide as it enters the estuary, and is surrounded by bush such as ferns, flax and gorse. There are no freshwater molluscs within the river, however there are freshwater crustaceans, fish and aquatic invertebrates (Lamb accessed 2011).

Fluvial Delta (Fig 5.2b)

The fluvial delta is located where the Parapara River enters the inlet on the North Eastern side of the estuary. The delta covers 15 ha. The main channel from the Parapara river extends 140 m into the estuary before separating into three smaller channels. Deltaic lobes of coarse material occur between channels in the fluvial delta. The delta is composed of subrounded clasts of mudstone, siltstone, sandstone, limestone, schist, quartzite and iron ore rich rocks. The main fluvial channel from the Parapara River has a similar gravel base. Deltaic lobes spread from this main channel. These lobes consist of predominantly coarse sand and gravel, and are dissected by smaller fluvial channels and



Figure 5.1: Map of surface environments within Parapara Inlet



Figure 5.2: Photographs of surface environments within Parapara Inlet:a)Parapara River, b)Fluvial Delta, c)Tidal Channels d) Intertidal Flate) Salt Marsh f) Embayed Mud Flats g) Flood Tide Delta and h) Beach Barrier.

tidal channels. The beds of these minor fluvial and tidal channels are composed of mud and silt.

Vegetation on the delta consists mainly of sea rush, jointed wire rush and sea primrose with gorse and toetoe also present at higher elevations on the largest section of the delta. The fluvial delta interfingers with the intertidal flat as tidal channels extend from fluvial channels.

Tidal Channels (Fig 5.2c)

Tidal channels branch across the intertidal flats, formed due to drainage from tidal exchange. These channels vary in size, described as level 1 (minor), level 2 (medium) and level 3 (major) channels, as the structure of these channels are similar to that of tributaries in watershed diagrams (Fig 5.3). Level 1 channels are fine (<0.5m width) and vary in length. These channels drain intertidal flats from tidal exchange, as well as draining smaller tributaries which flow into the estuary. The sediment in level 1 channel beds consists of mud and fine silt. A. Stutchburyi shells were found open but unbroken in these channels, however these shells were more visible in the intertidal flats which the level 1 channels ran across. Where level 1 channels combine, level 2 channels are formed. These vary in width from <0.5m to 2m. Sediment within these channels is poorly sorted coarse silt to fine sand. Level 2 channels which are closest to the fluvial delta or barrier have a greater percentage of coarse sediment along their channels. The main channel winds throughout the estuary covering 2745m between the delta and inlet. Vegetation within the channels is minimal, with visible seagrass and sea lettuce by the freshwater spring in the north, and an increase in seaweed varieties closer to the inlet. Shells are not common within these channels, however crabs are common within channels.



Figure 5.3: Map of tidal channels within Parapara Inlet

Intertidal Flat (Fig 5.2d)

The intertidal flats are the largest surface environment (98 ha), and extend from the north to the south of the estuary (Table 1). The flats are dissected by tidal channels, and edged with salt marsh. The flats are composed of fine grey mud to coarse grey silt. Some areas close to the tidal channels have coarser sediment at the surface, ranging from sand to gravel. Vegetation has a low coverage within the intertidal flat. Sea Rush fringes areas of coarse sediment and the edges of the estuary. Other intertidal salt tolerant plant species such as sea primrose and glasswort are found along tidal channels nearer to the fluvial delta. Populations of *A. crenata, H. crassi* and *A. stutchburyi* are found in this area, *A. stutchburyi* located approximately 5-10cm from the surface.

Salt Marsh (Fig 5.2e)

Areas of salt marsh border the intertidal flats and embayed mud flats, covering an approximate area of 26 ha (Table 1). Sediment within areas of salt marsh consists of fine mud and silt overlying coarse gravels. Salt marsh located behind the barrier forms on fine grey mud and silt, primarily vegetated with sea rush, jointed wire rush and sea primrose. Large areas of driftwood can be found stranded behind highly vegetated sections of back barrier salt marsh (Fig 5.4). Salt marsh is also visible bordering the embayed mud flats.



Figure 5.4: Driftwood trapped

behind Parapara barrier



Figure 5.5: Sediment within the cut off embayments, Milnthorpe

| Table 1: V | ariations in surface a | rea between 1938 a | nd 2009. |
|-------------------|---------------------------|---------------------------|------------------|
| Location | Approximate Area* 1938 | Approximate Area* 2009 | Area Difference* |
| Fluvial Delta | 8.99 | 14.75 | 5.76 |
| Tidal Channels | 13.38 | 20.18 | 6.79 |
| Intertidal Flats | 135.21 | 98.08 | -37.13 |
| Salt Marsh | 15.56 | 25.60 | 10.04 |
| Embayed Mud Flats | 11.42 | 18.22 | 6.80 |
| Flood Tide Delta | 8.70 | 11.76 | 3.06 |
| Barrier Beach | 15.47 | 28.14 | 12.67 |

*measured in hectares

Embayed Mud Flats (Fig 5.2f)

These form in the southernmost section of the estuary, in small bays formed from tributary erosion of Washbourn and Limonite Creeks, covering approximately 18 ha (Table 1). Causeway construction in the 1960s restricted transfer of fluvial and tidal waters between the southern section and the rest of the estuary, decreasing tidal exchange and increasing the time required for drainage during high tide and high rainfall events. Sediment within the embayed mudflats is predominantly fine to medium grained brown mud and silt, however samples of these sediments came only from northern area of the embayed mud flats, as access to the southern area was limited. Vegetation is not common within the centre of the embayed mud flats, however salt marsh vegetation such as sea rush and sea primrose are visible along the edges of the area, as well as closer to the drainage tunnel. The restriction of a single tidal channel allows plants which are less salt tolerant than other common mudflat vegetation to extend within the embayment, including toetoe, gorse and harakeke (flax). Native ferns and trees surround the embayment, and the causeway is also vegetated with pohutukawa, harakeke and common grasses.

Flood Tide Delta (FTD) (Fig 5.2g)

The flood tide delta occurs at the mouth of the inlet channel within the estuary. It is surrounded in the northeast by the main tidal channel and a smaller tidal channel which drains the freshwater spring. The delta has an area of 10.5ha. Sediment within the flood tide delta ranges from intertidal to supratidal. These areas are vegetated with glasswort and sea primrose. Shells found within the flood tide delta were broken valves, and not in life position.

Barrier Beach (Fig 5.2h)

A 1.5km barrier separates the estuary from Golden Bay to the east. It is primarily occupied with properties and small farms, vegetated with grasses, pine trees and shrubs. The beach of the barrier consists of medium to coarse grained sand. This sediment becomes more coarse northwards, with large pebbles and cobbles visible at low tide at the northeastern edge of the barrier spit. Vegetation at the beach of the barrier is composed of toetoe, marram grass, lupin and ice plant found above high tide. Broken shells of A.stutchburyi, Spisula aequilatera, Struthiolaria papulosa, Maoricolpus roseus, Pecten novaezelandiae and Ostrea chilensis are common along the beach. On the north of the spit, bushes and trees become more dominant, including lupin and Pinus radiata. Shells are common on the supratidal sand spit at the northern end of the barrier, and the mix of fine to coarse sands and gravel and shell provide a nesting ground for the Variable Oystercatcher.

Across the 85m wide inlet at Milnthorpe sediment is coarse, from sand and gravel to 15cm clasts directly opposite the northern tip of the barrier, between Milnthorpe wharf and beach. Two coastal embayments are visible behind the beach in the north, with flow from two small streams within Milnthorpe Park. Sediment within these embayments is predominantly fine silt, edged by large coarse clasts of greywacke and also quartz (Fig 5.5).

5.2 TEMPORAL STABILITY OF THE SURFACE ENVIRONMENTS

Aerial photography from 1938 (Fig 5.6) and 2009 (Fig 5.7) were analysed using Geographical Information Systems (GIS) to discover changes in surface environments over the prior 71 years. Variations in surface area measured using GIS can be seen in Table 1.



Figure 5.6: 1938 aerial photograph (NZ Aerial Mapping Ltd)



Figure 5.7: 2009 aerial photograph (NZ Aerial Mapping Ltd)

The loss of area within the intertidal flats (central mud basin) is relative to the growth of other areas in the estuary. The fluvial delta increased in size, extending further into the intertidal flats along tidal channels. Light sediment along the north of the fluvial channel in 1938 appears to have moved with the delta, forming lobes of coarse sediment within the intertidal flats. Salt marsh vegetation is more prevalent on the fluvial delta in 2009, contributing to the overall increase from 16 ha to 26 ha of salt marsh within the estuary.

The fluvial delta also differs from the 1938 aerial photograph as the fluvial channel appears unnaturally rectangular. This is likely to be the result of dredge activity within the estuary. A dredge was used as a gold mining technique, excavating the river channel within the fluvial delta. Dredging ended in 1907 and by 1938 the dredged channel extended into the estuary in a rectangular shape, 335 m by 52 m (Fig 5.6). The end of the channel is abrupt, changing to a 12m wide tidal channel extending from the northwest. This dredging may have occurred many years prior to the photograph, however aerial photography taken in 1950 shows the join between the dredged area, and by 1972 the dredging is not visible, removing evidence of the dredging within 34 years. The current channel has decreased in length, reaching 171 m into the estuary, and is now 47m wide with two channels 39m and 20m wide branching from the main fluvial flow (Fig 5.7).

Tidal channels remain in similar locations within the estuary. Level 1 channels vary mainly within the extended fluvial delta, while other level 1 channels run through their prior locations. The greatest variation can be seen in level 2 and 3 channels, which is also visible within the extended fluvial delta. The level 2 tidal channel which enters the embayed mud flats of the estuary remain in a similar position as their prior channel. This may be the result of the introduction of a causeway in the 1960s. This causeway has one

flow pipe at the southeast side of the estuary, in place of the main channel for both tidal and fluvial exchange. This has altered the drainage of the southern part of the estuary, as periods of high rainfall can fill this area similarly to a coastal lagoon, increasing time required for drainage within the southern section. This can be seen in Fig 5.7, and was also visible during field work. Level 3 tidal channels (those measured to indicate channel variations) grew by 7 ha, from 13 to 20 ha. Property development between 1938 and 2009 increased from dirt roads to 21 properties at Milnthorpe and 78 properties (two small farms) on the barrier at Parapara.

The barrier beach appears wider, and has a measured increase from 15 ha to 28ha. Variations in width are also noticeable along the beach to the north. Sand bars within the marine tidal delta zone of the estuary have become larger, however as these processes are temporal (over a period of weeks) this is likely to be a more active variation (Bird 2000).

5.3 SUBSURFACE SEDIMENTOLOGY OF PARAPARA.

18 cores were taken in the estuary, ranging in depth from 0.4m to 4.19m (Appendix 3 & Fig 5.13). Average compaction values of 0.28m were found. Several units are identified within the cores, some spatially continuous throughout the estuary, others restricted. Cores 5, 12, 14, 16 and 18 were analysed in order to identify grain size, carbonate content and organic carbon content, as well as XRF analysis of Core 18 (Figs 5.9 – 5.13).

Facies 1

The sediment found at the greatest depth within core samples was a brown sandy mud (Fig 5.8). This unit was found predominantly in the southern section of the estuary, and is represented in Cores 12, 14, 15 and 18. The basal contact of this mud in its repetition of

this facies (Cores 15 and 18) was a gradational contact. Thin woody roots and wooden fragments up to 5cm diameter were found within this unit in Cores 14 and 18. No fossils were found in any form. Within Core 15, the brown mud was visibly split (between 2.41-2.15m) due to loss of sediment during transport. This missing segment is assumed to contain Facies 1, as there were no indications of differing facies within sediment particles which remained upon the aluminium piping.

Carbonate analysis of this facies showed a mean of 5% and median of 3%, with a maximum of 19% and minimum of 1% (Table 3). Organic carbon analysis showed a mean of 14% and median of 10%, with a maximum of 60% sampled at the base of Core 18 (Table 4 & Fig 5.13). This was the highest result within all facies sampled. The minimum percentage was 3%. Results of major oxide analysis of Facies 1(taken from 1.8m and 3.3m depth in Core 18) can be seen in Appendix 2 and Fig 5.13.

Facies 2

Above the previous unit is unimodal to polymodal grey sandy silt. Located primarily within the intertidal flat, it is visible in Cores 10, 14, 15 and 18 (Fig 5.8). The grey silt appears stratigraphically first within Cores 10, 14 and 15, and also repeats within Cores 14 and 15. A gradational basal contact over 2 cm is visible at these repetitions and in Core 18 (Fig 5.13). Roots and large wooden fragments were found within this unit, and no fossils were found. Yellow mottling appears within upper sections of this facies within Core 14, and dark brown mottling within the lower section of this facies in Core 18 (Fig 5.13).

Table 3: Percent Carbonate within Cores 5, 12, 14, 16 and 18

Percent Carhonate

| בו כבווי | | ורכ | | | | | | | | | |
|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|-----------|-----------|
| | Facies 1 | Facies 2 | Facies 3 | Facies 4 | Facies 5 | Facies 6 | Facies 7 | Facies 8 | Facies 9 | Facies 10 | Facies 11 |
| MEAN | 4.93% | 6.05% | 8.98% | 10.50% | 6.64% | 10.32% | 14.18% | 7.38% | 12.45% | 11.83% | 13.44% |
| MEDIAN | 3.31% | 5.24% | 9.20% | 10.00% | 6.22% | 10.78% | 13.16% | 7.37% | 8.89% | 12.02% | 13.60% |
| ST DEV | 0.0403 | 0.0359 | 0.0108 | 0.0364 | 0.0296 | 0.0244 | 0.0375 | 0.0859 | 0.0241 | 0.037 | 0.037 |
| MAX | 19.21% | 14.24% | 10.22% | 21.93% | 11.77% | 15.00% | 17.96% | 13.84% | 22.25% | 15.77% | 17.80% |
| MIN | 1.24% | 1.27% | 7.26% | 4.71% | 2.05% | 6.12% | 11.90% | 1.90% | 6.22% | 8.52% | 8.76% |

Table 4: Percent Organic Carbon within Cores 5, 12, 14, 16 and 18

4 ć C + à

| Percent | t Urganic | Carbon | | | | | | | | | |
|---------|-----------|----------|----------|----------|----------|----------|----------|----------|----------|-----------|-----------|
| | Facies 1 | Facies 2 | Facies 3 | Facies 4 | Facies 5 | Facies 6 | Facies 7 | Facies 8 | Facies 9 | Facies 10 | Facies 11 |
| MEAN | 13.69% | 4.58% | 4.33% | 2.08% | 4.02% | 3.58% | 3.12% | 1.37% | 1.82% | 2.48% | 2.16% |
| MEDIAN | 10.87% | 2.57% | 4.06% | 1.71% | 1.32% | 2.40% | 2.75% | 1.31% | 1.13% | 2.57% | 1.98% |
| ST DEV | 0.1243 | 0.0467 | 0.0049 | 0.0195 | 0.0563 | 0.0312 | 0.0145 | 0.0088 | 0.0144 | 0.0044 | 0.0076 |
| MAX | 60.46% | 18.69% | 5.18% | 8.51% | 14.63% | 9.74% | 5.38% | 2.91% | 3.97% | 2.98% | 3.60% |
| MIN | 3.16% | 0.92% | 40.10% | 0.32% | 0.25% | 0.88% | 1.64% | 0.28% | 1.04% | 1.75% | 1.24% |



Facies Distribution in Vibrocore Samples 1-18, Parapara Inlet, Golden Bay, New Zealand

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Figure 5.8: Stratigraphy of each sampled core, denoting facies distribution

The percentage carbonate measured in samples of this facies showed a mean of 6% and median of 5%, with maximum and minimum results of 14% and 1% respectively (Table 3). Organic carbon measured showed a mean of 5%, and median of 3%, with a maximum of 19% and minimum of 1% (Table 4).

Facies 3

A similar sediment to that of Facies 2 is located in Core 16, in the northwest corner of the estuary by a freshwater spring (Fig 5.12). This blue grey polymodal muddy sand was very dense and prevented vibracoring at depth, therefore no basal contact can be described. No fossils were found, however thin wooden roots are visible throughout the facies.

Carbonate content within this facies had a mean of 9% and median of 9%, with a maximum of 10% and minimum of 7% (Table 3). Organic carbon analysis showed a mean of 4% and median 4%, with a maximum of 5% and minimum of 4% (Table 4).

Facies 4

Facies 4 is a layer of moderately sorted unimodal coarse dark sand. This unit is found in Cores 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 16 and 18 (Fig 5.8). This unit has an erosional basal contact above Facies 1`- 3. Facies 4 is commonly accompanied by mixed layers of broken shell beds, predominantly *A. stutchburyi*. These shell hash layers vary from 2-10cm thickness, in some cases becoming mixed with the coarse dark sand throughout the whole unit (Figs 5.9, 5.10, 5.12 & 5.13). There were no signs of vegetation within this facies.


Carbonate analysis of this facies showed a mean of 10% and median of also 10%. The maximum value was 22% carbonate, and minimum 5% (Table 3). Organic carbon showed a mean of 2% and median of also 2%, with a maximum 9% and minimum 0% (Table 4). Radiocarbon ages within this unit date from 7090-6910Y CalBP (Core 6, 2m depth) to 920-790Y CalBP (Core 6, 1.5m depth) (Fig 5.16, Table 2). Results of major oxide analysis of Facies 4 (taken from 1.2m depth in Core 18) can be seen in Appendix 2 and Fig 5.13.

Facies 5

Facies 5 consists of coarse, sub rounded greywacke gravel within a dark grey sandy mud matrix, and are found within Cores 1, 10, 11 and 12 (Fig 5.8). The basal contact is sharp in Cores 10 and 12, and is not visible in Cores 1 and 11 as the gravel clasts increase in size with depth. This facies contains broken shell fragments, mainly from *A. Stutchburyi*, with other broken valves unable to be classified. Vegetation in the form of root matter was visible within sections of this facies. Carbonate content within Facies 5 had a mean of 7% and median of 6%, with minimum and maximum readings of 12% and 2% respectively (Table 3). Organic carbon had a mean of 4% and median of 1%, with a maximum of 14% and minimum of 0% within samples (Table 4).

Facies 6

Facies 6 is a bimodal dark grey sandy mud, found in Cores 1, 2, 3, 4, 5, 6, 7, 8, 9, 12, 16, 17 and 18 (Fig 5.8). The basal contract is gradational over 2cm, usually fining upwards from either Facies 5 or 6. Lamination of fine sands and silt is visible within the upper section of this facies (Fig 5.9, 5.10, 5.12 & 5.13). Small fragments of shell were visible



Figure 5.10: Stratigraphic log of Core 12

within sections of this facies, but these are found only in cores taken in the centre of the estuary by the main channel (Cores 1, 2 and 5). No vegetation was visible in this facies.

Carbonate within Facies 6 had a mean of 10% and median of 11%, with a maximum of 15% and minimum of 6% (Table 3). Organic carbon results showed a mean of 4% and median of 2%, with a maximum of 10% and minimum of 1% (Table 4). Results of major oxide analysis of Facies 6 (taken from 0.6m depth in Core 18) can be seen in Appendix 2 and Fig 5.13.

Facies 7

This facies consists of a bimodal golden coloured fine muddy sand, visible in Cores 3, 4, 5, 8, 9, 10, 14, 15 and 17 (Fig 5.8). The basal contact is predominantly gradational, except for core locations in the southwest of the estuary. In these locations this facies is seen at the surface. Cores from this location also showed evidence of lamination within this unit. No vegetation or fossils were visible within this facies.

Carbonate within Facies 7 had a mean of 14% and median of 13%, with a maximum of 18% and minimum of 11% (Table 3). Organic carbon levels showed a mean of 3% a median of also 3%, a maximum of 5% and a minimum of 2% (Table 4).

Facies 8

Facies 8 is a coarse quartz dominated medium sand, visible in Cores 4, 6, 8, 10, 11, 12, 16, 17 and 18 (Fig 5.8). The basal contact for this unit is sharp, and is usually associated with an abrupt (<0.5cm) change from Facies 4, 5 or 6. The quartz sand has a texture of fine white sugar grains (0.5 ϕ), becoming quartz pebbles (-1 ϕ) in the upper section (Appendix 4) No vegetation or fossils were visible within this facies.





Carbonate within Facies 8 had a mean and median of 7%, with a maximum value of 14% and minimum value of 2% (Table 3). Organic carbon was very low in this core, with a mean and median of 1%, including a maximum of 3% and a minimum of 0% (Table 4). Results of major oxide analysis of Facies 8 (taken from 0.3m depth in Core 18) can be seen in Appendix 2 and Fig 5.13.

Facies 9

Facies 9 consists of a coarse gravel dominated by quartz and greywacke pebbles, in combination with a rust coloured mud and sand. This unit is visible in Cores 8, 9, 13, 16 and 17 (Fig 5.8). The gravel varies in predominant geology throughout the estuary as Core 9 in the southern embayed mud flats has a rust-coloured pebble matrix with sandstone gravel and small quartz pebbles. Within Core 8, Facies 8 mixes with Facies 9, as large quartz cobbles with fine quartz sand. The basal contact for this facies is sharp, and within Core 8, Facies 9 overlies Facies 7 on a 55° angle (Fig 5.8). This does not appear to be a result of compaction or coring, as facies overlying this angular discontinuity are deposited horizontally. No vegetation or fossils were visible within this unit.

Carbonate within Facies 9 had a mean of 12% and median of 9%, with a maximum of 22% and minimum of 6% (Table 3). Organic carbon results had a mean of 2% and median of 1%, with a maximum of 4% and a minimum of 1%. (Table 4).



Facies 10

Facies 10 is made up of yellow brown to light brown unimodal to trimodal very coarse silt. Layers visibly vary, as the colour of each silt layer switches from a fine light grey brown sandy silt to a coarse yellow brown silt within <1cm. This unit occurs predominantly above the coarse quartz and is found in Cores 6, 7, 10, 11, 12, 13, 14, 15, 16, 17 and 18 (Fig 5.8). In Core 16 this unit occurs both before (1.21m-1.08m) and after (0.28m-0.24m) the quartz unit. In Core 7 the silt layering occurs without a visible quartz component within the core. No fossils or vegetation are found within this facies.

Carbonate within this unit had a mean and median of 12%, with a maximum of 15% and minimum of 9%. Organic carbon within this unit had a mean of 2% and median of 3%, with a maximum of 3% and minimum of 2%.

Facies 11

The uppermost sedimentary unit is a grey trimodal sandy mud to muddy sand, visible in Cores 1, 2, 3, 4, 6, 7, 8, 11, 12, 13, 16, 17 and 18 (Fig 5.8). The basal contact for this unit is gradational throughout all cores. Vegetation was not found in this facies. *A. Stutchburyi* are visible in life position within 5-10cm of the surface, with some live samples found within cores as well as open valves.

Carbonate within Facies 11 had a mean of 13% and a median of 14% as well as a maximum of 18% and a minimum of 9% (Table 3). Organic carbon within this unit had a mean and median of 2%, with a maximum of 4% and minimum of 1% (Table 4).





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|---------------------------------|--------------------------------|-----------------------------|-------------------------------|---------------------------------|-----------------------------|-----------------------------|---|-----------------------------|--------------------------------|-------------------------|---------------------------------|-----------------------------|-----------------------------|
| Sa W | | Ŭ | | | | | | | | | | | |
| Sample Conditio n | Stail shell, broken/damaged | Small shells; damaged | Smil shell, broken/damaged | Half shell; slightly damaged | Complete valve | Complete valve | 2x valves (Not from same mollusc) | Complete valve | Complete valve | W ood | Half shell; slightly damaged | Complete valve | Complete valve |
| Material Dated | Amphibola crenata | Au strovenus stutchburyi | Amphibola crenata | Au strovenus stutchburyi | Au strovenus stutchburyi | Au strovenus stutchburyi | Au strovenus stutchburyi | Au strovenus stutchburyi | Marine Shell (Unidentified) | Wo od | Au strovenus stutchburyi | Au strovenus stutchburyi | Au strovenus stutchburyi |
| Calibrated Age (68.2%) (yrs) | 735-635 BP | 630-535 BP | 635-540 BP | 2450-2300 BP | 1 640-1480 BP | 6380-6260 BP | 330-180 BP & 170-140 BP | 920-790 BP | 7 090-6910 BP | | 4 940-4800 BP | 6 960-6790 BP | 6390-6260 BP |
| Con ven ti onal Age (yrs) | 1122 ± 21 BP | $987 \pm 31 \text{ BP}$ | 1001 ± 32 BP | 26 65 ± 32 BP | $1989 \pm 31 \text{ BP}$ | 58 83 ± 35 BP | 615 ± 31 BP | 13 07 ± 33 BP | 6481 ± 35 BP | $324 \pm 28 \text{ BP}$ | 4632 ± 34 BP | 63 98 ± 35 BP | 5891 ± 35 BP |
| Sample Depth (cm) | 43 | 120 | 41 | 217.5 | 188.5 | 175 | 40 | 155 | 200 | 112 | 110 | 190 | 152 |
| Core | 3 | 4 | 4 | 5 | Ś | 9 | 9 | 9 | 9 | ٢ | 12 | 12 | 16 |
| Dating number | WK28421 | WK28422 | WK28423 | WK28424 | WK28425 | WK28426 | WK28427 | WK28428 | WK28429 | WK28658 | WK28430 | WK28431 | WK28432 |
| Sample name | c3 -1 | c4 -1 | c4 -2 | c5 -1 | c5 -2 | c6 -1 | c6 -2 | c6 -3 | c6 4 | c7 -1 | c12-1 | c12-2 | c16-1 |

5.4 INFILL CHRONOLOGY

Four schematic cross sections have been created using a combination of surveying and vibracore sampling. Schematic cross sections of these transects provide a view of each facies within each core and their common depositional locations.

- Transect A to A' covers 1.3km, and includes (north to south) Cores 16, 17, 8, 7, 11, 5, and 1 (Fig 5.15). Radiocarbon dates are recorded in Core 16. Rates of deposition are also visible within Core 16.
- Transect B to B' covers 494m, and includes (west to east) Cores 13, 8, 7, 12, and
 6 (Fig 5.16). Rates of deposition are also visible within Cores 6 and 12.
- Transect C to C' covers 745m, and includes (west to east) Cores 15, 14, 18, 4, 3, 2 and 1 (Fig 5.17). Radiocarbon dates are recorded in cores 3 and 4. Rates of deposition are also visible with Core 4.
- Transect D to D' covers 293m, and includes (north to south) Cores 10, 9, 15 and 14 (Fig 5.18).



Figure 5.14: Map of schematic cross sections in Figures 5.15-5.18









CHAPTER 6: DISCUSSION

6.1 ASSESS THE DEPOSITIONAL RECORD OF PARAPARA INLET IN RELATION TO SEDIMENTOLOGICAL CHANGES ASSOCIATED WITH 19TH CENTURY MINING

In order to determine the sedimentological changes associated with mining at Parapara Inlet, the depositional facies need to be defined in relation to their formative environment. The stratigraphic record recovered from Parapara Inlet shows three main stages of deposition. Stage A includes the prior fluvial environment, within Facies 1-3; Stage B features the inundation of the fluvial environment to current sea level and channel processes which deliver sediment through the estuary; and Stage C describes the sediment changes associated with sluice mining within the Parapara River catchment. These stages are interpreted using calibrated AMS dating, XRF major oxide analyses and grain size, as well as carbonate and organic carbon levels within the sediment. The current surface environments will also be used to interpret features within each facies.

6.1.1 Stage A

The first stage of deposition within cores from Parapara Inlet began prior to marine inundation of the pre Holocene river valley. This can be seen as carbonate percentages of 1-2% within the bottom 0.2 m of Core 18 (Fig 5.13). In combination with organic carbon results of 30- 60%, this indicates a highly organic environment with little to no marine influence (Sutherland 1998; Roy 2001). The depositional environment in which Facies 1 formed is that of a swamp or marsh, in which fine sediments settled from suspension along with vegetation. The increasing presence of carbonate seen within Cores 14 and 18 also presents a chronological tool, representing the gradual increase in marine processes

within the prior environment as sea level rise inundates the fluvial environment. This also implies that a full record of estuarine deposition is visible in Core 18.

Facies 2 above the previous facies occurs gradationally, and has a higher carbonate content than Facies 1, peaking at 14% at 2m in Core 18 (Fig 5.13). Changes between these facies may indicate variations within the pre-inundation setting. Using Gibbs (1986) sea level curve in combination with the oldest AMS date (7090-6910 years CalBP at 2m depth in Core 6 (Fig 5.16 & Table 2)) of a shell in the depositional layer above Facies 1 and 2, inundation most likely occurred c. 6500-7500 years before present. This correlates with the common inundation period within New Zealand, as well as with the visible relationship between carbonate content and marine environment (Gibb 1986; Abrahim 2008).

Facies 3 is found at the base of Core 16, which was sampled within close proximity to the freshwater spring within the inlet. This facies is not visible in Core 17, despite the relative distance of their locations. Core 17 also does not show either Facies 1 or 2. As there are no cores within the centre of the estuary which reach a depth comparable to those in the southern section of Parapara Inlet, only interpretations can be made about the underlying sediment. It is possible that Facies 3 formed earlier than the previous facies, as the freshwater spring provided an inundation source which may have formed a lake in which facies 3 was deposited. The freshwater spring is clear and not coloured by tannins such as fluvial waters at Parapara (Fig 6.1). This water source may also be the cause of an elevated carbonate content within this facies, as the result of dissolved carbonates and limestone from the aquifer supplying freshwater to the inlet (Williams 1977).

Within Cores 14 and 15, Facies 1 and 2 show a repeating pattern to 0.52m. These upper sequences of mud have been termed Facies 1a and 2a, and are believed to be as recent as

the coarse river sediments within Stage B, as the recorded levels of carbonate change from an average of 3% to an average of 10%.



Figure 6.1: Water from the freshwater spring (left) mixes with

water from the estuary and river (right)

6.1.2 Stage B

During deposition of the upper facies units (Facies 1a and 2a) in the southwest section of the estuary, fluvial extension deposited coarse sediments close to the western side by the current fluvial delta, as well as toward the centre of the estuary in remnant fluvial or tidal channels. These are indicated by coarse lobes of sediment visible in schematic cross sections, similar to those visible by the fluvial delta at the surface (Fig 5.15 & 5.16). As the depositional location of sediment within an estuary is relative to the energy available to transport the sediment, the coarse sediment should be located at the fluvial delta (Dalrymple et al. 1992). Coarse gravels were visible within 30cm from the surface of Core 13, and sediment probing throughout the fluvial delta and salt marsh areas nearby averaged around 60cm depth before reaching coarse gravel. Gravel is also visible on the surface of the flood tide delta, including in aerial photography from 1938 (Fig 5.6). Gravels visible within the fluvial delta had been transported from the delta further into the estuary. The coarse sediment found at the northern cut off embayment may suggest that this gravel will be transported to the main channel and remain in the embayed areas.

The coarse sands and shell hash in Facies 4 represent the extent of initial fluvial deposition above the lower mud facies. Sands are lighter than gravel, and travel further than gravel through fluvial flow and tidal exchange (Woodroffe 2002). *A. stutchburyi* valves within Facies 4 imply that the depositional environment was shallow subtidal (Simpson 2009). This is reinforced through the spread of Facies 4 within ~2 metres depth through 12 of the 18 core samples, indicating that water depth had shallowed to the point where fluvial currents and tidal exchange were now able to move sands and gravels across the mud. Dating of *A. stutchburyi* shells within Facies 4 suggest it was deposited between 7090 and 790 years CalBP, but as the shells were not found in life position, they are likely to be older than the initial sediment in Facies 4. These shells are

also likely to be older than Facies 4 as their primary environment is fine sand, silt and mud. The angular pebbles within Facies 4 as well as the erosional contact visible in Core 12 suggest that an erosional event deposited this facies, and that the mud within this facies are likely to have originated from the layer in which the fossils were living.

Over time, the coarse gravel to cobble sediment deposited at the fluvial delta is reworked through fluvial and tidal channels. These channels are visible in the depositional record in schematic cross section A- A' (Fig 5.15), as a mix of fluvial sand and gravel (Facies 5). Estuary channels shift across the central mud basin as fluvial flow varies, as well as in relation to changes in fluvial channels (Roy 1984; Carter 1995; Roy et al. 2001; Woodroffe 2002). This is especially visible in schematic cross section B-B', which shows a large wedge of coarse fluvial gravels spread from the northern side of the fluvial delta (Core 13) to the main tidal channel (Core 12) (Fig 5.16). When viewed in correlation with cross section A- A', the lobes of coarse fluvial sediment appear spread in various deltaic shifts as the Parapara River moves across its delta, creating a riverine channel and alluvial plain (Fig 5.15). This is evident when comparing the current estuary to a geological map of Parapara Inlet from 1890 (Appendix 6) (Hector 1892). The flow of the Parapara River to the inlet in the 1890 map varies from its current position, instead forming a river delta further to the north and upriver from its current location. Remnant channels are also visible within the 1938 aerial photograph (Fig 5.6). By 1938 aerial photography showed the Parapara River flowing into the estuary at its current location. This means that between 1890 and 1938 the river moved across its delta, switching sediment deposition from one direction to another (from northwest to southwest). This provides a source for coarse gravels deposited in the northwest of the estuary; an area which is currently bypassed by the main tidal channel. This also explains the lack of coarse mining material in Core 5, which is located by the tidal channels and coarse sediment lobes.

When the sediment supply from the catchment decreased, a dark mud (Facies 6) formed across the estuary. As the Parapara River shifted across its delta, sections of the estuary previously dominated by coarse sediment lost their fluvial sediment supply. This meant that deposition of suspended mud became the primary sedimentation in these areas. In the southern section of the estuary Washbourn Creek flowed between the two larger embayed mud flats and deposited Facies 7, a depositional unit which widely differs in quality from the dark sand, gravel and mud (Facies 4, 5 and 6) of the Parapara River to a yellow brown sand and mud. This is likely a result of both the different geology in the southern catchment and the lower rates of fluvial flow.

6.1.3 Stage C

A sharp contact separates Facies 6 and 7 from Facies 8, a fine-medium grained polymodal quartz sand. Like Facies 4, the sand represents the beginning of fluvial deposition, as the sediment load transported by the Parapara River rapidly increased. This implies an abrupt change in depositional environment, as the sediment deposited varies in geology from the previous fluvial extension, assuming a second peak of fluvial erosion (Roy 1984; Carter 1995).

This erosion is believed to be the result of mining within the Parapara and Washbourn creek catchments. Mining occurred between 1856 and 1922, beginning with small scale claims and increasing to sluicing and dredging operations from 1890 until c.1910. Sluice mining creates a large amount of tailings. Photographs taken of sluice mining at Glen Gyle and Richmond Flat provide evidence of the scale of sluice mining within the catchment, as whole hillsides show exposed bedrock (Fig 2.6). Enga Washbourn described the immediate effects of mining on the area: "In those days Parapara was a grassy flat with patches of bush on the far side of the river, and grassy glades on the hillsides dotted with ngaios. Later the Hydraulic Sluicing co. ruined the whole valley, covering it feet deep in tailings." (Washbourn 1970, p179).

Above Facies 7 is a coarse sand and gravel layer, which is similar to that of Facies 5, as it is seen in schematic cross section B-B' as a wedge of coarse sediment, thickest by the river delta (Fig 5.16). This sediment also shows a different geology to Facies 5, which can be interpreted as the focussed erosion of quartz veins within the Waingaro Green Schist, rather than erosion throughout the entire catchment.

Facies 9 fines upwards to Facies 10, which can be seen as both layers of yellow brown and grey sandy silt closer to the fluvial delta, and as a light brown silt elsewhere in the estuary (Fig 5.8). The deposition of this mud above Facies 8 completes a repeated pattern of fluvial sedimentation: the first sequence of sand, gravel, mud visible in Facies 4-6, overlain by the same sequence in Facies 8-10. The scale of the second sequence is very different to that of the first, as Facies 8-10 were deposited between 0.03-1.08m depth, in comparison to the range of 0.18-2.94m (Fig 5.8). Mining produced a sediment supply into the estuary which had not been deposited for almost 1000 years. Once mining ceased, the source of sediment was cut off, and fluvial reworking spread Facies 9 across the estuary towards the inlet. Facies 10 differs from Facies 6 due to lamination within the mud; the source of the eroded mud varying the colour of the deposited layers. Photographs taken in 1908 show that Parapara Inlet was intertidal during the period of mining sediment deposition (Fig 6.2). This would have affected the depth of deposition as intertidal systems have a small amount of accommodation space and an increased tidal range, increasing the rate of sediment transportation through tidal channels to the inlet.



The Parapara ford at low tide near the Greenhill farm.

Figure 6.2: Photograph of Parapara Inlet during the 1900s. (Washbourn 1970)



Further evidence reaffirming the assumption that this depositional material is mining sediment can be found in Core 18. XRF results show that the amount of iron oxide in samples almost doubles from 3.54% at 1.20m depth to 6.64% at 0.6m depth (Fig 6.3). This increases again to 7.44% at 0.3m depth. The trend of increased iron oxide closer to the surface is likely the result of the mining and processing of ironstone for paint in the southern tributary (see Section 3.4).

6.1.4 Current stage

The uppermost facies unit (Facies 11) is the current depositional unit in the central estuary. Facies 7 which was also visible during the previous series of fluvial deposition, is the current depositional unit in the embayed mud flats of the southern section. These units are divided by a causeway, constructed across the southern section estuary during the 1960s (Dawber & Win 2008). Tidal exchange occurs through a large pipe* constructed in the causeway near the main channel of flow from the southern section to the rest of the estuary (Fig 5.6). The result of this restriction of flow is a lag time between high and low tide in which the embayed mud flats remain subtidal for longer. Periods of high rainfall and storm events can also submerge the embayed mud flats. This was noted during field work, as two days after a three day period of rainfall the embayed mud flats were still submerged. The catchment for the southern tributaries provides fine sediment to the embayed mud flats, which should be able to accumulate due to the lag time between tides, unlike sediment in the central estuary. At Stage C, intertidal estuaries have a low rate of sediment accumulation, as it is washed away in tidal flow. Had the mining event occurred with the current depth of sediment and tidal range, it seems likely that a Stage C estuary may have been forced into a supratidal elevation, beginning the process of vegetation and siltation to become a river estuary (Stage D).

6.2 COMPARE THE INFILL HISTORY AT PARAPARA INLET TO ESTABLISHED MODELS OF ESTUARINE DEVELOPMENT

The depositional history discussed in Section 6.1 describes a pre-inundation sequence overtopped by sandy silt layers and medium to coarse greywacke sand and gravel. A dark sandy silt is then deposited and is seen throughout most of the estuary (Fig 5.8). A rapid change to quartz-based sand and gravel is then deposited, overtopped by a light sandy silt with lamination. The current surface of deposition within the central mud basin includes a sandy silt, while the fluvial delta and tidal channels have gravel and coarse sand at the surface. These facies suggested a transition from a swamp or lake (A) to the extension of fluvial sediment (B), overtopped by mining remnants (C) before reaching a 'normal' mixed environment stage (Figs 5.15-5.18) This order of deposition is similar to that of Roy (1984; 2001), as it appears at Parapara that fine material within the central mud basin is deposited rapidly and coarse material is worked across the central mud basin and spread with the power of tidal channels. Using this evolutionary model, Parapara Inlet can be defined as currently developed past the onset of Stage C.

Parapara Inlet differs, however, from models of estuarine evolution as the introduction of a late stage sediment shifted the estuary from a sandy silt environment to a coarse sand and gravel area. This sediment is prevalent within areas of the estuary in which previous coarse material is also visible, centred on the mid to northern section of the estuary. This pattern is thought to be due to the migration and spread of channels. Rivers move across their fluvial delta when sedimentation decreases the gradient of the original channel (Woodroffe 2002). It is likely that the riverine channel shifted as a significant amount of tailings washed to the fluvial delta. Sediment from mining covered the prior estuarine mud, however many outlying areas of the estuary were not affected by this deposition (Figs 5.15-5.18). Level 2 and 3 channels have shifted sediment within the fluvial delta, and it seems their progress through the estuary has transported excess sediment from the estuary rather than leaving it as a deposit and transforming sections of the estuary into a supratidal stage (Figure 5.8). The channels also do not appear to have formed levees, which is another requirement for an estuary to shift from a stage C to stage D of evolution (Roy, 2001). The transportation of sediment through these channels suggests that sedimentation from fluvial flow is more likely to be transported offshore, bypassing large areas of the estuary – a factor suggested to be primarily functional within Stage D estuaries due to channel levee development.

It is possible then, that in order to become supratidal, rapid sedimentation within the outer areas of the estuary is required, putting a greater emphasis on vegetation as a dominant settlement factor. This will become visible within the southern section of the estuary within the embayed mud flats as the causeway isolates it from the main section of the estuary. As this embayment has its own fluvial source and varied geology, a study of sedimentation within the next 50 years may record the influence of this artificial development on the sedimentation and vegetation within this semi-enclosed environment.

Using the Roy (2001) model of evolution, the future of Parapara inlet would be a continued creation of deltaic lobes which build along Level 2 and 3 channel edges, eventually cutting off large sections of the southern estuary to influence. The presence of Washbourn and Limonite creeks would prevent total cut-off from the estuarine environment, however a mixed saline and freshwater lake may form behind the causeway with time. The formation of levees may be difficult due to the high tidal range of the estuary, suggesting that to enter this late stage of Stage C, the central mud basin and

channels must reach an elevation which is almost supratidal. The effect of this supratidal shift may cause a rapid evolution to Stage D, This will be especially visible within the embayed mud flats, however the elevation of sediment deposition within this area is likely to be higher than that of the other surface environments due to the sediment supply from Washbourn and Limonite creeks.

It appears that the introduction of mining sediment within this estuary did not cause rapid evolution due to the time period in which the sediment was created and the power of channel flow within the estuary. The time required to process and move this coarse material offshore suggests that if a sediment supply was formed and rapidly transported sediment to the estuary today, for decades after the estuary would continue processing the sediment offshore. However, as the depth of sedimentation (formed during the mining period) visible within the stratigraphic record provides an understanding of the depth of accommodation space within the estuary, the current environment may not respond in the same manner as before, and this would most likely lead to an extension of the fluvial delta within the central mud basin, moving the estuary further into a late stage of evolution.

CHAPTER 7: CONCLUSION

Estuaries act as a sink for sediment transported fluvially towards the coast. This sediment is deposited within various areas of the estuary and forms a stratigraphic record of sedimentation over time. The deposition within an estuary decreases the area in which sediment can be further deposited in relation to sea level and tidal exchange. The Roy (1984; 2001) model provides a basis for the depositional history of barrier estuaries and their evolution.

Parapara Inlet was a sediment sink for tailings material deposited within the 19th century. This is visible within the depositional record as the geological source sediment changes from predominantly greywacke to predominantly quartz-based sands and gravel (Section 5.3). This sediment decreased accommodation space within the estuary, however it did not cause the estuary to move into Stage D of the Roy model of estuarine evolution. This is believed to be due to tidal channels and their ability to move sediment throughout the estuary.

Future studies of this estuary could focus on vibracoring closer to the flood tide delta and within the main tidal channel, as well as the ebb tide delta at the mouth of the inlet. This would provide further information on the depositional history, such as the sediment deposition within tidal deltas in relation to the varying sediment conditions Coring to a greater depth within the central mud basin may also provide missing information as to the underlying topography. Also, analysing the core samples for marine Foraminifera would confirm the influence of marine or freshwater flow on depositional areas within the estuary.

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APPENDIX 1: Wind rose from Farewell Spit

Farewell Spit Wind Direction and Wind Speed From 1-Jan-1972 to 9-Jan-2009



| JOB REFERENC | 2E · SA13551 | | | | |
|--------------------------------|--------------|--------------|---------------|---------------|---------------|
| X-RAY FLUOF | | R OXIDE ANAI | -YSES | | |
| SAMPLE> | BR 18/1 30cm | BR 18/2 60cm | BR 18/3 120cm | BR 18/4 180cm | BR 18/5 330cm |
| SiO ₂ | 71.58 | 61.23 | 79.58 | 61.36 | 74.13 |
| Al ₂ O ₃ | 11.43 | 18.10 | 7.34 | 15.10 | 12.56 |
| Fe ₂ O ₃ | 7.44 | 6.64 | 3.54 | 2.58 | 1.64 |
| CaO | 0.11 | 0.32 | 0.68 | 0.29 | 0.13 |
| MgO | 1.31 | 0.92 | 1.44 | 1.60 | 0.49 |
| so ₃ | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| K ₂ O | 2.19 | 2.22 | 1.40 | 2.76 | 1.74 |
| Na ₂ O | 0.63 | 0.97 | 1.12 | 1.17 | 0.48 |
| MnO | 0.03 | 0.03 | 0.06 | 0.01 | 0.00 |
| TIO ₂ | 0.80 | 1.14 | 0.66 | 0.76 | 0.91 |
| P_2O_5 | 0.11 | 0.16 | 0.04 | 0.12 | 0.03 |
| LOI | 4.32 | 8.09 | 3.89 | 14.14 | 7.92 |
| SUM | 96.96 | 99.81 | 99.76 | 99.91 | 100.03 |
| depth | 30.00 | 60.00 | 120.00 | 180.00 | 330.00 |

APPENDIX 2: XRF result table

APPENDIX 3: Vibracore Data

| Core Number | Core Depth |
|-------------|------------|
| 1 | 0.91m |
| 2 | 1.04m |
| 3 | 1.39m |
| 4 | 1.38m |
| 5 | 2.94m |
| 6 | 2.18m |
| 7 | 1.17m |
| 8 | 0.92m |
| 9 | 1.12m |
| 10 | 2.84m |
| 11 | 1.03m |
| 12 | 2.68m |
| 13 | 0.40m |
| 14 | 3.06m |
| 15 | 3.25m |
| 16 | 2.09m |
| 17 | 1.67m |
| 18 | 4.19m |

APPENDIX 4: Grain size measurement



Core 5 Grain Size



Core 12 Grain Size





Core 16 Grain Size





Core 18 Grain Size

APPENDIX 5: Sedimentation rate table

| Sedimentation rates from AMS Dating | | | | |
|-------------------------------------|------------------|-------------|--|--|
| Core 3 | 1.2m to surface | 4.8 yrs/cm | | |
| Core 6 | 2.0m to 1.55m | 136.6yrs/cm | | |
| | 1.55m to 0.4m | 5.7 yrs/cm | | |
| | 0.4m to surface | 5.1 yrs/cm | | |
| Core 12 | 1.9m to 1.1m | 25.1 yrs/cm | | |
| | 1.1m to surface | 5.1 yrs/cm | | |
| Core 16 | 1.52m to surface | 41.6 yrs/cm | | |

APPENDIX 6: Hector Map Of Geology



APPENDIX 7: Aerial photographs from 1938 and 2009

(for easy comparison)

