Using Paleoecological Proxies to Determine Holocene Environmental Change: A Case Study at Onaero Beach, North Taranaki

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Frontispiece: The Onaero Beach section in outcrop Photo: Courtesy Brent Alloway

Abstract

A multi-proxy paleoecological and sedimentological record for the last ~8.3kyr is extracted from a 2.1m coastal seacliff at Onaero Beach, North Taranaki. This record is used to infer both local environmental changes including shoreline, coastal conditions, as well as regional changes in atmospheric circulation and climate wetness. Analysis of diatom and pollen populations, particle size, and loss on ignition provide the raw data from which inferences regarding salinity and vegetation are made. Changes are tied to a chronology determined through radiocarbon ages and tephrochronology.

Key objectives of this study are: (1) To characterize changes in salinity and relative shoreline position at Onaero Beach (2) To characterise changes in vegetation and relate these changes to overall state of the climate through the Holocene (3) Compare the results of this study with others from New Zealand and the wider south pacific to investigate how the Onaero Beach section fits in both a regional and global context.

Diatom analysis of the Onaero section revealed the dominance of brackish to marine species which suddenly at 7.3ka after which time diatom assemblages were dominated by fresh and salt intolerant species. The marine to freshwater transition represents a transition from a brackish to freshwater coastal lagoon.

Pollen analysis of the Onaero Beach section indicates the region was dominated by podocarp forest. The increasing dominance of *Dacrydium* and decline in other podocarps suggests an increase in overall climate wetness.

The disappearance of pollen in conjunction with the deposition of tephra at ~4.15ka is not conclusive proof of, but certainly fits with, the idea of a significant climatic event occurring at ~4.2ka resulting in a reversal of the current prevailing wind direction and supports the case for a formal Middle/Late Holocene boundary at this time.

Acknowledgements

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This thesis is dedicated to my mother and father

Kathleen and David Skudder

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1. Introduction

1.1 Research Aims & Objectives

The primary objective of this study is to perform a multi-proxy investigation on a small coastal seacliff with a view to determining environmental changes, and their causes, occurring in the Holocene, both locally and regionally. Documenting and understanding environmental changes and how they are influenced by changing climate is essential for understanding how future changes may present themselves.

Key objectives of this study are

- To characterize changes in salinity and relative shoreline position at Onaero Beach
- To characterise changes in vegetation and relate these changes to overall state of the climate through the Holocene
- Compare the results of this study with others from New Zealand and the wider south pacific to investigate how the Onaero Beach section fits in both a regional and global context.

The advantage of multi-proxy studies is that they can provide a more complete picture of changing environments, and how different environmental variables may be interlinked and it is hoped this study is able to do this convincingly.

1.2 Micro-Paleoecological Proxies

Holocene environmental changes are now commonly determined from the analysis of microfossil assemblages as they are ubiquitous in a wide range of depositional environments. A particular microfossil is typically more sensitive to a particular environmental variable than another, and so assemblages may be used as a proxy to infer changes in that particular variable. In the case of this study, pollen is used as a proxy for past vegetation and climate while diatoms are used to infer changes in salinity and i.e. transitions between marine, brackish and freshwater environments. The interpretation of paleoecological data must be made based on an understanding of the processes involved in

the emplacement of that indicator in addition to the use of the modern analogue technique (MAT). This is especially relevant for the Holocene where many of the organisms preserved in Holocene sediments are also alive today. This means their ecological preferences may be studied in environments today and if these assemblages are observed in the fossil record, that particular environment may be inferred in the past.

1.2.1 Diatoms

Diatom frustules are silica based remnants of a major group of phytoplankton that are sensitive to changes in salinity and nutrients in ocean waters. By looking at the proportion of fresh and marine diatom assemblages, they can be used to investigate the morphology of the coast, including the relative position of the shoreline and interaction between saline and non-saline waters. Transitions between marine, brackish and freshwater environments can tell us important information about small scale shoreline changes in estuaries and shallow harbours (Hayward *et al*., 2010; Witowski *et al*., 2000) which is important when using a coastal site such as Onaero Beach.

1.2.2 Palynology

As well as determining past changes in coastal conditions, it is also important to see how any observed changes relate to local and regional climate. Analysing changes in the populations of pollen grains can also be used to infer changes in vegetation, which in turn can be used to infer changes in overall climate as the two most important variables influencing vegetation are temperature and precipitation.

While pollen grains are most abundant in organic sediments, they can also be found in estuarine sediments, albeit in much lower concentrations. The use of pollen as indicators of past vegetation and environmental changes in New Zealand during the Quaternary has proven very informative. However fewer studies have been made of diatoms and pollen together. A number of pollen studies of Taranaki during the Holocene have laid the foundation for future work including the inland site of Eltham swamp (McGlone & Neall, 1994) and a study of a last-interglacial climate from a buried forest at the coast (Newnham & Alloway, 2004). However, a record of Holocene vegetation changes from a coastal site in

Taranaki does not yet exist. A vegetation record for the Holocene will be produced from the Onaero Beach seacliff with a view to inferring changes in the position of the shoreline.

1.3 Chronology

In addition to extracting quality paleo-ecological data, it is imperative that these data be constrained by a robust chronology. In paleo-ecological studies this can come from a variety of methods including radiocarbon dating and tephrochronology.

A number of methods are used to identify a particular tephra including its glass chemistry, spatial distribution and position relative to other tephra. Once a tephra has been identified, it provides an isochronous horizon, meaning wherever it is identified across the landscape upon which it was deposited, it carries the same age. This is the case at Onaero Beach where a number of tephras have already been identified including the Inglewood, Stent and Korito tephras with ages of 3.6, 3.9 and 4.2 cal. kyr. BP respectively (Alloway *et al*., 1994), tying the seacliff to the Holocene. The precision and accuracy of radiocarbon dating has also improved greatly over the past few decades and is commonly used to constrain paleoecological data. Combining data already existing from tephrostratigraphy with new radiocarbon ages, will provide a robust chronology that can be used to infer the timing of environmental changes recorded in the Onaero Beach Sediments.

1.4 Thesis Outline

This thesis is presented in 7 chapters. This chapter introduces the idea of using a multiproxy study of Holocene coastal sediments to determine Holocene environmental changes. Chapter 2 provides a brief account of Holocene paleoenvironmental history in New Zealand, a background to the relevant processes operating at the coast, and a more in depth look at the use of paleo-ecological proxies to infer environmental changes. Chapter 3 describes the local and regional setting in which Onaero Beach is situated. Chapter 4 outlines the methodology used to obtain data. Chapter 5 outlines the results which are then discussed in Chapter 6. Conclusions are presented in Chapter 7.

2. Background

This chapter outlines the principles behind multi-proxy paleo-environmental studies and the reasoning behind the proxies chosen and the methods used in the Onaero Beach study.

2.1 Multi-proxy paleoecological studies

Paleoenvironmental reconstruction is concerned with determining an aspect of a past environment through some form of paleo-ecological proxy. Proxies able to be used are determined by many factors including the purpose of the study, field characteristics of the study area and physical characteristics of the material to be analysed. Additionally, there are many variables affecting an environment at any one time so it is important to remember that the changes observed in a single proxy may be the result of a combination of environmental variables. Multi-proxy studies can also decrease uncertainty associated with the use of a single proxy, where the relationships between environmental variables and organisms may be over-simplified (Urrutia *et al*., 2010).

2.2 Coastal processes & shoreline movement

The coastal zone, which may be defined as the full extent to which the terrestrial system influences the marine system and vice versa (Harris, 1963), is a dynamic environment where a diverse range of physical and biological processes interact. Shorelines, the line between land and the water's edge (Bird, 2008), is but one component of a coastal system and subject to alteration by a variety of processes including eustatic sea level change, tectonic activity and terrestrial aggradation/degradation processes. Documenting shoreline changes is essential for determining coastal processes operating in an environment and, while shoreline changes today may be monitored through field measurements, it is also possible to determine past changes through the analysis of paleo-ecological proxies.

The processes operating at the coast directly influence the nature of coastal sediments used to interpret past depositional environments. The shape, composition, size, texture, structure and fossil assemblages of coastal deposits all arise as a result of the environmental conditions at the time of their deposition.

2.2.1 Factors affecting shoreline movement

Shorelines may change as a result of a variety of processes, the 3 most important of which are: (1) eustatic sea level change, (2) tectonic movements, and (3) shoreline regression or transgression as the result of terrestrial aggradation or degradation processes, all else being equal. Of course any changes are likely to be a result of a combination of some, or all of these, but are considered here in their own right.

Eustatic sea level in New Zealand during the Holocene is characterised by two main trends. The first is a period of relatively rapid sea level rise which stabilised at ~7.5ka while the second is from 7.5ka where sea level stabilised and remained relatively constant to the present day (Clement *et al*., 2010). An increase in eustatic sea level would result in movement of the shoreline inland while a decrease in eustatic sea level would result in movement of the shoreline seaward. Indeed many coastal deposits of Holocene age are preserved as the result of the increase in accommodation space caused by postglacial sea level rise (Kennedy, 2008).

In a tectonically active region such as New Zealand, it is imperative to consider the effects of any tectonic movements on coastal records. Vertical tectonic movements may create the illusion of an apparent change in sea level or shoreline position. Tectonic uplift may cause the shoreline to appear to move seaward while subsidence may cause a shoreline to appear to move inland, all else being equal. One such example of this is Gibb (2012) who found evidence for abrupt relative sea level changes associated with earthquakes along major faults on the west coast of the North Island. In addition to vertical land movement, tectonic activity can also destabilise coastal sand dunes and result in a change in shoreline position (de Lange, 2013).

Shorelines can still change even if eustatic sea level and tectonics bear no influence on a site at all. Coastal systems and shorelines are also subject to terrestrial aggradation/degradation processes which are constantly re-shaping them. Depending on sediment supply, tidal dynamics and other processes at play in a coastal environment, a coastal site may record changes in shoreline and influence from the sea.

2.2.2 Salinity in Estuaries & Coastal Lagoons

Particularly sensitive to changes in shoreline position are estuaries and coastal lagoons, as they lie within the inter-tidal zone. An estuary, first defined by Pritchard (1967) as a 'semi-enclosed body of water which has a free connection with the open sea and within which seawater is measurably diluted with fresh water derived from land drainage,' are a type of tide-dominated coastal system (Haslett, 2000). It is an environment where fresh water from an inflowing river and saline water brought into an estuary by tides, interact. Consequently, estuarine sediments are typically of both terrestrial and marine origin and as sediment accumulates over time, a specific site may record the interaction of fresh and saline waters. Estuaries can also be divided into three longitudinal sections, a marine-dominated section and a freshwater river-dominated section separated by a brackish mixed central section with the two outer sections highest in energy (Dalrymple, 1992). These sections may migrate landward and seaward in response to environmental pressures.

Because estuaries are in tide-dominated coastal settings, it is also important to consider the tidal regime operating as this affects the amount of salt-fresh water mixing within an estuary. Saline/freshwater mixing affects the movement of sediment within the estuary as well as the distribution of any organisms living in the estuary. According to Pritchard's (1955) salt-balance principle, the salinity at any given point in an estuary is a function of two processes, advection and diffusion. Advection refers to mixing of fresh and saline water due to the turbid nature of the environment while diffusion occurs in relatively quieter environments. These two processes dictate the level of mixing with an estuary or coastal lagoon from stratified, where the boundary between the fresh and saline waters may be sharp to well-mixed where there is essentially no boundary between fresh and saline waters.

Estuaries can consequently also be classified according to the level of mixing occurring. Stratified estuaries are most common in wave-dominated, micro-tidal settings where the boundary between saline and freshwater is defined by a reasonably sharp halocline with limited advection occurring. Partially mixed estuaries, common in macro-tidal settings, are influenced to a greater extent by tides and consequently the halocline is represented by a zone of mixing where both diffusion and advection operate (Haslett, 200). Understanding

how mixing occurs in an estuary has important implications for the sedimentology and ecology of the estuary.

Estuaries are also very diverse and encompass a wide range of environments. Most are closed off to some extent from the sea; however, some are particularly sheltered and may be classified as a coastal lagoon. Coastal lagoons are relatively shallow environments that are partly or even entirely sealed off from the sea by a sediment barrier (Haslett, 2000). While still subject to some tidal influence, they are much lower in energy than an open estuary. Coastal lagoons are still subject to the mixing of fresh and saline waters and have a general salinity gradient where a specific point may be subjected to changing salinity through time. Sediments found in coastal lagoons may also be a mixture of terrestrial in origin brought in by an inflowing river, or of marine origin, brought in by the tides, and material deposited may be of both organic and physical origins (Bird, 2008).

2.3 Diatoms and salinity reconstruction

Diatoms are a type of photosynthetic algae. They are microscopic unicellular plants which range in size from approximately 5µm to 500µm and live in a wide range of environments where there is moisture (Cochran, 2002). Diatom taxonomy is based on the morphology of the siliceous part of the cell wall, termed the frustule, which typically remains long after the death of the cell (Barber & Hayworth, 1981). Diatoms are extremely diverse in their morphology and identification is made upon observations of valve shape and striation patterns on the frustule. Identification is commonly carried out by comparing specimens with descriptions and illustrations from particular regions or ecological niches. Unfortunately, diatoms are affected by physical processes, including erosion, tidal currents and waves, bioturbation and dissolution. This must be taken into account when identifying diatoms.

2.3.1 Diatoms and salinity sensitivity

While diatom assemblages are affected by many environmental variables including moisture, pH, oxygen and nitrogen requirements, the two most controlling variables are habitat and salinity (Van Dam, *et al*. 1994; Cochran, 2002). Diatoms can inhabit a wide variety of environments from terrestrial to marine. However, a single species may tolerate a

range of environments with different salinities, so interpretations are improved when investigating entire assemblages. Each species has an optimum and a tolerance. Some species may be able to tolerate small changes in salinity while others can tolerate much larger changes. Since diatoms can be present over the entire salinity gradient from fully freshwater to fully marine, they are extremely useful in characterising past environments, especially in coastal settings (Cochran, 2002).

Important to consider when using diatoms to infer changes in salinity is that in environments where salinity fluctuates, the presence of a particular species is more likely to be representative of that species' ability to tolerate a range of salinities rather than a species living at its environmental optima. Additionally, species also behave differently particularly in brackish environments as they are affected by other environmental variables such as pH, water temperature, light regime, nutrient concentrations and exposure to wave action (Van Dam *et al*., 1994).

2.4 Pollen & paleo-vegetation reconstruction

Pollen analysis is a technique used for reconstructing past vegetation by investigating the pollen assemblages that a vegetation community has produced (Faegri & Iversen, 1989). It is a particularly valuable environmental proxy as the compound which pollen grains are composed of, sporopollenin, is particularly resilient to degradation. Pollen can also be dispersed over wide areas and found in a wide variety of environmental settings. The ideal site for an investigation of past vegetation is one that accurately records the vegetation of that site and is not influenced by the input of allocthonous material from rivers or erosion (Faegri & Iversen, 1989). Identification of pollen grains is based on their morphology including grain shape and the nature of any apertures (Moar, 1993).

The main assumption under-pinning vegetation reconstruction from pollen assemblages is that the ecological preferences of a taxon are the same for those still present today as they were in the past and also that they remain unchanged throughout the period of time in question (Faegri & Iversen, 1989).

2.4.1 Using pollen assemblages to determine environmental changes

Analysing changes in the populations of pollen grains is a commonly used in studies of environmental change during the Holocene. Pollen grains can be found in a variety of settings, including estuaries and coastal lagoons, but they are most abundant in those where sediments are high in organic material. From raw pollen data there are two steps that must be taken to complete an environmental reconstruction: the first is inferring past vegetation from raw pollen counts and the second is inferring changes in past climate from the observed changes in vegetation (Faegri & Iversen, 1989). This second step requires knowledge of how pollen arrived at the site, local topography, the underlying geology, soil types and local climate (Moore, Webb & Collinson, 1991).

The transport mechanism, or the means by which a pollen grain reaches a depositional site, must be considered when using pollen assemblages to interpret past vegetation changes. In coastal settings the majority of pollen may reach a site by wind, but pollen may also reach an estuary or coastal lagoon through secondary means by fluvial transport via an inflowing valley river. Therefore It is possible for a pollen assemblage to be the sum of these different transport mechanisms, where vegetation surrounding an inflowing river having the ability to distort the regional vegetation assemblage.

Each plant taxa also has its own environmental optimum and limit. So while certain taxa may be used to denote specific changes in environmental conditions, pollen assemblages as a whole are used to infer past vegetation and from these, inferences regarding local and regional climate can be made. Full interglacial conditions in Taranaki may be indicated by podocarp-angiosperm forest assemblages while glacial conditions are indicated by higher proportions of herbs and shrubs (Newnham & Alloway, 2004).

It is also possible to comment on the proximity of a site to the coast based on pollen assemblages. There are taxa more tolerant of coastal conditions, such as the salt tolerant plant *Apodasmia similis* (Briggs & Johnson, 1998) which may develop on the upper most limit of the sub-aerial intertidal zone, and taxa that prefer fresh water conditions, such as *Phormium*. Additionally, there are taxa that give an indication of the level of climate extremes. *Ascarina* is one such taxon and is particularly intolerant of drought and frosts (McGlone & Neall, 1994).

2.4.2 Relevant pollen taxa and their ecology

As previously mentioned, to make interpretations of climate based on observed vegetation changes, it is important to have knowledge of the ecology of a taxon in question. Below is a list of key taxa relevant when interpreting changes in coastal pollen assemblages.

- *Ascarina lucida* – This taxon is a small tree that is both frost and drought intolerant and presently widespread as part of the sub-canopy in the West Coast of the South Island. It is almost absent from Taranaki today but it was widespread during the Holocene. *Ascarina* prefers cool but highly equable climates. If it is found in pollen assemblages, the environment at the time was likely a highly equable, oceanic climate. It has been documented by McGlone & Neall (1994) as being dominant in the forest sub-canopy along the Taranaki coast during the Holocene.
- *Dodonaea viscosa* – This taxon is characteristic of warm, sunny coastal sites and favours well-drained, often dry conditions (McGlone & Neall, 1994).
- *Knightia excelsa* – This taxon grows under a wide range of conditions but does best as a pioneering tree on sunny and often well-drained slopes (McGlone & Neall, 1994).
- *Prumnopitys taxifolia* – As documented by Newnham & Alloway (2004), this taxon is indicative of interstadial conditions, more tolerant of drier and cooler conditions than *Dacrydium*.
- *Dacrydium cupressinum* – One of the most dominant pollen taxa for much of the Holocene, it is relatively frost intolerant and can grow in saturated soils and tolerate extended periods of flooding
- *Halocarpus, Dracophyllum, Leptospermum, Coprosma and Phyllocladus* – These taxa can all grow in relatively poorly drained soils (McGlone, 2009).

2.5 Abiotic proxies

Paleo-ecological data may also be complemented by the addition of data from abiotic proxies. Two common abiotic proxies used in Holocene paleo-environmental studies include particle size analysis and loss on ignition, which are outlined below.

2.5.1 Particle Size

Assessing coastal sediments is also possible in terms of particle size. As previously mentioned, the outer and inner sections of an estuary or coastal lagoon are generally higher in energy, and can produce a saddle shaped particle size distribution (Haslett, 2000). Particle size can also vary laterally as energy tends to decrease from the axis to the margins, corresponding to a similar decrease in particle size (Bird, 2008). However, particle size in an estuary or coastal lagoon may also be affected by the strength of the inflowing valley river. Therefore, interpretations based solely on particle size data must be treated with caution and are better used in conjunction with other environmental proxies.

2.5.2 Loss on ignition

Terrestrial sediment brought into an estuary via fluvial transport is commonly rich in organic material and poorly sorted. In contrast, marine-sourced sediment may be deposited via tidal currents or waves, and is usually much lower in organic material and well-sorted. Loss On Ignition (LOI) involves measuring the mass loss of a sample when heated to high temperatures and may be used as a proxy of organic carbon content and the relative influence of marine vs. fluvial transported material (Chambers *et al*., 2011). Consequently, LOI can also be used to make inferences about erosional sediment input.

2.6 Chronology

A paleo-environmental record is no use without being able to tie observed changes to a period in time. To be able to do this, a well constrained chronology is needed. In paleo-environmental studies, chronologies are commonly established through the use of both calibrated radiocarbon ages and tephrochronology. The advantage of the use of tephrochronology is that once a tephra has been identified and dated, it provides an isochronous marker horizon across the landscape wherever it is found. It can also allow for correlation between sequences if the same tephra occurs in more than one sequence being investigated. Tephra can be identified on the basis of their glass chemistry, physical characteristics and stratigraphic relationships with other tephra (Alloway *et al*., 2007).

The accuracy of radiocarbon methods has also improved in recent years including the development of new calibration curves (Reimer *et al*., 2013). However, the principles behind

the method have not changed where measurements of the radioactive isotope of ^{14}C relative to the stable isotope ^{12}C are made and where this ratio is a function of the age of the material in question.

2.7 Statistical Analysis of paleo-ecological data

Statistical techniques are very useful in estimating the inherent errors associated with raw paleo-ecological data. They are also essential for developing direct proxy-environment relationships. Paleoecological data are almost always expressed as percentages or proportions of a base sum in order to transform the results into relative percentage compositional data. There are a number of methods to choose from when analysing paleo-ecological data but common methods include:

- Cluster analysis – This quantitatively analyses which taxa occur most often together. Clusters may then be used make inferences regarding the ecological communities present at a site.
- Detrended Correspondence Analysis (DCA) – This method is used to analyse multi-variate paleo-ecological data and can inform about the environmental gradients that may be under-pinning any observed changes in paleo-ecological data (Maddy & Brew, 1995). Transformations are performed on the data that are then displayed on several axes which are ranked in terms of the variation they explain in the data. The axes derived from DCA represent environmental gradients and from these it is possible to infer the causes of any observed proxy-environment relationships.

3. Regional Setting

This chapter outlines the regional setting of the Onaero Beach section and how it fits in with the context of the Taranaki peninsula.

3.1 Introduction

The study site, Onaero Beach, is located on the northern side of the Taranaki Peninsula and can be found at the GPS co-ordinates of 174°21’54.5”E, 38°59’34.1”S (Fig. 1). The section is a ~2.1m high coastal seacliff, the base of which is the modern-day high tide mark. Onaero Beach is a small, enclosed bay where the Onaero River flows into the sea on the western side of the beach. Tides are of a macro-tidal nature, where the difference between Mean High Water Spring and Mean Low Water Neap tide 2.4m (Baker & Watkins, 1991).

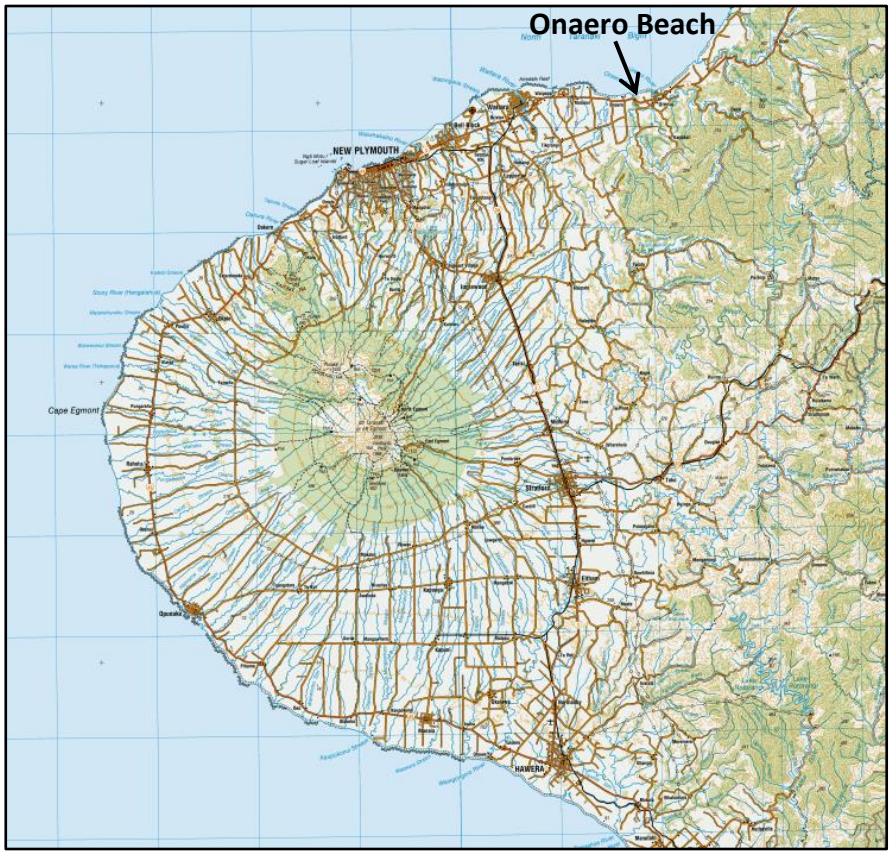

Figure 1: Map of the Taranaki Peninsula with the location of Onaero Beach labelled. Image: Land Information New Zealand (LINZ)

3.2 Tectonic Setting

The Taranaki Peninsula is a region known to have been uplifting throughout the late Quaternary. Sequences of uplifted interglacial marine terraces are visible on both the northern and southern sides of the peninsula (Chappell, 1975). A very good example of a flight of marine terraces in New Zealand is found in south Taranaki, which trend in a NW-SE direction, are roughly parallel to the present coastline, persist for more than 100km and rise to more than 300m above present mean sea level (Pillans, 1983). Some of these terraces have been correlated to equivalent terraces on the northern side of the peninsula (Newnham & Alloway, 2004). A number of fault systems have also been identified both onshore and offshore and are known to have been active throughout the Holocene with uplift rates on the order of ~1mm/yr (Townsend *et al*., 2010).

3.3 Volcanic Setting

The Taranaki peninsula is dominated by the andesitic strato-volcano, Mt Taranaki. Its eruptive products can be found across the entire ring-plain, along with material from the Taupo Volcanic Zone (TVZ), all the way out to the coast (Alloway *et al*., 1992). Many exposures of Holocene sediments, including coastal cliffs, stream banks and road cuttings, are often interbedded with volcaniclastic material (McGlone & Neall, 1994). This not only allows for the investigation of the effects of volcanic eruptions on vegetation and other ecological communities, but when identified and dated, they can provide good age-constraints for observed environmental changes.

3.4 Climate Setting

Coastal Taranaki has a mild warm-temperate climate with mean annual temperature at the coast currently 12-13˚C (McGlone & Neall, 1994). Climate is heavily influenced by the prevailing westerly winds with mean annual precipitation at the coast currently ~1600mm/yr (McGlone, 1982). Prior to deforestation by Maori and European settlement, Holocene vegetation in lowland Taranaki was dominated by conifer/broad-leaved forest including the tall-tree podocarps *Dacrydium, Prumnopitys* and *Podocarpus* (Wardle, 2002). Early Holocene climatic conditions were close to that of the present but variability and extremes were much less, as evidenced by the abundance of the frost intolerant *Ascarina*

and *Dodonaea viscosa* that declined through the Holocene, and reached present day levels by 3ka (McGlone & Neall, 1994).

3.4.1 Vegetation studies in Taranaki

Vegetation studies in the Taranaki region are greatly helped by the presence of the volcano. Visible vegetation zones can be seen which reflect temperature and precipitation gradients and these zones have been used in studies of modern pollen rain (McGlone, 1982) to determine pollen assemblages that arise from different vegetation communities, from temperate to alpine.

4. Methodology

In order to characterise past environmental changes at Onaero Beach, analysis of pollen, diatoms, particle size and % organic carbon of the sediments in the seacliff was carried out. The timing of these changes is constrained by analysis of tephra glass chemistry and radiocarbon dates. This chapter details both the field and laboratory work involved.

4.1 Field work – Monolith Acquisition

Field work at Onaero Beach (174°21’54.5”E, 38°59’34.1”S) was undertaken in two stages. The first stage was reconnaissance field work on 12/10/2013. Throughout the whole 2.2m section, 6 bulk samples were taken and returned to the Victoria University of Wellington (VUW) cool store. Subsequently, bulk samples were analysed for potential paleoecological proxies preserved at Onaero. The proxies investigated were pollen, diatoms and foraminifera. Pollen and diatoms were found to be present in sufficient concentrations for further analysis while no foraminifera were found.

The second stage of field work, carried out on 31/05/2014, was to extract a monolith of the section so that detailed sampling could then be undertaken at VUW. Five galvanised steel cases measuring 50x10x5cm, constructed at VUW, were used. Beginning at the top of the section, the cases were hammered into the cliff face, then extracted by hooking wire over the top and pulling down, holding the case containing the sediment in place. The monolith was extracted down to the base of the seacliff, also the present day high tide mark. This method proved effective, although the bottom 5cm of each case was consistently of poor quality or unsuccessfully extracted. To account for this, an overlap between adjacent cases of at least 5cm (up to 10cm) was used so the top of the next case would contain the missing section of the case directly above. Each case was then wrapped and stored in a sealed polystyrene box for transportation back to the VUW cool store.

4.2 Monolith Description & Sampling

Upon transporting the monolith back to VUW, sections were cleaned and photographed. Labels with the overall depth (from the top of the Onaero Beach section), taking into

account the overlaps, were placed on the side of each casing every 10cm. In total, the monolith measured a stratigraphic length of 2.15m.

The ample volume of sediment collected allowed separate samples for pollen, diatoms, particle size analysis and loss on ignition (LOI) to be taken from the same 4mm horizon. All samples were taken 2cm from the edge of the steel casing to avoid any disturbance that may have been caused by extraction of the monolith.

4.3 Diatom Analysis

4.3.1 Raw Sample Processing Technique

Raw sediment was processed using methods adapted from standard VUW procedure, which were modified from Battarbee (1986) by Dr Margaret Harper. These are described in detail in Appendix 1. As with pollen analysis, a sample was taken every 5cm with additional samples taken at equivalent depths in adjoining monolith sections to ensure correct overlap. Samples above and below the tephras were taken so that any effects on diatom assemblages, as a result of tephra deposition could be observed. This resulted in a total of 43 diatom samples.

4.3.2 Identification, Classification & Counting

Identification of diatoms and classification into groups according to salinity preferences was made using standard reference texts including Krammer & Lange-Bertalot (1986-1991), Hartley (1996), Hendey (1964) and Hustedt (1985) with assistance from Dr Margaret Harper. A specimen was counted if at least half of it was preserved including the middle and/or end to enable identification to species level. Counting proceeded until a minimum total count of 300 specimens was reached. Counts for all samples averaged 351 specimens, and raw % data is presented in Appendix 2.

4.3.3 Data Representation & Analysis

Raw data was input into Tilia (version 1.7.16) and diatom diagrams were constructed. For the purposes of this study, diatoms were assigned groups according to their salinity preferences with reference to Cochran (2002), Van Dam *et al*. (1994) and Hartley (1996).

Cluster analysis (Grimm, 1987) based on square root transformation was performed on the dataset with splitting based on the total sum of squares. This designated diatom zones.

Detrended Correspondence Analysis (DCA), using the statistical software package R was also performed on the dataset to assist with climatic and ecological interpretations of observed assemblage changes. This consisted of performing a number of transformations on the data, as outlined by Holland (2008), the last of which was a down weighting to reduce the influence of rare taxa on the distribution of taxa in DCA space. Due to insufficient counts in some samples, data included in DCA analysis was limited to taxa present between 80-210cm and that accounted for at least 2% of the total diatom assemblage in at least one sample. The results of these analyses are presented as part of the discussion in chapter 6.

4.4 Pollen analysis

4.4.1 Raw sample processing technique

Raw sediment was processed using methods adapted from standard VUW procedure and Faegri & Iversen (1989); these are described in detail in Appendix 3. Samples were taken every 5cm with additional samples taken at equivalent depths in adjoining monolith cases to ensure overlap was correct. Samples were also taken directly above and below each of the 5 tephras so that any potential vegetation disturbances recorded in the pollen assemblages, as a result of the eruptions, could be observed. This resulted in a total of 50 pollen samples.

4.4.2 Identification & counting

Pollen slides were examined under the microscope and identification was conducted using the VUW reference collection, Moar (1993) and assistance from Dr William McLea. Identification of Cyperaceae pollen was aided with reference to Moar and Wilmhurst (2003). Following McGlone (1982), after a slide was counted, it was scanned again for pollen types not recorded in the initial count. Counting proceeded until a minimum of 250 dryland grains, excluding aquatic plants and fern spores, was reached. Unfortunately, this was not possible for samples of depths 0-75cm so counting proceeded until pollen and spores on both slides were counted. Average dryland pollen counts from 0-75cm were ~9-10 grains while from 80-215cm dryland counts averaged 273 grains. Total counts of both pollen and spores through the entire section averaged 424 grains. Raw % data is presented in Appendix 4.

4.4.3 Data Representation & Analysis

Once counts were complete, data was input into Tilia version 1.7.16 (Grimm, 2011) and pollen diagrams were constructed. Grains were grouped into trees, shrubs, herbs, ferns and aquatics. Pollen diagrams are also presented alongside the stratigraphy and chronology of the Onaero Beach section (Fig. 3). The dryland pollen sum included all trees, shrubs and herbs, excluding all fern spores and aquatic species. Each dryland taxon is presented as a percentage of the dryland sum while each non-dryland taxon is presented as a percentage of the total sum. Examples of these calculations are outlined below:

$$\%Tree\ taxon = \frac{Tree\ taxon}{Trees + Shrubs + Herbs} \times 100$$

$$\%Shrub\ taxon = \frac{Shrub\ taxon}{Trees + Shrubs + Herbs} \times 100$$

$$\%Herb\ taxon = \frac{Herb\ taxon}{Trees + Shrubs + Herbs} \times 100$$

$$\%Aquatic\ taxon = \frac{Aquatic\ taxon}{Trees + Shrubs + Herbs + Aquatics + Spores} \times 100$$

$$\%Spore\ taxon = \frac{Spore\ taxon}{Trees + Shrubs + Herbs + Aquatics + Spores} \times 100$$

Once the diagrams were constructed, using only tree, shrub and herb pollen, cluster analysis based on square root transformation was performed on the dataset with splitting based on the total sum of squares. This designated pollen zones.

4.5 Particle Size Analysis

The particle size distribution was determined for 45 samples taken at 5cm intervals throughout the Onaero Beach Section using a Beckman-Coulter LS13320 Laser Particle Size Analyser at VUW. Full details of the raw sample preparation are outlined in Appendix 5.

Results of the particle size analysis are presented alongside both the diatom and pollen diagrams to assist in their interpretation. Summary statistical data is presented in Appendix 6.

4.6 Loss On Ignition (LOI)

Raw sediment samples weighing ~5g were taken at 5cm intervals throughout the whole section, including additional samples of the tephras. LOI analysis was carried out in 2 batches with one sample in triplicate for each batch to ensure results were replicable. Full laboratory procedures are outlined in Appendix 7. Raw LOI data are presented in Appendix 8.

4.7 Chronology

4.7.1 Radiocarbon Dating

Radiocarbon sample preparation was carried out, by the author, at the National Isotope Centre (NIC), Wellington. Wood samples were taken from the organic sediments at depths of 125 and 155cm. Sample cleaning involved the removal of mud and any root hairs. Chemical pretreatment followed an Acid-Alkali-Acid process, removing carbonates, humics and then returning the sample to a neutral pH. Samples were then dried in an oven and submitted to the Rafter Radiocarbon Laboratory for analysis. Results of these analyses are presented in the results section.

4.7.2 Tephra

The Inglewood, Stent and Korito tephras with ages of 3690 +/- 80, 3870 +/- 110 and 4150 +/- 100 yr. BP respectively (Alloway *et* al., 1994) were identified at Onaero Beach. These ages are recalibrated and are used in the Onaero Beach chronology.

4.7.3 Age Model

An age model using the radiocarbon dates obtained in this study and that of Alloway *et al*. (1994) was compiled using the Bacon package (Blaauw & Christen, 2014) in the statistical programme, R. It was as part of making this age model that radiocarbon ages from Alloway *et al*. (1994) were re-calibrated.

5 Results

This chapter details the results of the analyses described in the previous chapter. The changes observed in each proxy are described individually and are interpreted together in the discussion in chapter 6.

5.1 The Onaero Beach Monolith

The Onaero Beach Monolith is a total of 215cm thick from the ground surface to the base of the sequence at the modern day high tide level (Fig. 2). The stratigraphy can be broken into two main sections. The base of the section is the modern day high-tide mark and lower limit of where sediment could be extracted. The lower section, from 215-80cm, is a package of mud to fine sand, rich in plant material. Within this lower section are two distinctly more sandy sections with visibly less plant material. The upper section from 80-0cm is a package of yellow grey muds interbedded with 5 tephras. A detailed description of the Onaero Beach section can be found in Table 1.

Depth (cm)	Description
0-18	medium brown grey, sparse plant roots, silty clay
18-21	Inglewood tephra - dark grey-brown, fine-medium ash
21-29.5	medium grey, sparse oxidised root nodules, silty clay
29.5-33.5	Stent tephra - pink brown, fine ash
33.5-36.5	medium grey, silty clay
36.5-39.5	Korito tephra - dark grey brown, medium ash
39.5-49	yellow grey, sparse-moderate oxidised root nodules, silty clay
49-52.5	Pumice A (Upper) - pumiceous lapilli
52.5-59.5	yellow grey, sparse-moderate oxidised root nodules, silty clay
59.5-62	Pumice B (Lower) - pumiceous lapilli
62-80	yellow grey, sparse-moderate oxidised root nodules, silty clay
80-108	yellow brown grey, sparse-moderate oxidised root nodules, clayey silt
108-128	dark brown/black, woody plant material to 1cm, medium sand
128-160	very dark brown, woody plant remains to 2cm, fine-medium sand
160-198	dark grey, woody plant remains to 4cm, silty clay
198-215	dark brown, plant material to ~2mm, mud-fine sand

Table 1. Description of Onaero Beach section.

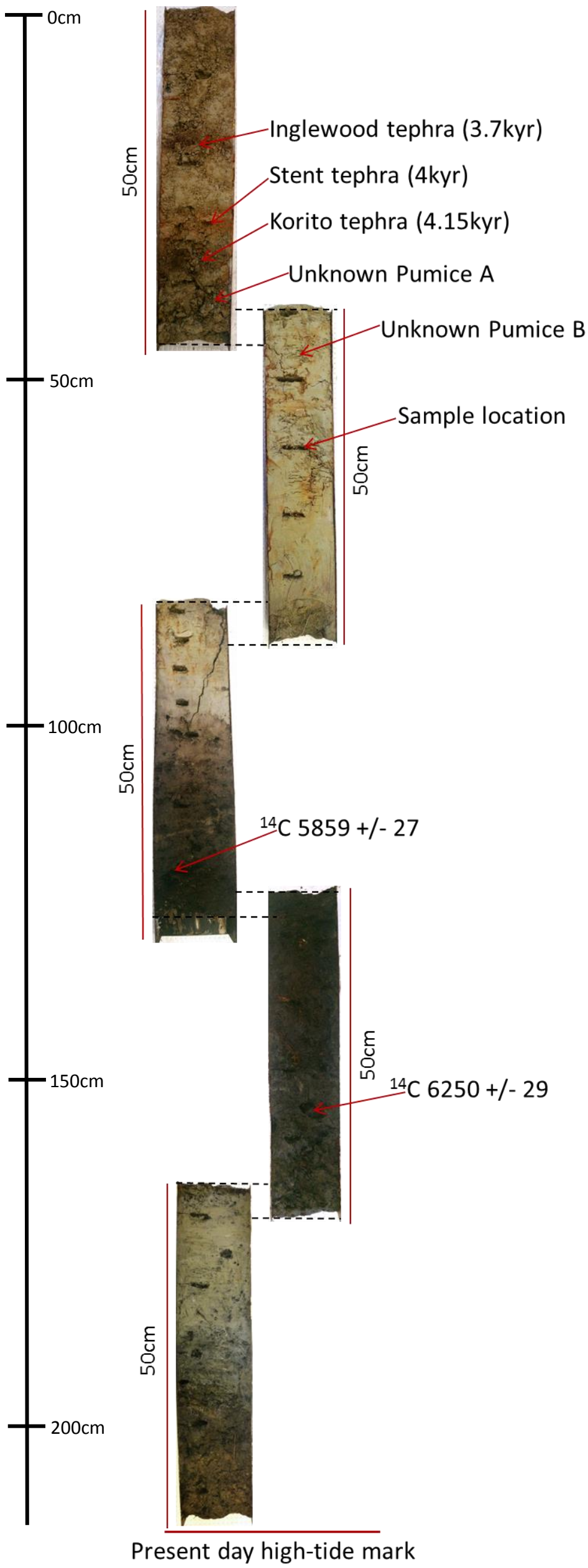

Figure 2: The Onaero Beach Monolith. Tephra are calibrated ages as reported in Alloway *et al*. (1994). The two radiocarbon ages are original, uncalibrated ages.

5.2 Diatoms

A total of 78 diatom species were identified throughout the Onaero Beach section. All were identified to species level with the exception of *Pinnularia gibba* and *Pinnularia maior* which are very similar in appearance and so could not be reliably distinguished. However, this is not an issue for the purposes of examining changes in salinity as both have the same ecological preference with respect to salinity, pH and moisture (Van Dam *et al*., 1994). The cluster analysis performed on the diatom dataset defined 3 principal zones, the first 2 of which are divided into 2 sub-zones. Diatom species have been assigned one of 6 groups according to their broad salinity preferences. These groups are salt intolerant, fresh, fresh-brackish, brackish, brackish-marine and marine (Fig. 3). The ecological preferences, including salinity, of diatoms were determined using key publications and reference texts including Van Dam *et al*., (1994), Hartley (1996), Foged (1979), Hustedt (1985), Hendey (1964) and Cochran (2002)**.** The changing assemblages within diatom zones are described below. A species is described as prominent if it occupies at least 10% of the total diatom assemblage in at least one sample pertaining to that particular zone.

5.2.1 Zone OB-D1a: 210cm – 162.5cm: 8.2-7.3ka

The diatom assemblages in the lowermost zone are dominated by brackish to marine species. Prominent species include *Diploneis subovalis, Campylodiscus echeneis, Paralia sulcata, Pinnularia schoederii* and *Tryblionella cf. levidensis*. *D. subovalis* is only present in this zone and rises to a peak of 12.6% at 185cm. *C. echeneis* begins comprises 16.6% at the bottom of the zone then falls to ~4% before disappearing completely at the top of the zone. *P. sulcata* increases from 23% to its maximum in the section of 35.7% before falling away to 26.7% at the top of the zone. *P. schoederii* follows a similar pattern to *D. subovalis* reaching a maximum of 13.7% at 190cm and subsequently falling away and disappearing completely by 175cm. *T. cf. levidensis* steadily increases from 3% to its maximum in the section of 11% before sharply declining at the top of the zone.

Despite being dominated by brackish to marine species, it is important to note that there are not insignificant amounts of fresh and fresh-brackish species. The freshwater community as a whole increases to 13.3% toward the top of the zone. However, there are no salt tolerant species present in this zone. Brackish species decrease steadily from 25% to

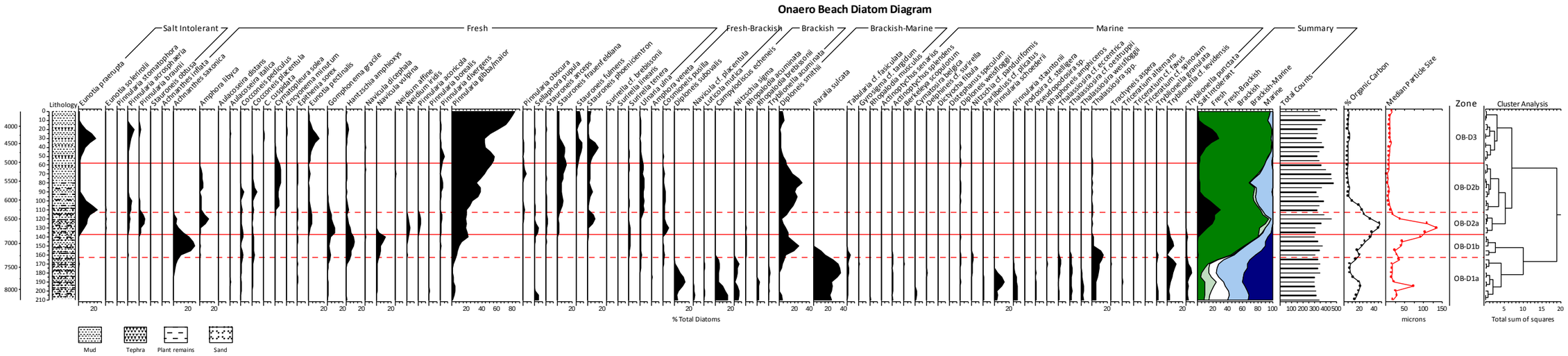

Figure 3: Diatom profile showing all taxa and their abundances throughout the Onaero Beach section. The chronology determined through age modelling and the Onaero Beach stratigraphy is shown on the far left. Taxa have been assigned one of 6 groups according to their broad salinity preference and a summary of these groups is presented on the right along with total counts, % Organic Carbon as measured by LOI, median particle size and the results of the cluster analysis which have been used to define diatom zones.

6.7% and while there is some fluctuation within each group, the combined total of brackish-marine and marine species remains relatively constant at ~45% throughout the zone.

5.2.2 Zone OB-D1b: 162.5cm – 137.5cm: 7.3-6.8ka

Prominent species in this zone include *Paralia sulcata, Diploneis smithii, Pinnularia gibba/maior, Navicula vulpina, Hantzschia amphioxys* and *Achnanthes saxonica*. *P. sulcata* continues its decline, disappearing entirely disappearing by 145cm. *D. smithii* increases steadily to a maximum of 25.5% at 150cm before declining to 11.5% at the top of the zone. *P. gibba/maior* increases steadily through this zone from 4.6% to 21.3%. *N. vulpina*, present in trace amounts at the base of this zone, increases steadily toward the top of the zone reaching a maximum of 12.1%. *H. amphioxys* increases from 4% to 10.2%, its maximum for the whole section. *A. saxonica* is the most prominent species accounting for more than 20% of total diatoms for the majority of the zone and also reaching its maximum for the record of 28.7%.

Overall, this zone is characterised by the almost complete disappearance of fresh-brackish and brackish species, the sharp decline in brackish-marine and marine species and the increasing dominance of freshwater species. At the top of the zone, freshwater species account for 80% of all diatoms.

5.2.3 Zone OB-D2a: 137.5cm – 112.5cm: 6.8-6.3ka

Prominent species in this zone include *Diploneis smithii*, *Pinnularia gibba/maior*, *Stauroneis phoenicenteron*, *Amphora libyca* and *Eunotia praerupta*. The only brackish-marine species present in this zone, *D. smithii* accounts for 11.1% of the assemblage at the base of the zone, falling away to 2.6% before sharply increasing back to 9.7% at the top of the zone. The *P. gibba/maior* group remains relatively stable throughout this zone at ~19%. *S. phoenicenteron* increases abruptly from trace amounts to just over 10% near the top of the zone. *A. libyca* follows a similar pattern to *S. phoenicenteron*, rising to 11.9% but then decreases slightly to 6.6% at the top of the zone. An important feature of this zone is the first appearance of salt intolerant species, which are dominated by *E. praerupta*. Making up 2.6% at the base of the zone, the taxon climbs to 14.8% by the top of the zone.

This zone is dominated by fresh to fresh-brackish species but with a significant proportion of the brackish-marine diatom *D. smithii.* Both the brackish and marine assemblages are present in trace amounts while the freshwater assemblage remains stable at ~70% and the salt tolerant assemblage increases in prominence, climbing to 22.8% by the top of the zone.

5.2.4 Zone OB-D2b: 112.5cm – 57.5cm: 6.3-5.0ka

Prominent diatom species in this zone are *Diploneis smithii*, *Pinnularia gibba/maior*, *Stauroneis frauenfeldiana* and *Eunotia praerupta*. *D. smithii* increases from 13.7% at the base of the zone to its maximum for the whole section of 30.1% at 80cm before declining sharply to 9.7% at the top of the zone. The *P. gibba/maior* group is the most prominent in this zone, increasing from 19.9% to 51.7%. *S. frauenfeldiana* follows a similar pattern to *P. gibba/maior* and increases steadily from 4.7% to 12.2% at the top of the zone. *E. praerupta* accounts for 24% of the total diatom assemblage at the base of this zone, its maximum in the section. However, it declines steadily over the entire zone, accounting for just 1.1% at the top.

Like zone OB-D2a, this zone is dominated by freshwater species, which increase steadily from 55.3% to 87.3%; salt intolerant species decrease from 23.3% to just 1.7% by the top of the zone. Brackish to marine species are all present in trace amounts with the exception of the brackish-marine *D. smithii*.

5.2.5 Zone OB-D3: 57.5cm – 0cm: 5.0-3.6ka

Prominent species in this zone include *Pinnularia gibba/maior*, *Stauroneis phoenicenteron*, *Stauroneis frauenfeldiana*, *Eunotia pectinalis* and *Eunotia praerupta*, all either fresh or salt intolerant species. *P. gibba/maior* continues its dominance and while fluctuating a little, continues to increase and accounts for 71.7% of the diatom assemblage at the top of the zone. *S. phoenicenteron* increases from 4.3% to a peak of 14.2% at 40cm before declining to 1.6% at the top of the zone. *S. frauenfeldiana* remains stable at ~10% for most of the zone but decreases to ~2.5% toward the top. *E. pectinalis* follows a similar pattern to *S. phoenicenteron*, reaching a peak of 13.4% at 30cm before falling away to 3% at the top of the zone. *E. praerupta* reappears in this zone as the most prominent salt intolerant species.

It too reaches a peak at 30cm, accounting for 22.3% of the total assemblage then decreasing to 3.6% at the top of the zone.

Overall, this zone is dominated by salt tolerant and freshwater species. The freshwater assemblage consistently comprises over 70% throughout the entire zone, peaking at just over 90% at 80cm. The salt intolerant assemblage, dominated by *E. praerupta*, increases from 2.9% at the base of the zone to a maximum of 27.7% at 30cm and then declines to 8.8% at the top of the zone.

5.3 Pollen

A total of 31 pollen and spore taxa were identified in the pollen analysis of the Onaero Beach section. Counting proceeded until a minimum of 250 dryland pollen grains were counted. However, this was not possible for samples in the top 75cm of the section as pollen concentrations were extremely low and in many cases total pollen counts in these samples did not reach more than 10 grains. Dryland counts below this depth averaged 273 grains and total pollen and spore counts over the whole section average 424 grains. Pollen data are displayed in Fig. 4 and have been divided into four principal zones based on the results of the cluster analyses. Taxa have been grouped into trees, shrubs, herbs, fern spores and aquatic plants. Changing pollen assemblages are described below using the zones defined by cluster analysis.

5.3.1 Zone OB-P1: 210 – 177.5cm: 8.3-7.6ka

The dryland sum of the lowermost zone is dominated by tree pollen (~80% for the entire zone) with small amounts of shrubs accounting for 15-20% of the dryland pollen sum. *Dacrydium cupressinum* is at its lowest abundance in the section, but still fluctuates around 30% for the entire zone. *Podocarpus* is overall at its highest proportion in the section, accounting for 19% of all dryland pollen at the base, increasing slightly to 23.9% at the top. *Prumnopitys ferruginea* also accounts for 19% of the total assemblage at the base of the zone, increasing to 31.3% at 200cm before decreasing to 16.7% at the top of the zone. Other important pollen taxa in this zone include *Metrosideros* sp., *Ascarina lucida* and Liliaceae.

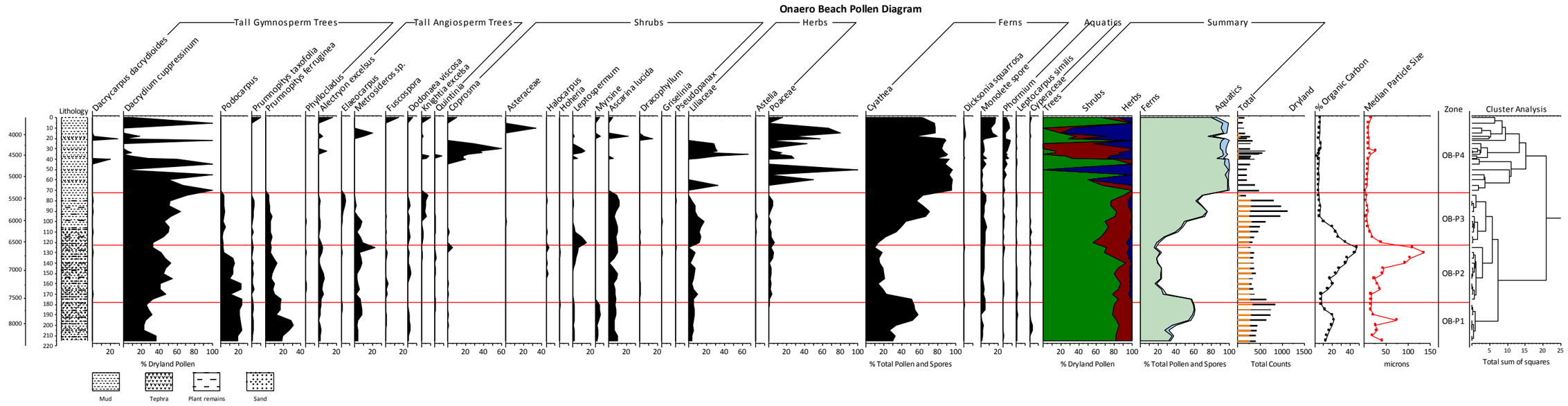

Figure 4: Pollen profile showing all taxa and their abundances throughout the Onaero Beach section. The chronology determined through the age modelling and the Onaero Beach stratigraphy is shown on the far left. Taxa have been assigned one of 6 groups and a summary of these groups is presented on the right along with total counts, % Organic Carbon as measured by LOI, median particle size and the results of the cluster analysis which have been used to define pollen zones.

Non-dryland taxa are heavily dominated by *Cyathea* fern spores increasing from 30.1% to 53.3% toward the top of the zone. Also present are small amounts of monolete spores and aquatic taxa including *Cyperaceae, Leptocarpus similis* and *Phormium*.

5.3.2 Zone OB-P2: 177.5cm – 122.5cm: 7.6-6.6ka

This zone is increasingly dominated by dryland taxa, the most prominent of which are *Dacrydium cupressinum*, *Podocarpus*, *Prumnopitys ferruginea, Metrosideros sp.* and *Ascarina lucida*. Other important taxa include *Alectryon excelsus* and *Liliaceae*. *Dacrydium* fluctuates between 33% and 54% within this zone, with 3 minor peaks of 47.7%, 54.6% and 53% at 170cm, 155cm and 140cm, respectively. *Podocarpus* also fluctuates but reaches peaks of 23.6%, 23% and 15.5% at 175cm, 160cm and 145cm, respectively, before decreasing sharply to 7% at the top of the zone. *P. ferruginea* follows a similar pattern although peaks are more subdued. *Metrosideros* remains at relatively low levels before a sharp peak of 20.3% at 125cm near the top of the zone. *A. lucida* remains relatively stable, fluctuating around 8% with the exception of a brief decline to 1.1% at 140cm.

Overall, trees account for ~75% of the dryland assemblage and shrubs account for 6.4-25.7%. The non-dryland assemblage is again dominated by *Cyathea* fern spores with not insignificant amounts of monolete spores (3-5%).

5.3.3 Zone OB-P3: 122.5cm – 72.5cm: 6.6-5.4ka

This zone is again dominated by tree pollen, including *Dacrydium cupressinum* which increases from 32.8% at the base of the zone to 51.7% at 80cm, the uppermost sample with a complete dryland pollen count. Both *Podocarpus* and *Prumnopitys ferruginea* are still present and remain relatively constant; but neither taxon reaches 10% at any point in this zone. Significant in this zone also is *Ascarina lucida* which remains relatively constant at ~10% for the entire zone. Liliaceae account for 12% at the base of this zone but fall away to 3.8% by 80cm. The dryland assemblage of this zone is dominated by trees, which as a group fluctuate between 56% and 80.4%, and shrubs, which steadily decline from 37.5% at the base of the zone to 18.9% at 80cm. Noticeable in the non-dryland count is the increasing dominance of *Cyathea* fern spores which rise from 13.1% at the base of the zone to 63.3% at the top.

5.3.4 Zone OB-P4: 72.5cm-0cm: 5.4-3.6ka

This zone is very chaotic in appearance as full pollen counts could not be reached. The total pollen and spore assemblage is dominated by *Cyathea* fern spores, which account for over 75% of the total assemblage throughout zone. Some modest counts were obtained for samples taken of the tephra but are still not significant enough to make reliable inferences of vegetation. However it is noted that similar species as recorded in the previous zones are still present.

5.4 Particle Size Distributions

Particle size distributions were obtained for each sample; but only mean and median particle sizes are presented here (Fig. 5) particle size. From the prominent peaks at a depth of 195cm, mean and median particle size decrease from 253µm and 75µm to ~150µm and ~30µm, respectively, at ~155cm. Particle size then rises rapidly to a peak of 273µm (mean) and 135µm (median) at 125cm before falling to 16µm (mean) and 6µm (median). Both the mean and median particle size remain relatively constant through the upper 90cm of the section, although small fluctuations can be seen which correspond to the tephras present in the upper ~60cm.

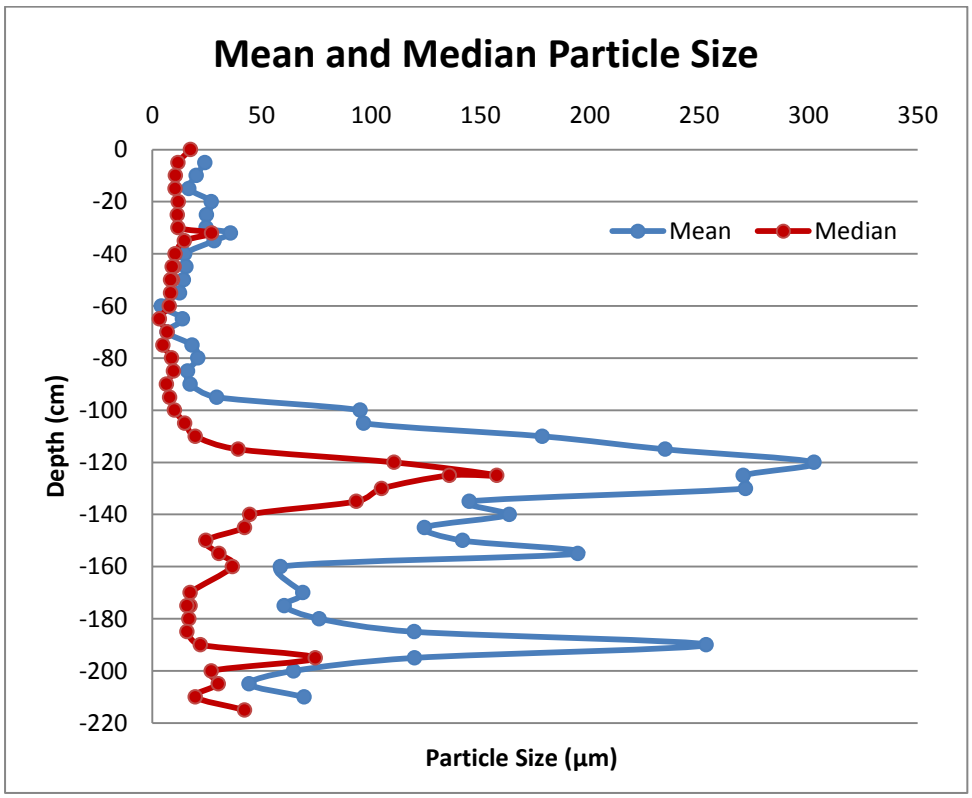

Figure 5: Mean & median particle size vs. depth of the Onaero Beach section.

With the exception of a peak in mean particle size at 155cm, both mean and median follow a similar pattern. However, the median particle size is consistently smaller than the mean, suggesting there is some distortion occurring due to the wider spread of particle sizes in the lower half of the section. Samples in the upper 90cm approximately resemble a normal distribution, while particle size distributions for samples below 90cm are much wider and flatter, indicating poor sorting. This is illustrated in Fig. 6. Owing to this apparent distortion that median particle size is used in both the pollen and diatom diagrams.

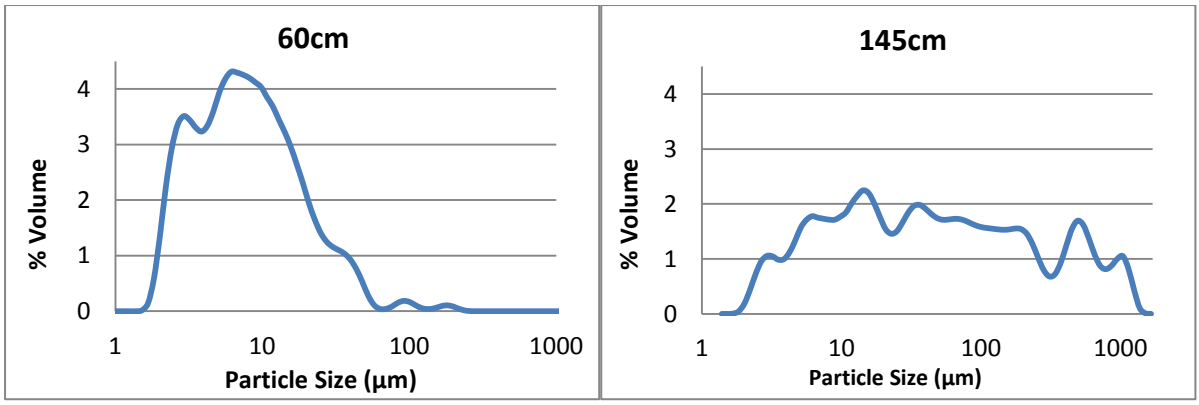

Figure 6: Particle size distributions of 2 samples from 60cm and 145cm depth illustrating the change in sorting that gives rise to very different median and mean particle sizes in each part of the section.

5.5 Loss On Ignition

The % Loss On Ignition (%LOI) as measured by LOI (Fig. 7) follows a pattern similar to that of particle size analysis. %LOI is relatively constant from 0-90cm, averaging ~5%LOI. At this point, %LOI sharply and consistently increases to a maximum of 49% at 125cm. After this point, there is a steady decline to 7.4% at 175cm. The zone of particularly high %LOI coincides with the visibly more plant rich part of the section and the low of 7.4% coincides with a plant rich sandy layer. %LOI climbs once again to a slightly more subdued peak at 21.7% and subsequently falls away to 12.7%, again coinciding with more visibly sandy sediments. %LOI data is presented alongside both the pollen and diatom data (Fig. 3 & 4).

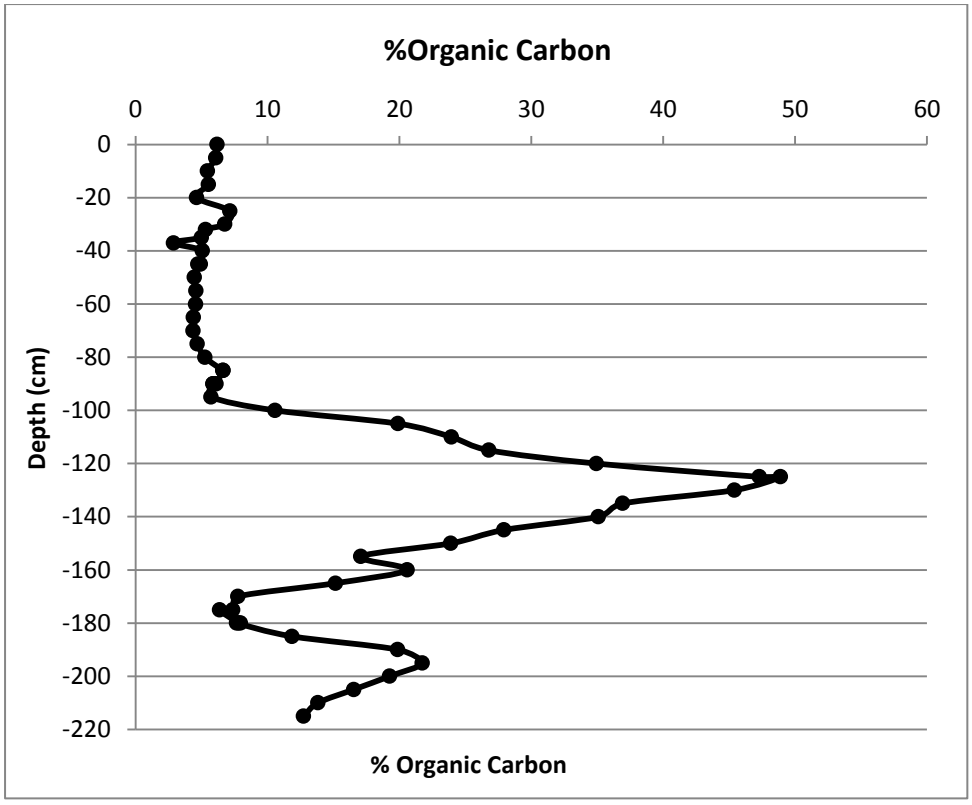

Figure 7: % Organic carbon as measured by LOI of the Onaero Beach section.

5.6 Age Model

The chronology for the Onaero Beach section has been established through the identification of already correlated and dated tephra (Alloway *et al*., 1994), shown in table 2, and radiocarbon dating of the organic sediments.

	^{14}C number	Reported age (yr B.P.)
Inglewood	3353	3610
Stent	1032	3870
Korito	1033	4150

Table 2. Radiocarbon ages of tephra as reported in Alloway *et al*. (1994).

5.6.1 Radiocarbon dating

Radiocarbon dating of plant material from the organic sediments yielded 2 ages of 5859 +/- 27 yr. BP at 125cm and 6250 +/- 29 yr. BP at 155cm depth. Details are presented in Table 3**.**

Sample depth	Date reported	Date analysed	Description	Fraction dated	^{14}C age	Error	NZA
125cm	22/12/2014	11/12/2014	Twig	wood	5859	27	58252
155cm	22/12/2014	11/12/2014	Branch	wood	6250	29	58259

Table 3: Details of radiocarbon samples submitted for analysis and ages used in model.

5.6.2 Age Model

Five radiocarbon age results were used to develop an age model for the Onaero Beach section (Fig. 8). The red line, representing the weighted mean age, is the input for the chronology used in both the pollen and diatom profiles (Fig. 3 & 4).

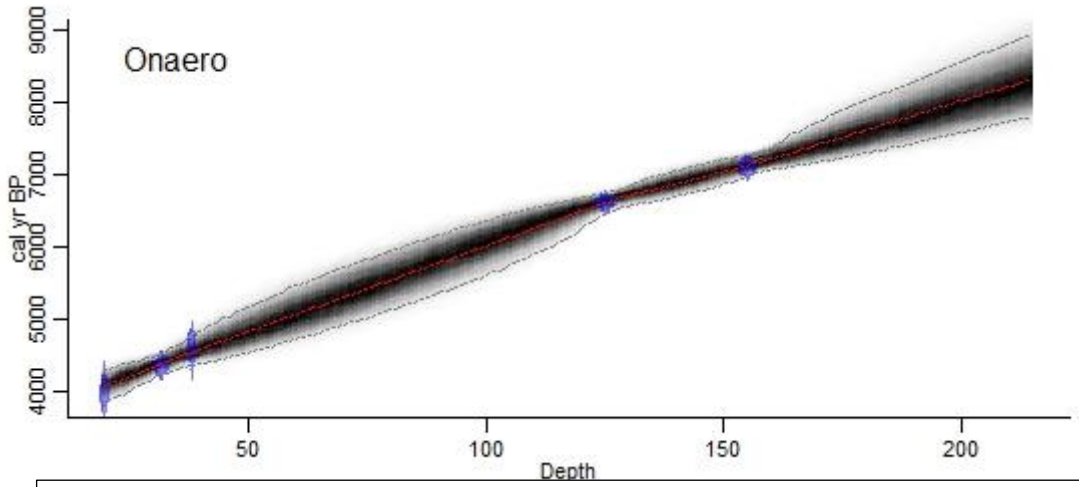

Figure 8: Output of age-depth modelling. Y axis show calibrated radiocarbon ages for a given depth on x-axis in cm. Blue points are radiocarbon dates with uncertainties, red line is weighted mean with these values used in diatom and pollen diagrams (Figs. 3 & 4).

6 Discussion

The purpose of this study was to investigate Holocene environmental changes at Onaero Beach, North Taranaki. Analysis of diatom and pollen communities, along with LOI and particle size analysis, was performed and the results of these analyses are discussed and interpreted in this chapter.

6.1 Salinity Changes

Diatom assemblages are affected by a variety of environmental variables, including moisture, pH and oxygen and nitrogen requirements. However, two of the most influential environmental variables are salinity and habitat (Van Dam, *et al*. 1994; Cochran, 2002) and these are the most relevant for reaching the objectives of this study. Consequently, interpretations of diatom assemblages are made predominantly in terms of these two variables. Diatoms were grouped according to their salinity preferences to enable interpretations to be made regarding tidal influence on the depositional environment.

6.1.1 Zone OB-D1a: 8.3-7.3ka

Figure 3 illustrates that the base of the section is characterised by distinctly marine diatom assemblages, with prominent species in zones OB-D1a and OB-D1b rarely found outside saline water bodies (Van Dam *et al*., 1994). The diatom assemblage in zones OB-D1a and OB-D1b is dominated by 26 marine species, the majority of which are only present in these zones. The brackish-marine assemblage is dominated by *Paralia sulcata*, a species particularly tolerant of changes in salinity (D'Costa *et al*., 2009) and commonly found in fine-grained organic rich sediment (Zong, 1997). Indeed, LOI values of the Onaero Beach sediments fluctuate between 10-20% for the part of the section in which *P. sulcata* is prominent, coinciding with highly variable particle size. Zone OB-D1a is not fully marine though, with fresh and fresh-brackish assemblages accounting for up to 20% of the total assemblage. This suggests a predominantly brackish to marine depositional environment, likely a tidally-influenced inlet or estuary. This would allow both organic matter, brought in by the inflowing valley river, to accumulate and the coexistence of fresh and brackish diatoms species.

6.1.2 Zone OB-D1b: 7.3-6.8ka

Zone OB-D1b contains the same species present in OB-D1a but their proportions of the total assemblage are markedly different, indicating changes in environmental conditions. As evidenced by Fig. 3, the proportion of freshwater species expands rapidly at the expense of brackish to marine assemblages. Brackish species disappear completely while brackish-marine and marine species decline significantly. The exception is the peak in *Diploneis smithii* at ~25% toward the centre of the zone while the brackish-marine assemblage as a whole continues to decline. The sharp increase in the fresh water assemblage in this zone suggests decreasing influence of the sea on the coastal lagoon and consequently increasing influence of the inflowing valley river. This is further supported by the persistent increase in organic matter, reaching ~30% at the top of the zone, and an overall increase in median particle size.

6.1.3 The Marine-Freshwater Transition

Zone OB-D1b is an extremely important part of the Onaero Beach section as it encapsulates a distinct marine to freshwater transition. Possible explanations for this include: (1) A fall in eustatic sea level (2) shoreline regression as the result of terrestrial aggradation processes, or (3) tectonic uplift. A fall in eustatic sea level significant enough to result in an almost complete disappearance of marine diatom species is very unlikely as New Zealand regional sea level stabilised at ~7.7ka (Clement *et al*., 2010) and has remained relatively unchanged since then (Gibb, 1986; Clement, 2010). The most likely scenario is a combination of both shoreline regression and tectonic uplift. The Taranaki peninsula has remained a tectonically active region of New Zealand throughout the Holocene as demonstrated by Townsend *et al*. (2010), who documented earthquakes across a fault system in the Taranaki Peninsula since 26ka. In addition, a succession of uplifted interglacial marine terraces is visible in the area behind the Onaero Beach section, several of which have been mapped by Chappell (1975) and correlated to the Rapanui (120ka) and Ngarino (185ka) marine terraces by Pillans (1983) on the southern side of the Taranaki peninsula. Uplift of the Onaero Beach site is therefore very likely and would have amplified the marine to freshwater transitions, contributing to the increasing isolating the Onaero Beach site from the sea.

6.1.4 Zone OB-D2a: 6.8-6.3ka

Zone OB-D2a is the initiation of a freshwater environment observed in OB-D1b with freshwater assemblages continuing to increase at the expense of brackish to marine assemblages (Fig. 3). However, this zone contains the first appearance of salt intolerant species. In this case the salt intolerant assemblage is dominated by the benthic species *Eunotia praerupta.* Most commonly found in shallow water, pools or lakes, *E. praerupta* is associated with shallower water depths than planktonic species and can even temporarily survive in dry environments (Finne *et al*., 2010; Van Dam *et al*., 1994). Over the course of this zone *E. praerupta* climbs to 24%, accompanying the almost complete disappearance of all fresh-brackish to marine species. This suggests not only a shallow freshwater depositional environment, but one with almost no marine influence. The predominant mode of transport of the minor abundance of brackish to marine species is likely by wind and sea spray rather than by tidal influence.

It is also in this zone that both organic matter and median particle size reach their peak for the Onaero Beach section (Fig. 3). The combination of the freshwater diatom assemblage and peaks in % organic carbon and median particle size suggests the depositional environment transitioned to a freshwater lagoon with material supplied by the river and a minimal tidal influence. In terms of depositional environment, this zone marks the establishment of an almost entirely freshwater lagoon at a time when New Zealand regional sea level was relatively stable, supporting the assertion that tectonic uplift and shoreline regression were most likely responsible for the observed changes.

6.1.5 Zone OB-D2b: 6.3-5ka

Zone OB-D2b as a whole continues as a predominantly freshwater assemblage but where the salt intolerant assemblage sharply falls away, concurrent with an expansion of the brackish-marine assemblage. However, this expansion is heavily dominated by *Diploneis smithii*, a species with a relatively wide tolerance to changing salinity (Cochran, 2002). Therefore, while *D. smithii* may be suggestive of an increased salinity and a brief shoreline transgression, the absence of similar changes in other brackish to marine species causes speculation. Similarly, the decline in organic matter and median particle size likely reflects segregation from the sea and a less energetic depositional environment. The total

proportion of the freshwater assemblage remains relatively stable for the duration of this zone (Fig. 3).

Contemporaneously with the expansion of *D. smithii*, both % organic matter and median particle size decline sharply to ~6% and 10µm, respectively, from which point they remain relatively stable for the rest of the section. The trend toward an overall more brackish assemblage, in combination with a sharp decline in organic matter and median particle size, suggests the depositional environment may have briefly reversed back to a coastal lagoon. Organic matter could not accumulate as effectively but still remained relatively unturbid due to the decrease in particle size.

6.1.6 Zone OB-D3: 5.0-3.6ka

Zone OB-D3 is similar to OB-D2a in that it shows the appearance of a salt intolerant assemblage dominated by *Eunotia praerupta* and the almost complete disappearance of all fresh-brackish to marine species. This is also the part of the section that contains a significant amount of volcanic material and yet diatom assemblages appear to be unaffected by the deposition of the three ashes and two lapilli, with no noticeable or abrupt changes in composition. The depositional environment appears to be similar to that of OB-D2a, an almost entirely freshwater lagoon, isolated from the sea, with non-freshwater diatom species most probably deposited via aeolian processes.

6.1.7 Detrended Correspondence Analysis

The distinction between marine and freshwater diatom assemblages can also be seen through plotting the scores of the first two axes produced through Detrended Correspondence Analysis (DCA). In Fig. 9, taxa have been grouped according to their salinity preferences. A clear distinction, particularly between fresh and marine taxa, can be seen along DCA1, indicating that the primary control on diatom assemblages at Onaero Beach is salinity.

Some variance is also explained by DCA2, particularly among the freshwater species. While taxa have not been labelled in Fig. 9, scores are presented in Appendix 9. Using the ecological preferences of fresh water diatoms in Van Dam *et al*. (1994), a general distinction can be seen between freshwater species with a DCA2 score >1 and those with DCA2 score

<1. Those with DCA2 scores <1 are generally more tolerant of alkali conditions and vulnerable to periodic desiccation while species with DCA2 scores >1 are less tolerant of alkali conditions but more tolerant of drier conditions. This suggests that a combination of pH and moisture acts as a secondary control on diatom assemblages, particularly among the freshwater species.

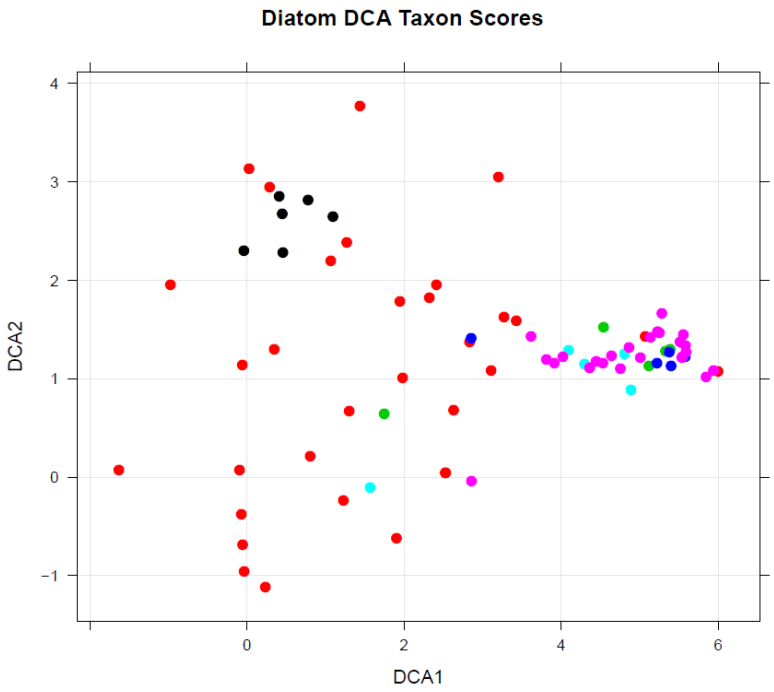

Figure 9: Taxon scores given by DCA for the first two axes are plotted. Species have been grouped as in figure 3, according to their salinity preferences. Colours correspond to the groups as follows:

- Black = Salt Intolerant
- Red = Fresh
- Light blue = Fresh-Brackish
- Dark blue = Brackish
- Green = Brackish-Marine
- Magenta = Marine

6.2 Vegetation Changes

Vegetation changes are interpreted at Onaero in conjunction with changes in diatom assemblages. Attempts are also made to relate the pollen and diatom zones defined by cluster analysis to one another.

6.2.1 Zones OB-P1 & OB-P2: 8.3-6.6ka

Vegetation assemblages in Zone OB-P1 between 8.3ka and 7.6ka are dominated by the tall tree podocarps including *Dacrydium, Podocarpus* and *Prumnopitys ferruginea* with the understory composed mainly of *Ascarina, Myrsine* and Liliaceae. The dryland assemblage remains relatively stable over this zone; but there are peaks in the proportion of ferns and aquatic taxa, % organic matter and median particle size coincide at ~7.9ka (195cm). A possible reason for this is that while the primary transport mechanism of pollen was by wind, there was still a significant fluvial source as well. It is likely ferns were growing on the

margins of the inflowing river and surrounding gullies. The coarser particle size and higher %organic matter suggest a stronger inflowing river that in turn would have brought in larger quantities of fern spores. The fern assemblage is almost 100% *Cyathea* for the entire Onaero section, a taxon known to be over-represented in Taranaki (McGlone, 1994).

Vegetation assemblages in Zone OB-P2 are relatively similar to OB-P1; the zone is dominated by the same tall tree podocarps *Dacrydium*, *Podocarpus* and *Prumnopitys ferruginea*. The main difference in pollen assemblage from OB-P1 is the greater proportion of herbs and the first appearance of Poaceae. At ~140cm, there is a slight increase in the total proportion of shrubs, mainly *Leptospermum*, at the expense of tree taxa. This persists through to OB-P3. OB-P2 is also characterised by the lowest proportion of *Cyathea* in the whole section.

Important to note in both OB-P1 and OB-P2 is the occurrence, albeit in minor amounts, of *Apodasmia similis* (Briggs & Johnston, 1998). *A. similis* characteristic of estuarine settings due to its tolerance of saline conditions (Hayward *et al*., 2010), so its presence suggests close proximity of the Onaero Beach site to the coast, despite increasing dominance of freshwater diatoms. Zones OB-P1 and OB-P2 occupy the same stratigraphic section as zones OB-D1a to OB-D2a in the diatom profile which shows increasing freshwater species at the expense of marine species.

6.2.2 Zone OB-P3: 6.6-5.4ka

This zone is also dominated by tall podocarp trees; but there is a small expansion of herbs, whose assemblage is dominated by Liliaceae. The expansion of shrubs occurs over approximately the same stratigraphic section as the expansion of brackish-marine diatoms (Fig. 3) and aligns with zone OB-D2b. As this zone was heavily dominated by just one species, *Diploneis smithii*, it would be spurious to suggest that these two events are related. By the top of the zone, herbs have almost disappeared and shrubs have significantly decline and the dryland assemblage is dominated by the tall tree *Dacrydium*. Notable also is the expansion of *Cyathea*, climbing to almost ~90% at the top of the sequence, and the occurrence of *Knightia excelsa*, a tree that grows under a wide range of conditions but is most commonly found in coastal lowland forests (McGlone, 1994).

6.2.3 Dacrydium Ratio

Interpretations of the pollen record are be aided by the ratio of *Dacrydium* pollen to the remaining podocarps, including both *Prumnopitys* species and *Podocarpus.* It has proved useful as an indicator of relative soil wetness and has previously been used in studies of New Zealand climate during the Holocene (Harris, 1963; McGlone & Topping, 1977; McGlone *et al.*, 1984; Newnham *et al.*, 1989). The ratio is calculated by dividing %*Dacrydium* in a sample by the sum of %*Prumnopitys* and %*Podocarpus*. *Dacrydium* is relatively frost intolerant, prefers warm moist conditions, can grow in saturated soils and can tolerate extended periods of flooding. In contrast, *Prumnopitys* and *Podocarpus* are more drought tolerant, preferring cooler and drier conditions (Alloway *et* al., 1992; McGlone & Topping, 1977). Therefore, higher ratio values suggest a relatively wetter climate while lower values suggest a drier climate.

Over the course of zones OB-P1 to OB-P3 as seen in Figure 10, *Dacrydium* increased while the remaining podocarps declined. Upon calculating ratio values for each sample, an increasing trend in values was seen (Fig. 10). Superimposed on this trend are several smaller fluctuations with prominent peaks occurring at 5.8ka, 6.3ka, 6.7ka, 7.1ka and 7.4ka. Values have not been calculated above 80cm depth due to insufficient pollen counts in these samples. The observed trend suggests an overall increase in regional soil moisture and decreasing frosts in northern Taranaki through the mid-late Holocene.

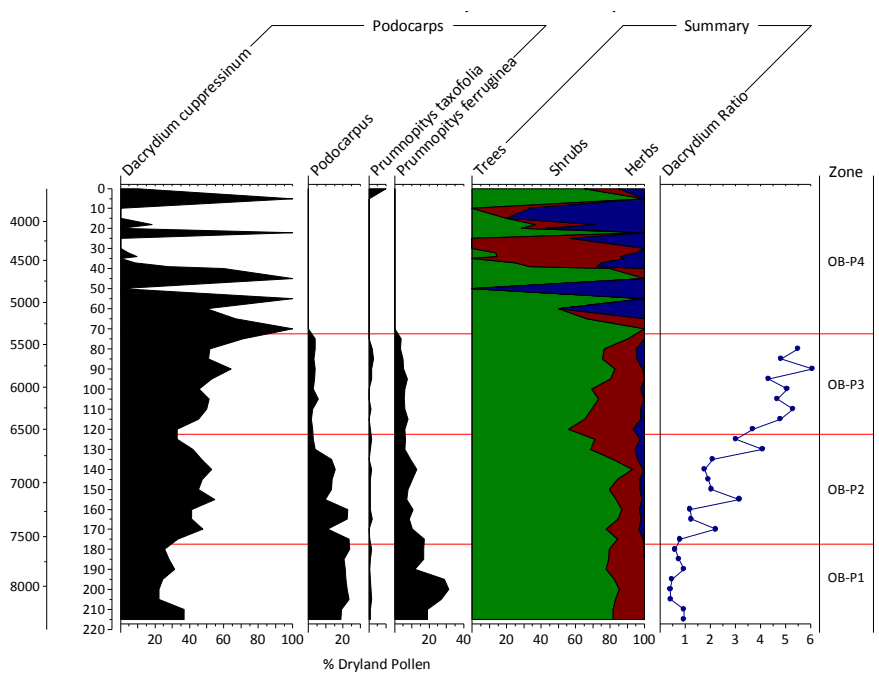

Figure 10: Dacrydium ratio and pollen profile summary. Included in the diagram are the taxa used to calculate ratio values, the dryland summary and pollen zones.

Further support for a decline in frost prevalence during this time comes from the occurrence of the extremely frost intolerant *Ascarina*, which persists at relatively constant levels through zones OB-P1 to OB-P3 from 8.3-5.4ka (Fig. 4). In addition, *Ascarina* is not found as part of the same vegetation as the coastal tree *Dodonaea viscosa* in the present day (McGlone *et al*., 1994) so the fact they occur together for the entire Onaero pollen profile, is further indication of a low frost, low drought and highly equable climate.

6.2.4 Zone OB-P4: 5.4-3.6ka

The uppermost pollen zone is distinct from the rest of the section in that full pollen counts could not be obtained so interpretations here are subject to greater uncertainty. While the same species were recorded as observed in previous zones, the total pollen and spore assemblages were heavily dominated by *Cyathea* and monolete fern spores. *Cyathea* produces robust spores which means they are able to persist in high-energy fluvial environments. An important feature of this zone is the marked increase in *Phormium*, a taxon that is often found in the coastal zone but also commonly found in freshwater settings (Weihi & Clarkson, 2007). This fits with the predominantly freshwater diatom assemblage in zone OB-D3. OB-P4 also coincides with a change in lithology from predominantly fine to medium sand rich in organic material to silt with minimal organic material and is part of the Onaero Beach section that contains volcanic material.

Such an abrupt change in pollen concentration or preservation is unlikely to reflect a similarly abrupt change in vegetation but more likely a result of a change in both local hydrological conditions and volcanic disturbance, such that pollen assemblages were not preserved. Indeed, during a study of Eltham Swamp in Taranaki, McGlone *et al*., (1994) found no clear indication that there was a change in the dominant tall-forest trees over the course of the late Holocene and that the dominant tree at this time was still *Dacrydium* (McGlone *et al*., 1988). A study by Lees & Neall (1993) of the effect of volcanic eruptions from Mt Taranaki on vegetation found that pollen assemblages may change for one of two reasons: (1) physical change to the site itself or (2) damage to vegetation caused by tephra fallout. In the case of Onaero, the most likely scenario is a change to the depositional environment itself, especially as there is a change in lithology at the same time as the appearance of the lower most tephra in this zone of low pollen counts.

6.3 Environmental Changes

6.3.1 8.3ka-6.3ka

Vegetation in North Taranaki was dominated by tall podocarps, with a number of taxa suggesting a warm, equable climate low in both droughts and frost. Local vegetation at Onaero consisted of ferns, dominated by *Cyathea*, and taxa indicative of a coastal environment. The prevailing depositional environment during this time was a coastal lagoon where influence from the sea declined, as evidenced by the increasing dominance of freshwater diatom assemblages. According Clement *et al.* (2010), who revised the Gibb (1986) Holocene sea level curve for the New Zealand region, sea level stabilised at ~7.7ka (Fig. 11). This suggests that at least since then, that shoreline regression, as a result of terrestrial aggradation processes and possibly amplified by tectonic uplift. By 6.3ka, the salt intolerant and fresh water diatom taxa accounted for over 90% of the total assemblage, the peak of the marine to freshwater transition.

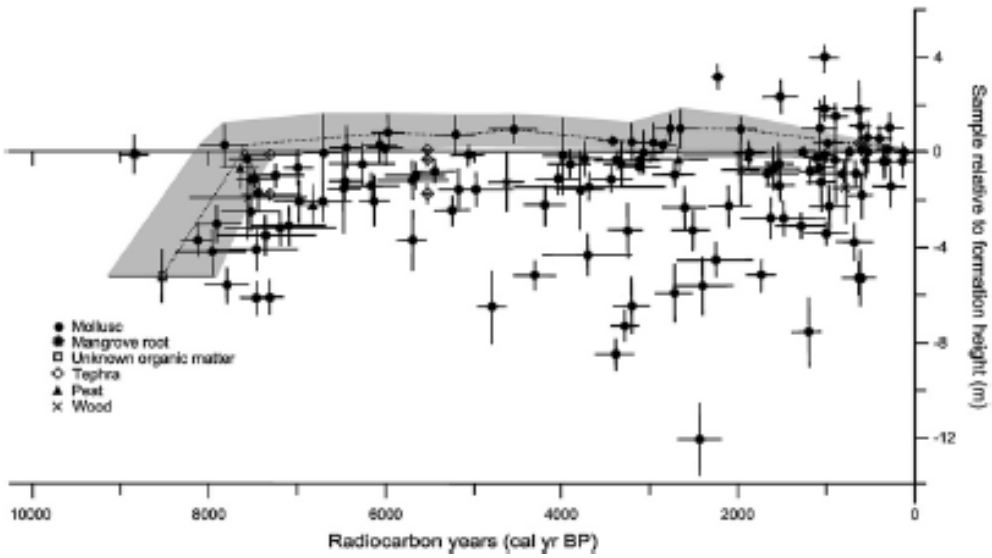

Figure 11: Revised New Zealand regional Holocene sea-level curve (Clement *et al*., 2010)

6.3.2 6.3ka-3.5ka

From ~6.3ka, there was a possible brief shoreline transgression indicated by the expansion of *Diploneis smithii*, which reaches its peak at ~5.5ka and has almost disappeared by 4.9ka, broadly contemporaneous with a small expansion of shrubs dominated by *Leptospermum* and herbs dominated by Liliaceae. However, vegetation is still dominated by podocarps and

taxa suggesting a warm climate low in droughts and frosts with the *Dacrydium* Ratio indicating an overall increase in climate wetness since the start of the Onaero Beach record.

6.3.3 5.4ka-

From ~5.4ka, a change in local hydrology and volcanic disturbance prevented the preservation of the regional pollen assemblage. Local vegetation is dominated by *Cyathea* lining gullies and the margins of the inflowing river. Very little can be determined from dryland pollen assemblages other than that the taxa present prior to 5.4ka are also present post-5.4ka. However, the abrupt change in pollen assemblage is unlikely to represent such an abrupt change in vegetation at this time. This is indicated by other studies of Holocene vegetation including that of McGlone & Neall (1994) who demonstrated that vegetation in Taranaki consisted of podocarp forest dominated by *Dacrydium, Prumnopitys ferruginea* and *Prumnopitys taxofolia,* which persisted through mid to late Holocene.

Diatom assemblages on the other hand appear unaffected by the local change in hydrology, and are still heavily dominated by freshwater and salt intolerant species, which is suggestive of a freshwater lagoon environment with almost no influence from the sea.

6.3.5 Atmospheric circulation and formal Holocene subdivision

The first appearance of tephra in the Onaero Beach section at suggests a major change in prevailing wind direction. Tephra have been recorded elsewhere in the Taranaki region throughout the Holocene (Alloway *et al*., 1995) and yet none are deposited at Onaero Beach prior to ~5ka. In addition, while the Korito and Inglewood tephras are both sourced from Mt Taranaki, the Stent tephra is distinctly rhyolitic in composition and is sourced from the Taupo Volcanic Zone (TVZ) (Alloway *et al*., 1994). ~150km upwind of the current prevailing wind direction, it is the only TVZ tephra preserved west of its source and its distribution pattern is distinct from other TVZ-sourced tephra (Fig. 12). The most likely explanation for this change is a reversal of the prevailing wind direction.

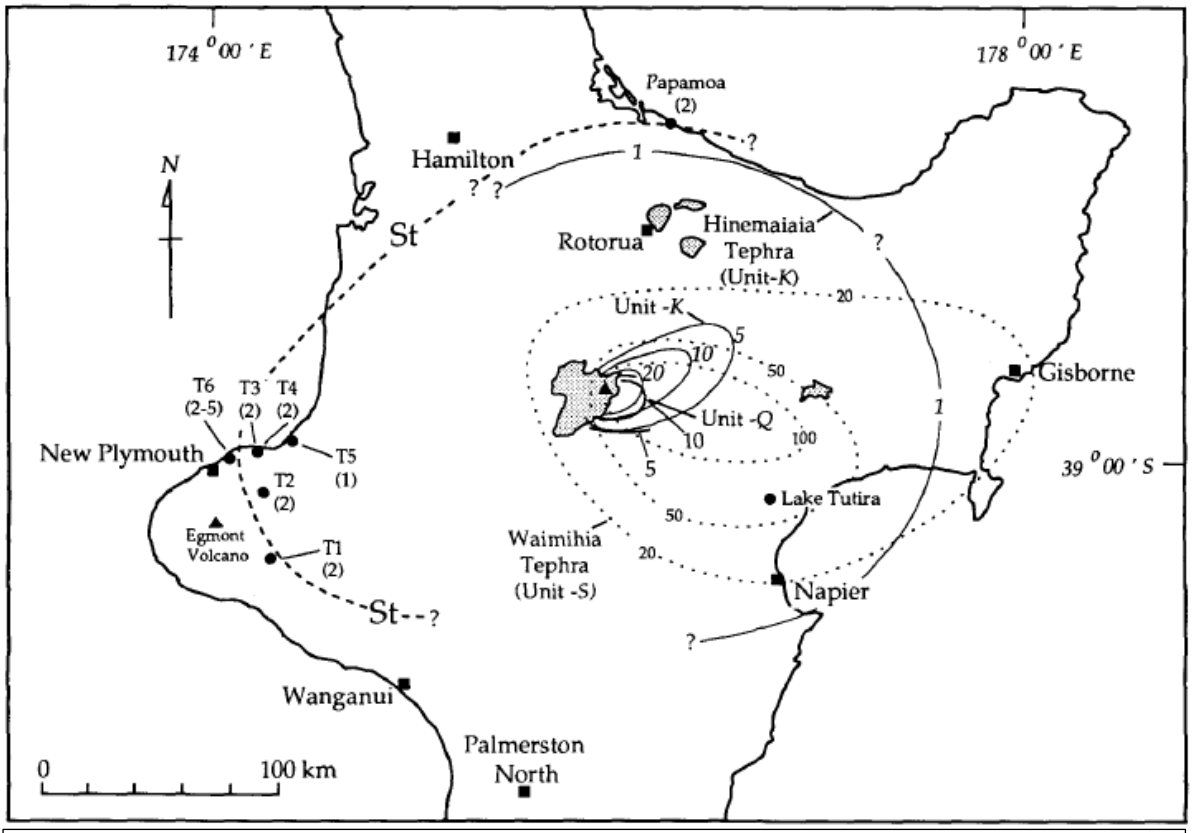

Figure 12: Taken from Alloway *et al*. (1994): Spatial distribution of the Stent tephra with the dashed line representing the possible 2cm isopach. The Onaero Beach section is labelled as T4. Typical tephra distribution is indicated by the dotted lines (cm), in this case the Hinemaia tephra with age of ~4.5ka.

Evidence for changes in atmospheric circulation in the southern hemisphere have been found by Gomez *et al*. (2013) who discovered that interactions between the El Nino Southern Oscillation (ENSO) and Southern Annular Mode (SAM) across the south Pacific could explain variations in rainfall, which is strongly influenced by prevailing wind direction, in both New Zealand and South America. A possible change in wind direction at ~4ka, as indicated by the occurrence of the Stent tephra at Onaero Beach, also fits with the suggestion of a formal subdivision of the Holocene based on climatic events. A '4.2ka' event has been proposed by Walker *et al*. (2012) as the boundary between the Middle and Late Holocene. The 4.2ka event is marked in the western south pacific by the onset of a climate dominated by ENSO from ~4ka and where a documented southward migration of the Inter-Tropical Convergence Zone (Haug *et al*., 2001) could explain the change in wind direction.

While the occurrence of the Stent tephra 150km west of its source is not conclusive proof, it occurs at the right time and with the right distribution pattern to suggest a change in

prevailing wind direction, and provides further support for a formal subdivision of the Middle/Late Holocene at 4.2ka.

7. Conclusions

This chapter presents a summary of the main findings of this multi-proxy paleo-ecological study undertaken at Onaero Beach:

Diatoms and salinity:

- Diatoms are good recorders of changes in salinity at Onaero Beach with a documented marine to freshwater transition occurring at 7.3ka.
- The transition occurred due to a combination of tectonic uplift and shoreline regression as the result of terrestrial aggradation processes
- There is a secondary control on diatom assemblages, particularly among freshwater species likely to be a combination of pH and moisture.

Pollen, vegetation & climate

- Regional vegetation assemblages at Onaero during the mid-Holocene were dominated by tall tree podocarps while local vegetation was dominated by tree ferns.
- Climate throughout the mid-late Holocene was relatively drought and frost free as indicated by the presence of pollen taxa intolerant of these conditions, particularly *Ascarina*.
- A phase of overall increasing climate wetness is indicated by the increasing trend in *Dacrydium* ratio values

Providing a regional and global context

- Deposition of tephra at Onaero Beach from 5.4ka, and in particular deposition of the Stent tephra at 4ka, is suggestive of a reversal in the direction of the prevailing winds.
- This reversal fits with the proposal of Walker *et al*. (2012) that a '4.2ka' event be treated as the formal boundary between the Middle and Late Holocene.

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9. Appendices

Appendix 1: Processing Raw Sediment for Diatoms

Oxidation of organic matter

- Weigh out 1g of sediment in a 50ml test tube for each sample, labelling the tube and tube lid with sample no.
- Add a few drops of H_2O_2 to each sample and observe the reaction. If the sample bubbles, continue adding H_2O_2 slowly up to 7.5mls. If there is a violent reaction, cool it by adding some distilled water and/or placing in a cold water bath.
- Leave tubes with lids loosely screwed on overnight.
- The next day add H_2O_2 up to 10mls and look carefully for any further bubbling. If bubbling has completely stopped, then centrifuge at 3000rpm for 3 minutes and decant off.
- Follow this with a water wash. This is done by filling each tube to 30ml with distilled water, mixing thoroughly and centrifuging as above.

Removal of carbonates

- Add a few drops of HCl to each sample and observe the reaction. Continue adding HCl slowly up to 10ml. For samples with high carbonate content, more may need to be added.
- Place in water bath at 96˚C for ~1 hour.
- Remove the samples from the water bath, centrifuge and decant off acid into a beaker to be disposed of later.
- It is important that all residual acid be removed so this should be followed by at least 3 water washes. The pH of the water can be tested using indicator paper.

Removal of Sand

- This involves wet sieving at 100µm. For each sample, set up a beaker and funnel with 100µm sieve cloth in the funnel. Wet the sieve cloth with distilled water so that the sieve cloth adheres to the side of the funnel.
- Pour samples onto sieve cloth and rinse through thoroughly with distilled water until water coming out the bottom of the funnel runs clear.
- Reserve the coarse (>90µm) fraction by rinsing material on sieve cloth into labelled 15ml test tubes.
- Centrifuge the <90µm fraction back into the 50ml test tubes.

Removal of clay

- This involves wet sieving at 6µm. For each sample, set up a beaker and funnel with 6µm sieve cloth in the funnel. Wet the sieve cloth with distilled water so that the sieve cloth adheres to the side of the funnel.
- Pour samples onto sieve cloth and rinse through thoroughly with distilled water until water coming out the bottom of the funnel runs clear. This may take some time and samples may need to be left to filter through before further rinsing.
- Reserve the coarse (6µm<sample>90µm) fraction as this is the diatom rich fraction. The <6µm may be discarded.
- Rinse the >6µm fraction into new labelled 15ml test tubes. Centrifuge these and decant off as much water as possible without losing any sample.
- Samples are now ready for density separation.

Density separation

- To remove heavy minerals, add SPT with Sg = 2.2g/cm^3 to each sample up to 6-7mls. Shake thoroughly then centrifuge at 2000rpm for 15minutes.
- Carefully remove the top 1-2ml with a pipette, and place in a new 15ml tube.
- Do at least 3 water washes, centrifuging after each one and reserving the diluted SPT for recycling later.
- Decant back to 4-5mls after the last water wash.
- Samples are now ready for mounting onto slides.

Slide mounting

- Place one glass cover slip and slide for each sample on a hot plate at 80°C
- Using a pipette, add 2-3 drops of sample on to the cover slips and add additional distilled water to ensure sample is spread over the entire cover slip.
- Wait for all the water to evaporate
- Turn the hot plate up to 130°C and using a glass rod, carefully drop a small amount of Toluene/Naphrax solution onto each slide.
- Invert the cover slips and place on top of the glass slides, pressing down with a toothpick.
- The Toluene/Naphrax will begin to bubble as the toluene evaporates.
- Once this bubbling ceases, remove the slides from the hot plate to cool. They are now ready to be examined under the microscope.

Appendix 2: Diatom Raw Percentage Data

		Sample Depth (cm)														
	Species	**0**	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**	**45**	**50**	**55**	**60**	**65**	**70**
Salt Intolerant	Eunotia praerupta	0.9	0.6	0.5	3.6	9	16.7	22.3	14.2	8.1	6.4	2.8	2	1.1	1.2	1.8
	Eunotia solerirolii	0.3	0.6	0.8	0.8	0.3	0.6	0.6	0.5	0.8	0.3	0	0	0.3	0.2	0
	Pinnularia stomatophora	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Pinnularia acrosphaeria	0	0	0	3.3	8.4	6.1	4.5	2.7	1.8	0.9	0.6	0.9	0.3	0.5	0.2
	Pinnularia braunii	0	0	0	0.8	1.5	1.2	0.3	0.3	0	0	0	0	0	0	0
	Stauroneis obtusa	0	0	0.3	0.3	0	0	0	0	0	0	0	0	0	0	0
Fresh	Achnanthes inflata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Achnanthes saxonica	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Amphora libyca	0	0	0	0	0.3	0	0	0	0	0	0.3	0.3	0.3	2.5	3.4
	Aulacoseira distans	0	0	0.3	0.3	0	0	0	0	0	0	0	0	0	0	0
	Aulacoseira italica	0	0	0	0	0.9	1.2	1	0.5	0	0	0	0	0	0	0
	Cocconeis pediculus	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Cocconeis placentula	0	0	0.3	0.3	0	0	0	0	0	0.3	0.6	0.6	1.4	0.7	0.5
	C. cuspidata	0	0	0	0	0.3	0.6	0.6	0.3	0	0	0	0	0	0	0
	Cymatopleura solea	0	0.3	0.5	0.3	0.3	0	0	0.5	1.3	1.7	2.4	4.3	6.6	7.6	7.4
	Encyonema minutum	0	0	0	0.5	1.5	1.2	0.6	0.3	0	0	0	0.3	0.3	0.2	0
	Epithenia sorex	0	0	0	0	0	0	0	0	0	0	0	0	0.6	0.2	0.2
	Eunotia pectinalis	0	0.9	1.3	3	5	10	13.4	8.4	5	3.2	1.8	2	0	1.2	2
	Gomphonema gracile	0	0	0	0.3	0.9	0.6	0	0	0	0	0	0	0	0.2	0.2
	Hantzschia amphioxys	0.6	0.3	0.3	1.9	2.8	1.8	1.3	0.5	0.3	0	0	0.3	0.8	0.7	0.5
	Navicula dicephala	0	0	0	0	0	0	0	0.3	0.5	0	0	0	0.3	0.5	0
	Navicula vulpina	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Neidium affine	0	0	0	0.3	0.3	0	0	0	0	0	0	0	0	0.5	1.4
	Neidium iridis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

	Pinnularia acoricola	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Pinnularia borealis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Sellaphora pupula	0	0	0	0	0.3	0.3	0	0.3	0.3	0	0	0	0	0	0
	Stauroneis anceps	0	0	0	0.3	0.6	0.3	0.3	0.3	0.3	0	0	0	0	0.2	0.2
	Stauroneis frauenfeldiana	1.8	2.3	2.8	2.2	2.2	2.7	3.2	6.8	9.7	10.1	9.2	10.4	12.2	10.1	8.1
	Stauroneis fulmens	4.5	6	6.6	3.8	1.2	2.1	3.2	7.6	8.1	6.4	4.9	3.2	2.5	1.5	1.1
	Stauroneis phoenicientron	4.8	4	3.8	1.6	0.9	1.5	2.9	10.4	14.2	10.7	6.4	4.3	3.6	3.9	3.2
	Surirella cf. brebissonii	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Surirella linearis	0	0	0	0	0	0	0	0	0	0.3	0.3	0	0	0	0
	Surirella tenera	0	0	0	0	0	0	0	0	0	0.3	0.3	0	0.3	0.2	0
	Pinnularia divergens	0	0	0	0.3	0.3	0	0	0.5	0.8	3.5	5.5	3.5	1.7	1	0.2
	Pinnularia gibba/maior	83.4	79.8	75.6	71.7	61	50.9	43.6	43.1	44.9	51.3	56.6	55.4	51.7	46.3	43
	Pinnularia obscura	0	0	0	0	0	0	0	0.3	0.5	0.3	0	0.3	0.6	1.5	3.6
	Ulnaria ulna	0	0.3	0.8	1.1	0.9	0.6	0	0.5	1.3	1.4	1.8	2.9	4.7	3.7	3.4
Fresh-Brackish	Amphora veneta	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Cosmioneis pusilla	0	0	0	0	0	0	0	0.3	0.3	0.3	0.9	0.6	0.3	1	2
	Diploneis subovalis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Luticola mutica	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Navicula cf. placentula	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Brackish	Campylodiscus echeneis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Nitzschia sigma	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Rhopalodia acuminata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Rhopalodia brebissonii	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Tryblionella acuminata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Brackish-Marine	Diploneis smithii	3.6	5.1	6.3	3.3	0.9	1.5	2.2	1.4	1.6	2.6	5.5	7.8	9.7	13.8	17.3
	Paralia sulcata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Tabularia cf. fasiculata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

	Gyrosigma cf. targidum	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Rhopalodia musculus	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Marine	Actinoptychus senarius	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Actinoptychus splendens	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Berkeleya scopulorum	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Cymatosira belgica	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Delphineis cf. surirella	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Dictyocha fibula	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Distephanus speculum	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Diploneis weisfloggii	0	0	0	0	0	0	0	0	0.3	0	0	0.3	0.3	0	0
	Nitzschia cf. panduriformis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Parlibeluss cf. plicatus	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Pinnularia schoederii	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Pinnularia stauntonii	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Podosira cf. stelligera	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Pseudopodosira sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Rhaphoneis amphiceros	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Thalassiosira cf. eccentrica	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Thalassiosira cf. oestruppii	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Thalassiosira weisfloggii	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Thalassiosira spp.	0	0	0	0	0	0	0	0	0	0	0	0.6	0.8	0.2	0.2
	Trachyneis aspera	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Triceratium alternans	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Triceratium cf. favus	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Triceratium cf. spinosum	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Tryblionella granulata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Tryblionella cf. levidensis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

	Tryblionella punctata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Totals	Salt Intolerant	1.2	1.1	1.5	8.8	19.2	24.5	27.7	17.7	10.8	7.5	3.4	2.9	1.7	2	2
	Fresh	95.2	93.8	92.1	87.9	79.9	73.9	70.1	80.7	87.1	89.6	90.2	87.8	87.3	83	78.4
	Fresh-Brackish	0	0	0	0	0	0	0	0.3	0.3	0.3	0.9	0.6	0.3	1	2
	Brackish	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Brackish-Marine	3.6	5.1	6.3	3.3	0.9	1.5	2.2	1.4	1.6	2.6	5.5	7.8	9.7	13.8	17.3
	Marine	0	0	0	0	0	0	0	0	0.3	0	0	0.9	1.1	0.2	0.2
	Total Counts	332	352	394	364	323	330	314	367	381	345	327	345	362	406	444

		Sample Depth (cm) (continued from p. 56)														
	Species	**75**	**80**	**85**	**90**	**95**	**100**	**105**	**110**	**115**	**120**	**125**	**130**	**135**	**140**	**145**
Salt Intolerant	Eunotia praerupta	1.5	1.9	1.9	1.6	6.3	9.4	17.6	24	14.8	11	10.6	7.4	2.6	0	0
	Eunotia solerirolii	0	0	0.3	0.3	0.3	0.5	0.6	0.9	0.5	0.9	0.6	1.6	0.3	0	0
	Pinnularia stomatophora	0	0	0	0	0	0	0	0	0.3	0.4	0	0	0	0	0
	Pinnularia acrosphaeria	0.4	0.6	0.8	0.6	1.5	4.7	4.3	3.7	2	2.4	2.2	1.9	1	0	0
	Pinnularia braunii	0	0	0	0	0	1.3	0.9	1.2	4.9	7.7	6.4	2.3	2	0.3	0.3
	Stauroneis obtusa	0	0	0	0	0	0	0	0	0.3	0.2	0	0	0	0	0
Fresh	Achnanthes inflata	0	0	0	0	0	0	0.3	0.3	0	0	0.3	0	0	0	0
	Achnanthes saxonica	0	0	0	0	0	0	0	0	2	4.4	3.6	6.8	14.1	21.3	26.7
	Amphora libyca	3.7	4.5	4.4	0.6	2.1	2.9	2.9	2.5	6.6	11.9	7.5	1.6	1	0.3	0.6
	Aulacoseira distans	0.2	0.2	0.3	0	0	0	0	0	0	0	0	0	0	0	0
	Aulacoseira italica	0	0	0	0	0	0	0	0	0.5	0.7	0.3	0	0	0	0
	Cocconeis pediculus	0	0	1.1	3.8	2.1	0	0.6	1.6	0.8	0.9	0.8	1.9	2.6	2.6	0.9
	Cocconeis placentula	1.1	1.5	3.3	6	3.3	0.5	0.9	2.2	1	0.7	0.3	0.6	1	1.6	1.5
	C. cuspidata	0	0	0	0	0	0	0	0	0	0	0	0.3	0	0	0
	Cymatopleura solea	8.1	7.5	6	4.7	5.1	6	5.5	1.9	1.3	0.7	0.6	0.6	0	0	0.3
	Encyonema minutum	0	0	0	0	0.6	0.8	0.6	0	0	0	0	0	0	0	0

	Epithenia sorex	0.2	0.2	0	0	0	0	0	0.3	0.3	0.2	0	0.3	0	0.3	0.3
	Eunotia pectinalis	1.1	0.2	0.5	0.9	1.2	1	2	3.4	4.3	4.4	3.6	2.3	1.3	0	0
	Gomphonema gracile	0	0.2	0.3	0	0.6	1.3	1.7	3.4	4.9	5.5	7.5	10	9.2	3.6	2.7
	Hantzschia amphioxys	0.7	0.2	0	0.6	0.3	1	2	2.5	1.3	2	3.4	4.9	6.2	9.2	10.2
	Navicula dicephala	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0.3
	Navicula vulpina	0	0	0	0	0	0	0	0	0	0	0	0	3.6	12.1	8.7
	Neidium affine	0.2	0	0	0	0	0	0	0	0	0.2	0	0.3	0	0	0
	Neidium iridis	0	0.2	0.3	0.6	0.3	0.3	0	0.6	1.8	2.2	3.4	4.2	3.9	2.3	0.9
	Pinnularia acoricola	0	0	0	0	0	0.5	0.3	0	2.6	3.3	3.4	2.3	1.6	0	0
	Pinnularia borealis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Sellaphora pupula	0	0	0	0	0	0	0.3	0.6	0.3	0	1.4	4.9	3.6	0.3	0.3
	Stauroneis anceps	0.4	0.2	0	0	0.6	1	0.9	1.2	1.3	2.2	2.2	1.3	1	0.3	0.6
	Stauroneis frauenfeldiana	7.3	6	5.8	5.1	6.6	7.9	6.6	4.7	2.3	1.5	2.2	2.3	2	0	0
	Stauroneis fulmens	0.4	0	0.3	0.3	0	0	0	0	0	0	0	0	0	0	0
	Stauroneis phoenicientron	3.3	3	4.4	6.3	3.3	2.1	1.7	1.6	7.9	10.1	7.3	1.6	1	1.3	0.6
	Surirella cf. brebissonii	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Surirella linearis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Surirella tenera	0	0	0	0	0	1	0.6	0	0	0	0.3	1.9	1.3	1.6	1.5
	Pinnularia divergens	1.5	3.4	2.5	1.3	0.3	0	0	0	1.5	2.2	1.1	0.3	0.3	0	0
	Pinnularia gibba/maior	38.1	32.7	37.5	38	35.2	27.6	23.3	19.9	19.9	18	19.3	18.8	20.3	21.3	12.6
	Pinnularia obscura	0.7	0	0	0	0	0	0.6	1.6	0.8	0.2	0	0	0	0	0
	Ulnaria ulna	4.8	5.2	5.8	3.8	3.9	4.7	4.6	5	2.8	0.7	1.4	1.3	1.3	1.3	0.9
Fresh-Brackish	Amphora veneta	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Cosmioneis pusilla	0.9	1.3	1.9	3.2	3.3	3.4	2.9	2.8	2.8	2	4.2	7.4	4.9	0.3	0.3
	Diploneis subovalis	0	0.2	0.3	0.3	0.3	0	0	0	0	0	0	0	0	0	0
	Luticola mutica	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Navicula cf. placentula	0	0	0	0	0	0	0	0	0	0.7	0.6	0.3	0	0	0

Brackish	Campylodiscus echeneis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Nitzschia sigma	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Rhopalodia acuminata	0	0	0	0	0	0	0	0	0	0.2	0.3	0.6	0.3	1	1.2
	Rhopalodia brebissonii	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Tryblionella acuminata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Brackish-Marine	Diploneis smithii	25.1	30.1	22.2	20.6	23	21.5	18.2	13.7	9.7	2.6	5	8.4	11.1	11.5	18.9
	Paralia sulcata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Tabularia cf. fasiculata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Gyrosigma cf. targidum	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Rhopalodia musculus	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Marine	Actinoptychus senarius	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Actinoptychus splendens	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Berkeleya scopulorum	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Cymatosira belgica	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Delphineis cf. surirella	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Dictyocha fibula	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Distephanus speculum	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Diploneis weisfloggii	0	0.2	0.3	0.3	0	0.3	0	0	0	0	0	0	0	0.3	0
	Nitzschia cf. panduriformis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Parlibeluss cf. plicatus	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Pinnularia schoederii	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Pinnularia stauntonii	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Podosira cf. stelligera	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Pseudopodosira sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Rhaphoneis amphiceros	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Thalassiosira cf. eccentrica	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Thalassiosira cf. oestruppii	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

	Thalassiosira weisfloggii	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Thalassiosira spp.	0	0.2	0	0.9	0	0	0.3	0.3	0.5	0	0.3	0	0	1.6	1.8
	Trachyneis aspera	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Triceratium alternans	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Triceratium cf. favus	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Triceratium cf. spinosum	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Tryblionella granulata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Tryblionella cf. levidensis	0	0	0	0	0	0	0	0	0	0	0	1.3	2.3	3.6	6.9
	Tryblionella punctata	0	0	0	0	0	0	0	0	0	0	0	0	0.3	1.3	0.9
Totals	Salt Intolerant	2	2.6	3	2.5	8.1	16	23.3	29.9	22.8	22.6	19.8	13.3	5.9	0.3	0.3
	Fresh	72	65.4	72.3	72.2	65.4	58.8	55.3	53.3	64.2	71.9	69.8	68.6	75.2	80	69.7
	Fresh-Brackish	0.9	1.5	2.2	3.5	3.6	3.4	2.9	2.8	2.8	2.6	4.7	7.8	4.9	0.3	0.3
	Brackish	0	0	0	0	0	0	0	0	0	0.2	0.3	0.6	0.3	1	1.2
	Brackish-Marine	25.1	30.1	22.2	20.6	23	21.5	18.2	13.7	9.7	2.6	5	8.4	11.1	11.5	18.9
	Marine	0	0.4	0.3	1.3	0	0.3	0.3	0.3	0.5	0	0.3	1.3	2.6	6.9	9.6
	Total Counts	454	465	365	316	335	381	347	321	391	455	358	309	306	305	333

		Sample Depth (cm) (continued)												
	Species	**150**	**155**	**160**	**165**	**170**	**175**	**180**	**185**	**190**	**195**	**200**	**205**	**210**
Salt Intolerant	Eunotia praerupta	0	0	0	0	0.3	0	0	0	0	0	0	0	0
	Eunotia solerirolii	0	0	0	0	0	0	0	0	0	0	0	0	0
	Pinnularia stomatophora	0	0	0	0	0	0	0	0	0	0	0	0	0
	Pinnularia acrosphaeria	0	0	0.3	0	0	0	0	0	0	0	0	0	0
	Pinnularia braunii	0.3	0	0	0	0	0	0	0	0	0	0	0	0
	Stauroneis obtusa	0	0	0	0	0	0	0	0	0	0	0	0	0
Fresh	Achnanthes inflata	0.3	0	0	0	0.3	0.3	0.3	0	0	0	0	0	0
	Achnanthes saxonica	28.7	23.1	10	6.1	4.2	2.7	1.1	0.3	0.3	0	0	0	0

	Amphora libyca	1.1	0.6	1.6	0.3	0	0	0	0	0.7	0.3	0.6	0	0
	Aulacoseira distans	0	0	0	0	0	0	0	0	0	0	0	0	0.3
	Aulacoseira italica	0	0	0.3	0.3	0.3	0	0.3	0.3	1.7	1	0	0	0.3
	Cocconeis pediculus	0	1.5	2.9	1.5	0.3	0.6	0.3	0	0.3	0.7	0.6	0	0
	Cocconeis placentula	1.6	2	3.2	2.1	1.4	1.2	1.4	1	0.7	0.7	0	0	0
	C. cuspidata	0	0.3	0.3	0	0	0	0	0	0	0	0	0	0
	Cymatopleura solea	0.3	0	0	0	0	0	0	0	0	0	0	0	0
	Encyonema minutum	0	0	0	0	0	0	0	0	0	0	0	0	0
	Epithenia sorex	0	0	0	0	0.3	0	0	0.3	0.3	0	0	0	0
	Eunotia pectinalis	0	0	0	0	0.3	0.3	0.3	0	0	0	0	0	0.3
	Gomphonema gracile	2.4	2.9	4.5	2.7	1.1	0.6	0.3	0	0.7	1	1.3	1	0
	Hantzschia amphioxys	9.9	6.7	6.1	4	0.6	0.3	0	0	0	0	0	0	0.6
	Navicula dicephala	0	0	0	0	0	0	0	0	0	0	0	0	0
	Navicula vulpina	5.6	5	4.8	2.1	0.8	0.9	0.6	0.7	1.3	0.7	0.6	0	0
	Neidium affine	0	0	0	0	0	0	0	0	0	0	0	0	0
	Neidium iridis	0	0.6	1.3	0.6	0.3	0	0	0	0	0	0	0	0
	Pinnularia acoricola	0	0	0	0	0	0	0	0	0	0	0	0	0
	Pinnularia borealis	0	0	0	0	0	0	0	0	0	0	0.3	0	0
	Sellaphora pupula	0	0	0	0	0	0	0	0	0	0	1.3	4.8	5.5
	Stauroneis anceps	0	0	0	0	0	0	0	0	0	0	0	0	0
	Stauroneis frauenfeldiana	0	0	0	0	0	0	0	0	0	0	0	0	0
	Stauroneis fulmens	0	0	0	0	0	0	0	0	0	0	0	0	0
	Stauroneis phoenicientron	0	0	0	0	0	0	0	0	0	0	0	0	0
	Surirella cf. brebissonii	0	0	0	0	0.3	0.6	0.3	0	0.3	0.3	0	0	0
	Surirella linearis	0	0	0	0	0	0	0	0	0	0	0	0	0
	Surirella tenera	1.6	0.9	0.3	0	0	0	0	0	0	0	0	0	0
	Pinnularia divergens	0.3	0	0	0	0	0	0	0	0	0	0	0	0

	Pinnularia gibba/maior	9.4	7.9	6.4	4.6	1.7	1.5	0.9	1.7	2.3	4.3	4.8	3.5	1.5
	Pinnularia obscura	0	0	0	0	0	0	0	0	0	0	0	0	0
	Ulnaria ulna	0.5	0.9	1.9	1.2	1.4	0.6	0	0	0.3	0.3	0	0	0
Fresh-Brackish	Amphora veneta	0	0	0	0	0	0	0.6	1	0.3	0	0	0	0
	Cosmioneis pusilla	0.8	1.5	2.9	1.8	0.8	0.3	0.3	0	0.3	0	0	0	0
	Diploneis subovalis	0	0	0	0	1.1	4.8	8	12.6	15	10.9	6.1	4.1	4.4
	Luticola mutica	0	0	0	0	0.6	0.3	0	0	0	0	0.3	0.3	0
	Navicula cf. placentula	0	0	0	0	0.3	0	0	0	0.3	1.3	1.9	2.2	1.7
Brackish	Campylodiscus echeneis	0	0	0	3.6	5.1	4.8	4.3	4	3.7	9.2	13.1	16.6	16
	Nitzschia sigma	0	0	0	2.7	5.9	4.5	3.7	3.3	1	3.6	6.1	6.4	5.2
	Rhopalodia acuminata	0.8	1.2	1.6	0.3	0	0	0	0	0	0	0	0	0
	Rhopalodia brebissonii	0	0	0	0	0	0	0	0.7	3.3	2	2.2	2.5	2.9
	Tryblionella acuminata	0	0	0	0	0.3	1.8	2.3	2	1.7	0.7	1.3	1	0.9
Brackish-Marine	Diploneis smithii	25.5	19	8.4	6.1	3.7	2.7	0	0	0	0	0	2.5	3.5
	Paralia sulcata	0.5	9.6	15.8	26.7	32.5	35.2	35.7	31.6	24	25.4	24	22	23.5
	Tabularia cf. fasiculata	0	1.2	3.9	2.1	1.1	1.5	1.4	1.3	0.7	0.7	1.3	0.6	0
	Gyrosigma cf. targidum	0	0	0	0.3	0.8	0.3	0	0	0	0	0	0	0
	Rhopalodia musculus	0	0	0	0.3	0.3	0	0	0	0	0	0	0.3	0.9
Marine	Actinoptychus senarius	0	0.3	0.6	0.3	0	0	0	0	0.3	0	0	0	0
	Actinoptychus splendens	0	0	0.3	0.3	0.6	0	0.3	0.3	0.7	0.7	0.3	0	0.3
	Berkeleya scopulorum	0	0	0	0	0.3	0	0	0	0	0	0	0	0
	Cymatosira belgica	0	0	0	0	0	0	0	0	0	0	1.9	1.6	0.6
	Delphineis cf. surirella	0	0	0	0	0	0.3	0.9	0	0	0	0	0	0
	Dictyocha fibula	0	0	0	0	0	0	0	0	0	0	0.3	0.3	0
	Distephanus speculum	0	0	0	0	0	0	0	0	0.3	0	0	0	0
	Diploneis weisfloggii	0	0	0.3	0.6	0.3	0	0	0	0.3	0	0	0	0
	Nitzschia cf. panduriformis	0	0	1.6	1.5	1.1	0.6	1.1	0.3	0	0	0	0	0

	Parlibeluss cf. plicatus	0	0	0	0	0	0	0	0.7	1.7	1.3	1.3	1	1.2
	Pinnularia schoederii	0	0	0	0	0	0	4.6	10.3	13.7	9.9	3.5	4.5	3.5
	Pinnularia stauntonii	0	0	0	0	0.8	1.5	2	4.3	4.7	5.6	5.8	5.4	5.8
	Podosira cf. stelligera	0	0	0	0	0	0	0	0.3	0.7	0.3	0.3	0	0
	Pseudopodosira sp.	0	0	0	0	0	0	0.3	0	1	0.3	0.6	0.6	0.3
	Rhaphoneis amphiceros	0	0	0	0	0.6	0.3	0	0	0	0	0	0	0
	Thalassiosira cf. eccentrica	0	0	1.3	3	3.7	2.7	1.7	0.7	0	0.3	0.6	0.6	0.9
	Thalassiosira cf. oestruppii	0	0	1.9	2.1	2.5	3.3	3.1	2.3	2	3	3.5	2.9	2.9
	Thalassiosira weisfloggii	0	0	0	0.3	0.3	0.6	1.1	1.7	2.7	3.6	4.2	3.2	3.5
	Thalassiosira spp.	1.6	11.1	14.8	12.2	9	9.3	8	7.3	5.3	5	5.1	5.1	4.9
	Trachyneis aspera	0	0	0	0	0.3	0	0	0	0	0	0	0	0
	Triceratium alternans	0	0	0	0	0.3	0	0	0.3	0.7	0.3	0	0	0
	Triceratium cf. favus	0	0	0	0	0	0	0.3	0	0	0	0	0	0
	Triceratium cf. spinosum	0	0	0	0	0	0	0.3	0	0	0	0	0	0
	Tryblionella granulata	0	0	2.3	1.5	0.6	0.6	0.6	0	0.3	1	2.2	2.2	2.9
	Tryblionella cf. levidensis	8	3.2	0	7	11	9	6.9	6.3	4.3	2.6	2.2	2.5	3.2
	Tryblionella punctata	0.8	0.6	0.3	1.5	2.5	5.7	6.9	4.3	2	3	2.2	2.2	2.6
Totals	Salt Intolerant	0.3	0	0.3	0	0.3	0	0	0	0	0	0	0	0
	Fresh	61.7	52.3	43.7	25.5	13.3	9.6	5.7	4.3	9	9.2	9.6	9.2	8.4
	Fresh-Brackish	0.8	1.5	2.9	1.8	2.8	5.4	8.9	13.6	16	12.2	8.3	6.7	6.1
	Brackish	0.8	1.2	1.6	6.7	11.3	11.1	10.3	10	9.7	15.5	22.7	26.4	25
	Brackish-Marine	26	29.8	28	35.6	38.4	39.8	37.1	32.9	24.7	26.1	25.2	25.5	27.9
	Marine	10.5	15.2	23.5	30.4	33.9	34	38	39.2	40.7	37	34.2	32.2	32.6
	Total Counts	373	342	311	329	354	332	350	301	300	303	313	314	344

Appendix 3: Processing Raw Sediment for Pollen

Night before – Sampling raw sediment

Prepare samples to soak overnight in distilled water. Use one 15ml test tube per sample. Fill tube up to 5ml with distilled water then add sample until 6ml, adding ~1cm^3 of sample. Shake/vortex the tubes to disaggregate the sample as much as possible and leave them to soak overnight.

Day 1

SPT Recovery

SPT used in previous analyses may need to be recycled and to do this, filter the used SPT through 90µm and then 6µm filters. Next, transfer liquid to a large beaker and place under heat lamp. For pollen extraction, SPT with a specific gravity of 2.2 is used, which can be tested with a hydrometer. Depending on how dilute the SPT is, this can take several days. Be sure to check the specific gravity every few hours.

HCL treatment – Removal of Carbonates

- Shake/vortex samples thoroughly before centrifuging at 3000rpm for 4 minutes (this is the rpm and run time used for all future centrifuging unless otherwise specifically stated).
- Decant off the distilled water, leaving the sample in the conical bottom of the tube.
- Add 1 lycopodium tablet to each sample, recording the batch number of the tablets used so pollen concentrations can be calculated later on.
- Add 10% HCl solution to each tube up to 10ml and place the tubes in a water bath at 75˚C for 5 minutes. If necessary, use pointed stirring rods to ensure all sample is well mixed and accessed by the acid.
- Centrifuge then decant off acid into a beaker to be neutralised and disposed of.
- Do 1 water wash. This is done by filling tubes up to 10ml with distilled water, shaking and vortexing to ensure thorough mixing, then centrifuging and decanting off the distilled water.

KOH treatment

- Fill tubes to 10ml with 10% KOH solution and boil samples in water bath at 96˚C for 10 minutes, stirring occasionally. Remove samples from water bath and centrifuge. Decant off KOH (this may be quite black) and do 2-3 water washes, shaking/vortexing before each centrifuge to ensure thorough mixing. Discard water after each wash.
- Cut 1 90µm sieve cloth circle per sample and place inside a small funnel, wetting with distilled water so the cloth adheres to the side of the funnel. Place the funnels over labelled beakers for sieving. Pour samples onto 90µm sieve cloth, thoroughly

rinsing test tubes with distilled water to ensure no sample is left in the tube. Continue rinsing with distilled water until water coming out the bottom of the funnel runs clear.

- To concentrate sample again, pour the contents of the beakers into 50ml test tubes and centrifuge, decanting off the water each time until all sample (<90µm) is collected at the bottom of the 50ml tubes.
- Transfer the sample back to the 15ml test tubes by rinsing with distilled water, ensuring they are not filled to more than 10-11ml. This may involve centrifuging and decanting off the water until all the sample is collected at the bottom of the 15ml tubes.

Density Separation

- To begin this step, make sure there is as little water as possible in each sample. This means the samples must be decanting especially carefully after the last centrifuge in the KOH step. This is to ensure that when SPT is added, the specific gravity of the SPT is not altered.
- Add 5-6mls of SPT and mix/vortex well then centrifuge for 6 minutes at 2000rpm. Leave samples to sit overnight so samples can separate fully.

Day 2

Density Separation (cont)

- Decant the light fraction off the samples into labelled beakers and make up the volume to 100ml for each sample with distilled water. Mix each beaker with a stirring rod to ensure distilled water is well mixed in with the SPT.
- Centrifuge material back in to new 15ml tubes. After each centrifuge decant off the SPT/water mix into a large beaker or flask so it can be recycled later. You may wish to begin this with the 50ml tubes to speed up the process.

Acetolysis

- Begin this step by putting on the water bath to heat to 96˚C.
- Wash the samples in glacial acetic acid by filling tubes to 10ml, shaking/vortexing then centrifuging. Decant off acid into a beaker to be neutralised and disposed of later. This dehydrates the sample, removing any remaining water to minimise the chance of a violent reaction between water and the acid mixture during acetolysis.
- Make a 9:1 ratio of acetic anhydride: sulphuric acid solution so that there is 5mls for each sample. For 8 samples this would be 36ml acetic anhydride and 4ml sulphuric acid.
- Pour out the acetic anhydride first then drop by drop add the sulphuric acid. A reaction occurs that will cause the mixture to become quite hot. Add 5mls of the

mixture to each sample, shake/vortex to ensure thorough mixing and place samples in water bath for 5 minutes. Keep the lids off and stir occasionally.

- Centrifuge and decant off into beaker. Wash again in glacial acetic acid, centrifuging and decanting. Follow this with 2 water washes.

Removal of Clay

- Set up one labelled beaker-funnel set for each sample as in the KOH step but this time with 6µm sieve cloth circles. Pour the samples from the 15ml test tubes into their respective funnel.
- Again, be sure to rinse out tubes with distilled water to ensure no sample is left behind. Wash thoroughly with distilled water to disaggregate the sample where necessary and ensure that all <6µm material passes through the sieve cloth. Leave samples to stand until as much water as possible has passed through.
- Keep the >6µm fraction by rolling the sieve cloth circles into a small funnel, place the point inside the 15ml tubes and rinse back in with distilled water. If sample cannot be fully removed from the sieve cloth with ~10ml of distilled water, you may need to centrifuge and repeat the process.
- Samples are now ready for slide making

Slide making

- Staining – centrifuge sample and decant off as much as possible. Add one drop of stain or two for samples with a lot of material. Fill tubes to 10ml with distilled water, shake, centrifuge and decant. Follow this with another water wash but after this one, only decant tubes back to 5mls. For samples likely to have low pollen concentrations they can be decanted back to 3mls. Material is now ready to be put on slides.
- Turn on hot plate to heat up. Make 2 slides per sample and name them with sample no. Put cover slips and slides on the hot plate to warm up. Add one drop of glycerine jelly onto the slides. Shake samples to ensure mixing then, using a pipette filled from the centre of the tube, add 1-2 drops of sample onto the jelly. Wait until all water has evaporated before placing the coverslips. This can be tested by holding the cover slip over the sample and watching for any condensation. Carefully place cover slips on slides to minimise any water bubbles. Wait until material has reached edge of cover slips then invert the slides on glass rods overnight to dry and settle out. Once dry, any excess jelly can be removed from around the coverslip with nail polish if needed.

Appendix 4: Pollen Raw Percentage Data

		Sample Depth (cm)															
	Species	**0**	**5**	**10**	**15**	**18**	**20**	**22**	**25**	**30**	**32**	**34**	**35**	**37**	**39**	**40**	**45**
Trees	Dacrycarpus dacrydioides	0	0	0	0	2	28.6	0	0	0	0	0	0	0	0	20	0
	Dacrydium cupressinum	10	100	0	0	18.4	0	0	0	0	4.5	9.5	0	8.3	27.8	60	100
	Podocarpus	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Prumnopitys taxifolia	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Prumnopitys ferruginea	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Alectryon excelsus	15	0	0	0	4.1	0	0	0	0	9.1	4.8	0	0	0	0	0
	Phyllocladus	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Elaeocarpus	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Metrosideros sp.	0	0	0	20	10.2	0	0	0	0	0	0	0	0	0	0	0
	Fuscospora	15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Dodonaea viscosa	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Knightia excelsa	10	0	0	0	2	0	0	0	0	0	0	0	8.3	5.6	0	0
	Quintinia	0	0	0	0	0	0	0	0	0	0	0	0	8.3	0	0	0
Shrubs	Coprosma	10	0	0	0	0	0	0	28.6	60	36.4	38.1	22.2	16.7	16.7	20	0
	Asteraceae	0	0	33.3	0	0	0	0	0	0	0	0	0	0	0	0	0
	Halocarpus	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Hoheria	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Leptospermum	0	0	0	0	2	0	0	0	10	13.6	9.5	0	0	5.6	0	0
	Myrsine	5	0	0	0	6.1	0	0	0	0	0	0	0	0	0	0	0
	Ascarina lucida	5	0	0	0	22.4	0	0	0	0	0	0	0	0	5.6	0	0
	Dracophyllum	0	0	0	0	4.1	14.3	0	0	0	0	0	0	0	0	0	0
	Griselinia	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Pseudopanax	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Liliaceae	0	0	0	0	0	0	0	28.6	30	31.8	23.8	66.7	33.3	11.1	0	0

	Astelia	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Herb	Poaceae	15	0	66.7	80	28.6	57.1	0	42.9	0	4.5	14.3	11.1	25	27.8	0	0
Ferns	Cyathea	63.2	77	77.8	77.9	54.6	87.5	89.2	86.5	85.1	87.1	88.9	91.4	89.3	78.8	92.7	88.6
	Dicksonia squarrosa	0	0	1.5	1.8	2.6	1.5	0.6	0	0	0.6	0.7	0	0	1.1	0.3	0
	Monolete spore	16.7	15.9	11.1	13.5	19	5	1.8	3.4	4.5	4.4	3.1	2.4	2.8	6.5	2.6	5.7
Aquatic	Phormium	4.2	6.2	7.4	3.1	3.3	2.5	8.1	7.8	5.2	4.4	3.3	4.3	3.8	6.5	2.1	4.9
	Leptocarpus similis	0	0	0	0	0.7	0	0	0	1.1	0	0	0	0	0	1	0.4
	Cyperaceae	2.1	0	0	0.6	1.5	0	0	0	0.4	0	0	0	0	0.7	0	0
Totals	Trees	65	100	0	20	36.7	28.6	0	0	0	13.6	14.3	0	25	33.3	80	100
	Shrubs	20	0	33.3	0	34.7	14.3	100	57.1	100	81.8	71.4	88.9	50	38.9	20	0
	Herbs	15	0	66.7	80	28.6	57.1	0	42.9	0	4.5	14.3	11.1	25	27.8	0	0
	Ferns	79.9	92.9	90.4	93.3	76.2	94	91.6	89.9	89.6	92.1	92.8	93.8	92.1	86.3	95.6	94.3
	Aquatics	6.3	6.2	7.4	3.7	5.6	2.5	8.1	7.8	6.7	4.4	3.3	4.3	3.8	7.2	3.1	5.3
	Dryland Count	20	1	3	5	49	7	1	7	10	22	21	9	12	18	5	1
	Total Count	144	113	135	163	269	200	333	296	269	619	540	465	290	278	383	264

		Sample Depth (cm) (continued)															
	Species	**50**	**55**	**60**	**65**	**70**	**75**	**80**	**85**	**90**	**95**	**100**	**105**	**110**	**115**	**120**	**125**
Trees	Dacrycarpus dacrydioides	0	0	0	0	0	0	1.4	0	1.1	0.4	0	0.4	1.1	0	0	0
	Dacrydium cupressinum	0	100	50	66.7	100	71.2	51.7	51	64.2	53.1	45.5	51.4	50.2	45.1	32.8	29.2
	Podocarpus	0	0	0	0	0	3.8	3.8	3.1	4	3.5	2.7	5.5	2.3	1.5	2.3	7
	Prumnopitys taxifolia	0	0	0	0	0	0	2.1	2.7	1.5	1.5	0.3	0	1.1	0	0.8	7
	Prumnopitys ferruginea	0	0	0	0	0	3.8	3.5	4.8	5.1	7.3	6	5.5	6.1	7.9	5.8	12.2
	Alectryon excelsus	0	0	0	0	0	0	1.4	1	1.1	0.4	2	1.2	0.4	0	2.3	4.1
	Phyllocladus	0	0	0	0	0	0	0	0	0	0	0.7	0	0.4	0	0	0
	Elaeocarpus	0	0	0	0	0	3.8	4.9	4.1	1.8	1.5	1	0	0.4	0	0	0

	Metrosideros sp.	0	0	0	0	0	0	1.4	1.7	0	3.5	8	6.7	2.7	6.4	9.7	20.3
	Fuscospora	0	0	0	0	0	0	0	0	0	1.2	0	0	1.1	0	0.8	0
	Dodonaea viscosa	0	0	0	0	0	0	1.4	2.4	0	1.5	1.7	0.4	1.1	2.3	0.8	0
	Knightia excelsa	0	0	0	0	0	7.7	4.9	4.8	4	6.2	0.7	1.2	2.3	2.3	0.8	0
	Quintinia	0	0	0	0	0	0	0	0	0	0.4	1	1.2	0.4	0	0	0
Shrubs	Coprosma	0	0	0	0	0	0	0	0	0	0	0	0	1.1	0	0	4.8
	Asteraceae	0	0	0	0	0	0	0	0	0	0	0.7	0	0	0	0	0
	Halocarpus	0	0	0	0	0	0	1.4	0	0.4	0	0.7	0	1.1	0	0	3
	Hoheria	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Leptospermum	0	0	0	0	0	0	0.3	1	0	0	0	1.6	2.7	10.2	15.1	0
	Myrsine	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Ascarina lucida	0	0	0	0	0	9.6	12.2	11.6	8.8	6.9	8.4	10.3	9.9	8.6	9.7	9.2
	Dracophyllum	0	0	0	0	0	0	0	0	0	0	0	0	0.4	0	0.8	0
	Griselinia	0	0	0	0	0	0	0	0	0	0	0.7	0	0	0	0	0
	Pseudopanax	0	0	0	0	0	0	1	0	0	0	0.3	0	0	0	0	1.1
	Liliaceae	0	0	0	33.3	0	0	3.8	7.2	6.9	10.4	17.4	13.8	11.8	13.5	12	0
	Astelia	0	0	0	0	0	0	0	0	0	2.3	0	0.4	1.1	0	0	0
Herb	Poaceae	100	0	50	0	0	0	4.5	4.5	1.1	0	2.3	0.4	2.3	2.3	6.6	2.2
Ferns	Cyathea	96.9	93	96.4	95.8	95.8	63.3	56.7	64.1	70.6	66.6	44.7	38.8	33.7	21.1	13.1	8.7
	Dicksonia squarrosa	0	0	0	0	0.4	0.6	0.4	0.4	0.1	0	0	0	0.2	0	0.3	1.2
	Monolete spore	1.5	2	1.5	2.4	1.7	5.6	5.6	3.9	4	3.4	5.1	7	5.3	5.4	5.2	3.7
Aquatic	Phormium	1	4	1	1	1.9	0.6	0.6	0.7	0.4	1.7	1	1	0.4	0.8	0.3	1.9
	Leptocarpus similis	0	0	0	0	0	0.6	0.9	0.3	0.1	0	0.3	0.2	0.2	0	0.6	0
	Cyperaceae	0	0	0	0	0	0	0.4	0.5	0.2	0.8	1.1	0.8	1.8	0.5	1.2	0
Totals	Trees	0	100	50	66.7	100	90.4	76.6	75.7	82.8	80.4	69.6	73.5	69.6	65.4	56	79.7
	Shrubs	0	0	0	33.3	0	9.6	18.9	19.9	16.1	19.6	28.1	26.1	28.1	32.3	37.5	18.1

	Herbs	100	0	50	0	0	0	4.5	4.5	1.1	0	2.3	0.4	2.3	2.3	6.6	2.2
	Ferns	98.5	95	98	98.2	97.9	69.5	62.7	68.4	74.8	70	49.8	45.8	39.2	26.6	18.7	13.7
	Aquatics	1	4	1	1	1.9	1.1	1.9	1.5	0.6	2.5	2.4	2.1	2.4	1.4	2.1	1.9
	Dryland Count	1	2	2	3	1	52	286	292	274	260	299	253	263	266	259	271
	Total Count	196	200	197	382	476	177	806	972	1114	947	626	485	451	369	327	321

		Sample Depth (cm) (continued)													
	Species	**130**	**135**	**140**	**145**	**150**	**155**	**160**	**165**	**170**	**175**	**180**	**185**	**190**	**195**
Trees	Dacrycarpus dacrydioides	1.1	0	0	0	0	0	0	0	0.8	0	0.3	0	0	0
	Dacrydium cupressinum	42	46.9	53	47.5	53.9	54.6	41.2	41.1	47.7	33.2	25.5	28.3	31.6	24.4
	Podocarpus	3.7	13.4	15.5	13.7	3.5	9.6	23	22.5	11.1	23.6	23.9	20.5	21.2	21.9
	Prumnopitys taxifolia	0.7	0	1.8	0.7	1.2	0.8	0.8	2	0	0.4	1.5	1	0.7	1.1
	Prumnopitys ferruginea	5.9	9	12.7	10.4	2.3	6.9	10.5	8.3	10.3	17.3	16.7	16.7	11.8	29
	Alectryon excelsus	3	0.7	1.1	2.5	6.6	6.2	4.3	3.2	5	3	2.1	1.4	1.4	0
	Phyllocladus	0.7	0	0	0	0	0	0.8	1.2	0	0	0.3	0	0	0
	Elaeocarpus	1.1	0	0	0	0	0	0	0	0	0	0.9	1	0.7	0
	Metrosideros sp.	5.6	7.2	8.1	6.1	3.5	3.1	3.5	5.1	1.5	6.3	7.3	8.5	8.3	3.9
	Fuscospora	1.9	0.7	0	0	0	0.8	2.7	1.2	1.5	0	0	0.3	0.7	1.1
	Dodonaea viscosa	1.1	0.7	0.7	2.5	3.5	1.5	0	0	0	0	0	0.3	1.4	1.1
	Knightia excelsa	0.7	1.4	0	0	0	0	0	0	0	0	0	0	0	0
	Quintinia	1.1	1.8	0	0.7	1.2	0	0	0	0	0.7	1.2	1	0	0
Shrubs	Coprosma	0	0	0	0	0	0	0.8	0	0.8	0	0	0	0.7	0
	Asteraceae	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Halocarpus	0.7	0	1.1	0	2.3	0	0	0	0	0	0	0	0	0
	Hoheria	0.7	0	0	0	0	0	0	0	0	0.4	0.6	0	0	0
	Leptospermum	5.6	3.2	2.5	1.1	0	0	0	0	0	0.7	1.5	1.4	1.4	1.8
	Myrsine	0	0	0	0	0	0	0	0	0	0	5.2	5.1	5.6	3.9

	Ascarina lucida	10.4	6.5	1.1	5.4	11.6	9.6	5.4	7.1	7.6	8.1	7	8.2	8.3	6.8
	Dracophyllum	0	0	0	0	0	0	0.8	1.2	0.8	0	0.3	0	0	0
	Griselinia	0.7	0	0	0	0	0	0	0	0	0	0	0	0	0
	Pseudopanax	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Liliaceae	7.4	4.3	1.8	6.8	7.4	5.4	3.5	5.1	9.5	5.5	5.5	6.1	6.3	5
	Astelia	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Herb	Poaceae	5.6	4	0.7	2.5	3.1	1.5	2.7	2	3.4	0.7	0.3	0	0	0
Ferns	Cyathea	18.1	13.8	15.3	19.2	22.7	20.4	13.1	19.1	22	50.6	53.3	54.6	58.7	51.9
	Dicksonia squarrosa	0	0	0	0	0	0	0	0.6	0.5	0.5	1	0.7	0	0.3
	Monolete spore	4	4.4	4	4.4	3.1	2.4	2.9	4.1	3.2	5.3	5.2	4.9	0	1.4
Aquatic	Phormium	0.8	0	0	0	0	0.3	0.6	0.9	1.3	0.3	0.1	0	0	0.3
	Leptocarpus similis	0	0	0	0.3	1.1	0.3	0.3	0.6	1.6	0.3	0.5	0.7	1.8	1.1
	Cyperaceae	1.1	0.3	0.8	0	0	0	1	0.6	0.8	0.5	0.6	0.4	0	1.4
Totals	Trees	68.8	81.9	92.9	84.2	75.6	83.5	86.8	84.6	77.9	84.5	79.7	79.2	77.8	82.4
	Shrubs	25.7	14.1	6.4	13.3	21.3	15	10.5	13.4	18.7	14.8	20	20.8	22.2	17.6
	Herbs	5.6	4	0.7	2.5	3.1	1.5	2.7	2	3.4	0.7	0.3	0	0	0
	Ferns	22	18.2	19.2	23.6	25.8	22.7	16	23.8	25.8	56.4	59.5	60.1	58.7	53.6
	Aquatics	2	0.3	0.8	0.3	1.1	0.6	1.9	2.1	3.8	1.1	1.2	1.1	1.8	2.8
	Dryland	269	277	283	278	258	260	257	253	262	271	330	293	288	279
	Total	354	340	354	365	353	339	313	341	372	638	839	755	728	640

		Sample Depth (cm) (continued)			
	Species	**200**	**205**	**210**	**215**
Trees	Dacrycarpus dacrydioides	0	0	0	0
	Dacrydium cuppressinum	22.5	22.4	36.8	36.8
	Podocarpus	22.5	23.4	19	19
	Prumnopitys taxofolia	1.1	1.7	0.8	0.7
	Prumnopitys ferruginea	31.3	26.9	19	19
	Alectryon excelsus	1.9	2.1	2	1.9
	Phyllocladus	0	0	0	0
	Elaeocarpus	0	0	0	0
	Metrosideros sp.	2.7	3.4	3.6	3.7
	Fuscospora	1.1	0.3	0	0
	Dodonaea viscosa	2.3	2.8	0.8	0.7
	Knightia excelsa	0	0	0	0
	Quintinia	0	0	0	0
Shrubs	Coprosma	0.4	0	0	0
	Asteraceae	0	0	0	0
	Halocarpus	0	0	0	0
	Hoheria	0	0	0	0
	Leptospermum	0.8	1.7	2	1.9
	Myrsine	2.7	3.4	2.8	2.6
	Ascarina lucida	6.1	6.2	9.9	10
	Dracophyllum	0	0	0	0
	Griselinia	0	0	0	0
	Pseudopanax	0	0	0	0

	Liliaceae	4.6	5.5	3.6	3.7
	Astelia	0	0	0	0
Herb	Poaceae	0	0	0	0
Ferns	Cyathea	33.1	25.8	32.5	30.1
	Dicksonia squarrosa	0	0	0.2	0
	Monolete spore	2.7	1.9	2.5	1.7
Aquatic	Phormium	0.5	0.2	0.7	0.5
	Leptocarpus similis	1.1	1.2	0.5	0.7
	Cyperaceae	3.2	2.8	0.7	0.5
Totals	Trees	85.5	83.1	81.8	81.8
	Shrubs	14.5	16.9	18.2	18.2
	Herbs	0	0	0	0
	Ferns	35.8	27.7	35.2	31.9
	Aquatics	4.8	4.2	2	1.7
	Dryland Count	262	290	253	269
	Total Count	441	426	403	405

Appendix 5: Preparing Raw Sediment for Particle Size Analysis

1. Weigh out 1g of sediment and soak in distilled water to disaggregate.
2. To remove carbonates, soak in 10% HCl for 10mins or until all carbonates have reacted and bubbling has ceased.
3. Centrifuge at 3000rpm for 5 minutes and decant off.
4. Follow this with at least 2 water washes. The pH of discarded water/HCl solution can be checked with pH paper.
5. Soak in 27% H_2O_2 in a water bath at 70°C for several hours, until bubbling has stopped. Follow with 2 more water washes. With samples high in carbon you most likely will not need the water bath step. Add H_2O_2 a few drops at a time to avoid sample spill over.
6. Add Calgon solution to each sample, agitating thoroughly.
7. Turn on the Beckman Coulter LS13320 laser particle size analyser (lasersizer) and run a standard through to ensure it is calibrated correctly.
8. Place sample into lasersizer, adding sample until the obscuration reaches a value of 8-12%, or as close to 10% as possible.

Appendix 6: Summary of Particle Size Statistics

Depth (cm)	Mean (µm)	Median (µm)	Mode (µm)	Mean/ Median	Standard deviation (µm)
0	95.2	17.38	6.542	5.478	145.7
-5	23.97	11.75	12.4	2.04	35.94
-10	20.11	10.53	12.4	1.91	30.24
-15	16.69	10.38	14.94	1.608	18.28
-20	27	11.85	2.78	2.278	39.77
-25	24.73	11.44	8.536	2.162	37.65
-30	24.66	11.76	14.94	2.097	36.51
-32	35.7	27.1	37.97	1.317	32.44
-35	28.2	14.71	14.94	1.917	34.26
-40	16.15	10.42	12.4	1.55	16.98
-45	19.18	9.982	8.536	1.921	28.09
-45	14.84	9.155	10.29	1.621	17.1
-50	15.38	9.275	8.536	1.658	17.85
-50	14.32	8.412	6.452	1.702	17.79
-55	14.17	8.377	6.452	1.692	17.6
-60	12.39	7.791	6.452	1.59	17.17
-65	4.163	3.252	2.787	1.28	2.929
-70	13.71	6.686	3.059	2.051	24.8
-75	6.814	4.906	2.787	1.389	6.146
-80	18.21	8.819	6.452	2.065	30.04

-85	20.79	9.692	6.452	2.145	33.54
-90	16.18	6.457	2.507	2.506	30.29
-95	17.31	7.876	6.452	2.198	30.38
-100	29.43	10.07	2.923	2.923	52.52
-105	94.98	14.85	6.452	6.396	178.8
-110	96.67	19.63	6.452	4.925	162.5
-115	178.3	39.28	517.2	4.539	272.2
-120	234.5	110.5	203.5	2.122	294.1
-125	273.3	135.8	517.2	2.013	330.2
-130	270.3	104.9	185.4	2.577	356.8
-135	271.3	93.26	517.2	2.909	365.2
-140	144.9	44.45	37.97	3.26	241.7
-145	163.2	42.14	14.94	3.873	266.1
-150	124.4	24.47	14.94	5.084	221.4
-155	141.8	30.47	14.94	4.654	236.6
-160	194.5	36.59	21.7	5.316	297.8
-170	58.53	17.32	16.4	3.379	128.9
-175	68.77	17.24	16.4	3.989	155.9
-175	25.75	15.82	16.4	1.628	33.09
-180	60.31	16.68	16.4	3.616	137.1
-185	76.33	15.83	14.94	4.822	165.5
-190	119.7	21.91	14.94	5.463	223.8
-195	253.3	74.59	517.2	3.396	336.2
-200	119.9	26.9	14.94	4.457	205.2
-205	64.61	30.12	14.94	2.145	89.84
-210	44.17	19.66	14.94	2.247	54.76
-215	69.47	42.17	168.9	1.647	69.77

Appendix 7: Processing Raw Sediment for Loss On Ignition

Raw Sediment Preparation

Below are the steps followed to measure % organic carbon of sediment samples from Onaero Beach:

1. Weigh porcelain crucibles to be used for LOI
2. Place samples in 50ml test tubes and fill to 40ml with distilled water. Agitate thoroughly and then centrifuge at 3000rpm for 4 minutes
3. Decant off water, transfer samples to porcelain crucibles and place these in an oven to dry.
4. Upon removal from the oven, place samples in a desiccator for 30mins to cool.
5. Record the dry sample weight. This is calculated by subtracting the crucible weight

6. Place samples in a furnace and heat to 550°C. Leave samples in furnace for 4 hours at this temperature.
7. Turn furnace off and wait for it to cool to 150°C before removing samples and placing them in a desiccator for 30 mins to cool further.
8. Record the post-ignition sample + crucible weight
9. The % Organic carbon is calculated as follows:

$$\%OM = \frac{(pre - ignition\ sample\ weight) - (post - ignition\ sample\ weight)}{(pre - ignition\ sample\ weight)} \times 100$$

Appendix 8: Raw LOI Data

Depth (cm)	Dry Sample Weight (g)	Post-Ignition Sample Weight (g)	Total Mass Loss (g)	%Weight Loss On Ignition
0	3.2182	3.0191	0.1991	6.1867
-5	3.4703	3.2591	0.2112	6.0859
-10	2.9845	2.8217	0.1628	5.4549
-15	3.1138	2.942	0.1718	5.5174
-20	3.4651	3.3052	0.1599	4.6146
-25	3.2922	3.0568	0.2354	7.1502
-30	3.7122	3.4615	0.2507	6.7534
-32	3.5554	3.3666	0.1888	5.3102
-35	3.9009	3.7067	0.1942	4.9783
-37	3.7874	3.6786	0.1088	2.8727
-40	3.8207	3.6272	0.1935	5.0645
-45	4.0187	3.8293	0.1894	4.7130
-50	3.8822	3.7098	0.1724	4.4408
-55	3.8688	3.6922	0.1766	4.5647
-60	3.8973	3.7203	0.177	4.5416
-65	3.6161	3.4575	0.1586	4.3859
-70	4.1567	3.9753	0.1814	4.3640
-75	3.2672	3.1144	0.1528	4.6768
-80	3.6593	3.4673	0.192	5.2469
-85	3.4703	3.2403	0.23	6.6277
-90	4.1843	3.9286	0.2557	6.1109
-90	4.0439	3.8062	0.2377	5.8780
-90	3.8365	3.6121	0.2244	5.8491
-95	4.0477	3.8161	0.2316	5.7218
-100	4.3657	3.9044	0.4613	10.5665
-105	2.5599	2.0506	0.5093	19.8953
-110	2.481	1.8873	0.5937	23.9299
-115	2.3277	1.7041	0.6236	26.7904
-120	1.9763	1.2861	0.6902	34.9238
-125	2.1841	1.1513	1.0328	47.2872
-130	1.8105	0.9887	0.8218	45.3908

-135	1.9954	1.2584	0.737	36.9350
-140	2.1835	1.4174	0.7661	35.0859
-145	2.1862	1.5758	0.6104	27.9206
-150	2.4735	1.8828	0.5907	23.8811
-155	2.7511	2.2815	0.4696	17.0695
-160	2.5641	2.0362	0.5279	20.5881
-165	3.2611	2.7671	0.494	15.1483
-170	3.3403	3.0817	0.2586	7.7418
-175	4.4484	4.1203	0.3281	7.3757
-180	3.8469	3.5468	0.3001	7.8011
-180	3.0805	2.8354	0.2451	7.9565
-180	3.3148	3.0613	0.2535	7.6475
-185	3.5312	3.1123	0.4189	11.8628
-190	3.1391	2.5155	0.6236	19.8656
-195	2.8582	2.2369	0.6213	21.7375
-200	2.4574	1.9841	0.4733	19.2602
-205	2.5828	2.1559	0.4269	16.5286
-210	2.7843	2.3993	0.385	13.8275
-215	2.3395	2.0417	0.2978	12.7292

Appendix 9: Taxon scores from Detrended Correspondence Analysis for DCA1 and DCA2

	Species	DCA1	DCA2	DCA3	DCA4
Salt Intolerant	Eunotia praerupta	0.45142731	2.68020575	-0.19108684	1.4068493
	Eunotia solerirolii	0.45706167	2.28145618	1.84753861	0.41046475
	Pinnularia stomatophora	0.77986898	2.82175836	1.96497951	5.50242619
	Pinnularia acrosphaeria	0.40967597	2.85146453	0.50528491	0.58715759
	Pinnularia braunii	1.09398638	2.64465351	1.49424205	2.85102046
	Stauroneis obtusa	-0.03867096	2.30700885	3.22428152	3.26531466
Fresh	Achnanthes inflata	3.2722513	1.62517617	-0.33342136	1.41848497
	Achnanthes saxonica	2.83594756	1.37475625	1.05635166	1.60498237
	Amphora libyca	1.3037664	0.67843237	1.09863341	2.21330348
	Aulacoseira distans	1.90401514	-0.6173755	3.3495362	-0.9261417
	Aulacoseira italica	3.20109601	3.0499769	-0.39623548	0.4952515
	Cocconeis pediculus	2.63320103	0.67952395	1.24179602	0.18579191
	Cocconeis placentula	2.53080065	0.04773794	1.29015	-0.15720477
	C. cuspidata	1.43747768	3.76972663	0.25718803	-0.08902275
	Cymatopleura solea	0.23355418	-1.11793328	0.02103531	0.63353162
	Encyonema minutum	0.02723054	3.13298222	0.75333658	-0.71857007
	Epithenia sorex	2.52641971	0.04969424	-0.59539318	2.14657783
	Eunotia pectinalis	0.28948698	2.94966705	0.30276823	1.29397912
	Gomphonema gracile	2.41383286	1.95762736	0.84459172	2.07196569

	Hantzschia amphioxys	2.3225276	1.82979075	1.12106622	1.22061854
	Navicula dicephala	0.80672974	0.21766338	-1.31657412	2.32229283
	Navicula vulpina	3.10802179	1.08321845	0.61385533	1.16001242
	Neidium affine	-0.05457461	-0.68475188	-1.18060746	2.92801829
	Neidium iridis	1.94598996	1.78766329	1.36930212	2.0307315
	Pinnularia acoricola	1.26957055	2.3848869	1.45001309	3.05271259
	Pinnularia borealis	5.99785975	1.08118551	2.18530831	1.97884466
	Sellaphora pupula	3.43122068	1.59062108	2.39025637	2.16223528
	Stauroneis anceps	1.06928	2.20217322	0.3990115	2.07235664
	Stauroneis frauenfeldiana	-0.09268792	0.0753033	-0.10711796	1.106583
	Stauroneis fulmens	-0.97227135	1.95253585	1.88453592	-0.51134325
	Stauroneis phoenicientron	-0.05636376	1.14140837	0.54546996	1.25487952
	Surirella cf. brebissonii	5.07267107	1.43407102	-0.53908035	0.71819435
	Surirella linearis	-1.62888706	0.07200838	-0.03911387	4.91722278
	Surirella tenera	1.98452319	1.00657628	0.21916936	1.31090691
	Pinnularia divergens	-0.06859103	-0.37450892	1.48597405	2.3115604
	Pinnularia gibba/maior	0.34999517	1.30056207	1.93877306	-0.51842178
	Pinnularia obscura	-0.03431946	-0.95853402	-2.06611318	3.17665845
	Ulnaria ulna	1.22898419	-0.23163356	0.60851948	0.61059625
Fresh-Brackish	Amphora veneta	5.38831573	1.29906611	-2.09331024	0.0947008
	Cosmioneis pusilla	1.74717705	0.64847154	0.32160406	0.90110231
	Diploneis subovalis	5.33122537	1.28155238	-0.66795814	0.20354463
	Luticola mutica	5.11725608	1.1296784	2.12620041	2.15838749
	Navicula cf. placentula	4.53950402	1.52784288	2.33519673	2.19424727
Brackish	Campylodiscus echeneis	5.40164548	1.1321181	2.24497783	1.98163834
	Nitzschia sigma	5.21906652	1.15871482	1.98554287	1.90463031
	Rhopalodia acuminata	2.85602018	1.41430322	1.03017885	1.33298496
	Rhopalodia brebissonii	5.57856668	1.22588037	1.91064932	0.84968969
	Tryblionella acuminata	5.37501289	1.27201302	-0.11321065	1.26552936
Brackish-Marine	Diploneis smithii	1.5674086	-0.10333402	1.43978026	0.0809511
	Paralia sulcata	4.8065482	1.25691357	0.59115726	1.25644162
	Tabularia cf. fasiculata	4.09403186	1.29256236	0.16042642	1.24670666
	Gyrosigma cf. targidum	4.2988111	1.15401949	1.34859638	1.13957459
	Rhopalodia musculus	4.88901313	0.89085397	2.81503916	2.13518801
Marine	Actinoptychus senarius	3.6160838	1.42960503	-0.1948255	0.01095961
	Actinoptychus splendens	4.86305327	1.32160088	-0.35186148	0.01361328
	Berkeleya scopulorum	4.36260017	1.11023335	1.20070035	0.45356983
	Cymatosira belgica	5.84557622	1.02120155	2.56569194	2.65690034
	Delphineis cf. surirella	5.13823227	1.42151394	-0.33576209	2.25731092
	Dictyocha fibula	5.93903563	1.08766265	2.43788004	2.82104716
	Distephanus speculum	5.28331099	1.66574141	-2.69240746	-4.09350483
	Diploneis weisfloggii	2.86002318	-0.03316314	0.30424096	-1.06880774

	Nitzschia cf. panduriformis	4.02319753	1.22869198	0.21247995	1.41899219
	Parlibeluss cf. plicatus	5.59164727	1.27114705	0.88414827	0.51209854
	Pinnularia schoederii	5.51382948	1.38000395	-0.92259152	-0.15455346
	Pinnularia stauntonii	5.53532667	1.21734239	1.51900296	1.22310349
	Podosira cf. stelligera	5.55585807	1.45380464	-1.67670324	-1.38053672
	Pseudopodosira sp.	5.58322653	1.33471991	0.65632065	0.71217199
	Rhaphoneis amphiceros	4.53106452	1.16062386	1.46512261	1.45102926
	Thalassiosira cf. eccentrica	4.4460895	1.17877713	1.51608272	1.69741529
	Thalassiosira cf. oestruppii	5.00830925	1.22152789	1.33264241	1.52558634
	Thalassiosira weisfloggii	5.54620231	1.22280097	1.76065496	1.27309248
	Thalassiosira spp.	3.91448978	1.1602599	0.68873476	1.20240679
	Trachyneis aspera	4.36260017	1.11023335	1.20070035	0.45356983
	Triceratium alternans	5.25037632	1.46729265	-1.9072802	-1.78606279
	Triceratium cf. favus	5.22724075	1.47830274	-0.75723587	2.14017614
	Triceratium cf. spinosum	5.22724075	1.47830274	-0.75723587	2.14017614
	Tryblionella granulata	4.75402608	1.10352716	2.31915305	1.99477313
	Tryblionella cf. levidensis	3.81309425	1.1994912	0.43351235	1.2556178
	Tryblionella punctata	4.64167094	1.23413606	0.32000953	1.548487