Hydrodynamic impacts of tectonics in prehistoric Ohiwa Harbour, North Island, New Zealand

A thesis submitted in partial fulfillment

of the requirements for the degree

of

Masters of Science

at

The University of Waikato

by

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The University of Waikato

2012

Abstract

Ohiwa Harbour is an estuarine lagoon located in the eastern Bay of Plenty, North Island, New Zealand. Ohiwa Harbour is bounded by two sand spits, Ohope and Ohiwa Spits.

This study assessed the likelihood of a resistant barrier underlying Ohiwa Spit, which would control the inlet and spit locations. The observed depths of layers unable to be penetrated by a vibrocorer on Ohiwa Spit supported this idea, along with the discovery of a rock outcrop on the eastern harbour entrance using sidescan SONAR.

Vibrocoring on Ohiwa Spit added to the knowledge of the prehistoric evolution of Ohiwa Harbour, and an attempt to infer various subsidence events on Ohiwa Spit were made. Fining upwards coarse sand sequences with dominant shell material were found in the cores. These sequences could be related to a change in harbour hydrodynamics, or recent subsidence events in Ohiwa Harbour, such as the 0.6m subsidence of the Waimana Fault 636 to 575cal yrs BP. A sharp change in the core profile was observed at 1.4m in core C and 1.7m in core C2, marked by increased grain size and an abundance of shell material, mostly *Austrovenus stutchburyi*. This could be related to a change in wave energy in the harbour or an erosional contact associated with subsidence of Ohiwa Spit. Comparison of radiocarbon dated shells in this study with Murdoch (2005) on Ohope Spit suggests that more subsidence has occurred at Ohiwa Spit than Ohope Spit; this may be associated with a fault through the harbour entrance.

Subsidence associated with earthquakes, and erosion associated with at least four tsunami events in the last 6000 years has increased the depth and extent of Ohiwa Harbour, increasing its volume. This study used numerical modeling to determine the hydrodynamic impacts of past catastrophic events (earthquake related subsidence and volcanic eruptions) on Ohiwa Harbour. Ten scenarios along with present conditions were modelled.

- In scenarios where sea level was modified only (scenarios 1-5 and 8), tidal range and surface elevation increased within the harbour, but not at the harbour entrance. The entrance hydrodynamics were also influenced by its

width; as Ohope Spit accreted, the surface elevation and flow velocities increased within the tidal inlet

- Flow speeds increased at the harbour entrance by up to 50% following subsidence in scenarios 9 and 10
- A drop in sea level during subsidence (scenario 6) resulted in a smaller tidal prism and hence reduced flow velocities at the inlet, despite the subsidence
- Scenario 7 involved subsidence and the breaching of Ohope Spit, which would divert flow away from the entrance and result in reduced flow velocities at the entrance

Acknowledgements

Firstly I'd like to thank my supervisor Dr Willem de Lange, for without him, this exciting project would not have been possible.

Thank you to the Broad Memorial Fund and the Department of Earth and Ocean Sciences for providing me with funding to do my work.

Thank you so much to the people who assisted me with field work or helped organise it. This includes Dirk Immenga and Seb Boulay, for taking their time to undertake a sidescan sonar for me in Ohiwa Harbour. Chris McKinnon for organising vibrocoring related equipment and helping me out with all things sediment related. Wingyan Man for your enthusiasm and helping me out in the field.

A big thank you to Janine Ryburn and Jacinta Parenzee for helping me with all my lab related work, and making sure I didn't accidentally cause a disaster in the process.

To anybody else who has helped me with my thesis in some way, a big thank you to you as well. This includes Bryna, for tirelessly answering all my questions and going out of her way to help me, and anyone else in the Coastal Marine Group who has given me some assistance from time to time, including Cathy and Rafael.

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1 Chapter One: Introduction and Study Objectives

1.1 Problem Background

Ohiwa Harbour is an estuarine lagoon located in the eastern Bay of Plenty. It is bounded by the 6km long sand Ohope Spit on the western end (Ohope), and the 1km long Ohiwa Spit on the eastern end. Ohiwa Harbour lies in between the rapidly uplifting Raukumara Ranges (East Cape) and the subsiding Whakatane Graben. Ohiwa Harbour is a drowned river valley (ria) with a diverse geology including Jurassic greywacke, Plio-pleistocene Huka Group and Holocene sediments (Richmond, 1977).

The coastline extended out to the present day 125m depth contour during the late Pleistocene. Since then, sea level rose rapidly to its current position approximately 7kya, which is now known as the Flandrian Transgression. Development of the Ohope and Ohiwa sand spits began sometime after the Holocene stillstand (7410 cal yrs BP to 5175 cal yrs BP); this is at a similar time to other barriers in the Bay of Plenty and Coromandel (Murdoch, 2005). Littoral drift supplies sediment to the sand spits from the Rangitaiki Plains and the Motu River to the east. Catastrophic events such as earthquakes and volcanic eruptions have resulted in losses and gains of sediment to the Rangitaiki Plains. However, subsidence associated with earthquakes, and erosion associated with at least four tsunami events in the last 6000 years has increased the depth and extent of Ohiwa Harbour, increasing its volume. Each stepwise increase in volume has been followed by an influx of sediment. A stable dry land surface is postulated to have existed on Ohope Spit by 5590 cal yrs BP, but the area of the Spit appears to have decreased over time, in recent years, associated with La Nina (Julian, 2006).

Ohiwa Harbour has long been used as a holiday and recreational destination, and for urban development. Of particular interest are the sand spits, Ohiwa and Ohope, which are, or have been, used for those purposes. Both sand spits at the harbour entrance have experienced cyclic erosion and accretion in historic times, but the location of the harbour entrance appears to be constrained to a relatively fixed position. Given that a number of tectonic events have modified the harbour since its formation, it is worthwhile to model the impacts of these events on the harbour, including the harbour hydrodynamics which hadn't been previously modelled.

1.2 Study Area

Ohiwa Harbour is an estuarine lagoon on the east coast of the North Island (Figure 1.1a and 1.1b). It is located between Whakatane township and Waiotahi Estuary, which has a similar geological history. Ohiwa Harbour is approximately 26km^2 in area, and contains six small islands that total 2.6km^2.

1.2.1 Composition and Origin

Tidal flats, which are exposed at low tide, take up approximately 70% of the harbour area. Plio-pleistocene Huka Group sediments dominate the inner harbour shoreline, with lesser amounts of Holocene sediments. The Huka Group sediments consist of sand, silts and gravels, marine sandstones, conglomerates and pumiceous tuffs. Holocene sediments consist of similar sands, silts and gravels, but also contain fan deposits, alluvium and various aeolian deposits; this sediment is dominant around the harbour entrance and also makes up the two sand spits that flank the harbour inlet (Ohope and Ohiwa). Ohiwa Harbour retains the characteristics of a river valley, which was infilled during a marine transgression in the Late Pleistocene. This valley is wider and deeper towards the harbour entrance, at a depth of approximately 14m; elsewhere water depth rarely exceeds 3m. Sediment that infills the harbour is mainly supplied by littoral drift from the Rangitaiki Plains, with a smaller component delivered from the Motu River to the east. Less than 1% of the tidal prism volume is fresh water contributed by local rivers, so it is assumed their effect on the harbour morphology is minimal (Richmond, 1977). It should be noted that the present streams in Ohiwa Harbour are too small to produce the observed river valleys. They may exist due to stream capture by the Whakatane River following an earthquake, postulated by Marra.

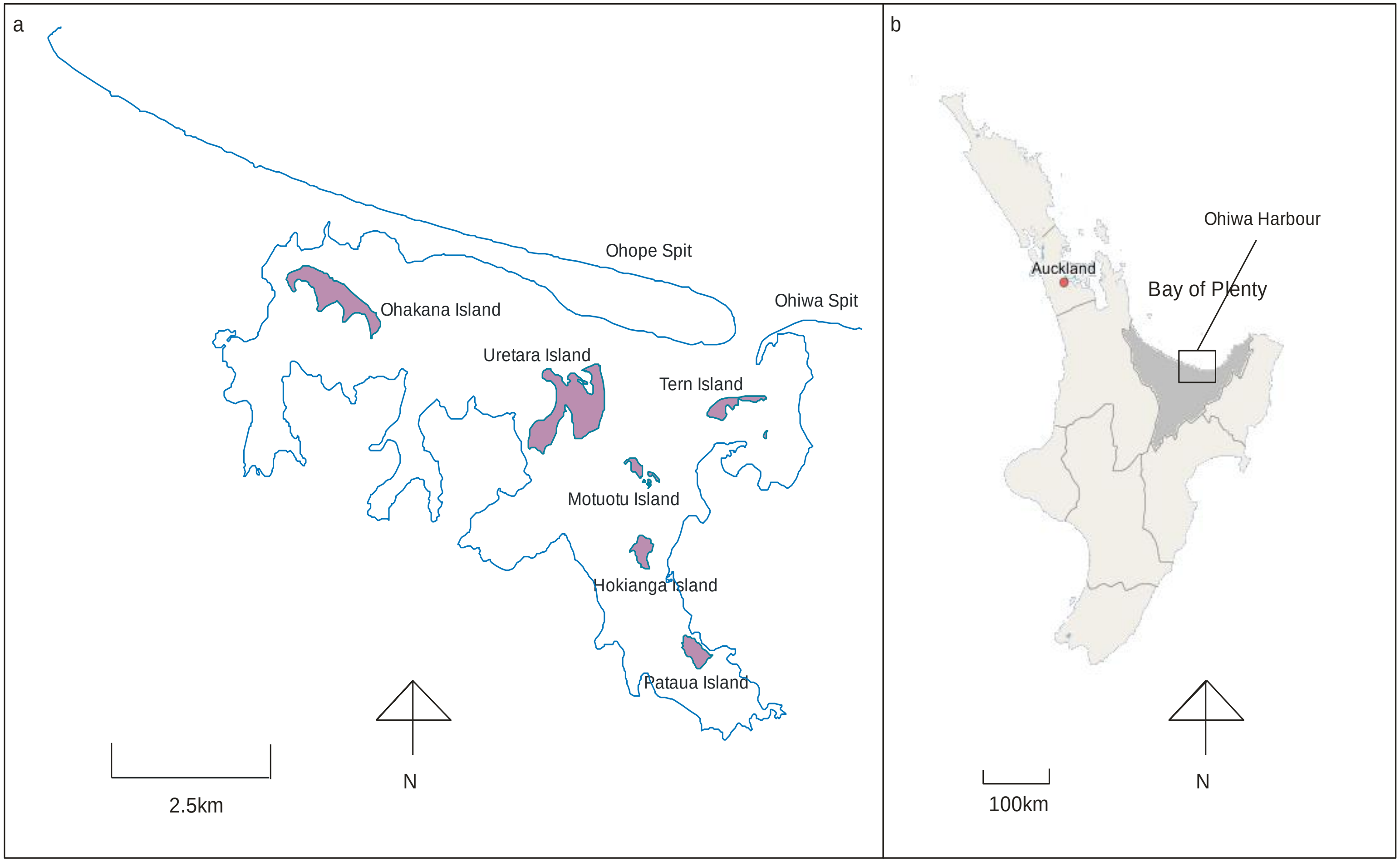

Figure 1.1 (a) Six islands located in the Ohiwa Harbour study area and (b) Location of Ohiwa Harbour in New Zealand. Source: ArcGIS and Google Earth

1.2.2 Harbour Hydrodynamic Environments

The hydrodynamics of Ohiwa Harbour can broadly be categorised into three zones: wave zone, current zone and mixed zone. The wave zone occurs mainly in shallow nearshore areas around the harbour margins. Waves are steep and choppy, but rarely greater than 0.5m high (Richmond, 1977). Their direction of propagation is directly related to the dominant wind direction, which varies between the El Niño and La Niña phases of the El Niño Southern Oscillation (ENSO) (Julian, 2006). The current zone is associated with the deeper regions of the harbour channels, and is dominated by tidal currents that produce a variety of ripple bedforms in different depositional environments. The mixed zone has properties influenced by waves and currents. It is found in between MHWM and MWLM, including the intertidal flats. Current strength varies with the lunar cycle (maximum at spring tides), while wave induced currents are influenced by weather conditions; being near zero during calm conditions, and significant during storms.

1.3 Objectives

The aim of this study is to investigate the effect of tectonics on harbour processes. There are two main objectives:

- To assess the response of the harbour to historic and prehistoric tectonic events
- To assess the likelihood of a resistant barrier underlying Ohiwa Spit, which would control the inlet and spit locations

A conceptual model of the evolution of Ohiwa Harbour has been constructed by Murdoch (2005), which suggests that Ohiwa Harbour started development during the mid-Holocene, at the same time as other barrier-enclosed harbours around the North Island. Murdoch took a geomorphic and stratigraphic approach, making use of tephrochronology and radiocarbon dating to develop his conceptual model. Murdoch also made use of photographs and surveys to determine the historic shoreline changes for Ohope and Ohiwa Spits. This model will be used to develop scenarios for numerical modelling of harbour processes.

1.4 Thesis Structure

Chapter One is an overview of the research project. It deals with motives for the research, the study area of interest, and the objectives for this thesis.

Chapter Two is a synthesis of literature relating to tectonic impacts on the evolution of Ohiwa Harbour. It is the background research for this project.

Chapter Three presents the methods used in this thesis to meet the objectives.

Chapter Four presents field work results obtained from vibrocoring on Ohiwa Spit, and SONAR in Ohiwa Harbour. These results are interpreted to advance on current knowledge of the coastal history of Ohiwa Harbour.

Chapter Five presents results from modeling the hydrodynamics of Ohiwa Harbour. These results show prehistoric changes in Ohiwa Harbour's hydrodynamics since development of Ohope and Ohiwa Spits.

Chapter Six discusses the prehistoric hydrodynamic changes within Ohiwa Harbour and their possible impact on Ohope and Ohiwa Spits. It also includes a summary of the material presented and recommendations for future research.

2 Chapter Two: Review and Synthesis of Literature

2.1 Introduction

This chapter provides a synthesis of the literature relating to the tectonic impacts on the evolution of Ohiwa Harbour. Geological evolution of the harbour as a whole is examined, including some of its geological history. The morphology and geological evolution of the Ohope and Ohiwa sand spits in the Ohiwa Harbour is discussed; this includes changes observed from 1865 onwards, in relation to climate trends. Historic tsunami in Ohiwa Harbour in relation to earthquakes and volcanic activity are also discussed.

2.2 Ohiwa Harbour Geological Evolution

Ohiwa Harbour is an estuarine lagoon enclosed by two barrier spits, Ohope and Ohiwa. 70% of the 26km^2 harbour is exposed at low tide. The harbour consists of four drowned river valleys which are aligned normal to the shoreline, and the sand spits are aligned parallel to the shoreline. Ohiwa Harbour's topography retains its characteristics of a river valley, which is wider and deeper (in general) towards the harbour entrance. Maximum depth of the harbour is approximately 14m at the entrance, though this varies as the littoral drift direction and intensity changes, along with the channel morphology (Richmond, 1977).

Ohiwa Harbour's sediments reveal a diverse and complex geological history. Urerewa Greywacke and Huka Group sediments dominate the Ohiwa Harbour, with small amounts of Holocene sediments (Figure 2.1). The Urerewa Greywacke is of Jurassic to Lower Cretaceous age. It consists of altering siltstones and sandstones, conglomerates with granite and granodiorite pebbles, and occasional fine-grained basic volcanic rocks. Plio-pleistocene Huka Group sediments are a major component of the Ohiwa Harbour, consisting of fossiliferous marine sandstones, conglomerates and interbedded pumiceous tuffs and fluviatile silts, sands and gravels. The Holocene and modern sediments consist of fluviatile silts, sands and gravels, terrace and fan deposits, peat, alluvium and various aeolian deposits (Richmond, 1977). These Holocene sediments make up the Ohope and Ohiwa sand spits. Volcanic tephra also mantles the Ohiwa Harbour catchment. Ohiwa cliffs reveal total ash thicknesses greater than 27metres, with the youngest dating from Tarawera eruption, and the oldest dating 125ka to 300ka (Pahoia Tuffs) (Healy et al, 1964).

Ohiwa Harbour is in between the rapidly uplifted East Coast and the subsiding Whakatane Graben. The Whakatane Graben is wedge-shaped and formed when the Taupo Volcanic Zone and the North Island Shear Belt intersected; since 1Ma it has been subsiding at a rate of 0.4-2mm/year, with a maximum of 2km subsidence. The late Pleistocene land surface at Ohiwa consisted of river valleys aligned normal to the shoreline, extending out to the present 125m depth contour. This contour is at approximately the same shoreline as the last glacial maximum around18-20kya. Sea level has risen rapidly since then, to its current position 7kya, during what is now known as the Flandrian Transgression (Curray, 1969). The drowned river valleys are now visible as the ‘arms’ of the harbour. Sea level is still rising but at a much slower rate. Kraft et al (1973) estimated the sea level rise at 15cm/century. More recent estimates from Ministry for the environment predict a nationwide sea level rise of 0.31 m to 0.49 m by 2100 (MfE, 2004b). Several sites at Ohiwa Harbour contain in situ Totara stumps, dating approximately 800 to 1200 cal yrs BP (Murdoch, 2005). These stumps indicated that either sea level was slightly lower back then, or subsidence has occurred at Ohiwa as a result of tectonic events or a general compaction of sediments. It is more likely that subsidence occurred as Schofield (1973, 1975) suggests that sea level was slightly higher than, or about the same as now, 1800 years ago. Also, Waimana Fault movement has caused the Harbour (and associated spits) to subside by 2m, which would have killed off the Totara forest. Ohiwa Harbour is said to have formed when the Ohope and Ohiwa spits enclosed the open embayment. At present, four faults constrain and dissect the harbour (Figure 2.2) (Gibb, 1977); (Hayward et al, 2004).

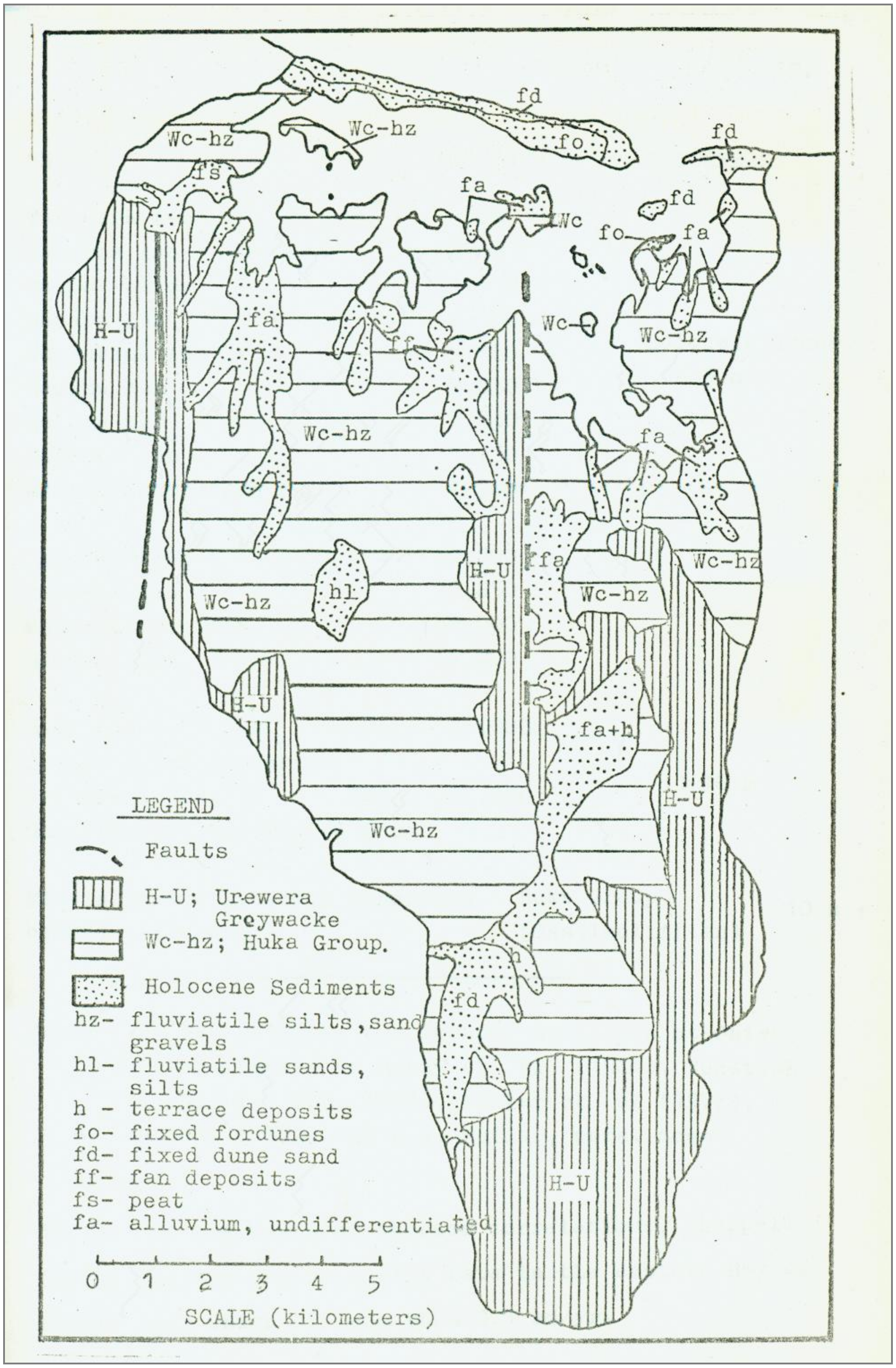

Figure 2.1 Geology of the Ohiwa Harbour Catchment after Healy et al, 1964

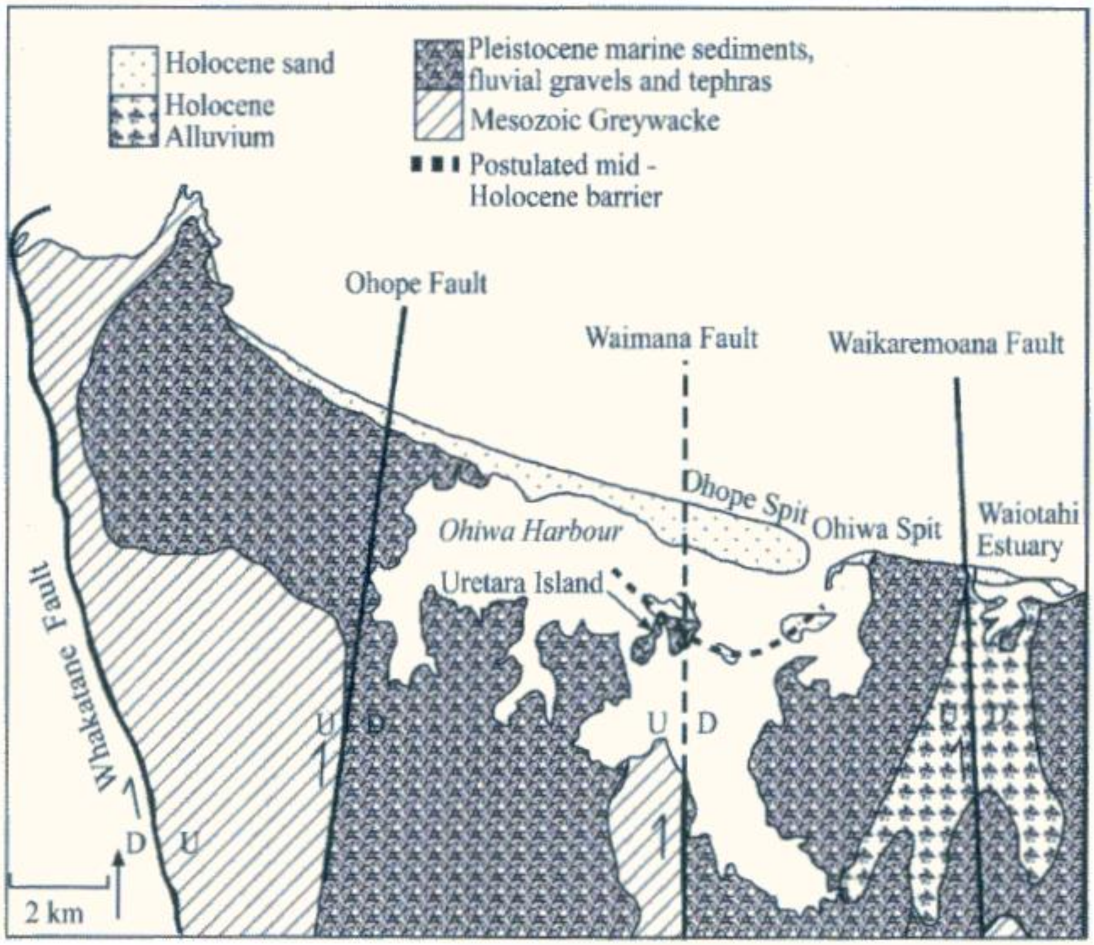

Figure 2.2 Geology and Major Faults of Ohiwa, New Zealand (Murdoch, 2005)

2.3 Ohope and Ohiwa Spits Evolution

2.3.1 Morphology of Ohope and Ohiwa Spits

The Ohope barrier spit and beach extends for 12km in an east-west direction, with a variation in width from 300m to 1000m. The spit itself is 6km long and is on the eastern harbour entrance. Richmond (1977) subdivided the barrier spit into three morphological zones: dune complex, barrier flats and distal terminus.

2.3.1.1 Dune Complex

Six parallel dune ridges recurve towards the harbour on the eastern end. The landward side of the ridges is an older area of blow-out dunes stabilized by vegetation. These dunes were identified as transverse parabolic dunes by Saunders (1999). Maximum dune height is approximately 15m, however wells drilled on the spit indicate fine sand extends to a depth of at least 12m.

2.3.1.2 Barrier Flats

A relatively low relief area on the harbour side of the Ohope dune complex. Small areas of the barrier flats contain characteristics of salt marshes.

2.3.1.3 Distal Terminus

This is the exposed end of the spit, directly affected by wind, wave and current activity (Figure 2.3). Small dunes on the terminus are rounded, roughly symmetrical and isolated; this is due to variations in prevailing wind direction. The sand dunes reach heights of greater than 2m in some parts. Broad, flat sandy areas on the distal terminus are inundated during storms and extreme high tides.

Figure 2.3 Distal end of Ohope Spit. The terminus is in the centre foreground, the barrier flats are along the left (southern) margin, and the dune complex comprises the rest of the spit (Richmond, 1977).

The Ohiwa barrier spit consists of a single dune ridge which reaches a maximum height of 10m. A steep erosional scarp 8m high is on the seaward margin. Ohiwa's distal terminus is tear dropped shape, and has undergone severe erosion in the last 100 to 150 years. By 1938, part of the sand spit had been separated by the mainland, and is now known as Whangakopikopiko Island (Richmond, 1977) (Figure 2.4). Soil and vegetation development on Ohiwa Spit is similar to what is observed on the older dunes. Ohiwa Spit has hummocky sand dunes with a maximum relief of 2m, and no preferred orientation.

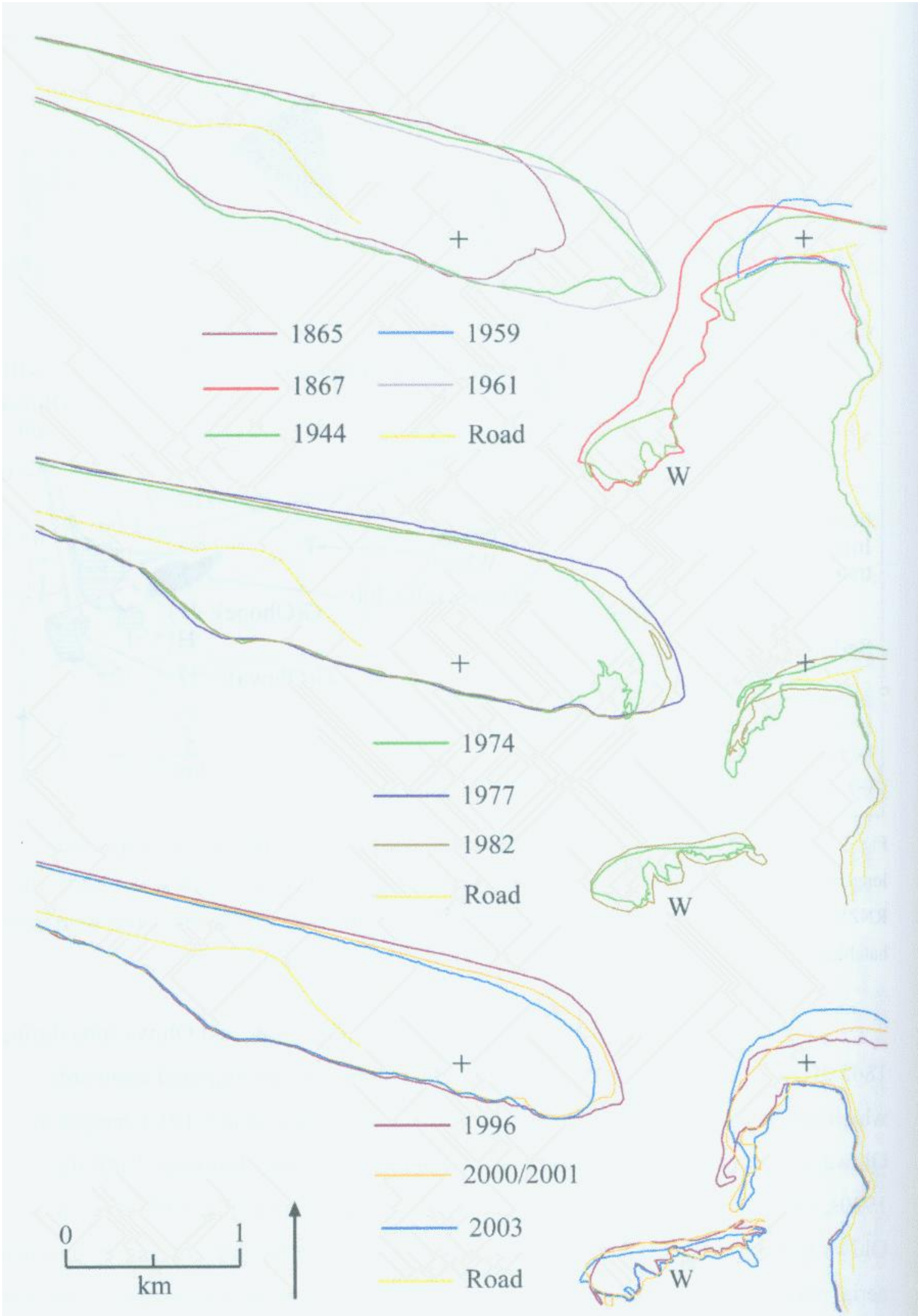

Figure 2.4 MHWM changes on Ohope and Ohiwa Spits from 1865 to 2003. W, Whangakopikopiko Island (Murdoch, 2005).

2.3.2 Formation and Evolution

Littoral drift is the main source of sediment supply to the sand spits. Sediment is transported to Ohope and Ohiwa spits from the Rangitaiki Plain via the Whakatane River, it is then transported by longshore drift on the coast to Ohiwa Harbour (Healy, 1978b). It is unlikely that rivers in the Ohiwa Harbour contribute much sediment, as river inflow to the harbour is small compared to the volume of the tidal prism. River inflow equated to 0.23% of tidal prism volume in 1976 (Richmond, 1977).

At least two conflicting theories have attempted to explain how the Ohope and Ohiwa sand spits formed and evolved. Initially it was believed infilling of the Ohiwa Harbour and sand spit formation occurred sometime after the infilling of the Whakatane Graben and Rangitaiki Plains (1935 to 1718 cal yrs BP) (Gibb, 1977); (Richmond et al, 1984); (Hayward et al, 2004). Late quaternary eruptives, consisting of airborne material and large pyroclastic flows, was transported along the Whakatane, Rangitaiki and Tarawera rivers (Healy et al, 1978b); (Lowe et al, 1998); (Nairn et al, 2001); (Hayward et al, 2004); (Manville et al, 2005). From 1935 cal yrs BP, there was an oversupply of volcanogenic sediment which infilled the Whakatane Graben and supplied more sediment to the Rangitaiki Plains and Whakatane Heads. Ultimately, this reworking and re-sedimentation of pyroclastic material would have caused progradation rates of 3mm/year in Ohiwa Harbour from 1935-1718 cal yrs BP. After the Taupo Tephra eruption in 1718 cal yrs BP, progradation rates increased to 4mm/yr in the Ohiwa Harbour, and initiated formation of the barrier spits. Richmond et al (1984) suggested that changes in wave refraction conditions occurred after the eruption, which led to irregular parabolic transgressive blowout dunes advancing inland after the Taupo eruption, on the Rangitaiki Plain. The surplus sediment then infilled the Ohiwa Harbour and formed the spits.

Evidence from tephra distribution, radiocarbon dating of shells and Totara stumps, dune morphology, soil stratigraphy and existing literature contradicts the earlier model. Murdoch (2005) proposed an alternative evolutionary model which suggests that Ohope and Ohiwa spit development commenced after the Holocene stillstand 7410 cal yrs BP to 5175 cal yrs BP (Julian, 2006). During this time, the core of Ohope and Ohiwa Spits prograded landward, and Ohope Spit formed a subtidal bar and narrow beaches. A stable dry land surface is postulated to have existed by 5590 cal yrs BP; this is based on preservation of Whakatane tephra at one site in the core of Ohope Spit. By 4190 cal yrs BP, Ohope Spit had attained its historical length.

At least four phases of dune formation have been identified on Ohope Spit, each having differing progradation rates. These phases are identified by radiocarbon dating, constructed chronologically by the presence or absence of Whakatane, Taupo and Kaharoa (636 cal yrs BP) tephras, and Loisells Pumice (<590 cal yrs BP) (Murdoch, 2005). Ohiwa Harbour's environment also changed significantly during these phases.

2.3.2.1 Phase One: 5590 cal yrs BP to 3515 cal yrs BP

The longshore progradation rates were 1.4m/yr, with Mid-Holocene sea level changes resulting in landward migration of Ohope and Ohiwa spits (Murdoch, 2005).

2.3.2.2 Phase Two: 3515 cal yrs BP to 2425 cal yrs BP

The longshore progradation rates decreased to 0.6 to 1m/yr, which was indicated from radio-carbon dating of shells. Three dunes then formed on Ohope Spit, which suggested the presence of a sub-tidal land surface. Ohope Spit increased in area and a stable harbour entrance existed within Ohiwa Harbour by 2780 cal yrs BP. Subsidence of the Waimana Fault (2600 cal yrs BP) by 2 to 2.4m and coastline erosion caused a breach in Ohope Spit by 2330 cal yrs BP (Murdoch, 2005; Julian, 2006).

2.3.2.3 Phase Three: 2425 cal yrs BP to 1718 cal yrs BP

The sedimentation rates declined at Ohope Spit, but an additional four dunes were formed on Ohope Spit from rafted Taupo pumice. During this phase, surplus sediment from the Rangitaiki Plains and Marapa Tephra (2160 cal yrs BP) also added sediment to the distal end of Ohope Spit and Ohiwa Harbour. Up until 1718 cal yrs BP, a sub-tidal salt marsh existed inside Ohiwa Harbour, which continued to exist 1110 cal yrs BP on the south side of Ohope Spit. The Taupo Eruption 1718 cal yrs BP dramatically changed the environment within the harbour. 6-13cm of ash and lapilli pumice blanketed the entire harbour from the Taupo Eruption; by this time, a stable land surface on Ohope Spit existed and soil formation was favoured (Murdoch, 2005; Julian, 2006).

2.3.2.4 Phase Four: 1718 cal yrs BP to 636 cal yrs BP

The longshore progradation rates were 0.75m/yr during phase four. A Totara forest grew on the spit up until 1110 cal yrs BP, as dated by Murdoch (2005). After that time, a possible earthquake along the Waimana Fault resulted in 2m subsidence within Ohiwa Harbour, drowning the Totara forest. Small episodes of movement on the Waimana Fault occurred after the earthquake (60cm subsidence occurred to the east), up until approximately 636 cal yrs BP.

2.3.2.5 Phase Five: 636 cal yrs BP and after

The longshore progradation rates were 0.4m/yr during phase five. The Kaharoa eruption occurred 636 cal yrs BP and aeolian sand dunes accumulated, two of which prograded ashore. A stable land surface then existed on Ohope Spit after 575 cal yrs BP; this existing land surface was punctuated by unstable environmental phases where the surface was buried by dune sands, and new soil horizons formed.

2.3.2.6 Barrier Formation, Rangitaiki Plain and comparison with Waiotahi Estuary

The Holocene Stillstandwas identified as the most rapid period of barrier formation in New Zealand. Murdoch's 2005 model is in agreement with other barriers formed in the Bay of Plenty and Coromandel coastline, most of which were developed by 5728 cal yrs BP. Onshore wave conditions transported sediment from the continental shelf. Low offshore slope angles are believed to have resulted in limited sediment accommodation space on the shelf, causing rapid progradation of sediment (Bradshaw et al, 1994; Dahm et al, 1994). In the Coromandel and Bay of Plenty, the slope to 20m depth is <0.5 to 1 degrees (Murdoch, 2005).

Infilling of the Whakatane Graben and Rangitaiki Plains has resulted in excess sediment being transported, by littoral drift, to sites on the Eastern Bay of Plenty and Coromandel as a whole, including Ohiwa Harbour. The Whakatane Graben is a wedge shaped tectonic depression, bounded by active normal faults on each side of the graben (Figure 2.5). Subsidence of the graben began at least 0.6Ma, at an average rate of 1-2mm/yr, and 0.4-0.8mm/yr during the late Pleistocene. Pleistocene sediments on each side of the graben have been uplifting at a long-term rate of 1mm/yr for approx 0.4 million years (Beanland and Berryman, 1992). The Rangitaiki

Plains bound the eastern fault (Edgecumbe) onshore with Holocene sediments. These plains are separated from the Ohiwa Estuary by the Whakatane Headland, and supply Holocene sediment to the estuary by longshore drift. The Rangitaiki Plains have advanced seaward since 6.5Ka by 10km to reach their current position 1.8Ka, when the Taupo eruption occurred. Tectonic subsidence and sedimentation of the Rangitaiki Plains mainly occur during catastrophic events. Tectonic subsidence of the plains, by earthquakes (such as Edgecumbe), has resulted in the loss of sediment from the plains. However, this has been compensated for by large amounts of sediment received from volcanic eruptions, directly as airfall, or transported by the three rivers within the Rangitaiki Plain. Since the 1.8Ka Taupo Eruption, a large volume of volcaniclastic sediment has been carried down the Rangitaiki River. Excess sediment has then been transported eastwards into the Ohiwa Estuary by longshore drift. The Rangitaiki Plains shoreline is now in equilibrium, neither prograding nor aggrading (Beanland and Berryman, 1992).

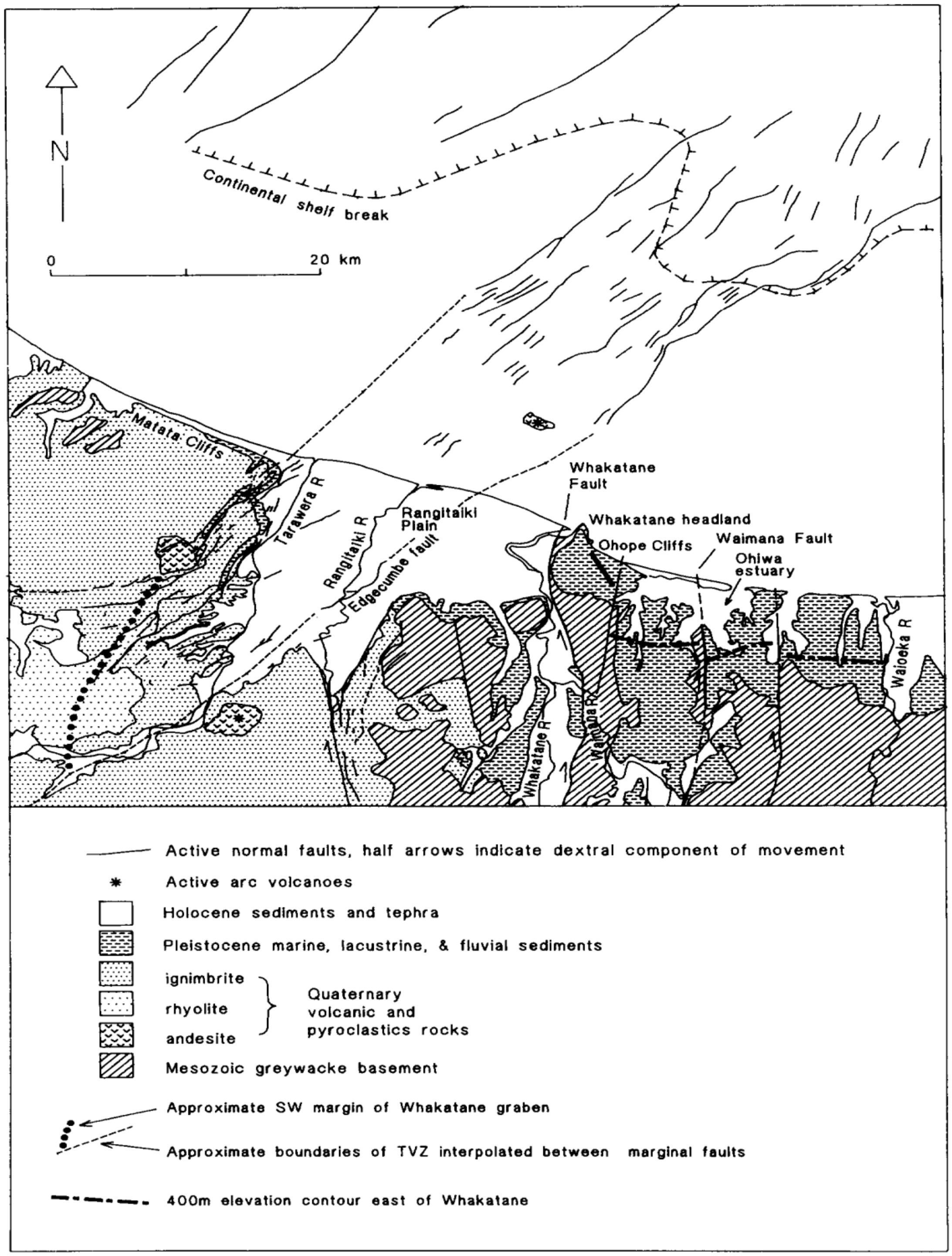

Figure 2.5 Geological Setting of the Rangitaiki Plain and Ohiwa Estuary (Beanland and Berryman, 1992).

The Bay of Plenty has received volcaniclastic sediment, which has infilled estuaries and prograded coastlines since the last sea-level still stand 6.5ky BP. The Waiotahi Estuary is located in the eastern Bay of Plenty, neighboring the Ohiwa Harbour. This estuary is wave dominated in a meso-tidal environment. Evolutionary processes for the Waiotahi Estuary fit the wider regional coastal area, the Bay of Plenty, which includes the Ohiwa Harbour. The modern day Waiotahi Estuary is the result of sea level rise and sediment supply over the last 7.5ky, as well as volcanic and tectonic subsidence. A combination of high sediment supply from volcanoes, and restricted accommodation space produced a rapidly infilling estuary, until 2kya, when aggradation of tidal flats produced an elevated tidal marsh. Presently, the estuary is in an advanced stage of infilling (Marra, 1997).

Full estuarine conditions were in place 7400 cal yrs BP, consisting of a central basin and barrier complex; this is at a similar time to development of the sand spits in Ohiwa Harbour. Stratigraphic records from surface sampling and subsurface sampling (vibrocoring) indicate transitions in estuarine morphology since then. The transitions were from central basin deposits to transgressive tidal flats, to stillstand vegetated tidal flats, and now back to transgressive tidal flats. Volcanic activity has contributed to 21% of the stratigraphic record, received from airfall and catastrophic catchment sedimentation after the eruption. The Whakatane eruption 4.8kya has had the biggest impact on the catchment and estuary. Episodic changes in relative sea level occur because of subsidence, the most recent event is linked with the Kaharoa eruption 800 cal yrs BP, which buried most of the eastern stillstand vegetated tidal flats. Over the last 800 years, sedimentation rates have been low for an estuary (1-2mm/yr). This rate is likely to continue for some time unless there is a return of volcanic and tectonic events (Marra, 1997).

2.3.3 Historic Changes (1865 to 2003)

From 1865 to 2005, shoreline changes were measured on the Ohope and Ohiwa Spits, as well as changes in the harbour entrance. The most notable studies are referenced in Chapters 2.3.3.1 and 2.3.3.2. Historical surveys and aerial photographs, beach profiling and real-time kinetic GPS (Global Positioning Survey) were used to measure rates of erosion or accretion. From 1865-1977 Ohiwa Spit had been eroding while Ohope Spit was accreting. Since 1982 the process has reversed. In spite of significant erosion having occurred, it is unlikely that Ohope Spit will erode completely in the near future as a stable land surface may have existed as far back as

5590 cal yrs BP. Palaeo-valley walls also constrain the tidal channel (Davis and Fitzgerald, 2004).

2.3.3.1 Aerial Photographs

Historically, sources of shoreline data included aerial photographs. Healy et al (1977) and Gibbs (1978) did the first major analysis of shoreline changes on Ohope and Ohiwa Spits. Photographs of the spits were taken from 1944 to 1974. Aerial changes were determined by planimetering zones on photos, which were set to a standard scale. Healy et al (1977) and Gibb (1978) reported large differences in migration rates of the spits however. Healy reported accretion rates of 0.76m/year on Ohope Spit and erosion rates of 0.76m/year on Ohiwa Spit from 1944-1977, while Gibb reported accretion rates of 2.26m/year on Ohope Spit and erosion rates of 5.16m/year on Ohiwa Spit from 1945-1976. These large differences in migration rates between Healy et al (1977) and Gibb (1978) could be explained by short term seasonal variations in the shoreline positions, which were not captured in the photos. Aerial photographs were often taken at times of opportunity rather than for strategic purposes however, limiting their effectiveness when used alone. Murdoch (2005) made use of photographs up until 2003 which were digitized into GIS software, which is detailed in the next section.

2.3.3.2 Beach Surveying

Beach surveying usually involves beach profiling which measures changes in beach morphology along transects. The first beach surveys were carried out on Ohope Spit in 1865 and Ohiwa Spit in 1867. The ‘Emery Pole Technique’ as described by Komar (1998) is commonly used to carry out beach profiling.

Saunders (1999) made use of beach profile data from 1876 to 1998 on Ohope Spit and presented the data using KALEIDAGRAPH. At each profile location the geographical references for the shoreline position were retrieved, distances between successive shorelines were calculated using Pythagoras’s theorem. Saunders (1999) showed that littoral drift and sedimentation was not continuous along Ohope Spit as Ohope Beach and Central received more sediment volumes than Ohope Spit.

Murdoch (2005) has done perhaps the most comprehensive analysis of recent shoreline changes on Ohope and Ohiwa Spits. Murdoch compiled together beach surveys, aerial photographs from 1944 to 2003 and Royal New Zealand Navy sounding sheets to determine rates of accretion and erosion on the sand spits from 1865 to 2003. Beach survey lines from Gibb (1977), Richmond et al (1984) and Hodges and Deely (1997) were 'resurveyed as close as possible following the descriptions given in the literature' by Murdoch (2005), who also did additional surveys; these surveys locations are in Figure 2.6. Aerial photos from 1944 to 2003 were orthorectified using ArcView 9 GIS software in order to measure shoreline changes. Erosion/accretion rates were determined by dividing the total erosion/accretion by the time period.

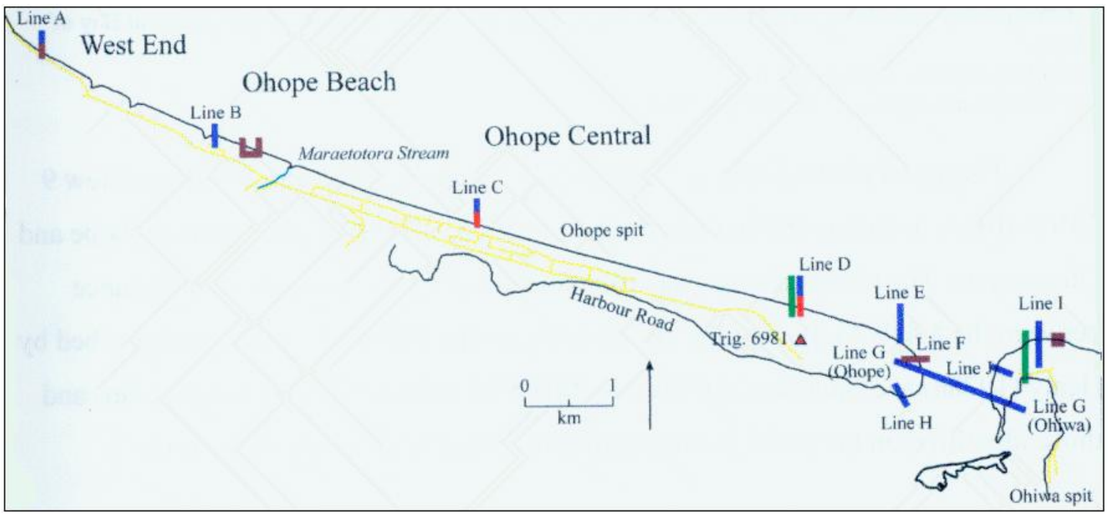

Figure 2.6 Survey lines used to measure rates of erosion and accretion at Ohope and Ohiwa Spits. Green, Gibb (1977); red, Richmond et al. (1984); brown, Hodges and Deely (1997); blue, Murdoch (2005).

Erosion and accretion rates given by Murdoch (2005) can be misleading as actual erosion and accretion rates were often much higher than what was calculated when they occurred. However, some beneficial information was acquired. On Ohope Spit, west of the Maraetotara Stream, the beach system was stable and erosion/deposition cycles were in sequence with El Nino/La Nina cycles; that is, accretion occurred during El Nino phases while erosion occurred during La Nina phases. Transects D-G (Ohope Spit) have not been consistent with El Nino/La Nina phases since 1976, possibly due to changes in the position and shape of the harbour entrance. Transect H (Ohope Spit) has been in sequence with El Nino/ La Nina cycles since 1974. All of the transects on Ohiwa Spit have had erosion/accretion cycles were in sequence with El Nino/La Nina cycles except for transect I during 1944-1959.

Julian (2006) made use of more recent beach profiling methods on Ohope and Ohiwa Spits, using a 'Total Station' and Real-Time Kinetic Global Positioning Survey (RTK-GPS). A total station is an electronic distance meter device which determines the angles and distances from the total station to the points of interest being surveyed. As used by Julian (2006), it is a faster and more efficient alternative to older surveying techniques. The RTK-GPS makes use of three dimensional GPS technology, involving communication between a mobile receiver (Trimble 4000ssi), base station receiver and GPS satellites. It is not only used for beach profiling, but also determining beach volume changes, monitoring shoreline morphodynamics and assessing storm cuts (Morton et al, 1993).

2.3.3.3 Discussion of Historical Changes

Erosion and accretion of the Ohope and Ohiwa Spits is a cyclic phenomenon, driven by the dominant littoral drift direction which is a response to changes in the Southern Oscillation Index (SOI). Changes in the littoral drift direction at the harbour entrance influence the size and position of the harbour entrance, which is suggested to influence whether erosion or accretion is occurring on the nearby sand spits.

The dominant littoral drift direction is defined by calculating the number of waves that appear on each side of a known location. The side of the beach profile with the greatest number of incoming waves is inferred as the littoral drift direction. A general trend has been observed in the Ohiwa Harbour from 1979 to 1998. During La Nina conditions, net north-west littoral drift occurred, and waves moved from the north-east. During El Nino conditions net north-east littoral drift occurred and waves moved from the north-west. During these years, El Nino phases dominated, with two La Nina phases occurring (Julian, 2006).

Since 1944, there has been a direct link between erosion/accretion rates on Ohope and Ohiwa Spits, and the width and size of the channel (Murdoch, 2005). Erosion on Ohiwa Spit was at its greatest when the harbour entrance was at its narrowest point, this occurred during La Nina conditions and accretion occurred on Ohope Spit. During El Nino conditions, the harbour entrance was at its widest; Ohope Spit eroded while Ohiwa Spit accreted.

Healy (2000) has also suggested that the position of the inlet channel (harbour entrance) is offset towards the littoral drift direction, influencing erosion and accretion on the spits. In 1995, the inlet channel was located on the concave side of Ohope Spit which was eroding, while Ohiwa Spit was accreting; this migration of the inlet channel was consistent with westward littoral drift (Saunders, 1999). Accretion at Ohiwa Spit is likely to be caused by landward migration of the swash bars across the swash platforms and subsequent welding to the beach face. Erosion at Ohope Spit is likely to be caused by a shift in the main ebb channel to the Ohope side, which increases pressure through the narrow inlet, causing scouring on the Ohope side. A shift in the main ebb channel allows migration of accompanying swash platforms, and Ohope Spit to be exposed to storm wave erosion. When littoral drift moves eastward, the ebb channel will be up against Ohiwa Spit instead and erosion will occur there in a reverse manner.

Ohope and Ohiwa Spits have been in dynamic equilibrium with each other as suggested by preservation of Taupo and Kaharoa tephras. That is, sand moves from one end of the harbour system to the other, without being lost, in response to the prevailing environmental conditions. The harbour entrance is most likely anchored to the position of the palaeo-channel, which dates back to when the harbour was an open valley. Sediment in the channel may be easily eroded by tidal flows, and the harbour inlet may move, but palaeo-valley walls constrain the tidal channel itself (Davis and Fitzgerald, 2004). Because of this palaeo-channel, Ohope and Ohiwa spits are unlikely to be completely eroded in the near future.

2.3.4 Historic Tsunami

Tsunami occurring in the last 6000 years have caused significant changes in the depth and extent of Ohiwa Harbour. Evidence for at least four tsunami events can be identified in Ohiwa Harbour occurring 5590 to 2750 cal yrs BP, 1718 cal yrs BP and 636 cal yrs BP (Murdoch, 2005). GeoEnvironmental Consultants carried out stratigraphic logging at Stoney Brook, Ohiwa and identified at least four to five tsunami units in their stratigraphic column (Figure 2.7a and 2.7b). The chaotic units were considered to be tsunami related because Ohope and Ohiwa Spits would have protected the sheltered location from storm surges. The first three chaotic units were speculated to be generated by volcano-meteorological tsunami associated with Whakatane, Whakaipo and Taupo eruptions (Julian, 2006). A subsidence event identified in the stratigraphic column, in between Taupo and Kaharoa tephras is thought to have generated another tsunami unit (Julian, 2006). Kaharoa tephra is buried by thin coarse units which is either thought to be tsunami or storm related (GeoEnvironmental Consultants, 2003; Lowe and de Lange, 2000).

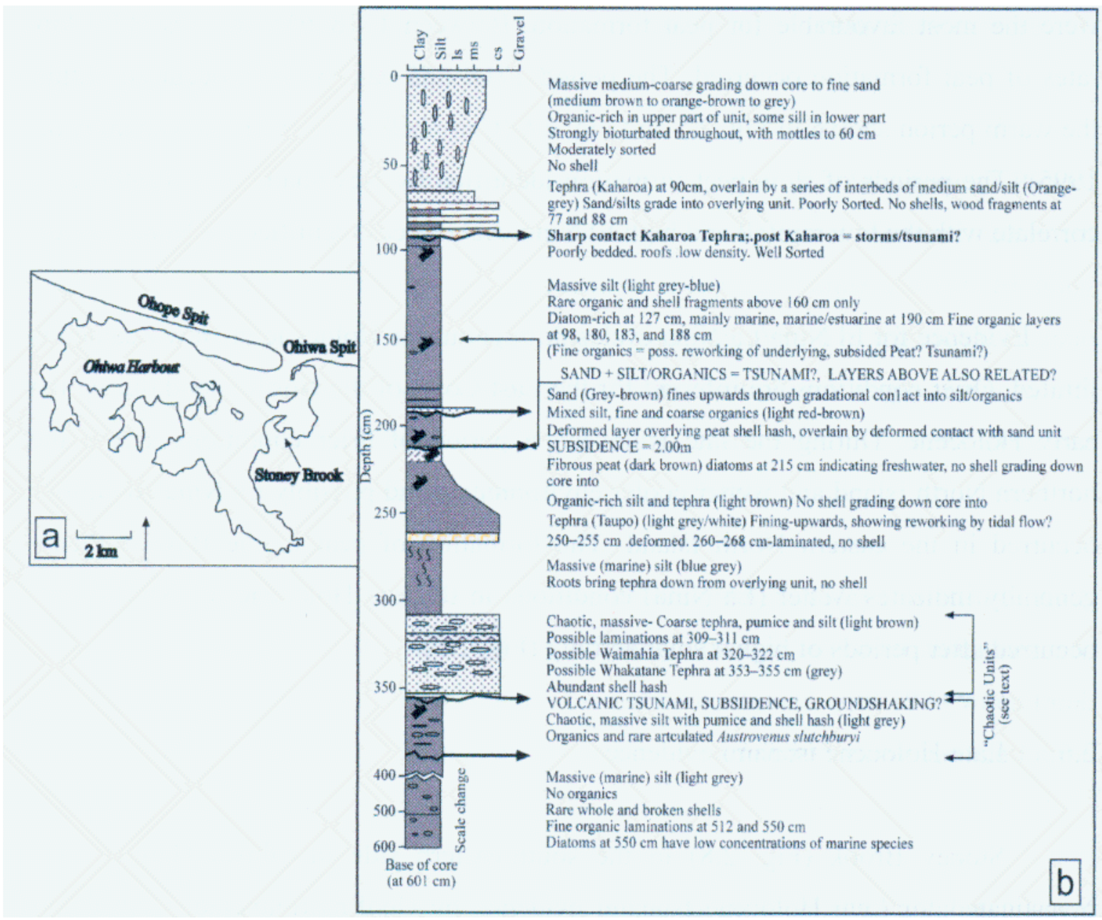

Figure 2.7 (a) Location of the Stoney Brook core site. (b) Stratigraphic column at Stoney Brook (adapted from GeoEnvironmental Consultants 2003).

At least 2m of earthquake related subsidence has occurred in Ohiwa Harbour during the Holocene. This subsidence may well have caused tsunami in the Ohiwa Harbour during that period. Hayward et al (2004) carried out vibrocoring in three locations in Ohiwa Harbour and identified 2m of subsidence in all three cores, which were 2km apart. The Holocene aged cores revealed an erosional contact in between freshwater peat or soil and overlying intertidal mud. This subsidence event was determined to have occurred 2600 cal yrs BP, and it was the only major subsidence event in the last 8ky. Fossil foraminifera and diatoms were used to identify sudden elevation changes in the cores. Age models for the cores were constructed using tephrochronology and radiocarbon dating.

2.4 Summary

Ohiwa Harbour is an estuarine lagoon with a complex geological history. Three major groups of sediment are identified in the harbour. These groups are Jurassic to Lower-Cretaceous Urewera Greywacke, Plio-pleistocene Huka Group and Holocene sediments which make up the sand spits. Four faults constrain the harbour which was once a river valley aligned normal to the shoreline. Since the Flandrian Transgression that ended approximately 7ka, sea level has remained in a similar position and the present configuration of the harbour has largely unchanged.

Ohope Spit is subdivided into three morphological zones: a dune complex, barrier flats and a distal terminus. Ohiwa Spit is aligned opposite to Ohope in the harbour entrance, consisting of a single dune ridge reaching a maximum height of 10m.

Conflicting theories explain the origin of the sand spits. Initially it was postulated that they formed 1935 cal yrs BP to 1718 cal yrs BP after infilling of the Whakatane Graben and Rangitaiki Plains. However more recent evidence from tephra distribution, radiocarbon dating of shells and Totara stumps on the sand spits suggest that the Ohope and Ohiwa spits began to form after the Holocene stillstand 7410 cal yrs BP to 5175 cal yrs BP. This is in agreement with other barriers formed in the Bay of Plenty and Coromandel coastline, most of which were developed by 5728 cal yrs BP. During the Holocene Period, four to five phases of dune formation are identified on Ohope Spit.

Recent changes on Ohope and Ohiwa Spit (1865 to present) were discussed. Up until 1982, Ohope Spit was eroding while Ohiwa Spit was accreting, but it has since reversed. Changes in erosion and accretion on the sand spits are speculated to be cyclic due to prevailing wave directions associated with El Nino or La Nina extremes, which determine which spit is eroding or accreting. However, Ohope and Ohiwa Spits have been in dynamic equilibrium with each other as suggested by preservation of Taupo and Kaharoa tephras. The harbour entrance is most likely anchored to the position of the palaeo-channel, which dates back to when the harbour was an open valley, so while erosion and accretion can occur, the harbour entrance and associated spits is suggested to be constrained by the underlying geology.

Tsunami events in the last 6000 years have caused significant changes to the depth and extent of Ohiwa Harbour, at least four have been identified 5590 to 2750 cal yrs BP, 1718 cal yrs BP and 636 cal yrs BP.

3 Chapter Three: Methods

3.1 Introduction

The approach of this thesis is part stratigraphic and part modelling. Previous stratigraphic data for Ohiwa Harbour had mostly been obtained from Ohope Spit, but not the adjacent Ohiwa Spit. It is therefore essential that logging and dating of sediment be also carried out on Ohiwa Spit, to confirm and advance knowledge of faulting and other tectonic related events in Ohiwa Harbour. It is postulated that Ohiwa Spit may be located on top of a submerged rock barrier; this would prevent migration of the channel further eastward, and would explain why the harbour entrance is possibly anchored to the position of the palaeo-channel, formed when the harbour was an open valley (Gibb, 1977). This study investigated this hypothesis using sidescan SONAR (SOund Navigation and Ranging) and drilling. Modelling of tidal flows was carried out for the Ohiwa Harbour entrance, in order to assess the response of the harbour to historic tectonic events.

The methods in this study were divided up into field work, laboratory analysis of the samples and numerical modelling. Field work involved vibrocoring, side-scan SONAR survey, and drilling using a trailer mounted rig. Laboratory techniques involved analysing the stratigraphy of sediment in the core by observations, using a laser particle sizer, and carbon dating. Field work and laboratory analysis was carried out to advance the current understanding of Ohiwa Harbour's geological history, and to collect more information for flow modelling. Modelling of the tidal flows and tsunami flows was carried out using the MIKE hydrodynamic model by DHI software. The numerical model was used to assess the flow response to various uplift and subduction tectonic events for Ohiwa Harbour.

3.2 Field Methods

3.2.1 Vibrocoring

Vibrocoring was carried out to sample the subsurface of Ohiwa sand spit. Vibrocoring is a sediment sampling method for collecting continuous, undisturbed cores under the land surface. It can obtain cores from unconsolidated loosely compacted sediment by driving a tube with a vibrating device attached to the tube

(Schwartz, 2005). In this study, vibrocoring was undertaken using 5 m long aluminium tubes, which were attached to a motor (Figure 3.1).

The principle of vibrocoring is transferring a high frequency, low amplitude vibration from the motor through the tube. The vibrational energy induces vertical penetration by temporarily displacing sediment particles, which overcomes frontal resistance and wall friction. As the tube penetrates the sediment, bedded particles are displaced on both sides of the wall, resulting in the collection of a largely undisturbed core of sediment within the tube (Schwartz, 2005). Once the core barrel has penetrated as far as possible, a lifting rig, consisting of a block and tackle, is used to extract the core out of the ground (Figure 3.2). The ends of the cores are tightly sealed with tape to avoid loss of sediment. After the cores were cooled, a saw was used to split the tubes for ease of transport, before they were prepared for laboratory analysis.

Figure 3.1 Vibrocore tube clamped to motor

Figure 3.2 Block and Tackle lifting rig for recovering the core

3.2.2 Drilling

A trailer mounted rig was used to determine the depth of bedrock underneath two beach sites on Ohiwa Spit (D1 and D2). The rig has iron rods attached to it, which are drilled into the sand (Figure 3.3a). More rods are put into the drill as drilling depth increases (Figure 3.3b), and drilling is carried out for as long as possible. Chains anchor the rig into the ground, to prevent the trailer being lifted while drilling. After drilling, the rods are extracted from the ground and measured, to determine drill depth.

Figure 3.3 (a) Trailer mounted rig in preparation (b) Drilling in operation

3.2.3 Side-scan Survey

SONAR equipment was used to search for a reef near the entrance of Ohiwa Harbour; this reef would be evidence of resistant strata that is confining the harbour entrance to its current position. A StarFish 452F side-scan SONAR was used in this study. It works by sending an acoustic signal (ping) to the sea floor, some of which gets reflected back as backscatter (Figure 3.4). As sound travels at a known velocity, we can directly relate the time an echo was received, to the range of the target that reflected it (Tritech International, 2010). The side-scan is directly connected to a computer for display, which stitches together data to get a continuous 2D planar image across a transect line (Figure 3.5). ISIS software is then used to create a mosaic of the different transects produced. Objects which reflect more sound (such as hard rock) show up as dark objects on the display such as the darker area on the left of Figure 3.5, while objects which absorb more sound show up lighter coloured, such as the sand ripple bedforms in the bottom right of Figure 3.5. This is standard approach, but it depends on the contrast of the images also. The white area in the middle of the transect is the water column directly under the sidescan fish, where some reflections from bubbles and suspended sediment are received.

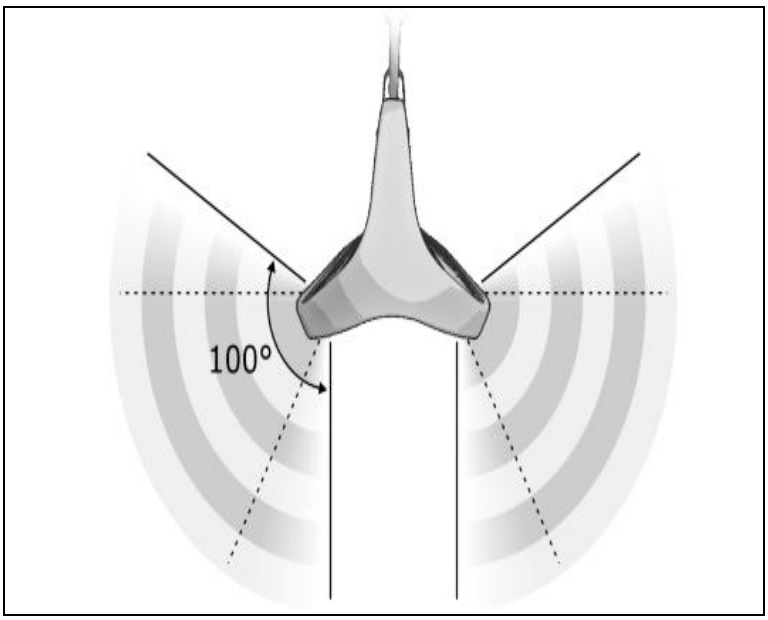

Figure 3.4 Typical Vertical Beam Angles of the Starfish 450F Transducer Head

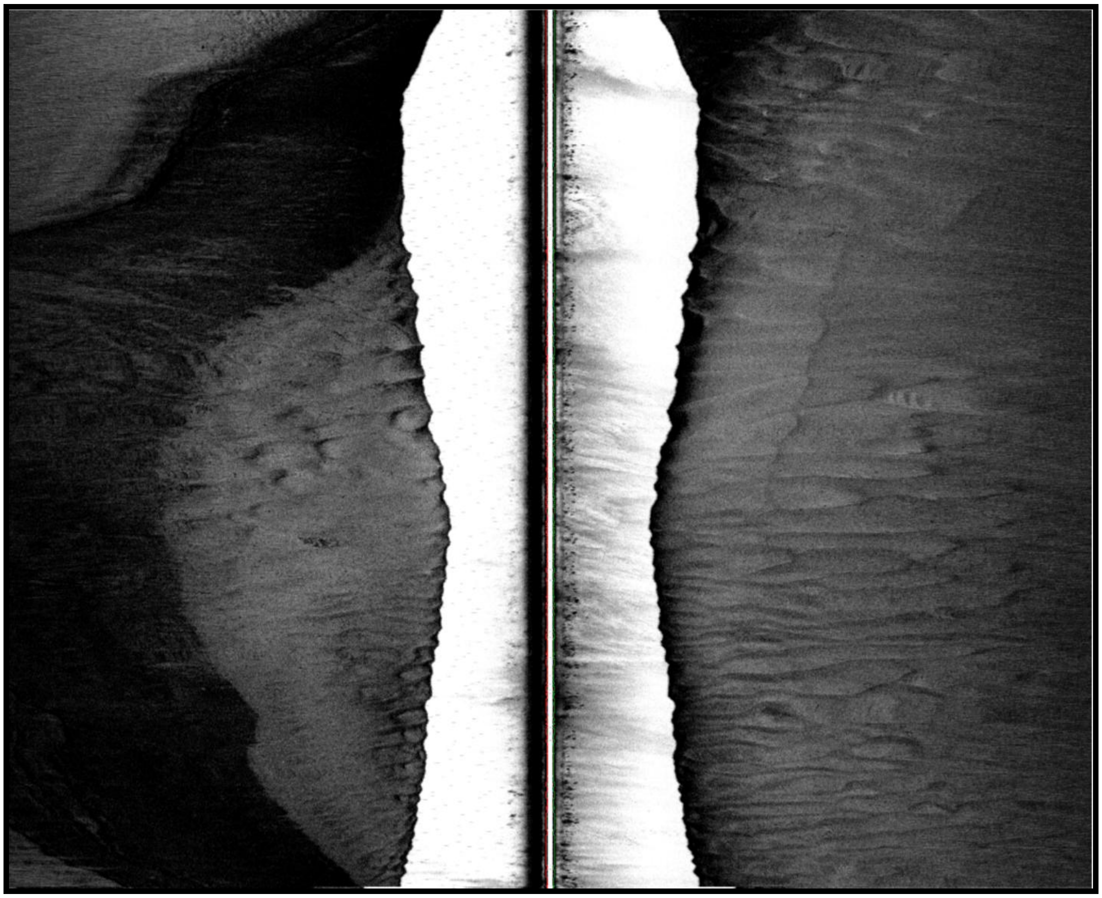

Figure 3.5 Raw data along a transect line from a side-scan survey.

3.3 Laboratory Analysis

3.3.1 Stratigraphy

The aluminium cores were cooled in a fridge before being split open with a saw. Stratigraphy was described by physical observations, which included the following characteristics: sand colour, moisture (loose dry sand versus wet compact sand), presence or absence of shell fragments, presence or absence of wood fragments. Sand color is described using Munsell soil colour charts. Different sand layers were identified, and each layer was photographed, any shells that were found were photographed too (such as in Figure 3.6).

Figure 3.6 Cockles (Austrovenus stuctchburyi) and other shell fragments inside core C.

3.3.2 Organic Content

Organic matter content (percentages) in the sandy cores was estimated using the semi-quantitative hydrogen peroxide method as described in Schumacher (2002). A total of 20 samples from the five cores A, A2, B, C, and C2 were collected and weighed before hydrogen peroxide addition. Each sample was taken from a different layer in the cores to represent variation. Another 20 samples taken from the same location were oven dried overnight at 105 degrees to account for the weight added by moisture content. Once the samples were weighed, 30% hydrogen peroxide was added to each sample in 20 millilitre batches until sample frothing ceased. Hydrogen peroxide was added whenever the sample had dried out and the reaction wasn't complete. Samples were also heated up to 90 degrees on a hot plate to speed up the reaction. After digestion, the samples are dried overnight at 105 degrees, cooled in a desiccator and weighed.

3.3.3 Particle Size Analysis

Detailed analysis of particle size was carried out by a Malvern 2000a particle laser sizer. Sediment samples were collected every 5cm or 10cm depth from the cores collected out in the field. The Malvern sizer sends a laser beam through a lens which gets reflected and refracted by the sediment in water. This reflection of light allows detailed information about particle size distribution to be acquired for each sample.

3.3.4 Radiocarbon Dating

Shell samples (mostly *Austrovenus stuctchburyi*) were collected from the aluminium cores on Ohiwa Spit and carbon dated. Each sample ranged from 20 to 45 grams of shell, and was pre-treated prior to carbon dating. This involved washing the shells in an ultrasonic bath, testing for recrystallization and washing the sample in 2M dilute hydrochloric acid. Carbon dating results give conventional age following Stuiver and Polach (1977). Sample sites are shown in Table 3.1.

Table 3.1 Location and Radiocarbon numbers for samples collected on Ohiwa Spit

Grid Reference (UTM-60)	Waikato laboratory number (Wk)	Depth (m)
5794447S 513590E	31477	1.28 to 1.38
5794447S 513590E	31478	1.73 to 1.83
5794453S 513602E	31479	1.2 to 1.4

3.4 Modeling

MIKE by DHI is software used for hydrodynamic modelling. It was used for Ohiwa Harbour to assess the response of the harbour to tectonic events. Hydrodynamics is the study of fluid flow behaviour, which in this study is tidal flow. The two main steps involved in DHI modelling are creating bathymetric grids and running the model with desired parameters.

3.4.1 Bathymetric Grids

First, a bathymetric grid of Ohiwa Harbour was constructed in MIKE Zero (Figure 3.7). Finite difference modelling was used for this study, so the domain was divided up into smaller regions, which are defined by fixed differences in space (dx, dy, dz) and time (dt). These dimensions are constant in a finite difference model, making each region rectangular. Within each region, there is information about surface elevation (for land) or water depth. In order for the grid to be constructed, hydrographic charts were digitised using the NZMG (New Zealand Map Grid) projection. Flow modelling measures the responses of water currents and surface elevation to the bathymetry, not the other way round; this means that different grids were constructed for different tectonic scenarios (uplift and subsidence).

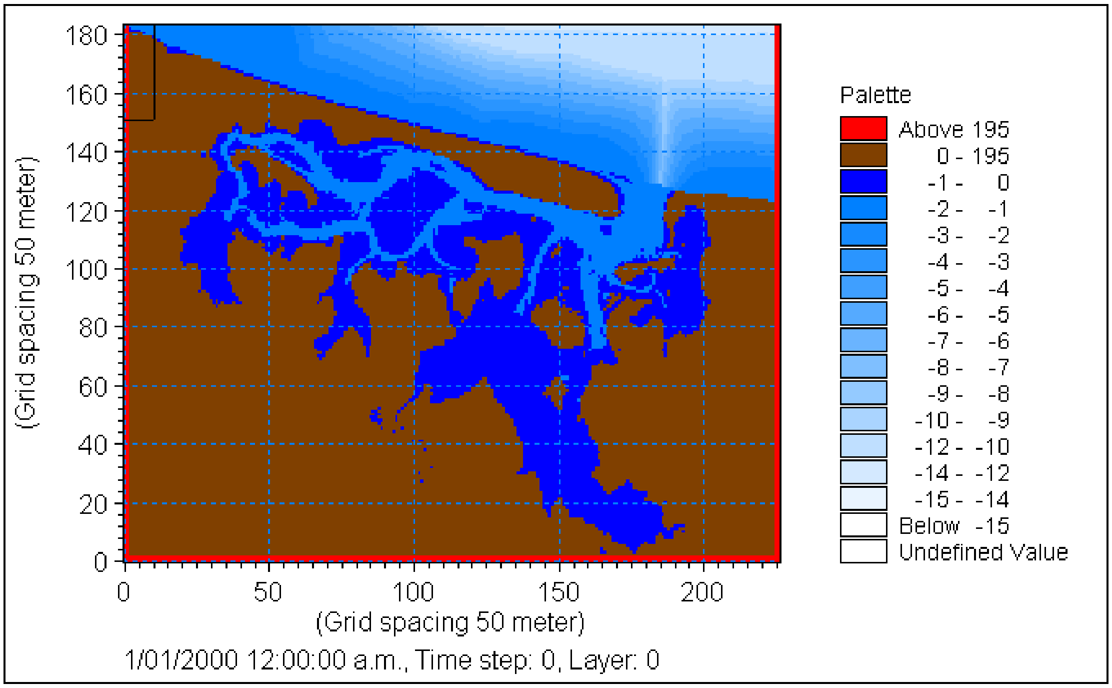

Figure 3.7 Bathymetric grid of Ohiwa Harbour in MIKE Zero.

3.4.2 Flow Modelling

MIKE by DHI has a flow model program (MIKE 21 Flow Model) that models sea-surface elevations and current velocities in 2D, for the bathymetric grids previously constructed. The model boundary conditions were forced at the northern boundary of the grid, and were forced in one of two ways. First a sine series wave was forced at the boundary, which had parameters based on known tidal amplitudes and periods for Ohiwa Harbour. Then, actual tidal data provided by NIWA was forced at the northern edge of the grid. Drying depth and flood depths were applied in this model, because a large proportion of the harbour is tidal flats that are dry at low-tide. These depths are the minimum values water can reach before it is taken out of calculation, and re-entered into calculation in each grid cell respectively. Time series data and animated flows of tidal currents were of interest when doing flow modelling.

4 Chapter Four: Sediment Core Samples and SONAR in Ohiwa Harbour

4.1 Introduction

This chapter describes the results obtained from vibrocoring and drilling on Ohiwa Spit, as described in Chapter 3. SONAR (Sound Navigation And Ranging) results are also displayed here. Vibrocoring produces undisturbed cores of sediment a couple of metres long. In this chapter, the general composition of the cores, and results obtained from carbon dating shell samples within the cores are included. Stratigraphic logging of the cores, sediment grain size analysis and a quantitative analysis of organic content are used to yield information on the composition within the cores. Data obtained from vibrocoring will ideally advance on current knowledge of the geological evolution and coastal history of Ohiwa Harbour. SONAR produces images of the sea floor within the harbour entrance in order to identify any outcropping rock that has anchored the harbour entrance to its current position.

4.2 Composition of the Sediment Core Samples

4.2.1 Core Logging

Vibrocoring using aluminium cores has previously been carried out on Ohope Spit by Murdoch (2005). The contents of the cores were analysed in order to construct a geological history of the sand spits within Ohiwa Harbour. However, Murdoch did not carry out vibrocoring on the neighboring Ohiwa Spit, which may have undergone a different evolution to Ohope Spit. In this study, five locations at Ohiwa Spit were vibrocored, and two locations were drilled (Figure 4.1).

Almost all of the sediment collected was sandy according to the Wentworth Scale, within the size range 0.063mm to 2mm. Sand color was described using Munsell soil colour charts, mostly revealing shades of grey and black sand, dependant on the shell content within the sand. Some of the cores (A2 and B) were not able to be driven much further than 1 m, so the information obtained from them is limited. A possible reason for this is that the vibrocoring equipment reached impenetrable bedrock which could be underlying Ohiwa Spit. This explanation holds some weight as cores A2 and

B are in close proximity to a rock outcrop (Figure 4.12a). The trailer mounted rig (see Chapter 3) managed to drill to 7.9m and 6.4m depth at sites D1 and D2 respectively, before reaching an impenetrable surface (Figure 4.1). The other cores (in particular C and C2) contained wood fragments, organic matter and a variety of shell material. Fragments of shells were found throughout all cores, however complete shells were abundant at the 1.4 to 1.5m depth mark in cores C and C2. The dominant shell species found were cockles (*Austrovenus stutchburyi)*, but mussels, paua and wheel shells were found also. Composition of the Ohiwa Spit cores is shown in Figures 4.2 and 4.3. More information about Ohiwa Spit could be obtained by vibrocoring on Tern Island and at greater depths where possible. Vibrocoring on Tern Island may require a low impact resource consent from Bay of Plenty Regional Council, depending on the coring location. The top of each core is located close to mean sea level for most cores, so a direct comparison can be made. The exception is core B, which was collected from an elevated dune (Figure 4.1).

Figure 4.1 Vibrocoring locations (yellow pins) and drilling locations (blue arrows) on Ohiwa Spit in Ohiwa Harbour.

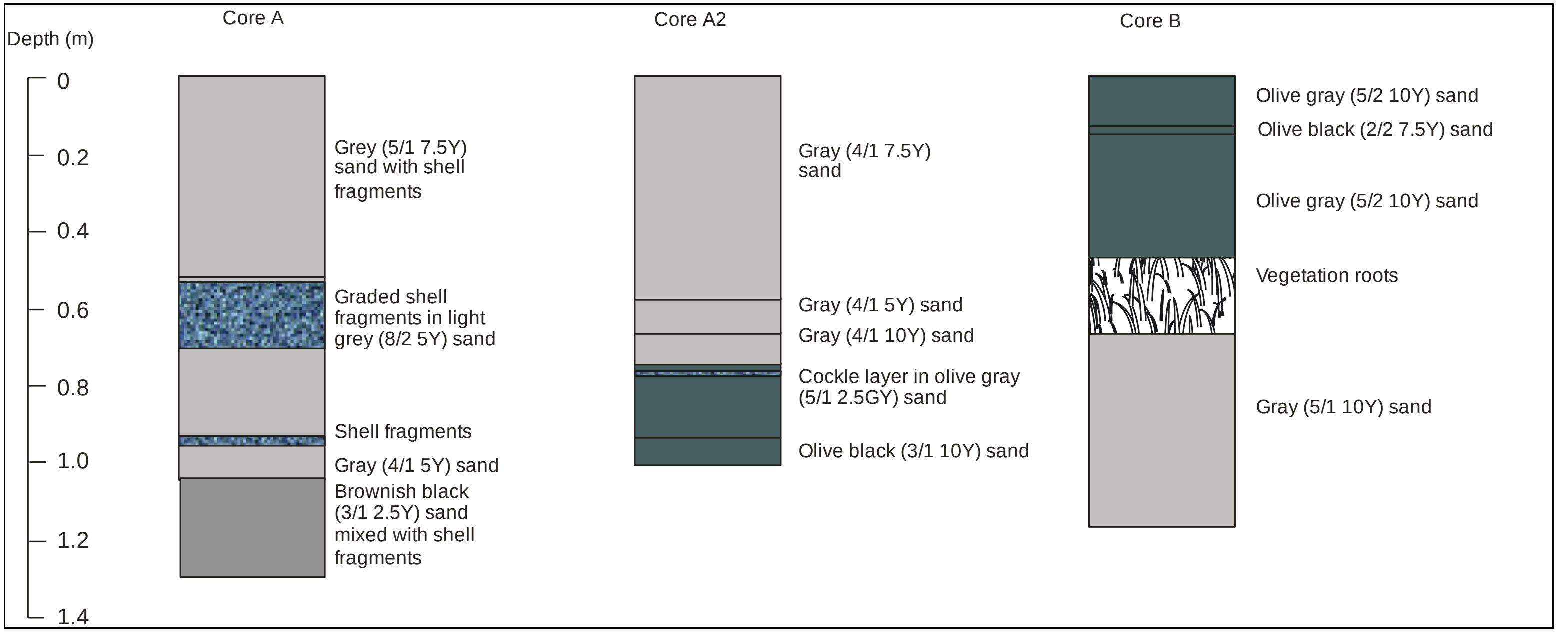

Figure 4.2 Stratigraphic Columns of Cores A, A2 and B on Ohiwa Spit.

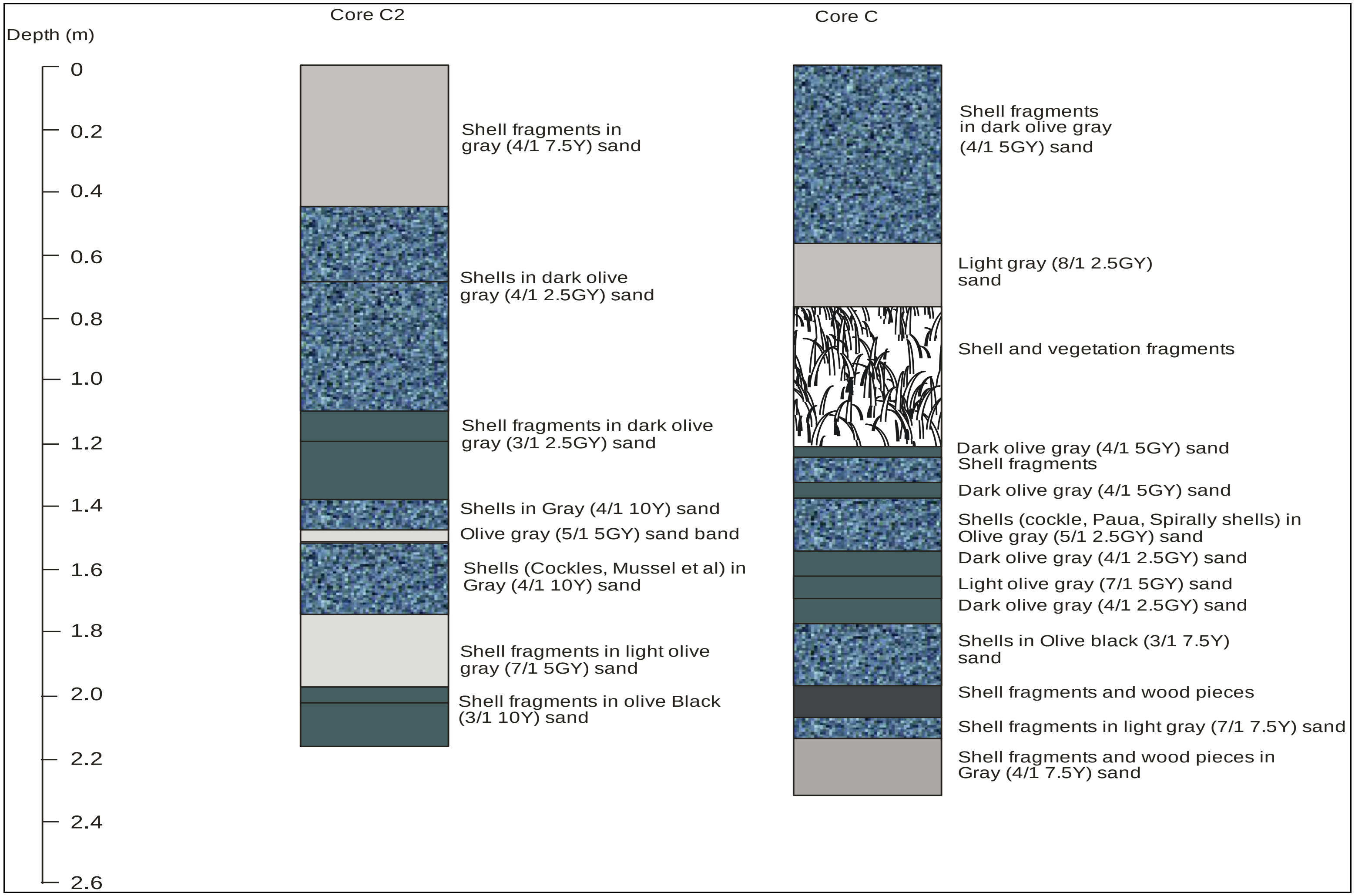

Figure 4.3 Stratigraphic Columns of Cores C and C2 on Ohiwa Spit.

4.2.2 Carbon Dating

Austrovenus stutchburyi was carbon dated in cores C and C2, using the methods described in Chapter 3. One sample of shells was dated from core C at a depth of 1.2 to 1.4m (Wk 31479), while two samples were dated from core C2, at depths of 1.28 to 1.38m (Wk 31477) and 1.73 to 1.83m (Wk 31478). These shells were chosen for carbon dating because they have a short life span, and mostly remain in their environment of deposition, giving them a reliable age. Samples are dated within these cores so that age comparisons between other cores in Ohiwa Harbour can be made; this can be used to infer subsidence.

Table 1 compiles radiocarbon dated material results from a previous study on Ohope Spit (Murdoch, 2005) with this study. Table 2 lists known subsidence events which can be used to compare and analyse dated material. Wk31478 fits well with Murdoch's data when considering depth and age (older samples at greater depths). However, Wk31477 and Wk31479 have much younger ages than expected (at greater depths). This suggests that additional subsidence has occurred by faulting on the Ohiwa Spit side of the harbour, which hadn't previously been accounted for. SONAR within the harbour entrance could reveal some of these faults. More shells at different locations may need to be dated on Ohiwa Spit and at greater depths also. Age comparisons are illustrated in Figure 4.4.

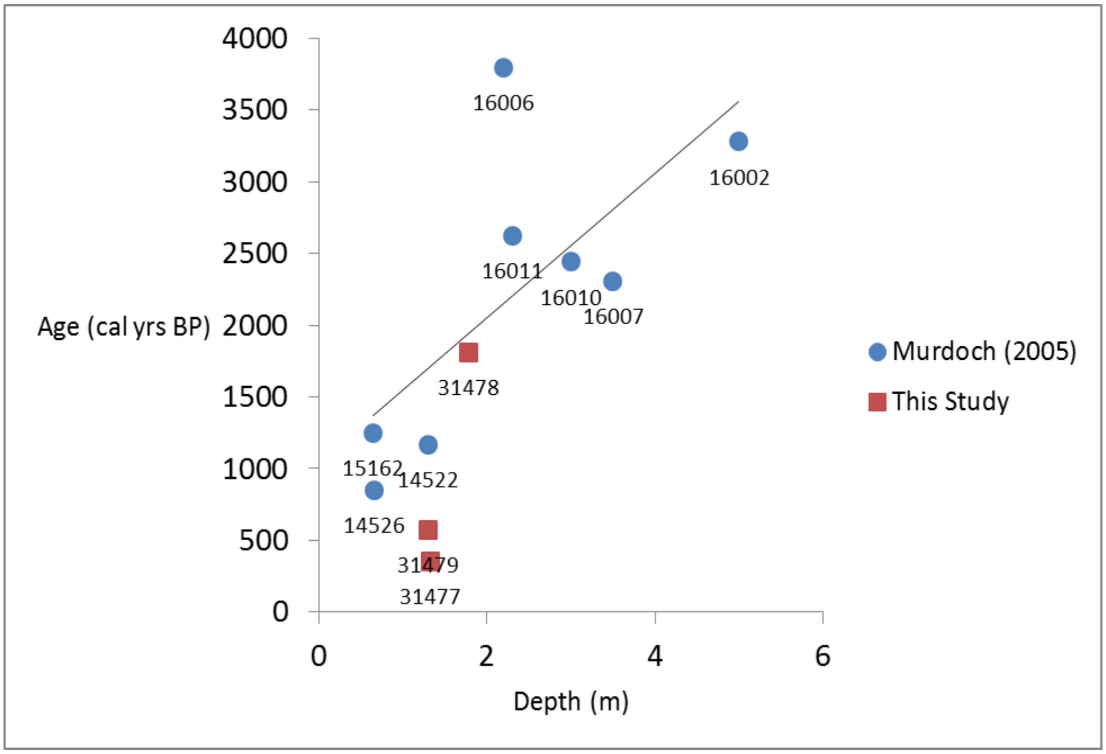

Figure 4.4 Age versus depth plot of radiocarbon material from Table 4.1. Numbers represent Waikato lab number (Wk); line represents a trend line for samples dated by Murdoch (2005). Ages are given in conventional radiocarbon age.

Table 4.1 Ages from radiocarbon dated wood, roots and shells on Ohope Spit and Uretara Island (adapted from Murdoch, 2005) and this study (highlighted in bold).

Sample material	Waikato lab number (Wk)	Age (^{14}C yrs B.P)[1]	Age(cal yrs B.P)[2]	Depth (m)
Totara wood	14523	226 +/- 37	430 to present	Above sea level
Totara root	15162	1251 +/- 36	1270 to 1060	0.6 to 0.68
Rushes	14526	853 +/- 62	920 to 660	>0.66
Totara stump	14522	1166 +/- 30	1180 to 970	1.15 to 1.45
Open water shell	16006	3798 +/- 39	4360 to 4000	2.1 to 2.3
Estuarine shell	16011	2624 +/- 39	2850 to 2610	2.2 to 2.4
Open water shell	16010	2440 +/- 44	2720 to 2350	3
Open water shell	16007	2305 +/- 50	2470 to 2150	3.3 to 3.7
Open water shell	16002	3278 +/- 38	3640 to 3390	5
Estuarine shell	**31477**	**356 +/- 42**	**248 to present (mean 207)**	**1.28 to 1.38**
Estuarine shell	**31478**	**1809 +/- 37**	**1563 to 1321 (mean 1428)**	**1.73 to 1.83**
Estuarine shell	**31479**	**571 +/- 41**	**386 to present (mean 257)**	**1.2 to 1.4**

[1] Conventional Radiocarbon age

[2] Two standard deviations from mean (95.4% probability)

Table 4.2 Known subsidence events within Ohiwa Harbour (adapted from Murdoch, 2005).

Subsidence events			
Cal Yrs BP	Subsidence (m)	Notes	Reference
84	0.3-0.7	Possibly from 1866 Taneatua Earthquake	Hayward et al (2004)
636 to 575	0.6	Subsidence of Waimana Fault	Murdoch (2005)
1718 to 1110	2	Possible 2m subsidence from earthquake 1110 yrs BP	GeoEnvironmental Consultants (2003)
1718	2.5-3	Movement of Waimana Fault (1718 to 1110)	Murdoch (2005)
2339	Unknown	East coast subsidence	Murdoch (2005)
2600	2-2.4	-	Hayward et al (2004)

4.2.3 Sediment Analysis

A Malvern 2000a particle laser sizer was used to determine grain size distribution and statistics within the cores. Sand samples were taken from each core at even intervals, at every 5cm or 10cm depth. A total of 119 samples were analysed from all five cores on Ohiwa Spit. Grain size statistics for each core are summarised in Table 4.3. Statistics were calculated by averaging all of the statistics for each sample within each core. These statistics summarise the bulk grain size properties within each core (including mean, median and standard deviation). Vertical profiles are often of importance when studying coastal sediment, as they can convey variations in grain sizes due to changes in wave energy and sediment supply in the past; this is of interest when studying hydrodynamics or coastal morphology. Grain size profiles of the cores are plotted in Figures 4.5 and 4.6.

Table 4.3 Summary statistics and uniformity for sandy sediment within the Ohiwa spit cores. All units are given as microns (besides skewness and uniformity which are dimensionless).

Core	d(0.1)[1]	d(0.5)[2]	d(0.9)[3]	Mean grain size	Standard deviation	Skewness	Uniformity[4]
A	200.80	328.92	538.67	352.58	133.86	0.85	0.32
A2	183.83	301.10	493.51	322.88	122.74	0.86	0.32
B	158.86	238.27	358.19	250.27	79.14	0.77	0.26
C	119.68	210.46	435.67	249.57	142.96	1.37	0.54
C2	128.97	221.97	391.36	249.19	129.64	1.65	0.40

[1] Diameter which is larger than 10% of all grains

[2] Median grain size

[3] Diameter which is larger than 90% of all grains

[4] Absolute deviation of grain sizes from the median grain size. A uniformity of 0 indicates uniform sediment sizes.

Using the information from Table 4.3 and Figure 4.1, an apparent trend of decreasing grain size closer to the tip of Ohiwa Spit is revealed. Core A has the largest grains overall, and cores C and C2 have the smallest grains overall. The last three cores don't have significant differences in mean grain size however, although the spread of grain sizes varies. Uniformity is close to zero in all cores; this is because the bulk of the sediment is sand, with negligible amounts of silt or clay. In all cores, grain size is positively skewed.

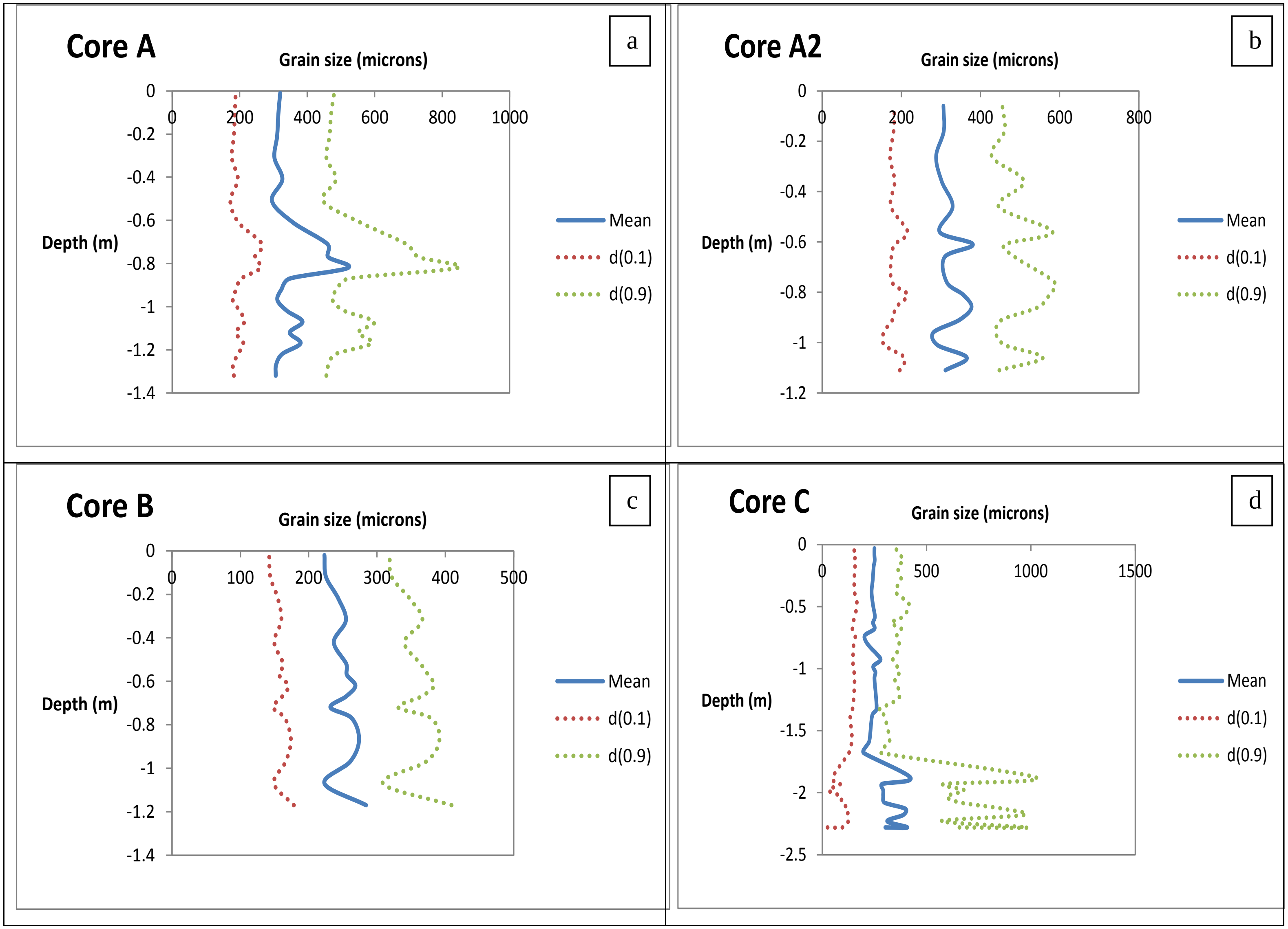

Figure 4.5 Vertical grain-size profiles within the cores. d(0.1) and d(0.9) represent the grain diameters which are greater than 10% and 90% of all the grains in the cores respectively.

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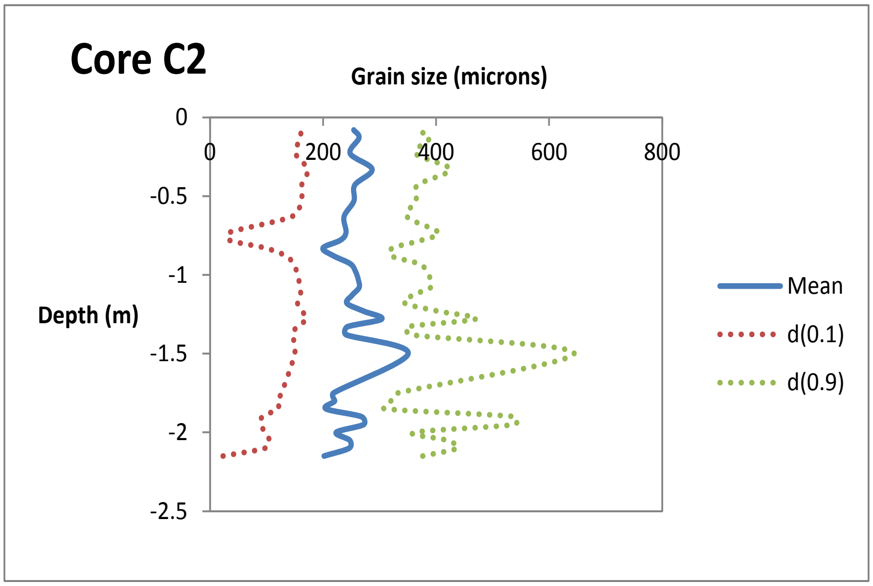

Figure 4.6 Vertical grain-size profile of core C2.

Analysis of the core profiles in Figures 4.5 and 4.6 reveals that mean grain size is around 200 to 300 microns most of the time within all cores, however the size variation and profiles between cores is somewhat different, which is to be expected. Cores A2 and B have a uniform variation of grain size throughout the cores, but with a couple of spikes where grain size increases (0.6m, 0.9 and 1.1m depth in core A2); this difference in grain-size may not be outside the range of normal variation however. Cores A and C2 have sections where the mean grain size and variation increases significantly. At core A this occurs at 0.6 to 0.9m depth; mean grain size increases by up to 50%, and grain size variation almost doubles. At core C2, this is at 1.5m depth; mean grain size increases by up to 40%, and grain size variation also almost doubles. Core C is the deepest core, revealing an increase in mean grain size and variation after 1.6m, the latter more than doubles. These sudden changes in grain size suggest there was a change in wave energy or current velocity when this sediment was deposited, a larger grain size indicates increased wave energy, and possibly increased sediment supply.

4.2.3.1 Prehistoric Interpretation of Core Profiles

Given that numerous subsidence events have occurred within Ohiwa Harbour during the last 7.ky, it would not be surprising if some of these events generated tsunamis within the harbour, and that these tsunamis could be identified in sediment core proxies. GeoEnvironmental Consultants (2003) had previously collected cores from Ohiwa Harbour at Stoney Brook. They identified certain proxies such as sharp changes in grain size, chaotic units with shell hash, peak concentrations in diatoms (in particular those found outside their normal environments) and changes in geochemical signatures (such as increased salinity). Some of these proxies may be applied to the cores in this study, but difficulty arises in distinguishing tsunami inundation with storm events, both of which would modify the sediment considerably. Figures 4.7 to 4.11 show the changes in organic matter composition, along with the mean grain size profiles from Figures 4.5 and 4.6; the presence of shelly material is also labeled. The information conveyed in Figures 4.7 to 4.11 may be of use in identifying prehistoric tsunami within Ohiwa Harbour, or at least useful for determining how the harbour hydrodynamics have changed. Because tephra wasn't analysed, it is difficult to characterize any of the depositional events as volcanic in origin, which they may be in some cases.

Core A (Figure 4.7) shows a fining upward coarse sand sequence at 0.6 to 0.9m depth. Within this sequence there are graded shell fragments, which increase in concentration toward the bottom. This sequence may be associated with increased wave energy from a storm event. Organic content is slightly higher in this sequence than the rest of the core. Core A2 (Figure 4.8) which was nearby however, showed no significant variation in grain size and organic matter with depth. Core B (Figure 4.9) shows no significant variation in grain size with depth, but there is a decrease in organic content. Vegetation roots found are possibly from the dune plants (spinifex) growing on a dune found there. Working upwards, Core C (Figure 4.10) shows medium sand with shell and wood fragments at depths greater than 2m, with a fining upwards sequence at approximately 1.7 to 2m depth. This sequence contained whole cockle (Austrovenus stutchburyi) shells, suggesting it is related to a storm event or possibly tsunami inundation. The rest of this core shows fine sand with shell fragments spread throughout the core. Core C2 (Figure 4.11), shows two distinct patterns where average grain size decreases (0.7 to 1m depth) and increases significantly (1.4 to 1.8m depth). In both those locations, shelly material is found, being indicative of a storm event or tsunami inundation. Organic content gradually decreases in C and C2 with depth, until after 1.5m depth where it increases significantly (Figures 4.10 and 4.11).

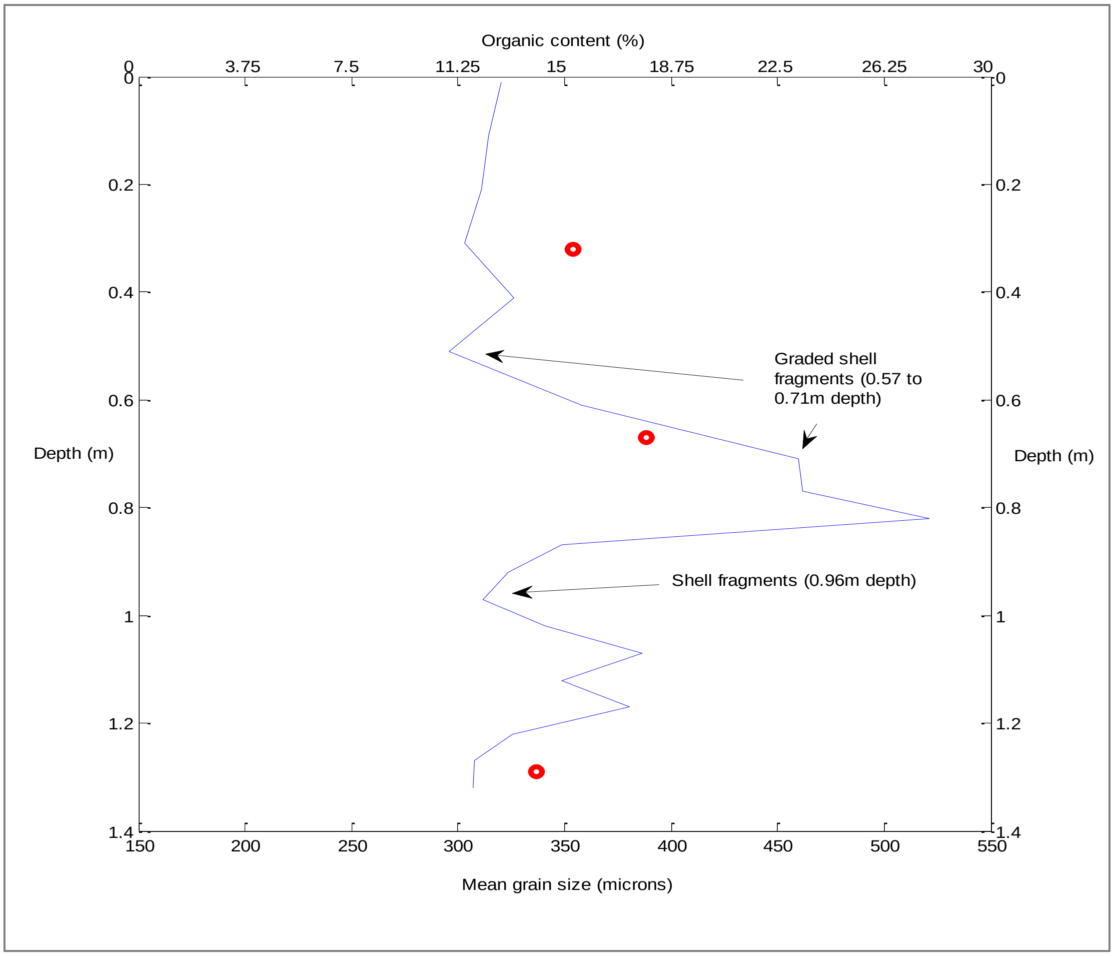

Figure 4.7 Grain Size, organic content and shelly material within Core A; Mean grain size (blue line), organic content (circles).

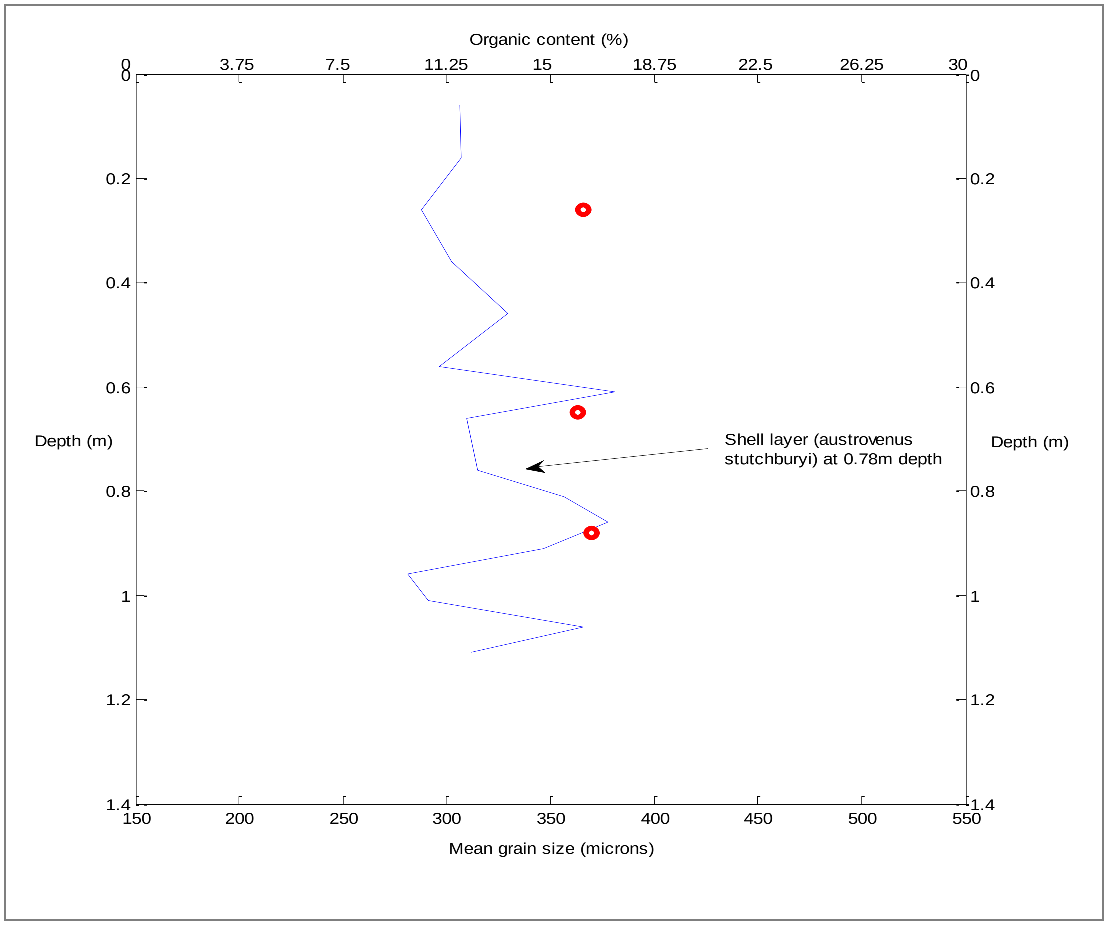

Figure 4.8 Grain Size, organic content and shelly material within Core A2; Mean grain size (blue line), organic content (circles).

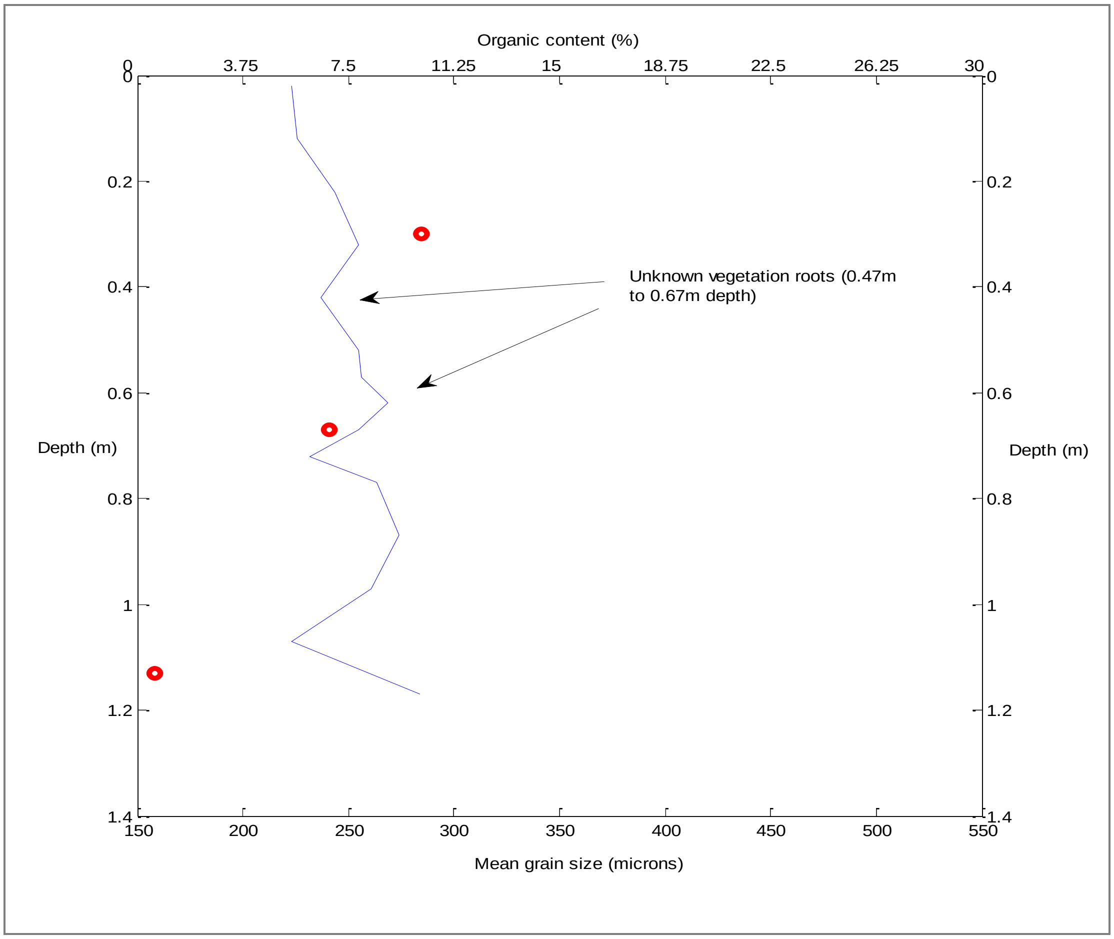

Figure 4.9 Grain Size, organic content and shelly material within Core B; Mean grain size (blue line), organic content (circles).

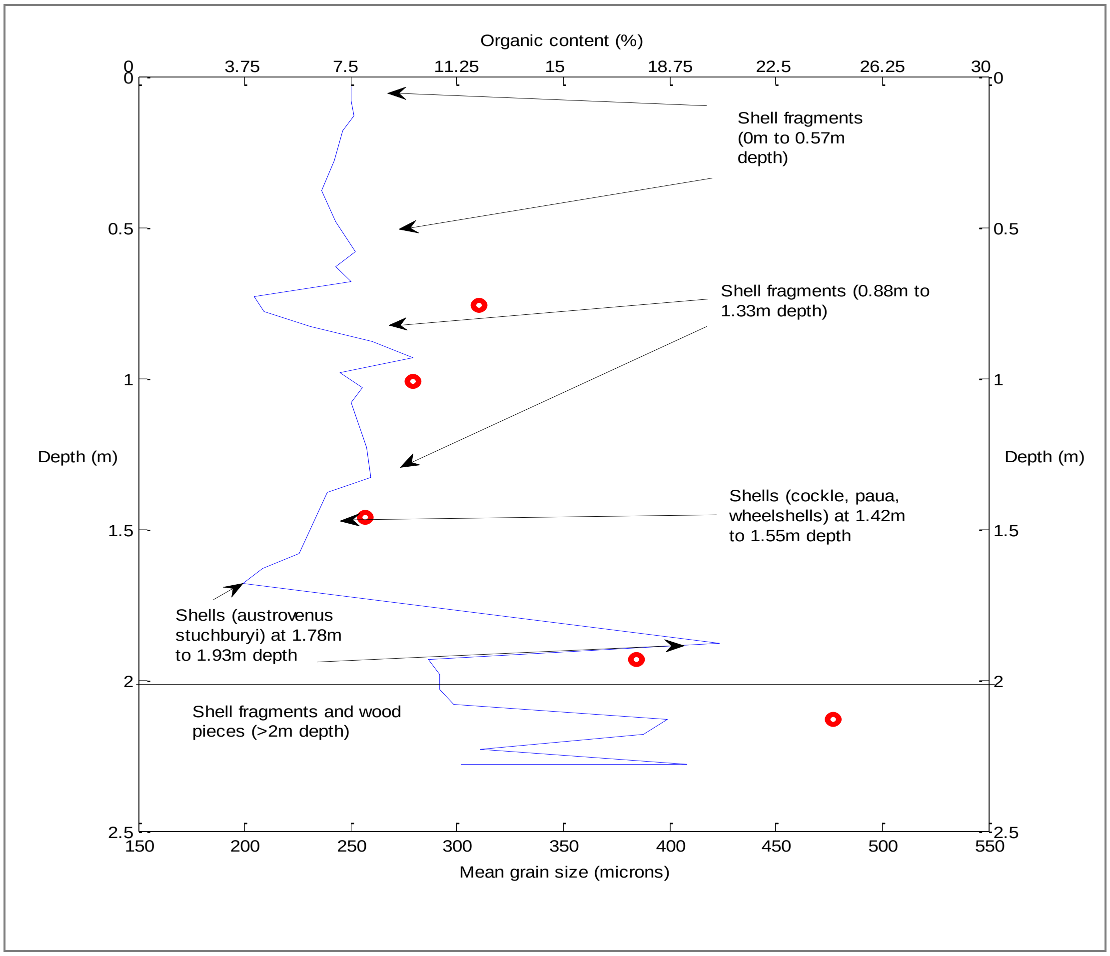

Figure 4.10 Grain Size, organic content and shelly material within Core C; Mean grain size (blue line), organic content (circles).

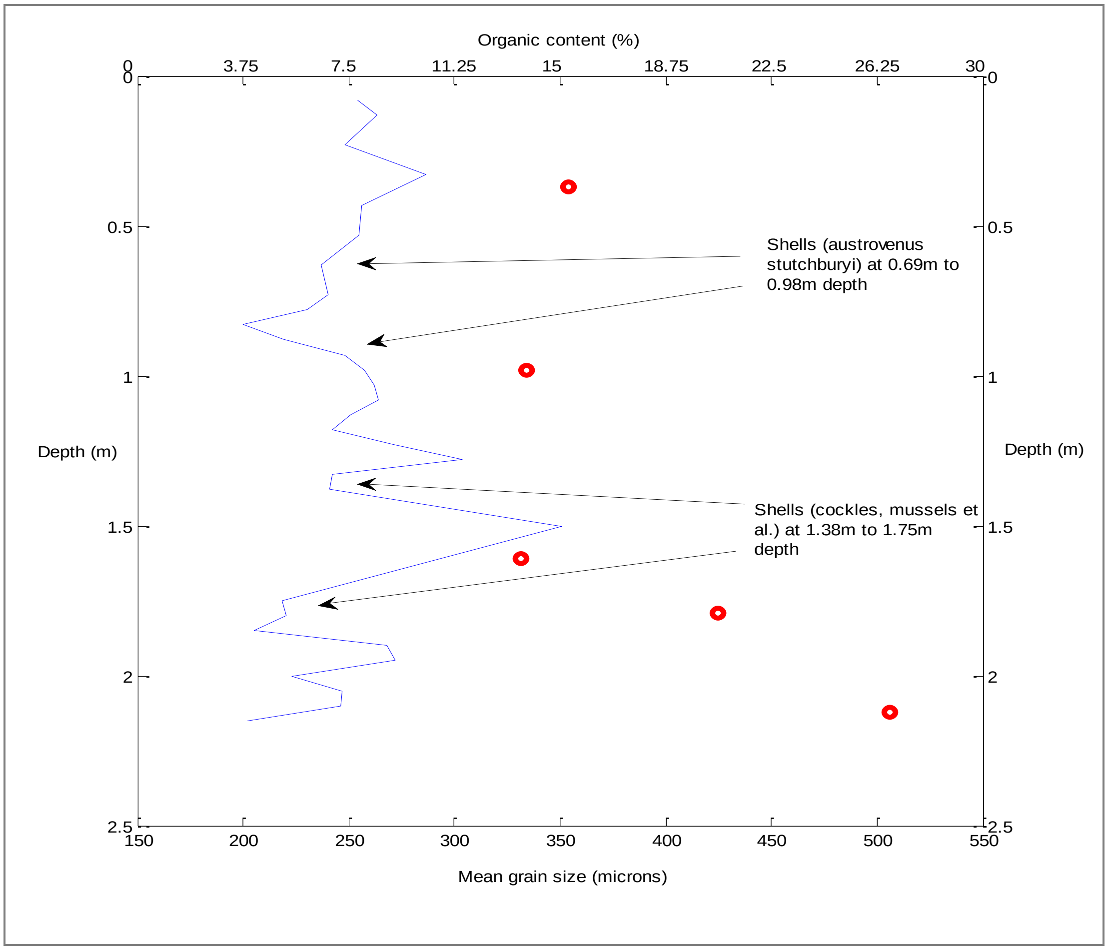

Figure 4.11 Grain Size, organic content and shelly material within Core C2; Mean grain size (blue line), organic content (circles).

4.2.4 Drilling on Ohiwa Spit

A trailer mounted rig was deployed on Ohiwa Spit to determine the depth of possible bedrock underneath the spit there (see Figure 4.1 for location). Table 4.4 shows the drill depths where an impenetrable surface was reached on Ohiwa Spit. These depths are somewhat greater than the lengths of the sediment cores from vibrocoring, but vibrocoring had a number of limitations in this study (see Chapter 6.1.1).

Table 4.4 Location and depth drilled on Ohiwa Spit, using a trailer mounted rig.

Site Name	Grid Reference (UTM-60)	Drill depth (m)
D1	5795080S 513512E	7.9
D2	5795080S 513497E	6.4

4.3 Side-Scan Survey (SONAR) in Ohiwa Harbour Entrance

SONAR equipment was deployed out at the harbour entrance to determine if any bedrock outcrops are present that could be confining the entrance to its current position. Eight transects were run within the entrance during this survey, using a Starfish 452F side-scan SONAR. After the survey was carried out, the overlapping transects were analyzed for possible bedrock. Dense objects such as rock reflect more sound than the surrounding objects, and show up as dark objects in the transects. Side-scan systems originally used thermal paper that burnt an image. The stronger the reflection signal, the greater the current through the stylus, and hence the darker that portion of the image is. Digital displays (such as the one in this study) were set up to replicate the thermal paper because of military requirements. A dark object interpreted as bedrock showed up in seven out of the eight transects, and there was considerable overlap. The bedrock was digitized over the transects in Google Earth, and revealed as a thin strip of rock near the eastern edge of the entrance (Figure 4.12). The approximate location of this strata is 512847E, 5794412S (southern end); 513451E, 5795138S (northern end) in UTM zone 60 south. It should be noted that these co-ordinates are approximate due to the transects not being mosaicked prior to digitizing. Refer to section 3.2.3 and Figure 3.5 for the methodology and a sample sonagraph.

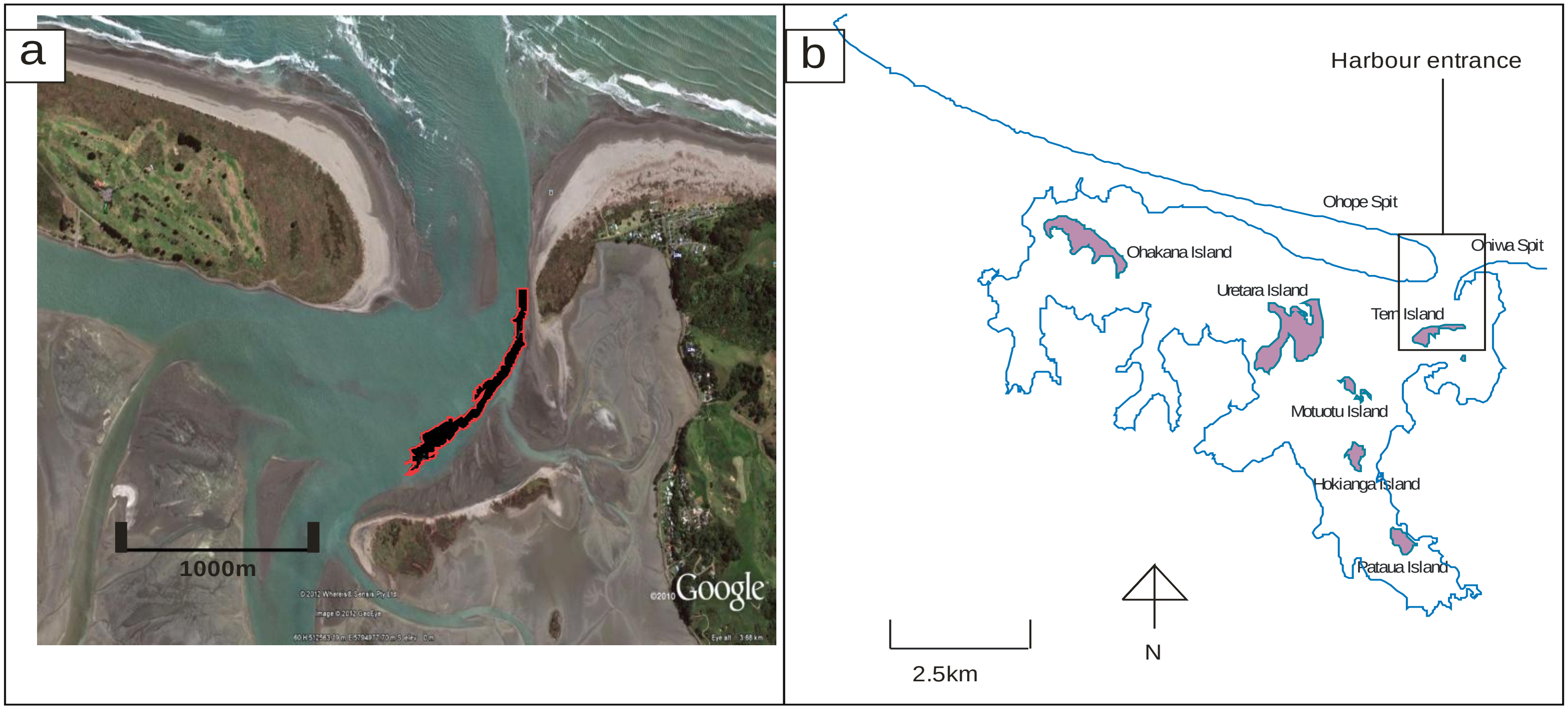

Figure 4.12 (a) Location of possible strata within Ohiwa Harbour entrance (outlined in red). (b) Location where side-scan was deployed.

4.4 Summary

Five aluminum cores of sediment were collected on the subsurface of Ohiwa Spit, to advance on current knowledge of the historical and pre-historical evolution of Ohiwa Harbour. These cores ranged from 1m to 2.4m long and contained shelly sand, wood material and some organic matter.

Austrovenus stutchburyi was carbon dated in cores C and C2 at various depths. Comparison of carbon dated shells in this study with Murdoch (2005) showed younger ages of shelly material at Ohiwa Spit compared to similar depths reported for Ohope Spit. This indicates that Ohiwa Spit is much younger than Ohope Spit and that additional subsidence may have occurred on Ohiwa Spit which has not previously been accounted for.

Grain size profiles were constructed for each core, showing variation in grain size, organic content and shelly material with depth. These profiles can be used to infer subsidence or changes in the harbour hydrodynamics, but it is difficult to infer tsunami inundation. Cores A, C and C2 had fining upwards coarse sand sequences with shelly material dominant in the sequences, indicating changes in the harbour hydrodynamics. Cores A2 and B however showed no significant variation in grain size with depth. There was no common trend in organic matter with depth.

Constraints on the vibrocoring depths suggest that bedrock is found underneath Ohiwa Spit and near the entrance, which is confining the harbour entrance in its place despite severe erosion. SONAR within the harbour entrance strongly suggests that submerged strata towards the eastern entrance are confining it.

5 Chapter Five: Hydrodynamic Modelling of Ohiwa Harbour

5.1 Introduction

This chapter describes the hydrodynamics within Ohiwa Harbour determined by MIKE 21 flow model software. Of particular interest was the response of the harbour hydrodynamics to past tectonic events in Ohiwa Harbour. Murdoch (2005) created an evolutionary model of the Holocene development for Ohope Spit, based on tephra distributions and radiocarbon dating of sediment cores. A combination of climate, tectonic events and sea-level changes in response to sediment supply has modified the harbour morphology during the Holocene. The models in this chapter used bathymetric grids of Ohiwa Harbour which were modified to reflect the changes postulated by Murdoch (2005), particularly the impacts of subsidence and uplift along the major faults intersecting the coast near Ohiwa Harbour.

5.2 Flow modeling

Sea surface elevation and horizontal current velocities (u and v) were of interest in flow modeling. These were output as time series sampled at 1.5 minute intervals at different locations within the harbour (Figure 5.1) to see the variation of flow within the harbour. Spatial variation of harbour hydrodynamics was represented as contour and vector plots produced by DHI Plot Composer (Figure 5.2). Different Ohiwa Harbour grids were constructed for major events which have changed the morphology of the harbour, and its hydrodynamics. The major events included tectonic subsidence, which altered the depth of the harbour and temporarily increased the tidal volume, possibly breached the sand spits from tsunamis and resulted in the diversion of the main fluvial input (Waimana River), and volcanic eruptions, which have supplied sediment to the harbour and sand spits. Figure 5.1 shows the original grid for the present day scenario, which was constructed by Hansford (2006). The rest of the grids in this chapter were developed from the Hansford (2006) grid by this study. All simulations were run from a cold start with an initial surface elevation of -0.95m across the entire domain, and no horizontal tidal currents. Therefore, the first few tidal cycles were ignored, starting at time step 1500.

5.3 Model output

5.3.1 The present-day scenario

The surface elevation shows a strong tidal signal at virtually all locations (Figure 5.1) with time; reflecting the strong influence of tides on the estuary hydrodynamics (>99%). Freshwater from rivers makes up <1% of the tidal prism in the harbour. In Ohiwa Harbour, sea-surface elevation reaches a maximum of approximately 1 m above mean sea-level; this only takes into account the M_2 tides however, and no other tidal constituents or storm surges. The maximum spring tidal range is approximately 2 m at the harbour entrance, making the estuary macro-tidal to meso-tidal in range. Further away from the harbour entrance, the surface elevation and tidal range decreases (Figures 5.1 and 5.4). The mudflat locations have partially flat time series because they completely dry out during low-tide (Figure 5.5).

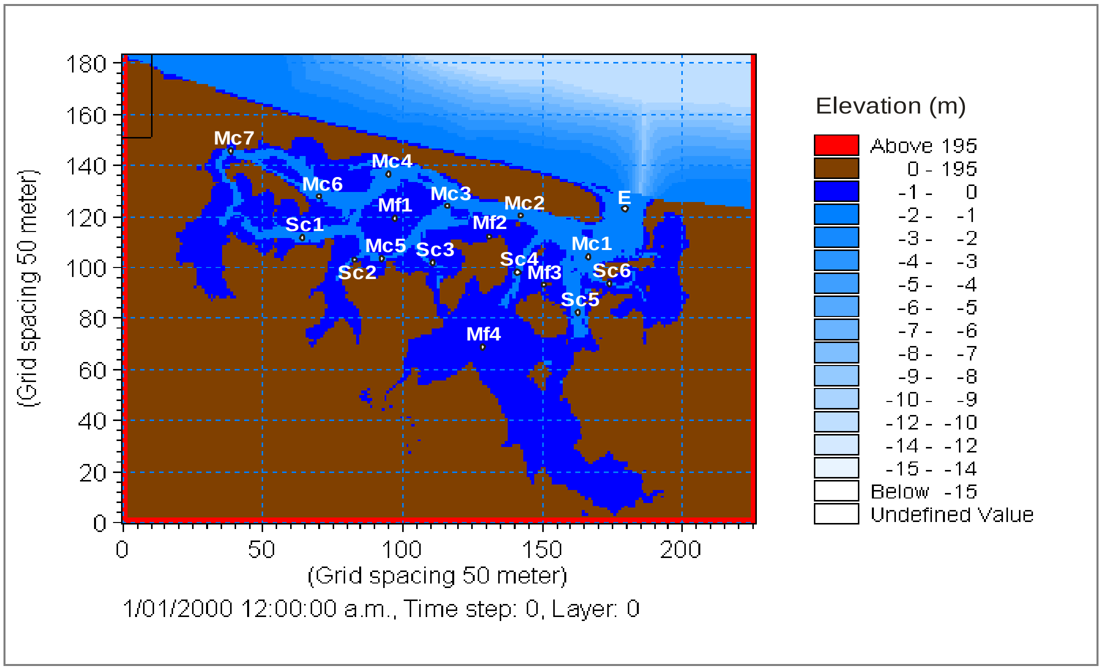

Figure 5.1 Locations of time series extraction sites within Ohiwa Harbour referenced within the text. E=harbour entrance; Mc=main channel, Sc=small channel; Mf=mudflat.

5.3.1.1 Harbour entrance

Flow velocities are strongest at the harbour entrance (site E), being up to 0.6m.s^{-1}. The direction of the current is determined by the tide direction at the entrance (Figure

5.2). The strength of the tidal current depends on the surface elevation of the water, being larger during spring tides. However, there is a time lag between current strength and surface elevation in Figure 5.3. Current strength is also stronger where flow is constricted, in order to conserve momentum of the water; this can be seen in Figure 5.2. Maximum flows are recorded at Mc2 and the harbour entrance. At Mc2, maximum flood and ebb flows are $0.49 m.s^{-1}$ and $0.43 m.s^{-1}$ respectively; at the entrance maximum flood and ebb flows are $0.53 m.s^{-1}$ and $0.58 m.s^{-1}$ respectively. Maximum current strength is much larger at the entrance than anywhere else because it is constricted; this should mean that the most erosion would occur at the entrance, but Murdoch (2005) showed that the position of the harbour entrance has remained largely stable for the past 7000 years, despite small fluctuations east-west. The stability of the entrance is presumably related to the rock outcropping on the eastern margin of the channel. Further away from the entrance, current strength quickly decreases down to less than $+/-0.1 m.s^{-1}$ at Sc1 to Sc3, and Mc6. Current strength doesn’t decrease where flow is constricted into narrower channels however (Figure 5.2).

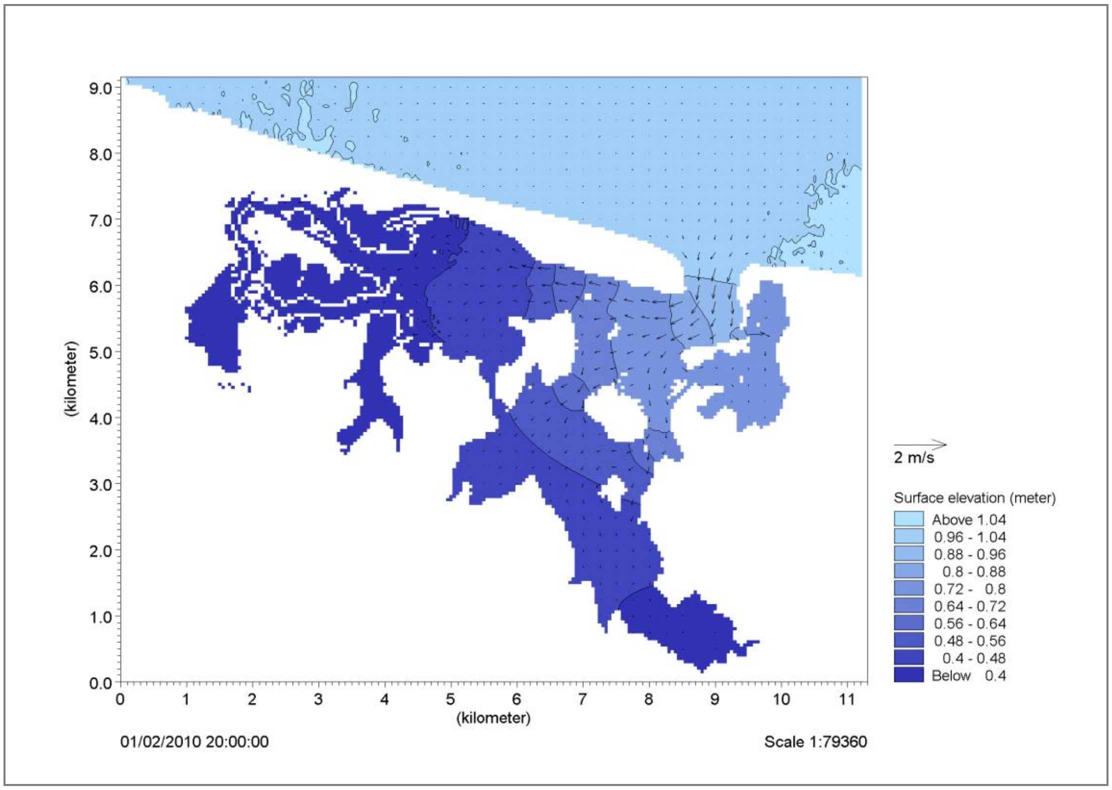

Figure 5.2 Peak flood flows into Ohiwa Harbour for the present-day scenario. Surface elevation is metres above mean sea level; arrows depict the strength of the current. Source: plot composer.

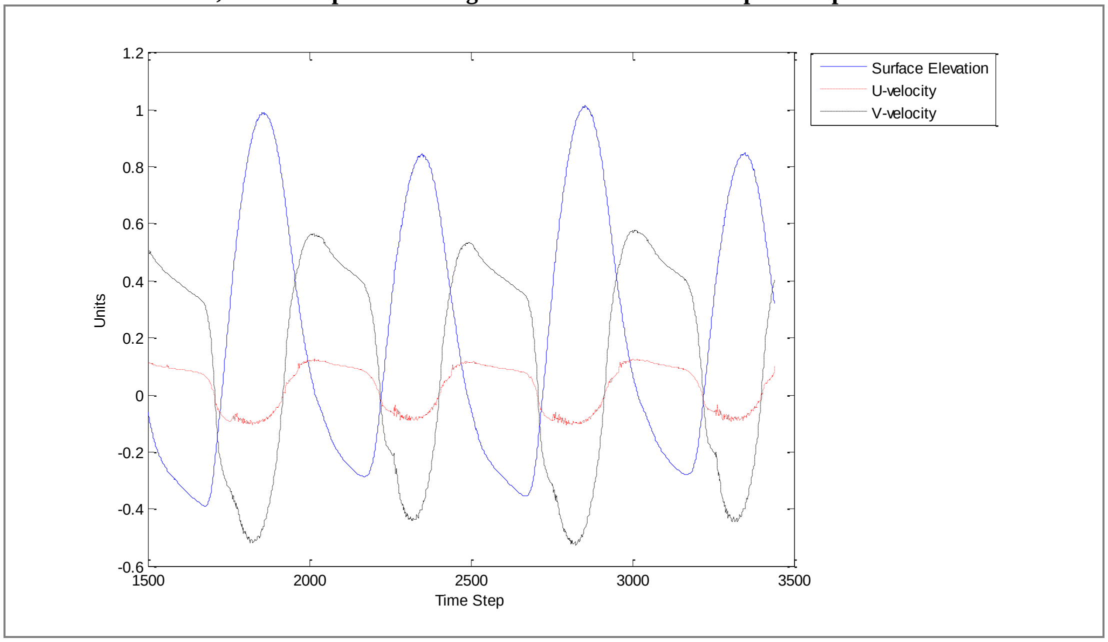

Figure 5.3 Current strength and surface elevations at Ohiwa Harbour Entrance (Site E). Surface elevation is given as metres above mean sea level (mamsl); u and v velocities are given as metres per second ($m.s^{-1}$). Note that v-velocity is much higher than the u-velocity, showing that flow is much faster through the entrance channel (north –south) than across it (east-west).

5.3.1.2 Main channel, small channels and mudflats

The main channel runs east-west parallel to Ohope Spit; seven locations (Mc1 to Mc7) were chosen for time series analysis along the length of the channel (Figure 5.1). Maximum surface elevation and tidal range decrease with distance from the harbour entrance (Figure 5.4); this is frictional dissipation of the tidal wave. Mudflats take up approximately 70% of the harbour area, and are mostly dry during low tide. This can be seen in Figure 5.5, where the bottoms of the tidal curves for Mf1-4 are almost flat. Small ephemeral channels branch off the main channel (Figure 5.1) Channels Sc4 to Sc6 have greater flow and tidal ranges than channels Sc1 to Sc3 (Figure 5.6).

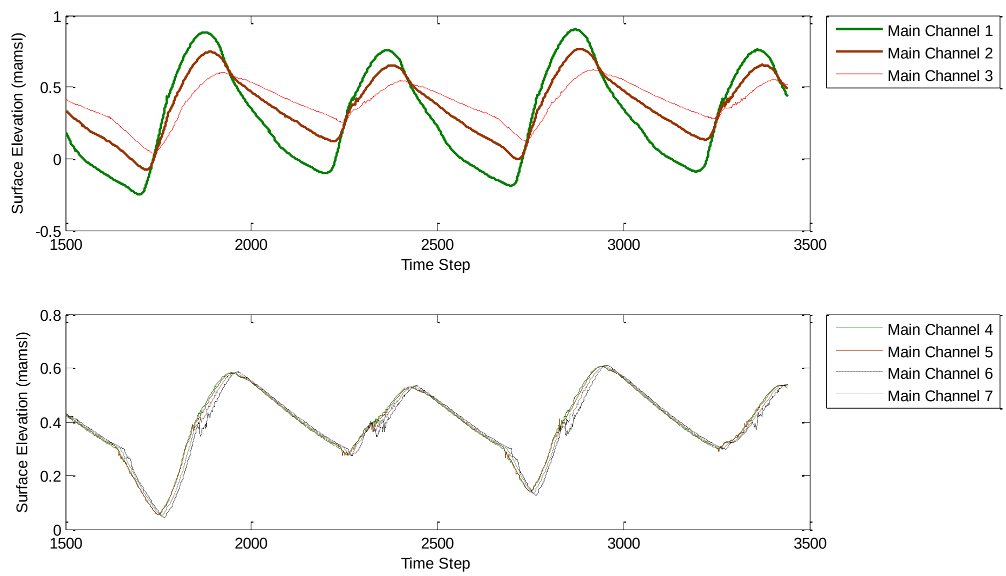

Figure 5.4 Surface elevations across main channel locations at Ohiwa Harbour.

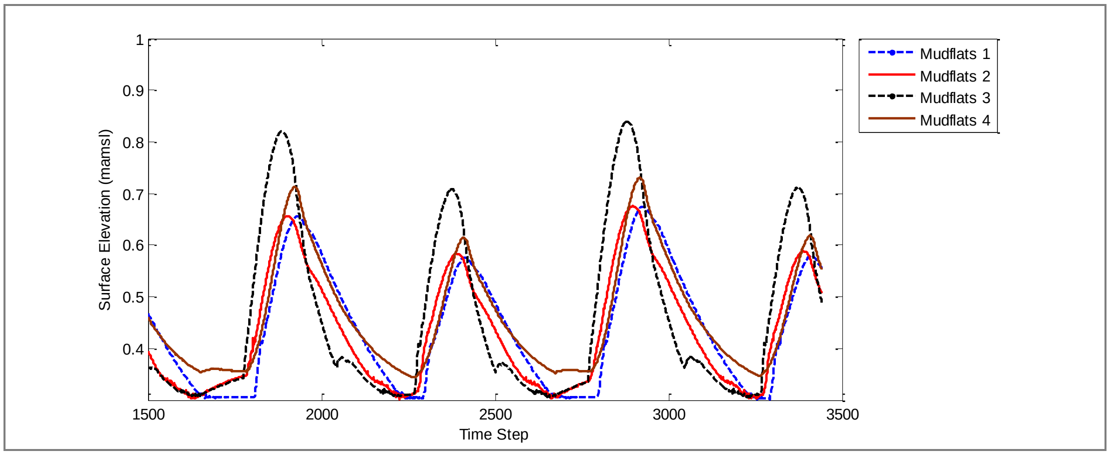

Figure 5.5 Surface elevations across mudflats at Ohiwa Harbour. Note that all sites dry for tidal elevations below 0.35-0.30 amsl.

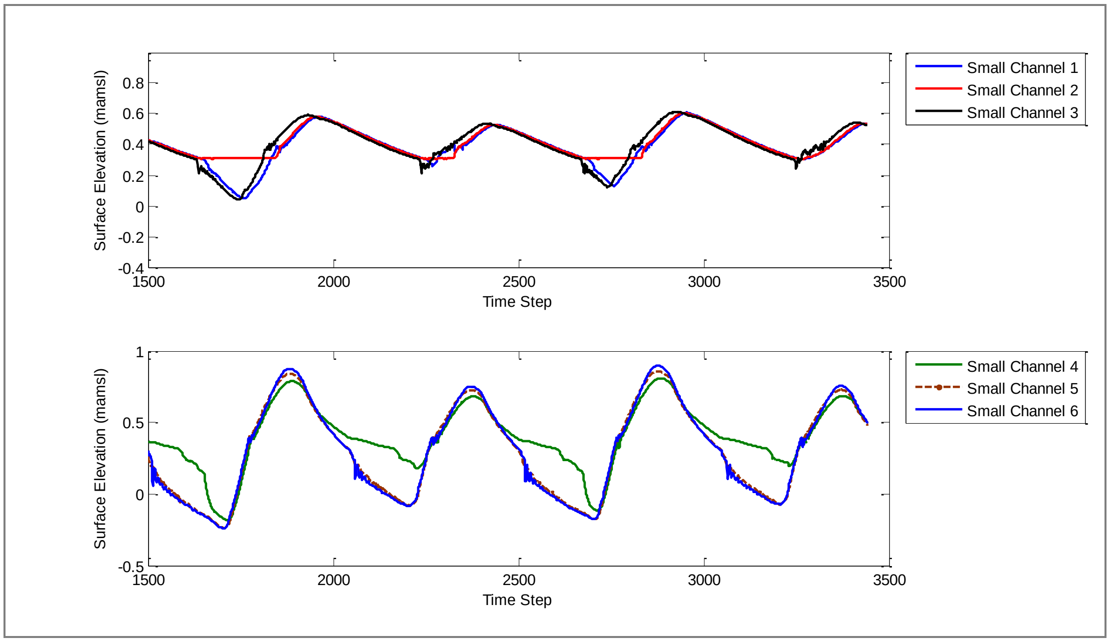

Figure 5.6 Surface elevations across small channels at Ohiwa Harbour.

5.3.2 Historical and pre-historical scenarios

Murdoch (2005) constructed a conceptual model of the geological evolution of Ohiwa Harbour. His model was constructed by information gathered from tephra distributions, and radiocarbon dating of shells and wood material in sediment cores. This section shows different hydrodynamic scenarios created from interpreting Murdoch's conceptual model. For each scenario, a bathymetric grid was constructed, and a finite difference hydrodynamic model was constructed in Ohiwa Harbour, outputting tidal and current flows. It was assumed that the forcing conditions and calibration parameters determined for the present-day scenario are applicable to the previous harbour configurations.

These scenarios give an insight into how the hydrodynamics of Ohiwa Harbour have changed as a result of tectonic activity and events which have modified sedimentation in the harbour. Sea level changes in this scenario are based on data published from the authors: Pullar and Patel (1972), Hull (1985) and Gibb (1986). For the time-series results, not all of the modeling locations (Figure 5.1) are published here, because analysis of the results indicated that a smaller subset of locations captured the overall behaviour well. Time-series results of importance are the harbour entrance, main channel (Mc1, Mc2, Mc3, and Mc4), and mudflats (Mf1 and Mf4). The time-series presented have a step size of 1.5 minutes.

5.3.2.1 Scenario one: 7410 cal yrs BP

Development of Ohope Spit and Ohiwa Harbour commenced at the start of the Holocene Stillstand around 7410 calendar years BP. Initially narrow beaches may have been found at the base of Ohope and Ohiwa cliffs. Harbour entrance is much wider than present (Figures 5.7 and 5.8). Sea level is close to present, being 0.13m lower than present. A number of channels are found in the inner harbour, representing river valleys when sea level was lower. In the locations measured, current strength is negligible being in between +/-0.1 $m.s^{-1}$, however it increases toward 'Mc3' to the west, reaching a maximum of 0.4 $m.s^{-1}$ (Figure 5.9a). Sea-surface elevation doesn't change much at each site except for the mudflats further inland, which appear to dry out during low tides (Figure 5.9b).

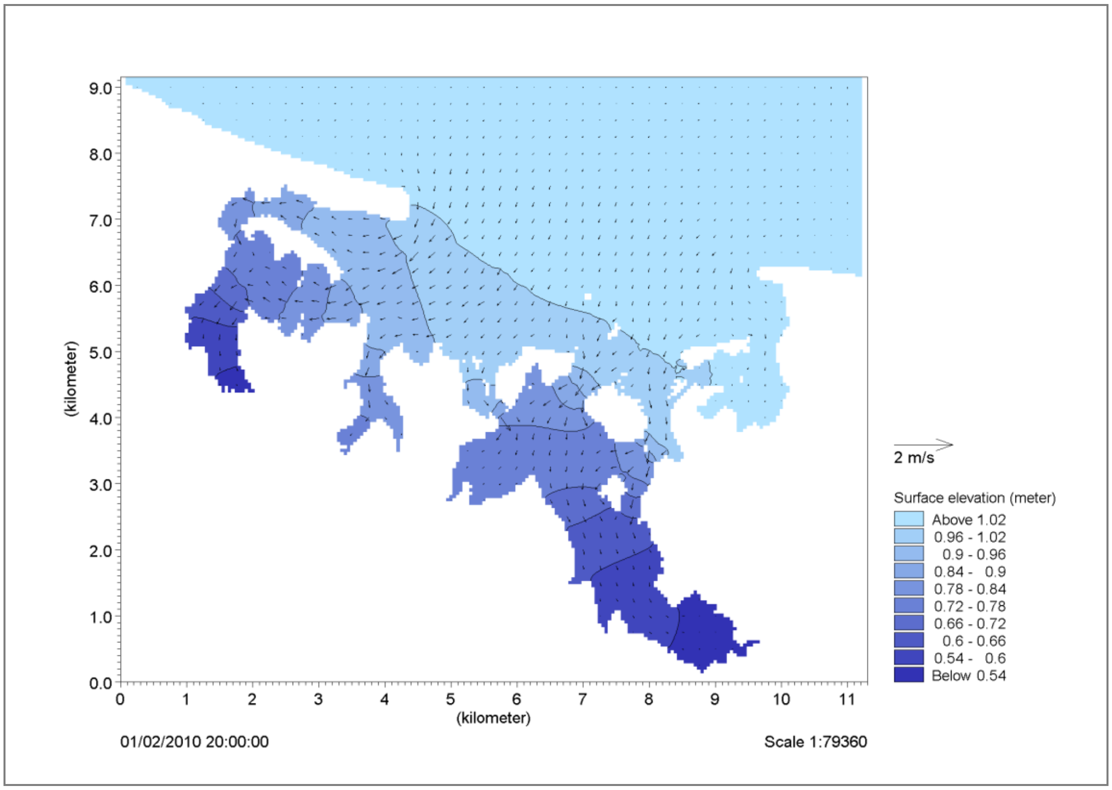

Figure 5.7 Ohiwa Harbour peak flood tide conditions around 7410 years BP.

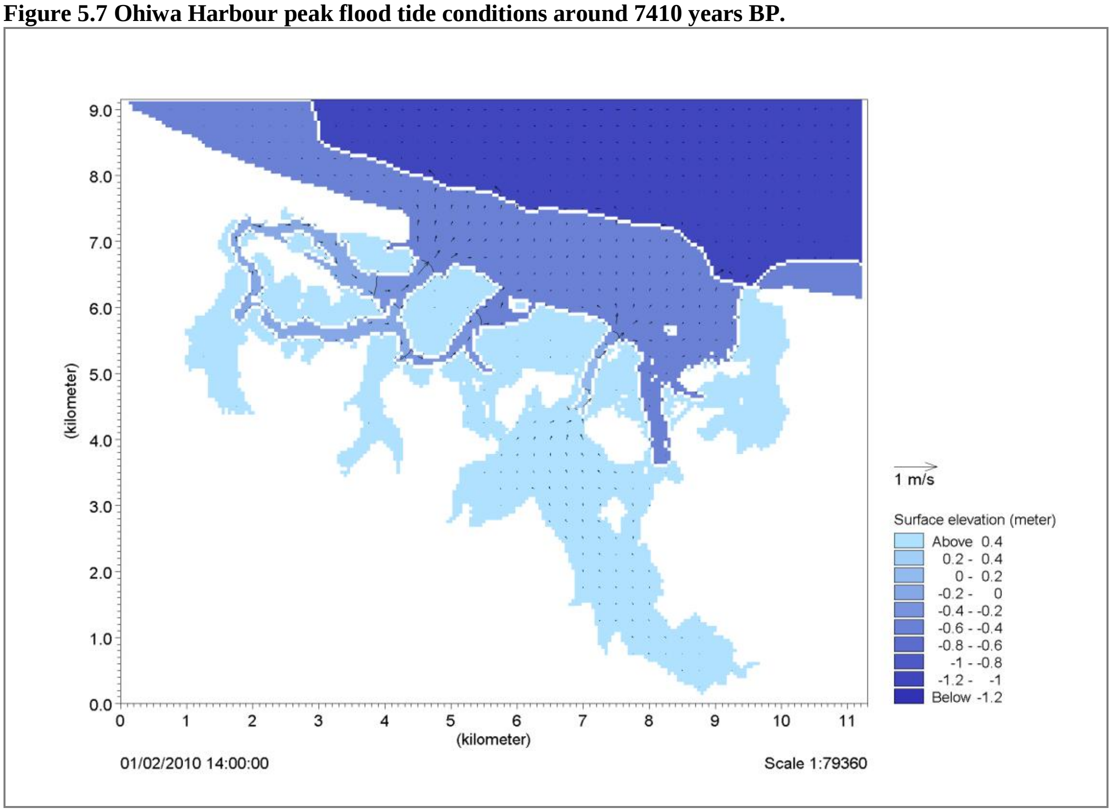

Figure 5.8 Ohiwa Harbour peak ebb tide conditions around 7410 years BP.

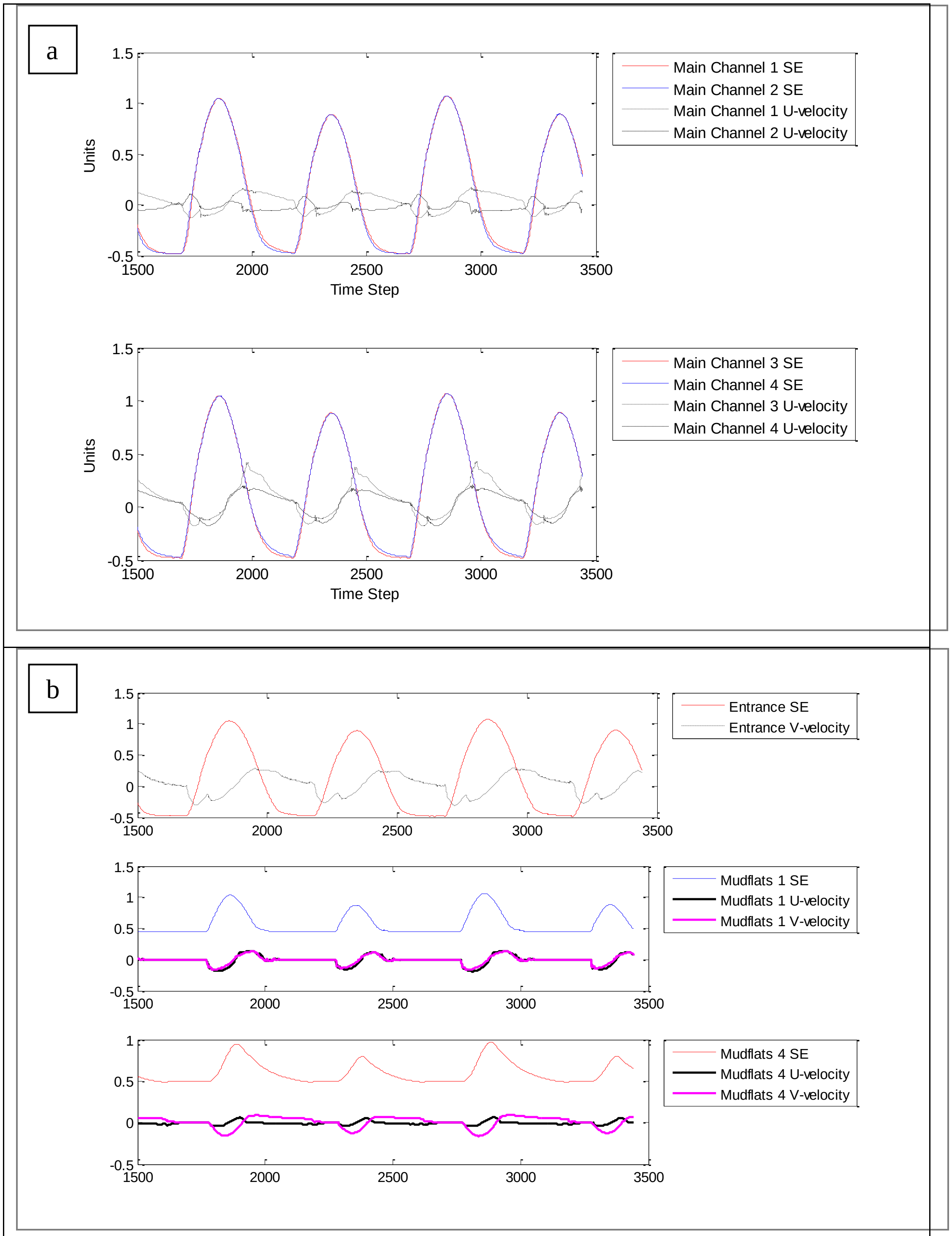

Figure 5.9 Surface elevation (SE) and current velocities at Ohiwa Harbour sites for scenario one. Surface elevations are in metres above mean sea level while current velocities are in m.s^{-1}. (a). Main Channels, (b). Entrance and Mudflats.

5.3.2.2 Scenario two: 4500 cal yrs BP

Murdoch (2005) postulated that development of Ohope Spit began around 7410 to 5590 cal yrs BP, and that by 4190 cal yrs BP the spit achieved its historical length. This was based on radiocarbon dating of Whakatane tephra and shell samples on two locations of the sand spit, however he doesn't show an 'in-between' scenario where Ohope Spit is half grown. During this scenario, Ohope Spit extends out to the position of the Waimana Fault, in line with Uretara Island (Figures 5.10 and 5.11). Sea level is assumed here to be close to present. There is a possible intertidal spit on the eastern margin of the entrance, which is revealed during low tide but covered in high tide (Figures 5.10 and 5.11).

The hydrodynamics of the harbour have changed since scenario one, showing increased maximum flow velocities at most sites, but little changes in surface elevation at most sites (Figures 5.12a and 5.12b). The harbour entrance has increased flow velocities by $0.2 m.s^{-1}$, while Main Channel 2 and Main Channel 3 have increased maximum flow velocities by up to $0.4 m.s^{-1}$. The mudflats and harbour entrance are the only locations with changes in surface elevation. Mudflats 1 and 4 don't dry out during low tide in this scenario, and the harbour entrance has an increased tidal range of 0.5m.

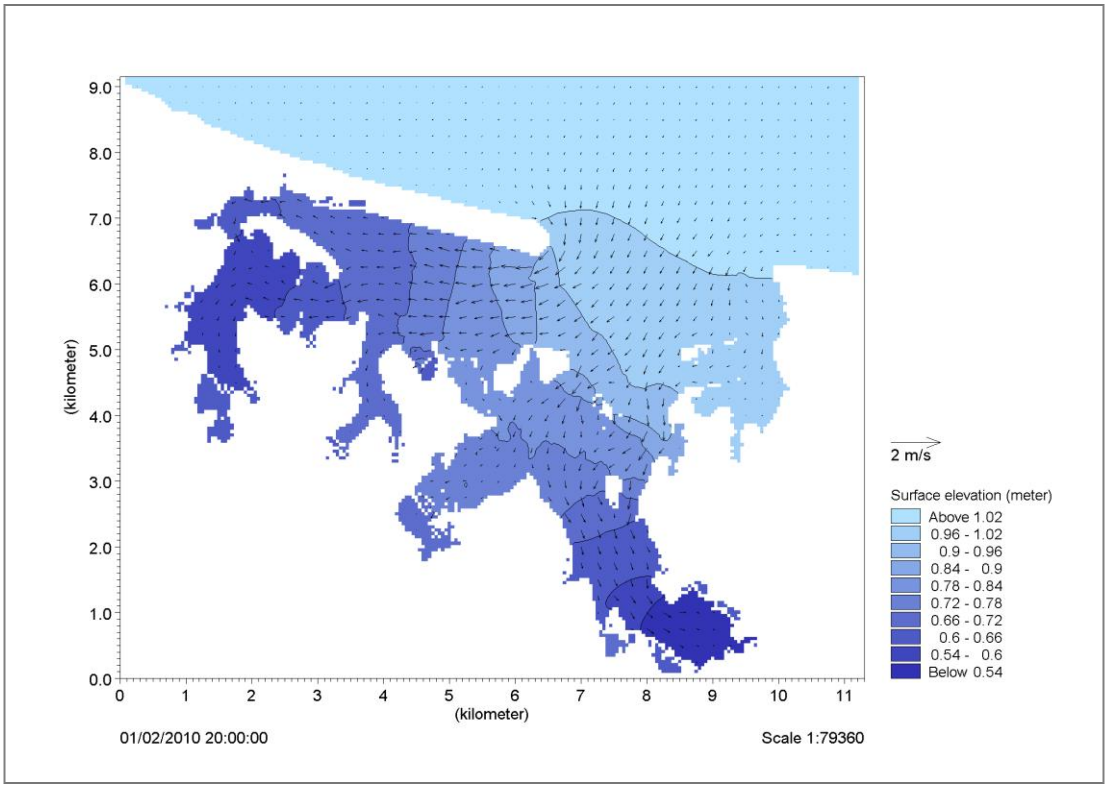

Figure 5.10 Ohiwa Harbour peak flood tide conditions around 4500 years BP.

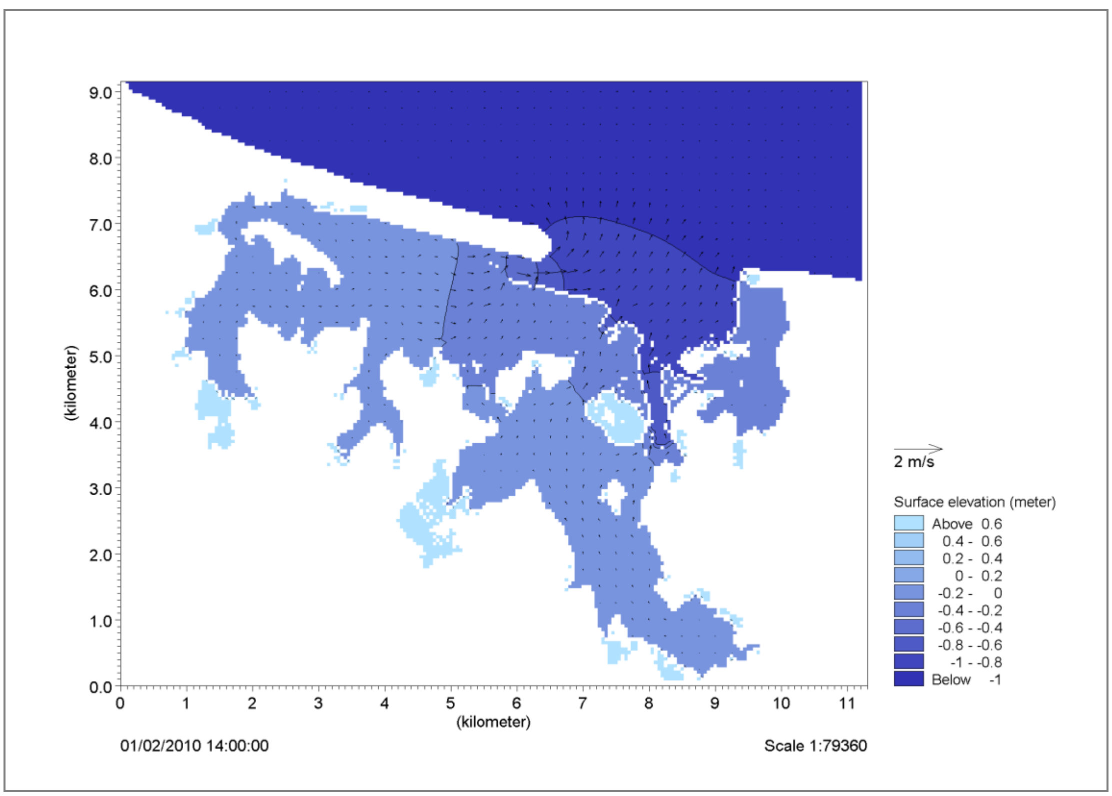

Figure 5.11 Ohiwa Harbour peak ebb tide conditions around 4500 years BP.

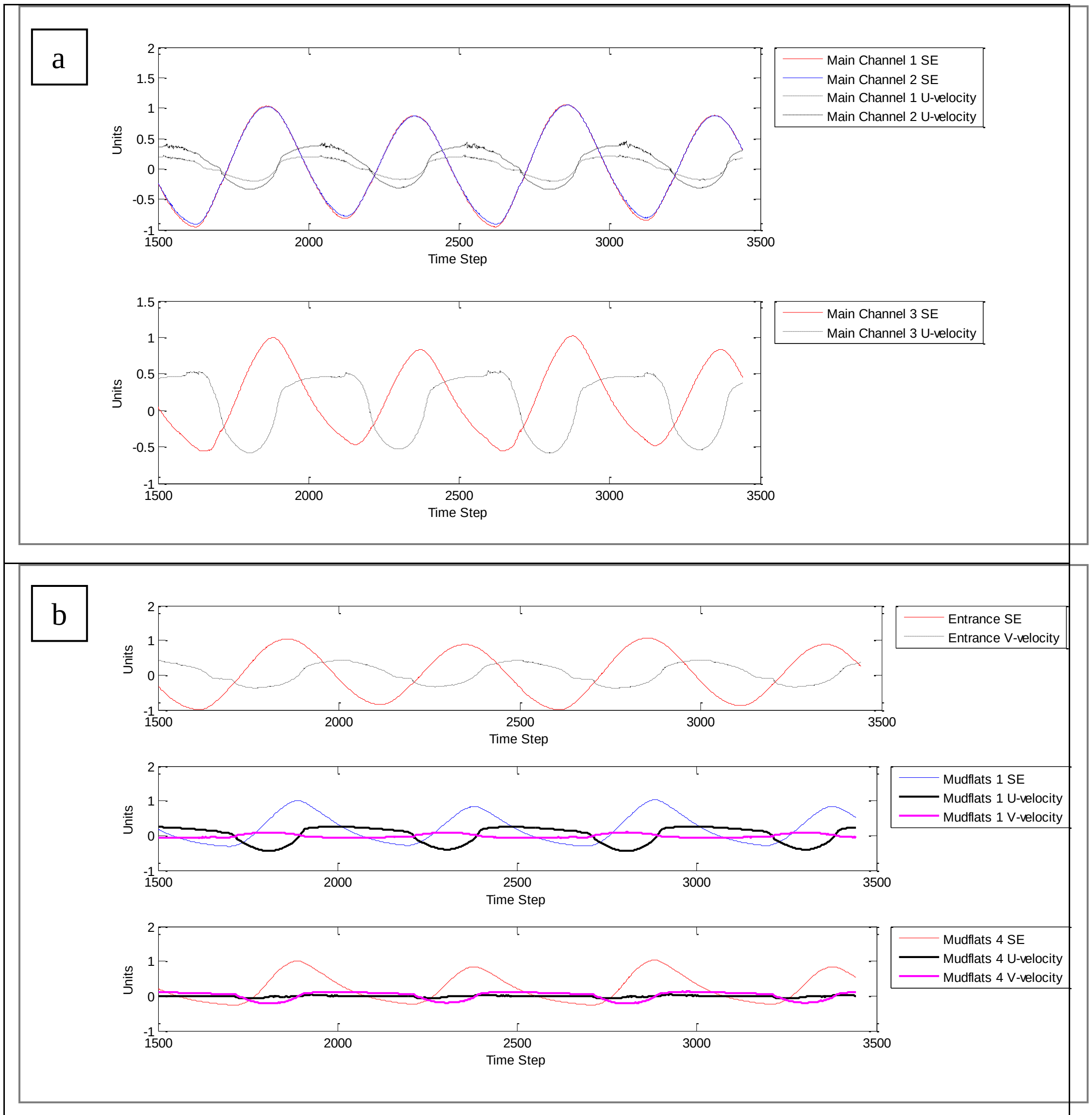

Figure 5.12 Surface elevation (SE) and current velocities at Ohiwa Harbour sites in scenario two. Surface elevations are in metres above mean sea level while current velocities are in m.s^{-1}. (a). Main Channels, (b). Entrance and Mudflats.

5.3.2.3 Scenario three: 4190 cal yrs BP

By 4190 cal yrs BP, a stable dry land surface may have existed on Ohope Spit, and it reaches its historical length. The length of Ohope Spit has not changed significantly since then. However, both Ohope and Ohiwa Spits appear to have migrated landward over time as evidenced by tree stumps in growth position within the present-day surf zone (Julian, 2006). Sea level was 0.6 to 0.7m higher than at present, indicating that subsidence has occurred for parts of the Spits. The harbour entrance between Ohope and Ohiwa sand spits was in the current location, and was a similar width to today (Figures 5.13 and 5.14). Note that Ohiwa sand Spit may have been intertidal, as it appears to be covered during low tide. Flow is strongest closest to the harbour entrance.

Changes in sea level and progradation of Ohope Spit have produced noticeable changes in the harbour hydrodynamics. Most locations show negligible changes in average sea surface elevation, however there is a decrease in tidal ranges in almost all measured locations, and an increase in maximum flow velocities. Tidal ranges decrease by 0.2 to 0.7m with main channel 2 having the most reduced tidal range, because it is cut off from the open ocean by Ohope Spit. Ebb and flood tide velocities increase by $0.3m.s^{-1}$ to $0.4m.s^{-1}$ at all locations except the mudflats and Main Channel 3, which decreases by $0.2m.s^{-1}$ to $0.3m.s^{-1}$ (Figures 5.15a and 5.15b). Main channel 4 is dry land in this scenario, so is not plotted.

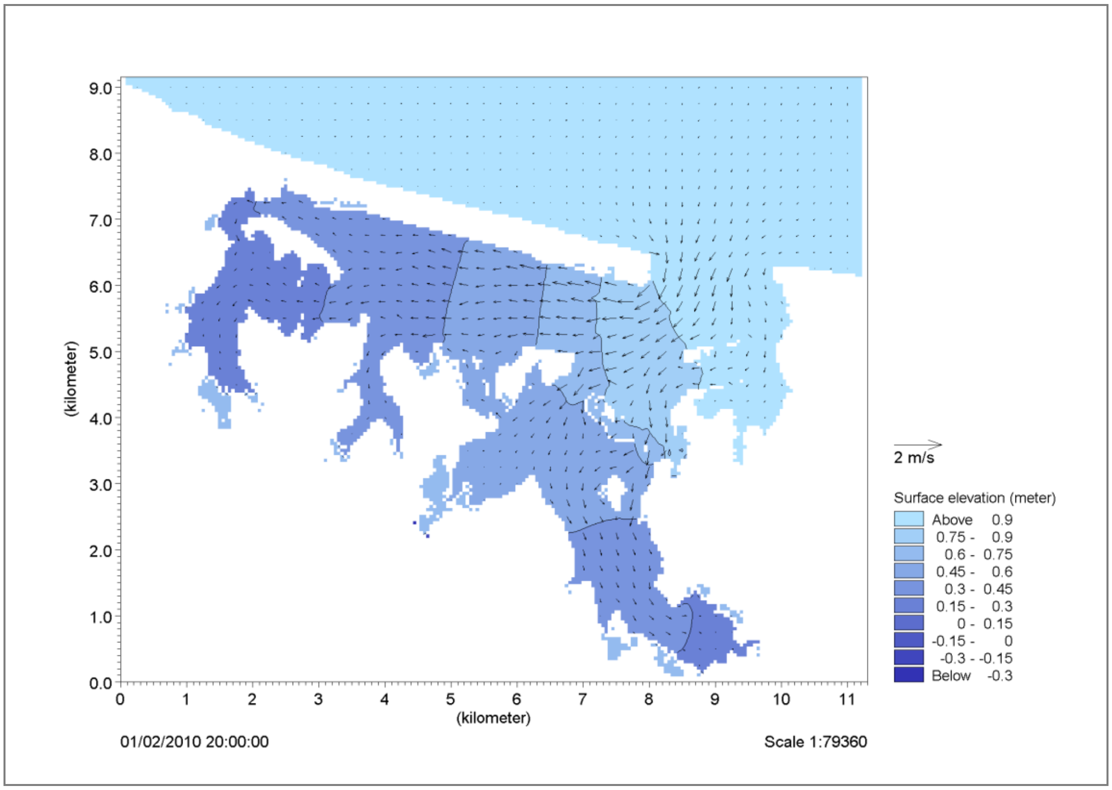

Figure 5.13 Ohiwa Harbour peak flood tide conditions around 4190 years BP.

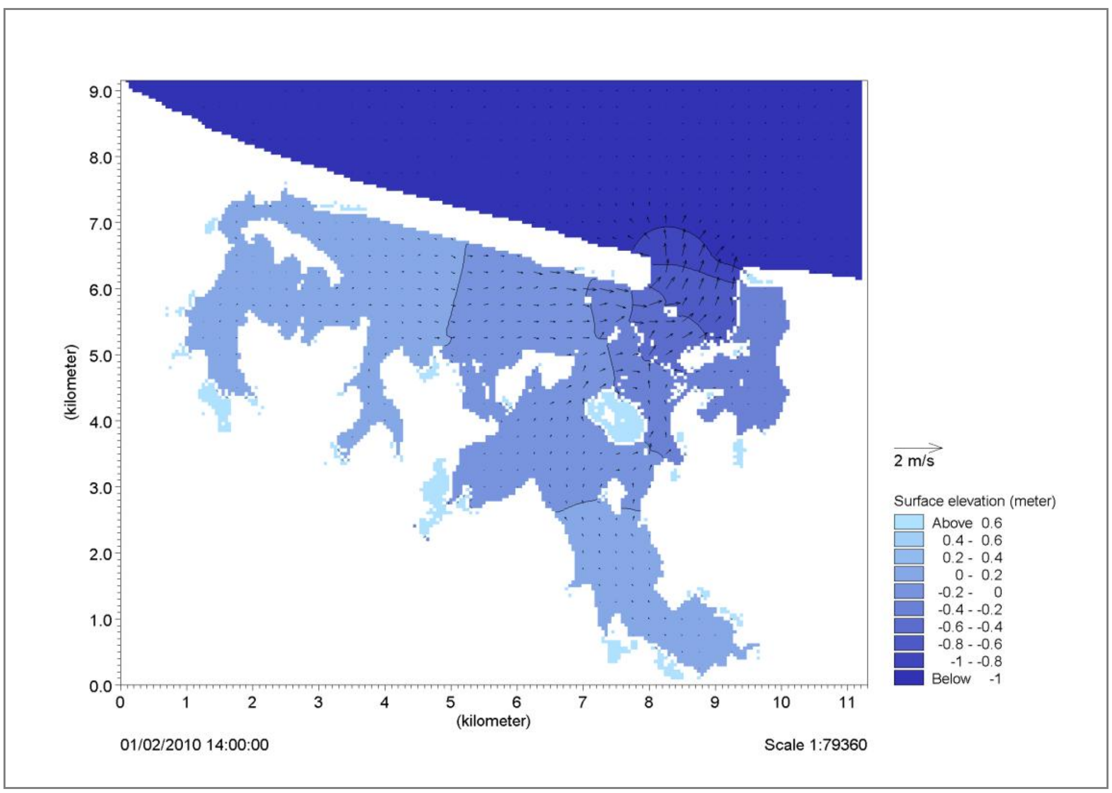

Figure 5.14 Ohiwa Harbour peak ebb tide conditions around 4190 years BP.

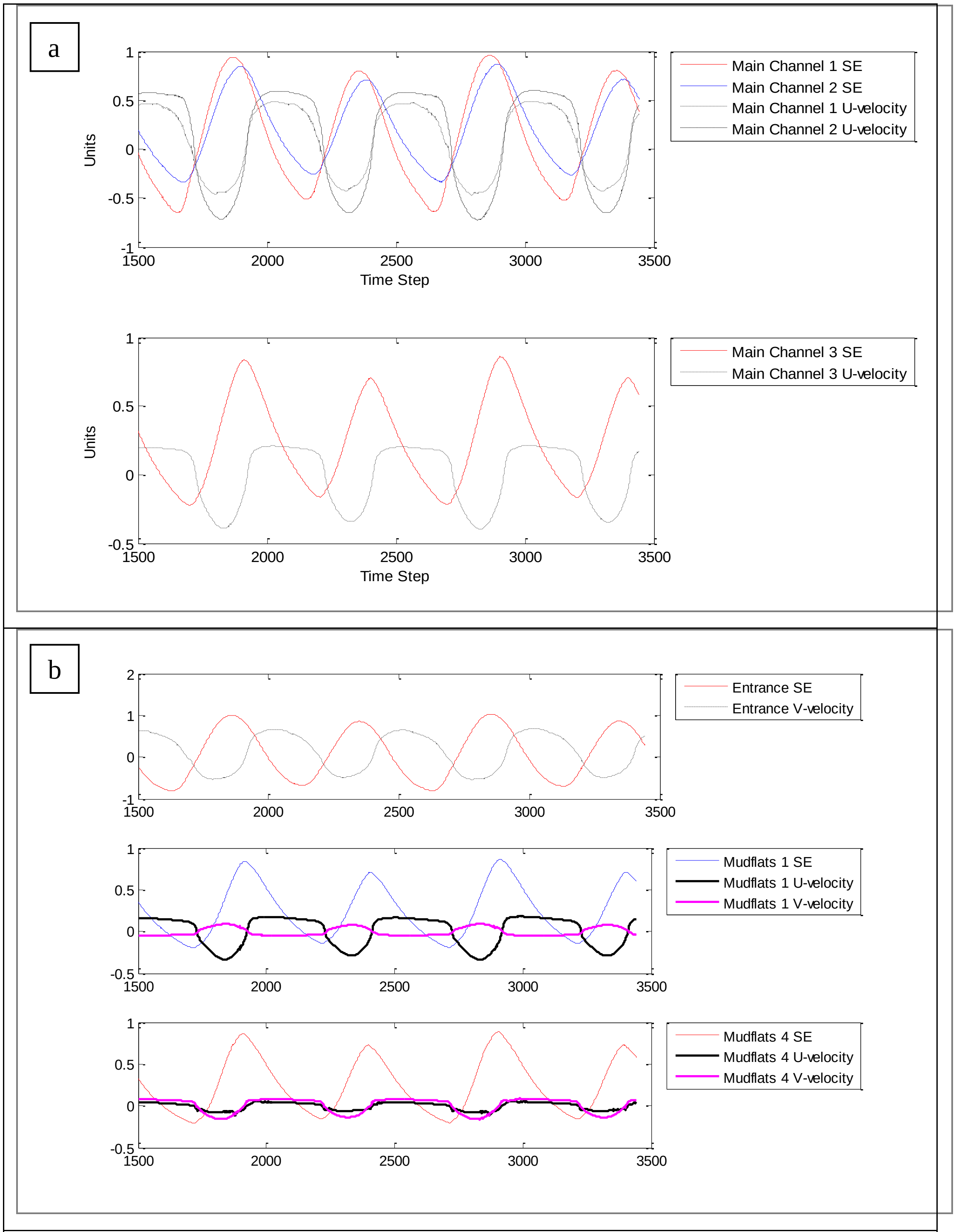

Figure 5.15 Surface elevation (SE) and current velocities at Ohiwa Harbour sites in scenario three. Surface elevations are in metres above mean sea level while current velocities are in $m.s^{-1}$. (a). Main Channels, (b). Entrance and Mudflats.

5.3.2.4 Scenario four: 4190 to 3515 cal yrs BP

Mid Holocene sea level changes resulted in landward migration of Ohope and Ohiwa sand spits. Sea level is 1.1m higher than present in this scenario (Figures 5.16 and 5.17). Apart from a slightly higher sea level, the hydrodynamics of Ohiwa Harbour is largely unchanged in this scenario, compared to the previous one. One exception to this is the increase in flow speed in the harbour entrance, up to +/- $0.8 m.s^{-1}$ (results in Figures 5.18a and 5.18b). Main Channels 2 and 3 have an increased tidal range by approximately 0.3m. Mudflats 1 and 4 have an increased tidal range by approximately 0.45m. Main channel 4 is dry land in this scenario, so is not plotted.

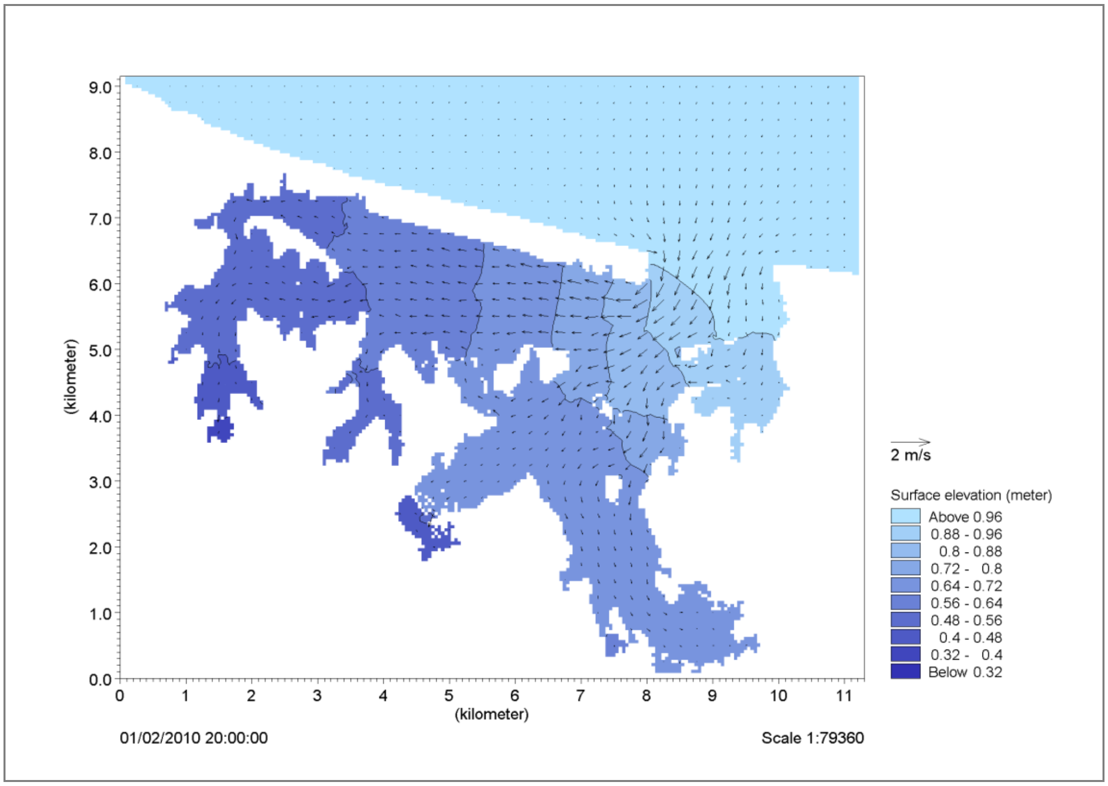

Figure 5.16 Ohiwa Harbour peak flood tide conditions around 4190 to 3515 years BP.

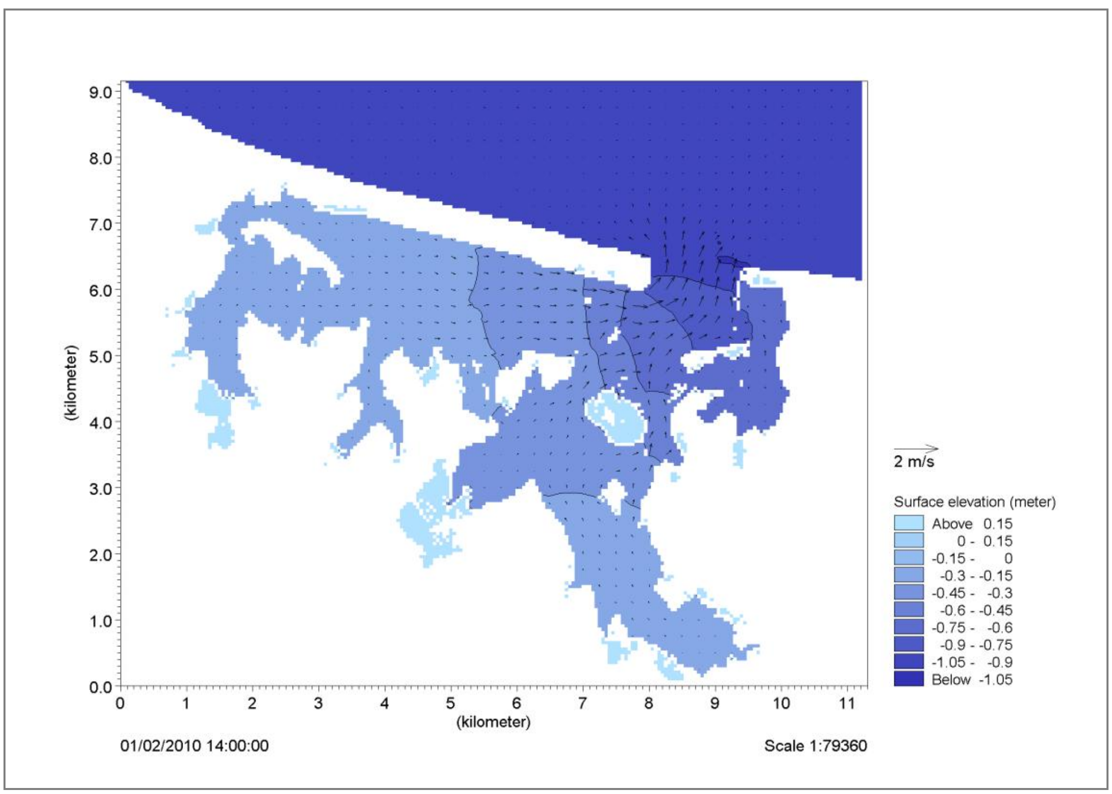

Figure 5.17 Ohiwa Harbour peak ebb tide conditions around 4190 to 3515 years BP.

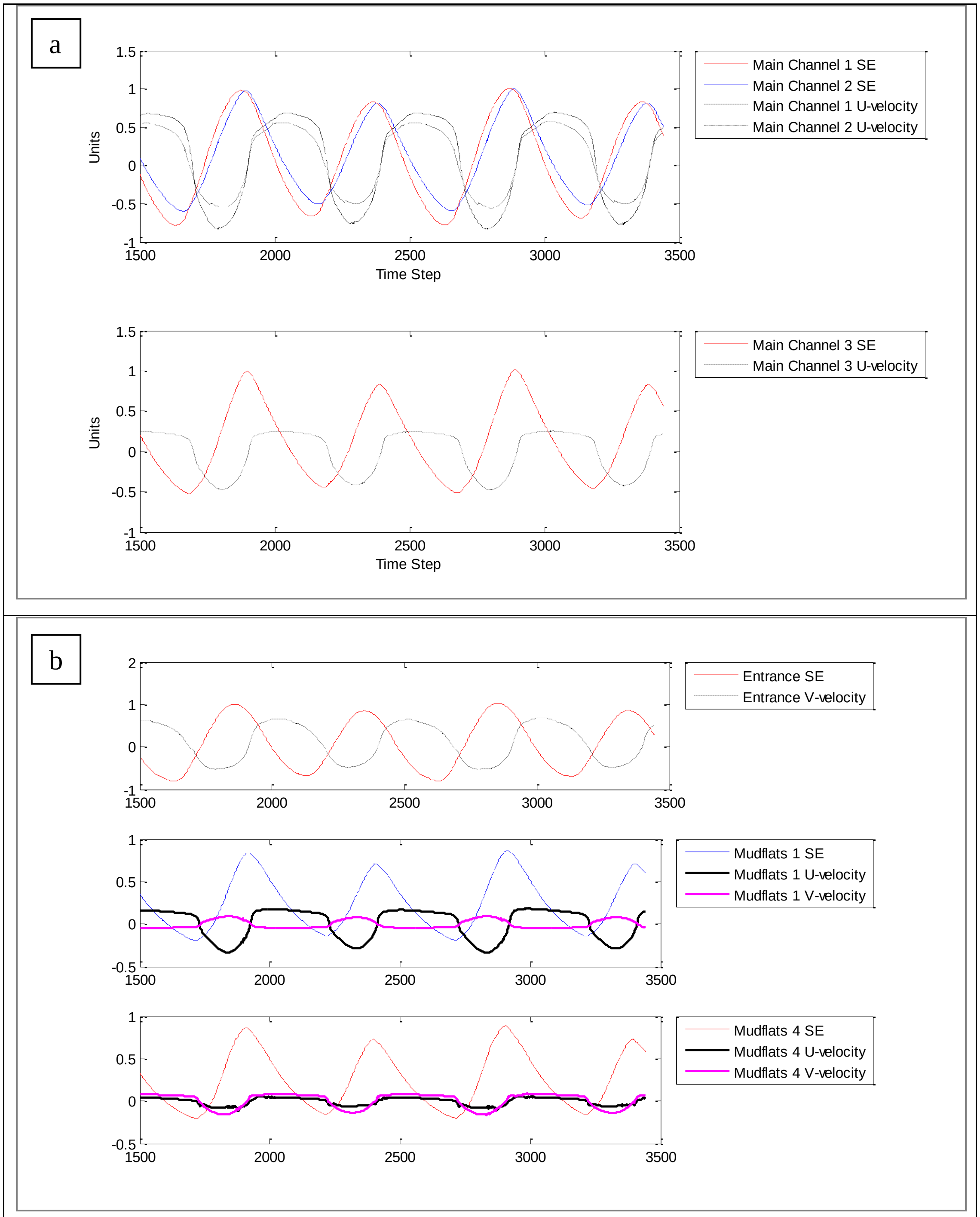

Figure 5.18 Surface elevation (SE) and current velocities at Ohiwa Harbour sites for scenario four. Surface elevations are in metres above mean sea level while current velocities are in m.s^{-1}. (a). Main Channels, (b). Entrance and Mudflats.

5.3.2.5 Scenario five: 3515 to 2780 cal yrs BP

Ohope Spit progrades landward at a rate of 0.6m to 1m/year. Location of harbour entrance is stable since 2780 cal yrs BP. Sea level falls, exposing a large segment of Uretara Island and Motuotu Island; but sea level is still 0.5m higher than present (Figures 5.19 and 5.20). An increase in area of Uretara and Motuotu Islands has caused formation of temporary tidal channels on either side of these islands (refer to Figure 1.1a for locations of these islands). These channels have stronger currents than in the rest of the harbour, so it is assumed that erosion there would be more significant than the rest of the harbour. The southernmost ‘arms’ of the harbour have decreased in area due to the sea level drop. At the sites measured, average surface elevation and current velocities have largely unchanged (Figures5.21a and 5.21b). However, there is a decreased tidal range at sites Main Channel 2, Main Channel 3 and the mudflats by 0.5m to 0.6m compared with the previous scenario.

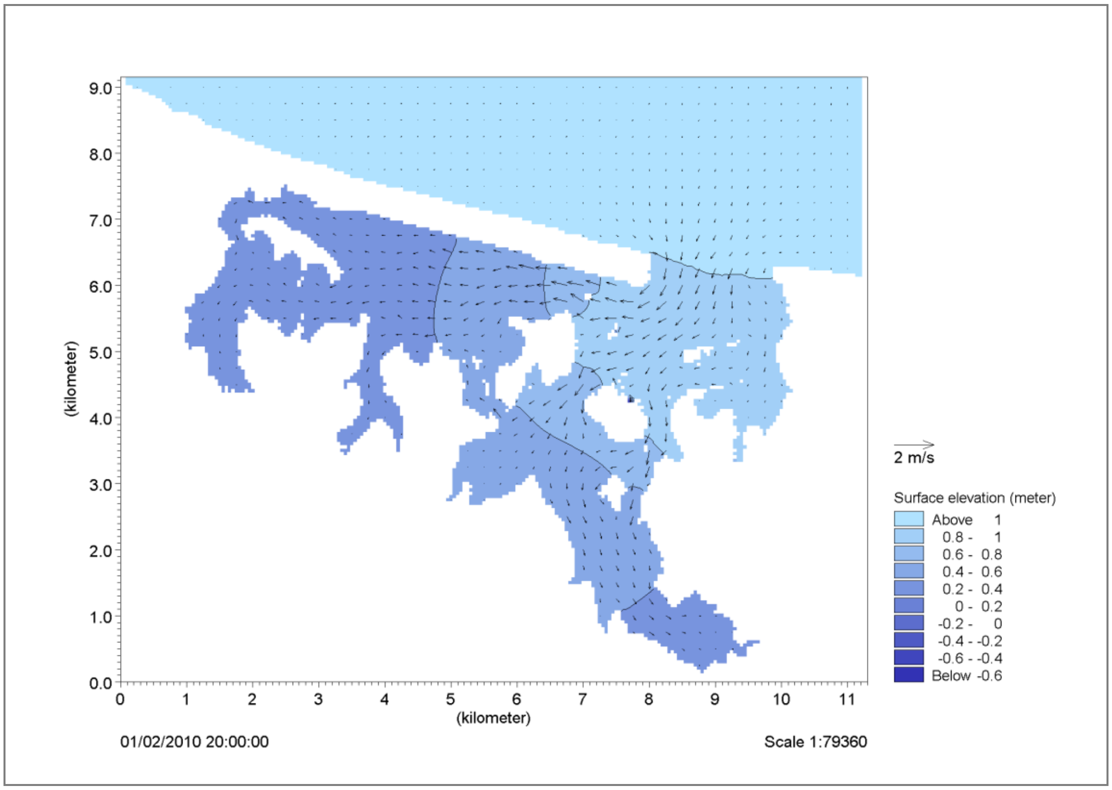

Figure 5.19 Ohiwa Harbour peak flood tide conditions around 3515 to 2780 years BP.

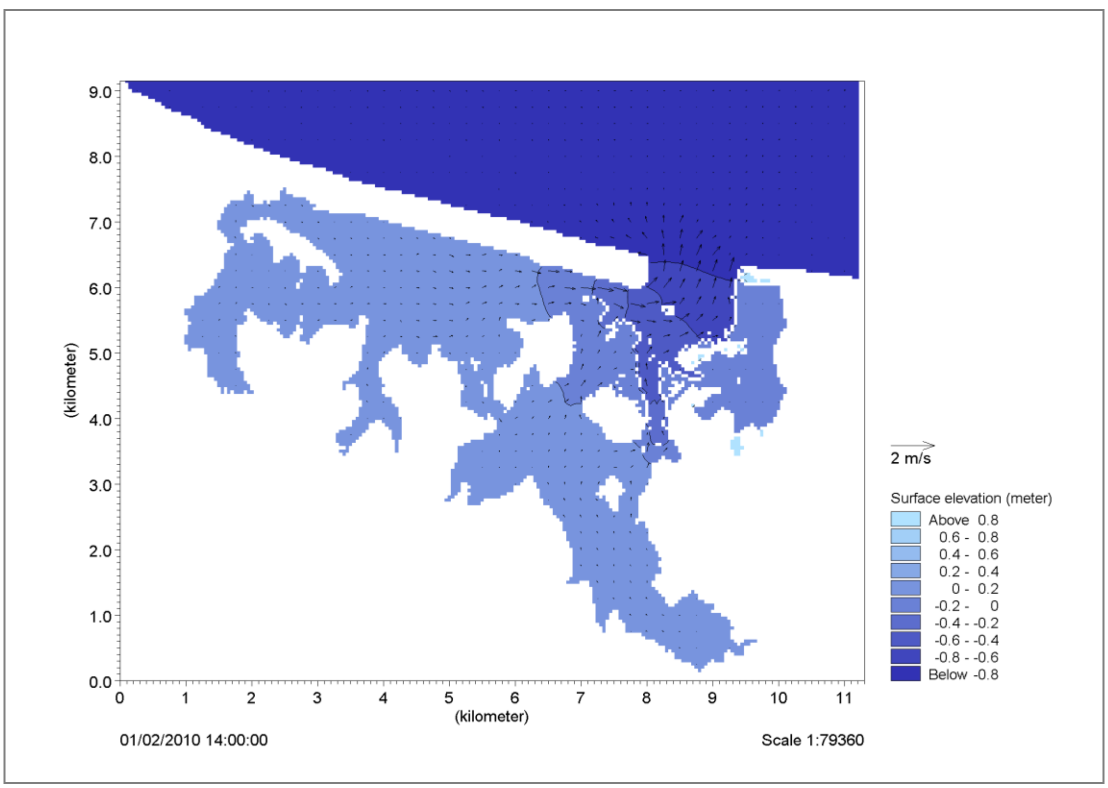

Figure 5.20 Ohiwa Harbour peak ebb tide conditions around 3515 to 2780 years BP.

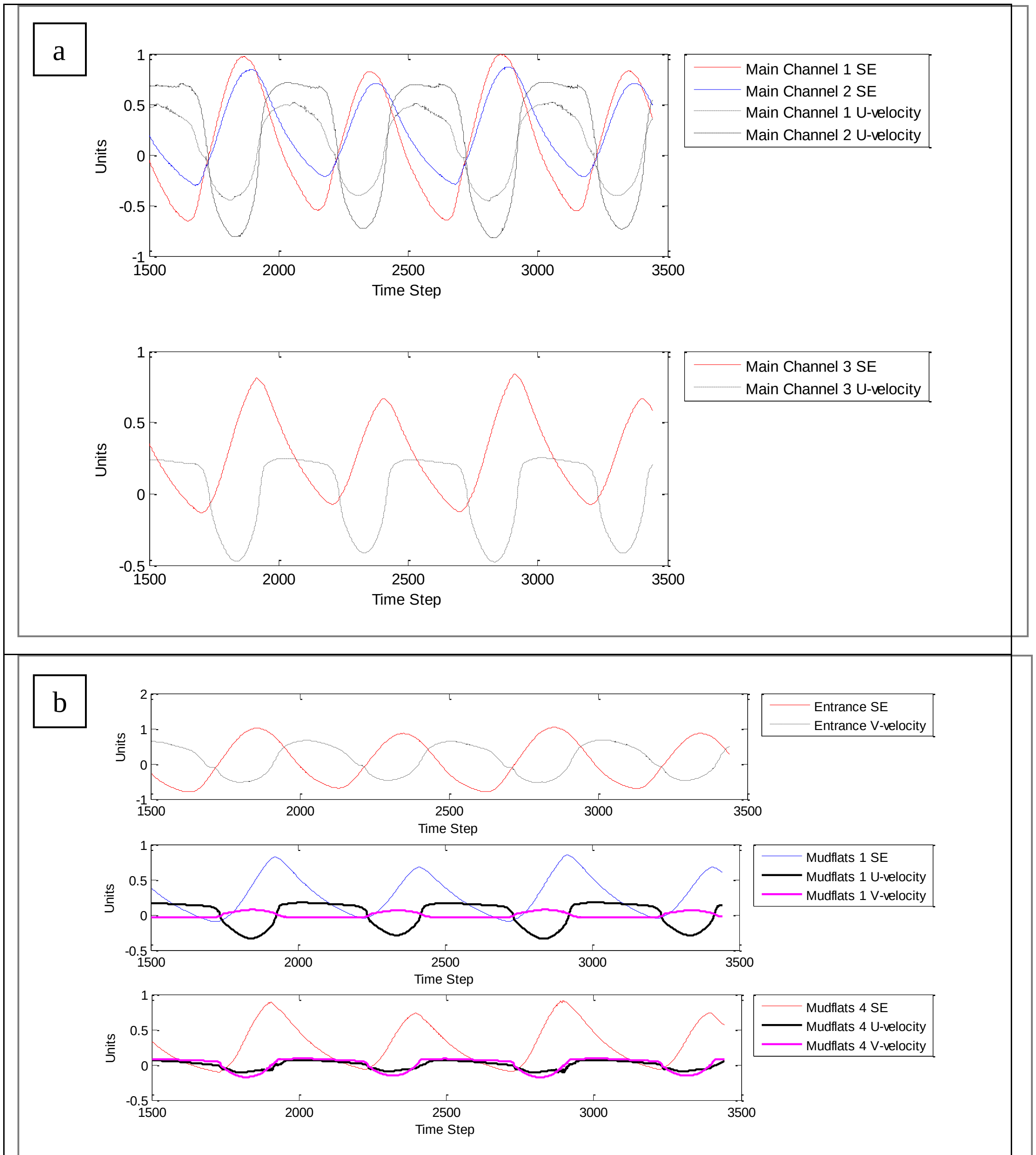

Figure 5.21 Surface elevation (SE) and current velocities at Ohiwa Harbour sites in scenario five. Surface elevations are in metres above mean sea level while current velocities are in m.s^{-1}. (a). Main Channels, (b). Entrance and Mudflats.

5.3.2.6 Scenario six: 2780 to 2425 cal yrs BP

An earthquake causes 2-2.4m subsidence along the Waimana Fault, which affected the entire harbour. Large scale erosion occurred on the southern ends of Ohope and Ohiwa spits, decreasing their thickness (Figures 5.22 and 5.23). Sea level ranges from present to 0.4m higher than present. The drop in sea level compared to the previous scenario has created mudflats in similar locations to the present which partially dry out during low tide (Figure 5.24b). Sea surface elevations have increased on average by a small amount no greater than 0.1m compared to the previous scenario. Flow is now recorded at 'Main Channel 4' due to erosion on the southern end of Ohope Spit (Figure 5.24a). Main Channel 4 has a similar behavior in flow to Main Channel 3 but with lowered surface elevation and u-velocities.

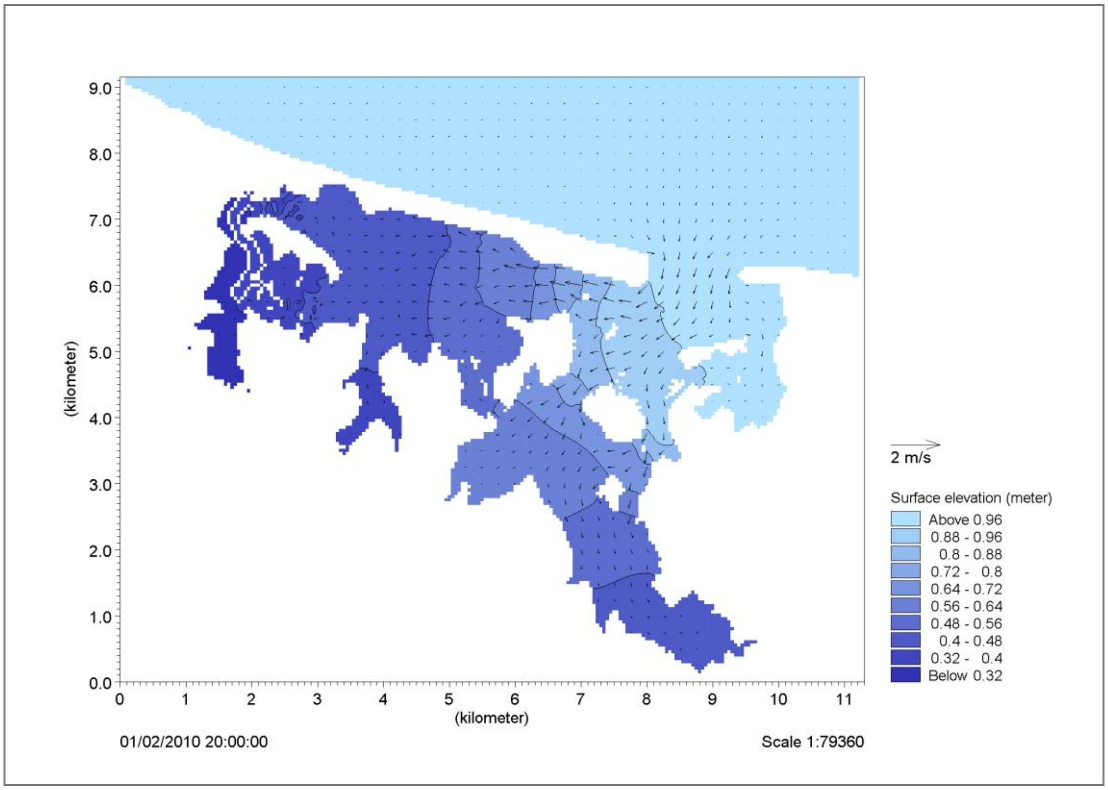

Figure 5.22 Ohiwa Harbour peak flood tide conditions around 2780 to 2425 years BP.

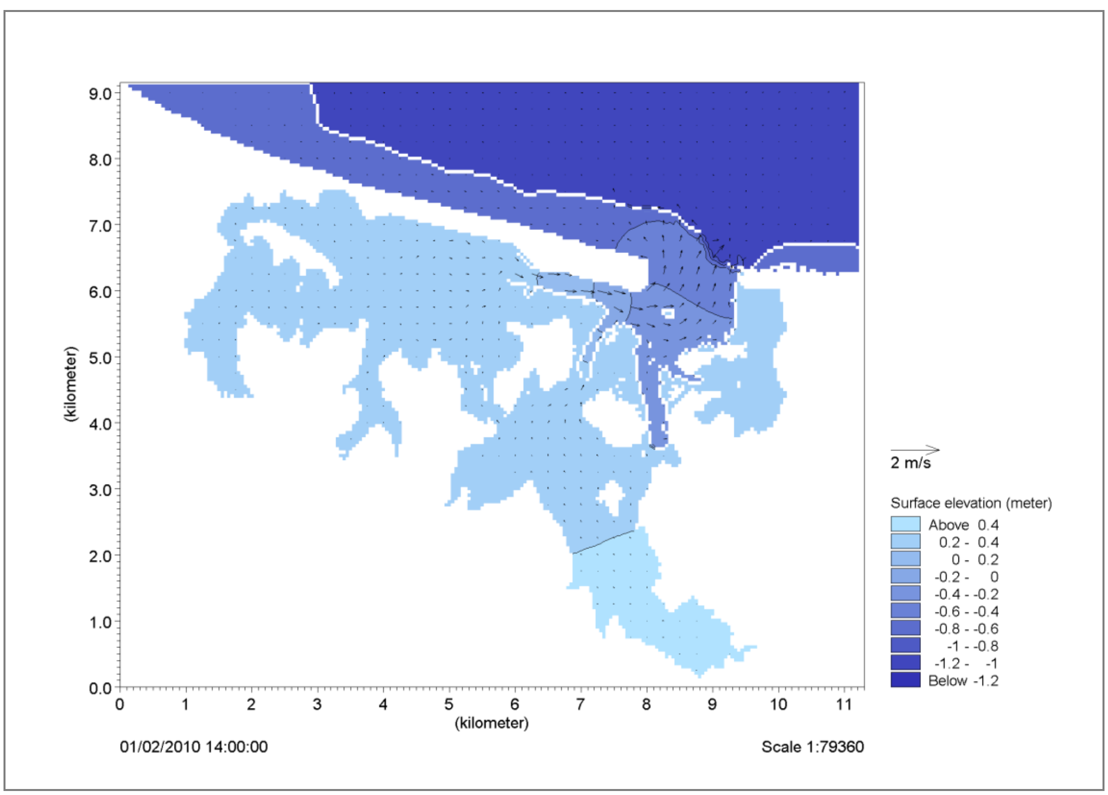

Figure 5.23 Ohiwa Harbour peak ebb tide conditions around 2780 to 2425 years BP.

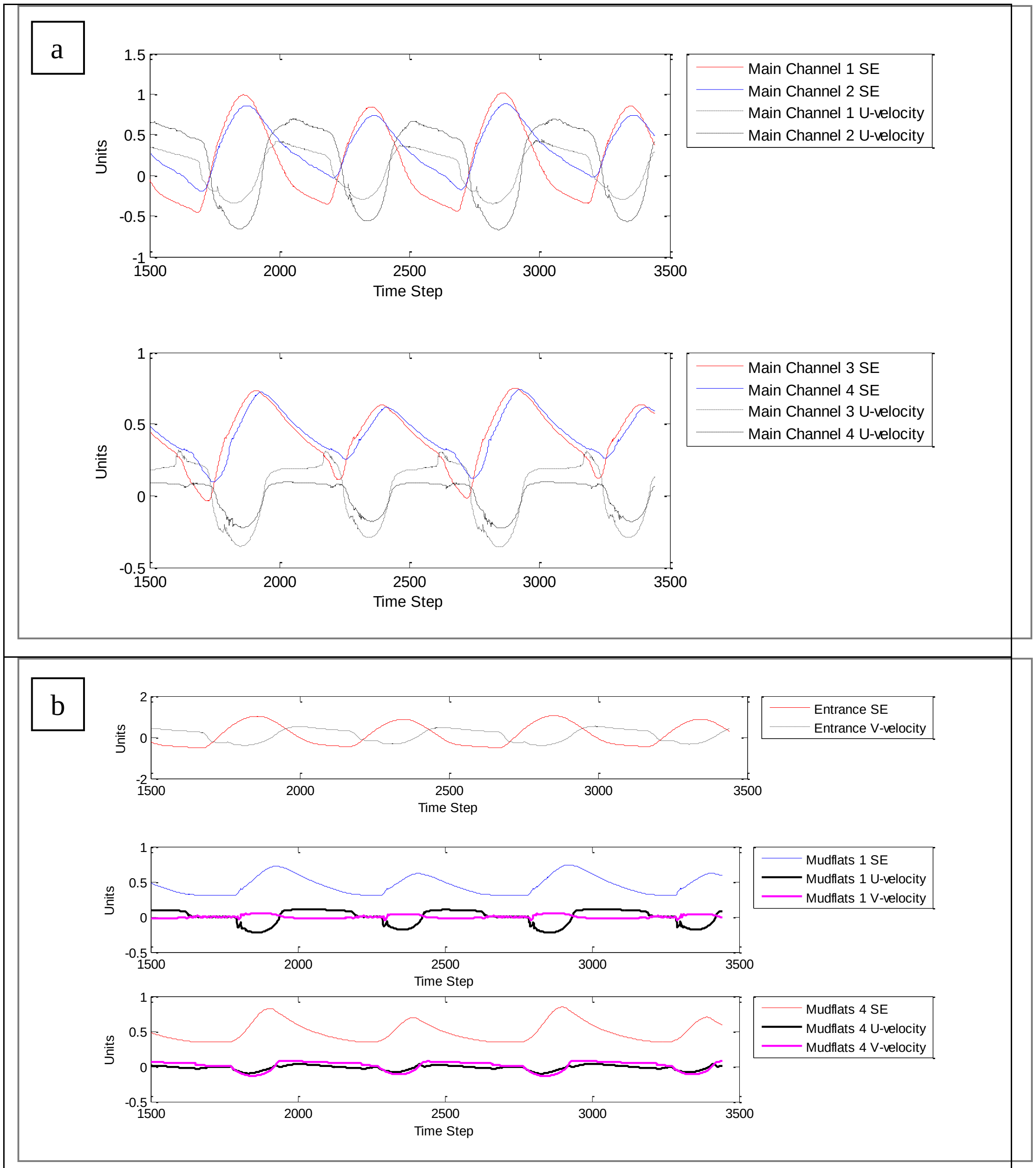

Figure 5.24 Surface elevation (SE) and current velocities at Ohiwa Harbour sites in scenario six. Surface elevations are in metres above mean sea level while current velocities are in $m.s^{-1}$. (a). Main Channels, (b). Entrance and Mudflats.

5.3.2.7 Scenario seven: 2425 to 2330 cal yrs BP

Subsidence and severe coastal erosion from the Waimana Fault Earthquake may have created a breach in Ohope Spit. This breach may have opened and closed, depending on sediment supply and weather conditions (El Nino/La Nina phases) in the harbour (Figures 5.25 and 5.26). The breach of Ohope Spit creates a second main channel within the harbour. Sea level is the same as its present position. Main Channels 2 to 4 have increased tidal ranges by 0.4 to 0.6m since the previous scenario, but decreased mean surface elevations. There are increased flow speeds at Main Channels 2 to 4 from the formation of a breach in Ohope Spit, but the increased flow is in the v-velocity component, not the u-velocity component (Figure 5.27a). Mean surface elevation in the mudflats has increased by approximately 0.2m to 0.3m since the previous scenario (Figure 5.27b).

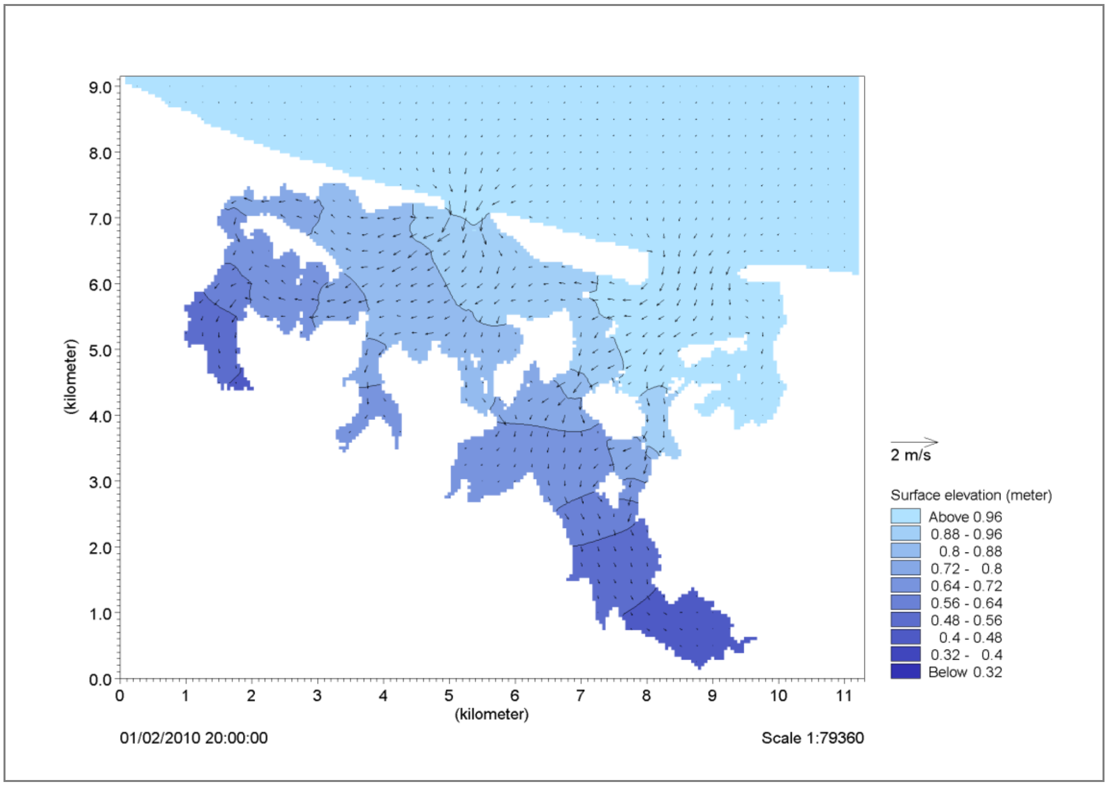

Figure 5.25 Ohiwa Harbour peak flood tide conditions around 2425 to 2330 years BP.

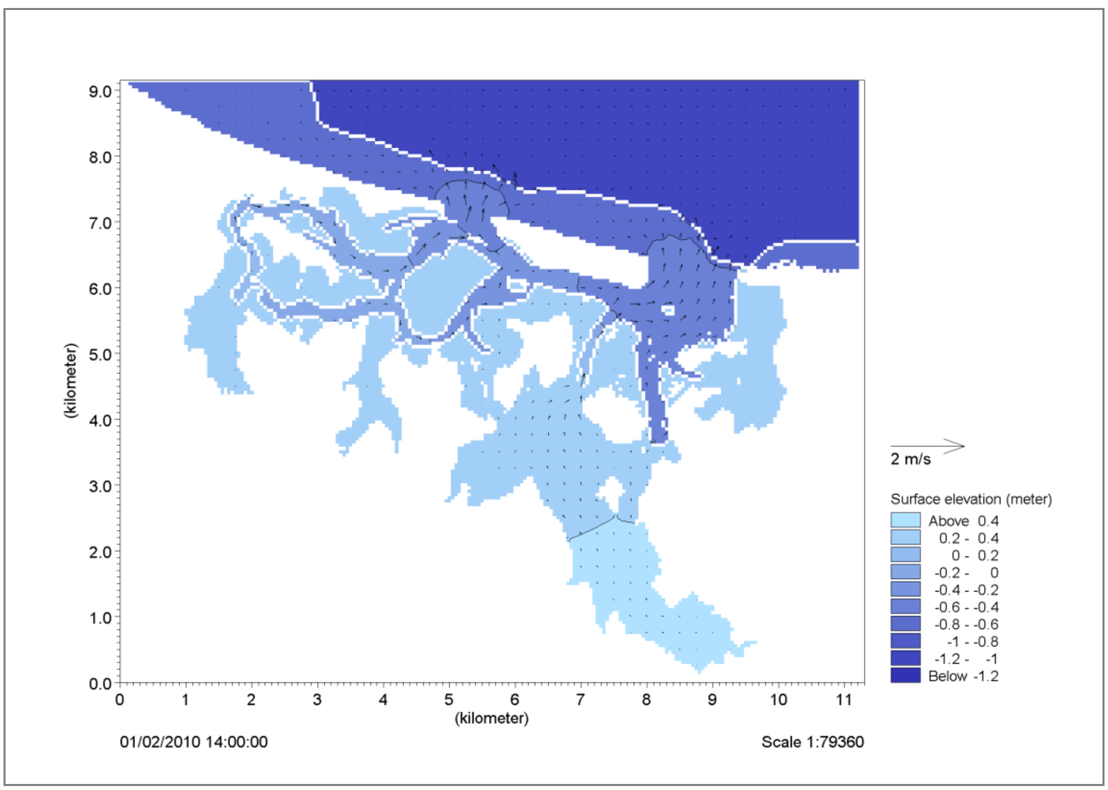

Figure 5.26 Ohiwa Harbour peak ebb tide conditions around 2425 to 2330 years BP.

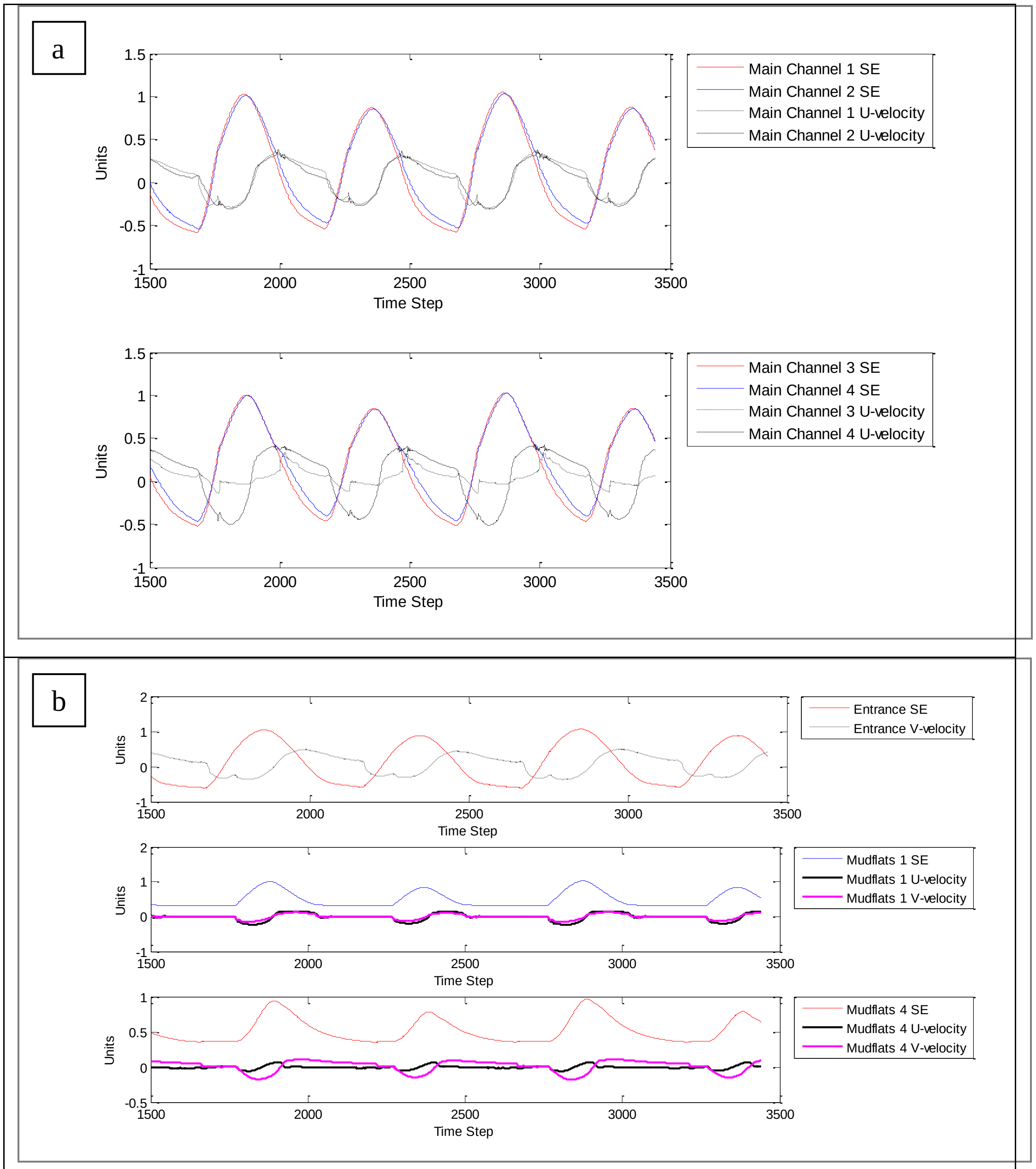

Figure 5.27 Surface elevation (SE) and current velocities at Ohiwa Harbour sites in scenario seven. Surface elevations are in metres above mean sea level while current velocities are in m.s^{-1}. (a). Main Channels, (b). Entrance and Mudflats.

5.3.2.8 Scenario eight: 2330 to 1718 cal yrs BP

Mapara tephra was deposited into Ohiwa Harbour and the sand spits. Infilling of the Rangitaiki Plains to the west results in surplus sediment being transported to Ohiwa, infilling the breach in Ohope Spit and building up the beach at its distal end. Sea level estimates range from present day sea level to 1.8m lower than present, so in this scenario sea level is set at 0.9m lower than present (Figures 5.28 and 5.29). In this scenario, the present-day main channel (Figure 5.1) is formed. But the area where water flows within the harbour is much smaller than previously, being constricted to this main channel and a few smaller channels branched off it. Some of the small channels and all of the mudflats in this scenario are completely dried up. Main Channels 1 to 4 are partly dry during low tide as evidenced by the flat tidal curves with a u-velocity of near 0 in Figure 5.30a. The harbour entrance also partly dries out during low tide, with a decreased tidal range of 0.8m compared with the previous scenario (Figure 5.30b).

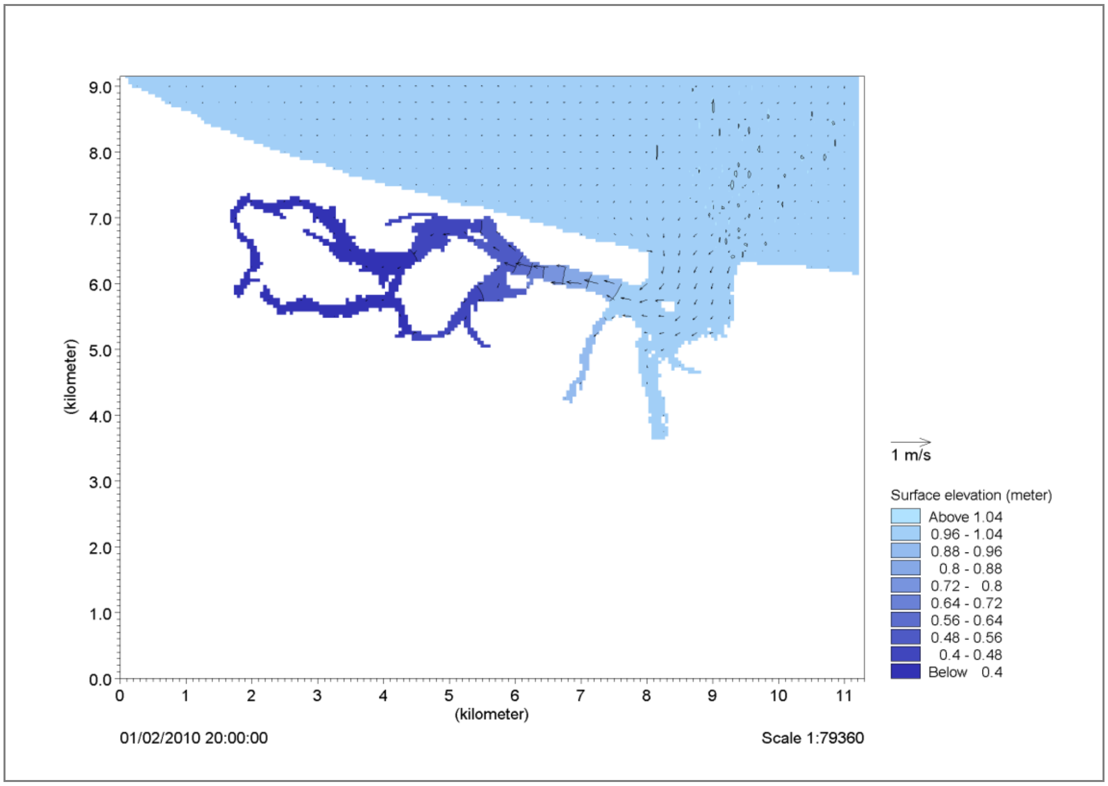

Figure 5.28 Ohiwa Harbour peak flood tide conditions around 2330 to 1718 years BP.

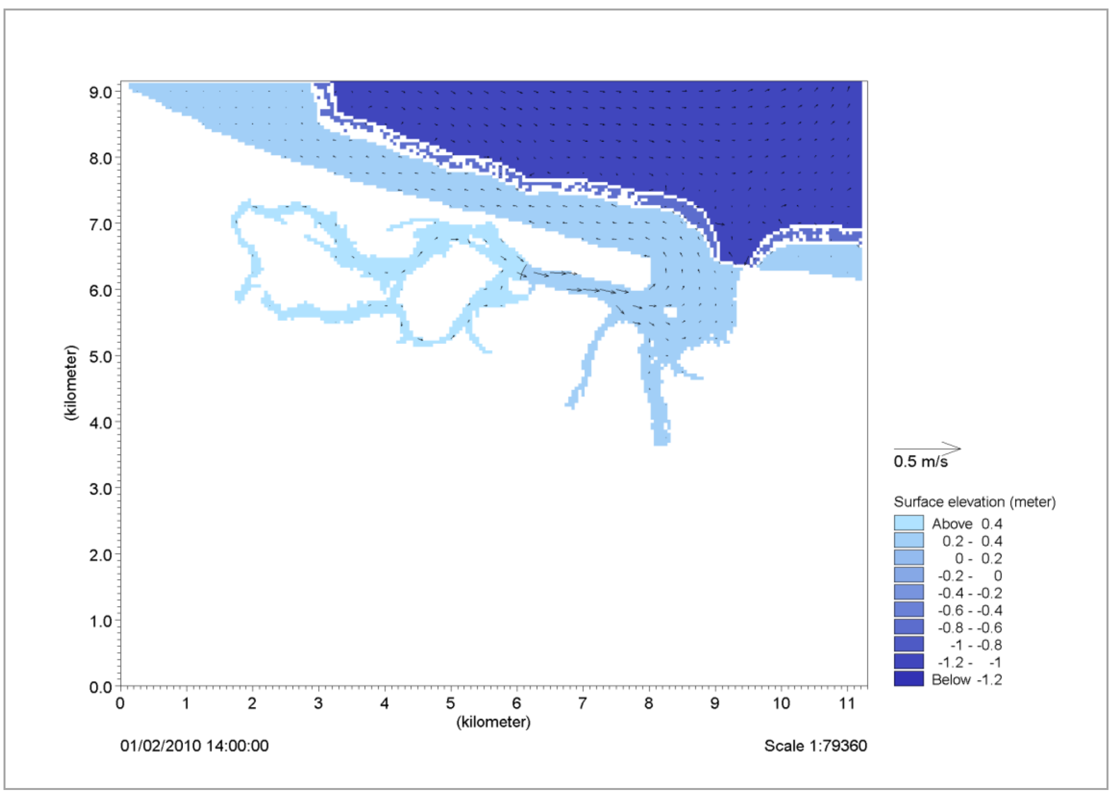

Figure 5.29 Ohiwa Harbour peak ebb tide conditions around 2330 to 1718 years BP.

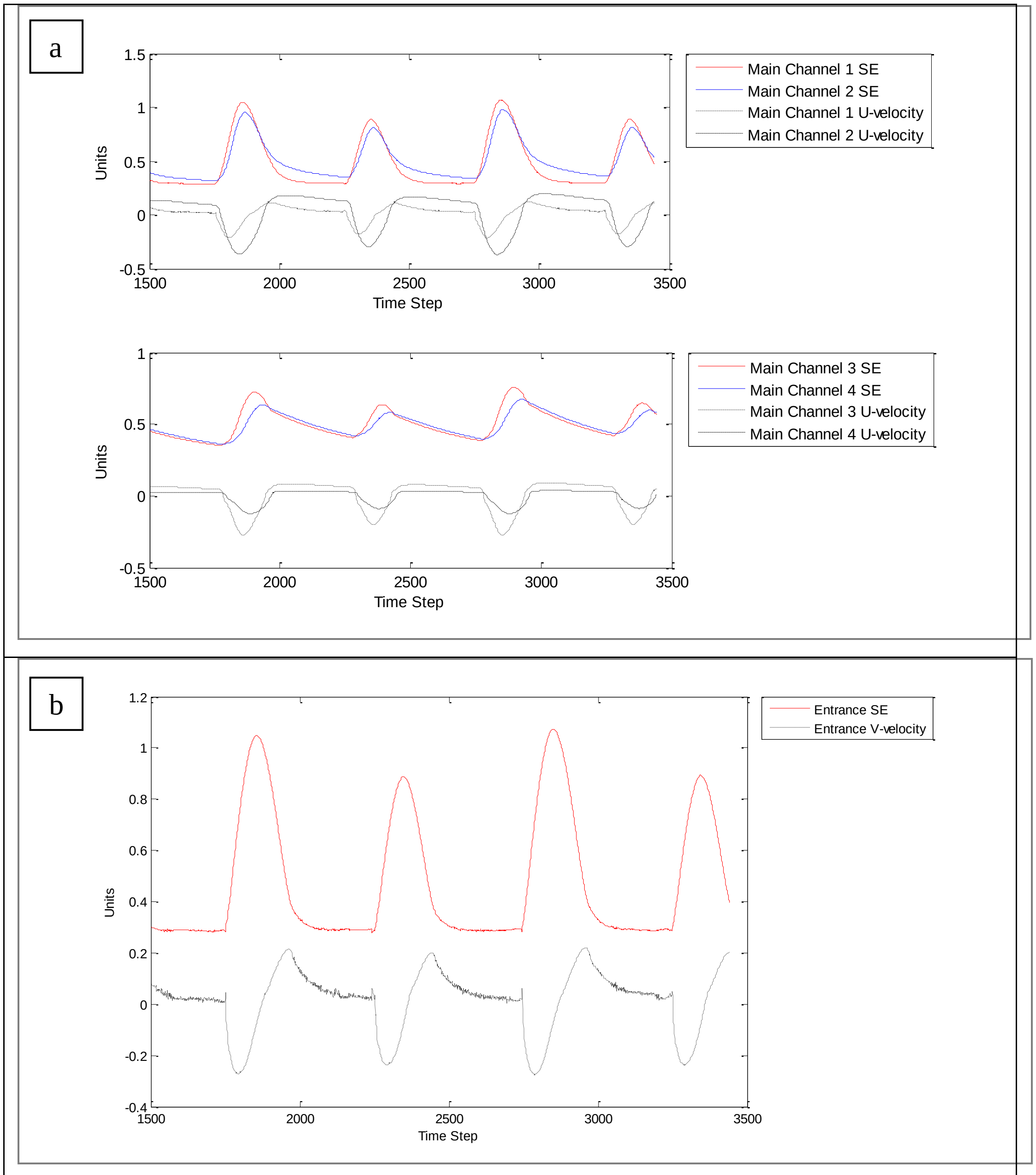

Figure 5.30 Surface elevation (SE) and current velocities at Ohiwa Harbour sites in scenario eight. Surface elevations are in metres above mean sea level while current velocities are in $m.s^{-1}$. (a). Main Channels, (b). Entrance.

5.3.2.9 Scenario nine: 1718 cal yrs BP

The Taupo tephra eruption blanketed the entire harbour with a 6-13cm layer of pumice lapilli and ash. Sea level is close to present (Figures 5.31 and 5.32). Flow conditions and harbour bathymetry is similar to present, but with a couple of differences. The harbour entrance is slightly wider than present because Ohope Spit was shorter than present- it would later increase in length due to deposition of aeolian sand accumulating on the spit (approximately 630m to 940m). Ohope Spit is thinner at the location of possible breaching. All of the major islands within the harbour are close to their current size. Flow conditions are similar to the present in two ways: the extent of flow within the harbour, and the behavior of tidal currents are similar, however the surface elevation is slightly higher on average than present (Harbour entrance and Main Channel 1), and this is despite sea level being the same as present. Compared to the previous scenario, the rise in sea level has caused all of the modelled locations except for the mudflats to be permanently covered in water (Figures 5.33a and 5.33b). Current flows within the mudflats vary but are negligible (+/-0.1m.s^{-1}).

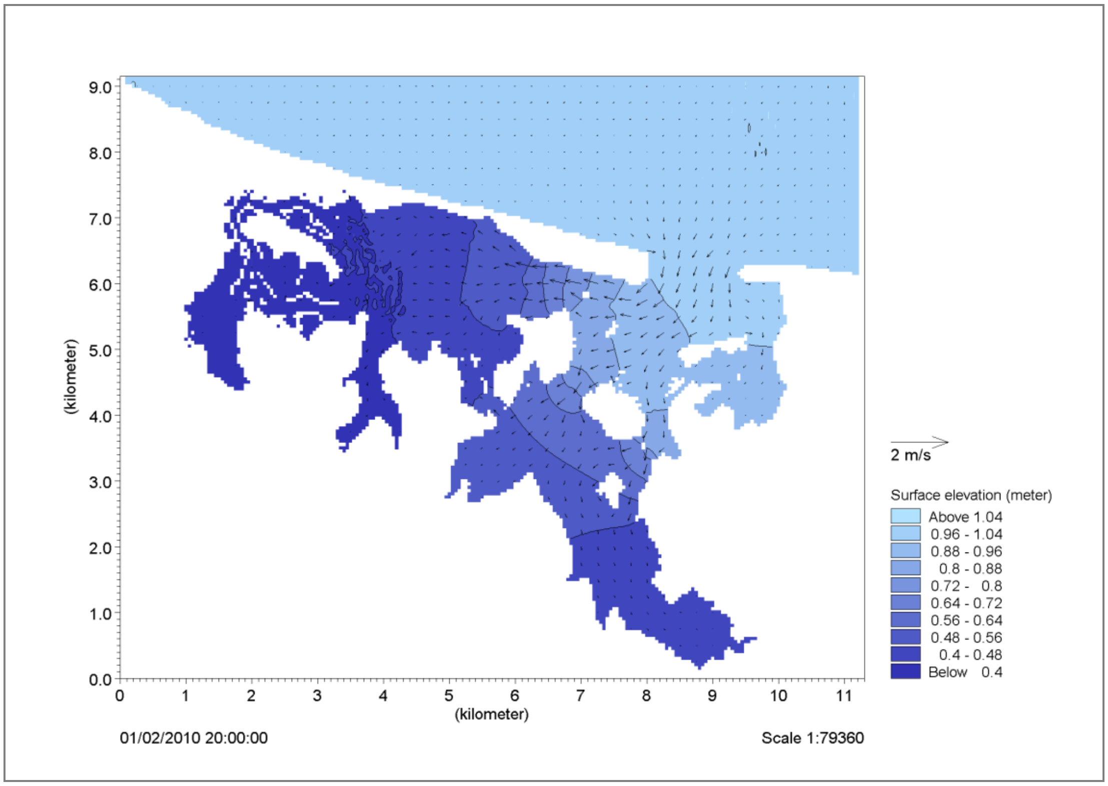

Figure 5.31 Ohiwa Harbour peak flood tide conditions around 1718 years BP.

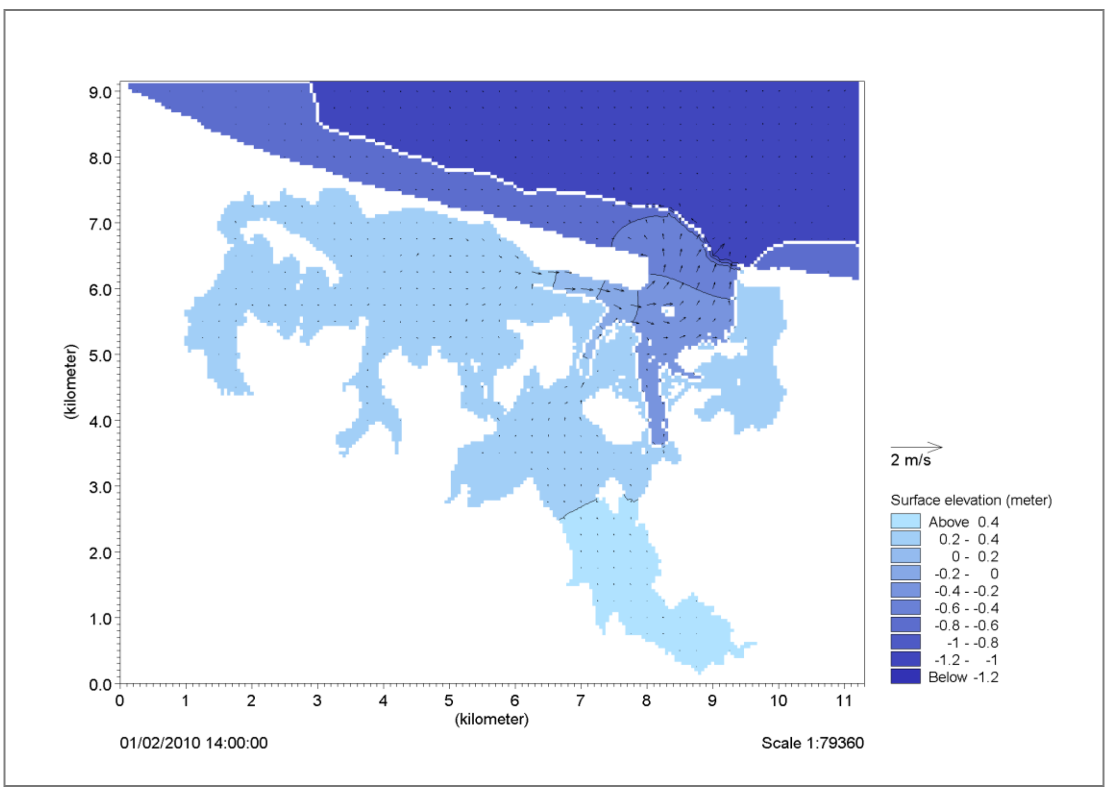

Figure 5.32 Ohiwa Harbour peak ebb tide conditions around 1718 years BP.

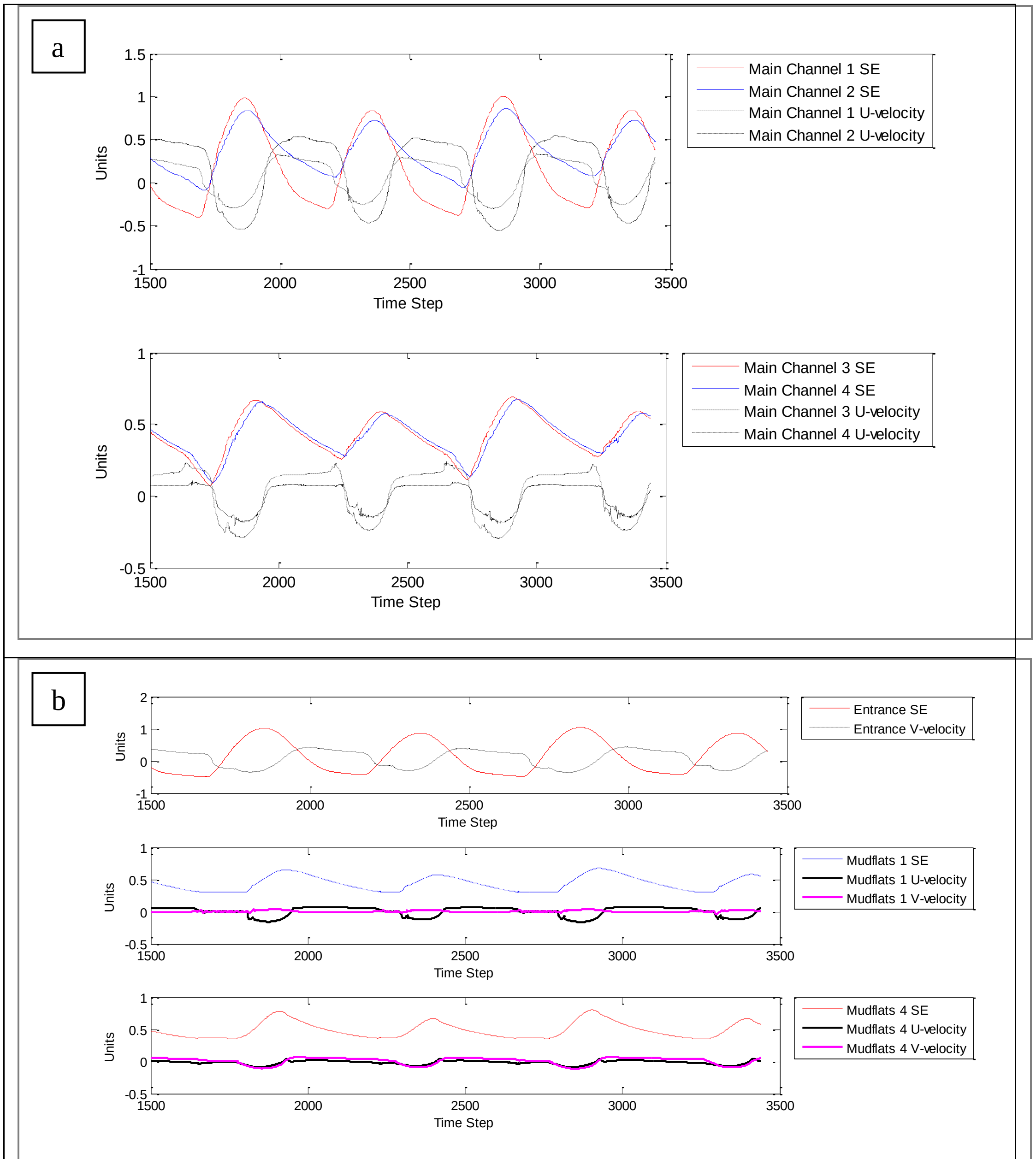

Figure 5.33 Surface elevation (SE) and current velocities at Ohiwa Harbour sites in scenario nine. Surface elevations are in metres above mean sea level while current velocities are in m.s^{-1}. (a). Main Channels, (b). Entrance and Mudflats.

5.3.2.10 Scenario ten: 1718 to 1110 cal yrs BP

An earthquake along the Waimana Fault resulted in up to 2m subsidence within the harbour. Excess volcaniclastic sediment from the Taupo eruption 1718 cal yrs BP was transported from the westward Rangitaiki Plains to the harbour. Ohope Spit then prograded eastward and seaward after the eruption, increasing its width and length (Figures 5.34 and 5.35). Despite the subsidence occurring, there are negligible changes in the harbour hydrodynamics compared with the previous scenario (Figures 5.36a and 5.36b).

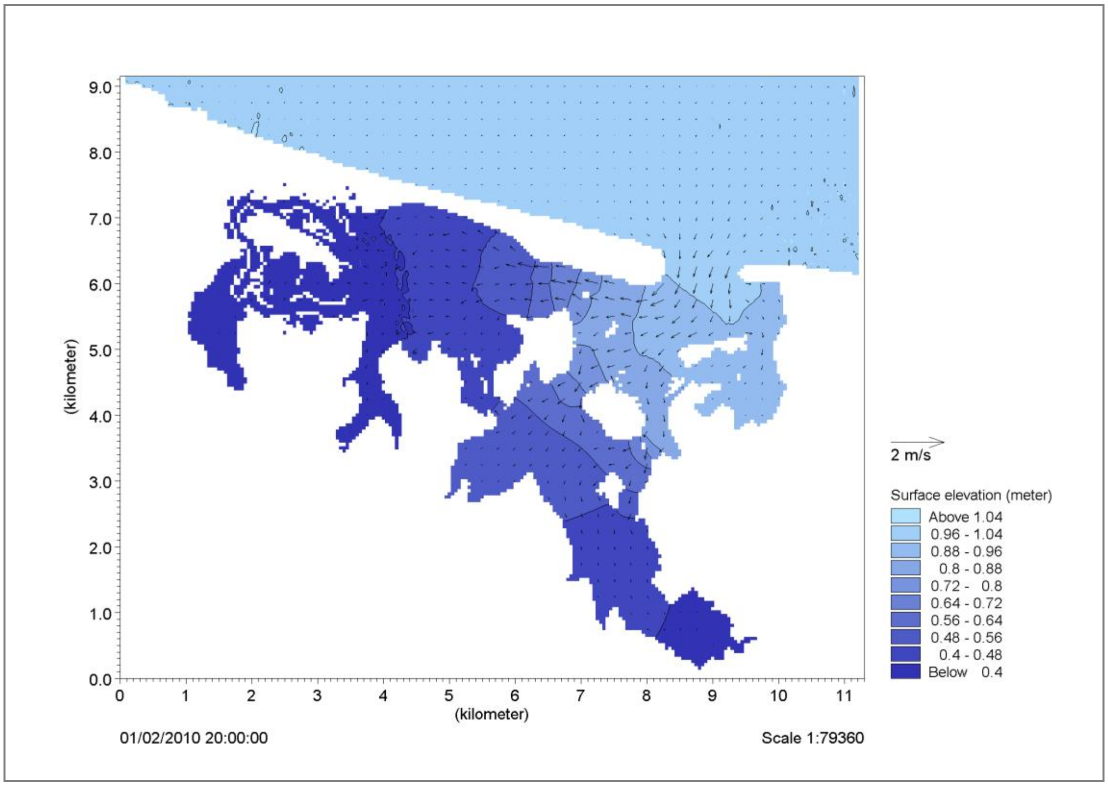

Figure 5.34 Ohiwa Harbour peak flood tide conditions around 1718 to 1110 years BP.

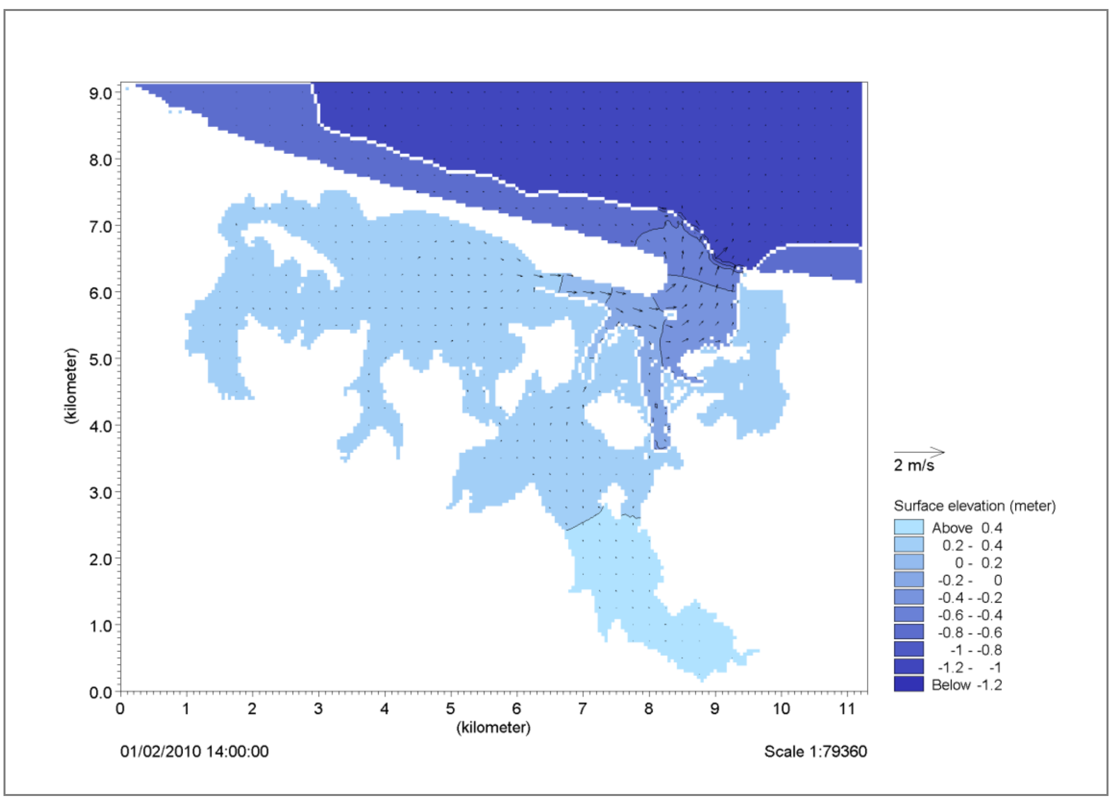

Figure 5.35 Ohiwa Harbour peak ebb tide conditions around 1718 to 1110 years BP.

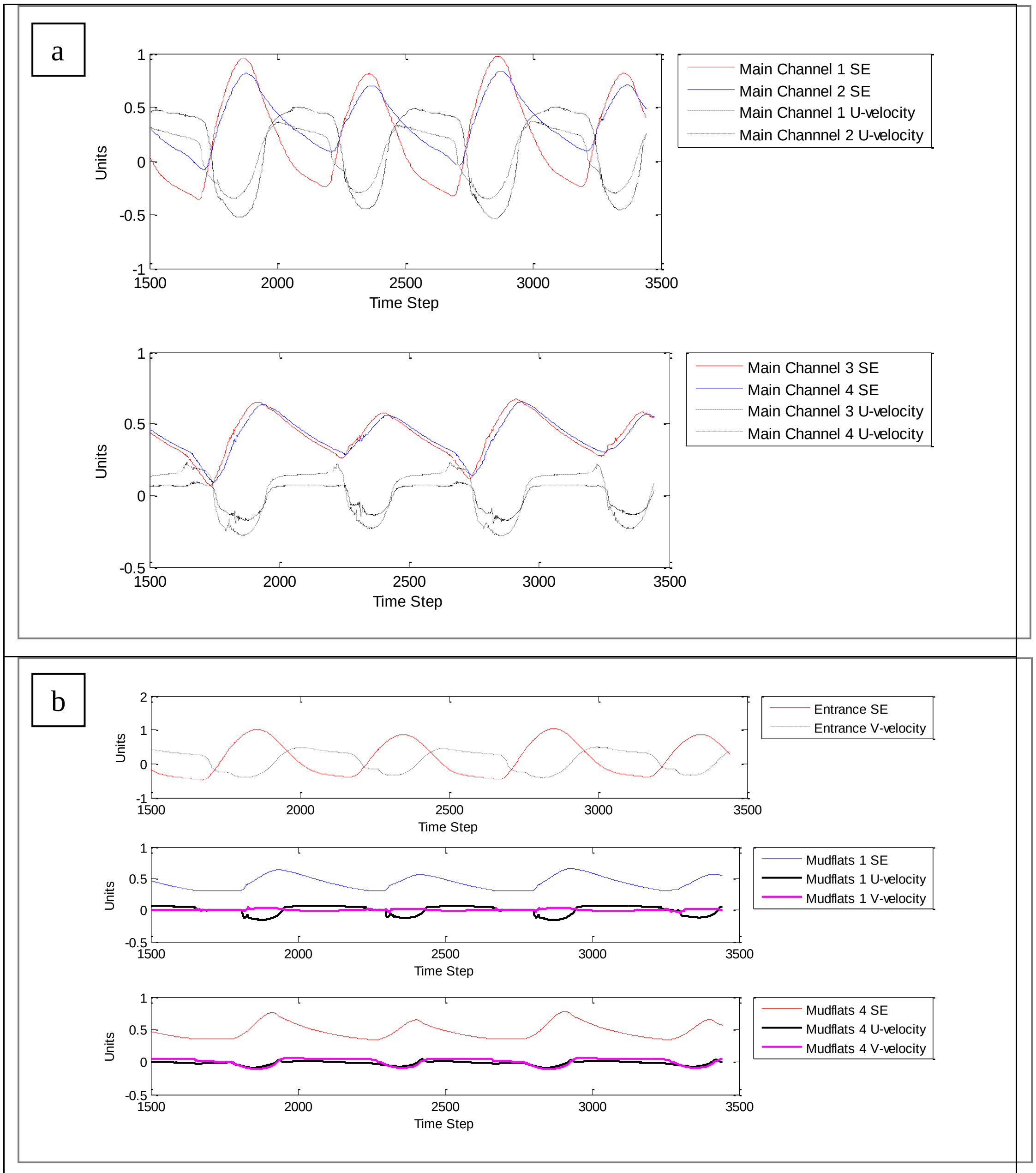

Figure 5.36 Surface elevation (SE) and current velocities at Ohiwa Harbour sites in scenario ten. Surface elevations are in metres above mean sea level while current velocities are in m.s^{-1}. (a). Main Channels, (b). Entrance and Mudflats.

5.4 Summary

The hydrodynamics of Ohiwa Harbour were modelled in response to prehistoric tectonic events since development of the harbour and Ohope Spit commenced. Hydrodynamic modeling was carried out in MIKE 21 for the present scenario, and nine other scenarios based on prehistoric tectonic events determined by Murdoch (2005) and others.

In Ohiwa Harbour, flow velocities depend on the surface elevation of the water and whether or not flow is constricted in the harbour. In the present scenario, flow velocities are strongest at the harbour entrance, being up to $0.6m.s^{-1}$, and in other locations where flow is constricted. Ohiwa Harbour is tidally dominated, with a maximum tidal range of 2m at the entrance. Maximum surface elevation and tidal range decreases further away from the entrance. Mudflat locations dry out during low tide. The other ten scenarios are summarized below.

Scenario one

- Development of Ohope Spit and Ohiwa Harbour commenced
- Channels formed in inner harbour

Scenario two

- Ohope Spit extends out to present position of Waimana Fault
- Increased tidal ranges at harbour entrance by 0.5m
- Increased flow velocities at Main Channel 2 and Main Channel 3 by $0.4m.s^{-1}$, increasing erosion there

Scenario three

- Progradation of Ohope Spit by 2km and the present day harbour entrance is established
- Flow speed was fastest close to the harbour entrance and the distal end of Ohope Spit
- Decreased tidal ranges at Main Channel 2 and Main Channel 3 by up to 0.4m compared with scenario one, but increased tidal ranges at harbour entrance by 0.3m

Scenario four

- Sea level rose to being 1.1m higher than present, but little changes in model output compared with scenario three

Scenario five

- Ohope spit prograded landward
- Sea level fell to being 0.5m higher than present, exposing more of Uretara and Motuotu Islands. Temporary tidal channels formed on either side of these islands

Scenario six

- Waimana fault subsided entire harbour by 2-2.4m
- Severe erosion occurred on the southern ends of Ohope and Ohiwa sand spits
- Surface elevation increased on average by 0.1m across the entire harbour

Scenario seven

- A breach on Ohope Spit created a second entrance channel
- Flow velocities (v-velocities) increased at Main Channel 2, Main Channel 3 and Main Channel 4

Scenario eight

- Mapara tephra was deposited over the harbour
- Sea level was 0.9m lower than present
- Present day main channel was formed; flow was restricted to this channel and a few smaller channels

Scenario nine

- Sea level rose again, being the same height as present.
- Dry mudflats refill up with water again

Scenario ten

- Possible subsidence by 2m within Ohiwa Harbour

6 Chapter Six: Discussion and Conclusions

6.1 Discussion

The information gathered from vibrocoring on Ohiwa Spit suggests that Ohiwa Spit developed at a later time than the neighbouring Ohope Spit within the harbour. This information was gathered from analysis of sediment, organic material and shelly material within the core profiles, along with carbon dating of *Austrovenus stutchburyi* (Cockle) in the cores. The details of these results are in Chapter 4.

A subsidence event may have been identified within cores C and C2, which wasn't found in cores collected by Murdoch (2005) on Ohope Spit. But comparison between cores is not always easy due to elevation differences between the cores and compaction of sediment during vibrocoring, which would cause collected sediment to be observed at a different depth than what it originally was.

SONAR findings (described Chapter 4) within Ohiwa Harbour suggest bedrock may be anchoring the harbour entrance to its current position.

Modelling of Ohiwa Harbour (Chapter 5) shows that pre-historical subsidence of the harbour significantly affected the harbour hydrodynamics, and also helps support the theory that bedrock is keeping the harbour entrance relatively stable. This chapter discusses:

- The information obtained from interpreting the sediment cores on Ohiwa Spit (described in Chapter 4)
- The relationship between subsidence events in Ohiwa Harbour and the harbours modelled hydrodynamics (described in Chapter 5)

6.1.1 Interpretation of Sediment Cores on Ohiwa Spit

Information about the cores in Ohiwa Spit is displayed in Figures 4.2 and 4.3 and Figures 4.7 to 4.11, while carbon dating results are displayed in Figure 4.4.

6.1.1.1 Rock Outcrop and Age of Ohiwa Spit

A possible rock outcrop was found exposed in the harbour entrance curved against the eastward Ohiwa Spit from SONAR (Figure 6.1). From observing Figure 6.1, it can be seen that the cores collected are reasonably close to this outcrop; this may explain why the cores struck a hard layer they could not penetrate resulting in some short cores. In particular, cores A, A2 and B couldn't be drilled more than 1.5 m deep, suggesting the presence of bedrock at the base of these cores. Cores C and C2 were drilled up to 2.4 m, while the trailer mounted rig managed to drill to depths of 7.9 m and 6.4 m at sites D1 and D2 respectively (Figure 6.1). All of the cores except B are close to sea level, so if there is underlying bedrock, it would not be distributed at all the same elevation underneath Ohiwa Spit.

Further, the vibrocorer cannot easily penetrate shell layers, so it is possible that shelly layers within the spit also produced the short core. Geophysical methods such as ground penetrating radar (GPR) and shallow seismic reflection could have been used to assess the sub-surface structure. However, the high water table would limit the application of the University's GPR, and a seismic survey was beyond the scope of this thesis.

The location of the rock outcrop and carbon dating of shelly material from Ohiwa Spit suggest that it developed at a later time than Ohope Spit, which formed when sea level reached approximately the current position. Cores C and C2 are 2.33 m and 2.17 m long respectively. Given that sample Wk 31478 (from core C2) was collected at 1.73 to 1.83 m depth, and dated at 1809+/-37 cal yrs BP, it is assumed that the bottom of these cores (which could be resting on bedrock) is not much older than this, and therefore the age of Ohiwa Spit wouldn't be much older. More samples may need to be cored from Ohiwa Spit, and on Tern Island, which was joined to Ohiwa Spit, in order for this interpretation to have more reliability however. It is likely that Ohiwa Spit was formed sometime between 2330 and 1718 cal yrs BP. Infilling of the Rangitaiki Plains 1935 to 1718 cal yrs BP resulted in surplus sediment being transported into Ohiwa Harbour, infilling the breach in Ohope Spit, and building it up at its distal end (Murdoch, 2005); this surplus sediment may also have been helped initiate formation of Ohiwa Spit. Another possibility is that Ohiwa Spit was formed when a large amount of volcaniclastic sediment from the Taupo Tephra eruption 1718 cal yrs BP was deposited within the harbour. Tephra has not been identified in the cores in this study however.

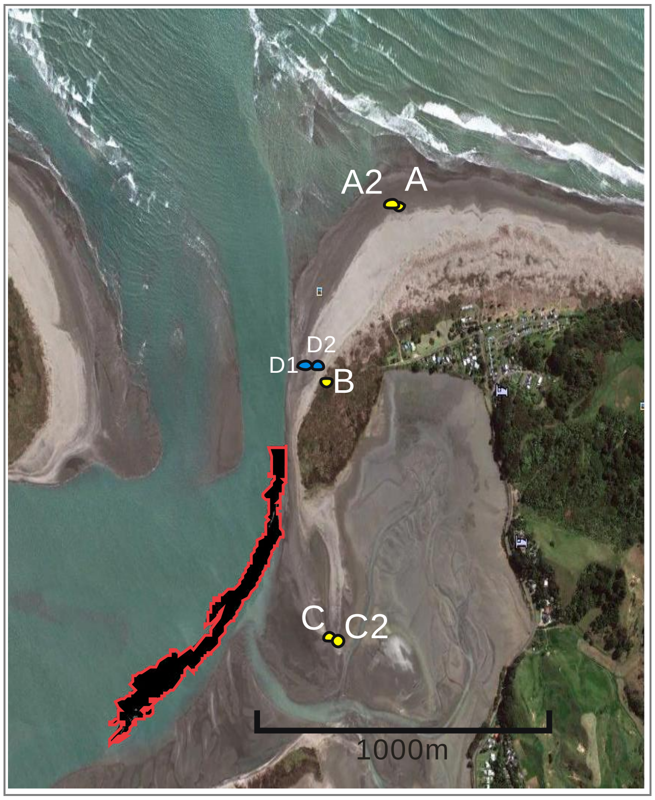

Figure 6.1 Core locations (yellow circles) and drilling locations (blue circles) on Ohiwa Spit, with possible rock outcrop (black with red outline) in Ohiwa Harbour entrance.

6.1.1.2 Subsidence of Ohiwa Spit

Information obtained from the composition of the cores, and carbon dating of shelly material within Ohiwa Spit can give an insight into possible subsidence events on Ohiwa Spit. Known subsidence events in Ohiwa Harbour are in Table 4.2. Two of the most recent known subsidence events were the subsidence of Waimana Fault by 0.6 m from 636 to 575 cal yrs BP and a possible 0.3 to 0.7 m subsidence from the 1866 Taneatua Earthquake. At a similar depth to the subsidence from the Waimana Fault (0.6 m), an abrupt change in the core profiles A, A2 and C2 are observed. Core A (Figure 4.7) shows graded shell fragments and an increase in grain-size at 0.57 to 0.71 m depth. Core A2 (Figure 4.8) shows a shelly layer at 0.78 m depth not found elsewhere. Core C2 (Figure 4.11) shows shell fragments at 0.69 to 0.98 m depth; however vibrocoring sometimes has an issue where the sediment gets displaced by compaction, so the actual depths of the sediment may be differ slightly. Core B was collected at a higher elevation and cannot be directly compared to the other cores due to its length, since it does not penetrate below sea level. As suggested by Goff et al in

GeoEnvironmental Consultants (2004) for similar layers found in cores further inland, these abrupt changes in the cores could be related to subsidence associated with the Waimana Fault or Taneatua Earthquake.

Additional subsidence may have occurred on Ohiwa Spit however, which wasn't identified in Bruce Murdoch's cores on Ohope Spit. This is implied in Figure 4.4, where some of the dated samples in this study are much younger than in Murdoch (2005) despite being at a similar depth. However, analysis of cores C and C2 may reveal more information. Shell samples Wk31477 (core C2) and Wk31479 (core C) have similar ages and are at a similar depth. Wk31477 is dated at 356 +/- 42 cal yrs BP while Wk31479 is dated at 571 +/ -41 cal yrs BP; both are at 1.2 to 1.4 m depth. Wk31478 (core C2) is dated much older with an age of 1809 +/- 37 cal yrs BP, yet it is not much deeper at a depth of 1.7 to 1.8 m. Furthermore, around the 1.4 m depth mark in core C2 (and 1.7 m depth in core C) there is a change in the profile marked by increased grain size and variation, abundance of shelly material and increased organic content. This suggests a change in the wave energy and hydrodynamics in the environment at that time, or perhaps an erosional contact associated with faulting. If it was subsidence, the dating of the event would almost certainly not match with the known subsidence events in Table 4.2.

6.1.2 Relationship between Subsidence events in Ohiwa Harbour and its Hydrodynamics

Table 6.1 summarises changes in the surface elevation observed at each modelling scenario. The details are explained in Chapter 5.3.2. Raising the sea level increased tidal range and surface elevation in the harbour in most sites. Subsidence also has the same effect as rising sea level on the harbour hydrodynamics. The harbour entrance didn't always behave the same way as other sites, primarily because the hydrodynamics there were influenced by the width of the harbour entrance. In the earlier scenarios where the entrance is wider, less flow would be observed at the site 'Entrance' because flow is more spread out. As Ohope Spit (and later Ohiwa Spit) grows, flow at the entrance becomes more constricted, average surface elevation increases and erosion of the sand spits at the entrance should increase (see Chapter 6.4).

Table 6.1 A summary of the changes in surface elevation that occurred in each modelled scenario.

Scenario	Scenario Number	Model Changes	Surface Elevation Changes
7410 cal yrs BP	1	Sea level 0.13m lower than present	Na
4500 cal yrs BP	2	Sea level close to present	Increased tidal range at most sites. Decreased surface elevation at entrance
4190 cal yrs BP	3	Sea level 0.67m higher than present	Decreased tidal range at most sites. Small increase in surface elevation at entrance
4190 to 3515 cal yrs BP	4	Sea level 1.1m higher than present	Increased tidal range at most sites. Small decrease in surface elevation at entrance
3515 to 2780 cal yrs BP	5	Sea level 0.5m higher than present	Decreased tidal range at all sites. Increased surface elevation at entrance
2780 to 2425 cal yrs BP	6	Sea level 0.2m higher than present. Subsidence 2-2.4m	Decreased tidal range and increased surface elevation at all sites
2425 to 2330 cal yrs BP	7	Sea level close to present. Breaching of Ohope Spit	Increased tidal range at all sites. Increased surface elevation at Mudflats 1 and 4. Decreased surface elevation at entrance
2330 to 1718 cal yrs BP	8	Sea level 0.9m lower than present	All locations dry out during low tide. Mudflats permanently dry
1718 cal yrs BP	9	Sea level close to present. 2.5-3m subsidence	Re-flooding of all modelled locations
1718 to 1110 cal yrs BP	10	Sea level close to present. Possible 2m subsidence	Little changes compared to previous scenario
Present		Sea level at present. Full development of Ohiwa Spit and Tern Island	Small increase in surface elevation at entrance and Main Channel 1, little changes elsewhere

[1] Refer to chapter 5.3.2 for details.
[2] Modelled locations (including mudflats and Main Channel 1) are shown in Figure 5.1.

6.1.3 Erosion and Accretion of Ohope and Ohiwa Sand Spits

Hydrodynamic modelling of Ohiwa Harbour revealed the strongest currents to be in the entrance, where Ohope and Ohiwa Spit meet. This should mean that erosion on the distal ends of the sand spits would happen faster, in particular Ohiwa Spit, because sediment is transported into the harbour primarily from the west. Erosion of the sand spits would also depend on the net sediment transport, as strong currents that merely transport the same sediment around will not result in any long term trend. Determining sediment transport was beyond the scope of this study however. This study is interested in the influence of recorded subsidence events on the flow velocities near the harbour entrance and the morphology of Ohope and Ohiwa sand spits, which would also be influenced by it (Table 6.2).

In theory, subsidence of the harbour would cause a rise in relative sea level, and increased flow velocities near the harbour entrance; this increased flow would accelerate erosion of Ohope and Ohiwa spits. This was not always observed in the DHI models however. Subsidence didn't always cause increased flow velocities at the harbour entrance. If subsidence did increase flows at the entrance, it did not always increase erosion on Ohope and Ohiwa Spits. In scenarios where sea level changed, but subsidence wasn't involved, flow velocities increased at the harbour entrance (scenarios 1-5 and 8, Table 6.2). In scenarios where subsidence was involved, flow increased at the harbour entrance in scenarios 9 and 10. However, flow decreased in the entrance during scenarios 6 and 7. A breach created in Ohope Spit during scenario 7 would divert some flow away from the entrance, explaining the decreased velocities and erosion there. A sea level drop by 0.5m in scenario 6 (compared to scenario 5) would result in a reduced tidal prism which would contribute to reduced velocities at the harbour inlet.

There are a number of possible reasons why subsidence in Ohiwa Harbour didn't always increase flow at the entrance and accelerate erosion of the sand spits. While subsidence has increased the depth and volume of Ohiwa Harbour, volcanic eruptions (such as the Taupo tephra eruption 1718 cal yrs BP) have supplied sediment into the harbour and helped fill it. This would undo some of the effects of subsidence. The exact effects of subsidence on the morphology of Ohiwa Spit are unknown, but the results obtained from hydrodynamic modelling of the harbour are not in vain. If Ohiwa Spit was formed 2330 to 1718 cal yrs BP as suggested, it should have significantly eroded since then, given that the strongest flows accelerated around the distal ends of the spit in the models. If Ohiwa Spit didn't erode, the harbour entrance and spits should have migrated somewhat, yet they haven't. This presents a good case for a resistant rock outcrop in the entrance (along with the information gathered from

SONAR in Chapter Four), which would cause water to flow around it instead of erode it, keeping the entrance in a relatively stable position. Modelling the harbour entrance had its limitations however, as it measures the response of the harbour hydrodynamics to changes in morphology of the harbour, and not the other way round. These morphological changes were based on data from Murdoch (2005). His data had some limitations, but his model for development of the harbour does convincingly fit with other coastal sites along the Coromandel/Bay of Plenty Coasts.

Table 6.2 A summary of the changes in flow velocities at the harbour entrance and Main Channel 1 that occurred in each modelled scenario. Also includes changes in the morphology of Ohope and Ohiwa Spits.

Scenario	Model Changes	Maximum velocities (Entrance)[1]	Maximum velocities (Main Channel 1)[1]	Changes in morphology of Ohope and Ohiwa Spits[2]
7410 cal yrs BP	Sea level 0.13m lower than present	0.3	0.1 to 0.16	
4500 cal yrs BP	Sea level close to present	0.33 to 0.44	0.18 to 0.23	Accretion of Ohope Spit
4190 cal yrs BP	Sea level 0.67m higher than present	0.45 to 0.7	0.43 to 0.49	Accretion of Ohope Spit
4190 to 3515 cal yrs BP	Sea level 1.1m higher than present	0.55 to 0.8	0.5 to 0.56	Landward migration of Ohope Spit
3515 to 2780 cal yrs BP	Sea level 0.5m higher than present	0.45 to 0.7	0.4 to 0.53	Ohope Spit progrades landward
2780 to 2425 cal yrs BP	Sea level 0.2m higher than present. Subsidence 2-2.4m	0.36 to 0.5	0.29 to 0.44	Erosion of southern ends of Ohope Spit
2425 to 2330 cal yrs BP	Sea level close to present. Breaching of Ohope Spit	0.27 to 0.5	0.2 to 0.37	Breach in Ohope spit.
2330 to 1718 cal yrs BP	Sea level 0.9m lower than present	0.2 to 0.28	0.11 to 0.22	Breach in Ohope spit infilled. Growth of distal end of Ohope. Possible first development of Ohiwa Spit
1718 cal yrs BP	Sea level close to present. 2.5-3m subsidence	0.31 to 0.43	0.25 to 0.34	Similar to previous scenario
1718 to 1110 cal yrs BP	Sea level close to present. Possible 2m subsidence	0.36 to 0.47	0.3 to 0.37	Growth of Ohope Spit eastward and seaward
Present	Sea level at present. Full development of Ohiwa Spit and Tern Island	0.44 to 0.58	0.37 to 0.45	Growth of Ohope Spit, Development of Ohiwa Spit and Tern Island

[1] Maximum flow velocities during ebb and flood tides respectively, in $m.s^{-1}$.
[2] Refer to Murdoch (2005) Chapter Four.

6.2 Summary and Conclusions

6.2.1 Holocene Hydrodynamics of Ohiwa Harbour

Hydrodynamic modelling was carried out on Ohiwa Harbour using DHI MIKE 21 flow modelling software. Modelling was carried out in order to determine the prehistoric changes in harbour hydrodynamics in response to tectonic events, as determined by the conceptual model of Murdoch (2005). Modelling of present day Ohiwa Harbour revealed the estuary flow to be tidally dominated, with dissipation of the tidal wave away from the entrance. The entrance also recorded the strongest flows in the harbour.

Ten scenarios were created for modelling prehistoric changes; in each scenario the sea level or bathymetry of the harbour was modified. Scenarios one to ten occur in chronological order. Scenario one (7410 cal yrs BP) occurs when the formation of Ohiwa Harbour initiated. Surface elevation at most recorded sites is the same, except for mudflats which are dry at low tide. Current strength is up to $0.1 m.s^{-1}$ at most sites, gradually increasing to the west up to $0.4 m.s^{-1}$ (Main Channel 1). In scenarios two to three (4500 and 4190 cal yrs BP), Ohope Spit accretes at the distal end and sea level rises. The resulting effect is decreased tidal ranges by 0.2 to 0.7m, more so in locations sheltered from the open ocean by Ohope Spit, such as Main Channel 2. Increased flow velocities are also recorded in all locations, increasing by 0.3 to $0.4 m.s^{-1}$, except at Main Channel 3 and the mudflats.

In scenario four, mean sea level rises; tidal ranges increase at most sites by 0.3 to 0.45m and flow velocities increase at the harbour entrance. A drop in sea level during scenario 5 created temporary tidal channels on either side of Uretara and Motuotu Islands which have increased velocities. Sea level dropped the most in scenario 8, being 0.9m lower than present. In scenario 8, flow was restricted to the main channels and entrance.

Out of the ten scenarios, four involved subsidence, these being scenarios 6, 7, 9 and 10. In scenarios 9 and 10, subsidence increased flow velocities by more than 50% at the harbour entrance; this increased flow was expected. In scenarios 6 and 7 this didn’t happen however. A drop in sea level during scenario 6 resulted in a smaller tidal prism and hence reduced flow velocities at the inlet. The formation of a breach in Ohope Spit created a second tidal channel which diverted flow away from the current harbour entrance, which had decreased flow velocities (Scenario 7).

6.2.2 Ohiwa Spit Subsidence and Stability of Harbour Entrance

Analysis of sediment cores on Ohiwa Spit suggests that additional subsidence may have occurred on Ohiwa Spit, than what was recorded on Ohope Spit from Murdoch (2005). This is based on radiocarbon dating of shell material on Ohiwa Spit, which revealed much younger ages than samples on Ohope Spit at similar depths. A large gap in radiocarbon ages of *Austrovenus stutchburyi* in core C2 over a small depth would support the theory of additional subsidence. A possible subsidence event was located at depths of 1.5-1.7m in cores C and C2, based on abrupt changes in the core profiles there. However it is currently difficult to determine if this change in profile was due to subsidence or some other event such as storm inundation.

Fluctuations in El Nino/La Nina have caused small fluctuations in the location of Ohiwa Harbour entrance, but its location has largely remained stable the past 7ka despite strong erosion occurring at the entrance. Constraints on the vibrocoring depths collected from Ohiwa Spit suggested that an impenetrable surface underlies part of the spit. SONAR in the harbour entrance also found a possible outcrop of this rock on the eastern side. This erosion resistant rock would help explain why the location Ohiwa Harbours entrance is largely stable.

6.3 Recommendations and Future Research

This study had some limitations which need to be addressed so as to pave the way for future research in Ohiwa Harbour and elsewhere. A number of cores collected from Ohiwa Spit weren't very long, so the information obtained from them is limited. Collecting more core samples from Ohiwa Spit and Tern Island would be ideal; the latter may require resource consent from the Bay of Plenty Regional Council. More information about Ohiwa Harbour's geological history would be gathered from these cores. Analysis of tephra in the core samples would help with identifying volcanic events in Ohiwa Harbour's history. More samples should be radiocarbon dated on Ohiwa Spit also, to more accurately date subsidence events on the spit. SONAR revealed a possible rock outcrop in Ohiwa Harbour entrance, this outcrop should be analysed in more detail, and samples collected where possible. Ground penetrating radar and shallow seismic reflection could be carried out on Ohiwa Spit, along with vibrocoring, to ground truth geophysical data there. In spite of some of these limitations, vibrocoring on Ohiwa Spit still revealed a lot of useful information about Ohiwa Harbour in this study.

For hydrodynamic modelling, a sediment transport model could be constructed of prehistoric Ohiwa Harbour, in order to determine erosion/accretion rates on Ohope and Ohiwa Spits. Tsunami modelling in Ohiwa Harbour would also be important, as it is an earthquake prone area, and it would be important to people who make use of the harbour.

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