The Tsunami and Co – Seismic Subsidence History of the Orowaiti Estuary, Westport, New Zealand

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UNIVERSITY OF CANTERBURY

Te Whare Wānanga o Waitaha

CHRISTCHURCH NEW ZEALAND

Frontispiece

A view down the transect location in the Orowaiti Estuary. Note the particularly damp conditions

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Abstract

The Orowaiti Estuary is located east of the town of Westport on the west coast of the south island, New Zealand. Surface and sediment records were recovered and analysed in an attempt to identify evidence of tsunami and co – seismic subsidence in the estuary. Proxies utilised for identification were sedimentology, palaeontology and geochemistry, along with historical records for correlation. The transect representing the modern environment behaved in a manner typical of New Zealand estuarine environments. It supported a gradient of sedimentology which correlated with tidal heights. It also exhibited a number of different genera of the microbenthic Foraminiferida. The dominant genera observed in the transect were repeated in the core at depth, suggesting a period of either erosion or subsidence in the estuary to prevent a gradual decrease in mean water level over time.

Caesium isotope dating revealed evidence of relatively shallow peaks in radioactivity in the core, placing the 1930's above the suspected subsidence or flooding event influencing foraminiferal distribution. ICP – MS analysis highlighted a section of the core below this where small increases in all common pollutants, including mercury appeared. This was correlated with the middle 1800's, where the gold rush was at its height. Due to bioturbation in the lower core sections, it was concluded that co – seismic subsidence was most likely responsible for the lack of speciation in the core compared to the transect. The suspected seismic event responsible was thought to be the potential 1717 Alpine Fault rupture. It was chronologically fitting, and was the only documented major rupture before the gold rush. Flooding evidence was thought to have occurred further up the core, in an undisturbed, sand dominated section that could be correlated to a 1979 avulsion of the Buller River into the Orowaiti. No evidence was found the supported the occurrence of tsunami in the Orowaiti estuary

1.0 Introduction

Little research has been conducted on the tsunami and subsidence history of Westport, a town on the West Coast of the South Island, New Zealand (Goff & Chague – Goff, 2015). To date, investigations have been undertaken both north and south of Westport, with the most notable southern subsidence and tsunami investigation occurring at the Okarito Lagoon 200 kilometres south of Westport (Nicol et al, 2007). Most research that has taken place in the North has been done on sheltered beach deposits (Goff et al 2010). Tsunami inundation of a low energy area, such as an estuary, sheltered beach or rice paddy can leave particular geochemical (Veerasingam et al, 2014), sedimentological (Le Roux & Vargas, 2007) and biological (Dominey – Howes et al, 2006) markers. Examples of these are spikes in heavy trace metals, sedimentary grading up a shoreline and the presence of organisms usually found in deeper water, such as specific foraminifera (Dominey – Howes et al, 2006).

This research thesis investigates of the Orowaiti Estuary; a small estuary east of the township of Westport. It was targeted due to it being a protected and sheltered area of the Estuary, away from seasonal storm influence which could disturb the sediment record. A surface transect and a sediment core were collected, with the goal of identifying any past Tsunami or co – seismic subsidence. As of the writing of this thesis, there have not been any palaeotsunami and/or co - seismic subsidence investigations in the Orowaiti Estuary (Goff & Chague – Goff, 2015). In fact compared to the east coast of New Zealand, the west has had very few studies undertaken concerning inundation and subsidence (Goff et al, 2010), (Nicol et al, 2007). This means that there is little related literature, and that proxies for identification have been utilised based on nation and region – wide studies in place of more localised publications.

Estuaries are low energy environments and therefore have good preservation potential for singular events such as a tsunami, or prolonged inundation or uplift related to subsidence (Goff et al 2010). The easterly section of the estuary is protected from the high energy West Coast shoreline, which has also undergone modifications by man since the township's inception and would therefore not be suitable for the study (Buller District Council, 2016), as a complete sediment record would be difficult to locate in such a dynamic area (Nicol et al, 2007).

1.1 Background Geology

The Buller District, and much of the North Western area of the South Island is built on a terrane known simply as the 'Buller' (Adams, 2004). This terrane, or sequence of rocks, is only present on the Western side of the Southern Alps, with another terrane known as the 'Takaka' lies to the East (Adams, 2004), (Fig 1.0). The Buller and Takaka Terranes are made up of early Palaeozoic rock. The part of The Buller terrane that outcrops in the Buller region is composed of carbonate, granitoids, siltstones, sandstones and mafic volcanics, but is dominated by deep water turbidites and shales (Jongens, 2006).

Quaternary sediment overlies the aforementioned units in much of the low – lying areas of The Buller District (Jongens, 2006). It is composed mostly of sediments sourced from the hinterlands, and therefore has chemical and physical traits from all the aforementioned units, along with a calcareous signature present in more recent Eocene rocks (Jongens 2006). This is exhibited at Cape Foulwind, where a body of limestone is quarried (Buller District Council, 2016). All of these formations contribute to the chemical and sedimentological properties of areas such as The Orowaiti Estuary (Nicol et al, 2007), affecting variables such as average grain size and background trace element concentrations. These quaternary sediments are obviously absent in hills and mountain ranges, as these areas lack accommodation space, and gravity dictates particle collection in low lying levels.

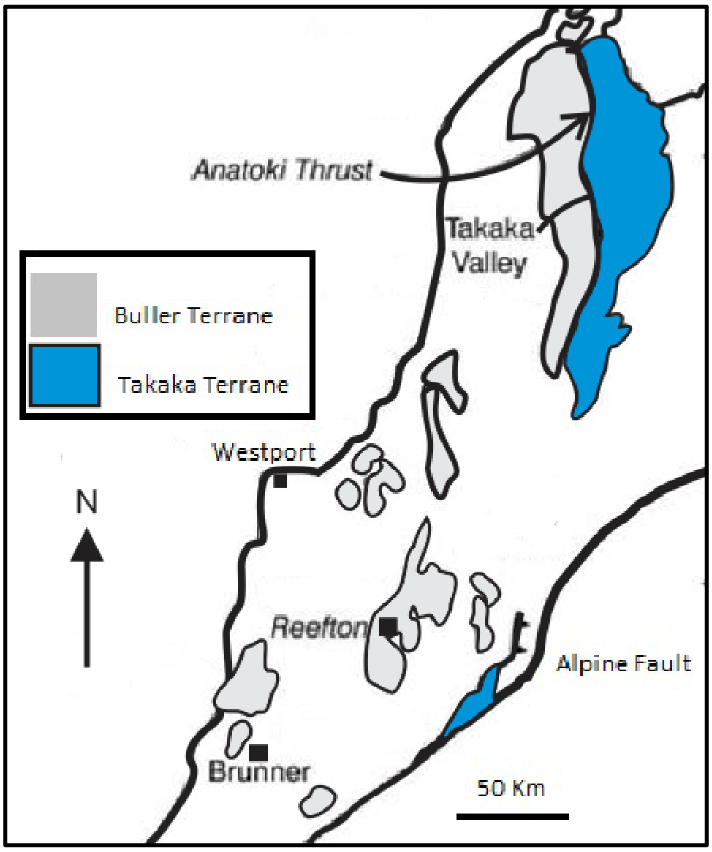

Fig 1.0 Present day outcrop locations of the Buller and Takaka terranes. Note the dominance of the Buller proximal to Westport (Adapted from Adams, 2004)

1.1.2 Regional Faulting

There are two offshore faults in close proximity to Westport; the Kongahu and Cape Foulwind faults (Stafford et al 2008). The town is also proximal to the Alpine Fault, which is thought to have a shorter recurrence interval than those offshore, and is therefore evidence of it rupturing is more likely to appear in the sedimentary record of the area (Stafford et al 2008). It is inland, as opposed to the other two which are offshore (Stafford et al 2008). This reduces the possibility of a tsunami being associated with it, as there is no seafloor offset to drive the wave (Srinivasalu et al, 2010). This does not rule out the chance of subsidence occurring, however, which could also be recorded in the local sediment record (Hayward, 2010).

In conjunction with the main faults of the Buller District, there are a number of lesser known, typically less active faults. These include the Inangahua, known for a large earthquake in 1968 McCahon et al, 2006). The White Creek and Lyell River faults are also included in the local map (Fig 1.1). Part of the White Creek fault was the source of the 1929 rupture (McCahon et al, 2006). Offshore, the Elizabeth and Razorback faults are included. Little is known of these faults, but due to their proximity to the active Cape Foulwind fault sequence they were included as potential sources of seismic activity in the area.

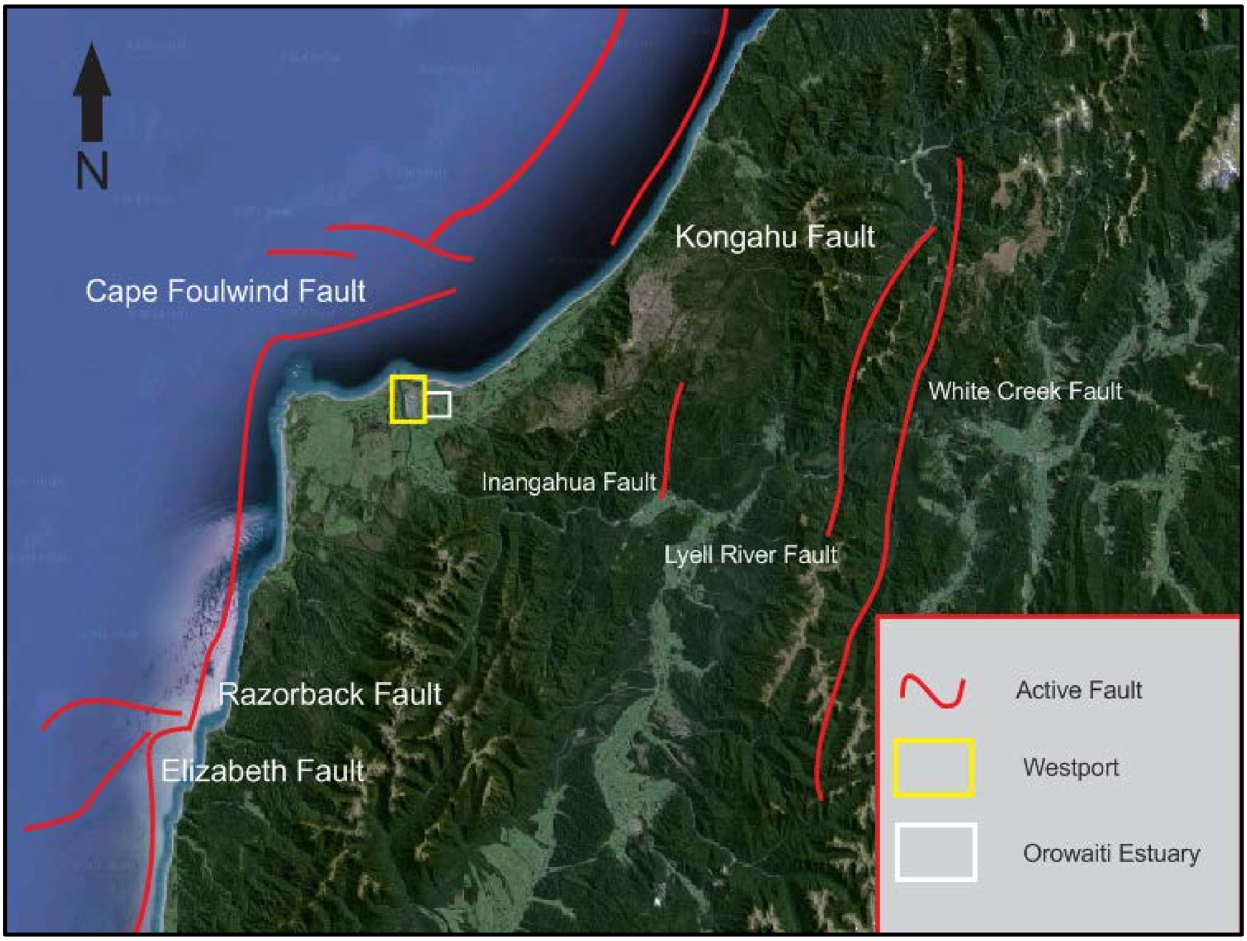

Fig 1.1 Map of active faults proximal to the Westport area. Out of shot; Alpine fault, can be seen in (Fig 1.0)

1.2 Historical Records of Seismic Events in Westport and New Zealand

As previously mentioned, the West Coast of New Zealand has had comparatively few investigations undertaken into its palaeoseismology (Goff et al, 2010). In terms of the township of Westport, there have officially been none. In terms of nationwide studies, the majority have been investigated in what are classed as ‘susceptible’ areas (Goff et al, 2010). This is despite the extensive seismic history of the area since colonisation (Fig 1.2).

More commonly researched areas include places like the Marlborough Sounds, The Hawke’s Bay and Bay of Islands (de Lange & Moon, 2007). The reasoning behind the lack of investigations on the west coast can be divided into three categories; historic bias, seismology and cultural recollection. In terms of bias, at the time of colonisation in New Zealand there were preconceptions about tsunami (Goff, 2008). These included the idea that faults were less active on their non – subducting side (Goff, 2008). This would place the west coast of the south island in the less active category. Since then, the second point of seismology has been rarely investigated in the Buller region, despite the North Western region of the south island being described as a highly seismic zone (Stafford et al, 2008)

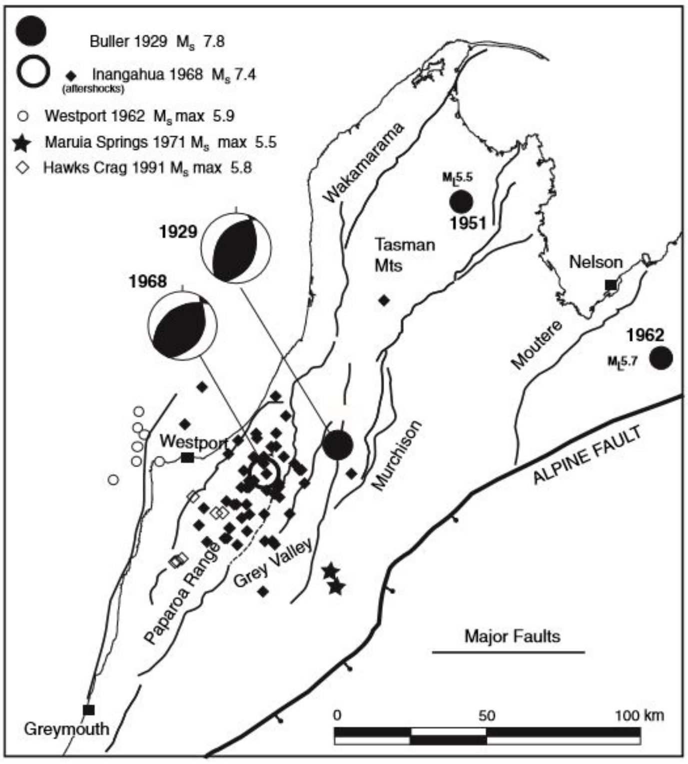

Fig 1.2 Localities and magnitudes of historical earthquakes proximal to Westport and the Orowaiti Estuary (Stafford et al, 2008)

There have been a small number of papers on the Kongahu (Inwood, 1997) and Cape Foulwind faults (Stafford & Pettinga, 2008); the dominant fault sets in the region, but no adamant recurrence interval or definitive potential magnitude for either set has been determined, although Stafford & Pettinga, (2008) suggest that utilising fault length and slip history could be used to compile a recurrence interval. This being said there is no complete history to date. This has resulted in a state where apart from The Alpine Fault, there is not a complete definitive history of seismology for the township of Westport and surrounding Buller region. There are only the historical events, along with research on the Alpine fault, revealing a potential date for the last rupture in 1717 (Robinson & Davies, 2013). The earthquakes in Table 1.0 occurred on other proximal faults. They are all post - colonisation of New Zealand, as of the time of this writing there was no complete verified history of rupture events previous to this (Table 1.0).

Table 1.0 Chronological order of large historical earthquakes in the Buller district. Alpine fault source (Robinson & Davies, 2013), all other events (geonet.org)

Date	**Location**	**Magnitude**
1717, exact date unknown	Last Estimated Alpine Fault Rupture	8.1
1st September, 1888	Lewis Pass – Southern Alps	7.0
9th March, 1929	Arthur’s Pass – Southern Alps	7.0
17th June, 1929	Murchison, Buller District	7.3
10th May, 1962	Westport	5.6
24th May, 1968	Inangahua, Buller District	6.7
August 16, 1971	Maruia Springs, Buller District	5.5
28th January, 1991	Buller Ranges, Hawks Crag	6.1
29th January, 1991	Buller Ranges, Hawks Crag	6.3
18th June, 1994	Arthur’s Pass – Southern Alps	6.7
24th November, 1994	Arthur’s Pass – Southern Alps	6.3

1.2.1 West Coast Tsunami History

There is a lack of evidence indicating any recent inundation in the Westport or greater Buller region. This is primarily due to a lack of investigation and the short length at which people have inhabited New Zealand (de Lange & Moon, 2007). Due to these factors, the region does not have a complete seismic history, although recent terrestrial failures have been well documented for the area (Stafford & Pettinga, 2007). Recent earthquakes, and some older ruptures, especially along the Alpine Fault have been recorded but the records do not extend further than the late 18th century, aside from potential Alpine Fault failures (Robinson & Davies, 2013). These have all been land based; subsidence would be expected as a reaction to the rupture. The only paleotsunami record for the west coast was discovered by Nicol et al, (2007) who found conclusive evidence in the Okarito Lagoon, utilising techniques used in this study to isolate an area dated between 1320 and 1450 AD thought to be a tsunami deposit.

It is important to note that historically the occurrence of tsunami on the West coast of New Zealand has been widely discredited (Goff, 2008). This is due to the perceived inactivity of areas on the non – subducting side of a fault. In the case of New Zealand, much of the west coast of the South Island lies on the non – subduction side of the Alpine fault; a south west/north east trending oblique dextral fault spanning over 400 kilometres (Stafford et al, 2007). While the west coast is not completely inactive, it is true that it experiences less tectonic activity than the east (Robinson & Davies, 2013).

1.2.2 West Coast Investigations and Case Studies

In terms of local investigations into tsunami inundation on the West Coast of the south island, there are only very few (Nicol et al, 2007). This can be attributed to the aforementioned lack of seismic activity in the oceanic crust of the Tasman Sea, and on the windward side of The Alpine Fault, along with a comparatively less active coastline when compared to the East (Goff et al, 2010). The Okarito Lagoon is a prime example of a similar investigation (Nicol et al, 2007). Located approximately 200 kilometres south of Westport, near the Franz Josef Glacier, the Okarito Lagoon resembles a similar shape to the Orowaiti, on a much larger scale (Nicol et al, 2007). Because of the abundance of certain saline – related elements such as Sulphur and Iron in the marshes, titanium was focussed on as an indicator of salt water inundation. It is present in deeper waters of the ocean, and is rarely found naturally occurring in an estuarine environment (Chague - Goff, 2010). Therefore any anomalous spikes in Titanium, the like of which was seen in the Okarito investigation, can be used to aid in identifying potential tsunami events.

It is important to note that in the Okarito investigation, many other elements associated with ocean water were found to spike in concentration at the same time the titanium did. Barium, strontium, calcium and sodium all matched the spike and were helpful in identifying the anomalous spike in concentrations (Nicol et al, 2007). These elements are used more commonly as they are common constituents of sea waters, but are not always as reliable as something such as Titanium. This was shown in the Okarito study, where Iron was not relied upon as an indicator of inundation due to a higher than normal background concentration in the Estuary (Nicol et al, 2007). This being said, a complete chemical digestion is the only means of gauging the Titanium concentration of the sediment, and cannot always be undertaken, as it requires the use of fluoric acid (Luo et al, 2011).

1.2.3 Eye Witness Accounts

Strangely, there is only one account of a large tsunami inundating the Westport coastline. It comes from a 1912 article in the local Westport newspaper, under the title 'interesting reminiscences' (Goff & Chague – Goff, 2012). The article is from a man named as Mr Nees. The once owner of the local sawmill, which he says stood in the centre of old Westport, which he stated in the article was 'many fathoms' below the current 1912 township. As he describes it, it was a still day in 1870. He did not note any ground tremors or shakes. He says he watched from his mill as the sea level dropped away from the coast, and suddenly a wall of water 40 feet, or 13 metres high swallowed much of the town. He describes the wave travelling up the Buller, rerouting its path as it subsided, making it flow through parts of the town. The slaughterhouse and cemetery were destroyed, along with many local businesses. This article has only surfaced due to the research of Dr James Goff, who was looking for a correlating event to match with a tidal surge in Sydney, which has been dated to the same time in 1870 (Goff & Chague – Goff, 2012). While this is all the evidence pertaining to this tsunami at the moment, it may provide an explanation for any spikes in data that cannot otherwise be explained. This being said, at the time of the event, the township would have been increasing in population (Buller District Council, 2016). Therefore some form of obituary report or damage report would have been expected, detailing the supposed destruction. There are none to date.

As the above recollection describes, New Zealand has a comparatively short colonial history (de Lange & Moon, 2007). This has led to an unreliable record of natural disasters. For approximately nine hundred and fifty years before European colonisation, the New Zealand Maori inhabited much of the country, including areas around the location of Westport in the current day. Much of their history of natural disaster is linked with their cultural mythology, citing great beasts known as 'Taniwha' as the source of some events, including Tsunami (de Lange & Moon, 2007), (McFadgen & Goff, 2007). Even during the time of early European colonisation the only recollections of natural hazards on the west coast of the south island are inconclusive at best.

1.2.4 Other Forms of Inundation: Flooding and River Avulsion

Historically, Westport has been in consistent danger from aquatic hazards (Berrill et al, 1988). These recurred in the forms of aggressive storms and river flooding, occasionally accompanied by avulsion (Benn, 1991). This mainly occurred on the Buller River, migrating and flowing down the Orowaiti (Benn, 1991), (Table 1.1). The Buller River has a higher flow rate and wider channels, explaining its higher chance of flood than the Orowaiti, a comparatively smaller river (Berrill et al, 1988).

Flood deposits are high energy events, often depositing sands (Aoki et al, 2015). These are irregular deposits, however, and are rarely preserved in the sediment record (Condo et al, 2013). The more relevant effect of a flood deposit to this research would be the potential reworking of foraminiferal taxa in historic sediments i.e.; the core taken form the estuary. A study by Figueira & Hayward (2014) outlined the possibility of reworking in wetland and estuarine environments, stating that intertidal zones, such as the one studied in the transect, were most susceptible to mixing of genera. This holds implications for identification of environments based on palaeontological evidence, as they may be misinterpreted (Figueira & Hayward, 2014).

Table 1.1 Chronological history of Buller River floods since the colonisation of Europeans. Note the two occurrences of river avulsion. Date source (Benn, 1991)

Flood Date	Description
1860	Buller river overtopped banks
1863	Westport CBD floods. Buller river produces waves many feet high
1867	Westport floods. Infrastructure such as wharves and sawmills washed away Buller River course diverted North for a short time due to sediment deposition in the main channel
1872	Worst flood in colonial history Buildings washed away, including two story hotel Buller River avulses into the Orowaiti
1887	Bank – high flood on the Buller River
1926	Buller River floods Surface flooding throughout Westport
1955	Buller River floods Westport esplanade experiences surface flooding
1970	Buller River floods All of Westport experiences surface flooding
1971	Buller River avulses into the Orowaiti
1979	Buller River floods All of Westport experiences surface flooding

1.3 Proxies

As previously mentioned, many proxies can be utilised to aid in identifying tsunami and co – seismic subsidence in the sediment record (Goff et al, 2012), (de Lange & Moon, 2007), (Nichol et al, 2007). Changes in grain size and sedimentology are the initial choice, as both phenomena produce noticeable changes in the composition of a typical core (Nichol et al, 2007). Unfortunately, due to the ambiguity of tsunami deposits with large storm deposits, the identification of anomalous sedimentary deposits is not enough to confirm the presence of either event (de Lange & Moon, 2007). This calls for the use of alternate proxies. In this case, both micropalaeontology and geochemistry were utilised. In palaeontology's case, the focus was on foraminifera; single celled protozoa which construct carbonate shells (Hayward & Hollis, 1994). The benthic, or sediment dwelling genera are of particular use in an estuarine environment, due to its terrestrial location. These organisms were chosen specifically, as they have high sensitivities to changes in salinity and water depth (Hayward & Hollis, 1994). This makes them excellent environmental markers (Hayward et al, 1999).

Geochemistry was employed to identify a number of chemical aspects in sediment samples. Initially the idea was to identify high levels of elements associated with a high energy inundation of ocean water (Srinivasalu et al, 2010). These included strontium and titanium, along with a suite of others. Further into the research the point was made that the core will most likely cover a period of time where gold mining was rife in The Buller region (Newcombe, 2008). This prompted the question whether or not mercury would be present in the sediment, as during the 1850's it was still a commonly used amalgam for isolating gold (Newcombe, 2008), (Buller District Council, 2016). If so, spikes in Mercury and other gold – associated elements such as Arsenic could aid the dating for the relative age of the core length.

In terms of further dating, radiocarbon was decided against. The reason for this was its half - life. The proximity of the Orowaiti Estuary to the Southern Alps; a 400 kilometre active range, resulted in a higher rate of sedimentation (Robinson & Davies, 2013). The length of core would not likely represent a longer period of time than a few hundred years, meaning there would not be a relevant number of daughter isotopes in the sediment for dating. Also, with the colonisation of the Buller area occurring in the mid 1800's, there would be a saturation of carbon isotopes in the sediment that accumulated over this period. This was associated with the introduction of coal as a combustible resource and fuel. Instead $Cs^{137}$was decided on, as it had a much more applicable half - life of thirty point two years (Loughran & Balog, 2005). The presence of radioactive caesium, among other metals, can be attributed to the detonation and testing of nuclear weapons, the first of which occurred in the 1950's (Loughran & Balog, 2005). In terms of data, logic would state that caesium isotope presence will not occur in sediments prior to this date, making it an excellent chronological marker.

1.3.1 Palaeontology

Foraminifera are either planktic or benthic, referring to the substrate in which the organisms live; open water or sediment respectively (Murray, 2015). Planktic foraminifera live solely in the water column, and are increasingly more common with water depth. Benthic foraminifera live on or in the sediment in an aquatic or semi – aquatic saline environment (Murray, 2015). Estuarine species in New Zealand are well defined (Hayward et al, 1999) making the identification of benthic foraminifera simple to achieve. This is advantageous to palaeontological research in the Orowaiti Estuary, as inundation produced by events such as a tsunami may introduce planktic genera, marking the event in the biological record. They are common throughout the marine slope gradient (Murray, 2015).

The benefit of the estuary is that the mean water level is low, to a degree where planktic foraminifera are extremely rare in comparison to benthic species (Hayward & Hollis, 1994). This almost completely eliminates an archetype of foraminifera immediately, and therefore a large number of species from being present in the core or transect. While this lowers the diversity of the estuary in comparison to a marine slope, for example, it can be advantageous as the endemic estuarine fauna are so well described, and hence easier to work with. This is due to the number of species. Statistically speaking, the less species in an area, the stronger the associations appear between those with the most numbers (Hayward et al, 1999). Ultimately this is controlled by salinity (Hayward & Hollis, 1994). Different fauna have varying tolerances of salt concentration in water (Hayward et al, 1999). This leads to the zonation of genera in an estuarine or tidal environment (Fig 1.3).

The use of foraminifera is not limited to marking sea water incursions, but also variance in mean ground level (Hayward & Hollis, 1994). The focus of this research outside of tsunami history is also co – seismic subsidence. Foraminifera can be useful for identifying subsidence within the same bounds as they would be for tsunami (Nicol et al, 2007). As the foraminifera are so sensitive to environmental change, the change in grain size that accompanies a subsidence event also changes the genera of individuals found in the sediment (Hayward et al, 1999). Estuaries are a low energy environment, making coarse grain sizes rare, and muds and silts more common (Prandle, 2009). This caters to less of a harbour environment and more of a lagoon and back estuary setting. This aids in identifying periods of subsidence as the coarse infill not only contrasts the fine background of grain sizes, but introduces lesser seen species to the sediment record.

1.3.1.1 New Zealand Foraminiferal Record

The literature concerning endemic foraminiferal genera in New Zealand is dominated by a small number of publishers (Hayward & Hollis, 1994). This is due to a small number of reasons; there are few endemic genera (Hayward & Hollis, 1994, Fig 1.3), the science is relatively new and the applications for foraminiferal studies in this particular field are not wholly recognised and/or utilised in international academia. This being said, the small number of studies has been restricted by a smaller number of study areas, in comparison to other countries (Frontalini et al, 2009). However, this is not entirely negative. It has allowed for the complete documentation of endemic brackish/estuarine genera and their tolerances to differing habitats (Hayward et al, 1999). As foraminifera are excellent environmental markers, their relative lack of diversity and subsequent ease of identification in New Zealand has allowed for a high resolution guide on what to expect when conducting micro – palaeontological studies (Hayward et al, 1999).

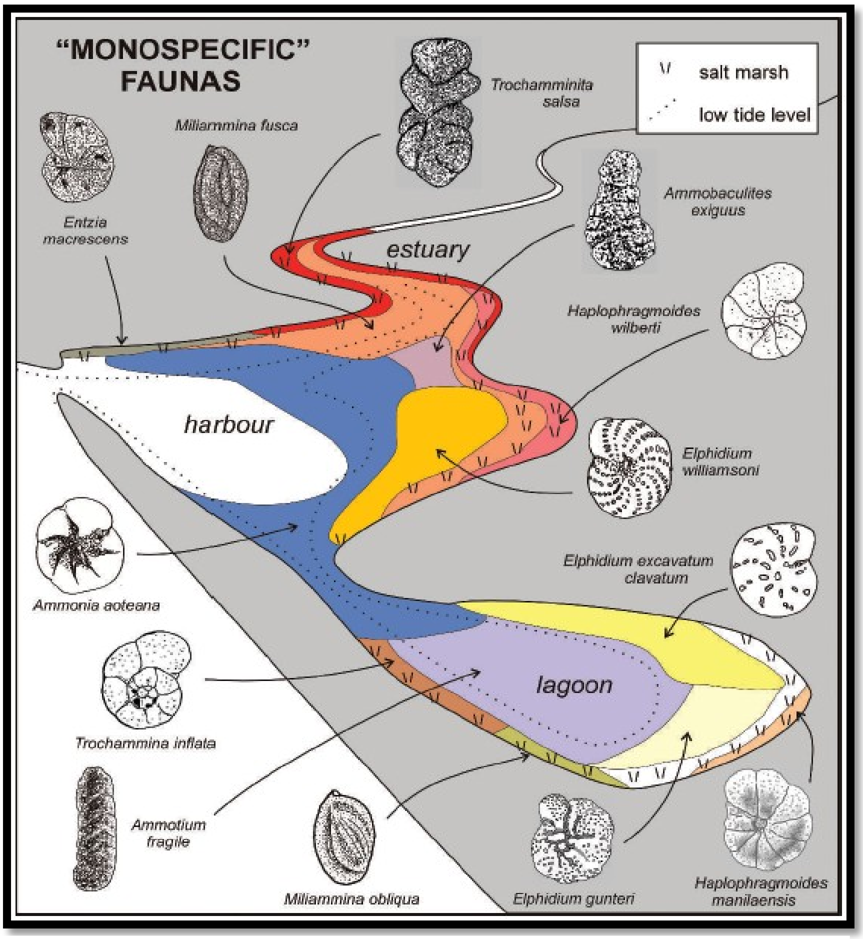

Fig 1.3 Typical habitats for brackish foraminifera in New Zealand (Hayward & Hollis, 1994)

In terms of previous studies internationally, the New Zealand texts are not as applicable. This is not to say that they are not utilised in this setting, as the techniques used for identification of foraminiferal features are widely recognised. They may simply not observe the species seen in New Zealand in their respective environments, as there is a lack of globalised species in New Zealand, and therefore dominant endemic population (Hayward & Hollis, 1994).

1.3.2 Chemistry

Chemically, ocean water is a stark contrast to estuarine or river water (Goff et al, 2010). This has resulted in a number of palaeotsunami studies utilising geochemistry as a proxy (Veerasingam et al, 2014), (Skrabal et al, 1992), (Chague - Goff, 2010). Traditionally a specific suite of elements is focussed on. These included strontium, iron, zinc, sulphur and calcium for subsidence and gradual inundation, and for Tsunami; titanium. titanium is specific to high – energy events, as its density leads to it being found in deeper water, only seen on the surface when it has been forced up by either a storm or a tsunami (Nicol et al, 2007), (Goff et al, 2010). River and estuarine waters on the other hand do not generally possess the metallic qualities of ocean waters (Chague - Goff, 2010). Brackish waters are liable to contain a smaller percent, as they experience interaction with the ocean with the changing of the tides (Nicol et al, 2007).

Geochemical signature of tsunami deposits has been more widely explored than the palaeontological side (Chague - Goff 2010). This is due mostly to the fact the deposits do not always contain foraminiferal assemblages, or other microfossils (Figueira & Hayward, 2014)). This can be attributed to the environment being studied. As the wave created by a fault rupture, volcanic eruption or landslide is much higher energy than standard ocean waves, it drags sediments from deeper ocean settings in to harbours and estuaries (Goff et al, 2010). This sediment has different chemistry to terrestrial and shallow water sediment (Nicol et al, 2007). The greatest difference lies in the titanium content (Nicol et al, 2007). As titanium is a heavy metal and is also relatively abundant in comparison to other heavy elements, it commonly accumulates in deeper environments (Goff et al, 2010). This is a likely and expected signature in the Orowaiti estuary as the West Coast of New Zealand has a very steep shore gradient (Stafford & Pettinga, 2007). This is due to the shorelines close proximity to the Southern Alps (Stafford & Pettinga, 2007).

Along with the evident titanium spike, the previously mentioned combination of other elements would be expected in higher concentration than normal (Chague - Goff, 2010). These would all be accounted for by the inundation of sea water in an estuarine environment (Nicol et al, 2007). It has been discovered that ocean water possesses higher concentrations of certain elements (Nicol et al, 2007). These include iron, sulfur, strontium, barium, sodium and chloride (Veerasingam et al, 2014). The Orowaiti estuary has a constant fresh water flow and the sampling will be undertaken in its more sheltered eastern end (Location fig). We could therefore expect that there would not be a constant oceanic signature in the sediment record. Consequently, any spike of these elements in the core could be indicative of sea water inundation (Chague - Goff, 2010), (Nicol et al, 2007).

The other use for geochemistry in this instance was identifying trace metals associated with mining. In the immediate vicinity of the township of Westport there were multiple incursions into the surrounding hinterland to search for gold and eventually coal (Newcombe, 2008). One study in particular has investigated the potential for specific elements such as mercury and arsenic contaminating the surrounding environment following the mining and metal purification/amalgamation process (Newcombe, 2008).

1.3.3 Sedimentology

Unlike the palaeontological and geochemical investigations into tsunami and co – seismic subsidence deposits, sedimentological investigation are better established as markers for this (Nicol et al, 2007). All Tsunami and subsidence – related events are more consistently associated with a sedimentological deposit (Morton et al, 2007). Co - seismic subsidence occurs in an estuarine environment when the sediments are compacted during the seismic shaking (Nicol et al, 2007). Accommodation space may also be produced co – seismically when the liquefiable sediment in the estuary, mostly silts and fine sands, is mobilised by an earthquake (Wotherspoon et al, 2012). This produces liquefaction, which is often ejected to the surface as sand volcanoes (Reid et al, 2012). The loss of this sediment from the estuary may create a net drop in the ground level of the estuary, potentially creating the aforementioned accommodation space (Wotherspoon et al, 2012). The drop in ground level may also increase water depth in a channel setting, providing coarser grains of material in a deeper, higher energy environment (Wotherspoon et al, 2012), (Nicol et al, 2007). In the sediment record this often appears as a rapid increase in grain size, gradually returning to the background grain size as the accommodations space fills over time.

A local study of the Avon – Heathcote Estuary in Christchurch displayed a clearly recorded and recent example of seismicity – related ejecta following the earthquake sequence in 2010/2011 (Reid et al, 2012). This was not, however, linked to any subsidence (Reid et al, 2012). This showed that liquefaction may not induce subsidence in an estuary. A study by Zong et al (2003) showed a relationship between seismic shaking and compaction of sediments in an Alaskan estuary. It showed that co – seismic subsidence could be isolated from background subsidence in an estuary by using both sedimentological and palaeontological characteristics (Zong et al, 2003). This was evident in the form of a change in foraminifera, as the environment changed with the rapid co – seismic subsidence. A rapid influx of sediment was also recorded. The study proved that an earthquake produced both a distinguishable sedimentary and biological signature different from the background conditions of the estuary (Zong et al, 2003).

At a certain threshold, sediments liquefy (Berrill et al, 1988). This is associated with PGA, or peak ground acceleration, which is a direct result of earthquake magnitude and location proximity to a rupturing fault. Essentially, the greater the magnitude of the shaking in the estuary, the higher peak ground acceleration (PGA) (Bastin et al, 2015). Studies such as that undertake by (Bastin et al, 2015) also revealed that these accelerations trigger liquefaction at an acceleration of 0.06*g* in the most susceptible locations. Susceptibility being determined by the silt and fine sand content of the quaternary sediment in the area. It is estimated that liquefaction will rarely occur in New Zealand quaternary sediments without a magnitude of five or greater. This was once thought to be as high as six point nine but has been refined as further tremors have occurred in the country (Berrill et al, 1988). The higher the PGA in the estuary, the more liquefaction ejects towards the surface. This may also trigger subsidence in an estuarine environment (Zong et al, 2003). This space allows for a larger amount of coarse sediment to accumulate in the space before conditions return to pre – earthquake settings, leaving a sediment signature (Zong et al, 2003).

Evidence of tsunami and subsidence has been discovered in both beach and estuary environments (Dominey – Howes et al, 2006). It is important to note that there is a difference between the types of deposits tsunami leave in these environments. In a beach environment the palaeo - dune systems can be observed to obtain evidence, as a singular, high energy wave produces unique morphologies in the dunes (Morton et al, 2007). This is not possible in an estuarine environment, as there are no dunes present to deform. Instead the sediment record must be utilised, and so a core is often taken (Nicol et al, 2007). The energy in a Tsunami is much greater than the background currents in the estuary (Morton et al, 2007). Providing it reaches the area of the estuary surveyed, the energy of the wave would contribute a coarser grain size from deeper waters (Nicol et al, 2007). This appears in the sediment record as a rapid increase in grain size, followed by a gradual fining into mud sized particles as the wave retracts (Nicol et al, 2007).

1.4 Chapter Summary

The Orowaiti Estuary has never been the subject of tsunami and co – seismic subsidence research. Local studies had been undertaken on the west coast (Nicol et al, 2007). These showed definitive proof of older tsunami deposits dating back to the 1300’s (Nicol et al, 2007), (Goff, 2008). The area was also well known for seismic activity, with a number of documented, active faults both on and offshore.

A transect was recorded, and a two metre core recovered from the southern area of the estuary to ensure sediment with a more consistent preservation history. Commonly utilised proxies were employed to determine both the age and history of the Orowaiti. These included mass spectrometry, foraminiferal analysis, laser sediment sizing, and Cs^{137} isotope dating. These were decided upon by referring to modern day inundation and subsidence research in estuarine environments.

2.0 Methods

The scientific methods behind this project were split in to a number of categories, the first being the selection of field sites and sampling methods. The second concerned laboratory techniques undertaken by the author. This included core logging and sampling, sediment preparation and specific machine use. The third category included actions which the author could not undertake alone, either due to lack of knowledge or training. The fourth category concerned methods used by a third party to process samples, namely ANSTO. The fifth included a series of methods utilised by specific programs for data manipulation and presentation, especially for statistics.

2.1 Site selection

Initially, a rough site selection was undertaken using Google Maps and Google Earth (Fig 2.0). A timescale of ten years could be utilised to identify the areas of the estuary which had undergone the least change in that time. From that, the two northernmost channels draining off the reserve were selected as ideal sites, as they had undergone little change in recent years and were also far enough into the estuary to be unaffected by anthropogenic influence. Upon inquiry with local Iwi and the Department of Conservation, it was made clear that a permit would be required from DoC to take soil and sediment samples from the reserve. This was precautionary as it was not certain at the time whether or not the transect and/or drill core would be taken from protected land, but was necessary as we were unsure of conditions on the ground in the estuary. Ultimately passage through the reserve was necessary, as was placement of a small section of the transect, validating the extensive application process.

Once in Westport, the collection sites were surveyed more closely. It seemed that we would need to cross a small farmland peninsula to access the reserve, or cross the river channel. Access was granted by a local farmer, and collection ensued the following day. Using a university vehicle, the collection gear was transported to the edge of the farmer's property, and then carried the rest of the way to the first of the two most ideal channels. This was at approximately 2:00pm, when the tide was at its highest. This was done to ensure the transect started from high tide, from which we could follow it out to the lowest tidal stand.

Fig 2.0 Map of the Buller Region, including the Buller and Orowaiti Rivers and the study site in the Orowaiti Estuary

2.2 Transect

The transect was completed using both digital surveying equipment and a physical sampling and measuring technique (Fig 2.1). To begin, a tree at high tide was attached to a measuring tape. This was unwound down the centre of the draining channel, to its extent of 100 metres. At the base of the tree the first samples were taken. This was done using a device that measured a set volume of sediment with every sample. Two samples were taken at every ten metre interval of the transect, one for foraminiferal study and another for sediment analysis. Any changes in vegetation and ground type were recorded for use in the graphical representation of the transect in this thesis. After the 100 metre mark was reached on the tape, it was retrieved from the tree and extended to 200 metres. The same process as before was repeated, with two identical samples taken every ten metres. Beyond the 150 metre mark, there were no observable changes in the surface conditions, so the decision was made to take samples every 20 metres to save time. These measurements extended out to 250 metres.

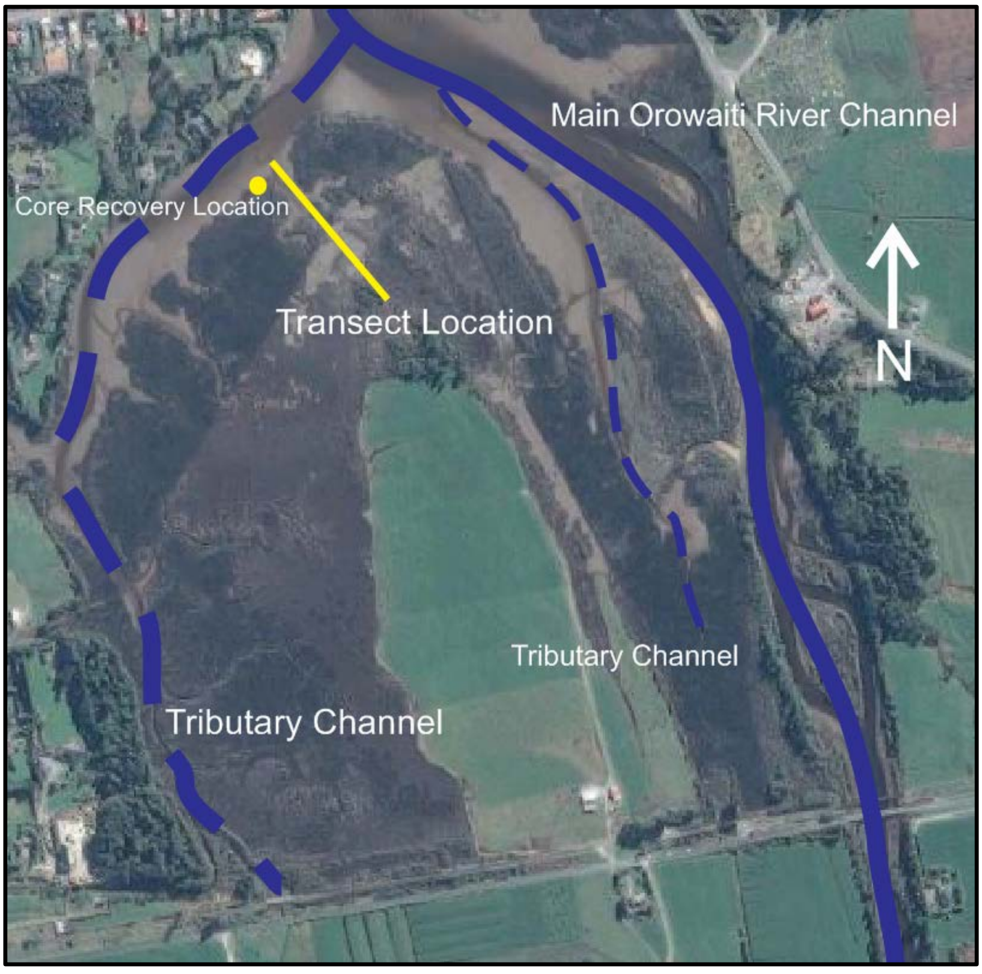

Fig 2.1 Transect and core recovery location in the Orowaiti Estuary

A Trimble Real Time Kinematic (RTK) surveying device was then used at every ten metre interval to measure the elevation at each point. Initially it had been planned to calibrate the device with local LINZ points in the Westport Township. Unfortunately the highest grade point had recently been sealed shut by road works. The second option was a lower grade, but was better than no calibration point at all. This had unfortunately been converted to a manhole in the decade since its initial documentation had been placed on the LINZ website. The website, provided by the New Zealand Government, displays all current calibration points across the country. It is unfortunately not always updated on the condition of said points. This left us with no other option but to rely on the GPS measurements provided by the device. Fortunately the readings that it provided in the field before storing them indicated it was taking accurate measurements. This meant all points were accurate relative to one another, but were not calibrated to local datum. The data from the RTK survey device was then downloaded to a hard drive and used for graphing the transects elevation profile.

2.3 Core Collection

The initial plan for taking the core was for it be done approximately half way down the transect line, in an area that had been sheltered and unaffected by erosive processes in the estuary. This was to ensure that the core had maximum preservation potential, meaning that it had as fewer unconformities as possible. Unfortunately sand horizons made it difficult to force the hand auger bit far enough into the substrate to collect a sizeable core. In the end we took a 197 centimetre core from reeds approximately twenty metres from the main channel. This was difficult enough, and we had to resort to using a smaller bit for the last 50 centimetres, as the larger bit was encountering too much resistance, making it impossible to fill the core barrel.

By forcing the core barrel into the sediment, and gently twisting in a clockwise direction (to ensure that the barrel did not unscrew under the surface) 50 centimetre pieces of core were removed. The depth of sediment recovered was marked on the core barrel, so the next 50 centimetres could accurately be obtained. As the individual sections were pulled up, we gently wrapped them in a plastic half barrel with cling film. This was folded at the ends and taped to ensure that the sediment would not move about. Each core segment was stored flat to prevent any shifting, and labelled accordingly.

2.4 Preliminary Core Analysis

The core needed to be logged before it could be sub sampled. This involved retrieving it from refrigeration and laying it out so that it could be studied. Every part of the core was looked over and recorded, with particular notation given to changes in grain size and vegetation. The entire log can be found in the appendices of this document. Once it was sure that every detail of the core had been scrutinised, the sub sampling began. This involved isolating areas of importance, mostly indicated by the aforementioned changes in grain size. Three centimetre sections were retrieved for foraminiferal analyses, while two were taken for geochemistry and a half centimetre for sedimentology. The reason for these amounts is not arbitrary. As it is commonly less likely to have an abundance of foraminiferal individuals in core samples, a larger sample was taken. Geochemistry rarely requires more than a few grams of a dried sample for testing, but due to there being a plan to also use some samples for Cs^{137}dating significantly larger samples than needed were taken; two centimetres were taken to ensure an optimal weight for each sample. The sediment samples were small as they were positioned on sedimentary transitions, and the DigiSizer requires a very small amount of sample material to provide readings. Large sample sizes would have skewed the resolution of changes in grain sizes as they would not represent the area being targeted in the first place.

2.4.1 Identifying Tsunami Horizon(s) and Periods of Subsidence

A main constituent of the preliminary core analysis was determining where to sub – sample from. This involved using basic sedimentology to identify changes in the core. The more pronounced a change, the greater attention it received. For example, there is a section of core at approximately 188 centimetres. This section exhibits a spike in grain size consistent with what local literature described as a tsunami deposit. As a result this section was targeted for sub sampling.

Unfortunately these events are not always so obvious to the naked eye during the logging process, regardless of the level scrutiny involved. For example, following the sub sampling and sediment sizing processes, it became apparent that there were two periods of apparent subsidence in the core, the extent of which could never had been realised without the laser sizing equipment.

2.5 Sediment Sizer Utilisation

Surface and core samples were taken for analysis in the Geology Department's laser sediment sizer (Appendix 1). The machine, a Saturn Digisizer was set up in the sediment analysis laboratory, on the second floor of the Von Haast building. It was operated through an attached computer. To begin, the machine had to be calibrated. This took approximately eight minutes. It assures that the water being used as the analytical fluid in the tests was not obscuring the laser to too greater a degree. This is important as although the water is deionised it can still have minor impurities related to the degassing process.

Sediment preparation was undertaken using a chemical known as Sodium Hexa – Meta Phosphate, an industrial anti - flocculent. Approximately twenty grams of a sample was mixed with a small amount of water and around 50 millilitres of the chemical. This was stirred with a flea; a magnetic stirrer, that, with the help of the chemical mixed the sediment evenly, keeping it suspended as it was stirred. A pipette was cut at the taper, so to act as a crude sieve to sediment greater than two millimetres in diameter. The pipette was filled as the sediment was mixed, ensuring a homogenised sediment sample. This was dropped drip by drip into the calibrated machine while the percentage of obscuration was observed. It increased from around -1.5% at calibration level to the ideal percentage between 12.5 and 30. Three tests were undertaken once this level was achieved, taking around 15 minutes. These were then saved in three different formats; the report format for the sizer software, pdf and excel.

2.6 Extraction of Foraminifera

All surface samples intended for foraminiferal analysis were stained. The stain is known as Rose Bengal and dyes proteins in live cells a pink colour. This aids in distinguishing the live from dead individuals during the picking process (Murry & Bowser, 2000). A solution of it was made up at one gram of dye powder per Litre of water. It was added to sample bags in approximately 30 millilitre increments. These were left for 24 hours to allow ample time for the stain penetrate all biological material in the samples. After this period the samples were individually washed through a 63 micron sieve, to remove all muds and residual stain from the sample. This allows for an easier time distinguishing the sand – sized foraminifera from the remaining sediment grains. Once the washing was complete for each sample, it was backwashed from the sieve into a large beaker. These were labelled accordingly and placed in a drying oven at 60 degrees Celsius. After three days these were removed and placed in sealed paper envelopes for ease of use when picking foraminiferal specimens from the surrounding sediments.

2.7 Isolation of Foraminifera

Often the foraminifera recovered from samples are present in a large quantity of sand sized particles (Caffrey & Horn, 2013). This can make identifying and locating specimens more difficult than it needs to be. To navigate this problem, the sample is added to a mixture of Lithium Polytungstate. This fluid changes the specific gravity of water. Once the specific gravity is altered to that of Quartz (1.5), the sample will begin to separate. This is because the carbonate tests of the foraminifera have a lower specific gravity than the quartz (Caffrey & Horn 2013). This results in the foraminifera and other light material floating in the solution, while the heavier material, including the quartz sand, sinks to the bottom. The floated material was then collected with a filter.

To achieve a specific gravity of a liquid, calculations were utilised to obtain the initial density of laboratory LST as to identify the specific amount of water required to obtain the ideal dilution of 1.5 necessary to isolate foraminifera. This section of the process was particularly important as fresh LST was not always used in the floating stage. This was due primarily to the cost of LST (approximately $1000 per Litre). For this reason, used LST was treated with bleach and gently heated to evaporate added water and return it as close as possible to the factory laboratory standard. The calculations for density are shown in the next section. After obtaining this number, it was processed through a free software known as ‘LSTCalc’, a program provided online by a company known as ‘Central Chemical Consulting’. This company is a provider of LST to the University of Canterbury, among other establishments, and so offers the software free of charge. The program, once provided with the density of the LST then calculated the amount of water needed to complete the dilution.

2.7.1 LST Density Formula

a) Bottle Weight

Bottle (pycnometer) + water weight

Total – Bottle Weight

b) Liquid (LST) Weight (+bottle)

Liquid – Bottle Weight

c) (Liquid (minus bottle)/water (minus bottle)) water temperature = Density

d) Density then processed through LSTCalc

2.8 Identification of Foraminifera Using Literature

As previously mentioned, Foraminifera can often be identified through the morphology of their test, or shell. The first key point is whether the targeted specimen is agglutinated or calcareous (Hayward et al, 1999). Agglutinated foraminifera compose their test from individual grains of surrounding sediment, giving the test a grainy texture. Calcareous tests are produced by the individual and excreted over the soft body. They are a translucent white when new, and exhibit a smooth appearance (Hayward & Hollis, 1994). Once this has been determined, there are only a small amount of foraminifera that inhabit the inlets, harbours, rivers and estuaries of New Zealand (Hayward & Hollis, 1994). These species are known as being monospecific, meaning that they will typically inhabit a singular area, and are rarely found outside of it (Hayward & Hollis, 1994, Fig 1.3). This is part of why they are important as environmental indicators. A table of expected brackish species follows:

Table 2.0 Common brackish foraminifera observed in New Zealand estuaries. Source (Hayward et al, 1999)

Genera	Agglutinated/Calcareous	Distinguishing Features
Entzia macresens	Finely Agglutinated	Compressed trochospiral tests. Collapsed chambers. Raised sutures. Brown Test
Trochammina inflata	Agglutinated	Inflated test, hence name. 5 – 6 globose chambers in outer whorl. Dark brown early chambers. Deep umbilicus.
Trochaminnita salsa	Agglutinated	6 – 7 inflated chambers. Early portion of test planispiral.
Miliammina fusca	Agglutinated	Quinqueloculine arrangement of chambers Unlike whorl shaped taxa
Haplophragmoides wilberti	Agglutinated	6 – 10 inflated chambers. Planispiral. Straight to slightly sigmoidal sutures.
Ammonia parkinsoniana	Calcareous	6 – 10 chambers Vaguely trochospiral Star – shaped umbilicus in one side
Elphidium excavatum f.		7 – 20 chambers

clavatum	Calcareous	Planispiral Characteristic backwards extension of chamber walls
Ammobaculites exiguus	Agglutinated	Linear chamber arrangement with bulbous final chamber
Ammotium fragile	Aggultinated	5 - 15 Linear chambers Herringbone arrangement

2.9 Identification of Foraminifera Using a Palaeontological Microscope

Once all sub – sampling had been completed, the foraminifera could be picked and mounted on plates. This was done using a department palaeontological microscope; a Meiji Techno binocular microscope with built in halogen/white lighting and a PLS – 1 stand. All 36 sample had to be picked, with an ideal total of 100 individuals per sample. This number ensures that any statistical analyses undertaken using the foraminifera counts will be reliable and relevant. Unfortunately that is not always the case, as we see in the core samples.

All foraminiferal samples were floated, as it was higher in volume than what was ideal for picking. Once this was completed, sediment was loaded into small gridded trays where it could be surveyed for foraminifera. Using a fine damp paintbrush, located individuals could be ‘picked’ from the surrounding sediment. These were then placed on a ‘plate’. This is a precise gridded rectangle of cardboard with raised edges to prevent sample loss. To secure samples, the plate is covered with xanthan gum, which dries quickly but acts as an adhesive when wet. Samples were then organised by genus. Once 100 samples were reached, or the maximum amount that could be found if there were less than 100, a glass slide and aluminium backing were attached, sealing the specimens.

It is important to note that the transect was saturated with foraminifera (Fig 3.2) (Appendix 4). To make the picking process completely random, and to preserve the statistical integrity of the sampling, a random number process was set up. This involved constructing a numbered grid representing the grid on the floor of the sample tray. When this was done a number generator found on the internet provided reliable random squares in the grid to sample from. Once all forams in that square were sampled, another number would be generated and so on until 100 individuals had been retrieved. Once the core samples were reached, it became evident with depth that the ideal number of individuals per sample was never going to reach 100. This resulted in the abandonment of the previous method as it would take far too long to find the already sparse specimens. Instead a methodical method was employed by going square by adjacent square until an entire tray was exhausted, and then to repeat with the remaining sediment. Unfortunately even this painstaking process failed to fill the 100 specimen goal for most core samples (Appendix 5).

2.10 High Resolution Scanning Electron Microscope Imaging

The Scanning Electron Microscope was implemented in this research for the purpose of high resolution imaging for foraminiferal specimens. This is integral as it aids in identification of diagnostic features on the test of a foraminifera. It also allows the user to gauge whether there has been any degree of weathering upon the samples. This is important because it can allow for elaborations on dissolution during burial, which, as previously mentioned is a likely factor in this research. Initially, multiple samples of each genus had to be isolated from clean sediments, meaning that they could not be sourced from the transect sediment as this had been previously treated with Rose Bengal.

Specimens also had to be devoid of any organics, once again ruling out the transect material, as the staining revealed that many of the surface foraminifera had been alive at the time of sampling. The need for the samples being clean of any organics or particulates is due to how they affect the microscope. Particulate matter will distort the surface of the samples, marring the resolution as the microscope scans horizontally. Organics and chemical components pose a more sinister risk, as during the imaging, the intensity of the beam vaporizes these material. The vapour then travels into various area of the machine. While this is not immediately damaging, the precipitate will build up over time, eventually requiring a costly service from a qualified professional. The process of this vaporisation also causes an effect that can only be described as 'lightning' across the sample surface, which is a giveaway for remaining organics, and also a severe inconvenience to imaging.

Four samples of *A. fragile, H. wilberti* and *M. fusca* were obtained, along with one each of *J. macresens, T.salsa* and *T. inflate*. The reason for a single sample for some of these is because of their scarcity in the sample material. They were the highest quality unstained individuals available. After selection, the samples were immersed in de – ionised water overnight before being placed in a 50 degree Celsius oven for twenty four hours. This was to make sure all impurities had been removed and that the entirety of the samples were dry, leaving no possible vaporizable material in the tests that could affect the SEM. Following this, the samples had to be attached to a 'stub'. A stub is a small aluminium cylindrical base built for fixing sample to for SEM usage. The exact diameter in this case was 12mm. To this, a 'Smoothest' pure Carbon dot was affixed. Carbon is used due to its lack of reactivity, high level of adhesion and good homogeneity. This is important as the lower the charge, the less an object will interfere with the imaging process. Samples were attached one by one, with their orientations being chosen carefully as they would not easily be moved once attached to the Carbon. Following this, the sample was placed in a desiccator overnight. The desiccator is filled with silica gel to dry the sample entirely. This is important as small amounts of water are used in manipulating the foraminifera, which must be removed before SEM use.

Prior to the imaging, the final preparatory step is to coat the surface of the stub in gold. It was undertaken by Kerry Swanson, a technician in the Geology department whose involvement in this project was invaluable. The preparation was done at the University using an Emitech K975X coater for three minutes. The device was set to ‘sputter’ mode. Following this the imaging could begin. Using the department of mechanical engineering’s JEOL JSM 7000F Field Emission microscope, individual foraminifera could be isolated and imaged at the desired magnification. This was undertaken at a viewing distance of 10 millimetres with a 12 kV current. Higher resolution and magnification was made difficult in some specimens due to residual particulate matter accumulating on some genera. This was found most commonly in those genera with a deep umbilicus, such as *T. inflata*, where its umbilicus was almost full of particles.

2.11 Geochemistry and Targeted Elements

To analyse a complete suite of elements in the core sediments, the chemistry departments Inductively Coupled Mass Spectrometer, or ICPMS, was utilised. The laboratory preparation was aided by Dr Sally Gaw; one of the departments environmental scientists and her MSc student; Christopher Sampson. This was for two reasons; one being that I could not be in certain labs unsupervised, and the second being that Chris was about to undertake his Masters research. He assisted with laboratory and sample preparation.

It was decided that elements such as Mercury and Arsenic should be targeted also, as they could highlight the peak of the gold rush and beginning of industry in Westport, around the mid 1800’s. Essentially instead of just identifying areas of subsidence and sea water inundation in the core, the chemical analyses would also aid in obtaining a relative age for some sections. Mercury has since been replaced with other techniques as it is hazardous to the miners, and also to the environment. It ‘accumulates’ in biological systems, rather than being metabolised into a degradable bi - product. For this reason, and the fact that there would have been no other viable sources of Mercury in the Westport area at the time, it had the potential to be an excellent chronological marker.

2.11.1 Typical Marine Concentrations

The sediment used for Certified Reference Material (CRM) in this research had all major trace element concentrations documented (Wise & Watters, 2012). It was sourced from an estuarine to marine environment, providing a geochemical comparison for sediment taken from the Orowaiti. It also provided insight on typical marine sediment compositions (Wise & Watters, 2012).

Table 2.1 Typical marine sediment compositions in New Zealand, source (Wise & Watters, 2012)

Elements	Typical Concentrations (mg/kg) or % per weight
Na	0.681%
Al	8.41%
K	2.054%
Ca	0.343%
Ti	0.884%
Mn	1757
Fe	7.91%
Cu	117.7
Zn	485.3
As	45.3
Sr	119.7
Cd	0.817
Pb	132.8

2.12 ICPMS Preparation

The University of Canterbury chemistry department has a series of steps used to prepare sediment samples for use in their ICPMS. Initially, all samples taken from the core in the sub sampling process had to be dried. This was done in the sediment lab in Von Haast at fifty degrees Celsius for three days. Following the drying process, samples had to be sieved to remove any pieces of shell, as the carbonate can alter the appearance of final results and react with acids during the digestion process. This was done in the PC2 laboratory on the sixth floor of the Rutherford building at The University of Canterbury. A stainless steel sieve with a two millimetre aperture was used, and processed samples were collected in clean, labelled zip lock bags. Brass sieves were avoided as there was a risk of contamination by the metals present in the alloy.

Following drying and sieving, samples were weighed into acid washed polycarbonate vials. Approximately one gram was weighed for each vial, with allowances between 0.95 and 1.05 grams. Also two blank vials were added with no sample, and two with ‘reference materials’. These materials are kept in the PC2 lab and have had their chemical properties thoroughly documented.

Acid was added to samples to start the digestion. Four millilitres of Nitric acid at one to one acid to water ratio was added to each sample. Ten millilitres of hydrochloric acid was added at a one to four ratio. The samples were left to stand overnight to ensure all material was exposed to the acid, and no sediment remained in suspension. This was important as sediment in the acid mix could severely damage the ICPMS equipment.

The Heating blocks in the lab were turned on and left to heat to 85 degrees Celsius, taking approximately two hours. At this point the vials were inserted. The goal of heating the samples was to prompt the acid in the samples to reflux. This is where the acids vaporise, condensing on the walls of the vials and dripping back into the liquid. The process was utilised to conduct the reaction at a higher temperature than possible in a liquid state, therefore shortening the time required for it to complete. This was occurring after ten minutes of heating. The vials were left to reflux for forty minutes, without letting the temperature dip below eighty degrees. Lower temperatures would halt the reflux and subsequent reaction process, potentially lowering the amount of recovery for CRM.

Once the samples had cooled, they were mixed with twenty millilitres of Milli – Q water each. Milli – Q water is essentially a more efficiently produced de – ionised water, made using a specific piece of machinery that is renowned worldwide for purity and consistency. The water was added via a squirt bottle to wash any acid droplets on the vial walls back into the rest of the solution. After this, the samples were left once again to settle overnight, as the addition of water agitates small particulates, which are detrimental to the ICPMS analysis.

The final preparatory step before the actual ICPMS usage was another dilution. Each sample had to be diluted 21 times. This was undertaken under the supervision of Robert Stainthorpe; the operator of the ICPMS in the chemistry department. Samples were taken to a sterile lab known as the clean room. Equipment such as static free coats and foot covers were utilised to prevent contamination of samples. Small previously acid – washed vials were utilised. 10 millilitres of Aqua Regia was added to each vial. The Aqua Regia maintains the suspension of any elements stripped from the sample material and is composed of Hydrochloric and Nitric acid at a four to one ratio. This batch in particular included an amino acid proven to aid in the continued suspension of particularly difficult elements such as Mercury. 0.5 millilitres of sample was added to each vial, completing the dilution. Samples were then mixed seventeen times to adequately homogenise them.

Following the dilution process, samples were processed through the chemistry departments ICMPS, using a variety of mixes. These mixes or ‘recipes’ were used by Mr. Stainthorpe to standardise the samples and highlight variation in them. This process was unfortunately not able to quantify the amounts of Strontium in the samples, as the mix used for Strontium was no longer stocked by the department. As a result of this, the Strontium results appeared to be far greater than the known certified reference material.

When it came time to tabulate and subsequently construct figures from the geochemical data (Appendix 6), the measurements of µg/L had to be converted to mg/kg. This was primarily so that certified values could be compared with values obtained from the certified reference material. This was important as it confirms whether or not the collected results were at a high enough concentration to be considered valid. The calculations are as follows:

2.12.1 Calculations for µg/L to mg/kg

[ICPMS weight (µg/L)] x 21 (Dilution count) x 20 (acid millilitres)/1000 (eliminating the ‘litre’ part of measurement) = µg extracted

µg extracted/sediment sample weight (g) = µg/g = mg/kg

Calculations for comparison of measured CRM concentrations to that of certified value

% recovery CRM (Certified Reference Material) = value collected (mg/kg)/certified value (mg/kg) x 100

2.13 CRM Recovery

By comparing the percentage of each element recovered from reference material with documented reference concentrations, a recovery percentage, and therefore a measure of the accuracy of dilutions could be acquired.

Table 2.2 Certified Reference Material recovery demonstrating the quality of ICPMS results. Some values were low, such as iron, but anything above 75 percent recovery was deemed of high quality

Element	Recovery percentage
Na	**50**
Al	**119**
K	**101**
Ca	**63**
Ti	**190**
Mn	**76.50**
Fe	**80**
Cu	**80.5**
Zn	**75.5**
As	**67.9**
Sr	**80**
Cd	**86.4**
Pb	**85.1**

2.14 Cs^{137} Dating

$Caesium^{137}$ is a radioactive isotope commonly found in the aftermath of nuclear detonations, the first of which were undertaken in the 1930's (Hutchinson & Prandle, 1994). This had led to a worldwide 'blanketing' of atoms in sediment (Hutchinson & Prandle, 1994). Since the end of World War II, and Hiroshima, the use of nuclear weapons has been in decline. In the sediment record this appears as the initial spike or 'horizon' followed by a gentle tapering off (Hutchinson & Prandle, 1994). This spike aids in the dating of recent sediments, as it can be correlated to the same period globally.

The Caesium isotope was selected for the above reason, but also due to its short half – life of thirty point two years (Hutchinson & Prandle, 1994). Compared to other commonly used methods, like radiocarbon, Caesium is much more applicable. Carbon has a five thousand, seven hundred and thirty year half – life, and is the closest contender for dating recent sediment isotopically. As The Orowaiti Estuary is so close to the Southern Alps, compared to Eastern estuaries such as the Avon Heathcote, it was hypothesised that the amount of sediment being contributed to the estuary over such a short time would result in a comparatively short amount of time being represented by the two metre core. This would mean there would not likely be any daughter isotopes present for Carbon isotope methods.

A third party; ANSTO, the Australian Nuclear Science and Technical Organisation, were commissioned to process the core samples for Caesium dating. As previously mentioned, $Cs^{137}$was utilised for its short thirty year half – life. The unfortunate aspect of this was that the dating method could not be undertaken at the University, hence ANSTO. In order to process the author's samples, they had to be sent to ANSTO in Sydney. Due to budget restrictions, only three samples could be sent away for analysis.

The processing required for international travel included the labelling, documentation and drying of individual samples. Fortunately, samples taken for ICPMS were still clean and dry at this stage, and very small amounts were needed for the elemental analysis. This left a large amount of ideal, pre – treated sample mass per individual sample that could be used for age dating. All that remained was to isolate the samples that were of interest to be dated based on their elemental compositions following ICPMS analysis. They were sent via Fed Ex with a specially requisitioned permit from ANSTO allowing the material to enter Australia on the condition that it be irradiated at 50 KGrays to remove any possibility of contamination.

2.15 Software and Data Plotting

In terms of figure production, the Microsoft program EXCEL was utilised for the majority. Many graphs and figures only needed the organisation and processing of data, and not an inbuilt statistical module. Data was plotted in cells, which were labelled, and the required data highlighted. This could then be translated into the desired graph or table type. This being said, the program was also capable of statistical functions, such as evenness.

The main statistical analyses were undertaken using specialised software. Two programs were used, one called ‘PAST’ and another, known as ‘C2’. Both programs were free to use. PAST, a program developed specifically for the statistical analysis of palaeontological data, was used to execute such functions as cluster analyses. This was useful primarily for isolating and identifying foraminiferal associations within the transect and core. C2 could be used for similar functions, but was more useful for plotting stratigraphic information. It was not as applicable as PAST in this instance, as the software did not function well with the author’s hardware.

2.15.1 Drawing Software

Corel Draw was primarily used for the construction of figures. It is a drawing software installed on the Geological Sciences' computers and allows for precision drawing and custom fill design. This was used throughout the research, but was relied upon the most for profile construction, namely the core and transect figures. They would not have possessed the level of resolution, especially the core, without Corel's line and polygon drawing capabilities. It also allowed for custom symbol construction as well, so debris such as shell fragments and rootlets could easily be represented in the figures.

2.16 Chapter Summary

Before going into the field, the site in the Orowaiti Estuary was chosen. On entering the estuary, a transect was taken, and surface samples collected every ten metres to construct an image of the current environment in the estuary from high to low tide. A core was taken closer to the low tide mark.

The core was logged in the Geology department sediment laboratory. This provided information with which to construct a core profile. Following this the core was sub sampled at target depths of interest for sedimentological, foraminiferal and geochemical analyses. Much of the analysis was undertaken in the sediment laboratory. This included laser sediment sizing, foraminiferal washing, staining and floating. Foraminiferal identification was undertaken in the author's office using a department palaeontological microscope and literature by Hayward et al, (1999). Foraminifera were imaged by Kerry Swanson using the Scanning Electron Microscope in mechanical engineering.

Chemical analyses were undertaken in the chemistry department under Dr Sally Gaw, Rob Stainthorpe and Sally's masters student; Chris Sampson. Chris aided with sediment preparation and acid digestion. Sally guided the process and helped on delicate tasks such as dilutions. She also aided the author in interpreting ICPMS results and conversions. Rob Stainthorpe aided on the final dilution and operated the ICPMS.

The Australian Nuclear Science and Technology Organisation in Sydney, Australia were commissioned to undertake gamma spectrometry on the three samples selected for Cs^{137} dating. A laboratory manager named Daniela Fierro both completed the analysis and maintained correspondence throughout the process.

3.0 Results

The research undertaken for this thesis has been separated into two sections; core results and transect results. The transect results depicted the state of The Orowaiti Estuary at the present time, so that it could be compared with the core results. It included a fully detailed cross section of the transect, complete with vegetation, grain size and relief. The transect cross section also describes the distribution of foraminifera from high to low tide, and is accompanied by graphical descriptions of each identified species. This data is also comparable with the results obtained from the core.

3.1 Transect Results

The following results cover variation in foraminiferal speciation and number, along with sedimentological changes down the 250 metre transect taken from the Orowaiti Estuary (Fig 3.0). At the time of sample collection, visual records were also taken. This included variations in the surface of the estuary, including morphology, sedimentological variation, and observations concerning flora and fauna.

The beginning of the transect, at zero metres, started just above the high tide line in a lightly wooded area. It was started just outside the borders of the peninsula known locally as the ‘island’ (Fig 4.0). This is an area where the currently used farmland extends into the estuary. At this point a wide range of flora was observed, with flax of the *Phormium* genus (Wehi & Clarkson, 2007). The bramble – like plant known as gorse was also observed, scientific name *Ulex europaeus* (Butler & Weis, 2009). Salt grasses, *Puccinellia raroflorens* were observed in abundance (Butler & Weis, 2009). Small trees were identified as being covered with a lichen known as *Plagianthus reguis* (de Lange, 2008). From this point to 10 metres, we entered the tidal zone, and therefore left much of the diverse flora behind, instead seeing a bloom in salt water grasses. Up to the 10 metre mark, we saw an abundance of one of these, a jointed sedge known locally as ‘Oi Oi’. The scientific name is *Apodasmia similis*. It is a reed with fine grey/green leaves, and distinctive brown coloured joints. It was observed to grow in clumps.

For the following 10 metres, up to 20, a previously absent plant species was seen to cover the estuary surface in a mat – like fashion. Known as *Selleria radicans* it is a small broadleaf colonial plant. This section of the transect was dotted with another species known as *Juncus pallidus* (Chague – Goff, 2004). This was growing in patches similar to the Oi Oi sedge earlier in the transect. Towards 20 metres the *Juncus* began to dominate and formed a salt marsh up to the 28 metre mark. At this point the vegetation ceased in its abundance and from 31 to 33 metres, transitioned into a small channel that meandered across the length of the transect. From this point to 42 metres, a non – descript sand flat was observed, before the previously mentioned channel meandered back across the transect. At this stage it was dotted with crab burrows, and expressed small asymmetrical rippling. The depth was measured to approximately ten centimetres.

Following the channel was another sand flat. This extended to 62 metres, where a small berm covered in *Juncus* and crab burrows protruded from the surface. This continued for another four metres before reverting back to sand flats. These were similar to those before, with the exception being an abundance of small snails seen across the surface. These were Titiko, small air breathing snails often found on mud flats. The scientific name for the snail is *Amphibola crenata*, which is endemic to New Zealand. It is a curiosity due to its transitional stage between air breathing and marine living. This also makes it an excellent marker in sediments as it solely lives in intertidal zones.

At approximately 100 metres, the transect intersected a fence. The posts were clearly very old, but it had been re – wired recently, enough so that the wire and fixings were free of corrosion. The interesting aspect of the fence was that it was low in the estuary sediment, and that it mimicked a wider border of the previously mentioned ‘island’. It was observed to be so low in the sediment that it could not have been that height originally. From 108 to 112 another berm intersected the transect. It was similar to the previous one, sporting an abundance of Oi Oi. Following this, to the 250 metre termination of the survey, all that was observed was sand and mud flat. Along this section there were numerous sightings of crab burrows, along with many more *Amphibola crenata*.

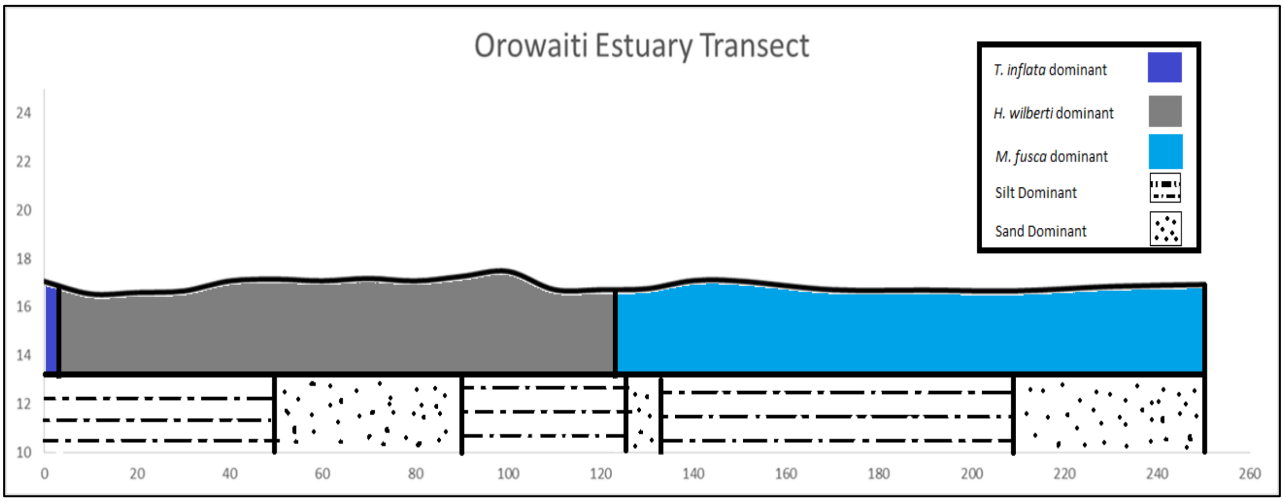

Fig 3.0 Combination of sedimentological and foraminiferal gradients down the transect. Note that elevation is not relevant as the RTK unit could not be synced to local conditions.

3.1.1 Transect Sedimentology

The sedimentology of the Orowaiti Estuary transect was separated into the clay, silt and sand components (Fig 3.1) (Appendix 2). As expected the very first section of the transect is dominated by sand, due to it being found above the high tide mark (Abrahim et al, 2008). This is quickly followed by an increase in the silt and clay percentages, which spike between ten and twenty metres. Following this, the silt percentage dropped substantially, while the clay did only a small amount. Bearing this in mind, the scales at which these constituents are represented in the figure below varies. Clays never exceeded four percent and so look to change drastically in the graphs, while in reality the change was only a fraction of a percentage. This compared to silt and sand, which each reached percentages of nearly 85 and 60 respectively (Fig 3.1). Regardless of this, the values for each variable correlate well.

At the 30 metre mark, we see the sand plateau at just over 20 percent of the sediment composition (Fig 3.1). This is accompanied by steady increases in both silt and clay until 50 metres, where sand percentages increase towards 40, seeing a marked drop in silt and clay. It is apparent that the silt and clay percentages are grouped against the sand, where an increase in them results in a decrease of sand in the transect, and *vice versa*. This is especially evident when the clay section of the figure is ignored. It was clear that sand and silt very nearly mirrored one another.

From 50 metres we see increase in sand percentage up to nearly 40 percent, where it plateaus (Fig 3.1). This continued for another 40 metres. At the 90 metre mark, we see a rapid increase in silts, up to almost 85 percent. This subsequently produced the aforementioned drop in sand content. The spike is also evident in clays. At the next sample distance of 110 metres the spike has reverted almost entirely, with the clay and silt components only slightly higher than they were previous to the spike. They then increased again, but did not drop to the same degree as they had previously, instead tapering off towards 230 metres. At this point the sand percentage was around 20 percent, while the silt was close to 75. The clay percentage was elevated in comparison to the rest of the transect.

Between the 230 metre mark and the end of the transect we see a drop mainly in silts (Fig 3.1). They dropped to the lowest they had been in the entire survey. Sand percentages, characteristically mirroring the silt, rose to a higher amount than they had in the entire core. The percentage dropped but not to the degree seen in the silt. This was one of only a few small sections of the transect where the clay percentage did not seem to be directly correlated to the silt.

Fig 3.1 Sedimentology of the transect recovered from the Orowaiti Estuary. Split into three different graphs exhibiting percentages of sand, silt and clay at each distance

3.1.2 Transect Foraminifera Counts

Overall, the numbers of foraminifera recovered from transect sediments were statistically viable (Fig 3.2). The objective being to get as close to 100 individuals as possible, was fulfilled by most samples. The only exception to this was the zero metre measurement, where only a very small amount of individuals were recovered. Interestingly, the individuals present in the first sample were rare in the remainder of the transect. The sixteen individuals present were *T. salsa* and *T.inflata*. The otherwise more common *H. wilberti* and *M.fusca* were not observed (Fig 3.2).

The first good recovery numbers came from the ten metre distance, and continued through the rest of the transect (Fig 3.2). It was apparent in this first sample that *H. wilberti* was a prolific species, making up more than 90 of the 100 individuals. *A. fragile* and *M.fusca* made up the final ten percent in even contributions. From this point to 120 metres the *M. fusca* populations for each sample increased to an average of 40 individuals per distance surveyed. *H. wilberti* numbers consequentially decreased, but remained as a dominant percentage. At 30, 60 and 80 metres, small numbers of *T. inflata* were observed. These numbers were less than ten per sample, but are important as the species is rare across that transect, and its presence could imply changes in the surface environment. Additionally, there were small numbers of *T.salsa* observed at thirty and fifty metres (Fig 3.2).

Once the 120 metre mark had been reached, we saw a decline in the *M.fusca* numbers, which had been replaced with *H. wilberti* (Fig 3.2). The opposite followed, with *H. wilberti* numbers dropping to around twenty individuals per sample for the remainder of the transect. The majority for this remainder was made up mostly of *M. fusca*, while *A. fragile* maintained consistent numbers of between five and twenty individuals throughout the transect (Fig 3.2).

Near the end of the transect, we saw both a drop in overall numbers per sample and the introduction of a previously unobserved species; *E. macresens* (Fig 3.2). It was seen in a group of two at the two hundred and thirty metre mark. The presence of the two other sparsely identified species; *T. salsa* and *T.inflata* were also present, both before and after the sightings of *E. macresens,* in similar numbers to what had been observed earlier in the transect (Fig 3.2).

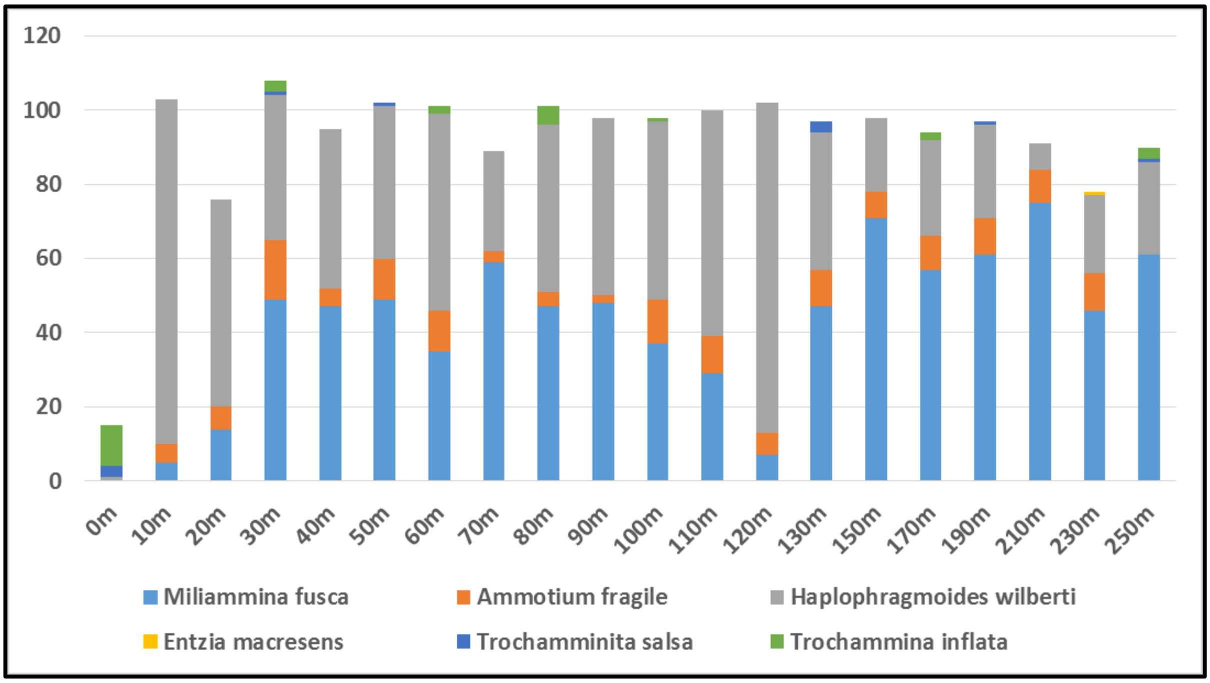

Fig 3.2 Transect counts for each surveyed distance down the transect recovered in the Orowaiti Estuary

3.1.3 Transect: Foraminiferal Species Diversity

The transect taken from the Orowaiti Estuary produced very high numbers of foraminifera (Fig 3.2). Due to this, the target number of one hundred individuals per distance was, for the most part, easily attained. This excluded the '0 metre' distance, where the survey left the intertidal zone (Fig 3.2). In terms of diversity, the same prevalent species seen in the core were also observed in the transect, with *Haplophragmoides wilberti*, *Ammotium fragile* and *Milliammina fusca* contributing to the majority of individuals at all distances (Fig 3.2).

At the beginning of the transect, the lowest numbers were observed, along with the lowest species count. *Trochamminita inflata* and *Trochamminita salsa* were the only species present at this distance (Fig 3.2), with the previously mentioned more dominant species becoming more prevalent into the transect. Following the initial lack of numbers, we see a spike to over one hundred individuals immediately after (Fig 3.3). The species count, however, does not change, remaining at three (Fig 3.3). The species present are instead replaced with the common *M. fusca, H. wilberti* and *A. fragile* (Fig 3.2). This trend persisted for the rest of the transect, with species counts only wavering when outlying anomalous species were included in small numbers. These were either *T. inflata* or *T. salsa* and reached no more than three of each species per transect distance surveyed (Fig 3.2, 3.3).

Nearing the channel, it could be observed that the numbers of foraminifera began to steadily drop (Fig 3.3). This started at 120 metres before reaching a low of slightly under 80 individuals at the 230 metre mark (Fig 3.3). The count then begins to increase at 250 before the survey ended (Fig 3.3). It is important to note that this has little to no correlation to the wavering species count during the same section (Fig 3.3). While this process was designed to be an unbiased method of test collection, the undulation in counts could be related to unintentional human bias or error.

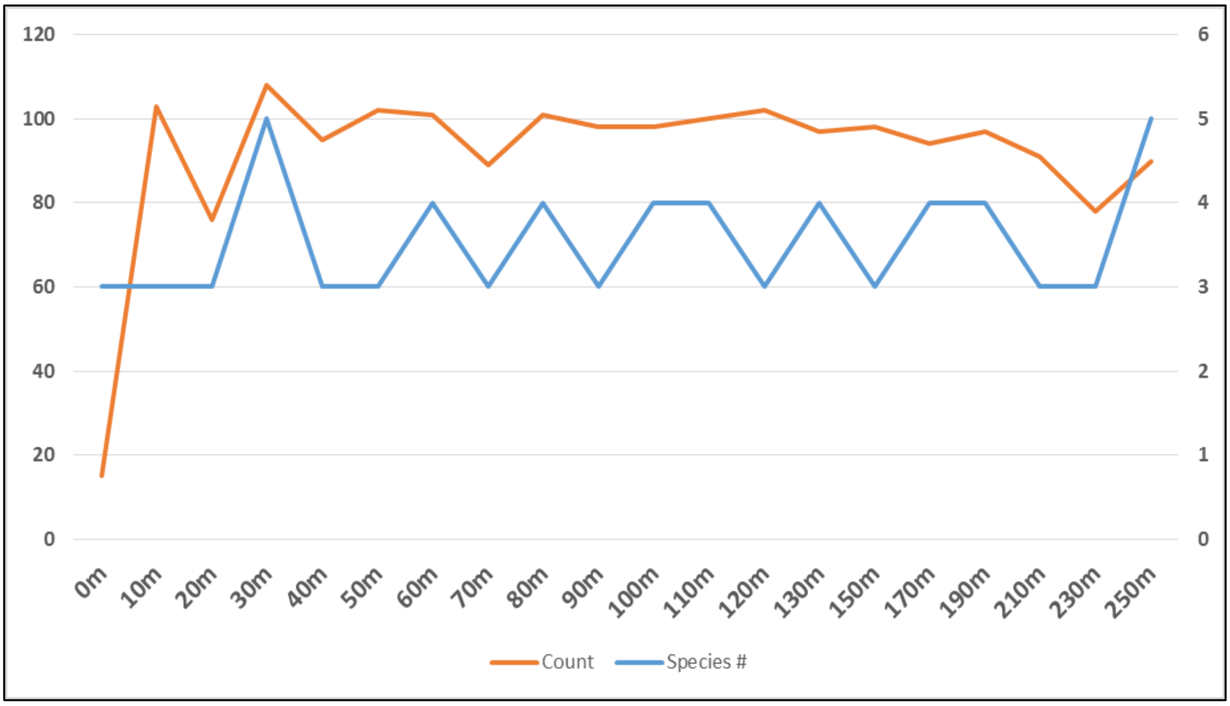

Fig 3.3 Comparison of species numbers to individual foraminifera recovered at each distance down the transect

3.1.4 Transect: Foraminiferal Cluster Analysis

Using the program ‘PAST3’, a palaeontological statistics software, the distribution and associations of the transect foraminifera could be analysed (Fig 3.4). Before this could be done, the data was normalised. This aided in portraying the foraminiferal associations despite fluctuating numbers in places. Essentially the software produced a figure showing how closely associated different species and transect distances were associated based on their distribution and abundance (Hayward et al, 1999). The closer the groupings to the original branching, the stronger the associations between different clusters. We see vague relationships between samples from the earliest half of the transect, up to 110metres (Fig 3.4). We see similar relationships between other samples in the second half of the transect.

The relationships between samples in the first and second ‘halves’ of the transect data are not even to each side (Fig 3.4). There are outlying points in each half that come from the other side of the transect. In the first 110 metres, the 30 metre data point appears as an anomaly (Fig 3.4). This occurs in the data points above 120 metres, with the 70 metre sample appearing (Fig 3.4). Ten, twenty and 120 appear in a loosely associated cluster, and the zero distance sample is present in a group of its own (Fig 3.4). This was expected as it had an abnormally small sample size and species distribution.

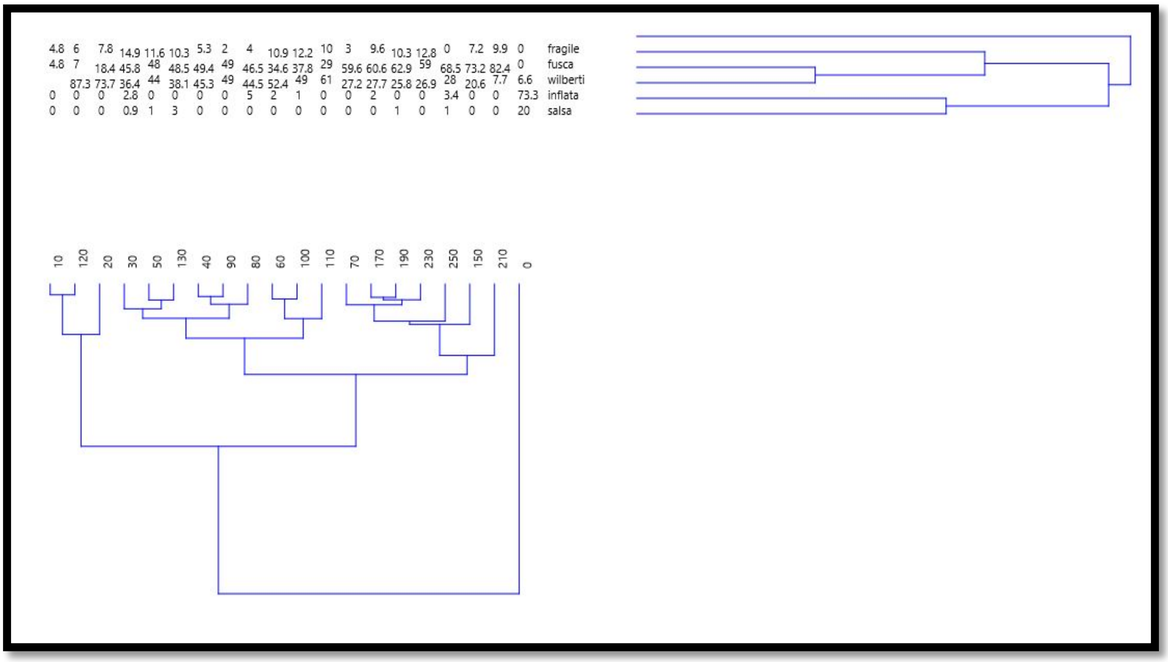

Fig 3.4 Normalised cluster analysis dendrograms for the transect taken in the Orowaiti Estuary. Compiled with PAST3 using Bray Curtis distributions

3.1.5 Transect: Foraminiferal Associations

By analysing the cluster analysis produced by the PAST software, the associations between different foraminiferal genera could be established (Fig 3.4). The above cluster analysis pre – empts the associations, as the graph is used as a primary template. The clusters previously described can be isolated based on dominant species in each section, and are labelled as so.

The associations can be seen below, and were separated in to TN (*T. inflata*), MF/H (*M. fusca, H. wilberti*), H (*H. wilberti*) and MF (*M. fusca*). They were labelled according to the genus/genera that were the most dominant in terms of mean percentage. We see that these percentages separate the groupings identified in the cluster analysis into four of these associations. It is apparent that the species most common in the transect and core were distributed across the transect as the dominant species at certain points. This included *M. fusca, H. wilberti* and surprisingly not *A. fragile*. The reason for this was that *A. fragile,* while present in high percentages, was never present in high enough numbers to dominate an association. This is also the reason that *T. inflata* was present as a dominant genus; it and *T. salsa* were the only species present at the zero metre mark of the transect. This resulted in its dominance, despite the actual numbers for that area being substantially lower than the rest of the transect.

***T. inflata* (TN)**

Habitat: Salt Marsh, Sheltered shrubbery

Tidal Level/Depth: MHW

Sediment: Medium sands/peat soils

Fauna: *T. inflata* (73.33%), *T.salsa* (20%), *H. wilberti* (6.67%)

Diversity: Unable to be completed with low numbers

Transect Location: 0m, above high tide

***M. fusca, H. wilberti* (MF, H)**

Habitat: Sand flat

Tidal Level/Depth: 0 – 0.5m

Sediment: Fine to medium sands, muds

Fauna: *A. fragile* (8.92%, mean), *M. fusca* (44.45%, mean), *H.wilberti* (46.18%, mean), *T. inflata* (1.19%, mean), *T. salsa* (0.55%, mean)

Diversity: Shannon – H: (0.9 – 2.3, mean 1.73), Evenness: (0.63 – 1, mean 0.85), Fisher Alpha: (0 – 9, mean 3.28)

Transect Location: 30 – 60m, 80 – 110m, and 130m

***H. wilberti* (H)**

Habitat: Salt Marsh, Juncus Berm

Tidal Level/Depth: MHW

Sediment: Fine to medium sands, peat soils

Fauna: *A. fragile* (6.21%, mean), *M. fusca* (10.04%, mean), *H. wilberti* (83.78%, mean)

Diversity: Shannon – H: (0.8 – 2.5, mean 1.86), Evenness: (0.42 – 1, mean 0.7), Fisher Alpha: (0 – 9, mean 2.83)

Transect Location: 10, 20 and 120m

M. fusca **(MF)**

Habitat: Mud Flats, Channels

Tidal Level/Depth: 0 – 2m

Sediment: Silts, muds

Fauna: *A. fragile* (8.84%, mean), *M. fusca* (67.49%, mean), *H. wilberti* (23.79%, mean), *T. inflata* (0.78%, mean), *T. salsa* (0.3%, mean)

Diversity: Shannon – H: (0.9 – 2.5, mean 1.62), Evenness: (0.2 – 0.95, mean 0.76), Fisher Alpha: (0 – 3.6, mean 2.2)

Transect Location: 70m, 150 – 250m

3.2 Core Results

Initially, the core was made up of predominantly silts and muds (Fig 3.5). These were a brown colour, with even distributions of micaceous and organic material. Early sections exhibited a very light oxidative staining, which is characterised by its red/orange colourisation. From 8 to 15 centimetres there was a rich organic horizon. It was immediately recognisable by the black colour and visible decaying plant matter. Following this the core graded gently into fine sands. It was increasingly micaceous with more evident and frequent oxidation. This coincided with a drop in organic matter, namely small rootlets, until they halted altogether at 38 centimetres. By 45 centimetres the core had fined to homogeneous silts. This then progressed into an angular contact with the next horizon that went from 52 to 55 centimetres (Fig 3.5).

The following section was composed of fine grey sands littered with rootlets and wood chips (Fig 3.5). This progressed to 62.5 centimetres, where the core fined into silts and muds. Organics became noticeably larger, with a 4 cm long wood chip standing out. A rapid gradation at 73 centimetres to the next section saw a colour change, with oxidation staining marking an increase in grain size to fine sands. Micaceous grains were evident along with rootlets until the 88 centimetre mark, where a sharp contact fined into silts and muds. This section extended to 97.5 centimetres and exhibited less staining and a greater degree of consolidation. It graded rapidly into a grey, well consolidated fine sand section up to 105.5cm. From 105.5 to 135 centimetres a layer gently grades from silts to fine sands. Colours change from brown to grey, and there are multiple examples of rootlets, wood chips and plant seeds. This section ends with a sharp contact to the next layer. This layer is only five centimetres long, reaching the 140 centimetre mark. It is composed entirely of fine sands and silt, and is particularly micaceous. Small rootlets can be seen throughout. Rapidly grading to the next layer, form 140 to 164.5 centimetres we saw a brown fine silt with a high mud percentage. It had a five centimetre band of rootlets from 145 to 150 centimetres. It graded coarsely from 160 centimetres into the next section. This section spanned from 164.5 to 175 centimetres and was a more homogenous version of the previous section; with greater silt percentages, no rootlets and more mica particles. This ended with another sharp gradation (Fig 3.5)

From 175 to 187 centimetres we saw a grey fine sand which graded coarsely (Fig 3.5). It was full of very small woodchips and ended abruptly after a 1 centimetre thick medium sand layer at its base. Following this was a single centimetre of grey silt and mud, with no sand obviously present. From 188 to 192 centimetres there was a fine to medium sand layer which rapidly graded to fine silts at the end of the core.

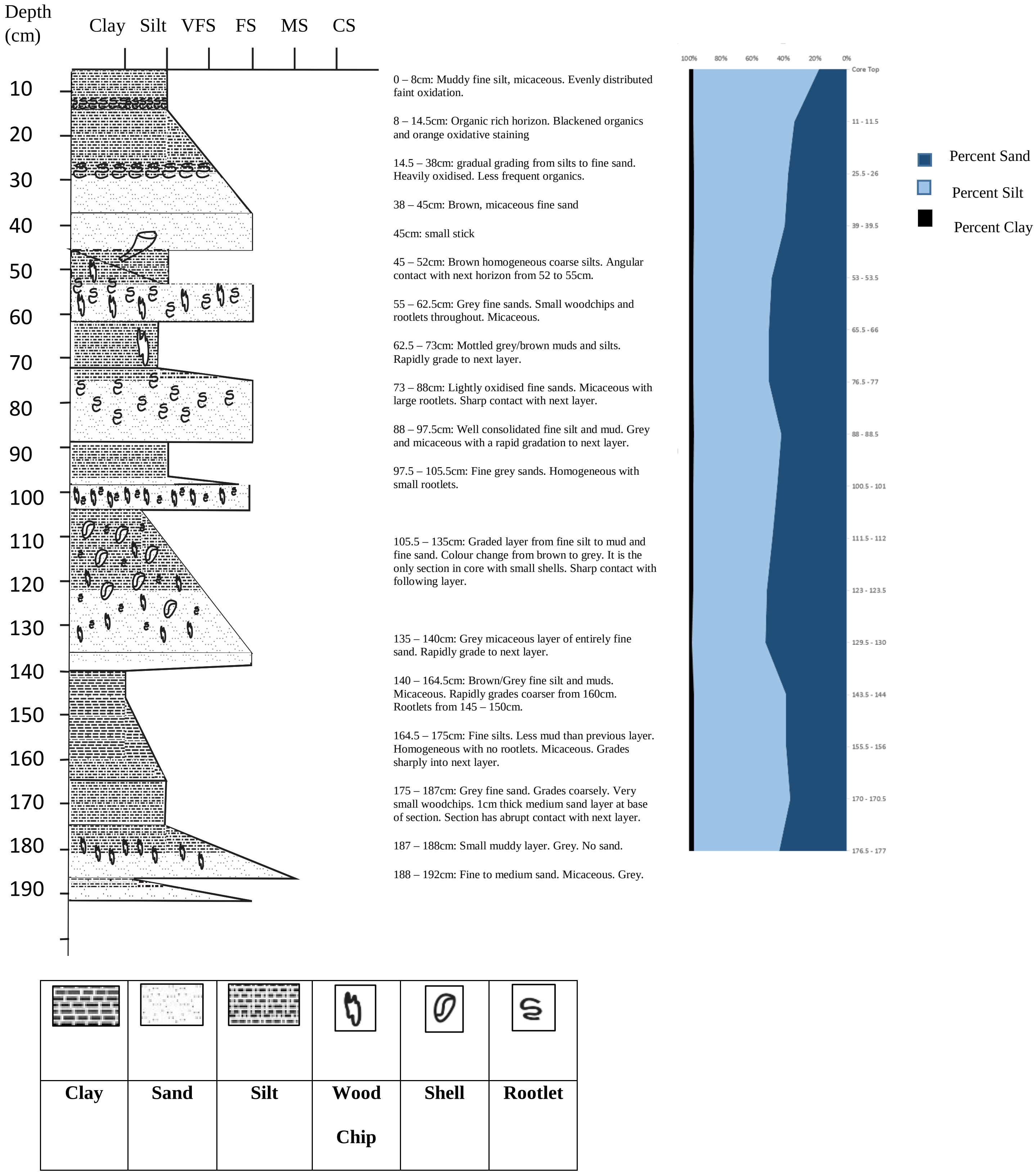

Fig 3.5 Core profile accompanied by preliminary core log and sediment sizer data. Sediment sizer data (Appendix 3)

3.2.1 Foraminifera Distribution in 'ES – CORE'

Unfortunately, the core taken from the Orowaiti Estuary has a distinct lack of tests with depth (Fig 3.6). While this makes the counts statistically irrelevant, a count and interpretation can still be undertaken for the core profile. We see immediately that the top 40 centimetres of core hold the greatest numbers of foraminiferal tests (Fig 3.6). After this depth numbers drop off notably, but for a small spike at approximately 100 centimetres. It is evident that in the early section of the core the most prevalent genera of foraminifera are *H. wilberti, M. fusca and A. fragile* respectively. *T. inflata, T.salsa* and *E. macresens* are also present throughout the core in much lower numbers. It is important to note that *H. wilberti* was the most consistent in numbers through this early section. It was also the genus with the greatest numbers, even with the spikes in *M. fusca* and *A. fragile*. In fact *H. wilberti* had increased numbers and a series of small spikes that were not present in the other genera counts (Fig 3.6).

At the spike in test counts at 100 cm, we see that *H. wilberti* remains that most prevalent test type, while there are very few other genera spikes (Fig 3.6). There were also gentle increases in both *macresens* and *fusca* at the same depth. At this point we saw a drop in sediment sizes, with the overall grain size reducing to silt and mud size. Although this happens again at the 140cm mark, it is not accompanied by an increase in test numbers. It is important to note that the foraminiferal test count finishes at 180cm, where the actual core extends to 192cm (Fig 3.6). The decision was made to not sample lower than 180cm as there were no points of interest lower than this point. The increase in grain size observed in the initial core log was not translated into coarse grain sizes when surveyed by the laser sizer (Fig 3.5). The middle section of this suspected inundation event was targeted as it was the area with most sediment density.

Fig 3.6 Core profile compared with total numbers of foraminifera per depth. Counts of individual genera are also included

3.2.2 Core Foraminiferal Clusters

Unfortunately, foraminiferal numbers in the core were not high enough for any statistical analyses to be considered relevant. As a consequence, the clusters outlined below cannot be compared with that of the transect (Fig 3.7). Even so, the cluster analyses of the present species can be described and interpreted.

We see five associated groups in the vertical columns. The first shows us close associations between 39.5, 53.5, 63, 101 and 74 centimetres (Fig 3.7). The first four three are loosely associate while there is a stronger connection between 101 and 74 centimetres. The second group contained four depths. It was much the same as the first, with the first three depths of 112, 144 and 170.5 centimetres showing a vague relationship and consequent proximity of the grouping to the end of the graph. This grouping, however, was more strongly associated as a group to the last depth in the cluster. This was 156 centimetres, which reached back approximately one third into the graph (Fig 3.7).

The third association was associated with the first and second, but only loosely with the fourth and not at all with the fifth (Fig 3.7). It contained three depths; 123.5, 130 and 177 centimetres. The first two have a weak relationship, while again, their grouping is strongly associated to the other depth in the association. This grouping, along with the initial two associations, nucleated from a split between them and the fifth association. Immediately after this split, a singular depth formed the fourth association at 88.5 centimetres. It extended as far as the graph would allow, suggesting that it was a very well established association, despite its singular set of values (Fig 3.7).

The fifth and final association contained depths from early in the core, including the shallowest value attainable; at the surface of the estuary. It was the oldest association, which nucleated all others seen in the vertical graphs. Along with the core top it included 11.5 and 26 centimetres. The association contained a grouping of the core top and 11.5 centimetres, which as a group was traced to stronger relationship with twenty six centimetres.

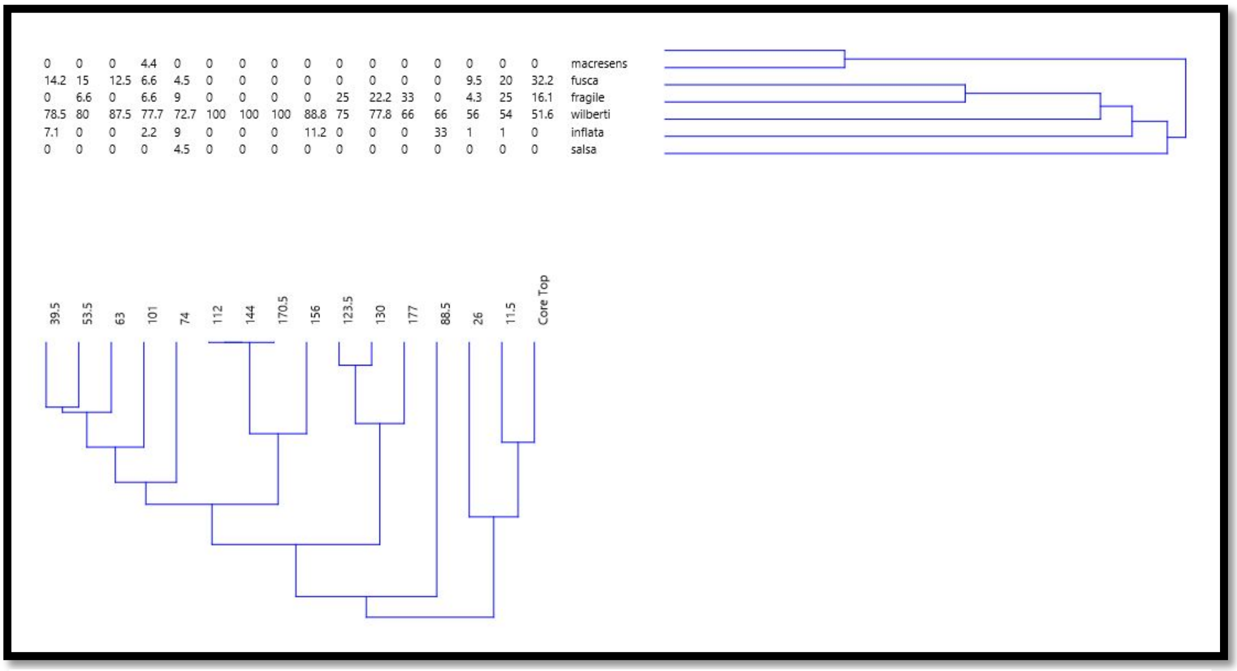

Fig 3.7 Appearance of associations and clusters of foraminifera in core samples despite low numbers. The normalised data skews the appearance of associations

3.2.3 Foraminiferal Diversity in 'ES Core'

Viewing the core diversity figure, where numbers of species per depth is compared directly with number of foraminifera, it was immediately obvious that, for the majority of the core, the fluctuations in foraminiferal numbers coincided with that of the species (Fig 3.8). The top 25 centimetres of the core represent the only area in the entire length where foraminifera are present in high enough numbers for them to be of any statistical relevance (Fig 3.6). These numbers then drop to below 20 for most of the remaining core (Fig 3.6). The initial drop coincides with a gradual increase in grain size from silts to fine sands (Fig 3.5).

From approximately 40 centimetres, the next three spikes in species and foraminifera numbers loosely coincide (Fig 3.8). They also coincide with sedimentological data (Fig 3.5). Whenever there is an intermediate stage between sands and silts at either a rapid gradation or a sharp contact, there is a spike in both species and specimen numbers (Figs 3.5, 3.8). These occur at 53, 74 and 101 centimetres in depth (Fig (3.8). Following the spike at 101 centimetres, there are two more small rises in both variables, but both are to a scale significantly less than those previous. This marks the beginning of a small plateau at 123 centimetres, which is also an area that is not mirrored exactly by a specimen number increase. Following the plateau, there was a drop of both variables to the lowest either of them experienced in the entire core, with one species and less than five specimens. Following this at 156 we see the last coinciding spike, after which the specimen numbers taper to less than five, and the species numbers increase to two before reaching the extent of sampling at 180 centimetres (Fig 3.8).

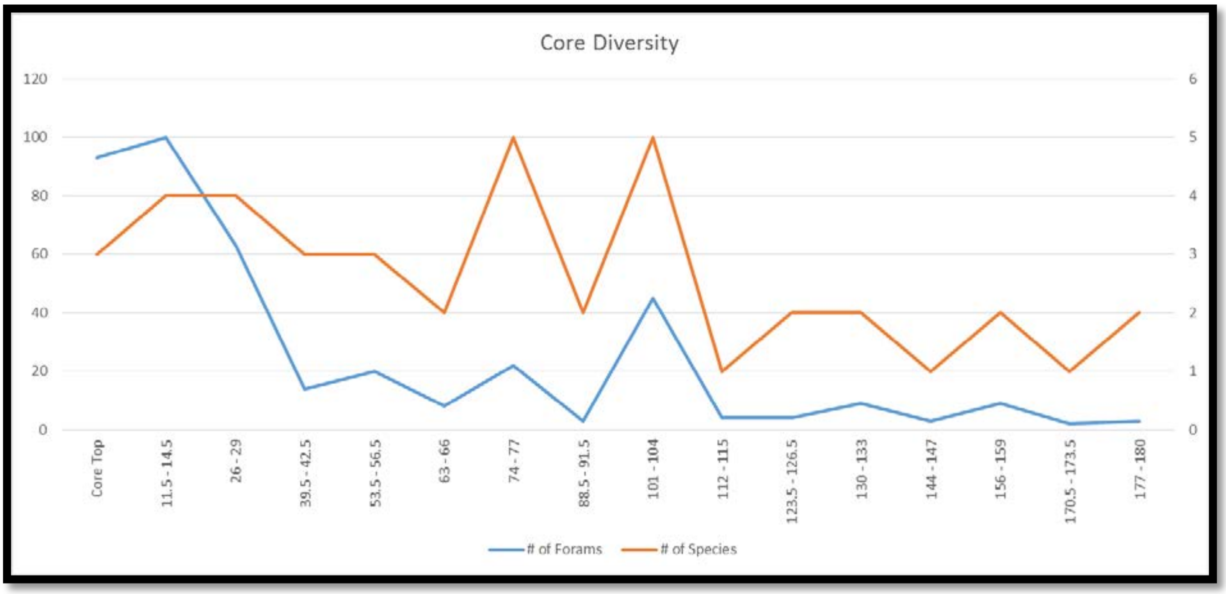

Fig 3.8 Comparison of core foraminiferal species and individual counts per depth. Note the lower average species counts than the transect.

3.3 Scanning Electron Microscope Imaging

The result from the Scanning Electron Microscope were generally clear (Fig 3.9). The defining characteristics of each species can easily be identified. In top left, we see one of the more dominant species in the Orowaiti; *H. wilberti*. It exhibits a planispiral symmetry, with a moderate relief of the umbilicus (Hayward & Hollis, 1994). The sample also expresses the characteristic lengthening of the final chamber. These particular species were extremely plentiful and as a result a near perfect specimen could be chosen for use in the SEM (Fig 3.2). *M. fusca* is oriented in such a way that the median inflated ridge that runs the length of the test is exposed. This is primarily to eliminate any confusion between *M fusca* and *M. obliqua*. The most obvious difference between these two is the aforementioned central ridge (Fig 3.9). In *obliquas* case the ridge is more oblique instead of straight from end to end, such as its namesake (Hayward et al, 1999).

T. salsa was a difficult specimen to obtain in an acceptable state. Mainly due to its greatest abundance in the more terrestrial environment, where it would have been exposed to organic acids and other weathering factors (Fig 3.2). The sample; mid left, was the greatest quality. It was arranged so that the gentle trochospiral nature of the test was evident (Fig 3.9) (Hayward & Hollis, 1994). Unfortunately one of the intermediate chambers was damaged in the mounting process, but it does little to take away from the defining characteristics of the sample. Note also the globose nature of the chambers, where they are inflated to the point where the orientation of the specimen is sometimes difficult to perceive. This is characteristic of *salsa* (Hayward & Hollis, 1994). While it is seen in other species, it is rare to occur to this degree, especially in benthic brackish foraminifera (Hayward & Hollis, 1994).

A. fragile was another abundant species in the samples taken from The Orowaiti Estuary (Fig 3.2). It has a distinctive elongate shape, which stacks in twos like a herringbone. This occurs in a linear fashion, stacking chambers on top of one another (Hayward et al, 1999). The sample in the image (mid right) is in excellent condition, but this is not the case with many specimens, as the species is true to its namesake, being exceedingly easy to break while moving or manipulating (Fig 3.9).

Unfortunately, the *T. inflata* sample (bottom left) did not express its characteristic features to the degree seen under the microscope (Fig 3.9). The umbilicus is generally very deep, with the chambers tending to express a greater degree of inflation, hence *inflata (*Hayward et al, 1999). The umbilicus in this, the better of many specimens, was unfortunately obscured by debris (Fig 3.9). In the preparation stage the samples were washed with de – ionised water in an attempt to remove debris, but cleaning is restricted due to the fragility of foraminiferal tests.

E. macresens was very rare in sample sediment (Fig 3.2). So much so that there were only a handful to choose from for Scanning Electron Microscope use. The specimen, seen bottom right, was initially in as close to perfect condition as possible, but had a chamber broken during the mounting process (Fig 3.9). Aside from this flaw, the compressed, planispiral nature of the chambers could easily be observed. Another diagnostic feature, unable to be seen in the image, is that the test of *E. macresens* is often a deeper brown colour than other foraminifera (Hayward et al, 1999).

Fig 3.9 Foraminiferal genera present in both the core and transect displayed under a scanning electron microscope. Top left: *H. wilberti*, top right: *M. fusca,* mid left: *T. salsa*, mid right: *A. fragile*, bottom left: *T. inflate*, bottom right: *E. macresens*

3.4 Geochemistry - ICPMS

The geochemical analysis of core sediments was separated into two areas; elemental quantification and relative age dating. As previously mentioned, ICPMS was undertaken in the Chemistry department, utilising their laboratories and equipment with the help of Doctor Sally Gaw, Chris Sampson and Rob Stainthorpe. Results were returned in a spreadsheet, where samples were listed against a suite of elements. Respective concentrations in micrograms per litre (ug/L) were included as the main source of data, along with the recovery percentages of reference materials. These were included to ensure ample sample concentrations following the acid treatment and dilution processes.

3.4.1 Trace Element Distribution in 'ES – CORE'

When looking at the variations in chemical elements contained in the Orowaiti core sediment, it was expected that an increase would be seen in pollutants such as Arsenic, Zinc and Lead would be observed at some point (Chague – Goff, 2004). This would have been correlated with the increase in industry and roading/infrastructure as the population of Westport increased and technology advanced. While a number of spikes occurred in the surveyed elements, the expected gradual increase never occurred (Fig 3.10).

In terms of actual elements surveyed, both pollutants and typical oceanic components were targeted (Fig 3.10). This was done to both target inundation events in the estuary and aid in strengthening any dating evidence with evidence for development in the area. The elements targeted as pollutants showed weak correlations in three out of the four; arsenic, copper and lead (Fig 3.10). Arsenic was present in lower quantities per kilogram than the Arsenic, which was expected as even though the area had experienced a gold mining boom Newcombe, (2008), and Arsenic blooms are often associated with mining, it naturally occurs in lower quantities than lead, which has a higher natural presence in marine and semi – marine sediment (Nicol et al, 2007), (Newcombe, 2008).

The Arsenic initially spiked at the top of the core at just over five mg/kg, where the Lead was already at a higher plateau of close to ten mg/kg (Fig 3.10). Both of the elements drop at 42 centimetres, with Lead at less than five mg/kg and Arsenic around two. They both then experience a smaller spike to seven and four mg/kg respectively. This was followed directly by a larger spike at 91 centimetres where Lead increased to over eight mg/kg and Arsenic to slightly under five. Both elements then taper to a low point at 133 centimetres (Fig 3.10). This low point was observed in all of the surveyed elements, if not exactly on the 133 centimetre mark, then at the 126 centimetre previous depth. Both elements then increased slightly before plateauing (Fig 3.10).

Zinc was correlated with lead, copper and arsenic, but expressed less anomalous values in every depth but one (Fig 3.10). It is important to note that it is present in higher quantities than the lead and Arsenic, at 40 mg/kg average values, and so the small changes seen as large scale change in the Lead and arsenic readings were not as dramatic as the graph showed (Fig 3.10). It truly stood out with a single anomalous value at 147 centimetres. The concentration spiked to just below eighty mg/kg. This correlates with the previously mentioned smaller spikes before the end of the core for lead, copper and arsenic (Fig 3.10).

Three of the four elements related to sea water inundation followed a similar trend to those seen in the pollutants; sodium, iron and titanium (Fig 3.10). Their initial concentrations in the core dropped towards the 42 centimetre mark. In this shallow area of the core, calcium followed similar drops in concentration, but went on later in the core to steadily increase in concentration, ending in a peak of 2000 mg/kg at 104 centimetres. The other three elements followed the pattern of pollutants, with small spike occurring at 66 centimetres, followed by a larger one at 91. Following this peak, all elements diversified in concentrations and fluctuated towards the end of the core. Titanium dropped slightly after 91 centimetres, down to 450 mg/kg before spiking one final time at the 126 centimetre mark, with a concentration of nearly 600 mg/kg. Titanium concentrations for the last section of the core dropped to below 400 mg/kg for 133 centimetres before following the pollutant element trend of a small spike and gentle taper before the core ended (3.10).

Sodium and iron behaved very similarly in terms of their fluctuations in concentrations, though it should be noted that Iron was present in the core in concentrations five times that of Sodium (Fig 3.10). The beginning of the core showed Iron at a plateau of 13,500 mg/kg for the first ten centimetres, while sodium exhibited a maximum concentration for the core of almost 2500 mg/kg. Unlike iron, this concentration quickly tapered to a low at 56 centimetres. This low was emulated by iron only after a staggered drop in concentration. Following this both elements underwent two increases in concentration over 30 centimetres. This ended at 91 centimetres and was the highest concentration in the core for iron at over 16,000 mg/kg. Sodium then tapered to a low of 1250 mg/kg at 126 centimetres. This was not the case for iron, which in fact saw a small increase in concentration instead of tapering at 126, and in fact reached a low point ten centimetres later than sodium. Following this, the two elements follow an almost identical pattern of small increase in concentration followed by an even smaller increase over the last 30 centimetres (Fig 3.10).

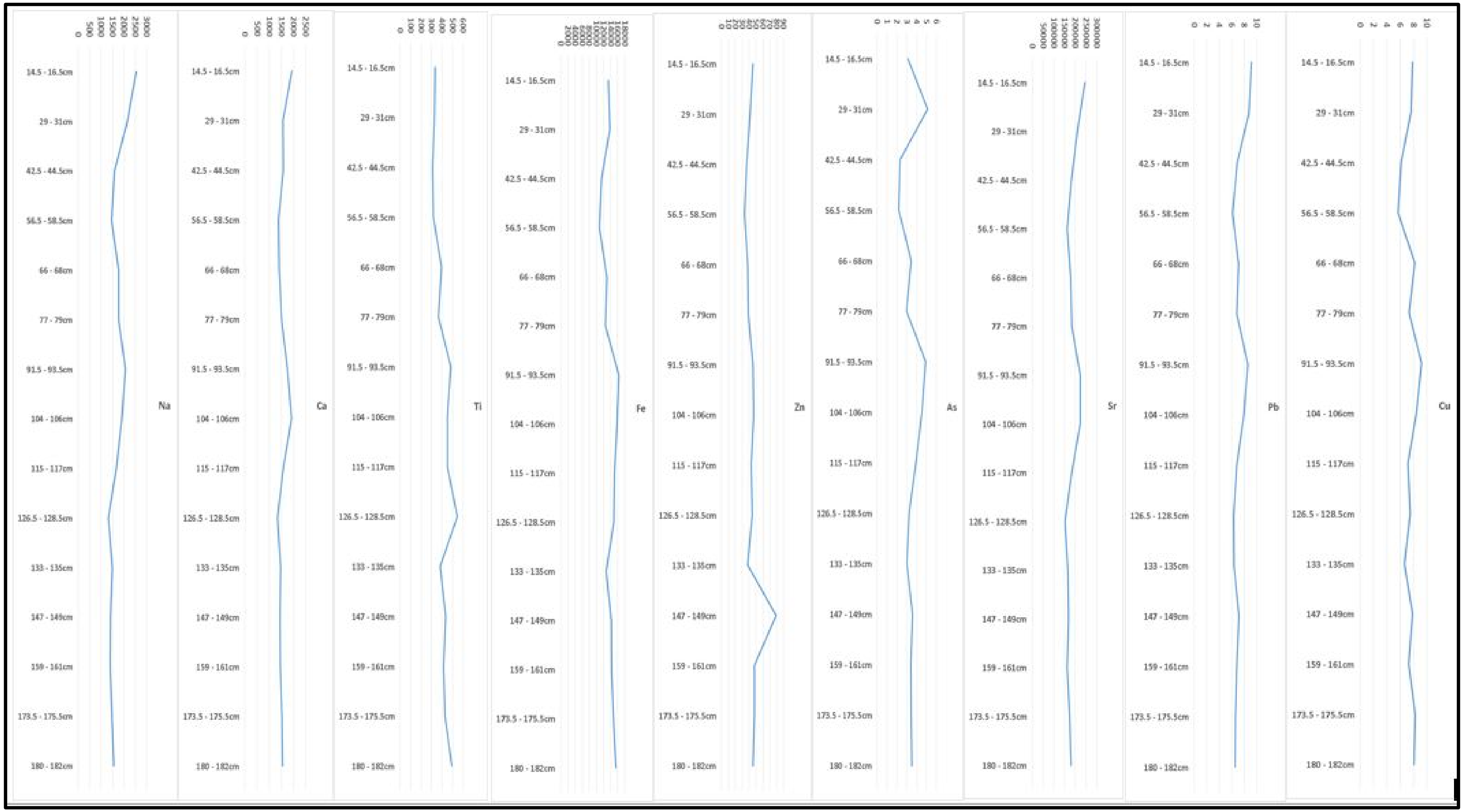

Fig 3.10 Comparison of trace elements concentrations in mg/kg per depth in the core recovered from the Orowaiti Estuary

3.4.2 Mercury Presence in ‘ES – CORE’

Mercury was presented in a separate figure to the rest of those tested for in the ICPMS analysis (Fig 3.11). This was due to its aforementioned concentration during the gold mining phase (Newcombe, 2008). We see that in the entirety of the core recovered from The Orowaiti Estuary, there is a singular spike in Mercury concentrations per kilogram of sediment (Fig 3.11). This coincides with the hypothesis of there being an anomalous amount of mercury associated with a specific period of time (Section 1.3.2, 3.4.1).

It should, however, be noted that the Mercury present in the spike between 66 and 68 centimetres in depth is a very small amount. Background concentrations are typically 0.03 mg/kg in soils, so the mercury observed in the core could not be assumed to be mining related (Bigham et al, 2015). While this is not directly indicative of mining related influx, or lack thereof, it is intriguing. Not because of the single spike, but the fact that the rest of the core exhibits absolutely no Mercury (Fig 3.11). If the spike was attributed to a fault in machination or an instance of contamination in the ICPMS’ workings, a degree of Mercury would be expected in all samples, not simply the one as seen in the core results.

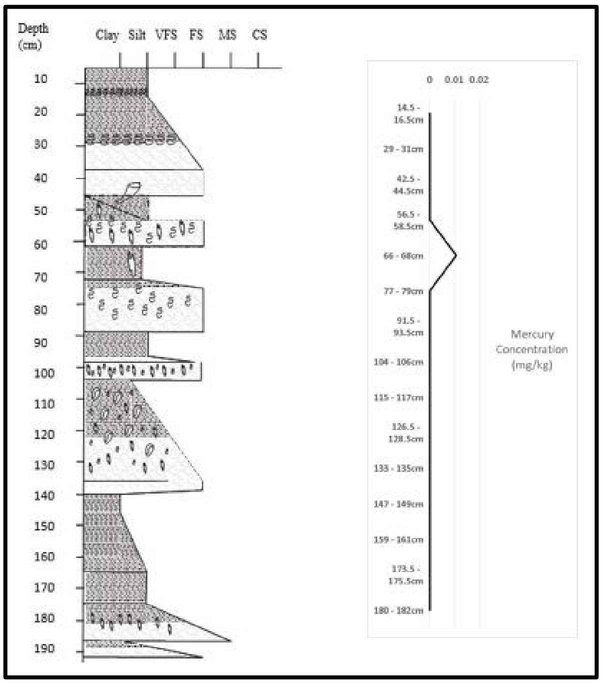

Fig. 3.11 Mercury concentration in mg/kg for the core recovered from the Orowaiti Estuary

3.5 Cs^{137} Data

Sediment was chosen from intervals in the core above and below the hypothesised section covering the gold rush in the Buller region (Section 3.4.1, 3.4.2). An additional sample was taken from the top of the core to ensure the identification of any Cs^{137} activity increase, or lack thereof, depending on results (Table 3.0). The isolation of the lower samples was based on the anomalous mercury concentration found in a shallow section of the core, at 66 centimetres (Table 3.0). This also coincided with a small increase in arsenic, copper and titanium (Fig 3.10). Ideally, targeting an older yet proximal section of the core along with a sample from a younger section would isolate the beginning of Cs^{137} activity in the sediment. As the gold rush occurred prior to the use of atomic weapons, the spike in activity would be expected slightly after this.

Results were returned from ANSTO in the Becquerel unit (Bq/kg) (Table 3.0) (Appendix 7). This is a standard unit of radioactive measure, representing activity of a material where one nucleus decays per second (Loughran & Balog, 2005). The results showed an initial small spike in radioactive caesium activity at less than 0.5 Bq/kg. This occurred before a much larger spike in the sample found just above the increase in pollutants seen at 66 centimetres (Table 3.0). This was measured at 1.2 plus or minus 0.3 Bq/kg. This was the only sample returned with an error bar accompanying its reading. The activity then dropped to 0.4 Bq/kg, lower than both of the previous samples at the earlier depth of 14.5 centimetres (Table 3.0).

Table 3.0 Unprocessed gamma spectrometer data showing the radioactivity per kilogram in the core taken from the Orowaiti Estuary

Core Depth (cm)	Cs^{137} Activity (Bq/kg)
14.5 – 16.5	<0.4
56.5 – 58.5	1.2 ± 0.3
77.0 – 79.0	<0.5

Cs^{137} Age constraints

To gauge the periods of time, and consequentially the amount of core represented by the Cs^{137}activity, it was useful to combine it with the core figure (Fig 3.12). This showed a spike in radioactivity at the 56.5 centimetre mark, highlighting that as the peak of Cs^{137} activity and placing it in the 1930’s to 1940’s (Fig 3.12).

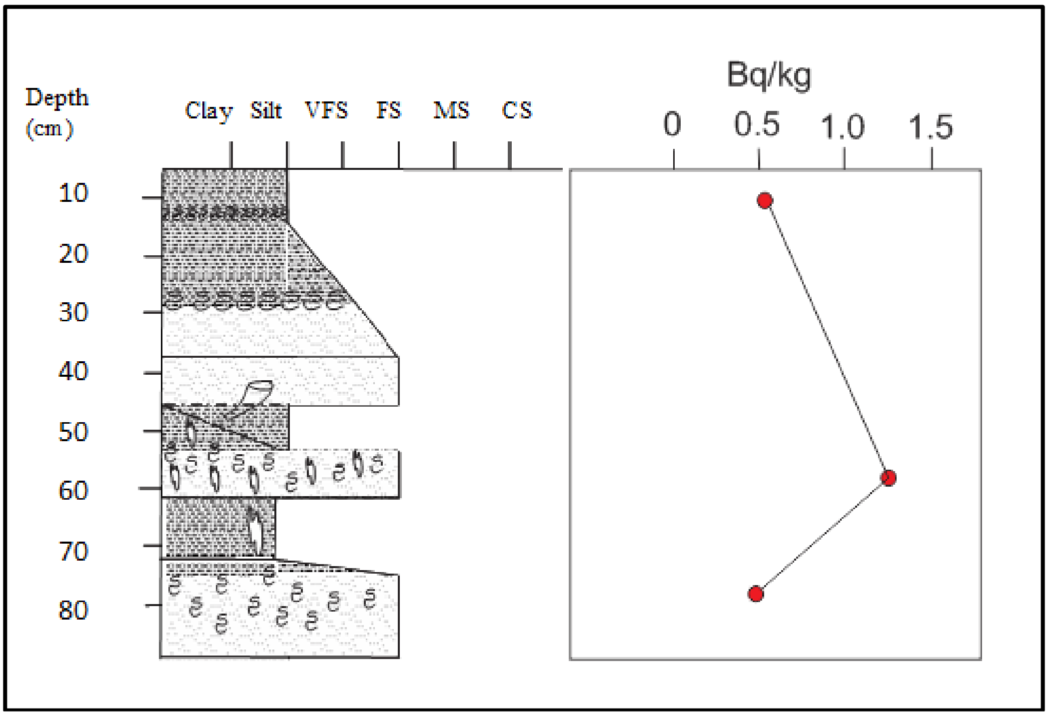

Fig 3.12 Comparison of Cs^{137}activity to the core profile describing the core recovered from the Orowaiti Estuary

3.6 Chapter Summary

The results produced by the analyses described in Section 2 highlighted changes in foraminiferal, sedimentological and chemical aspects of the core and transect. They also provided age constraints for the core and the features present in it.

Foraminiferal results were separated into the genera observed (Fig 3.9), general core and transect dispersion (Fig 3.2 & 3.3) and statistical analyses (Fig 3.4). They showed that the transect behaved in a textbook manner, with a gradient of genera appearing from the high to low tide marks (Fig 3.2). The cluster analysis on the transect revealed associations to be determined by environmental conditions (Fig 3.4). This was expected, as foraminiferal distribution has been proven to be dictated by variables such as salinity and water depth (Hayward et al, 1999). Foraminifera in the core could not be reliably analysed by statistical methods as the overall counts were too low (Fig 3.7). A preliminary analysis, however, aided in identifying the presence of two similar association at the top and middle of the core (Fig 3.7).

Sediment recovered from the transect showed a sand dominance closer towards the high tide mark, with silts becoming more prevalent towards the channel (Fig 3.0 & 3.1). Sands were increasing, however, in the metres before the end of the transect at 250 metres. This was expected closer to the higher energy of the active channel. Sediment in the core exhibited a greater silt composition than the transect, and two potential periods of subsidence (Fig 3.5). These were identified as periods of rapid sediment accumulation, analogous to the conditions seen burying the fence on the surface (Fig 4.0).

Chemical analyses of the core showed a bloom in the central section for most elements (Fig 3.10). This was followed by an all - encompassing drop in concentrations before a final increase at the top of the core (Fig 3.10). A section exhibiting mercury presence, along with arsenic, copper and lead was identified at 66 centimetres (Fig 3.10 & 3.11). This was of interest due to the presence of those elements during the gold rush and related potential age constraints (Section 3.4.2).

Caesium isotope methods identified an increase in radioactivity at 56.5 centimetres to 1.2 Bq/kg (Table 3.0). From the three samples chosen for analysis, this was the central locality. The lower sample displayed an activity of 0.5 Bq/kg, while the upper sample had 0.4 Bq/kg (Table 3.0). This put the middle sample at the height of nuclear activity which occurred in the 1930’s to 1940’s (Loughran & Balog, 2005).

4.0 Discussion

The interpretation of results produced by this investigation fall under the same variety of categories covered in the research methods and results sections. While the basic geochemical, sedimentological and palaeontological discussions are based around the findings in the results section, the discussion also allows for the inclusion of interpretations. This is where results can be collaborated into solidifying evidence for or against events of co – seismic subsidence and/or tsunami deposits in The Orowaiti Estuary. Essentially, the basic findings can be correlated with past events, local geomorphology and local history to aid in strengthening scientific evidence for any sections of the core or transect previously identified as areas of interest.

4.1 Transect: Introduction

There were a variety of sedimentological, and consequentially environmental and foraminiferal changes along the length of the transect taken from the Orowaiti Estuary (fig 3.0). These ranged from semi – terrestrial, non – marine settings, to fully established tidally controlled channels, the likes of which have been studied by Abrahim et al, (2008). If a transect is taken from the high to low tide extent, as the one for this research was, this range of environments observed down the transect length was to be expected (Fig 3.0), (Figueira & Hayward, 2014). The objective of taking a transect from this position was to gauge the spectrum of monitored variables in the estuary in its present state and to apply them to the variations observed in the core data.

4.2 Transect Sedimentology: Interpretations

Variations in the sedimentology of the transect taken from The Orowaiti Estuary pertain to environmental influences, such as tidal height, vegetation distribution and drainage patterns across the intertidal zone (Abrahim et al, 2008, Butler & Weis, 2009). This is used to elaborate about the variations in the accompanying core. An assumption is made at this stage; that the conditions observed on the surface, and their consequent sedimentological properties are close to, if not the same as historically preserved material. This is necessary as the interpretations for the core would be less feasible without the evidence from historical material, in this case, the core. It is also made more relevant due to the young age of the core, as it is quaternary sediment (Adams, 2004), and represents the modern climate.

The transect exhibited sand – dominant channel environments, soil and sand high/spring tide zones interstitially, but was made up predominantly of mud and silt flats, dominated by silt – sized grains (Fig 3.1). By looking at these variations, we can elaborate on the previous surface environment seen in the core.

The zero metre mark in the transect was above the high tide mark, (Fig 3.1). It was characterised by soils. These conditions were not observed in the core, suggesting that the core location had not ever, in the period of time represented in the two metres recovered, been located above the tidal zone. This not only proves that the estuary has not transgressed towards the mountains in that time, but that the current borders of the meadows and vegetation have not migrated either. Had a transgression occurred, changes in sedimentology and foraminiferal diversity would be expected, as the environment surrounding the area the core was collected from would be altered morphologically.

As this area of the estuary was located towards the rear of the reserve, this was expected. Because of the sheltered location, no wave action could influence sediment conditions in the area. This is reinforced by the presence of fine grain sizes, mainly silts, at the high tide mark (Fig 3.1). If the energy is high in a depositional environment, it would not be characteristic to see silts (Abrahim et al). Sand would be more common (Morton et al, 2007). This zone was dominated by these fines, while also being heavily carpeted with *Selleria radicans*; the broadleaf carpeting plant described in the transect results section (section 3.0).

The rest of the transect wavered between either mud, or sand flats (Fig 3.1). Sand became more prominent at the end and middle sections of its length (Fig 3.1). In this case the sand was either associated with the main channel at the end of the transect, or a series of channels and berms around the aforementioned middle zone. One berm in particular at one hundred and eight metres interrupted a drop in grain size from a sand flat to silts, exhibiting a sandy spike in the transect grain size (Fig 3.1). It is important to note that the other berm and channelized areas of the transect did not appear distinctively in the sediment data, but as more of a transition from finer grain sizes. Overall, the transect became coarser with progression towards the active channel and low tide mark. This was expected as greater water flow and subsequent kinetic energies are found in active channels in comparison to mud flats (Abrahim, 2008).

4.3 Transect Foraminifera, Distribution and Associations: Interpretations

The changes observed in the transect were accompanied by variations in the dominant foraminiferal genera (Fig 3.0). Essentially a shift from *H. wilberti* and *M. fusca* sharing dominance of the first one hundred centimetres occurred, changing to *M. fusca* becoming the dominant genera for the remaining half, down to the channel (Fig 3.0 & 3.2). Of course, small channels and berms, along with the anomalous zero metre survey provided a number of outlying values (Figure 3.0). This was because they introduced a different environment, and therefore a different tolerant genera to the transect (Hayward & Hollis, 1994). These were identified in the cluster analysis process, and further highlighted the presence of the associations present in the transect (Fig 3.4). This is what would be expected, as described by (Hayward & Hollis, 1994). The foraminifera were reacting to changes in the mean water depths and subsequent salinities in the Orowaiti (Fig 3.0). This was due to their low tolerance to environmental change. It created a distribution of species along the transect, as was indicated by the literature (Hayward et al, 1999).

Collectively, the data for the transect from both sedimentology and palaeontology show a trend where the steadily increasing grain size down the length of the transect is accompanied by the change to *M. fusca* as the dominant species. Figure 1.3 shows that within New Zealand, the endemic species are commonly found in specific areas (Hayward & Hollis, 1994), (Dominey – Howes et al, 2006). With the current data, the species *H. wilberti* is commonly found in a back estuary setting (Fig 1.3). This was expressed in the transect (Fig 3.2). The setting the transect was taken from specifically targeted a back estuary and active channel system, so the biological evidence seen in the foraminifera was to be expected (Hayward et al, 1999), (Hayward & Hollis, 1994). *M. fusca* was commonly seen to inhabit the channel environment in the transect. This was exactly as was portrayed in the literature (Fig 1.3). Essentially the surface environment in the Orowaiti Estuary behaved exactly as the data from the endemic literature.

When the sedimentological and foraminiferal data is compiled into a single figure, it is evident that sediment sizes do not have the ultimate defining influence on the foraminifera (Hayward & Hollis, 1994). There is a trend in average grain size, where it increases towards the active channel, but there are also a number of areas where, for example, sand is shown to be dominant for a forty metre section where silt had previously been dominant. This was not reflected in the foraminiferal counts, and so could be confirmed as not being the only influence on the organisms. Previous foraminiferal research would suggest that the tidal gradient present along the transect, along with the accompanying variation in salinity at different tidal heights had a greater influence on the foraminiferal distribution (Hayward & Hollis, 1994).

4.4 Westport Morphology and Current Local Environment

The morphology composition of the estuary and surrounding environment has been affected anthropogenically. This has been achieved by both the construction of breakwaters and the confinement of waterways, along with the introduction of a sewerage drainage system into the Orowaiti Estuary in 2008. (Buller District Council, 2016).

Confinement has not been as extensive on the Orowaiti as the Buller River. This is because the Buller River has a greater flow rate, and at its peak, the greatest flood rates in New Zealand (Robinson & Bottrell, 1996). It also empties into the Tasman Sea directly west of the Westport town centre, whereas the Orowaiti River mouth is located further to the east, directing water away from the town (Fig 1.0). The Orowaiti historically has had a lesser flow than the Buller, but shares the same floodplain; the area of land between the two waterways which Westport has been constructed on (Berrill et al, 1988).

At present, there is a port built in to the Buller river bank at the north side of Westport (Berrill et al, 1988). It is complemented on the western bank by a breakwater to protect docked vessels in extreme weather (Fig 1.0). These modifications to the Buller River have reduced the risk of avulsion through the town, and into the Orowaiti where sediment records could be disturbed (Berrill et al, 1988). The core does exhibit periods of tumultuous activity before the final forty centimetres, where the sediment gradually decreases in average grain size and silts become more dominant (Fig 3.5). This could be explained by the lack of waterway modifications, allowing for high flow events to disturb the sediment in The Orowaiti Estuary.

Currently, Westport has a population of just over 4000 people (Buller District Council, 2016). A large percentage of them are workers for Solid Energy; a company that owns the largest open cast coal mine in New Zealand; Stockton (Buller District Council, 2016). Coal is burnt locally as a heat source, and renders the area unusable for carbon dating. This is because the coal contributes excess carbon isotope 'pollution', making readings for recent sediment unreliable (Table 3.0).

Gold mining has slowed since the end of the gold rush in the Buller region, in the mid 1860's (Buller District Council, 2016), with a mine in the township of Reefton being the closest active source (Buller District Council, 2016). There is also a cement works near Cape Foulwind. This highlights the extent of carbonate facies in the Eocene deposits (Buller District Council, 2016). This, along with carbonate shales and siltstones in the Buller terrane provide potential sources for carbonates in the Orowaiti.

Apart from the mining industry, the region has turned largely to agriculture (Buller District Council, 2016). Initially settlers had trouble cultivating in what appeared to be fertile soil, as acidic, iron rich layers were found lower in strata (Wright & Mew, 1979). These were found to be inhibiting plant growth (Wright & Mew, 1979). This has been remedied by overturning up to three metres of soil, to expose more fertile ground (Wright & Mew, 1979). This highlights potential for iron saturation in local soils, a point which was mentioned by Nicol et al, (2007) when the Okarito lagoon study was undertaken. These iron pans could contribute to chemical blooms in the Orowaiti.

4.4.1 Development and Alteration of the Orowaiti Estuary

It is important to note that there have been at least two stages of agricultural development in the Orowaiti. The most recent centres around the previously mentioned peninsula. This piece of land, known locally as ‘The Island’ extends from the base of the estuary in a northerly direction, and is grassed and fenced as to keep livestock (Fig 4.0). There is, however, older evidence of prior cultivation. This is found further into the estuary, within the western bounds of the natural reserve. The most important point surrounding the fence posts mentioned in section 1.2.3 is that they are not their original height; they have been buried gradually. For whatever reason, the farmland protruding into the estuary was reduced to its present size. Whether this was due to the implementation of the reserve is unknown. There is no literature concerning the agricultural development of this area.

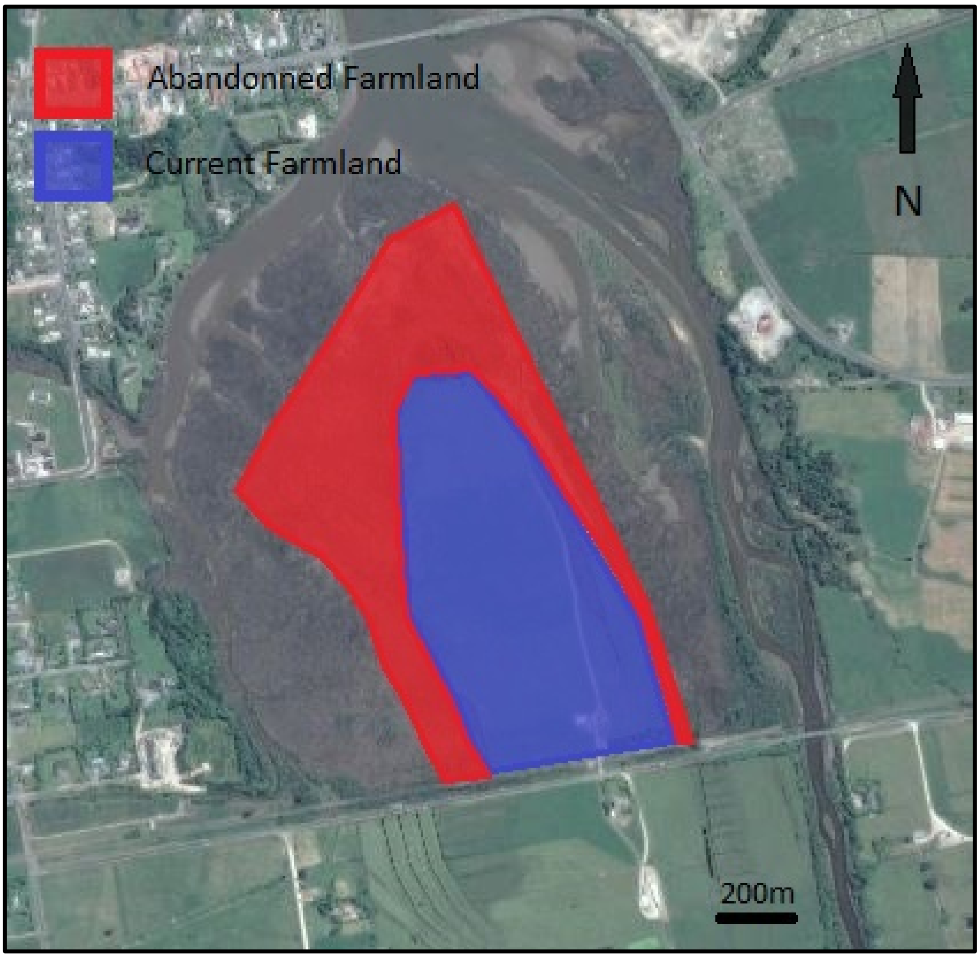

Fig 4.0 The Orowaiti Estuary, highlighting currently utilised farmland and seemingly abandoned land

4.5 Current Estuary Environment: Summary

The transect taken from the Orowaiti Estuary exhibits a typical gradient in average grain size and dominant foraminiferal genus from high to low tide (Figure 3.0). There is evidence of subsidence, or rapid sediment accumulation since European colonisation in the form of a half – buried fence that crosses the transect (Fig 4.0). In recent history, there have been chemical and sedimentological influences impacting the present environment in the Orowaiti. The potential chemical influence occurs the form of sewerage drainage and processing potentially contributing pollutants such as lead, zinc and copper (Chague – Goff, 2004). This is very recent, however, and would not likely have a noticeable effect on deep sediment, rather effecting the surface material.

The sedimentological influence by river avulsion is more likely to have occurred deeper in the sediment, as the present day break waters and river drainage alterations were not present until after the arrival and settlement of the Europeans in the mid 1800's. This means that the current environment has likely not been as heavily influenced by the avulsion of the Buller River than what the Orowaiti has experienced in the past (Benn, 1991). This being said, there have been occasional historic flooding events where the Buller River avulsed into the Orowaiti, notably in 1872 and 1979. For this to occur, the Buller River needs to increase 8.5 metres in water height to overtop its man - made stop banks and cross the floodplain (Benn, 1991).

4.6 Core: Introduction

The core taken from The Orowaiti Estuary exhibited variations in sedimentology (Fig 3.5), foraminiferal diversity (Fig 3.6) and geochemical signatures (Fig 3.10). There were no immediate signs of tsunami evidence in the core, even though the initial core analysis and log showed a typical rapid coarsening of sediment size followed by fining into a mud (Fig 3.5). This was not represented in the laser sizing analysis or chemical analyses (Fig 3.1 & 3.10). This evidence does not support the historical occurrence of tsunami in the Orowaiti Estuary. Two periods of grain coarsening and gradual fining in a more extended fashion were exhibited in the core (Fig 3.5). This kind of sedimentation was more feasible as co – seismic subsidence (Nicol et al, 2007), as the periods of grain size increase were more prolonged, and never reached the coarse grain size typical of a tsunami deposit (Morton et al, 2007). Unfortunately the foraminifera were not numerous enough to compile a feasible cluster analysis (Fig 3.7). If the full associations had been compiled, there would have been a single cluster at the top of the core, as this was where the individuals were most plentiful.

4.7 Core Foraminiferida distribution and interpretation

As previously mentioned, different genera of Foraminifera are sensitive to environmental changes, namely salinity, sediment grain size and water depth (Hayward, 1999). In general, the greater the energy of an environment, the larger the median grain size (Morton et al, 2007). This pertains to a correlation between water activity and the type of substrate in a setting, and is the reason estuarine environments contain a large percent of mud and silts (Morton et al, 2007), (de Lange & Moon, 2007). Considering the distance in to the estuary the core sample was taken, it is safe to assume that the average energy of water in the area was relatively low, compared with the estuary mouth or an active river channel (de Lange & Moon, 2007), such as the likes of the Buller (Berrill et al, 1988). It also suggests that salinity will be relatively low as the site is at the near maximum distance from the ocean without leaving both the estuary and the optimum sampling area, reducing the probable genera in the area based on their tolerance of fresh/saline waters (Hayward & Hollis, 1994), (Fig 1.3).

At the top of the core is where the most tests were located (Fig 3.5). The material for the first 15 centimetres was made up primarily of muddy fine silts (Fig 3.5). This was the section that yielded the most tests, but is not the only section composed of organic rich silts (Fig 3.5). The composition of the core at this stage is representative of what was observed on the surface at the core site, and what was surrounding the river channel in the estuary (Fig 3.1). As the tests were so plentiful close to the surface at the test site, the homogeneous material is treated as a representative of the current estuarine environment. The gradual changes in depth, proportion of foraminiferal genera and grain size represent changes in the estuarine environment. By referring to the tolerances of different genera (Hayward et al, 1999), along with the changes in sediment grain sizes (Fig 3.5), the history of the estuary in terms of uplift and subsidence can be determined for the length of the core.

The first change in the sediment size of the core occurs at 15 centimetres, where the sediments begin to grade up to fine sands. We see an increase in *A. fragile* and a decrease in *M. fusca* but no change in the other common genus; *H. wilberti* (Fig 3.5). This suggests a change in the energy of the estuary, where larger grains are being transported further into the estuary (Abrahim et al, 2008). This is commonly associated with subsidence or a general rise in ocean level (Wilson, 2006), though it could simply be associated with a gentle migration of the Orowaiti River, which would flow with greater energy than the incoming tide and would therefore transport larger grains (Nicol et al, 2007). At the 40 cm mark the substrate had graded completely into fine sands. This is where the foraminifera test numbers drop. Perhaps the Orowaiti had avulsed over the sample site, reducing the salinity in the water to the point where it became inhospitable for foraminifera in general. This evidence is also consistent with subsidence in the Orowaiti, maintaining the tidal heights despite gradual uplift, and therefore maintaining the dominant foraminiferal genera. .

It is only apparent in the counts for *H. wilberti*, where there are multiple smaller spikes in numbers prior to the 100cm secondary spike (Fig 3.6). These follow trends in an increase in grain size after periods of lower grain sizes (Fig 3.5), suggesting that *wilberti* prefers a slightly coarser grain size in comparison to the other two most common genera in the core (Hayward & Hollis, 1994). Therefore *H. wilberti* is most likely to be found in deeper, faster flowing water than *fragile* and *fusca*. This only correlates with literature in a situation where the location is centred on an active channel, which is exactly the case (Fig 2.1), (Hayward 1999).

M. fusca is only prevalent in the top section of the core, but in this area appears to behave in the completely opposite manner to *wilberti* (Fig 3.5). It has its greatest numbers in muds and silts, which taper off as the grain size increases towards fine sands (Fig 3.5). This opposition between genera suggests that the two prefer entirely different depositional environments, with *fusca* preferring lower energy mud flat/tidal flats over active channel or coastal environments (Fig 3.6), (Hayward et al, 1999).

The counts for *A. fragile* behaved in a manner unlike the previous two common genera. They spiked at a stage in the first section that fell between the muds and fine sands (Fig 3.5 & 3.6). This put the mean grain size per test count for the genus at a very fine silt. This makes theoretical sense as the test of *fragile* is, as per its namesake, very fragile and composed of very fine sediment grains (Hayward & Hollis, 1994). Due to this fragility, it tends to prefer a lower energy environment, but one that has ample sediment grains to build its test (Hayward & Hollis, 1994). This would be a low energy environment that had little mud but not enough energy to transport sands. Most likely something like a drainage channel such as the one sampled for the transect mentioned earlier in the document (Fig 3.1).

The smaller, secondary spike in the counts occurred at 100cm (Fig 3.6). It does not follow the trends set at the beginning of the core. It has a small spike at least in all genera but *T.salsa*. The combination of genera at this depth suggests a more transitional environment than those described in the transect. The alternative to the idea that the top of the core misrepresenting the ideal habitats of certain genera is that this small spike gives us an insight to the genera present in a transitional environment. The environment at the 100cm depth is a short section of fine sand (Fig 3.5). Above it are silts and below it are muds (Fig 3.5). An assumption is made here that the rate of sedimentation in the estuary is elevated in comparison to most New Zealand estuarine environments due to its proximity to the Southern Alps (Wilson, 2006). Following the theory that the central section of the core represents transitional environments, the time at the 100cm depth would have been best compared with the 100 metre section of the transect, where the intertidal process resulted in the highest diversity of foraminifera in the modern environment (Fig 3.1).

4.8 Core Profile/Sedimentology Interpretation

The core has an overall greater sand composition than that of the transect. There are two sections of the core that may show evidence of periods of gradual subsidence (Fig 3.5). The mean grain sizes were exhibited at 45 to 80 and 80 to 145 centimetres in depth. They both showed the same trend of a stoss and lee side, with a steeper gradient lower in the section, and a gradual fining to background grain size as the accommodation space filled. The lower event in the core was longer than the more recent one, but aside from this, they appear to be largely identical. This suggests that the accommodation space created to prompt the suspected subsidence events was potentially influenced a seismic event.

As a consequence of the transect having less sand than the core, it has an average grain size that is smaller (Fig 3.1). This is observed in many estuarine environments, where the very fine silts and muds are less prominent in the sediment record than in the sediment found on the surface, as larger grains have greater preservation potential (Morton et al, 2007). This is because the fine grains are more easily removed from the environment before preservation and/or burial, unlike larger grains with subsequently greater mass (Abrahim et al, 2008).

There is a colour change associated with this that is seen in the core, and was observed first hand whilst recovering core materials (Fig 3.5). The deep sediments were a light grey while surface material often exhibited blacks and browns (Fig 3.5). This could also be attributed to the presence of anoxic decomposition and organic acids (Chague – Goff, 2004). There is evidence in the transect especially of weathering in some foraminiferal individuals (Fig 3.2), suggesting that there was an acidic presence in the surface environment of the Orowaiti Estuary.

4.9 Geochemical Interpretations – Core Pollutants and Anthropogenic Development

The township of Westport was born from the discovery of gold in the Buller region (Buller District Council, 2016). Before the height of the gold rush in 1867 it had a population of approximately 80 people and was known simply as Buller (Buller District Council, 2016). Prior to the gold rush it was a trading town on the eastern banks of the Buller River, which nucleated from trading between colonial Europeans and native Maori people (Buller District Council, 2016). The Maori inhabited the Buller region long before colonisation by the British, from 950AD (Buller District Council, 2016). They lived along the banks of rivers and coastlines primarily, but would venture into the hills and mountains in search of nephrite jade (greenstone) and occasionally gold (de Lange & Moon, 2007). The presence of the Maori people did not attribute the same level of pollutants in the area as that of the European colonisation in the middle 1800's (Newcombe, 2008). Therefore it is expected that there would be an increase in the trace elements found in estuary sediments after that point.

The discovery of gold by Europeans led to a huge inflation in the Buller townships population, and it ballooned to over 1500 people (Buller District Council, 2016). Around this time of population increase, highly bituminous coal was discovered in the Denniston area, which led to further inflation in the mining industry of the region (Buller District Council, 2016). At this time there was no trans – alpine rail system, so a port at the mouth of The Buller was gradually developed from 1884, including a breakwater so that the port would be sheltered from the westerly fronts (Berrill et al, 1988). The tunnel through Otira and Arthurs Pass was not completed until 1923 (Ministry for Culture and Heritage, 2015). The port eventually served as the main export for coal across the entire North West of the South Island, but also required the confinement of The Buller River, as its meandering and subsequent avulsing nature would jeopardise any development when it broke its banks, potentially impacting the township (Berrill et al, 1988).

As previously mentioned, the Buller region was developed heavily during the mining boom of the mid - 19^{th} century (Buller District Council, 2016). This included an increase in population which was accompanied by a need for a greater standard of infrastructure (Buller District Council, 2016). Roads, drainage, milling a construction were all either introduced, or the existing facilities developed. This would have been expected to increase the amount of pollutants seen in the Orowaiti, especially the likes of Lead and Zinc, two commonly fluctuating pollutants that easily accumulate in low energy environments (Chague – Goff, 2004).

The core itself did not express the typical ‘bloom’ of pollutants seen in typical estuarine studies, where a recent core is analysed (Chague – Goff, 2004). Generally these samples contain horizons at which the progress of industry has contributed pollutants and bi - products to the surrounding environment (Chague – Goff, 2004, Frontalini et al, 2010). The concentrations then increase towards the core top. In the case of this study, the concentrations did not follow this pattern (Fig 3.10). There were indeed multiple spikes across all elements surveyed, and the results show a vague trend across both the elements deemed as pollutants and those surveyed due to their association with marine environments. Instead of this ‘bloom’, an increase was observed in the middle of the core, and once again, to a lesser extent towards the top (Fig 3.10).

Mercury was included in a separate results section due to its affinity with gold mining (Fig 3.11). In this instance it only peaked once in the entire core (Fig 3.11). This was at sixty six centimetres, outside of the two larger blooms in concentration, but coinciding with one of many small spikes throughout the core (Fig 3.10). The reason it was not included in the other results was because of the ambiguity and potential unreliability of the Mercury results (Bigham et al, 2015). The presence of a large percentage of fines in estuary was the source of this; the mercury will bind itself to the finer grain sizes (Bigham et al, 2015). This often results in areas with more fines expressing a larger concentrations of the metal, as it does not bind as aggressively to larger grain sizes, potentially leading to the aforementioned misrepresentation.

4.9.1 Catchment Geology and Elemental Sources

The North – Western side of the south island of New Zealand is made up predominantly of two ‘terranes’. These terranes, known as the Buller and Takaka (Jongens, 2006), express stratigraphic history extending back as far as the Cambrian (Adams, 2004). They contain a wide range of rock types and sources, and would therefore contain an equally extensive range of chemical compounds (Chague – Goff, 2004). Minerals and variations of rock type, once eroded from the rock as either grains of sand/silt or on a molecular scale can contribute to the sediment found in estuarine settings (Chague – Goff, 2004). Here, a blanket analysis of elements against the source rock of the area will be presented to attempt an explanation for certain spikes in the estuaries chemical composition.

To confirm that the elements seen in the Orowaiti core were indeed sourced from the ocean, and not from the catchments feeding the Buller and Orowaiti Rivers, we need to investigate the rock types found in the hinterlands of the Buller district. The Takaka terrane, it can be assumed, would not have contributed more than a few percent of the sediment seen in the Orowaiti, as it is located on the leeward side of the Southern Alps, the previously mentioned four hundred kilometre active mountain range spanning the length of the south island (Adams, 2004). One would instead expect signatures from the Buller terrane, as it is found on the Western side of the Alps (Adams, 2004).

The majority of the turbidite sequences observed in the Buller terrane are tightly folded mid to proximal fans with periodic sections of greywacke and graptolites (Adams, 2004). There was enough of a degree of metamorphism to move some of the Buller terrane into a greenschist facies in places also (Adams, 2004). This is where the mineral chlorite is formed from other micas, and sequesters within the rock during pressurisation and compaction, forming a foliation (Craw et al, 2010). This type of metamorphism is liable to produce further mineralisation with amphiboles and even garnet forming (Craw et al, 2010).

Table 4.0 List of likely minerals in the Orowaiti and Buller River catchment systems and the potential elements contributed to the environment upon weathering

Mineral	Formula	Element(s) of Interest
Quartz	SiO_2	None
Muscovite	$KAl_2(AlSi_3O_{10})(OH)_2$	Potassium, Aluminium
Biotite	$K(Mg,Fe)_3(AlSi_30_{10})(OH)_2$	Potassium, Magnesium, Iron, Aluminium
Feldspar	$(K,Na)AlSi_30_8$	Potassium, Sodium, Aluminium
Calcite	$CaCO_3$	Calcium
Chlorite	$(Mg,Fe)_3(Si,Al)_4O_{10}(OH)_2$. $(Mg,Fe)_3(OH)_6$	Magnesium, Iron, Aluminium
Glauconite	$(K,Na)(Fe^{3+},Al,Mg)_2(Si,Al)_4O10(OH)_2$	Potassium, Sodium, Iron, Aluminium, Magnesium
Amphibole: Hornblende	$Ca_2(Mg,Fe_{2+},Fe_{3+},Al)_5(Si,Al)_8O_{22}(OH)_2$	Calcium, Magnesium, Iron, Aluminium

If Table 4.0 accurately represents the potential raw composition of sediment contributing to the Orowaiti, then the concentrations of potassium, aluminium, iron, magnesium and sodium could have potentially been inflated, and affecting the concentrations observed in the ICPMS data seen in figure 3.10. This is especially important as many of the above elements are also commonly found in sea water (Section 3.4.1). This complicates area of the core where the oceanic signature is strong elementally. There is a possibility that the core composition was altered by an influx of recently eroded calcareous siltstones, for example. This would increase the Calcium presence in the estuary at that time, potentially translating into the chemical composition of the core.

4.9.2 Background Soil Chemistry: West Coast, New Zealand

Unfortunately no definitive chemical description of Buller and Westport soils. Instead a study describing the wider west coast area was used to provide an analogous description of soil composition proximal to the Orowaiti research area. Mew and Palmer (1989) attempted to describe the chemical composition of soils for northern and southern regions of the west coast. The research was compiled of a number of independent studies looking at different elements in the soils. It also described background soils acidity and identifies that older soils were more prone to increased acidification. This was linked to iron pan accumulation in lower layers (Section 4.4).

Overall, the composition of the west coast soils was found to have elevated iron and, to a lesser extent, aluminium (Mew & Palmer, 1989). This well established presence of iron in soils may have contributed to high levels of iron in the core taken from the Orowaiti. In terms of soil mobilisation, many soils were described as exhibiting ‘flood banding’, suggesting that they had been influenced by flood inundation, and had therefore undergone a sequence of erosion and deposition, providing a mechanism for transport into drainage zones like the Orowaiti.

4.9.3 Biological Causes for Trace Element Fluctuation in Sediments

A recent paper by (Chague – Goff, 2004) surveyed the plants commonly found in wetland and estuarine environments. This included a species commonly observed colonising the survey site for this research in The Orowaiti Estuary; *Juncus Pallidus*. The paper highlighted the ability of certain plants to remove trace elements and heavy metals from active semi – marine environments. The study was undertaken at a waste water treatment plant, where the water was passed over an artificially placed wetland covered with a variety of local wetland flora (Chague – Goff, 2004).

Results showed that *Juncus sp.* the entire genus, was capable of removing a portion of trace elements and pollutants from the system (Chague – Goff, 2004). These included Zinc, Copper and Lead. It did not, however, work well as a sink for Iron, even releasing into the environment during colder months (Chague – Goff, 2004). This was not the first time research had been undertaken in heavy metal and trace element removal from wetland environments via the use of naturally occurring flora (Peng at al, 2013), but was a local and recent study, and so was chosen for a case study on the subject.

The importance to this research that the study holds is that the study site was saturated with *Juncus pallidus*, a species of the widely common *Juncus* genus seen in the study by (Chague – Goff, 2004). This was seen especially in the area where the core was collected from. The results do not exhibit decreased concentrations of all trace metals in early sections of the core where plant roots could reach. That being said Arsenic does show a drop for the first surveyed depth. Unfortunately the study by (Chague – Goff, 2004) did not cover this element. There have been other studies, however, that document the uptake of heavy metals such as arsenic and mercury by specific flora as a sequestration process (Peng et al, 2013). These species were not observed in the Orowaiti estuary, and so it can be assumed there was little influence on heavy metals or trace elements by the local flora, despite the recent studies. The study by Chague – Goff (2004) offered an explanation for poor uptake of these elements, stating that young estuaries with poorly established or young floral communities often failed to remove quantifiable amounts of pollutants from wetlands.

4.10 Potential Shortfalls in Soft Sediment Core Recovery

The core taken for this research was done so using an open barrelled auger. The device was entirely man powered, with the core sections extracted every fifty centimetres, and another length attached to reach further into the sediment. There is research that suggests this method may in fact shorten less cohesive layers in the sediment record, such as muds, clays and silts (Hongve & Erlandsen, 1978). It is dependent on the velocity at which the barrel is inserted, and the method used for extraction, and so is not confirmed to occur with every case (Hongve & Erlandsen, 1978). On the premise that it did, however, this would lead to a misrepresentation in overall true core length, along with miscalculation of the years represented by the sediment (Hongve & Erlandsen, 1978). This is especially relevant to this research as correlating the core with Cs^{137}data and subsequently with past seismic events is the ultimate goal.

4.11 Data - Based Age Constraints for the Orowaiti Estuary

As mentioned in section 3.5, there is a lack of caesium presence in recent sediment prior to the 1930's (Hutchinson & Prandle, 1994). This is because it was only introduced to the environment after the use of nuclear technology (Hutchinson & Prandle, 1994). This sudden blanketing of isotopes is observed as a peak in activity (Hutchinson & Prandle, 1994). This was observed in the core at the 56.5 – 58.5 centimetre mark, where the radioactive activity, expressed as 'Bq/kg', or Becquerels per kilogram, increases to a maximum of 1.2, plus or minus 0.3 (Table 3.0). This puts the age of the 56.5 – 58.5 centimetre section at the late 1930's at the very earliest.

Chemically, the spike of pollutants in the core seen at 66 centimetres was initially discredited as being evidence for the presence of gold mining in section 3.4.2 as it was comparable with background mercury concentrations for New Zealand soils (Bigham et al, 2015). Mercury was commonly used in colonial times as an amalgam for gold (Newcombe, 2008). Zinc, lead and copper are associated with both the mining process and the presence of industry, and are all known as common pollutants (Chague – Goff, 2004). As there are coincidental increases in the concentrations of these elements in the core at the same depth, it is possible that they represent a time close to the 1850's, where the gold rush was at its height in the Buller area (Buller District Council, 2016). The sediment thickness between this section and the 1930's section, isolated by the Caesium isotope data, is between ten and fourteen centimetres (Fig 4.1). It represents approximately 80 years (Fig 4.1). The section thickness wavers due to sample thicknesses of two centimetres for each sample. This data generates a sedimentation rate of between 8 and 5.7 centimetres per decade if calculated from the extremities of the sample thickness variables.

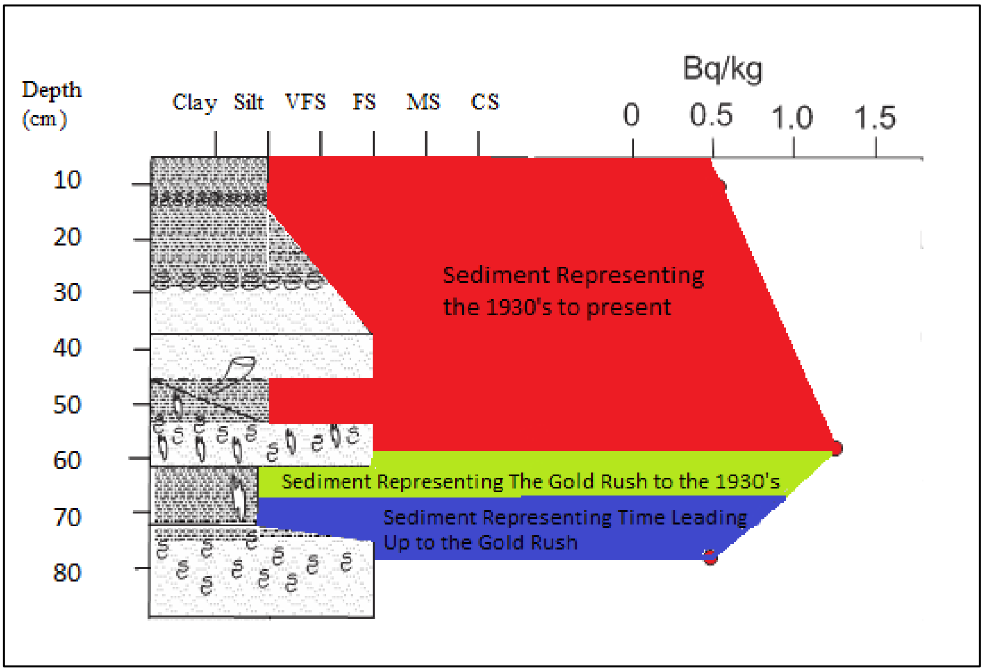

Figure 4.1 the time represented by correlating the maximum caesium activity in the core with the likely gold rush chemical markers. Note the blue section does not have a lower constraint and therefore could not be given an age range.

4.12 Event – Based Age Constraints for the Orowaiti Estuary

Past flood and earthquake events can potentially be correlated with the above age ranges (Section 4.11). It was discovered that the Buller River had avulsed into the Orowaiti Estuary twice since the 1850's (Benn, 1991). Once in 1872 and again in 1979 (Benn, 1991). These flooding events, and potentially prior unrecorded incursions could be isolated as sporadic grain size shifts in the core, as flood energy mobilises larger grain sizes than standard channel flow (Aoki et al, 2015). A number of sharp contacts are observed in the core, where the grain size moves from silts to fine sands for up to 20 centimetres (Fig 3.5). There are four of these, all occurring before 110 centimetres (Fig 3.5). As three of the four are disturbed by rootlets and have prominent biological presence, such as shells, it is unlikely that these are flood related. This is because flood deposits are rarely preserved with bioturbation evidence (Condo et al, 2013). The top section, however, is sand dominated, rich in foraminiferal tests and low in evidence of bioturbation, making it more likely to be flood related (Condo et al, 2013), (Fig 4.2). There is evidence of rootlets pert way through the section, but not in the lower part (Fig 3.5).

As it has been determined that the distance of 56.5 – 58.5 centimetres represents the mid 1900's, it is feasible that the top flood – like deposit in the core was a result of the 1979 avulsion by the Buller River into the Orowaiti Estuary (Fig 4.2). This would place the section from 29 to 45 centimetres at approximately 37 years old. This supports the idea that sedimentation rates across the Orowaiti's existence have likely not remained the same, with flood and storm event potentially contributing vastly increased amounts of sediment to the environment over short periods of time.

There is little chance that flood influence has altered the section of the core below the Caesium isotope results as only one event has been recorded prior to the 1979 flood, which was in 1872. There is thought to be 76 years represented in the first 45 centimetres of the core, as this is the difference between the Cs^{137} maximum activity and the top of the core. At 104 centimetres a section of core exhibiting similar foraminiferal diversity to the top section can be observed (Fig 3.6). To correlate with the 1872 avulsion, this section would need to represent nearly 100 years. As it sits lower chronologically in the core than the suspected gold rush event, this is unlikely.

Instead a more likely influence on sediment reworking and subsidence would be an earthquake. There are two periods of extended sediment deposition observed in the core, and no viable datable evidence lower than the potential gold rush evidence at 66 – 68 centimetres (Fig 3.10 & 3.11). Below this, foraminiferal associations were still dominated by genera that prefer environments similar to the current estuary conditions (Fig 1.3 & 3.6). This would require outside influence to maintain an environment despite gradual sediment infill. Reworking by a flood event was discredited, as if potential flood deposits are bioturbated, they are generally deemed unlikely to be flood – sourced (Condo et al, 2013). Had an earthquake caused the subsidence, it could explain the bloom in sand grains recorded by the laser sediment sizer along with the retained foraminiferal dominance. The likely event would be the projected 1717 Alpine Fault rupture (Table 1.0, Fig 4.2). There is little data on this event, as it is not well documented, but it is thought to have been an 8.1 magnitude event, releasing more than enough energy to trigger subsidence in unconsolidated sediments (Zong et al, 2003).

Below the 56.5 – 58.5 centimetre section of the core, aside from fault related speculation, there was no evidence for further dating. As the projected sedimentation rates varied, no accumulation rate could be determined below this, and consequentially neither could a representative age for the entire core.

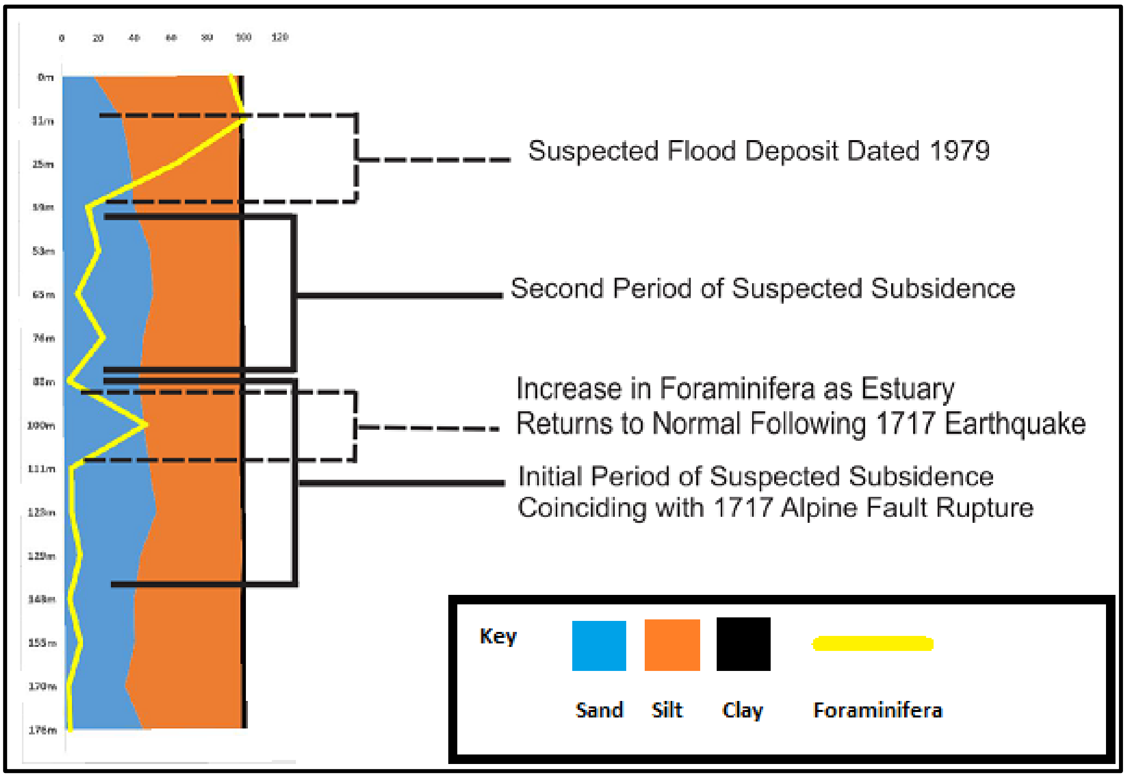

Fig 4.2 Suspected periods of subsidence and correlated seismic and flood events in the core recovered from the Orowaiti Estuary

4.12.1 Consequences of Inundation Events on Foraminifera in the Orowaiti Estuary

The aforementioned energy of random flooding events has the potential to rework sediment, and therefore also the foraminifera living in the substrate (Condo et al, 2013). It is likely that with flooding events potentially influencing the conditions in the Orowaiti Estuary that this reworking has occurred. Figueira & Hayward, (2014) showed that this occurs most commonly in intertidal zones; exactly where the transect was collected from for this research (Fig 2.1). Consequentially, the foraminifera seen in the core may have been from a wider range of tidal zones than the combination of genera would suggest.

The combination of genera seen in the core initially suggested that the section of the Orowaiti Estuary the core was recovered from had undergone subsidence. This was evident as there were the same two dominant genera at the top and middle sections of the core (Fig 3.6). Had unhindered sedimentation occurred over time, the gradual tidal height would drop, shifting the environment to shallower and shallower species. This did not happen and therefore was hypothesised to have occurred due to one or more periods of subsidence. If there was flood – related mixing, however, the species present in the core may have been transported there (Figueira & Hayward, 2014

4.13 Core Summary

Large fluctuations or anomalously high peaks in the sediment record are characteristic of rapid inundation (Goff et al, 2010). This could be related to tsunami or storm events (Morton et al, 2007). There was no definitive evidence for tsunami in the core data. The sedimentological evidence seen in studies such as Nicol et al, (2007) were not present. Chemically, fluctuations were observed in the core, but no definitive anomalous concentrations were isolated as being tsunami. Foraminifera showed no indication of a rapid inundation either, with no planktic or fully marine benthic species being observed in the core sediments (Fig 3.6). This led to the conclusion that the two metre core taken from the Orowaiti Estuary did not show evidence for tsunami inundation.

Steady increases in grain size tend to signify gradual subsidence (Zong et al, 2003). This kind of data is observed in the core and is directly comparable with the data taken from the transect, confirming that the tidal states experienced by the core location in the past were similar. Two periods of erratic sedimentation occur in the core (Fig 3.5). Alone this did not prove to be evidence of co – seismic subsidence, as an event such as a flood could provide an influx of sediment to the estuary. It was concluded that there may have been such a deposit in the sand – dominant section at the top of the core.

The chemical data monitored the sea water fluctuations into the estuary, along with any anomalous trace metal incursions that may have occurred during the colonisation of the Buller Region. There was a bloom of chemical concentrations at the top and middle sections of the core (Fig 3.5). The lower bloom coincided loosely with the first increase in average grain size, while the other coincided with a drop in chemical concentrations. Overall the most relevant section was a small area around 66 centimetres, where all pollutants, including mercury increased (Fig 3.10 & 3.11). As this fell between the lower and middle Cs^{137} sample depth, it was feasibly correlated with the gold rush, placing the 66 centimetre mark in the middle to late 1860’s (Table 3.0, Figure 3.12).

The core was also sampled for foraminiferal data (Fig 3.6). The foraminifera showed a trend usually associated with subsidence; the dominant taxa; *H. wilberti* and *M. fusca*, did not lose dominance through the entire core length. While this is interpreted solely on numbers, as statistical analyses were impossible with such low numbers, it would be expected that species would change with depth (Bandy, 1953).

The gradual subsidence that occurs within estuaries, as seen by Zong et al (2003), would change the environment around a static point, resulting in varying salinities (Figueira & Hayward, 2014). These conditions would prompt a change in the dominant foraminifera, as it would be unlikely one genus could tolerate such change (Hayward et al, 1999). This left the identification of a potential historic rupture to correlate with the suspected subsidence. There was no consistent earthquake data for the time before European colonisation, save for potential Alpine Fault ruptures (Robinson & Davies, 2013). The most recent potential rupture, shown in Table 1.0 occurred in 1717, which, considering the projected amount of time covered by the first 80 centimetres of the core, is not within the age constraints generated by the caesium isotope and ICPMS evidence (Fig 3.12). This being said, the core was suspected to have been influenced by flood deposits which commonly skew sedimentation rates.

5.0 Conclusions

Identification of tsunami in the Orowaiti Estuary was inconclusive. Sedimentological, foraminiferal and geochemical analyses failed to show any of the typical signs of inundation in the estuary. The initial core analysis identified what seemed to be an anomalously high grain size in a small section low in the core. This isolated the section as a target for analysis, but tests from all aspects failed to separate it from the rest of the core.

While there may not have been a confirmed tsunami event in the core, it was likely that there was at least one flood deposit. The flood history of the Buller district described two events occurring where the Buller River avulsed into the Orowaiti (Benn, 1991). A section of sediment at the top of the core displayed a sharp lower contact and fine sands, as opposed to the background silts. It was not bioturbated and gently returned to background grain sizes. It was therefore suspected to represent the 1979 Buller River avulsion into the Orowaiti Estuary, recorded by Benn, (1991).

The sedimentological and foraminiferal results were interpreted as to display at least one period of subsidence in the core. Sediment results from the department laser sizer depicted two periods of sediment accumulation in the estuary (Fig 3.5). They appeared as a rapid increase in grain size, represented as an increased sand percentage which was then followed by an extended period of the mean grain sizes resetting to the background state.

The sediment data pattern seen in the core was not reflected exactly in the foraminifera. Instead evidence for subsidence was observed in the limited individuals that a change in dominant genera with depth did not occur (Fig 3.6). Instead, *M. fusca* and *H. wilberti* remained prevalent. This was not expected, as with constant sedimentation it was expected that the fixed point in the Orowaiti where the core was recovered from would have steadily increased its relative height, producing an environment more suited for shallow water, lower salinity – preferring genera. The reason given for this was a period of subsidence, so that the recent estuarine environment was preserved throughout the core.

A combination of sedimentological, geochemical and foraminiferal interpretations also ultimately contributed towards the construction of age ranges in the core (Sections 4.11 & 4.12). The use of Cs^{137} in combination with these interpretations provided the isotopic proof for age constraints, while correlation with past events such as the gold rush allowed for basic sedimentation rates to be provided for the top of the core. The suspected position of the gold rush was determined by chemical markers in the sediment, highlighting a zone where there was an overall increase in pollutants in the core. This included mercury and arsenic, two elements strongly related to gold mining in the middle 1800's. This provided an area in the core below the Caesium activity limit where another potential age range could be introduced. At this stage, the Caesium peak activity placed the 1930's to 1940's at 56.5 – 58.5 centimetres in depth, while the pollutant increase placed the mid 1800's at 66 to 68 centimetres. If the supposed gold rush is placed correctly, the sedimentation rate at that depth was approximately 5.7 - 8 centimetres per decade. Considering the proximity of the Orowaiti Estuary to the Southern Alps, this sedimentation rate was unexpected and much smaller than few hundred years hypothesised to be represented by the entire core.

The sedimentation rate for the remainder of the core, however, could have varied greatly. It was concluded earlier that there was potential for flood deposit preservation in the core. The presence of a high energy event such as a flood likely both eroded and deposited sediment, leaving unconformities in the core record. This would skew the sedimentation rate throughout the core. Reliable rates could not be determined for later core sections due to this, as the sedimentation history was deemed erratic.

5.1 Future Work

If time and budget were no longer restraints on this research, modifications could be made to the process to refine the data collected and potentially provide a greater resolution to the tsunami and co – seismic history of the Orowaiti.

- Take multiple cores from across the estuary to track potential flood and/or tsunami events using the same techniques used for this research.
- Take multiple cores from the same area to make up poor foraminiferal counts and allow for relevant statistical analyses.
- Utilise complete digestion of sediment instead of partial for ICPMS research. The method was unavailable to the author but utilises fluoric acid to release elements like titanium from clay and mineral lattices. This would provide a higher resolution for chemical data.
- Locate and sample historical sites of ‘flood banding’ in sediment to use as a potential comparison to estuary sediments. This would aid in identifying the features of flood deposits in the Buller District.

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Appendices

All appendices available in electronic form

Appendix 1

Raw unprocessed laser sediment sizer data for both core and transect

Appendix 2

Processed laser sizer data for the transect

Appendix 3

Processed laser sizer data for the core

Appendix 4

Transect foraminiferal counts and locations

Appendix 5

Core foraminiferal counts and depths

Appendix 6

Raw and processed ICP – MS data

Appendix 7

Gamma spectrometry raw data