Volcanic ash in Holocene valley deposits and its chronostratigraphic implication, Banks Peninsula, Canterbury, New Zealand.

Judith L. van Dijk

November 2011

Universiteit Utrecht
Faculty of Geosciences

Lincoln University
Te Whare Wānaka o Aoraki
CHRISTCHURCH•NEW ZEALAND
New Zealand's specialist land-based university

“Volcanic ash in Holocene valley deposits and its chronostratigraphic implication, Banks Peninsula, Canterbury, New Zealand.”

MSc Thesis

In order of completion of the MSc Research programme “Physical Geography” at Utrecht University, The Netherlands. In corporation with Lincoln University, New Zealand

Judith Louise van Dijk

June 2010 – November 2011

Supervisors:

Dr Wim Z. Hoek

Department of Physical Geography, Utrecht University, NL

Dr Peter C. Almond

Department of Soil & Physical Sciences, Lincoln University, NZ

Contents

List of figures

List of tables

Preface

This thesis reports on my MSc Research. This research is carried out as part of the Master Programme "Physical Geography" that I have followed at Utrecht University (UU), The Netherlands. Within this programme an MSc Research exists of three parts: the MSc Research preparation, the MSc Research and the MSc Thesis.

In the preparation I have written a research proposal: *"The study of volcanic ash in a buried peat layer, presumably of Holocene age, Banks Peninsula, Canterbury, New Zealand"* (JUNE 2010) and a literature review: *"The methodology and implication of tephrostratigraphy in the palaeoclimatic reconstruction of New Zealand"* (FEBRUARY 2011).

The research part took place in New Zealand, where I did fieldwork on Banks Peninsula and carried out most of the laboratory and analytical work while based at Lincoln University (LU), Canterbury, New Zealand. Part of the analytical work is carried in collaboration with Victoria University, Wellington and GNS Science, Lower Hutt. Supervision of the research is by Dr. Peter C. Almond (LU) and Dr. Wim Z. Hoek (UU).

The literature review and research proposal describe previously carried out research on the topic, and the aims and objectives for this project. During the research part the aims and objectives slightly changed, new information came to light and opportunities for other analyses were created. The results are not quite as expected (or as hoped), but are nevertheless very interesting and show that much more research is necessary to fully comprehend the Quaternary history of the area.

I hereby want to thank my supervisors and the people from Lincoln University, Victoria University, Utrecht University and GNS Science for helping me, and for creating the possibilities that have made this research into what it is.

The results of this research have been presented in the form of a poster at INQUA 2011 in Bern, Switzerland.

Judith van Dijk, November 2011

Abstract

Two peaks of volcanic glass are found in Motukarara Valley, an enclosed valley on the western flanks of Banks Peninsula, Canterbury, New Zealand. The age and provenance of this tephra needed to be determined as only one Late Quaternary tephra was known to be present in South Island, New Zealand. This is the Kawakawa Tephra of 25.45 cal ka BP (Vandergoes et al., 2011). The presence of other primary airfall tephra in the study area, and thus South Island, could have major implications for correlation, validation of dating, chronostratigraphy and the understanding of geomorphic processes based on Kawakawa Tephra. This thesis reports on the results of the tephra research and the accompanying environmental analysis that are used to identify the cryptotephra and to reconstruct the depositional environment and a chronology for Motukarara Valley.

1 Introduction

1.1 The research

On the foothills of Banks Peninsula, Canterbury, New Zealand (NZ), two records have been taken from deposits in the enclosed Motukarara Valley, just north of the village of Motukarara (Figure 1.1). The first record was taken in 1984 and radiocarbon dates reveal that peat in the valley is of Holocene age, samples taken from the open core over three depth increments (top 32 cm, middle 44 cm and bottom 12 cm) revealed the presence of volcanic glass.

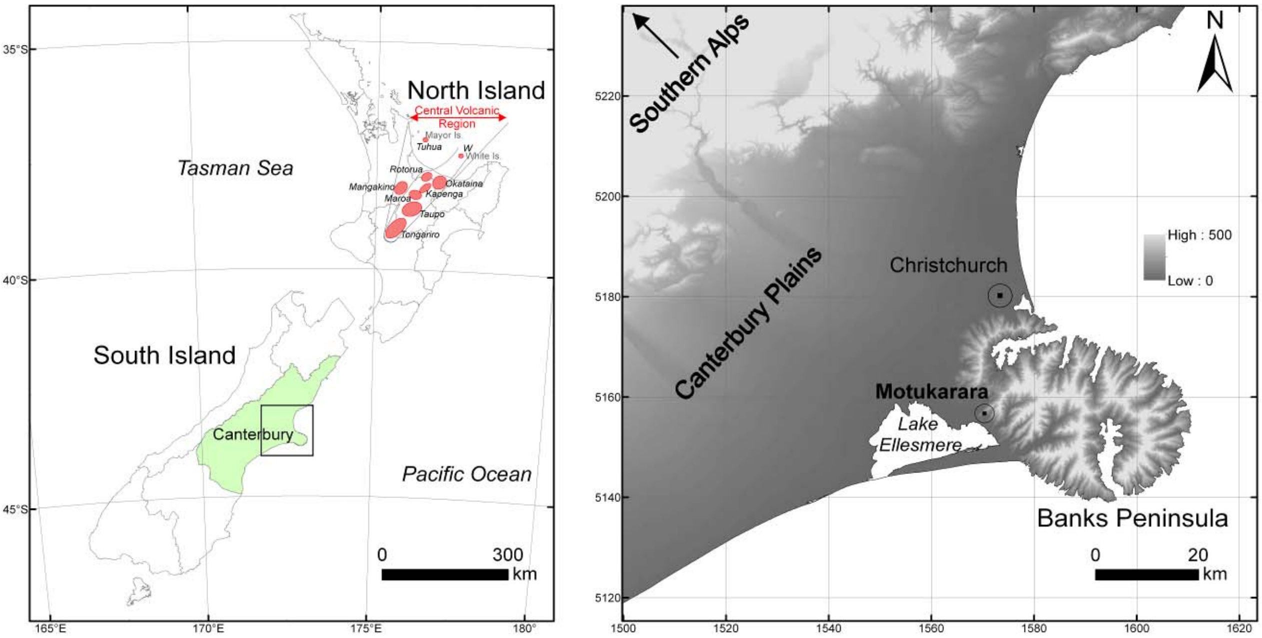


Figure 1.1: Map of New Zealand, with the location of Motukarara, Canterbury, New Zealand on Banks Peninsula in South Island, and also the location of the Central Volcanic Region in North Island.

The presence of this tephra needs to be confirmed and, subsequently, the origin and age have to be determined. If this concentration represents a primary airfall deposit then it has major implications for interpretation of other cryptotephra occurrences in South Island, NZ, where only Kawakawa Tephra (25.45 cal ka BP; Vandergoes et al., 2011) is known to be present. If other Late Quaternary primary airfall tephra deposits are present in South Island, it does not only have implications in creating a better potential in correlation and validation of dating, but also in chronostratigraphy, loess stratigraphy and accumulation rates and understanding of other geomorphic processes and their rates.

Based on previous tephra studies it seems only logical that more than one volcanic ash cloud, most likely of some of the many eruptive events in North Island, has reached South Island. Therefore more tephra deposits are likely to be present in calm depositional environments, such as peat swamp, bogs or lakes. This is the first study in South Island that aims to confirm the presence of primary airfall Holocene tephra and determine its age and provenance. The main research question is:

How does the volcanic ash, present in the valley deposits, fit into the Late Quaternary stratigraphy of South Island, New Zealand?

To answer this question several aims and objectives have been put together to use the analysis of the old core (Core 1984) and combine those unpublished results with the results of relevant analysis on a new core (Core 2011).

1.2 Aims and objectives

The aims of the research are:

- To determine whether primary airfall tephra exists at the study site, and if so, to determine its provenance and age and to correlate it to a volcanic eruption, presumably from the North Island.
- To reconstruct a chronology for the depositional environment in the study area.

These aims are achieved through the following objectives:

- Characterise the depositional environment of the valley and its deposits.
- Quantify the distribution of volcanic glass grains within these deposits.
- Chemically characterise the volcanic glass grains and correlate them to known volcanic deposits.
- Construct a chronology for the depositional events at the study site.

A lithological survey has been carried out to create two cross sections through the valley deposits and determine the best sample location. Analyses carried out on the sampled core include quantitative cryptotephric analysis to create a concentration profile of volcanic glass grains within the record, pollen, diatom and plant macrofossil analysis to characterise the depositional environment. Additionally, measurements of moisture and carbon content and pH and EC are carried out. Volcanic glass grains are chemically identified using electron microprobe analysis. And five samples of Core 2011 have been submitted for radiocarbon dating to reconstruct an age model.

1.3 Outline of thesis

This thesis starts with a literature review on tephrology and its implication in New Zealand (chapter 2) and a climatic reconstruction for New Zealand (chapter 3). The focus is on the Late Glacial and the Holocene before human arrival; a geological timeframe based on radiocarbon dates on Core 1984.

Chapter 4 contains a detailed description of the geological and geomorphological setting of the study area on Banks Peninsula. This is followed by a chapter (5) on methods, which is structured based on the series of objectives from paragraph 1.2. Chapter 6 gives the results of the environmental research and the tephra research respectively.

Chapter 7 interprets and discusses the results. It discusses the reliability of methods and results, the explanation of unexpected results and possibilities for further research. Furthermore, it gives a chronology for the deposits in Motukarara Valley based on a series of palaeogeographical maps. The conclusion (chapter 8) attempts to answer the main research question (paragraph 1.1).

2 Tephrology in New Zealand

2.1 Introduction

Tephrology is a widely applied technique in which volcanic ash layers are identified and used to correlate between records. An example project in which tephrostratigraphy is used is INTIMATE. INTIMATE is a core-project in the INQUA Palaeoclimate Commission. It focuses on the INTegration of Ice-core, MArine and TErrestrial climate records. The aim of this project is to determine nature, timing and extent of climate changes and events related to the transition from the Last Glacial to the Holocene. It now extends from 30 ka to 8 ka (Lowe et al., 2008). It is aimed to obtain higher resolution for palaeoclimatic records and a better calibration model for radiocarbon dates (Björck et al., 1998; Walker et al., 1999; Lowe & Walker, 2000; Turney et al., 2004). Key records within existing records have been identified and new records are added (Alloway et al., 2005; 2007; Shulmeister et al., 2006; Turney et al., 2006). Its first focus was on the North Atlantic region (more reading: Lowe, 2001; Lowe et al., 2001, 2008; Walker, 2001; Walker et al., 2001; Bogaard & Schmincke, 2002; Davies et al., 2002; Turney et al., 2004, 2006; Wastegård, 2005; Blockley et al., 2007, 2008; Hoek et al., 2008; Wastegård & Davies, 2009).

An extension of this project is the Australasian INTIMATE, consisting of an Australian (OZ) and New Zealand (NZ) INTIMATE. The role of tephra in NZ-INTIMATE so far is that all palaeoclimatic records presently identified within the project (apart from speleothems) are linked by one or more tephra layers (Barrell et al., 2005).

Here a brief overview of tephrology and its general implication will be given. . This is followed by a detailed description of the application of tephrostratigraphy in New Zealand. For more detailed reviews see: Sarna-Wojcicki, 2000; Shane, 2000; Turney & Lowe, 2001; Dugmore et al., 2004; Turney et al., 2004; Alloway et al., 2007; Lowe 2011.

2.2 The study of tephra

Tephrology literally means “the study of tephra”. Tephra refers to all loose, unconsolidated, pyroclastic deposits resulting from a volcanic event, including: airfall deposits, deposits from pyroclastic flows or surges, co-ignimbrite ash, deposits generated under water or ice and deposits that are created through explosions as a result of the interaction of hot lava with water. In this research the focus is on cryptotephra: tephra that are invisible to the naked eye and require analysis by microscopy (Lowe & Hunt, 2001).

The study of series of tephra layers and related deposits, including relative dating, definition, description, characterization and identification of tephra layers to provide a tool in correlation between different depositional records is correctly called tephrostratigraphy. It includes both tephrochronology and tephrochronometry. Tephrochronology is the use of tephra deposits as time-stratigraphic marker beds or chronohorizons and tephrochronometry is the determination of a numerical age of a tephra deposit (Lowe & Hunt, 2001). Stratigraphy is the interpretation of rock or sediment successions as sequences of events in the geological past by dividing the record into units (Hedberg, 1976).

Tephrology is not just applicable in stratigraphic and chronological research, but also in other geoscientific fields of research, such as volcanology, palaeoenvironmental research, soil science and archaeology (Lowe & Hunt, 2001). For example, tephrostratigraphical records provide information on evolution of geochemistry and eruption frequency in both time and space (e.g. Shane, 2000; 2005; Carter et al., 2003), which provides information for volcanic hazard prediction and risk management (among others: Shane & Hoverd, 2002; Hurst & Smith, 2004; 2010; Jenkins et al., 2007; Turner et al., 2008; 2009; Lindsay et al., 2009).

Tephra deposits can be used in linking, dating and synchronizing between records. Even if they are not (yet) dated correctly or precisely, their role as a chronohorizons still applies (Lowe, 2011). Tephra is unique in providing isochronous stratigraphic marker beds for three reasons (Lowe & Hunt, 2001).

1. First, the deposit of a tephra layer is restricted to a relatively short timeframe, relative to the geological timescale. Eruption and deposition typically lasts for just hours or days, sometimes up to weeks or months (among others: Christiansen & Peterson, 1981; Zielinski et al., 1994; Carter et al., 1995; Carey, 1997; Miller & Casadevall, 2000; Manville & Wilson, 2004; Rose & Durant, 2009; Lowe, 2011)

2. Secondly, tephra deposits can be widespread, and therefore be present in marine, terrestrial and ice-core records. A couple of examples of how widespread tephra can be: Hekla tephra from Iceland, 1947AD, was found up to approximately 3800 km from its source (Walker, 1981). Tephra from eruptions in Alaska (Mt Spurr, 1992AD and Klyuchevskoy, 1994AD) reached over 5000 km (Schneider et al., 1995; Miller & Casadevall, 2000; Rose et al., 2001). The more recent eruption on Iceland, Eyjafjöll in 2010, covered distances up to 8000 km (Davies et al., 2010). El Chichón in Mexico in 1982 up to 10,000 km (Zielinski et al., 1997). Tephra from Huaynaputina, Peru, 1600AD and from Krakatau and Agung, Indonesia, resp. 1883 and 1963AD was found at distances up to 12,000 km (De Silva & Zielinski, 1998; Laluraj et al., 2009). The latest big eruption was the

eruption of the Puyehue volcano, Chile, in June 2011. Ash of this eruption has travelled over the South Atlantic and Indian Ocean and reached Australia and New Zealand (bbc.co.uk/news).

Older tephra have so far only been found in less distal areas. Vedde Ash from Germany, dated to 12.1 ka cal BP is found in the Greenland NGRIP ice core, in North Atlantic marine sediments and in terrestrial records in northern, eastern and central Europe and has travelled up to approximately 2500 km (among others: Blockley et al., 2007; Davies et al., 2010). A similar tephra in New Zealand is the Kawakawa Tephra, dated to 25.45 ka cal BP (Vandergoes et al., 2011), and found throughout New Zealand and the southwest Pacific Ocean up to distances of 1500 km (among others: Newnham et al., 2007a; Lowe et al., 2008; 2010; Holt et al., 2010).

3. Third, tephra from different centres have a different geochemical composition, often unique for every eruption or period of eruptions. The identification of a cryptotephra layer to a volcanic source, eruptive event or period of events can be done based on several characteristics: chemical composition, stratigraphic position, the age of related sediments and the size and shape of the shards (Schaetzl & Anderson, 2005). The chemical composition of glass shards, also known as the chemical fingerprint is the most important one. It can be enough to assign a tephra to a single eruptive event. However, subsequent eruptions from the same volcanic centre can produce a series of ash layers that have very similar composition (Lowe & Walker, 1997), which only allows the assignment to a period of eruptive events. Erosion or dissolution of diagnostic minerals can change the relative chemical composition and can therefore lead to misidentification (Lowe, 1988; Hodder et al., 1991). The same problem may arise with distal tephra, as heavier minerals might drop out from the volcanic ash cloud closer to the source than lighter minerals (Lowe et al., 2008).

   The chemical composition of tephra can be derived through various methods (Table 2.1). Statistical tools, such as bi-plots or canonical discriminant function analysis (DFA) can make compositionally similar tephra distinguishable (Stokes et al., 1992; Cronin et al., 1997; Lowe et al., 2008; Lowe, 2011). In this research EMPA is used. For more information on the other methods read Lowe et al. (2008).

   EMPA is a widely applied technique and is used to determine the major element composition of individual glass shards. Previously applied methods often made use of bulk samples. Bulk samples may include material other than the glass shards, which may affect the results of the chemical composition (Shane, 2000; Lowe, 2011).

Dating of tephra in relatively young material (up to approximately 40 kyr) can be done through radiocarbon dating of associated organics. In older material methods such as K/Ar fission track dating, thermoluminescence (TL) or optical stimulated luminescence (OSL) can be used (Lowe & Walker, 1997). Furthermore, correlation can be used as an indirect dating tool between a dated and non-dated record, that both contain tephra with the same chemical fingerprint.

If more than one dated tephra is present in a record, correlation can lead to a detailed age-model for the record. If tephra from different sources overlap this can be used to establish interrelationships between these different sources and provide a stratigraphic recording of eruptions from multiple volcanic sources, which can aid in narrowing down ages for tephra and events coinciding with the deposit. Tephrostratigraphy than even has the potential to enable timing in leads and lags (Lowe, 1988; 2008; 2011; Lowe et al., 1999; Shane & Hoverd, 2002; Shane et al., 2002; 2006; Molloy et al., 2009; Kuehn & Negrini, 2010).

Table 2.1: Summary of main methods in chemically characterizing tephra (after Lowe et al., 2008; 2011).

Tephra components and properties	Methods of analysis
Glass shards or selvedges	
Major elements	Electron microprobe
Rare-earth and trace elements	Laser-ablation or solution nebulisation inductively-coupled plasma mass spectrometry; Instrumental neutron activation analysis; Spark source mass spectrometry; Secondary ionization mass spectrometry
Shard morphology	Optical microscopy; Scanning electron microscopy
Fe-Ti oxides	
Major and minor elements in crystals	Electron microprobe; Mössbauer spectroscopy
Eruption temperatures and oxygen fugacites	Electron microprobe
Ferromagnesian minerals	
Assemblages	Petrographic microscopy
Pyroxenes, amphiboles, olivine, biotite crystals	Electron microprobe
Feldspars	
Anorthite content of plagioclase crystals	Electron microprobe
Statistical analysis of compositional data	Bi-plots; Canonical analysis; Discriminant function analysis; Cluster analysis

Problems in using tephra as chronohorizons might occur when tephra is moved post-depositionally. In tephrostratigraphy it should always be taken into account that not all tephra is necessarily a primary airfall deposit. Only primary airfall tephra can be used as a chronohorizon. Ideally, the indirect age given to a deposit based on the geochemical fingerprint of the present tephra should be tested by dating the deposits in which the tephra is present. Sometimes the concentration profile can provide information on this problem as well (Froggatt & Lowe, 1990; Lowe et al., 2008).

Within an intact (or untouched) tephra layer the vertical distribution of glass shards is often asymmetrical. Concentrations often show an upward tailing-off profile above the initial, primary deposition (Eden et al., 1992). An intact base can be interpreted as an isochronous surface and is of importance in tephrostratigraphy (Froggatt & Lowe, 1990). Different processes can disturb the concentration profile, such as soil mixing processes and erosion and deposition. This could lead to the presence of a relatively old tephra in younger deposits and vice versa (Carter et al., 1990). This has been recorded in many sediment and soil types (Eden et al., 1992). Relatively high rates of post-depositional movements have been recorded in peat deposits. Experimental studies have shown movement of glass shards of up to 6 cm down in 2 years time and movement of the concentration peak up to 1.5 cm within 18 months. These dislocations can lead to remarkable errors if misinterpreted as isochrones, as peat formation can be a slow process with sometimes only 1.5 cm of peat representing 100 yrs (Payne & Gehrels, 2010).

An indicator for tephra not being primary airfall, but redeposited older tephra could be the presence of unexpected peaks in for example mineral influx, grain size or pollen assemblages. The process of erosion and redeposition would include all material related to the initial tephra deposit. Misinterpretation of redeposited tephra as primary airfall may lead to wrong assumptions about the age of the sediments and inferred rates for deposition and other geomorphic processes (Boygle, 1999; Dugmore et al., 2004; Gehrels et al., 2006; Shane et al., 2006; Payne & Gehrels, 2010). This process of post-depositional movement has been recorded in several different sediment and soil types (Eden et al., 1992).

2.3 Tephrostratigraphy in New Zealand

In New Zealand volcanic activity during the Late Quaternary is restricted to the Central Volcanic Region (CVR), North Island (Froggatt & Lowe, 1990; Figure 1.1). Before that, volcanic activity occurred both on North and South Island. Volcanic activity in North Island has occurred at least since the Early Quaternary and is associated with the convergence and westward subduction of the Pacific plate beneath the North Island (Ballance, 1976). In South Island there was volcanic activity in the Miocene at what is presently known as Banks Peninsula, with the last eruptions around 6 Ma BP (Weaver et al., 1985) and at the Dunedin Volcanic Centre, with the last eruptions around 10 Ma BP (Coombs, 1965). And in the Early Pleistocene the Timaru basalts formed, the last eruption from Mt Horrible was 2 Ma yr BP ago (Duggan & Raey, 1986).

Many Late Quaternary tephra formations, originating from the CVR, are used as stratigraphic markers in NZ and are therefore well documented on (among others: Froggatt & Lowe, 1990; Alloway et al., 2007; Lowe et al., 2008). Reconstructions of a climate event stratigraphy for New

Zealand are based on a series of 22 key marker tephra for the last 30,000 yrs (Table 2.2; Alloway et al., 2007; Newnham et al., 2007b; Wilmshurst et al., 2007; Lowe et al., 2008). These 22 tephra are chosen to be the most useful marker beds, based on 3 criteria (Lowe et al., 2008):

1. They are most widespread.
2. They occupy a stratigraphic position that supports regional correlations.
3. They are exceptionally distinctive in composition.

These 22 key marker tephras in particular have been used to aid chronology and provide onshore-offshore correlations for shallow-marine cyclothems (Pillans, 1991, 1994; Alloway et al., 1992, 2005). There have however been many more eruptions. For example, Wilson (1993) described 25 tephra units (Unit B to Z) erupted from Taupo Volcanic Zone since the Late Glacial/Early Holocene (Table 2.3). Some of these units have been correlated to the key marker beds described above. The distribution of these tephra is only established up to 100 km around the volcanic centre.

To distinguish between tephra, determination of the relative abundances of ferromagnesian minerals typically is enough to give the volcanic source and sometimes the eruption (Froggatt & Lowe, 1990; Shane et al., 2003). Tephra formations younger than 30,000 cal. yrs BP, originating from TVC, are dominated by orthopyroxene. OVC-tephra are dominated by biotite, hornblende, cummingtonite or orthopyroxene. Deposits from TuVC are unique in containing sodic phases such as aegerine. And tephra from ToVC is relatively rich in both orthopyroxene and clinopyroxene (Lowe et al., 2008). Furthermore the compositions of pyroxene, amphibole and olivine can be used to identify the volcanic centre and sometimes the individual tephra. For example: olivine in TgVC-tephra is relatively rich in magnesium; whereas olivine from TuVC is richer in iron (Lowe, 1988). Shifts in the characteristics for each volcanic centre can occur, for example at OVC, where shifts in the ratio between ironoxides and magnesiumoxides have been recorded (Shane et al., 2003).

In New Zealand tephrostratigraphy has mainly been applied in North Island, in close proximity to the CVR (Froggatt& Lowe, 1990). So far only two Quaternary tephra have been identified in South Island: the Early Quaternary Rangitawa/Mt Curl tephra (350 ka; Milne, 1973; Eden et al., 1992; Pillans et al., 1996) and the Late Quaternary Kawakawa/Oruanui tephra (KOT; Froggatt & Lowe, 1990; Lowe et al., 2008).

Table 2.2: New Zealand stratigraphical tephra marker beds for the last 30,000 yrs: name, source, age, coinciding climate events and geochemistry (after: Lowe et al., 2008).

Tephra name	Source [1]	Age (cal. yr BP ±2σ)	References for age	Coinciding climate event [2]	Ferromagnesian minerals (relative) [3]	References for geochemistry, proximal stratigraphy and isopach maps
Kaharoa	OVC	636 ± 12	Hogg et al. (2003)	LHWE	T1: Bio » Hbe » Cgt ± Opx T2: Bio » Cgt › Hbe ± Opx	Nairn (1989, 2002); Nairn et al. (2001); Shane et al. (2008)
Taupo	TVC	1717 ± 13	Sparks et al. (1995, 2008)	End of MHCV	Opx » Cpx	Wilson & Walker (1985); Wilson (1993)
Whakaipo	TVC	2760 ± 20	Froggatt & Lowe (1990)		Opx	Wilson (1993)
Waimihia	TVC	3410 ± 40	Hajdas et al. (2006)		Opx » Hbe	Wilson (1993)
Unit K	TVC	5120 ± 150	Hajdas et al. (2006)		Opx	Wilson (1993)
Whakatane	OVC	5530 ± 60	Hajdas et al. (2006)		T1 + T2: Hbe › Cgt › Opx T3: Opx › Hbe › Cgt	Nairn (2002); Kobayashi et al. (2005); Smith et al. (2006); Shane et al. (2008)
Tuhua	TuVC	7005 ± 155	Hajdas et al. (2006)	Just before MHCV	Aeg › Cpx › Opx ± Aen ± Rie ± Hbe ± Olv(fa) ± Tuh	Houghton et al. (1992); Manighetti et al. (2003)
Mamaku	OVC	8005 ± 45	Hajdas et al. (2006)		Hbe › Opx » ± Cgt	Nairn (2002); Smith et al. (2006)
Rotoma	OVC	9505 ± 25	Hajdas et al. (2006)		T1: Cgt › Hbe › Opx T2: Hbe › Opx › Cgt T3: Opx › Hbe › Cgt	Nairn (2002); Smith et al. (2006)
Opepe	TVC	10,075 ± 155	Hajdas et al. (2006)		Opx » Cpx	Wilson (1993)
Poronui	TVC	11,190 ± 80	Hajdas et al. (2006)	Start EHW	Opx » Cpx	Wilson (1993)
Karapiti	TVC	11,410 ± 190	Hajdas et al. (2006)	Start EHW	Opx » Cpx + Hbe	Lowe (1988); Wilson (1993); Donoghue et al. (1999); Lowe et al. (1999)
Okupata	TgVC	11, 620 ± 190	Hajdas et al. (2006)	Early start EHW	Opx › Cpx » ± Olv (fo) ± Hbe	Donoghue et al. (1995, 1999, 2007)
Konini	EVC	11,720 ± 220	Hajdas et al. (2006)	Early start EHW	Hbe › Cpx » ± Opx	Lowe (1988); Alloway et al. (1995); Lowe et al. (1999)
Waiohau	OVC	13,635 ± 165	Hajdas et al. (2006)	End of LGWP	Opx › Hbe	Nairn (1989, 2002); Speed et al. (2002); Shane et al. (2008)
Rotorua	OVC	15,425 ± 325	Hajdas et al. (2006)	Strong warming	T1: Opx › Hbe » Cpx T2: Bio › Hbe » Opx	Nairn (2002); Smith et al. (2004); Shane et al. (2008)
Rerewhakaaitu	OVC	17,625 ± 425	Hajdas et al. (2006)	Start of LGIT	T1 + T3: Opx › Hbe T2: Opx + Hbe » Cgt	Nairn (1989, 2002); Newnham et al. (2003); Darragh et al. (2006); Shane et al. (2008)
Okareka	OVC	21,800 ± 500	Reimer et al. (2004)	Just below LGCP	T1: Opx + Hbe » Cgt T2: Hbe + Bio » Opx T3: Opx › Hbe	Nairn (1989, 1992, 2002); Darragh et al. (2006); Shane et al. (2008)
Te Rere	OVC	25,271 ± 779	Reimer et al. (2004)	Just below LGCP	T1 + T3: Opx + Hbe T2: Opx + Hbe + Bio › Cpx	Nairn (1992, 2002)
Kawakawa	TVC	25,454 ± 433	Vandergoes et al. (2011)	Just after LGM	Opx › Hbe	Wilson (2001); Manville & Wilson (2004); Wilson et al. (2006)
Poihipi	TVC	28,181 ± 383	Hughen et al. (2006)	Start of LGCP	Opx › Hbe › Bio	
Okaia	TVC	30,092 ± 340	Hughen et al. (2006)	Start of LGCP	Opx › Hbe	Vucetich & Howarth (1976)

[1] EVC: Egmont Volcanic Centre; OVC: Okataina Volcanic Centre; TVC: Taupo Volcanic Centre; TgVC: Tongariro Volcanic Centre; TuVC: Tuhua Volcanic Centre.

[2] LGCP: Last Glacial Cold Period (28-18.5 cal ka); LGM: Last Glacial Maximum (29-26 cal ka); LGIT: Last Glacial Interglacial Transition (18.5 11.6 cal ka); LGWP: Last Glacial Warm Period (18.5-13.5); EHW: Early Holocene Warming (11.6-6.5 cal ka); MHCV: Mid Holocene Cooling and Variability (after 6.5 cal ka); LHWE: Late Holocene Warming Event (900-500 yr BP); after Alloway et al. (2007).

[3] Opx: Orthopyroxene; Cpx: Clinopyroxene; Hbe: Hornblende; Cgt: Cummingtonite; Bio: Biotite; Aeg: Aegirine; Aen: Aenigmatite; Rie: riebekite; Olv: Olivine (fa: fayalite; fo: forsterite); Tuh: Tuhualite.

Table 2.3: Series of eruptions from Taupo Volcanic Zone as recorded, by Wilson (1993). Ages by Froggatt & Lowe (1990) and Wilson (1993).

Unit	Correlated key marker bed (Table 2.2)	Age (^{14}C yrs BP)	Age (cal yrs BP)
Z			1740
Y	Taupo Tephra	1850	1770
X		2150	2150
W		2650	2750
V	Whakaipo Tephra	2700	2800
U		2750	2850
T		3000	3200
S	Waimihia Tephra	3300	3550
R		3950	4450
Q		4050	4550
P		4100	4750
O		4150	4800
N		4200	4850
M		4500	5250
L		4550	5300
K	Unit K	4600	5350
J		4620	5370
I		5200	5950
H		5300	6050
G		5800	6650
F		6150	7050
E	Opepe	9050	9950
D		9780	11380
C	Poronui	9800	11400
B	Karapiti	10100	11800

The KOT originates from the Kawakawa or Oruanui eruption of the Taupo volcano in the Taupo Volcanic Zone and is found at a distance of up to 1500km of its source and is relatively widespread in a southern direction (among others: Newnham et al., 2007b; Lowe et al., 2008; 2010; Holt et al., 2010; Figure 2.1). For comparison, Rerewhakaaitu, Waimihia and Taupo tephra are presently only known to have reached a distance of 500 to 650 km and are most widespread, like most other NZ-tephra in a eastern direction (Froggatt & Lowe, 1990). The age of KOT has been used to infer loess accretion, soil transport and erosion rates (Roering et al., 2002; Eden & Hammond, 2003; Almond et al., 2007). The KOT is dated several times and derived ages range from approximately 17 ka to 31 ka BP (among others: Wilson et al., 1988; Froggatt & Lowe, 1990; Berger et al., 1994; Fairbanks et al., 2005; Lowe et al., 2008; Grapes et al., 2010). In this study an age of 25.45 cal ka BP is accepted, this is an actively-weighted pooled mean age from 8 radiocarbon dates from carbonised wood and wood fragments within and below the tephra (Vandergoes et al., 2011). Previously accepted was an age of 27.1 cal ka BP, based on radiocarbon dates from four carbonised branches at separate sites within ignimbrite (Lowe et al., 2008).

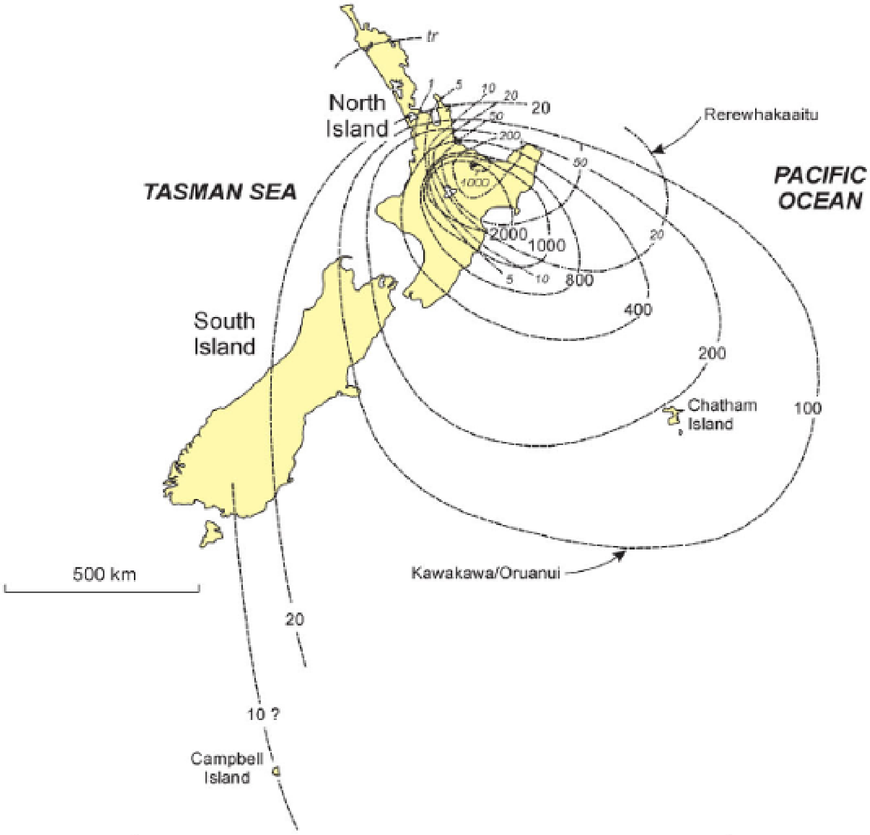


Figure 2.1: Isopach maps of Kawakawa and Rerewhakaaitu tephra, Taupo Volcanic Centre (Wilson, 2001; Newnham et al., 2003; Lowe et al., 2008; Alloway et al., 2002).

Loess deposits can cover many geomorphological features, such as glacial deposits, river terraces, marine benches and is present in soils anywhere downwind of loess sources (such as river floodplains). Loess stratigraphy is used as a climate proxy, assuming loess deposition during cold periods and soil formation during warmer periods, to infer mass accumulation rates and in dating land surfaces (Bruce, 1973; McIntosh et al, 1990; Eden et al., 1992; Almond, 1996; Almond & Tonkin, 1999; Berger et al., 2001; Eden & Hammond, 2003).

In South Island results of radiocarbon and luminescence dating on loess have proven to be poor, KOT provides the only basis for regional correlation of loess sheets in South Island. Also, the presence of KOT within deposits plays a key role in correlated dating of LGM-deposits in New Zealand (Suggate, 1990; Suggate & Almond, 2005). Vegetation records support an extended LGM ranging from 29 to 19 ka, with three cold periods from 29 to 26 ka and 24.5 to 22 ka and 20 to 19 ka (Newnham et al., 2007a). KOT is deposited in between the first two cold periods. The presence of KOT in loess coverbeds and soils on top of moraines provides a minimum age.

The presence of other tephra might provide a useful tool for more distal correlation (Eden et al., 1992; Eden & Hammond, 2003). KOT is found in loess deposits at several locations in South Island. In some places it is geochemically analysed and identified as KOT (Eden et al., 1992; Wilson, 2001; Hughes et al., 2009). In other places it is assumed to be KOT as it is the only tephra known to be present in SI (Almond, 1996; Roering et al, 2004; Almond et al., 2008). The age of KOT has sometimes led to age reversals within stratigraphic sequences (Suggate & Almond, 2005; Almond et al., 2007). Also, tephra with a geochemical composition similar to KOT sometimes occurs in more than one concentration peak in the same record. For example Carter et al. (1995) find two concentration peaks of tephra with a KOT-signature in a loess deposit.

These age reversals and multiple concentration peaks could mean that other tephra layers are present in South Island, which may or may not have a similar geochemical composition as KOT. The age reversals can also be explained by post-depositional movement of older tephra through erosion and redeposition or through lateral movement (upwards and downwards) by biogenic processes (Hughes, 2008; Payne & Gehrels, 2010). Post-depositional movement causes the problem of indicating the stratigraphic position of the initial, primary tephra deposition which can be used as an isochron (Eden et al., 1992).

3 Late Glacial and Holocene climate in New Zealand

3.1 Introduction to Quaternary climate reconstruction

Quaternary climate reconstruction makes use of many techniques. In this research environmental reconstruction is based on an integration of lithology, pollen, diatom and plant macrofossil data.

Lithological data gives information on changes in the depositional environment, for example, fluvial, lake and landslide deposits can be distinguished based on average grain size, sorting and rounding and sedimentary structures. Lithological data is used in the interpretation of most climatic records and is very useful in classification of a record into several units, events or periods (Lowe & Walker, 1997).

Palynological (or pollen) analysis is used to correlate Quaternary stratigraphic units, to reconstruct vegetation history and to determine the influence of anthropogenic activities on vegetation and landscape (Huntley & Birks, 1983; Behre, 1986; Delcourt & Delcourt, 1991). By using present vegetation patterns and modern analogue techniques it is made possible to not just use palynological data in reconstructing vegetation history, but sometimes also to determine past climate variables such as maximum and minimum temperatures and lake levels (Overpeck et al., 1985). In some cases correlation between pollen diagrams can aid as an indirect dating tool.

Diatoms are present in almost all aquatic habitats, for example in deep and shallow, cold and warm and marine to fresh water bodies. Diatoms have proven to be useful as indicators of local habitat changes in lakes and shallow to deep marine environments. Diatom taxa retain their preferences even when widely dispersed (Bennett et al., 2010). Diatoms are used to reconstruct past lake level changes, sea-level variations and disturbances of wet ecosystems (Lowe & Walker, 1997). They can also be useful in monitoring variations in water chemistry and pollution (Cassie, 1983; Kilroy & Bergey, 1999).

Plant macrofossils can be a valuable addition to microfossil data such as pollen and diatoms. For example: palynological data from a certain location does not only reflect local vegetation that actually was present at that location, but does also contain pollen blown in from large distances. In comparison plant macrofossils, such as leaves and branches are more likely to be deposited relatively close to where the plant was actually present (Birks & Birks, 1980; Lowe & Walker, 1997).

In the following paragraphs an introduction to the New Zealand climate system and vegetation is given, followed by an overview of Late Quaternary and Holocene climate reconstructions relevant for this study.

3.2 New Zealand climate system

Due to its elongated shape and longitudinal geographical position, New Zealand is located in different climatic zones. This, together with complex orographic effects, due to the interaction of climate and topography, means that New Zealand has localised spatial climate variations and can be divided in 6 climate regions (Figure 3.1; Kidson, 2000; Lorrey et al., 2007). Climate records from different regions can show different responses to the same climatic changes (e.g. stronger westerlies; Salinger et al., 2004).

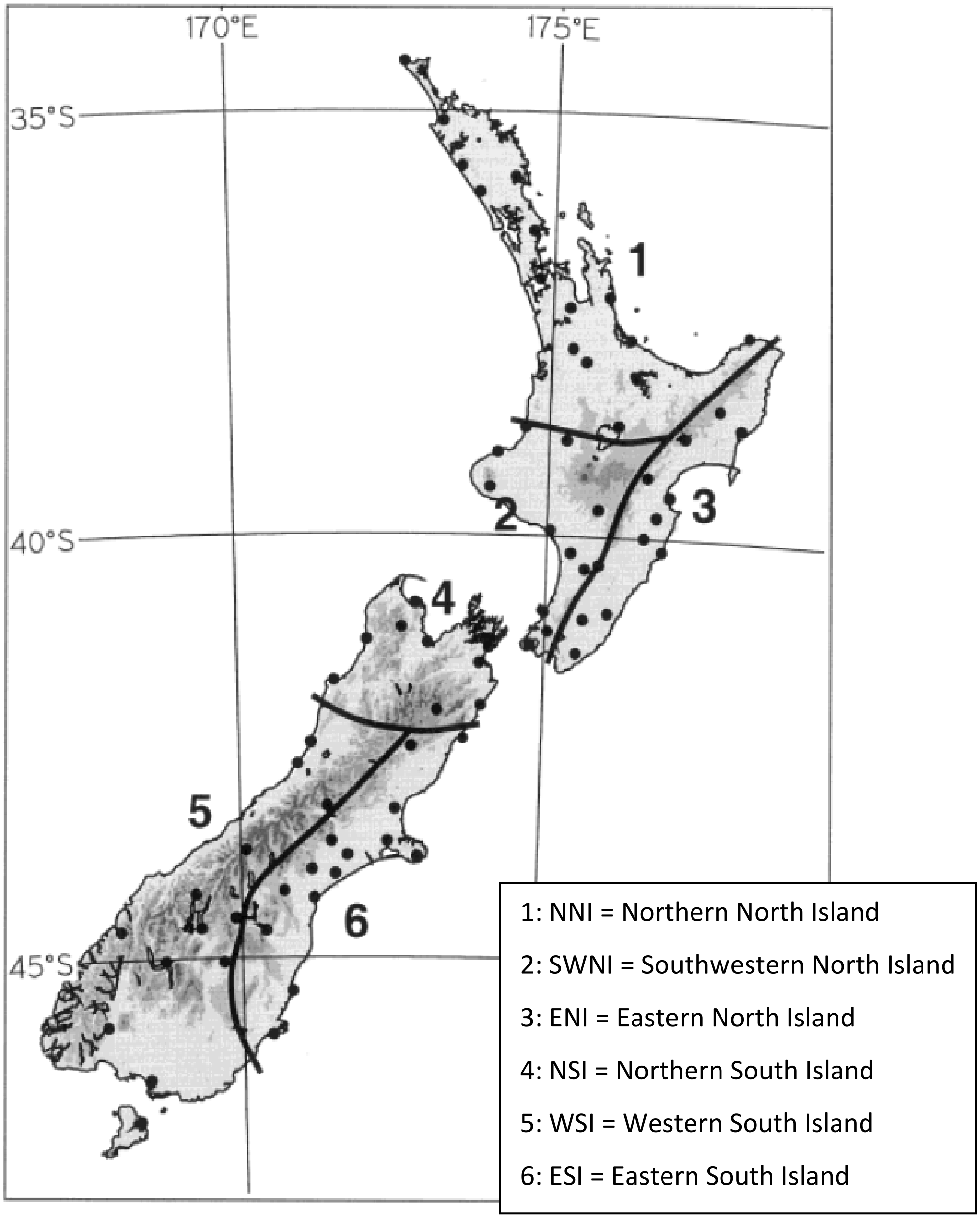


Figure 3.1: Climate regions of New Zealand (Kidson, 2000).

The climate of New Zealand is strongly influenced by its wind regimes. Wind regimes in New Zealand are influenced by El Niño and the Southern Oscillation (ENSO). Changes in ENSO-regimes can affect the intensity and latitudinal position of the Southern Hemisphere westerlies as well as temperature, precipitation and climate seasonality (e.g.: Reid & Penney, 1982; Alloway et al., 1992; Shulmeister et al., 2004). In periods of stronger ENSO-regimes New Zealand is colder and wetter which is sometimes reflected in vegetation (for example in southeast Otago: McGlone & Wilmshurst, 1999 and in south Westland: Li et al., 2008).

Palaeowind reconstructions show stronger westerlies over New Zealand during the LGM (±19,000 yr BP), Marine Isotope Stage (MIS-) 2 (± 24,000 yr BP), and probably MIS-4 (76,000 to 62,000 yr BP; Alloway et al., 1992; Shulmeister et al., 2004) and between 12.5 to 11 ka BP and 9.2 to 5.8 ka BP (McGlone et al., 2010). Palaeowind reconstructions could also be useful in predicting the distribution of tephra. Most palaeowind reconstructions for New Zealand however are based on tephra distribution (Palmer, 1982; Carter et al., 1995).

Climate reconstructions for New Zealand are often based on palynological research and comparable records, such as from diatoms and phytoliths. Most reconstructions focus on the transition from the Late Glacial into the Holocene and are not very detailed for the Holocene (among others: Moar & Suggate, 1996; McGlone et al., 2004; Newnham et al., 2007ab). Furthermore most reconstructions that do include the Holocene are located in other climate regions than the study area and therefore seem irrelevant to this study (for example: Newnham & Lowe, 1991, at Auckland, NI; Newnham et al., 1995, at Kopouatai Bog, NI; McGlone et al., 2000, on Auckland Island, Subantarctic New Zealand). Locations are given in figure 3.2.

The climate regions in New Zealand that are relevant for comparison to the study area on Banks Peninsula are considered to be Eastern South Island and Easter North Island and possibly parts of Western South Island. There are no palynological records in any of the relevant climate regions that provide enough detail to make a useful comparison to the time frame of the palynological study in this research.

3.3 New Zealand vegetation

New Zealand vegetation has not been disturbed by human activity until approximately 1200 BP (Davidson, 1984). The original dry land vegetation of New Zealand exists mainly of evergreens and perennials; annuals and summergreens are rare. From origin most of New Zealand was covered in forest. Traditionally there are two categories of forest: conifer-broadleaved or podocarp-hardwood forest and *Nothofagus* or Beech forest. The two types of forest are hardly ever found in a mixed form, it's mostly one or the other (McGlone, 1988; Wardle, 1991; McGlone et al., 1993).

Podocarp-hardwood forests are very divers and exist in all climate zones (Wardle, 1983). On relatively warm lowland sites these forest are complex and diverse multistoried forests. Tall conifers (Podocarpaceae; e.g. *Dacrydium, Dacrycarpus, Podocarpus and Prumnopitys*) and angiosperms (*Metrosideros robusta*) form the upper story reaching 40 to 60 meters in height. The first sub-canopy is 15 to 25 m high and consists mainly of angiosperms. In the southern regions this is mainly *Metrosideros, Plagianthus, Quintinia* and *Weinmannia*. A second sub-canopy exists of small trees such as *Griselinia, Hoheria, Phyllocladus, Pittosporum* and *Pseudowintera*, but also includes tree ferns (*Cyathea* and *Dicksonia*). Underneath these canopies grow diverse shrubs, including *Aristotelia, Coprosma, Pittosporum* and *Pseudopanax*, together with ferns and mosses. Lianes and vines are abundant, some prominent genera are *Clematis, Metrosideros* and *Rubus*. In cooler upland sites these forest exist of less stories. There are less tall trees and the main conifer species are *Libocedrus, Phyllocladus* and *Podocarpus* existing both as small trees and shrubby podocarps. Other shrubs are *Coprosma, Dracophyllum, Hebe, Myrsine* and *Pseudopanax*. In dry areas *Dacrydium, Quintinia* and *Weinmania* are more abundant, in wet areas *Dacrycarpus, Plagianthus* and *Prumnopytis* are more common.

Beech forests have a much simpler structure than conifer-broadleaved forests. Beech forests are generally found in sites less favourable for plant growth than those dominated by conifer-broadleaved forests. The forests are mainly found on hillsopes and in low alpine areas in the cooler, southern regions of NZ. Beech forest can also be present at lower altitudes on young shallow soils before competing species could dominate. Dominating species are *Nothofagus fuscaspora* (red beech) and *Nothofagus menziessii* (silver beech). *N. menziessi* occurs generally in wetter areas in central and south NZ. *N. fuscaspora* exist on dryer warmer slopes. Beech forest often continues up until the treeline. Above this treeline there is a rapid transition to tussock grassland. Conifer-broadleaved forests can also continue up to the treeline, a more subtle transition to tussock grassland then exists, with herbs and shrubland with small trees above the treeline (with a maximum of 100 m above the treeline).

The tussock grasslands above the treeline are often abundant with herbs, shrubs and small trees, which decrease with increasing altitude. An important shrub species for the Banks Peninsula is *Dodonaea*, a frost-sensitive coastal shrub. *Dodonaea* pollen are quite heavy and large and therefore are likely to reflect local changes. In comparison: *Nothofagus* pollen are light and flat and can travel great distances (McGlone, 1988; Wardle, 1991; McGlone et al., 1993).

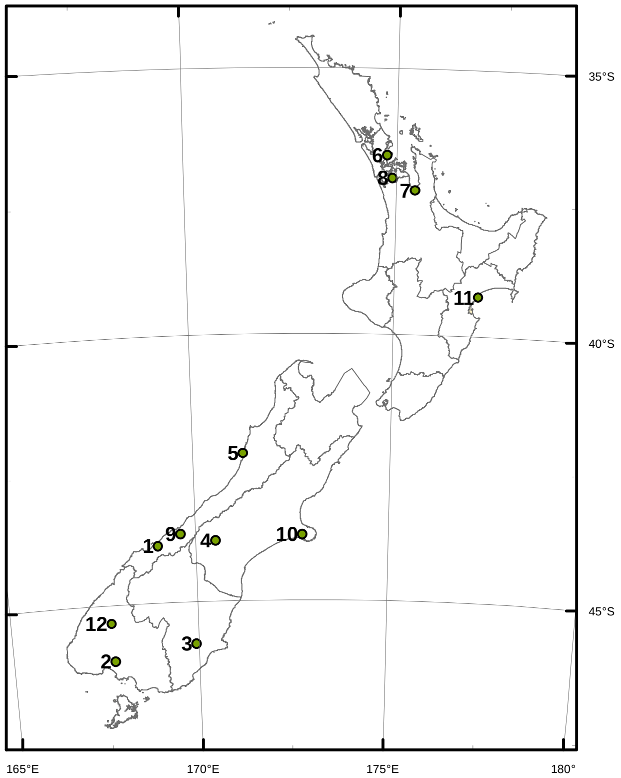


Figure 3.2: Locations of described pollendiagrams: 1) Li et al. (2008) 2) McGlone & Bathgate (1983) 3) McGlone & Wilmshurst (1999) 4) McGlone et al. (2004) 5) Moar & Suggate (1996) 6)Newnham & Lowe (1991) 7) Newnham et al. (1995) 8) Newnham et al. (2007a) 9) Newnham et al. (2007b) 10) Soons et al. (2002) 11) Wilmshurst et al. (1997) and 12) Wilmshurst et al. (2002).

3.4 New Zealand climate reconstruction for the Late Glacial and Holocene

A vegetation record from Banks Peninsula that covers the last two glacials and three interglacials (MIS 7 to MIS 1; Soons et al., 2002), combined with records from Haast, WSI (Li et al., 2008), Lake Te Aroha, WSI (Wilmshurst et al., 2002), Merrivale and Longwood Range, WSI (McGlone & Bathgate, 1983), southeast Otago, ESI (McGlone & Wilmshurst, 1999) and Hawke's Bay, ENI (Wilmshurst, 1997) are used to give an overview of Late Glacial and Holocene climate change relevant to the study area. Locations are given in figure 3.2.

Palynological climate reconstructions covering the transition from the Late Glacial into the Holocene in New Zealand show a start of deglaciation between 21 and 19 ka in the Auckland region, NI (Newnham et al., 2007b) and around 17 ka in Cass Basin River, SI (McGlone et al., 2004) and southwest New Zealand (Newnham et al., 2007a). This is mainly indicated by a retreat of grasses.

Up to approximately 11.5 ka continuing deglaciation and warming is recorded. This is indicated by a transgression from grassland to shrubland and further into podocarp forest. A slight cooling period occurs between 14 to 12.5 ka, indicated by a minor forest reversal in 20 records from the Westport-

Hokitika region, West Coast, NZ (Moar & Suggate, 1996). This cooling is also recorded at Cass Basin, in Auckland and southwest NZ (McGlone et al., 2004; Newnham et al., 2007ab). The cold period between 14 and 12.5 ka is defined by Jouzel et al. (2001) as the Antarctic Cold Reversal.

In the Westport-Hokitika and Auckland region podocarp forest stays dominant after 11.5 ka into the Mid-Holocene (McGlone et al., 2004; Newnham et al., 2007b). In Cass Basin, beech forest starts to slowly replace podocarp forest after 11.3 ka (Newnham et al., 2007a). The climate amelioration indicated by this beech forest is also reflected in the Holocene records from Longwood Range, Lake Te Aroha and southeast Otago. These records are located in the southern area of New Zealand with a generally cooler climate than in previously discussed locations. In southern South Island, grassland remains dominant until 12 ka and only few shrubs are present. After 12 ka shrubland starts to take over indicating warming. Only around 9.5 ka tall shrubs and podocarp forest starts to appear and becomes dominant until approximately 7 ka (McGlone & BathGate, 1983; McGlone & Wilmshurst, 1999; Wilmshurst et al., 2002). In Merrivale and Longwood Range a cooler and wetter period starts after 7 ka with a mixed podocarp-beech forest in which the amount of beech forest continues to increase after 4 ka (McGlone & BathGate, 1983). In southeast Otago this cooler and wetter period is reflected by the establishment of a montane-subalpine low conifer forest and after 4 ka beech forest starts to establish and takes over the conifer forest around 1.3 ka (McGlone & Wilmshurst, 1999).

The period after 7 ka is described in more detail for Sponge Swamp, Haast, south Westland, SI (Li et al., 2008), where from 7.7 ka lowland podocarp forest is dominant with *Dacrydium cupressinum* being the dominant species. From 7.6 to 6.8 ka *D. cupressinum* starts to decline, coinciding with an increase in *Nothofagus menziessi*. Other important species during this period are *Prumnopitys ferruginea* and *Podocarpus* spp., *Ascarina lucida* which peaks and drops shortly before the end of this period and *Coprosma* which is only present in the rest of the record in really small amounts.

At Sponge Swamp, from 6.8 to 3.7 ka *D. cupressinum* increases again and *P. taxifolia* becomes more abundant, these species together with *P. ferruginea* and *Podocarpus* spp. remain relatively constant throughout the rest of the record. *N. menziessi* slightly decreases throughout this period. From 3.7 to 1.2 ka most species remain relatively constant. *A. lucida* and *Coprosma* decrease further, *Cyathea* and *Dicksonia* peak but then decrease again, coinciding with a large increase in *Leptospermum* towards the end of this period. In general, since the Mid-Holocene a slight deterioration in climate is recorded, with cooling, increased frosts and drought and more variable and stronger seasonality (Li et al., 2008).

4 Study area

4.1 Geology of Banks Peninsula

The study area is located on Banks Peninsula (Figure 1.1). The geology of Banks Peninsula is important for the geomorphology in and around the study area. It is mainly shaped through its past volcanic activity. A Triassic greywacke island is underlying Cretaceous andesitic and rhyolitic rocks, subsequently there were five eruptive sequences during the Miocene (Table 4.1) that created a hilly surface of volcanic rocks (Figure 4.1). Further development involved erosion through fluvial activity and the formation of several bays due to the sea level rise during the LGIT, which drowned deltas, streams and craters (Weaver et al., 1985).

Table 4.1: Miocene history of eruptive sequences on Banks Peninsula, Canterbury, NZ (Weaver et al., 1985; see also figure 4.1).

Diamond Harbour Group	*7.8 – 5.8 million years*
Akaroa Group	*9.1 – 8.0 million years*
Mt Herbert Volcanics	*9.7 – 8.5 million years*
Lyttelton Group	*12 – 10 million years*
Governors Bay Volcanics	*15 – 12 million years*

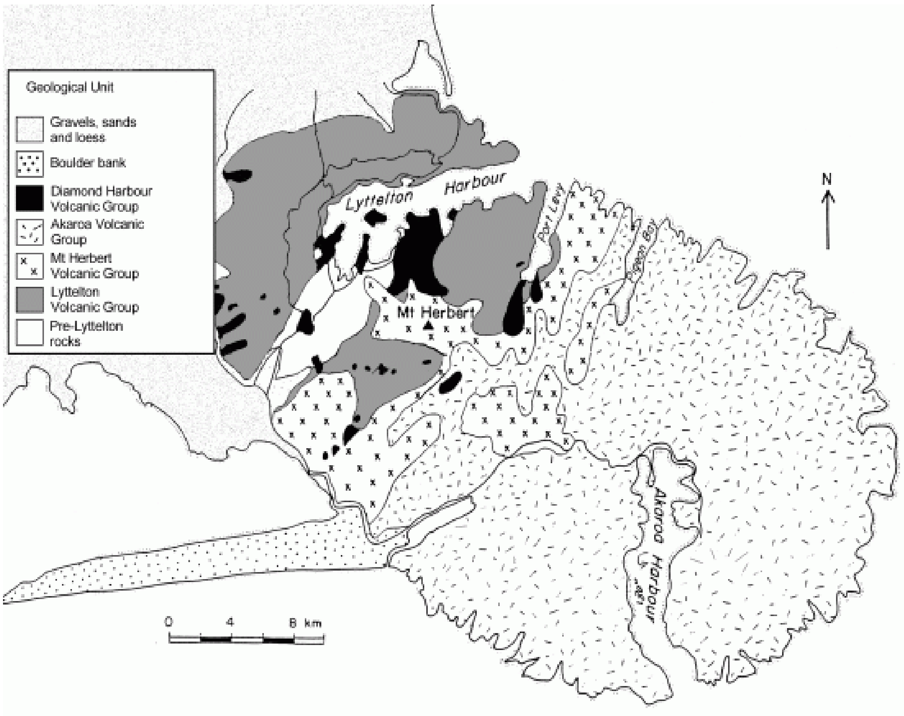


Figure 4.1: Volcanic geology of Banks Peninsula (Weaver et al., 1985; see also table 4.1).

Banks Peninsula was a stable island in interglacial times and was positioned somewhat inland from the east shore of South Island in glacial times (Liggett & Gregg, 1965; Raeside, 1964; Harris, 1983). Fluvial activity both on Banks Peninsula and in the Southern Alps created the Canterbury Plains (Figure 1.1; Wilson, 1985) which stopped Banks Peninsula from being an island. Loess deposits from the Canterburian river flood plains were deposited on and against Banks Peninsula (Griffiths, 1973; Almond et al., 2007). Due to coastal processes several valleys southeast of Banks Peninsula were closed off by beach ridges, behind which swamps and bogs formed. An important coastal development at Banks Peninsula is the formation of Lake Ellesmere (Figure 4.2) which used to be the estuary of the Waimakiriri River, before it avulsed to its present, more northern, location. Through the development of Kaitorete Spit, Lake Ellesmere is now a shallow fresh to brackish water lake in which the Selwyn River terminates. The lake used to be larger and deeper, covering the low lying areas surrounding the lake (Stout, 1975; Soons et al., 1997). The beach ridges closing of Banks Peninsula valleys are associated with these former higher water levels. A Mid-Holocene sea level high for Banks Peninsula, with slightly higher sea levels than at present, around 6000 yr Banks Peninsula, after which a regression took place is suggested (Suggate, 1968; Armon, 1973; Gibb, 1986; Kirk, 1994; Soons et al., 1997, 2002).

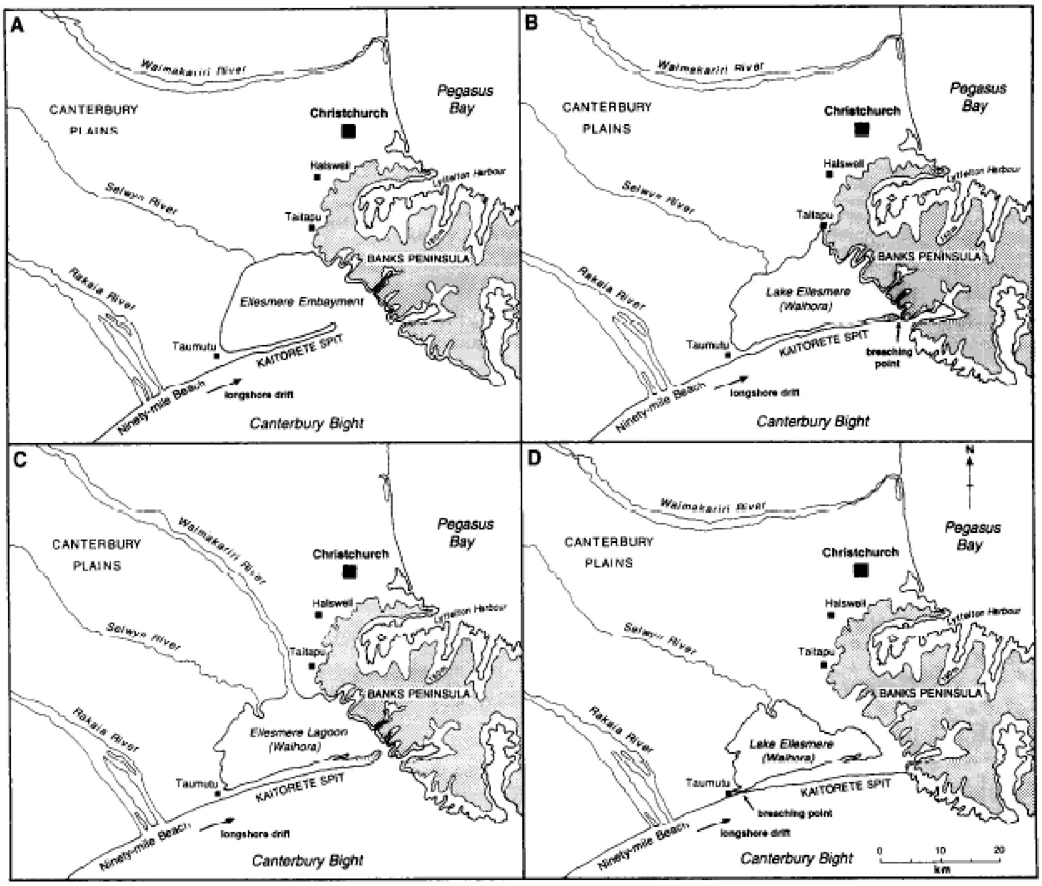


Figure 4.2: Model of the closure of Kaitorete Spit and development of Lake Ellesmere: A) Early to Mid Holocene, B) Mid to Late Holocene, C) Late Holocene and D) last 500 yrs (Soons et al., 1997).

Banks Peninsula is located in a cool temperate bioclimatic zone, except for land situated higher than 750 m AMSL, which is in cool temperate montane bioclimatic zone. The mean annual rainfall ranges widely over short distances, from 600 mm in the eastern and northeastern regions, up to 2000 mm at the southeastern flanks (Soons et al., 2002).

Up to approximately 800 yrs BP, the peninsula was covered with tall podocarp forest (*Dacrycarpus* spp., *Podocarpus* spp., *Prumnopitys taxifolia*), combined with warm temperate and frost sensitive shrub species such as *Dodonaea viscosa*. In the southeast above 300 m AMSL beech forest (*Nothofagus* spp.) was present (Wilson, 1993). About 800 years ago the first Polynesian settlers arrived in New Zealand and in a couple of centuries one third of the native forest was destroyed, including large parts of Banks Peninsula (Lowe et al., 2000). In the early 19th century Europeans arrived and deforestation continued to provide timber for ships and housing and to develop farm land (Soons et al., 2002). At present there is little native forest left and many introduced species have flourished. Banks Peninsula is mainly covered in grassland and tussocks.

4.2 Motukarara Valley

At the flanks of Lake Ellesmere and Banks Peninsula, a thick, calcareous, texturally banded loess, referred to as Birdlings Flat loess, has been deposited. The Birdlings Flat loess has been subject to climatic and stratigraphic research (among others: Griffiths, 1973; Goh et al., 1977; Almond et al., 2007).

The loess deposits in the area have been subject to erosion and redeposition and form large loess spurs. Motukarara valley is surrounded by loess spurs and drainage is restrained by Mid-Holocene beach ridges related to Lake Ellesmere and alluvial fans. Due to the poor drainage a swamp developed in which peat deposits, later buried by overbank and fan deposits, have accumulated. Motukarara Valley is located 1.6km north of Motukarara and west of Ahuriri Road (Figure 4.3). The valley floor slopes gently (1–2 °) to the south, the mean annual rainfall is 700 mm and due to poor drainage the average groundwater table is 0.5 m above the valley floor. The mean annual temperature is 11.4 °C (NIWA).

Tephra research has been carried out in the Birdlings Flat loess close to the study area, in the Ahuriri Quarry (Almond et al., 2007). OSL, radiocarbon dating and tephrochronology have been used in an attempt to provide a detailed and reliable chronology for Birdlings Flat loess. The accepted age of Kawakawa Tephra (identified based on EMPA) at 1.35 m is not supported by other dating methods, which indicate a much younger age for the tephra.

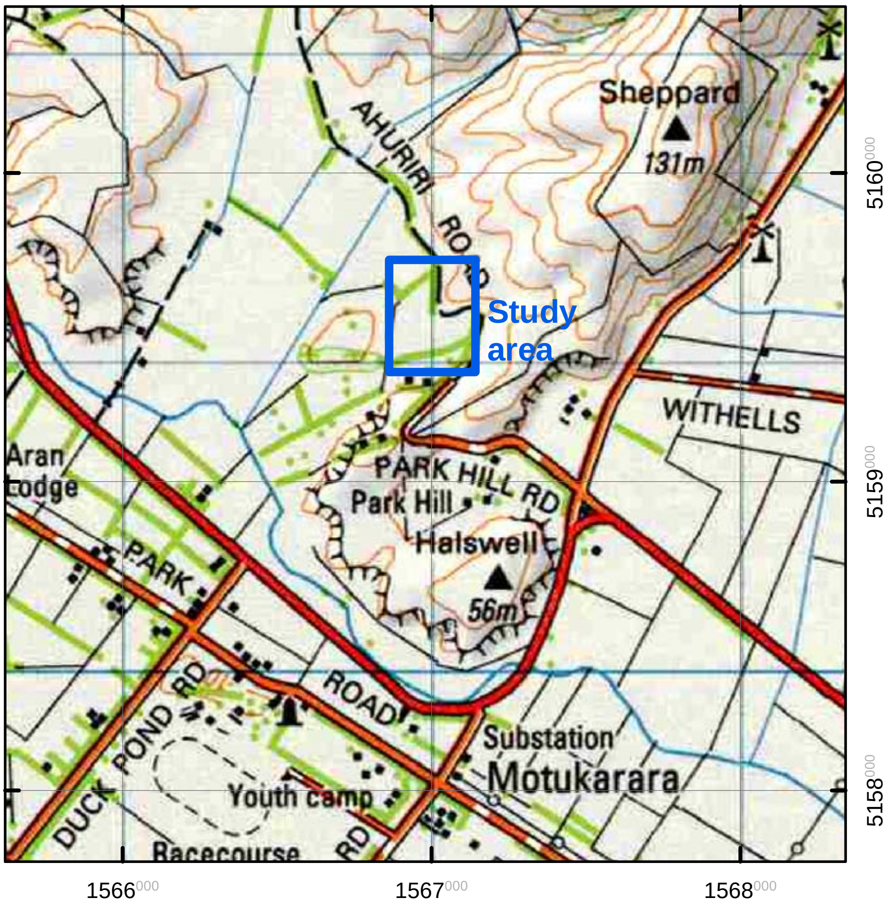


Figure 4.3: Location of the Motukarara Valley study area relative to Motukarara and Ahuriri Road.

Some research on the peat in the study area has been carried out between 1984 and 1987 but remained unpublished (Tonkin & Trangmar). A description of the lithology and soil profile of Core 1984, taken at the edge of Motukarara Valley, mentions that volcanic glass is found in the buried peat at unspecified depth (Eden; 1987, unpublished) and gives two radiocarbon dates for the base and the top of the peat (chapter 6). This study focuses on the description of a new core: Core 2011.

5 Methods

5.1 Characterisation of the depositional environment of the valley deposits

5.1.1 Lithological survey and sampling

A lithological survey of Motukarara Valley was carried out in order to create two cross sections and determine the best sample locations. This was done by hand coring with a so-called Dutch or Edelman auger system (Figure 5.1). The augerhead used was a combination head, suitable for all sedimentary units present in the valley.

Figure 5.1: Dutch or Edelman auger.

Core samples were taken at irregular intervals varying between 10 and 20 m along two transects, one aligned north-south direction and the other east-west. The exact sample locations were determined based on the distance and differences in local elevation (from observations in the field and a digital elevation model) to previous sample locations. The core descriptions included pariticle size class, colour description, oxidation/reduction state and soil horizon designation. Some of the cores were described in more detail, including information on the presence of roots, organic matter, concretions and mottles.

Supplementary observations were made outside the transects in order to determine the distribution of different geomorphogenetic units. Core locations were determined after preliminary analysis of the cross-section profiles. The distance between core locations was between 10 to 30 metres. At the edges of the valley a zigzag mapping technique is used aiming to find the borders of sedimentary units by zigzagging around it.

At the best sample location two adjacent continuous records, in 50cm increments, are taken. The best sample location is assumed to be where the buried peat layer is thickest and least disturbed. Both records cover a depth from 50 to 250 cm. This is done using the D-section or Russian peat sampler from Eijkelkamp (Figure 5.2). Samples are stored airtight at a temperature of 4-6 °C.

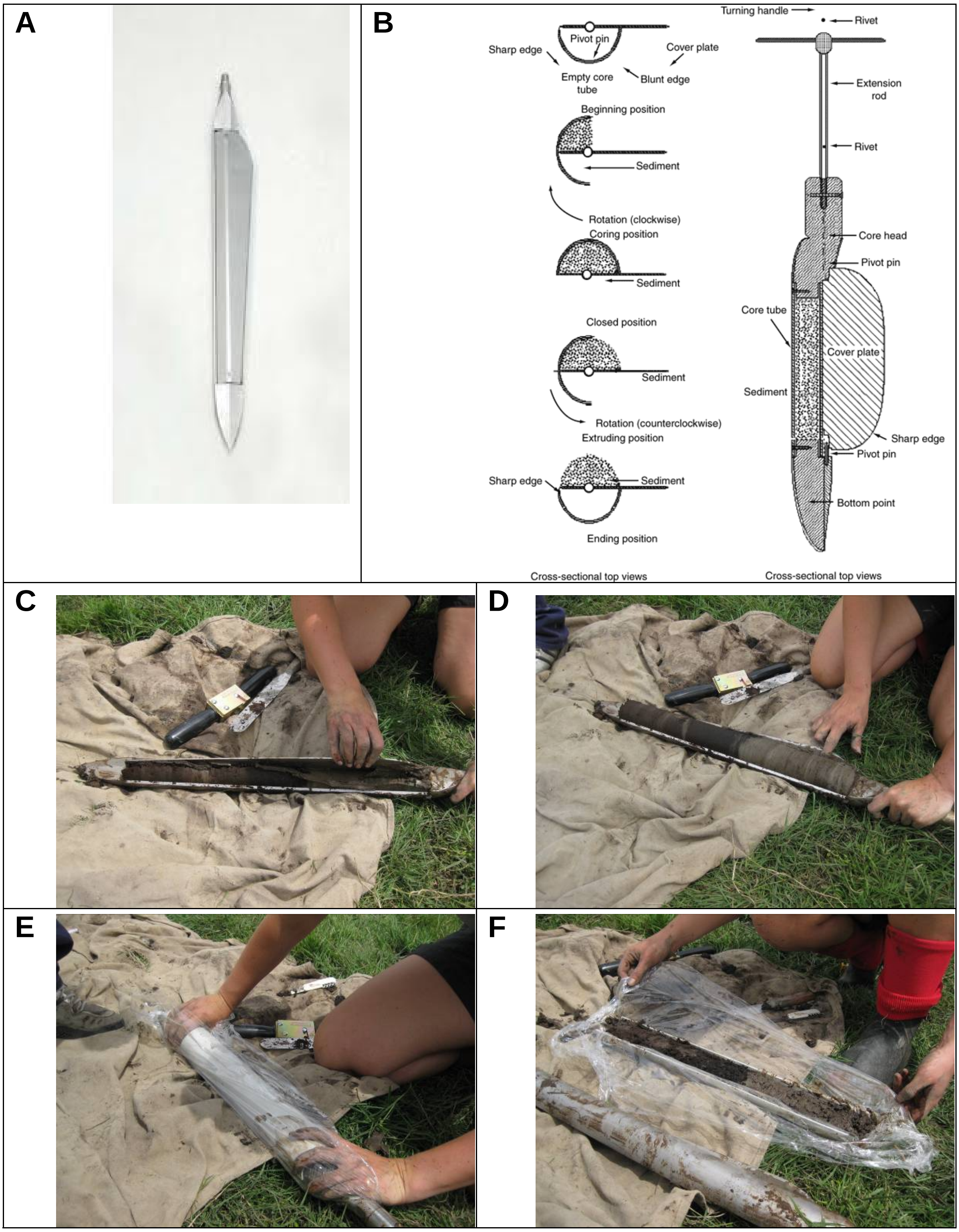


Figure 5.2: A) The D-section peat sampler of Eijkelkamp; B) how it works (USEPA, 1999) and retrieving of the sample: C and D) turn open the corer and E and F) transfer to storage halfpipe.

5.1.2 pH and EC

At some core locations samples from different sedimentary units (present throughout the valley) were taken. These are analysed for pH and electrical conductivity (EC). For pH-measurements 25ml of deionised water is added to a subsample of 10 g ± 0.05 air-dried soil, this is left for 8 hours to stabilise (Blakemore et al., 1987). Samples are measured using a Mettler Toledo pH meter using pH4 and pH7 buffers for calibration. For EC-measurements 100ml water is added to 20 g ± 0.05 air dried soil. This is shaken for 30 minutes, then centrifuged for 5 minutes at 1500 rpm and measured directly (Blakemore et al., 1987), with a Mettler Toledo conductivity meter.

5.1.3 Organic carbon and moisture content

Loss on ignition is a method to establish the amount of organic carbon in a sediment sample. The record is sampled continuously with a sample size of $1cm^3$, covering a depth of 2 cm (½ · 1 · 2 cm). Preparation of the samples includes air drying the samples, with which the moisture content is established. The amount of moisture is indicated by the amount of weight loss after air drying the samples and the organic carbon content is indicated by the amount of weight loss after burning the dried samples. Drying the samples is done by leaving the samples overnight in an oven set at 40 °C. Burning of the dry samples is done in an oven for 4 hours at 550 °C (Blakemore et al., 1987; Heiri et al., 2001).

5.1.4 Pollen analysis

Pollen analysis is carried out at, and in collaboration with, the School of Geography, Environment and Earth Sciences, Faculty of Science, Victoria University Wellington (VUW), NZ, under supervision of Dr Rewi M. Newnham and with help of Dr Bill McLea.

Pollen samples are taken from the record with a sample-increment of 5 cm. One lycopodium spore tablet is added to each sample, to create the ability to obtain quantitative pollen concentrations. The tablets used in this study are from Batch No. 938934 from the Department of Quaternary Geology at Lund University; they contain 10679 ± 953 spores per tablet.

Pollen concentrates are prepared following the method of Faegri et al. (1989): Samples of 1 cm^3 together with the lycopodium spore tablet are added to 15ml of water. Carbonates are removed by gently heating the samples and adding 2 ml of HCl. Humic acids are dissolved by heating the samples in a 5% potassium hydroxide solution. Samples are than sieved over 90µm mesh and the part >90µm is discarded. Sodium polywolframate (SPT) with a specific gravity of 2.2, is used to separate pollen from minerals (density separation). The mineral part is discarded. Acetolysis is applied by using 5 ml per sample of a solution existing of 9 parts acetic anhydride and 1 part sulphuric acid, and heat the samples for 5 minutes in a water bath at 95 °C. Samples are than sieved over 6µm mesh and the part < 6 µm is discarded. The pollen concentrates that are now left over are kept refrigerated in 2 ml of water. In between all steps the samples are rinsed with distilled water, before and after the acetolysis the samples are rinsed with glacial acid because the acetolysis solution reacts very strongly with water.

Microscope slides are made by mounting a drop of pollen concentrate in glycerin between a glass microscope slide and a cover glass. The slides are made airtight with a colourless laquer to prevent the pollen from oxidizing.

Analysis of the microscope slide is done using a magnification of 400 to 800 times. Per sample at least 250 dry land pollen are counted. Classification of pollen is, when possible, to species level; sometimes classification was only possible up to family level. Some groups are created, mainly within podocarp-hardwood forest and aquatics. The keys used for classification include Moar, 1993 and Newnham, 1993ab.

The pollensum is the sum of all dry land pollen (minimum of 250 per sample), this includes trees, hurbs, shrubs, treeferns and grasses and excludes aquatics. A pollen diagram was created using Tilia (Grimm, 1990, 2004) giving pollen concentration as a percentage of the pollensum. CONISS (Grimm, 1987) is used for zonation of the diagram. Climate indications of the different species found in the record are based on Wardle (1991).

5.1.5 Diatom analysis

Diatom analysis is carried out, in collaboration with VUW, by Dr Margareth A. Harper.

Nine samples from Core 2011 are analysed for diatoms (4 silt samples, 2 saline mud samples, 3 peat samples of which one sample was oxidized). Samples are prepared following Piperno (2006). From each sample 1 gram is oxidized with 20 ml of hydrogen peroxide. Then the samples are heated with 20 ml of hydrochloric acid to remove carbonates. Sand is removed by decanting 15 ml tubes after settling for 45 seconds. The decanted material was left to settle for 8 hours after which all material in suspension (including most clay) is discarded. Diatoms in the peat samples were separated using heavy liquid (SPT; $\rho = 2.2$; Leng & Swann, 2010).

The diatom concentrations were mounted in Naphrax on microscopic slides. A magnification of 1000 with differential interference contrast optics is used to identify over 200 diatom valves for each sample, except for the sample from 152.5 cm depth, for which only 149 valves were identified. Identification and taxonomy of the diatom species was based on Krammer & Lange-Bertalot (1986-1991). Diatom species were then expressed as relative abundance per sample.

5.1.6 Macrofossil analysis

Plant macrofossil analysis is also carried out in collaboration with VUW, by Dr Aline M. Homes.

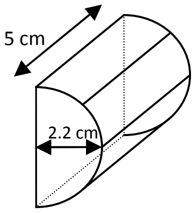
Subsamples from each 5 cm increment covering a depth from 70 to 220 cm are analysed for macrofossils. The method used to extract macrofossils from the sediment is by Blackburn (1980), modified by Holden (1987), and was originally developed for lignite. Sediment samples were cleaned with a mixture of equal parts hydrogen peroxide and filtered water, to which a few crystals of tetrasodium pyrophosphate were added. Samples were cooled to minimise frothing during the strongly exothermic reaction.

When all reaction had ceased, fragments for analysis were handpicked from the sample, washed in filtered water and mounted in glycerine jelly. Analysis was carried out using a Leitz Diaplan microscope and identifications were made by comparison to a macrofossil reference set. Reference specimens are prepared by clearing fresh or dried plant material with hydrogen peroxide and sodium pyrophosphate after which softened tissue was removed from the cuticles.

This was a pilot project and no attempt was made to quantify the results.

5.2 Quantification of the distribution of volcanic glass grains

Samples for cryptotephra analysis are taken from the record continuously. Only half of the half-circle shaped record (due to the use of the D-section corer) is used, this leads to quarter-circle shapes subsamples. The radius of this circle is 2.2 cm; this is after scraping of a thin outer layer to avoid contamination. Each sample covers a depth of 5 cm. This leads to the approximate size of the subsamples:



$$\frac{1}{4} \cdot 2.2^{2} \cdot \pi \cdot 5 = 19 \text{ cm}^{3}$$

All soil samples are covered with deionised water. Organic matter is removed by heating the samples to approximately 100 °C and adding 2 to 4 ml of hydrogen peroxide every 30 minutes, until the fluid is clear. To keep the sample wet, deionised water is added when necessary. The next step is to remove particle covering oxides (such as iron-oxide). The samples are heated to approximately 80 °C after adding 40 ml of a 0.3M sodium citrate solution and 10 ml of a 1M sodium bicarbonate solution. When warm 1 g of sodium dithionite is added and samples are heated for another 15 minutes. Samples are than sieved to 38 μm, 63 μm and 250 μm. The > 250 μm and < 38 μm fractions are discarded. The 38 < 63 μm and 63 < 250 μm fractions are dried at 60 °C and dry samples are weighed.

The 63 < 250 μm fraction is used for glass counting and for the 38 < 63 μm fraction is simply determined whether there are any glass shards present or not. A known amount of impact beads is added to the 63 < 250 μm sample in order to calculate quantitative glass shard concentrations (Table 5.1). The impact beads used are Potters designation number 10, from Potters Industries Inc.. The particle size of the beads is 90 to 150 μm and the number of beads per kilogram is estimated by Potters Industries at $6.657960 \cdot 10^{8}$.

To count the samples microscopically some sample is sprinkled onto glass slide and 2 drops of clove oil are added. Volcanic glass shards can be distinguished from the mineral particles with a polarizing or petrographic microscope. Volcanic glass will appear in a shade of pinkish white when viewed under plane polarized light, but will appear black when viewed under crossed polarized light. Other minerals show different colours when viewed under crossed polarized light (so-called interference colours, useful in identification of minerals). Furthermore, glass shards will show random sharp edges (similar to large shards obtained when breaking a glass), whereas minerals might show a crystal shape.

Table 5.1: Constants, variables and equations used in quantitative glass counting by means of spiking.

Beads		
Number of beads in a gram	*B(-)*	**6.657960 * 10^5**
Mass of 1 bead	*b(g)*	(1 / 6.657960 * 10^5 =) **1.50196 * 10^-6 g**
Sample		
Initial volume of soil	V_i *(cm^3)*	*e.g.* ***20***
Weight of beads added (± 5%)	w_b *(g)*	*e.g.* ***0.05***
Total number of beads added	$T_b = w_b * B$ *(1/g)*	*e.g. (0.05 * 6.657960 * 10^5 =)* ***33289.8***
Counting		
Counted number of beads	C_b *(-)*	*e.g.* ***40***
Counted number of glass shards	C_g *(-)*	*e.g.* ***10***
Calculations		
Total number of shards in sample	T_g *(-)* $= C_g * T_b / C_b$	*e.g. 10 * 33289.8 / 40 =* ***8322.45***
Shards per cubic centimetre of soil	Q *(1/cm^3)*$= T_g / V_i$	*e.g. (8322.45 * 20 =)* ***166449***

5.3 Chemical characterisation of volcanic glass grains

Microprobe analysis and correlation of volcanic glass grains was carried out, in collaboration with VUW, by Dr. Brent V. Alloway. Chemical identification of the volcanic glass shards is done through electron microprobe analysis (EMPA; initially established by Froggatt & Gosson, 1982). EMPA makes use of an electron beam that causes the elements in the sample to emit X-rays. Each element has a characteristic frequency of X-rays which can be detected by the electron microprobe (Wittry, 1958; Jansen & Slaughter, 1982).

From samples 17B (= Tephra I at 145 cm) and 31B (= Tephra II at 215 cm) grains including glass shards are mounted in a resin and then polished to expose fresh internal surfaces (Figure 5.3). All major element determinations were made on a JEOL Superprobe (JXA-8230) housed at Victoria University of Wellington, using the ZAF correction method. Analyses were performed using an accelerating voltage of 15 kV under a static electron beam operating at 8 nA. The electron beam was defocused to 20 μm. All elements were calculated on a water-free basis, with H_2O by difference from 100%. Total Fe was expressed as FeOx. All samples normalised against glass standard VG-568.

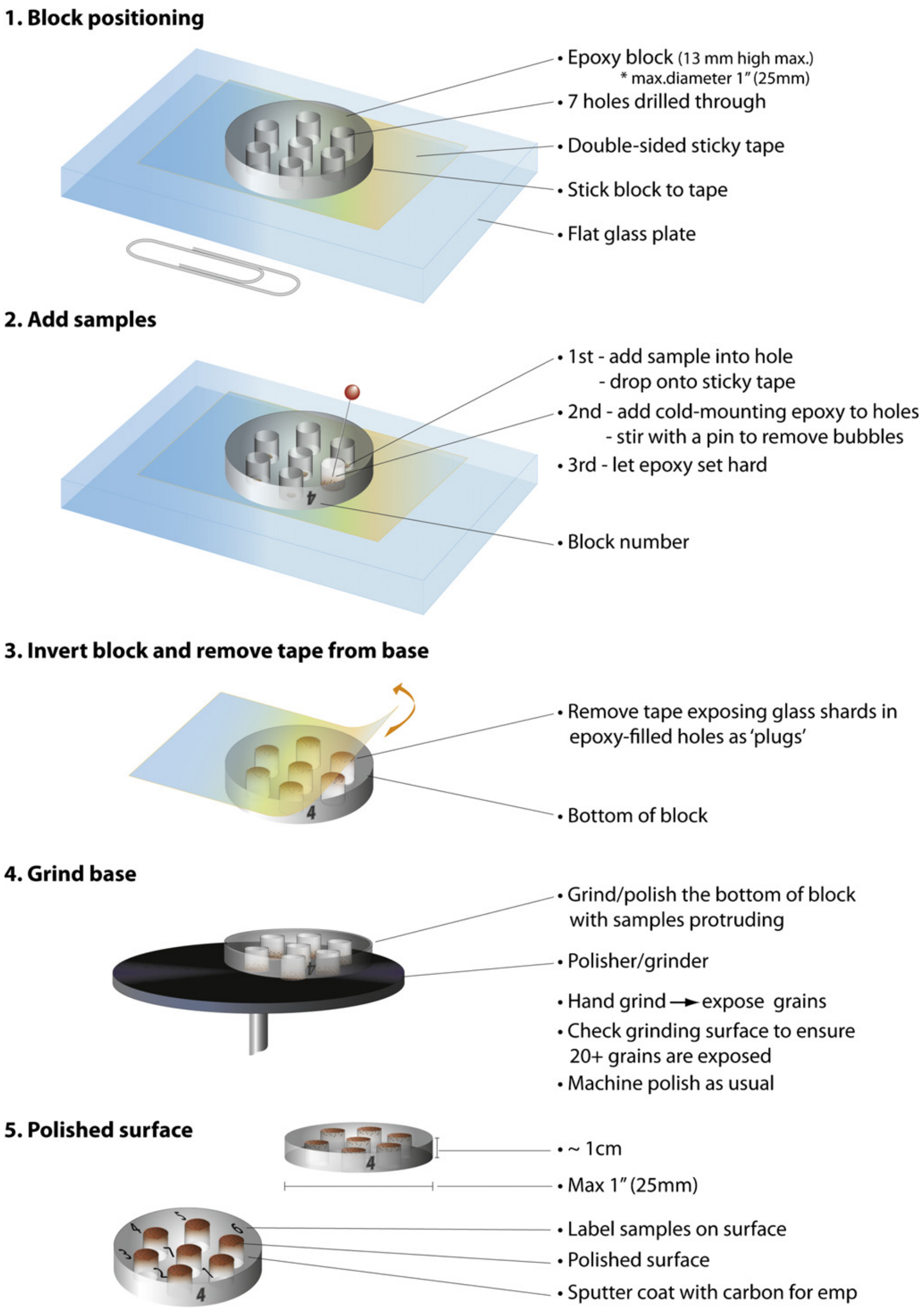


Figure 5.3: Preparation procedure for mounting multiple samples of glass shards or free crystals in 'blocks' for analysis by electron microprobe, based on methods provided by Dr P.A.R. Shane, University of Auckland (after Froggatt & Gosson, 1982; Lowe, 2011).

5.4 Construction of a chronology for Motukarara Valley

A chronology for Motukarara Valley was constructed based on the results of the lithological survey and radiocarbon ages. The extensions of different lithogical units have been established and are used to create a series of palaeogeographical maps that show the development and changes in the valley through time. A timeframe for these maps is based on the radiocarbon ages from Core 1984 and 5 new radiocarbon ages derived from Core 2011.

Radiocarbon dating is carried out by Dr Marcus J. Vandergoes, in collaboration with GNS Science, Lower Hutt.

Five samples from Core 2011 have been submitted for radiocarbon dating. Radiocarbon dates are derived at a depth of 199 to 200 cm to determine the timing of the transition from brackish to fresh water and at 190 to 191 cm and 102 to 103 cm respectively to determine the beginning and end of peat formation. Samples from a depth of 142 to 143 cm and 211 to 212 cm are submitted to determine the time of deposition for respectively Tephra I and Tephra II. In this study samples from the interval with the highest tephra concentration have been submitted for radiocarbon dating. For Tephra I this coincidentally is the only interval in which glass shards are found. For Tephra II, glass shards are found in all intervals over a depth of more than 70 cm. There is no indication of an intact base and therefore the highest concentration is the best option.

All samples from Core 2011 have been sieved over 90 μm fraction and plant remains have been separated for dating. For Core 1984 bulk samples of peat from a depth of 125 to 130 cm and 172 to 177 cm have been dated. Radiocarbon dates have been calibrated following calibration data for the southern hemisphere by McCormac (2004).

6 Results

6.1 Valley fill stratigraphy

The cores included in the lithological survey are plotted on a elevation map (Figure 6.1), based on LIDAR-data with a grid size of 2x2 m. The complete descriptions of these cores can be found in appendix A. The two transects, north-south and east-west oriented (Figure 6.2 a and b respectively; locations in figure 6.1), show the generalized distribution of the sedimentary units present in the valley.

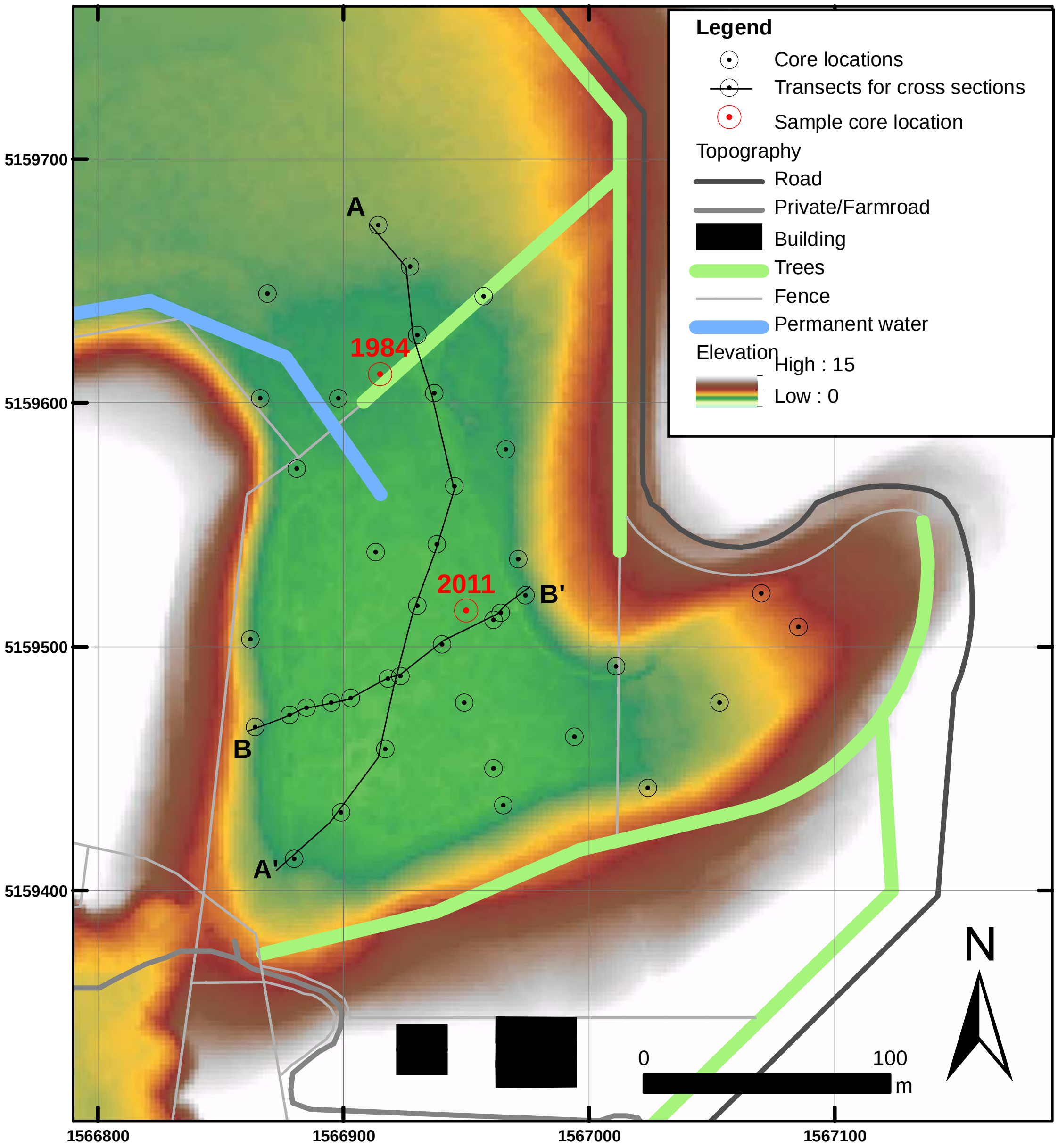


Figure 6.1: Core, sample and transect locations within the lithological survey, plotted on the digital elevation model, with a simplified topography.

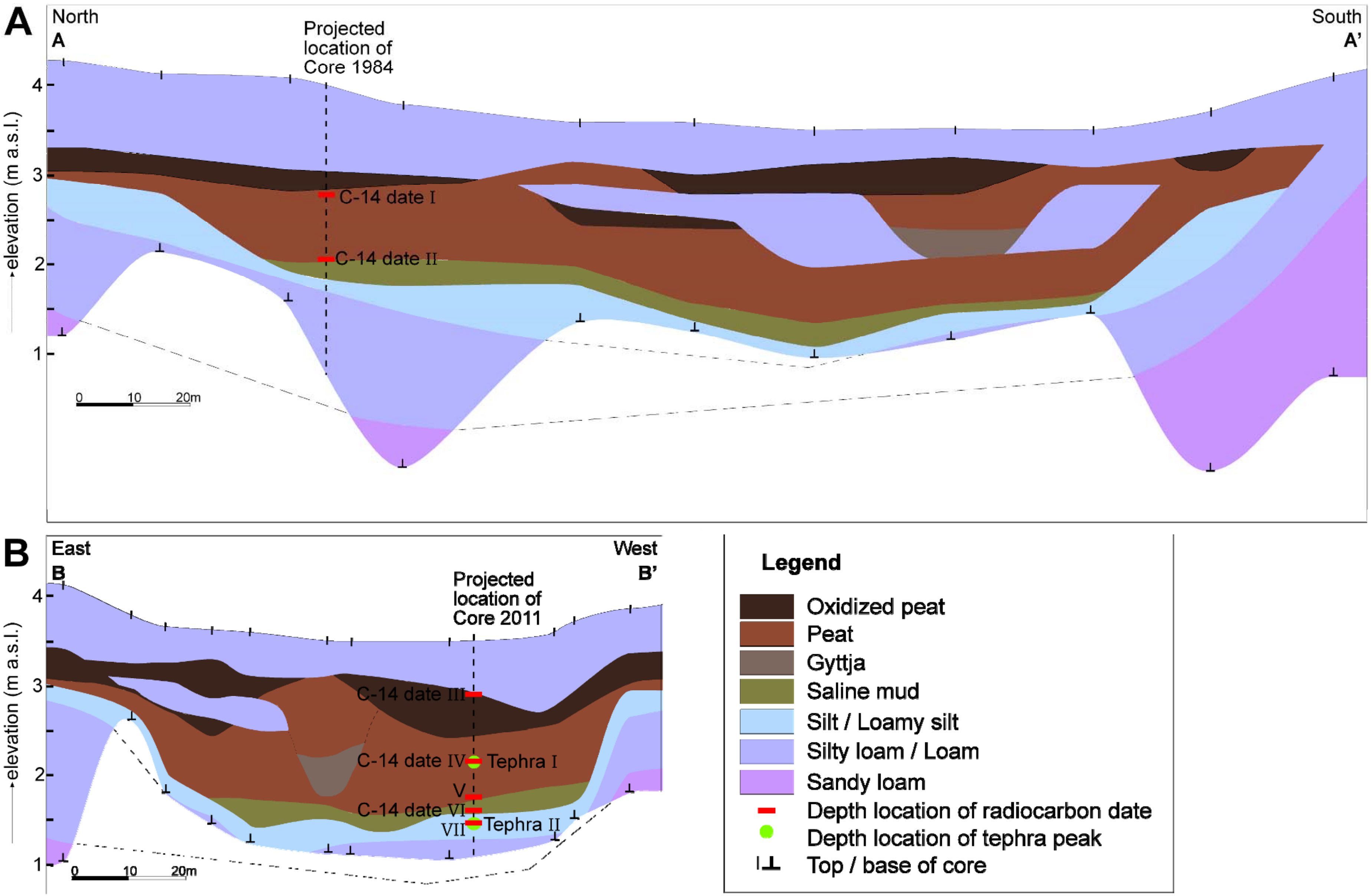


Figure 6.2: Cross sections through the study area: A) north-south and B) east west with the depth locations where tephra concentration peaks are found and samples for radiocarbon dating are taken.Locations of cross sections in figure 6.1.

The lowermost unit of the cross sections, between elevations ranging from approximately 1 m to 3 m.a.s.l., is a sandy loam. These deposits are covered by 50 to 100 cm of silt loam to loam. All these loamy deposits become less oxygen reduced pattern with increasing depth: the deposits reached in the corings for the cross sections are grey, with sometimes yellow mottles at the base of the corings. In other corings greater depths were reached where the grey material with yellow mottles transitioned into yellow material with grey mottles and at greater depths became completely yellow.

These loamy units define a former valley shape that is now filled in with a sequence of silt (10 to 50 cm), covered by gyttja formed in a saline environment (saline mud; 10 to 30 cm) and peat (up to 150 cm). The peat is locally cross-cut by channel-shaped deposits. Palaeo-channel bank and levee deposits are of silt loam to loam texture and the channel is infilled with gyttja and peat. Before or during the formation of this channel the top of the peat has locally oxidized. While peat formation occurred in the channel, it also continued throughout the rest of the studied area. Most of the top of this peat is also oxidized. The complete area is covered with disturbed silt loam to loam deposits of 20 to 60 cm thick.

The results of these cross sections are supported by the other corings carried out. And based on a combination of all corings the location of Core 2011 is taken where the peat is continuous, thick and least disturbed. The locations of Core 1984 and Core 2011 are plotted in figure 6.1 and projected onto the cross sections.

6.2 Depositional environment

6.2.1 Carbon and moisture content

The results of the analyses carried out in order to characterise the depositional environment of Motukarara Valley are plotted next to the lithological columns of Core 1984 and 2011 in figure 6.3. Carbon content is very low in the silt deposits with values under 5 %, it shows a rapid increase between 215 and 190 cm up to a value of 50 % in the saline mud. This is followed by a decrease to approximately 20 % at 170 cm. Values increase up to 75 % in the peat between 160 and 110 cm with two dips to 40 and 30 % around respectively 145 cm and 12 5cm. Above the peat there is a rapid decrease of carbon content back to 20 %, followed by another increase to 50 % at 100 cm. The more mineral layers at the top have values of approximately 20 %.

The moisture content is low in the lower silt deposits, with a relatively constant value of 40 %. It increases abruptly around 220 cm (still in the silt deposits) to 70 to 85 % and remains constant for the saline mud and peat layers. It decreases in two steps at 110cm to 55 to 60 % and at 95 cm to 45 to 50 %. It increases again in the oxidized top peat to just over 60 %.

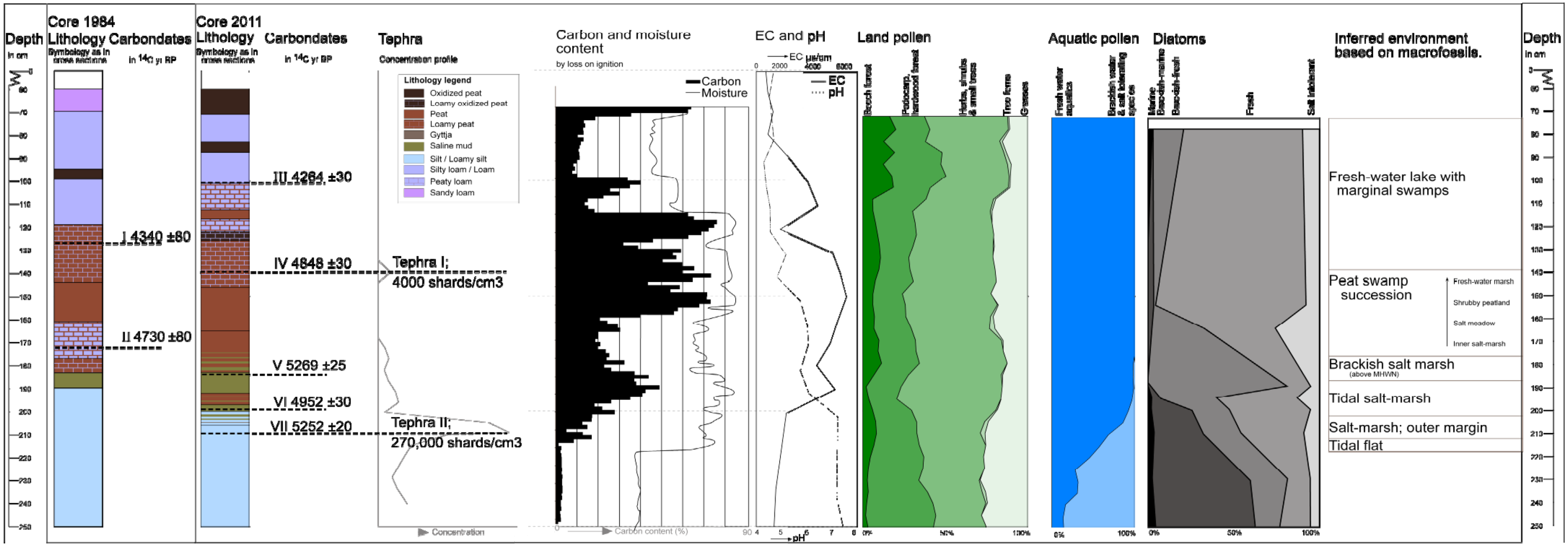


Figure 6.3: Environmental diagram: For Core 1984: Lithological column with uncalibrated radiocarbon dates I and II and for Core 2011: Lithological column with uncalibrated radiocarbon dates II to VII; the locations of tephra peaks I and II; carbon and moisture content; pH and EC; summaries of the pollen analysis (dry-land pollen and aquatics) and diatom analysis and the inferred environment based on the macrofossil data. All plotted against depth, 0cm is ground level. Top of Core 2011 is at 3,6 meter above mean sea level.

6.2.2 pH and EC

The pH and EC show opposite trends for the lower part of the diagram, pH is high, around 7.5, and EC is low, around 2000 µs/cm. Between 200 and 190 cm pH decreases to values around 6, indicating increasing acidity, coinciding with the transition to peat. EC values increase to 6000 µs/cm. Up to 100 cm depth acidity continues to increase, with pH reaching 4.5. Above 100 cm the values stay relatively constant. The EC stays around 6000 µs/cm up to 130 cm. A slow decrease to values of 1000 µs/cm at 80 cm is interrupted by a low peak at 120 cm of 2000 µs/cm. Above 80 cm values stay relatively constant.

6.2.3 Pollen

The summary of the palynological analysis, as given in the environmental diagram (Figure 6.3), gives a general image of the vegetation in the and around the study area: first a salt marsh, later a swampy lake, in a valley; podocarp-hardwood forest with many herbs, shrubs and small trees on the surrounding slopes; influxes of beech and grass pollen, presumably less local, from higher grounds. Most striking results from this evidence is the change from a salt-brackish water to a fresh water environment and the changes in *Dodonaea* that seem strongly linked to the fresh water aquatics.

The complete pollen diagram is given in figure 6.6. The classification into zones is based on two sets of CONISS results. For the first set all species were included, whereas for the second set aquatics were left out and only dryland species were taken into account. This resulted in 4 main zones subdivided into several 9 subzones.

Zone 1 (250 – 193 cm). Dryland vegetation in this zone is characterized by a decline in forest and grasses and an incline in herbs and shrubs. Aquatics are characterized by a shift from salt and brackish water species to fresh water species. Zone 1 is subdivided into two subzones:

In zone 1a (250 – 208) a slight increase in *Nothofagus fuscaspora* is recorded. This coincides with a decline in podocarp-hardwood forest. *Podocarp* spp. and *Prumnopytis taxifolia* decrease. Herbs and shrub species present throughout the record are: *Asteraceae, Coprosma, Coriaria, Dodonaea, Hebe, Hoheria, Muehlenbeckia* and *Myrsine*. These mostly are present in small amounts that remain constant throughout this zone. Exceptions are *Asteraceae*, which slightly drops and *Hebe*, which slightly increases. Furthermore, *Forstera, Galium, Gaultheria* and *Gunnera* are present in small amounts in this zone only. Values for Poaceae are high in this zone. Salt and brackish water aquatics are high at the base and drop rapidly towards the top, fresh water aquatics slowly increase. Some photos of pollen found in the record are given in figure 6.5.

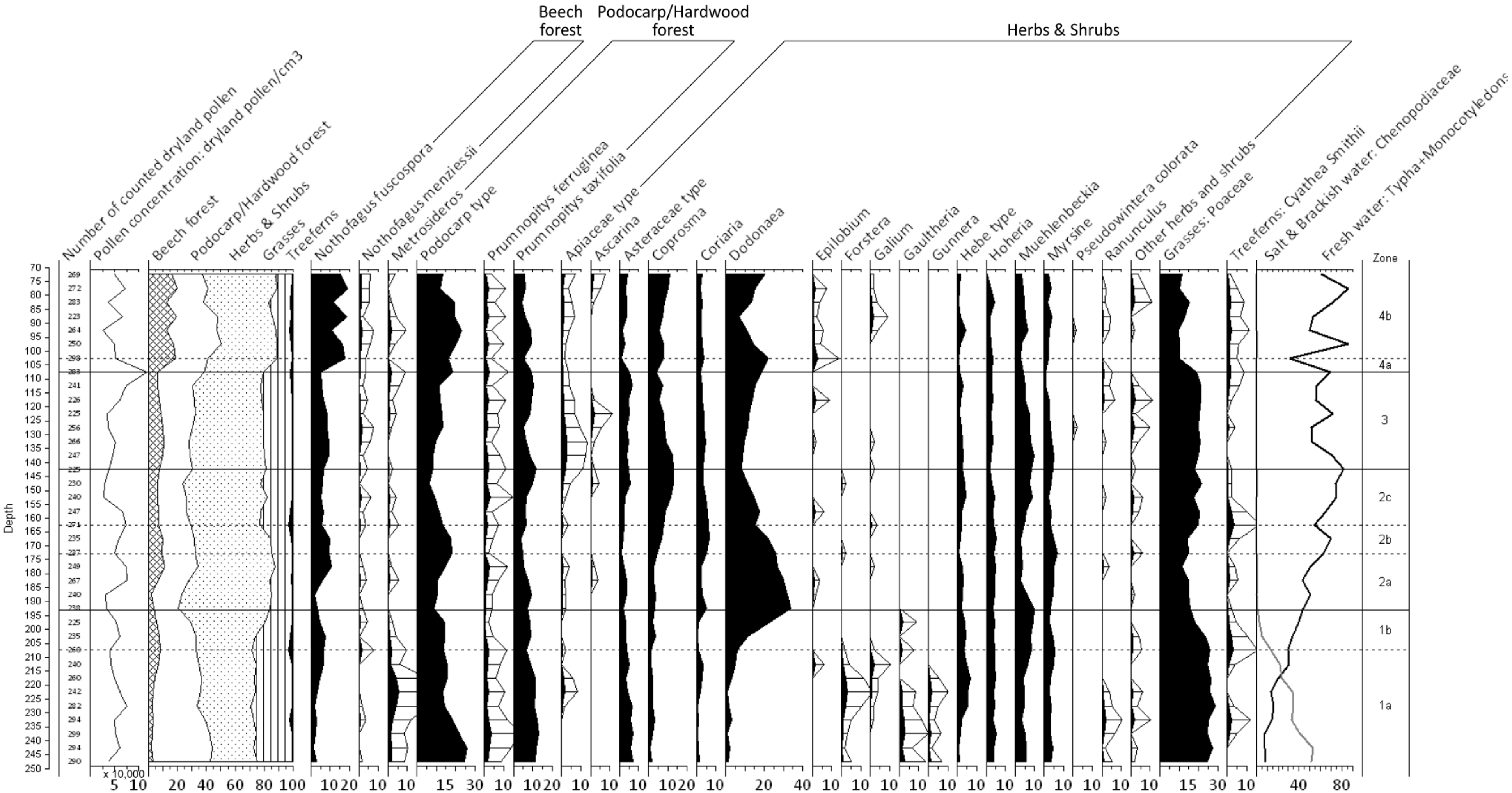


Figure 6.4: Pollendiagram for Motukurara Valley Fill Core 2011.

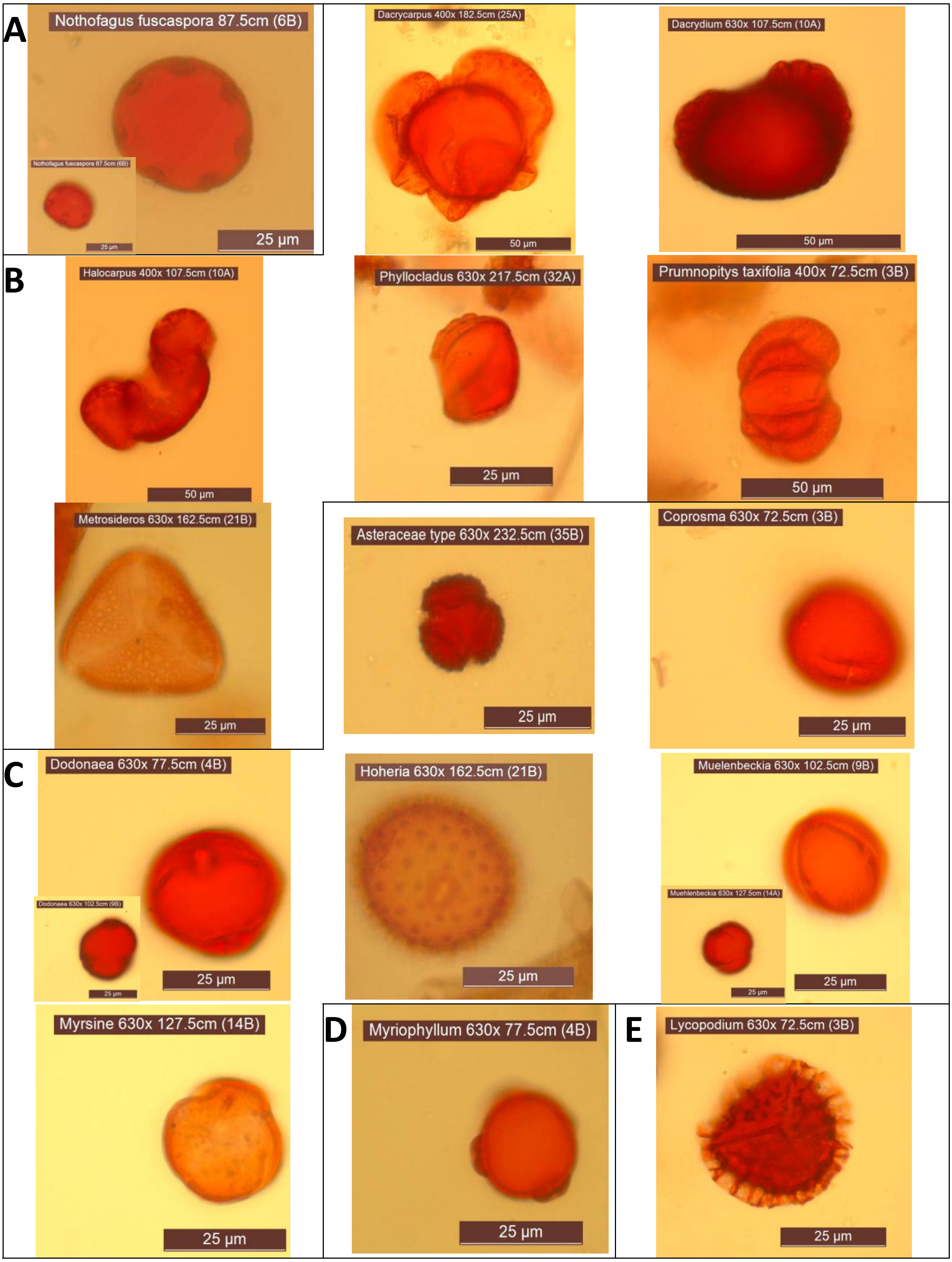


Figure 6.5: Microscopical photos of pollenin Core 2011. species associated with: A) beech forest; B) podocarp-hardwood forest; and C) herbs, shrubs and small trees.D) An example of a fresh water aquatic and E) a photo of one of the reference spores.

In zone 1b (208 – 193 cm) forest declines as *N. fuscaspora*, *Podocarp* spp. and *P. taxifolia* decrease. Most herb and shrub species remain constant. *Dodonaea*, however, shows a very striking, rapid increase. *Muehlenbeckia* also slightly increases. *Forstera, Galium, Gaultheria* and *Gunnera* disappear. Poaceae start to decrease. Salt and brackish water aquatics disappear and fresh water aquatics continue to increase.

Zone 2 (193 – 142 cm). Dryland vegetation is dominated by herbs and shrubs and a slightly expand in beech forest. Salt and brackish water species have disappeared, fresh water species increase. This zone is subdivided into three subzones.

In zone 2a (193 – 173 cm) forest inclines as *N. fuscaspora* and *Podocarp* spp. increase, *P. taxifolia* continues its slight decrease. Most herbs and shrub species remain constant, *Dodonaea* starts to decrease and so does *Muehlenbeckia*. Poaceae remains constant. Fresh water aquatics further increase.

In zone 2b (173 – 162 cm) *N. fuscaspora* shows a small drop, as does *Podocarp* spp., *P. taxifolia* starts to slightly increase. Most herb and shrub species also remain constant in this zone, except for *Coprosma* and *Coriaria*, which increase and *Dodonaea* which further decreases. Grasses increase slightly and fresh water aquatics peak before they drop.

In zone 2c (162 – 142 cm) *N. fuscaspora* remains constant, *Podocarp* spp. first further decreases and towards the top of the zone, slightly increases again. *P. taxifolia* increases. As for herbs and shrubs: *Coprosma* further increases, *Coriaria* drops to previous values, *Muehlenbeckia* increases again, and *Dodonaea* continues to drop. Poaceae remain constant at relatively high values. Fresh water aquatics continue their general increase

Zone 3 (142 – 108 cm). Herbs and shrubs slightly decline as podocarp-hardwood forest slightly incline. There is no subdivision of this zone. In zone 3 *N. fuscaspora* and *P. taxifolia* are relatively constant, *Podocarp* spp. further increases throughout the zone with a rapid increase at the top. Most herbs and shrubs remain constant again. *Coprosma* drops back to previous values, *Dodonaea* increases again and in the top of this zone *Ranunculus* enters the record. Poaceae and fresh water aquatics remain constant.

Zone 4 (108 – 70 cm). is characterized by an increase in beech forest, coinciding with a drop in grasses. It is subdivided into two subzones:

In zone 4a (108 – 102 cm) *N. fuscaspora* increases abruptly. *Podocarp* spp. remains relatively high, but *P. taxifolia* decreases. *Coprosma* increases again, *Dodonaea* continues to increase. *Ranunculus* remains present and *Epilobium* enters the record, other herbs and shrubs remain constant. Poaceae rapidly drops, as do the fresh water aquatics.

In zone 4b (102 – 70 cm) *N. fuscaspora* remains high, as does *Podocarp* spp., but that does show a decline towards the top. *P. taxifolia* remains relatively constant. *Coprosma* further increases, *Ranunculus* and *Epilobium* are still present, *Galium* enters again. *Dodonaea* first drops, than increases again. Other herbs and shrub species remain constant. Poaceae remains relatively constant. Fresh water aquatics start with an increase, which is followed by two drops.

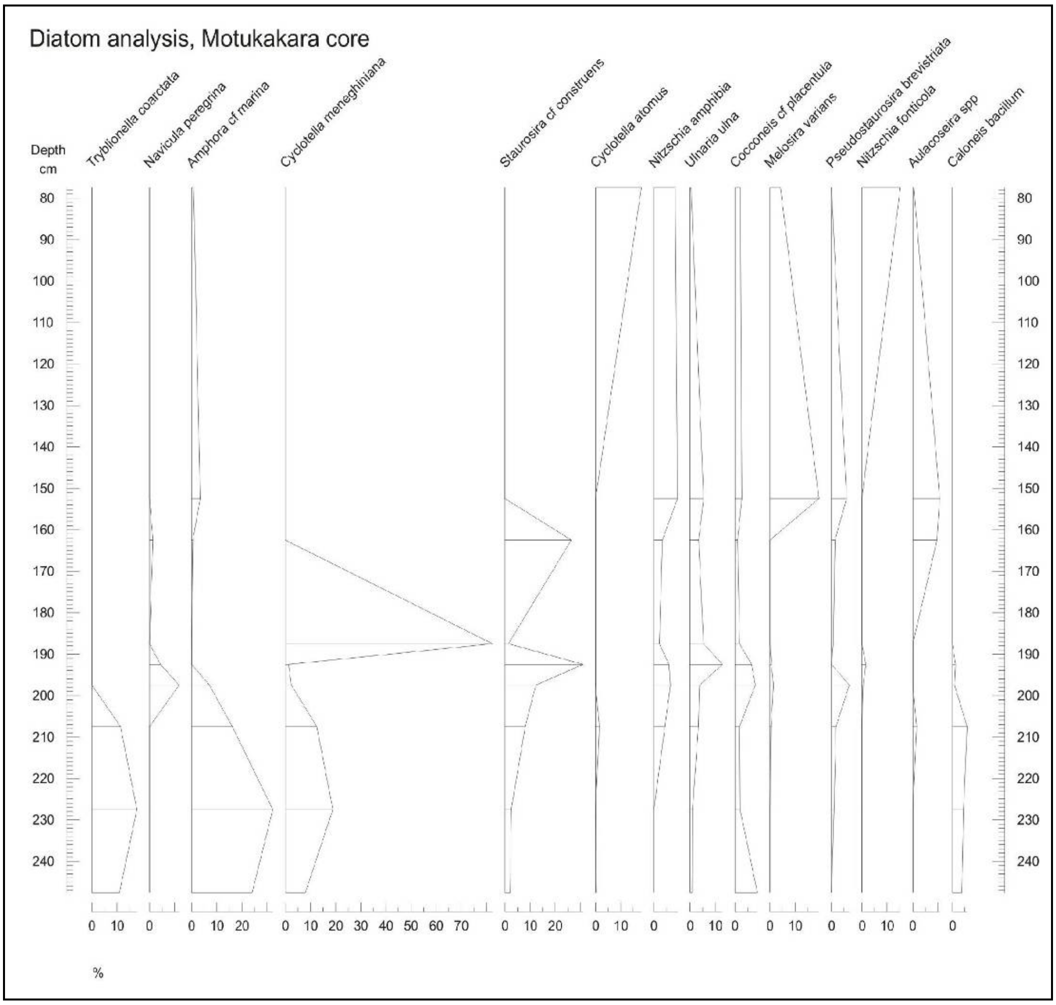


Figure 6.6: Diatom diagram of Motukarara Valley Fill Core 2011 (by Dr Margareth A. Harper).

6.2.4 Diatoms and macrofossils

Detailed results of the diatom and macrofossil results are given in figure 6.6 and table 6.1. These show a transition from marine to fresh water environments, consistent with the pollen data.

The diatoms and macrofossils give more detailed information on this transition that starts at a depth of 230 cm and continues up to 150 cm. Between 220 to 175 cm mainly brackish-marine species are present, with only a few brackish-fresh to fresh species. A transition from a tidal flat to a salt to brackish salt marsh is indicated by the macrofossils. Between 175 to 150 cm brackish-marine and brackish species almost disappear within a peat swamp succession. Above 150 cm there are almost solemnly fresh water species in a fresh water lake where peat formation takes place. The environmental interpretations are based on work in The Netherlands (Van Dam et al., 1994).

Table 6.1: Macrofossil analysis results for Core 2011 from Dr Aline M. Homes.

Depth (cm)	**Inferred environment**		**Organisms/Remains**	
75 80 85 90 95	Fresh-water lake with marginal swamps. Largely peat, minor influx of terrigenous mineral matter.		Plant tissue Annelid/insect Spores Pollen Diatoms Rootlets Cuticles Fern sporangia Sparse wood & conifer remains Fungal hyphae & fruiting bodies	*Cordyline/Phormium* Sedges *Astelia* *Blechnum minus*
100 105 110 115 120 125 130 135				Rushes Sedges Sparse Ferns *Blechnum* *Dacrydium* *Dacrycarpus*
140 145	Peat swamp succession	Fresh-water marsh	Degraded wood Roots and &rhizomes Spores Pollen Monocot cuticle Mineral matter	*Juncus* *Phormium*
150 155		Shrubby peatland		Sedges & grasses *Plagianthus divaricatus* *Coprosma*
160 165		Salt meadow		
170 175		Inner salt marsh	Diatoms Insect remains	*Juncus* *Leptocarpus*
180 185 190	Brackish salt-marsh above MHWN.		Rootlets Diatoms Shell fragments Insect/annelid remains Pollen Fungus remains	*Juncus* *Leptocarpus* *Isolepis* *Chenopodiaceae*
195 200 205	Tidal salt-marsh			
210	Salt-marsh, outer margin		Root periderm	*Juncus* *Chenopodiaceae*
215 220	Tidal flat		Shell fragments Annelids Pollen	*Chenopodiaceae* *Zostera*

6.3 Tephrostratigraphy

6.3.1 Concentration profile

The concentration profile of volcanic glass shards in Core 2011 shows two distinct tephra peaks (Figure 6.7). The depth location of the highest concentration within these peaks are taken for further analysis and will be referred to as Tephra I at 140 to 145 cm and Tephra II at 210 to 215 cm (Figure 6.3). Both Tephra I and II do not coincide with any abrupt or major environmental changes.

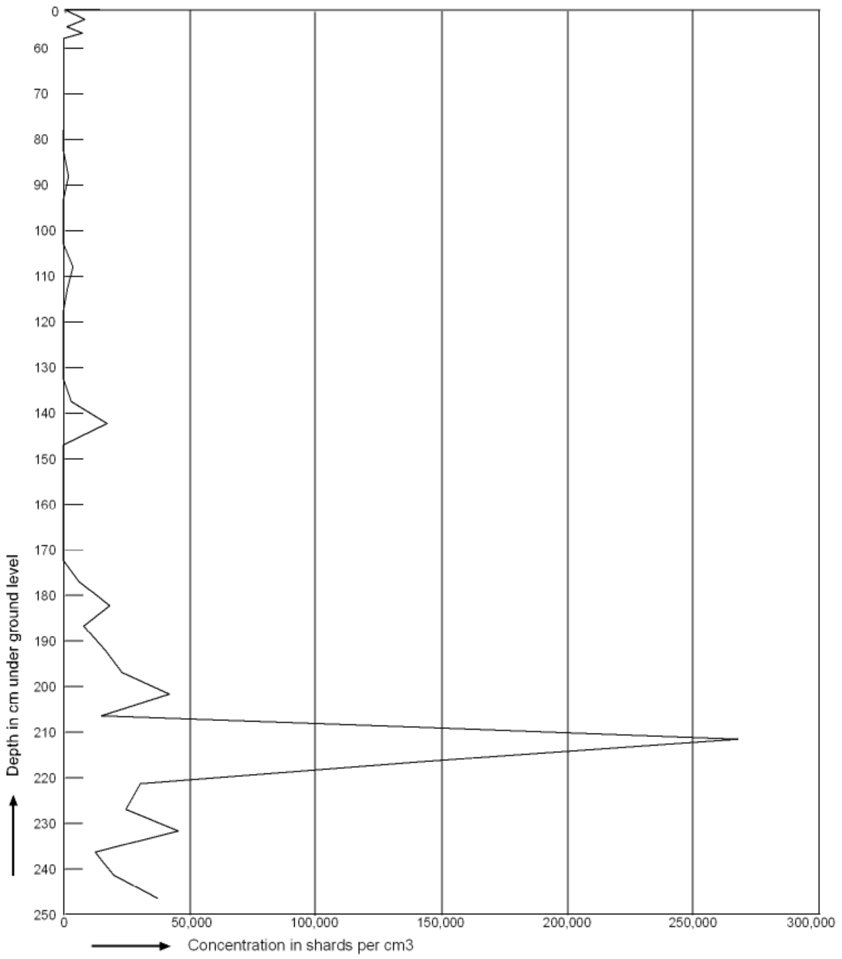


Figure 6.7: Concentration profile of volcanic glass shards in Core 2011.

Tephra I is a small peak of approximately 4000 glass shards per cm^3, but it is very distinct as there is no glass found from 115 to 135 cm and neither from 150 to 170 cm. Tephra I is located in the main peat de posits. The organic carbon content is very high at this depth, some mineral influxes have been recorded in the peat, but the depth of the tephra does not coincide with any of these.

Tephra II is a very high peak at 215 cm, of approximately 270,000 glass shards per cm^3, it is however much more spread with several peaks, covering a depth from 175 cm up to the base of this record at 250 cm. The smaller peaks above 145 cm have been considered to be too small for analysis. Tephra II is spread in the loamy, silt and saline mud deposits. The peak concentration is found in the silt deposits. These deposits are very fine and indicate a relatively low energy depositional environment.

Some photos of the volcanic glass shards in the record are given in figure 6.8.

Figure 6.8: Microscopical photos of glass shards of Tephra I and II in Core 2011, Potters Industries glass neads (bottom right), all on the scale of the scale bar (bottom left).

6.3.2 Chemical composition

Chemical compositions of glass grains, 2 for Tephra I and 23 for Tephra II, isolated from Core 2011 are given in table 6.2 alongside reference compositions for Unit K, Whakatane and Kawakawa/Oruanui tephra. The reference tephras were chosen based on the time of eruption occurring within the range defined by the ages established by the two radiocarbon ages of Core

1984. Kawakawa Tephra was included as it is the only Late Quaternary tephra known to be present in South Island.

Both tephra deposits show the highest correlation with Kawakawa Tephra. This is visualised in figure 6.9 in two bi-plots. This implies that both tephra have a Kawakawa signature.

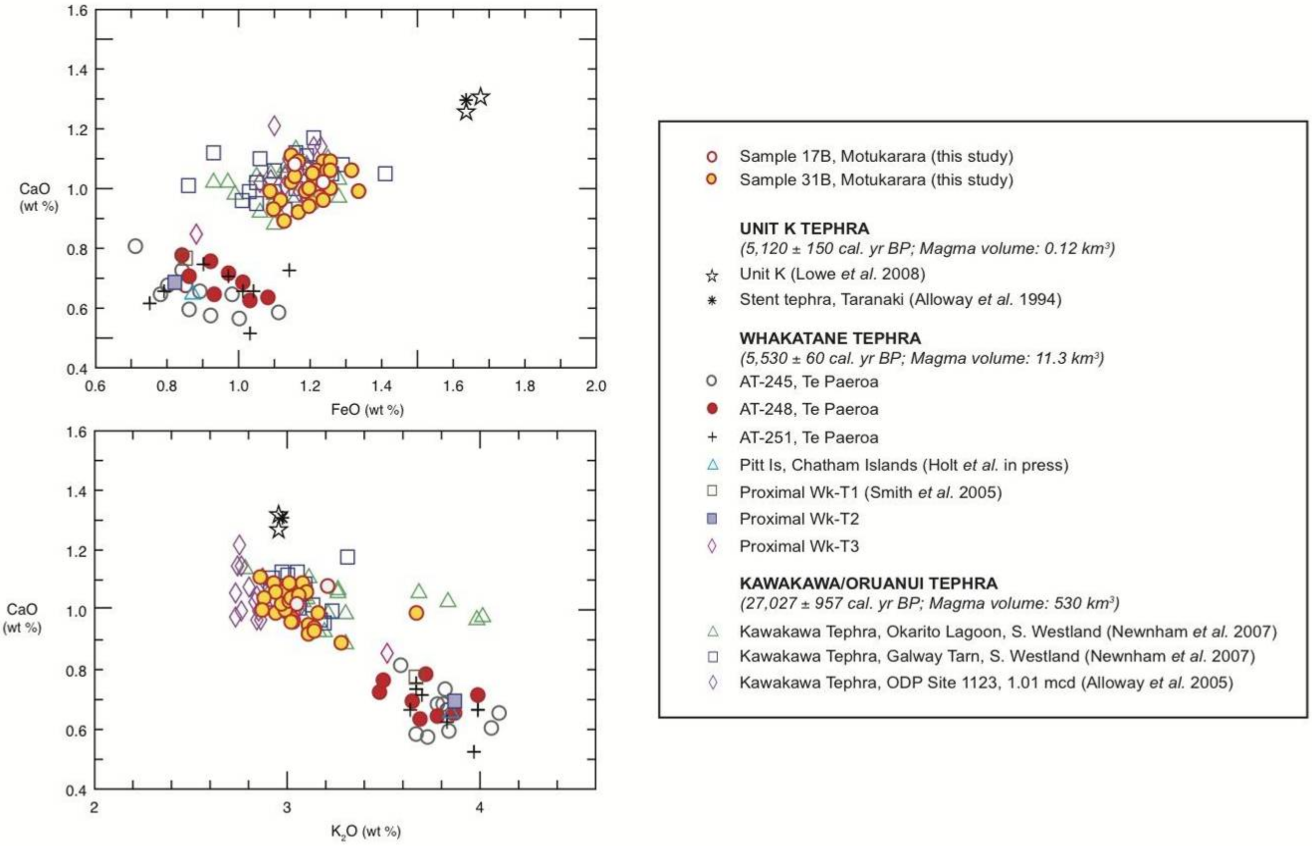


Figure 6.9: Biplots of the results of microprobe analysis on sample 17B (Tephra I at 145cm) and 31B (Tephra II at 215cm) of Motukarara Valley Fill Core 2011. Visualized in comparison to three closest correlating tephra: Unit K, Whakatane and Kawakawa Tephra.

6.4 Chronology

The results of the radiocarbon dates (Table 6.3) show that at the location of Core 1984, at the edge of the peat layer, peat formation seems to have started around 5433 cal yr BP (date II) and continued until 4811 cal yr BP (date I). In the middle of the depression, at the location of Core 2011, peat formation seemed to have started earlier, presumably 5960 cal yr BP (date V). Peat formation in Core 2011 continued until 4691 cal yr BP (III), which is longer than in Core 1984. As for the deposition of the tephra layers: Tephra I is found in sediments dated to 5532 cal yr BP (date IV) and Tephra II in sediments dated to 5950 cal yr BP (date VII). The transition from salt/brackish to fresh water occurred around 5648 cal yr BP (date VI).

Table 6.2: Mean major element composition of glass shards from Motukarara Valley Fill Core 2011, Banks Peninsula, and potential South Island & offshore tephra correlatives.

	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	Cl	H_2O	*n*
Tephra I; 145cm; 17B	78.13 (0.36)	0.13 (0.02)	12.59 (0.05)	1.20 (0.06)	0.06 (0.02)	0.11 (0.03)	1.05 (0.04)	3.61 (0.29)	3.13 (0.11)	nd[a]	5.74 (2.77)	2
Tephra II; 215cm; 31B	78.34 (0.17)	0.12 (0.02)	12.57 (0.10)	1.18 (0.05)	0.05 (0.02)	0.12 (0.02)	1.00 (0.06)	3.59 (0.12)	3.02 (0.12)	nd[a]	4.60 (1.58)	23
Whakatane Tephra, Pitt Island, Chatham Islands[b]	77.84 (0.19)	0.15 (0.05)	12.16 (0.12)	0.87 (0.06)	0.06 (0.07)	0.08 (0.06)	0.65 (0.06)	4.11 (0.15)	3.85 (0.17)	0.25 (0.03)	6.44 (0.51)	14
KkT, Okarito Lagoon, south Westland [c]	78.04 (0.30)	0.14 (0.03)	12.65 (0.15)	1.13 (0.10)	0.06 (0.06)	0.13 (0.02)	1.02 (0.07)	3.34 (0.41)	3.27 (0.34)	0.20 (0.05)	5.05 (1.42)	20
KkT, Galway Tarn, south Westland [c]	77.75 (0.36)	0.13 (0.03)	12.59 (0.16)	1.13 (0.13)	0.08 (0.05)	0.13 (0.03)	1.04 (0.06)	3.79 (0.24)	3.06 (0.11)	0.23 (0.16)	4.40 (1.62)	20
KkT, AT-331, ODP Site-1123, 1.01 mcd [d]	77.98 (0.29)	0.13 (0.03)	12.31 (0.12)	1.16 (0.08)	nd	0.11 (0.02)	1.07 (0.11)	3.98 (0.10)	3.05 (0.19)	0.15 (0.02)	4.23 (1.02)	15

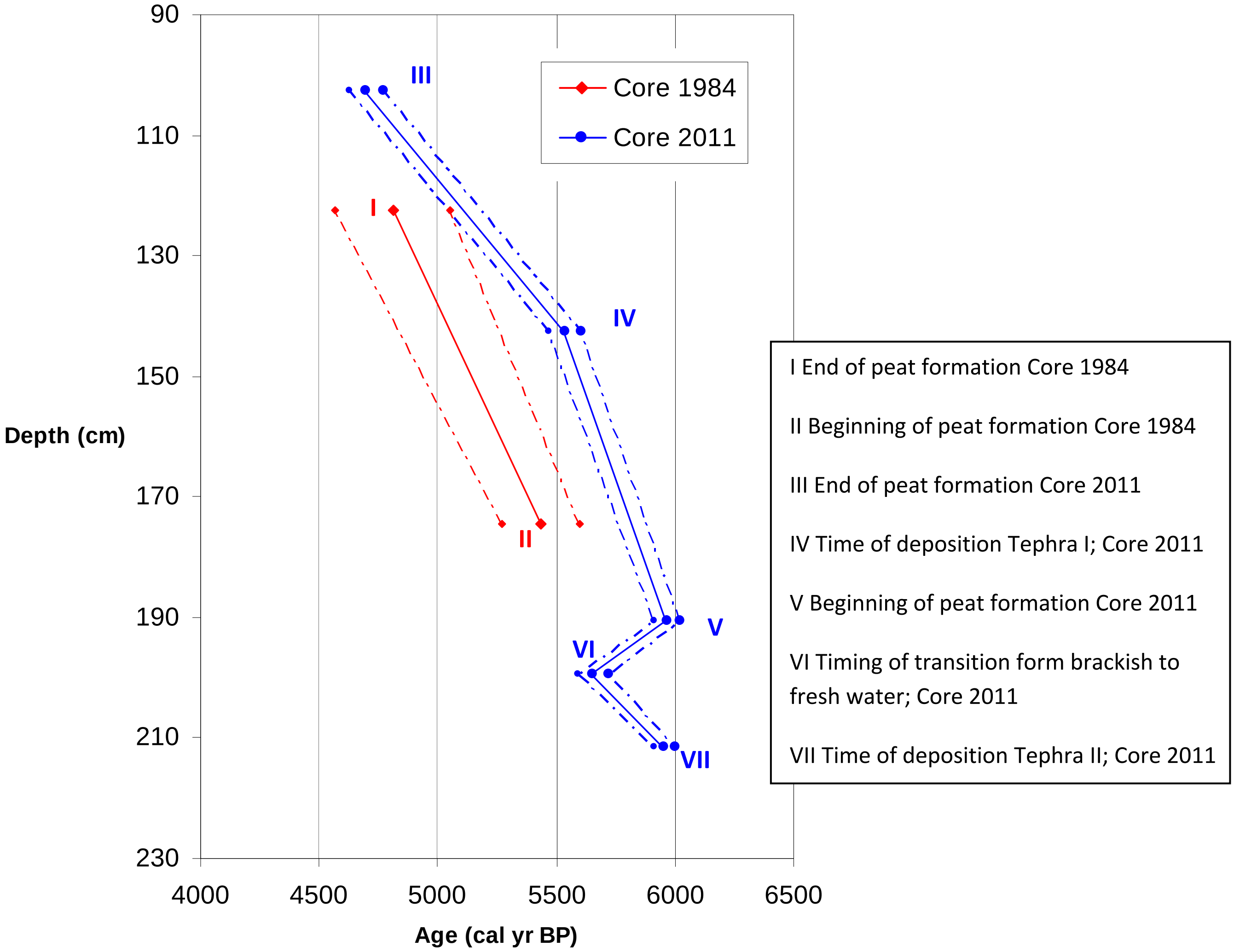
[a]Not determined or not available. References (analist and/or source): [b]D.J. Lowe in Holt et al., 2011; [c]J.L. Horrocks in Newnham et al., 2007b; [e]Alloway et al., 2005.

Date I and Date II are based on radiocarbon dating on bulk samples of peat. For Date III a mixture of twig, leaf and stem fragments and some seed cases have been extracted from a sample of the slightly oxidized top of the peat in Core 2011. For Date IV a mixtiure of twig and stem fragments, some seed cases and mosses were retrieved from a peat sample. For Date V a mixture of seed pods, plant rootlets and some fibers were taken from a peat sample just above the gyttja. For Date VI a mixture of twig and stetm fragments and some seed cases were retrieved from a gyttja sample just above the silt. For Date VII fibrous plant material is used as little more was present in the silt sample.

Average rates for peat formation are ± 10 cm in 100 yr before deposition of Tephra I and ± 7 cm in 100 yr after. Deposition rates for the silt and saline muds are hard to determine as the results of radiocarbon dating cause an age reversal towards the bottom of the core.

Table 6.3: Calibration of radiocarbon Date I and II from Motukarara Valley Fill Core 1984. References for calibration datasets: McCormac, 2004.

Radiocarbon date		Depth	Radiocarbon age (yrs BP)			Calibrated age							
						(cal yrs BC)		(cal yrs BP)		(cal yrs BP)			Probability
						Up	Low	Up	Low				
CORE 1984													
I	NZA7282 R11275/2	172-177	4340	±	80	3105	2619	5055	4569	4811	±	243	93.0%
II	NZA7280 R11275/1	120-125	4730	±	80	3645	3323	5595	5273	5433	±	161	88.9%
CORE 2011													
III	NZA37494 R32756/10	102-103	4264	±	30	2813	2671	4762	4620	4691	±	71	64.5%
IV	NZA37569 R32756/11	142-143	4848	±	30	3651	3515	5600	5464	5532	±	68	93.3%
V	NZA37500 R32756/7	190-191	5269	±	25	4065	3957	6014	5906	5960	±	54	89.7%
VI	NZA37493 R32756/9	199-200	4952	±	30	3763	3635	5712	5584	5648	±	64	95.1%
VII	NZA37518 32756/8	211-212	5252	±	20	4044	3958	5993	5907	5950	±	43	95.1%



I End of peat formation Core 1984

II Beginning of peat formation Core 1984

III End of peat formation Core 2011

IV Time of deposition Tephra I; Core 2011

V Beginning of peat formation Core 2011

VI Timing of transition form brackish to fresh water; Core 2011

VII Time of deposition Tephra II; Core 2011

Figure 6.10: Age-depth model for Motukarara Valley Fill Core 1984 (in red) and 2011 (in blue).

7 Discussion

7.1 Chronology

The radiocarbon dates from Core 1984 are less reliable as the dates from Core 2011 as bulk samples have been dated instead of separated plant material. The age reversal in the age-depth model of Core 2011 implicates that there are, however, some errors in the radiocarbon dates. The biggest error is probably in date VI, which is much too young. Small errors might have occurred for Date V, being too old, and Date VII being too young. Causes for these errors are the fact that Date V is taken at the transition from gyttja too peat where possibly mixing has occurred and older carbon has mixed in with the younger material. For Date VI rootlets are dated, which, if in situ, can be from younger plants that rooted in the older material and transferred younger carbon. Date VII is taken in from very scarce hard to identify fibrous material from the silt for which it is hard to say whether they are mixed in or not.

To solve the age reversal problem in 2011, let's assume that gyttja formation is the first step in peat formation and that Date V is unreliable, then it can be said that Tephra II was deposited around 5950 cal yrs BP (Date VII), 10 cm of silt was deposited before gyttja and peat formation started, around 5648 cal yrs BP. Then, 10 cm of gyttja and 45 cm of peat were deposited before Tephra I was deposited, around 5532 cal yrs BP. After this another 45 cm of peat formed before 4691 cal yrs BP.

If the age-depth models from both cores are compared is looks like peat formation has started later and stopped earlier in Core 1984 at the edge of the valley than in Core 2011 in the middle of the valley.

7.2 Environment

The palynological evidence clearly shows that mainly local site factors are reflected in the record. This is mainly implicated by the fact that changes in dryland vegetation occur coinciding with major changes in aquatics. The local signal is a transition from a salt/brackish to a fresh water environment. This is solidly supported by evidence from pollen, diatom and macrofossil analysis.

Correlation to other Holocene records is difficult due to lack of evidence on regional environmental changes in this record, but also due to the lack of detailed vegetation descriptions for the time frame of the Motukarara Valley Fill (approximately 6000 to 4500 cal yrs BP) in any of the comparable climate regions (eastern South Island and eastern North Island). Any indications of regional climate change from the pollenrecord should be interpreted carefully.

One scenario of the regional climate that can be interpreted from the pollendiagram, is one of podocarp-hardwood forest on the lower stable slopes, beech forest on the less stable slopes and tussock grassland on the higher grounds, with herbs and shrubs present throughout the area. Beech forest and herbs and shrubs expand at the expense of grasses. There is a general trend of climate amelioration.

This is based on the presence of podocarp-hardwood forest tree species throughout the record, the general increase in *Nothofagus fuscospora* and an absolute decline of grasses and relative decline of forest. The first herb and shrub species present in the tussock grassland are (sub-)alpine species such as *Gaultheria* and *Forstera*. With the ameliorating climate *Hebe* flourishes on young bare soils, quickly followed by an increase in pioneer species such as, *Coprosma* and *Coriaria*, which enter where grasses disappear. *Gunnera* indicates a wet environment and disappears when the area gets dryer, indicated by the strong increase in *Dodonaea*.

This general scenario since the Mid-Holocene is climate deterioration, which is supported by the pollen diagram, especially in the general rise in *Nothofagus fuscospora* and *Dodonaea*. However, the coinciding rise in *Podocarpus* spp. is contradicting to this.

An interesting observation made from the environmental data is that the transition from a salt/brackish to a fresh water environment occurs 1.2 to 2.2 meter above present sea level. This is consistent with a relative sea level decline (regression) after the Mid-Holocene sea level high (paragraph 4.1). This result has significance for sea level reconstruction in New Zealand and/or constraining uplift rates on Banks Peninsula. The latter has been made very pertinent by the recent demonstration of reverse faulting and uplift associated with the devastating Canterbury earthquakes of 2010 and 2011. Similar environmental research in more valleys on Banks Peninsula could aid in a detailed reconstruction of relative sea level changes on Banks Peninsula. This should be combined with a reconstruction of erosion on hill slopes on Banks Peninsula and the mineral influx into the valleys.

There are sources of error in the methods used to obtain the envirionmental data that should be taken into account in the interpretation.

The pH and EC values of solutions are very sensitive to changes in temperature and settling time and extreme differences between sequential samples could simply be reflecting errors, opposed to environmental changes. For loss on ignition, the location in the oven could affect the results by incomplete burning. This would however be likely to have reflected as a re-occurring pattern in the carbon content profile.

Errors might have been made within the microscopical analysis for pollen, diatoms and macrofossils. This can include misidentification of species or not recognizing something as being of importance. And, although species present in the record might indicate certain environmental characteristics, it should be taken into account that not all organisms that lived in the valley have been preserved. For example, for the diatoms counts that many diatom species are good indicators of salinity. On an isolated land mass such as New Zealand the physiology of the apparent species and their responses could differ in the absence of particular competing species, therefore values should be taken as indicating general preferences. Furthermore, for pollen as well as diatoms and macrofossils, there seem to be some inconsistencies of fresh water species being present in the marine/brackish environment and vice versa. Freshwater material could have washed into the lower sediments from surrounding land. Vice versa, salt and brackish water indicators in the upper core could have been moved upcore by bioturbation, carried in by sea birds or washed in by occasional storm tides.

7.3 Cryptotephra

Two concentration peaks of volcanic glass are found, plant remains in deposits related to the intervals with the highest concentration peaks are radiocarbon dated to 5532 and 5950 cal yrs BP. Geochemical analysis of glass shards from both tephra show a Kawakawa signature.

If the tephra in the study area is Kawakawa/Oruanui Tephra (KOT), it means that no previously recognized cryptotephra have been identified in this study. KOT then remains the only unequivocally recognised Late Quaternary tephra in South Island, NZ. This study would then show that KOT appears to reoccur as a reworked tephra in deposits with ages widely ranging from the time of primary deposition, 25.45 cal ka BP.

However, very similar geochemical composition does not mean that the tephra deposits are by definition KOT. It does imply that the tephra in the study area have the same source of origin as KOT, Taupo Volcanic Centre, but it could be from another eruptive event, as different tephra deposits from the same volcanic source can have very similar geochemical composition.

Recent eruptions, like the one of the Puyehue-Cordón volcano, Chile (June 2011), have shown just how far volcanic ash can travel and how distal tephra can be deposited. Other tephra from the CVR or from other volcanic sources are likely to have dispersed over South Island and therefore must have been deposited, and potentially preserved in favourable environments.

Based on the lithological data both tephra are deposited in a low energy depositional environment. Tephra I and Tephra II are found embedded in sediments where the pollen, macrofossil and diatom records do not show an irregular influx of older material. Tephra I is embedded in peat and the peak concentration does not coincide with a mineral influx. This contradicts that Tephra I is reworked older material from the surrounding hill slopes and implies thatit is a primary airfall tephra.

Tephra II is spread over a wide depth range in fine material that does not show any influx of minerogenic material with a larger grain size. This also implies the tephra to be primary airfall tephra. However the fine sediments have been deposited in a tidal flat and if eroded material from the surrounding hill slopes would have been deposited in this tidal flat, larger grains could have been washed out. This would explain the difference between the grain size of the silt deposits in which the tephra has been found and the grain size of the material on the surrounding hill slopes. This could mean that hill slope material with Kawakawa Tephra is deposited in the tidal flat and sorting due to tidal activity has resulted in silt deposits with a high concentration of tephra.

This would mean that at least one, and possibly two, primary airfall tephra have been deposited in the study area and that several tephra from eruptions from Taupo Volcanic Centre have the Kawakawa signature. The eruption history of Taupo Volcanic Centre, as recorded by Wilson (1993; Table 2.3) gives 11 eruptions (Unit H to R) within the time frame of Motukarara Valley Fill (approximately 6000 to 4500 cal yrs BP). The highest correlation is between Tephra II of Core 2011 and Unit I Tephra, both dated to 5950 cal yrs BP. However, as discussed, the age of Tephra II is uncertain and Tephra II could represent reworked Kawakawa Tephra.

Tephra I is less easy to correlate as it is dated at 5532 cal yrs BP and falls in a gap between Unit I (5950 cal yrs BP) and Unit J (5370 cal yrs BP). This could be explained by post-depositional movement of the peak concentration or an error in the radiocarbon date. A concentration profile with a smaller depth increment is necessary to define this post-depositional movement.

The possibility that the chemical composition of the tephra has been altered should be taken into account. It is distal tephra and heavy minerals present close to the source might not be present in the study area. Furthermore, the tephra are buried in an acid peat environment which might have lead to dissolution of certain chemicals. Chemical fingerprinting of the small glass grains associated with these distal cryptotephra is challenging. New techniques and refined methods should be explored to isolate the small glass grains and to even better identify the geochemical affinities of these tephra, possibly based on rare earth elements as well as major element composition.

Another interesting point of study would be the erosion of basaltic surfaces on Banks Peninsula and the influx of basaltic material in valley deposits. During the cleaning of soil samples for tephra, black sand grains, likely to be basaltic, were observed in the cleaned samples.

7.4 Palaeogeography

Based on the combined results a series of palaeogeographical maps (Figure 7.1) for Motukarara Valley has been constructed. These maps are accompanied by a chronology for the valley, described in 7 stages.

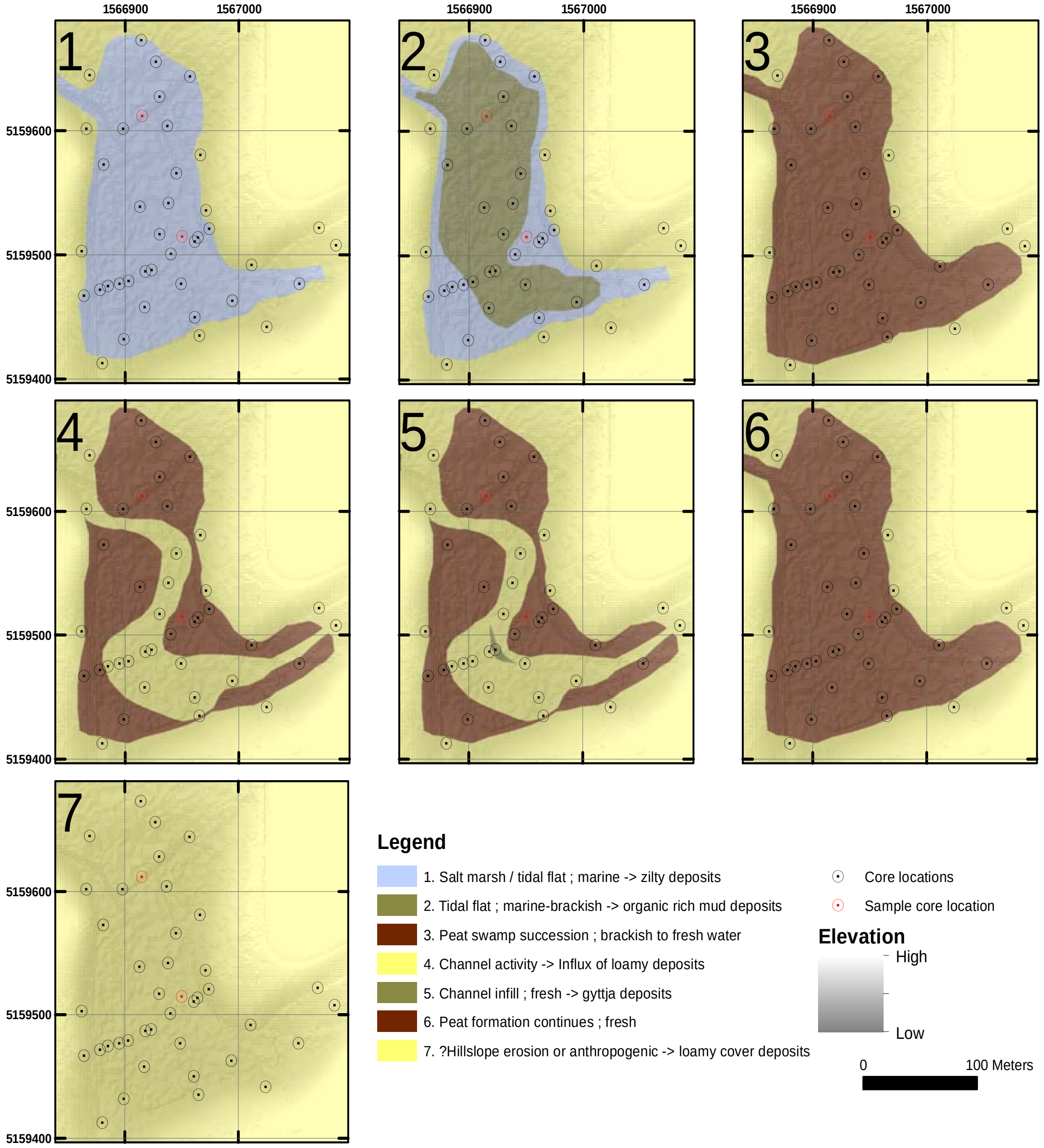


Figure 6.10: Palaeogeographical maps for Motukarara Valley.

Stages 1 to 3 describe the scenario for the larger part of the valley as recorded in Core 1984 and 2011, radiocarbon dates are used to time these stages. Stages 4 to 7 are not recorded in the cores and are purily based on the lithological research. In the middle of the valley, peat formation is not continuous, it is interfered by the formation and abandonment of a channel, described in stage 4 and 5. Stage 6 is a continuation of stage 3 and stage 7 described the development of the current topsoil.

The chronology starts when a presumably dry valley, with a loamy top soil, is intruded by the sea. An abandoned channel, entering the valley from the west, is presumably the channel that connected the valley with the present Lake Ellesmere area. Where possible radiocarbon dates are added.

Stage 1. The intrusion of the sea into the valley led to the deposition of silt deposits in a marine environment. This started before **5950 cal yr BP** and lasted until **5648 yrs BP** at the longest. These deposits occur between 0 and 2.5 m.a.s.l. The tidal flat slowly progressed into a tidal salt-marsh with increased vegetation locally, indicated by the presence of roots. In this tidal salt-marsh Tephra II is deposited around **5950 cal yr BP** with its peak at the final stage, before transition into a brackish salt-marsh. Stage 1 coincides with zone 1a of the pollen diagram. The environment is still salt/brackish and tussock grasslands are still relatively widespread. Beech forest is still rare, a first sign of shrubs developing in grassland areas is the rise in Hebe.

Stage 2. In this brackish salt-marsh organic rich mud is deposited in the deepest parts of the valley, this presumably started around **5648 yrs BP**. These deposits are interfered with thin layers of peat like deposits. During this stage diatoms and macrofossils are very abundant, while pollen are scarce. At the end of this stage, hardly any brackish and salt tolerating species are present and fresh water aquatics have started increasing dramatically. This transition takes place between 1.2 and 2.2 m.a.s.l. This indicates closure of the valley from the sea, which implies the formation of a beach ridge before the end of this stage. Stage 2 coincides with zone 1b and 2a of the pollen diagram. The fresher environment is ideal for *Dodonaea*, which rapidly rises. In combination with the disappearance of *Gunnera* this indicates a local transition to a dryer environment. Tussock grasslands slowly disappear, herb and shrub species take over and beech forest expands.

Stage 3. Peat formation starts in a brackish environment, indicated by macrofossils and diatoms. It starts around **5433 cal yrs BP** at the edge of the peat, **earlier** in the middle of the peat, indicated by the age of Tephra I, **5532 cal yrs BP**, which is embedded in the peat. Peat formation continues until **4691 cal yrs BP**. The first part of the peat records a further transition from a brackish to fresh environment. This occurs before the deposition of Tephra I. The peat formation during this continuing transition is deposited between 1.5 and 2.3 m.a.s.l. and coincides with zone 2b and 2c of the pollendiagram. The environment becomes wetter, indicated by an increase in fresh water aquatics and a decrease of *Dodonaea*. After deposition of Tephra I, peat formation continues in a shallow fresh water lake, coinciding with zone 3 and 4 of the pollendiagram. Beech forest further expands, grasslands further decline. The local environment in the valley becomes wetter, indicated by the entrance of *Epilobium*.

Stage 4. At some stage during peat formation water levels dropped and the influx of minerogenic matter increased for part of the valley. A channel developed and it formed levees. These levees are locally positioned above oxidated peat which is likely to have happened due to the same drop in water levels, but may also have happened in stage 6 or 7.

Stage 5. Channel activity has stopped and channel infill starts with the formation of gyttja at the base of the abandoned channel. Gyttja is only found in one coring but is likely to have formed in a larger part of the abandoned channel. After the formation of gyttja further infill of the channel with peat occurred.

Stage 6. The peat formation in the channel coincided with the continuation of peat formation throughout the valley. This stage of peat formation occurred in the shallow lake described in stage 3.

Stage 7. This phase is characterized by deposition of loamy cover materials that in the corings looked very disturbed and therefore was not included in Core 2011 and the analysis. It is unclear whether these deposits were of natural or anthropogenic cause.

8 Conclusion

Two tephra have been found in Holocene valley deposits. This is the first study to report on distinct cryptotephra in Holocene deposits. The cryptotephra have a Kawakawa signature and could therefore be identified as reworked Kawakawa/Oruanui tephra (KOT). However, they strongly look like primary airfall deposits, especially Tephra I, rather than reworked older material, based on the fact that the lithological and environmental evidence indicate a calm depositional environment and no influx of older material is recorded. Tephra II could be explained as a reworked Kawakawa Tephra based on the depositional processes in a tidal flat. At least, the tephra are likely to have the same origin as KOT: Taupo Volcanic Centre.

In answer to the research question: "*How does the volcanic ash, present in the valley deposits, fit into the Late Quaternary stratigraphy of South Island, New Zealand?"*

There is tephra present in Holocene deposits. These tephra have a Kawakawa signature, Tephra I does not seem to be reworked and Tephra II could be reworked. Whether the tephra are reworked or not, this has major implications for the Late Quaternary stratigraphy of South Island, New Zealand in which KOT is widely applied as a chronohorizon. It raises the question: How distinct is Kawakawa Tephra, based on the mean major element composition, and is it suitable to use in tephrochronology?

More than one tephra are present in South Island deposits, they have similar geochemical compositions but very different ages. There could be more than one primary airfall tephra and these could be reworked. This means that KOT should not be used as a chronohorizon in South Island lightly and tephra in South Island should never be assumed to be KOT from 25.45 cal ka.

The valley deposits in which the tephra is found, records on a Mid-Holocene sea level high. Deposits from marine depositional environments have been found above present sea level. Transgression has caused the sea to slowly retreat from the valley and the tidal flat developed into salt-marsh in which the influence of the sea slowly decreased. A transition took place in which the salt-marsh changed into a brackish peat swamp and eventually a fresh water environment was established. Peat formation took place in a fresh water peat swamp and later a fresh water lake. The increased water levels to form a lake have been interfered by at least one period of regression during which a small scaled channel belt is present in the peat deposits and the top of the peat has been oxidized.

9 References

Alloway, B.V., R.B. Stewart, V.E. Neall and C.G. Vucetich – 1992 – Climate of the last glaciations in New Zealand, based on aerosolic quartz influx in an andesitic terrain. – Quaternary Research, vol.38, p.170-179.

Alloway, B.V., V.E. Neall and C.G. Vucetich – 1995 – Late Quaternary (post-28,000 yr BP) tephrostratigraphy of northeast and central Taranaki, New Zealand. – Journal of the Royal Society of New Zealand, vol.25, p.385-458.

Alloway, B.V., B.J. Pillans, L. Carter, T.R. Naish and J.A. Westgate – 2005 – Onshore–offshore correlation of Pleistocene rhyolitic eruptions from New Zealand: implications for TVZ eruptive history and paleaoenvironmental construction. – Quaternary Science Reviews, vol.24, p.1601-1622.

Alloway, B.V., D.J. Lowe, D.J.A. Barrell, R.M. Newnham, P.C. Almond, P.C. Augustinus, N.A.N. Bertler, L.Carter, N.J. Litchfield, M.S. McGlone, J. Shulmeister, M.J. Vandergoes, P.W. Williams and NZ-INTIMATE members – 2007 – Towards a climate event stratigraphy for New Zealand over the past 30,000 years (NZ-INTIMATE project). – Journal of Quaternary Science, vol.22(1), p.9-35.

Almond, P.C. – 1996 – Loess, soil stratigraphy and Aokautere Ash on late Pleistocene surfaces in south Westland: interpretation and correlation with the glacial stratigraphy. – Quaternary International 32/33, 163-176.

Almond, P.C. and P.J. Tonkin – 1999 – Pedogenesis by upbuilding in an extreme leaching and weathering environment, and slow loess accretion in south Westland, New Zealand. – Geoderma, vol.92, p.1-36.

Almond, P.C., F.L. Shanhun, U. Rieser and J. Schulmeister – 2007 – An OSL, radiocarbon and tephra isochron-based chronology for Birdlings Flat loess at Ahuriri Quarry, Banks Peninsula, Canterbury, New Zealand. – Quaternary Geochronology, vol.2, p.4-8.

Almond, P.C., J.J. Roering, M.W. Hughes, F.S. Lutter and C. LeBouteiller – 2008 – Climatic and anthropogenic effects on soil transport rates and hillslope evolution. – Sediment in Changing Environments, IAHS Publications, 325.

Armon, J.W. – 1973 – Late Quaternary shorelines near Lake Ellesmere, Canterbury, New Zealand. – New Zealand Journal of Geology and Geophysics, vol.17, p.63-73.

Ballance, P.F. – 1976 – Evolution of the Upper Cenozoic magmatic arc and plate boundary in northern New Zealand – Earth and planetary science letters, vol.28, p.356-370.

Barrell, D.J. A., B.V. Alloway, J. Shulmeister and R.M. Newnham (eds) – 2005 – Towards a climate event stratigraphy for New Zealand over the past 30 000 years. – Institute of Geological and Nuclear Sciences, Science Report, SR2005-07 (includes poster).

Behre, K.-E. (ed) – 1986 – Anthropogenic Indicators in Pollen Diagrams. – Balkema, Rotterdam.

Bennett, J.R., B.F. Cumming, B.K. Ginn and J.P. Smol – 2010 – Broad-scale environmental response and niche conservatism in lacustrine diatom communities. – Global Ecology and Biogeography, vol.19, p.724-732.

Berger, G.W., B.J. Pillans and A.S. Palmer – 1994 – Test of thermoluminescence dating of loess from New Zealand and Alaska. – Quaternary Science Reviews, vol.13, p.309-333.

Berger, G.W., P.C. Almond and B.J. Pillans – 2001 – Luminescence dating and glacial stratigraphy in Westland, New Zealand. – New Zealand Journal of Geology and Geophysics, vol.44, vol.25-35.

Birks, H.J.B. and H.H. Birks – 1980 – Quaternary Palaeoecology. – Edward Arnold, London.

Björck, S., M.J.C. Walker, L.C. Cwynar, S. Johnsen, K.-L. Knudsen, J.J. Lowe, B. Wohlfarth and INTIMATE Members – 1998 – An event stratigraphy for the last termination in the North Atlantic region based on the Greenland ice-core record: a proposal by the INTIMATE-group. – Journal of Quaternary Science, vol.13, p.283-292.

Blackburn, D.T. – 1980 – Megafossil/lithotype correlations in a transect of the Yallourn Opencast Coal Mine. – State Electricity Commission of Victoria Palaeobotany Project, Major Report No. 1, 84pp.

Blakemore, L.C., P.L. Searle and B.K. Daly – 1987 – Methods for chemical analysis of soils. – NZ Soil Bureau Scientific Report, vol.80.

Blockley, S.P.E., C.S. Lane, A.F. Lotter and A.M. Pollard – 2007 – Evidence for the presence of the Vedde Ash in Central Europe. – Quaternary Science Reviews, vol.26, p.3030-3036.

Blockley, S.P.E., C. Bronk Ramsey, C.S. Lane and A.F. Lotter – 2008 – Improved age modelling approaches as exemplified by the revised chronology for the Central European varved lake Soppensee. – Quaternary Science Reviews, vol.27, p.61-71.

Bogaard, C. van den and H.U. Schmincke – 2002 – Linking the North Atlantic to central Europe: a high-resolution Holocene tephrochronological record from northern Germany. – Journal of Quaternary Science, vol.17(1), p.3-20.

Boygle, J. – 1999 – Variability of tephra in lake and cathcment sediments, Svinavatn, Iceland. – Global and Planetary Change, vol.21, p.129-149.

Bruce, J.D., D.W. Ives and M.L. Leamy – 1973 – Maps and sections showing the distribution and stratigraphy of South Island loess deposits, New Zealand. – New Zealand Soil Bureau Soil Survey Report, vol.7.

Carey, S. – 1997 – Influence of convective sedimentation on the formation of widespread tephra fall layers in the deep sea. – Geology, col.25, p.839-842.

Carter, B.J., P.A. Ward III and J.T. Shannon – 1990 – Soil and geomorphic evolution within the Rolling Red Plains using Pleistocene volcanic ash deposits. – Geomorphology, vol.3, p.471-488.

Carter, L., C.S. Nelson, H.L. Neil and P.C. Froggatt – 1995 – Correlation, dispersal, and preservation of the Kawakawa Tephra and other late Quaternary tephra layers in the southwest Pacific Ocean. – New Zealand Journal of Geology and Geophysics, vol.38, p.29-46.

Carter, L., P.A.R. Shane, B.V. Alloway, I.R. Hall, S.E. Harris and J.A. Westgate – 2003 – Demise of one volcanic zone and birth of another - a 12 m.y. marine record of major rhyolitic eruptions from New Zealand – New Zealand Jounral of Geology and Geophysics, vol.38, p.493-496.

Cassie, V. – 1983 – A guide to algae in oxidation ponds in the Auckland district. – Tane, vol.29, p.119-128.

Christiansen, R.L. and D.W. Peterson – 1981 – Chronology of the 1980 eruptive activity. – In: The 1980 Eruptions of Mount St Helens, washinton. By: P.W. Lipman and D.R. Mullineaux (eds). – Geological Survey Professional Paper, vol.1250, p.17-30.

Coombs, D.S. – 1965 – Dunedin Volcanic Complex and Waipiata Volcanic Formation. – New Zealand Department of Scientific and Industrial Research, information series, vol.51, p.54-67.

Cronin, S.J., V.E. Neall, A.S. Palmer and R.B. Stewart – 1997 – Methods of identifying late Quaternary tephras on the ring plains of Ruapehu and Tongariro volcanoes, New Zealand. – New Zealand Journal of Geology and Geophysics, vol.40, p.175-184.

Darragh, M., J.W. Cole, I.A. Nairn and P.A.R. Shane – 2006 – Pyroclastic stratigraphy and eruption dynamics of the 21.9 ka Okareka and 17.6 ka Rerewhakaaitu eruption episodes from Tarawera Volcano, Okataina Volcanic Centre, New Zealand. – New Zealand Journal of Geology and Geophysics, vol.49, p.309-328.

Davidson, J. – 1984 – The prehistory of New Zealand. – Longman Paul, Auckland.

Davies, S.M., N.P. Branch, J.J. Lowe and C.S.M. Turney – 2002 – Towards a European tephrochronological framework for Termination 1 and the Early Holocene. – Philosophical Transactions: Mathematical, Physical and Engineering Sciences, vol.360, No.1793, p.767-802.

Davies, S.M., G. Larsen, S. Wastegård, C.S.M. Turney, V.A. Hall, L. Coyle and T. Thordarson – 2010 – Widespread dispersal of Icelandic tephra: how does the Eyjaflöll eruption of 2010 compare to past Icelandic events? – Journal of Quaternary Science, vol.25(5), p.605-611.

De Silva, S.L. and G. A. Zielinski – 1998 – Global influence of the AD 1600 eruption of Huaynaputina, Peru. – Nature, vol.393, p.455-458.

Delcourt, H.R. and P.A. Delcourt – 1991 – Quaternary Ecology: A Palaeoecological Perspective. – Chapman & Hall, London.

Donoghue, S.L., V.E. Neall and R.B. Stewart – 1995 – Stratigraphy and chronology of andesitic tephra deposits, Tongariro Volcanic Centre, New Zealand. – Journal of the Royal Society of New Zealand, vol.25, p.112-206.

Donoghue, S.L., A.S. Palmer, E. McClelland, K. Hobson, R.B. Stewart, V.E. Neall, J. Lecointre and R. Price – 1999 – The Taurewa eruptive episode: evidence for climatic eruptions at Ruapehu volcano, New Zealand. – Bulletin of Volcanology, vol.60, p.223-240.

Donoghue, S.L., J. Vallance, I.E.M. Smith and R.B. Stewart – 2007 – Using geochemistry as a tool for correlating proximal andesitic tephras: case studies from Mt Rainier (USA) and Mt Ruapehu (New Zealand). – Journal of Quaternary Science, vol.22, p.395-410.

Duggan, M.B. and A. Raey – 1986 – The Timaru Basalts – In: “Late Cenozoic volcanism in New Zealand.” By: I.E.M. Smith (ed). – Royal Society of New Zealand bulletin, vol.23, p.264-277.

Dugmore, A.J., G. Larsen and A.J. Newton – 2004 – Tephrochronology and its application to late Quaternary environmental reconstruction, with special reference to the North Atlantic Islands. – In:Tools for constructing chronologies: crossing disciplinary boundaries. By: C.E. Buck and A.R. Millard (eds) – Lecture Notes in Statistics, vol.177, p.173-188 – Springer, London.

Eden, D.N. and A.P. Hammond – 2003 – Dust accumulation in the New Zealand region since the last glacial maximum. – Quaternary Science Reviews, vol.22, p.2037-2052.

Eden, D.N., P.C. Froggatt and P.D. McIntosh – 1992 – The distribution and composition of volcanic glass in Late Quaternary loess deposits of southern South Island, New Zealand, and some possible correlations. – New Zealand Journal of Geology and Geophysics, vol.35, p.69-79.

Faegri, K., J. Iverson and K. Krzywinski – 1989 – Textbook of Pollen Analysis – 4th edition – John Wiley, Chichester and New York.

Fairbanks, R.C., R.A. Mortlock, T.-C. Chui, C. Li, A. Kyrplan, T.P. Guilderon, T.W. Fairbanks, A.L. Bloom, P.M. Grootes and M.-J. Nadeau – 2005 – Radiocarbon calibration curve spanning 0 to 50,000 years BP based on paired 230Th/234U/238U and radiocarbon dates on pristine corals. – Quaternary Geochronology, Quaternary Science Reviews, vol.24, p.1781-1796.

Froggatt, P.C. and G.J. Gosson – 1982 – Techniques for the preparation of tephra samples for mineral or chemical anlysis and radiometric dating. – Geology Department, Victoria University of Wellington, Publication 23, p.1-12.

Froggatt, P.C. and D.J. Lowe – 1990 – A review of late Quaternary silicic and some other tephra formations from New Zealand. – New Zealand Journal of Geology and Geophysics, vol.33, p.89-109.

Gehrels, M.J., D.J. Lowe, Z.J. Hazell and R.M. Newnham – 2006 – A continueous 5300-yr Holocene cryptotephrostratigraphic record from northern New Zealand and implications for tephochronology and volcanic hazard assessment. – Holocene, vol.16, p.173-187.

Gibb, J.G. – 1986 – A New Zealand regional Holocene eustatic sea-level curve and its application to the determination of vertical tectonic movements. – Royal Society of New Zealand Bulletin, vol.24, p.377-395.

Goh, K.M., B.P.J. Molly and T.A. Rafter – 1977 – Radiocarbon dating of Quaternary loess deposits, Banks Peninsula, Canterbury, New Zealand. – Quaternary Research, vol.7, p.177-196.

Grapes, R., U. Rieser and N. Wang – 2010 – Optical luminescence dating of a loess section containing a critical tephra marker horizon, SW North Island of New Zealand. – Quaternary Geochronology, vol.5, p.164-169.

Griffiths, E. – 1973 – Loess of Banks Peninsula. – New Zealand Journal of Geology and Geophysics, vol.16, p.657-675.

Grimm, E.C. – 1987 – Coniss : a Fortran 77 program for stratigraphically constrained cluster analysis by the method of incremental sum of squares. – Computers and Geosciences, vol.13, p.13-35.

Grimm , E. C. – 1990 – TILIA 2.0 - Software. Illinois State Museum, Research and Collection Center, Springfield.

Grimm , E. C. – 2004 – Tilia Graph Software. Illinois State Museum, Research and Collection Center , Springfield.

Hajdas, I., D.J. Lowe, R.M. Newnham and G. Bonani – 2006 – Timing of the late-glacial climate reversal in the Southern Hemisphere using high-resolution radiocarbon chronology for Kaipo bog, New Zealand. – New Zealand Quaternary Research, vol.65, p.340-345.

Harris, S.A. – 1983 – Infilled fissures in loess, Banks Peninsula, New Zealand. – Polarforschung, vol.53(2), p.49-58.

Hedberg, H.D. – 1976 – International Stratigraphic Guide – Wiley, New York, United States of America.

Heiri, O., A. F. Lotter & G. Lemcke – 2001 – Loss on ignition as a method for estimating organic and carbonate content in sediments: Reproducibility and comparability of results. – Journal of Paleolimnology, vol**.**25, p.101-110.

Hodder, A.P.W., P.J. de Lange and D.J. Lowe – 1991 – Dissolution and depletion of ferromagnesian minerals from Holocene tephra layers in an acid bog, New Zealand, and implications for tephra correlation. – Journal of Quaternary Science, vol.6, p.195-208.

Hoek, W.Z., Z.C. Yu and J.J. Lowe – 2008 – INTegration of Ice-core, MArine and TErrestrial records (INTIMATE): refining the record of the Last Glacial–Interglacial Transition. – Quaternary Science Reviews, vol.27, p.1-5.

Hogg, A.G., T.F.G. Higham, D.J. Lowe, J. Palmer, P. Reimer and R.M. Newnham – 2003 – A wiggle-match date for Polynesian settlement of New Zealand. – Antiquity, vol.77, p.116-125.

Holden, A.M. – 1987 – Vegetation-lithotype correlation in New Zealand lignites. – New Zealand Energy Research and Development Committee Report, vol.150.

Holt, K.A., R.C. Wallace, V.E. Neall, B.P. Kohn and D.J. Lowe – 2010 – Quaternary tephra marker beds and their potential for palaeoenvironmental reconstruction on Chatham Island, east of New Zealand, southwest Pacific Ocean. – Journal of Quaternary Science, vol.25(7), p.1169-1178.

Holt, K.A., D.J. Lowe, A.G. Hogg and R.C. Wallace – 2011 – Distal occurrence of Mid-Holocene Whakatane tephra and potential for cryptotephra. – Quaternary International, vol.264(1-2), p.344-351.

Houghton, B.F., S.D. Weaver, C.J.N. Wilson and M.A. Lanphere – 1992 – Evolution of a Quaternary peralkaline volcano: Mayor Island, New Zealand. – Journal of Volcanology and Geothermal Research, vol.51, p.217-236.

Hughen K.A., J. Southon, S. Lehman, C. Bertrand and J. Turnbull – 2006 – Marine-derived ^{14}C calibration and activity record for the past 50,000 years updated from the Cariaco Basin. – Quaternary Science Reviews, vol.25, p.3216-3227.

Hughes, M.W. – 2008 – Reconstruction late Quaternary environmental change in Charwell Basin, South Island, New Zealand - Part I: Loess stratigraphy, pedogenesis and chronology. – In: PhD thesis – Lincoln University.

Hughes, M.W., P.C. Almond and J.J. Roering – 2009 – Increased sediment transport via bioturbation at the last glacial-interglacial transition. – Geology, vol.37, p.919-922.

Huntley, B. And H.J.B. Birks – 1983 – An Atlas of Past and Present Pollen Maps for Europe: 0-13,000 Years Ago. – Cambridge University Press.

Hurst, T. and W. Smith – 2004 – A Monte Carlo methodology for modelling ashfall hazards. – Journal of Volcanology and Geothermal Research, vol.138, p.393-403.

Hurst, T. and W. Smith – 2010 – Volcanic ashfall in New Zealand - probabilistic hazard modelling for multiple sources. – New Zealand Journal of Geology and Geophysics, vol.53, p.1-14.

Jansen, W. And M. Slaughter – 1982 – Elemental mapping of minerals by electron microprobe. – American Mineralogist, vol.67(5-6), p.521-533.

Jenkins, S.F., C.R. Magill and K.J. McAneney – 2007 – Multi-stage volcanic events: a statistical investigation. – Journal of Volcanology and Geothermal Research, vol.161, p.275-288.

Jouzel, J., V. Masson, O. Cattani, S. Falourd, M. Stievenard, B. Stenni, A. Longinelli, S.J. Johnsen, J.P. Steffenssen, J.R. Petit, J. Schwander, R. Souchez and N.I. Barkov – 2001 – A new 27 kyr high resolution East Antarctic climate record. – Geophysical Research Letters, vol.28, p.3199-3202.

Kidson, J.W. – 2000 – An analysis of New Zealand synoptic types and their use in defining weather regimes. – International Journal of Climatology, vol.20, p.299-316.

Kilroy, C. and L. Bergey – 1999 – Diatoms: biological gems. – Water & Atmosphere, vol.7(3), p.13-16.

Kirk, R.M. – 1994 – The origins of Wihora/Lake Ellesmere. – In: Waihora/Lake Ellesmere: Past, Present, Future. By: J.D.G. Davies, L. Galloway and A.H.C. Nutt (eds). – Lincoln University Press.

Kobayashi, T., I. Nairn, V. Smith and P.A.R. Shane – 2005 – Proximal stratigraphy and event sequence of the c. 5600 cal yr BP Whakatane rhyolite eruption episode from Haroharo volcano, Okataina Volcanic Centre, New Zealand. – New Zealand Journal of Geology and Geophysics, vol.48, p. 471-490.

Krammer, K. & H. Lange-Bertalot – 1986-1991; translated in 2000 – Bacillariophyceae. – In 1-4 Süsswasserflora von Mitteleuropa. By: H. Ettl, G. Gärtner, J. Gerloff, H. Heynig and D. Mollenhauer (eds). – Gustav Fischer Verlag, Stuttgart, New York.

Kuehn, S.C. and R.M. Negrini – 2010 – A 250 k.y. record of Cascade arc pyroclastic volcanism from late Pleistocene lacustrine sediments near Summer Lake, Oregon, USA. – Geosphere, vol.6, p.397-429.

Laluraj, C.M., K.P. Krishnan, M. Thamban, R. Mohan, S.S. Naik, W. D'Souza, R. Ravindra and A. Chaturvedi – 2009 – Origin and characterisation of microparticles in an ice core from the central Dronning Maud land, east Antarctica. – Environmental Monitoring and Assessment, vol.149, p.377-383.

Leng, M.J. and G.E.A. Swann – 2010 – Stable isotopes from diatom silica. – In: The diatoms: Applications for Environmental and Earth Science. By: J.P. Smol and E.F. Stoermer (eds.) – 2nd edition, Cambridge University Press, Cambridge, p.575-589.

Li, X., G.L. Rapson and J.R. Flenley – 2008 – Holocene vegetational and climatic history, Sponge Swamp, Haast, south-western New Zealand. – Quaternary International, vol.184, p. 129-138.

Liggett, K.A. and D.R. Gregg – 1965 – The geology of Banks Peninsula. – New Zealand DSIR Info, vol.51, p.9-25.

Lindsay, J., W. Marzocchi, G. Jolly, R. Constantinescu, J. Selva and L. Sandri – 2009 – towards real-time eruption forecasting in the Auckland Volcanic Field: application of BET_EF during the New Zealand National Disaster exercise 'Ruaumoko'. – Bulletin of Volcanology, vol.72, p.185-204.

Lorrey, A., A.M. Fowler and J. Salinger – 2007 – Regional climate regime classification as a qualitative tool for interpreting multi-proxy palaeoclimate data spatial patterns: A New Zealand case study. – Palaeogeography, Palaeoclimatology, Palaeoecology, vol.253, p.407-433.

Lowe, D.J. – 1988 – Stratigraphy, age, composition and correlation of Quaternary tephras interbedded with organic sediments in Waikato lakes, North Island, New Zealands. – New Zealand Journal of Geology and Geophysics, vol.28, p.125-165.

Lowe, D.J. – 2008 – Globalization of tephrochronology: new views from Australasia. – Progress in Physical Geography, vol.32(2), p.311-335.

Lowe D.J. – 2011 – Tephrochronology and its application: A review. – Quaternary Geochronology, vol.6(2), p.107-153.

Lowe, D.J. and J.B. Hunt – 2001 – A summary of terminology used in tephra-related studies. – In: "Tephras: Chronology, Archaeology." by Juvigné, E.T. and J.P. Raynal (eds), "Les Dossiers de l'Archéo-Logis". – CDERAD éditeur, Goudet, France. – p.17-22.

Lowe, D.J., R.M. Newnham and C.M. Ward – 1999 - Stratigraphy and chronology of a 15 ka sequence of multi-sourced silicic tephras in a montane peat bog, eastern North Island, New Zealand. – New Zealand Journal of Geology and Geophysics, vol.42, p.565–579.

Lowe, D.J., R.M. Newnham, B.G. McFadgen and T.F.G. Higham – 2000 – Tephras and New Zealand Archaeology. – Journal of Archaeological Science, vol.27, p.859-870.

Lowe, D.J., P.A.R. Shane, B.V. Alloway and R.M. Newnham – 2008 – Fingerprints and age models for widespread New Zealand tephra marker beds erupted since 30,000 years ago: a framework for NZ-INTIMATE. – Quaternary Science Reviews, vol.27, p.95-126.

Lowe, D.J., C.J.N. Wilson, R.M. Newnham and A.G. Hogg – 2010 – Dating the Kawakawa/Oruanui eruption: Comment on "Optical luminescence dating of a loess section containing a critical tephra marker horizon, SW North Island of New Zealand." By Grapes et al., 2010 (Quaternary Geochronology 5) – Quaternary Geochronology, vol.5, p.493-496.

Lowe, J.J. – 2001 – Abrupt climatic changes in Europe during the last glacial–interglacial transition: the potential for testing hypotheses on the synchroneity of climatic events using tephrochronology. – Global and Planetary Change, vol.30, p.73-84.

Lowe, J.J. and M.J.C. Walker – 1997 – Reconstructing Quaternary Environments. – 2nd ed – Pearson Education Limited, Essex, England. – p.265-267.

Lowe, J.J. and M.J.C. Walker – 2000 – Radiocarbon dating of the last glacial - interglacial transition (ca. 14-9 ^{14}C yr BP) in terrestrial and marine records: the need for new quality assurance protocols. – Radiocarbon, vol.42, p.53-68.

Lowe, J.J., H.H. Birks, S.J. Brooks, G.R. Coope, D.D. Harkness, F.E. Mayle, C. Sheldrick, C.S.M. Turney and M.J.C. Walker – 1999 – The chronology of palaeoenvironmental changes during the last glacial–Holocene transition: towards an event stratigraphy for the British Isles. – Journal of the Geological Society London, vol.156, p.397-410.

Lowe, J.J., W.Z. Hoek and INTIMATE Group – 2001 – Inter-regional correlation of palaeoclimatic records for the Last Glacial–Interglacial Transition: a protocol for improved precision recommended by the INTIMATE project group. – Quaternary Science Reviews, vol.20, p.1175-1187.

Lowe, J.J., S.O. Rasmussen, S. Björck, W.Z. Hoek, J.P. Steffensen, M.J.C. Walker, Z.C. Yu – 2008 – Synchronisation of palaeoenvironmental events in the North Atlantic during the Last Termination: a revised protocol recommended by the INTIMATE group. – Quaternary Science Reviews, vol.27, p.6-17.

Manighetti, B., A. Palmer, D. Eden and M. Elliot – 2003 – An occurrence of Tuhua Tephra in deep-sea sediments from offshore eastern North Island, New Zealand. – New Zealand Journal of geology and Geophysics, vol.46, p.581-590.

Manville, V. and C.J. N. Wilson – 2004 – The 26.5 ka Oruanui eruption, New Zealand: a review of the roles of volcanism and climate in the post-eruptive sedimentary response. – New Zealand Journal of Geology and Geophysics, vol.47, p.525-547.

McCormac, F.G., A.G. Hogg, P.G. Blackwell, C.E. Buck, T.F.G. Higham and P.J. Reimer – 2004 – SHCal04; Southern Hemisphere Calibration 0-11.0 cal Kyr BP. – Radiocarbon, vol.46, p.1087-1092.

McGlone, M.S. – 1988 – Glacial and Holocene vegetation history; 20kyr to present, New Zealand. – In: Vegetation History. By: B. Huntley and T. Webb III (eds). – Kluwer Academic Publishers, Dordrecht.

McGlone, M.S. and J.L. Bathgate – 1983 – Vegetation and climate history of the Longwood Range, South Island, New Zealand, 12,000 BP to the present. – New Zealand Journal of Botany, vol.21, p.293-315.

McGlone, M.S. and J.M. Wilmshurst – 1999 – A Holocene record of climate, vegetation change and peat bog development, east Otago, South Island, New Zealand. – Journal of Quaternary Science, vol.14(3), p.329-254.

McGlone, M.S., M.J. Salinger and N.T. Moar – 1993 – Palaeovegetation studies of New Zealand's climate since the Last Glacial Maximum. – In: Global Climates since the Last Ice Age. By: J. Kutzback, A. Street-Perrot, T. Webb III and H. E. Wright Jr. (eds). – University of Minnesota Press, Minneapolis.

McGlone, M.S., J.M. Wilmshurst and S.K. Wiser – 2000 – Lateglacial and Holocene vegetation and climatic change on Auckland Island, Subantarctic New Zealand. – The Holocene, vol.10(6), p.719-728.

McGlone, M.S., C.S.M. Turney and J.M. Wilmshurst – 2004 – Late-glacial and Holocene vegetation and climatic history of the Cass Basin, central South Island, New Zealand. – Quaternary Research, vol.62, p.267-279.

McGlone, M.S., C.S.M. Turney, J.M. Wilmshurst, J. Renwick and K. Pahnke – 2010 – Divergent trends in land and ocean temperature in the Southern Ocean over the past 18,000 years. – Nature Geoscience, vol.3, p.622-626.

McIntosh, P.D., D.N. Eden and S.J. Burgham – 1990 – Quaternary deposits and landscape evolution in northeast Southland, New Zealand. – Palaeogeography, Palaeoclimatology, Palaeoecology, vol.81, p.95-113.

Miller, T.P. and T.J. Casadevall – 2000 – Volcanic ash hazards to aviation. – In: Encyclopaedia of Volcanoes. By: H. Sigurdsson (ed). – Academic Press, San Diego, CA, p.915-930.

Milne, J.D.G. – 1973 – Mount Curl Tephra, a 230 000-year-old marker bed in New Zealand, and its implications for Quaternary chronology. – New Zealand journal of geology and geophysics, vol.16, p.519.

Moar, N.T. – 1993 – Pollen Grains of New Zealand Dicotyledonous Plants – Manaaki Whenua Press, Lincoln, Canterbury, New Zealand.

Moar, N.T and R.P. Suggate – 1996 – Vegetation history from the Kaihinu (Last) Interglacial to the present, West Coast, South Island, New Zealand. – Quaternary Science Reviews, vol.15, p.521-547.

Molloy, C., P.A.R. chane and P. Augustinus – 2009 – Eruption recurrence rates in a basaltic volcanic field based on tephra layers in maar sediments: implications for hazards in the Auckland volcanic field. – Geological Society of America Bulletin, vol.121, p.1666-1677.

Nairn, I.A. – 1989 – Sheet V16AC Tarawera - Geological Mapof New Zealand 1:50,000. – New Zealand Department of Scientific and Industrial Research, Wellington, New Zealand.

Nairn, I.A. – 2002 – Geology of the Okataina Volcanic Centre, Scale 1:50,000 Institute of the Geological and Nuclear Sciences geological map 25. 1 sheet + 156pp.. – Institute of Geological and Nuclear Sciences Ltd., Lower Hutt, New Zealand.

Nairn, I.A., P.A.R. Shane, J.W. Cole, G.J. Leonard and C. Scutter – 2001 – Distribution, stratigraphy and history of the proximal deposits from the c. AD 1305 [sic] Kaharoa eruptive episode at Tarawera volcano. – New Zealand Journal of Geology and Geophysics, vol.44, p.467-484.

Newnham, R.M. – 1993a – Palynology Laboratory Manual and New Zealand Pollen Identification Key. – Department of Geography, University of Otago.

Newnham, R.M. – 1993b – New Zealand Pollen Identification Manual, Illustrations. – Department of Geography, University of Otago.

Newnham, R.M. and D.J. Lowe – 1991 – Holocene vegetation and volcanic activity, Auckland Isthmus, New Zealand. – Journal of Quaternary Science, vol.6(3), p.177-193.

Newnham, R.M., P.J. de Lange and D.J. Lowe – 1995 – Holocene vegetation, climate and history of a raised bog complex, northern New Zealand based on palynology, plant macrofossils and tephrochronology. – The Holocene, vol.5(3), p.267-282.

Newnham, R.M., D.N. Eden, D.J. Lowe and C.H. Hendy – 2003 – Rerewhakaaitu Tephra, a land-sea marker for the Last Termination in New Zealand, with implications for global climate change. – Quaternary Science Reviews, vol. 22, p.289-308.

Newnham, R.M., D.J. Lowe, T. Giles and B.V. Alloway – 2007a – Vegetation and climate of Auckland, New Zealand, since ca. 32 000 cal. yr ago: support for an extended LGM. – Journal of Quaternary Science, vol.22(5), p.517-534.

Newnham, R.M., M.J. Vandergoes, C.H. Hendy, D.J. Lowe and F. Preusser – 2007b – A terrestrial palynological record for the last two glacial cycles from southwestern New Zealand. – Quaternary Science Reviews, vol.26, p.517-535.

Overpeck, J.T., T. Webb and I.C. Prentice – 1985 – Quantitative interpretation of fossil pollen spectra: Dissimilarity coefficients and the method of modern analogs. – Quaternary Research, vol.23, p.87-108.

Palmer, A.S. – 1982 – Kawakawa Tephra in Wairarapa, New Zealand, and its use for correlating Ohakea loess. – New Zealand Journal of Geology and Geophysics, vol.25, p.305-316.

Payne, R. and M. Gehrels – 2010 – The formation of tephra layers in peatlands: an experimental approach. – Catena, vol.81, p.12-23.

Pillans, B. – 1991 – New-Zealand Quaternary stratigraphy; an overview. – Quaternary Science Reviews, vol.10(5), p.405-418.

Pillans, B. – 1994 – Direct marine-terrestrial correlations, Wanganui Basin, New Zealand; the last 1 million years. Quaternary Science Reviews, vol.13, p.189-200.

Pillans, B., P. Froggatt, B.P. Kohn, G. Berger, R.C. Walter., G. Duller, B.V. Alloway and P. Hesse – 1996 – Multi-method dating comparison for mid-Pleistocene Rangitawa Tephra, New Zealand. – Quaternary Science Reviews (Quaternary Geochronology), vol.15, p.641-653.

Piperno, D.R. – 2006 – Phytoliths: a comprehensive guide for archaeologists and palaeoecologists. – Altimira, New York.

Raeside, J.D. – 1964 – Loess deposits of the South Island, New Zealand, and soils formed on them. – New Zealand Journal of Geology and Geophysics 7, 811-838.

Reid, S.J. and A.C. Penney – 1982 – Upper level wind frequencies and mean speeds for New Zealand and Pacific Island stations. – New Zealand Meteorological Service miscellaneous publication,

Reimer P.J., M.G.L. Baillie, E. Bard, A. Bayliss, J.W. Beck, C.J.H. Bertrand, P.G. Blackwell, C.E. Buck, G.S. Burr, K.B. Cutler, P.E. Damon, R.L. Edwards, R.G. Fairbanks, M. Friedrich, T.P. Guilderson, A.G. Hogg, K.A. Hughen, B. Kromer, F.G. McCormac, S. Manning, C. Bronk Ramsey, R.W. Reimer, S. Remmele, J.R. Southon, M. Stuiver, S. Talamo, F.W. Taylor, J. van der Plicht and C.E. Weyhenmeyer – 2004 – IntCal04 terrestrial age calibration, 0-26 cal kyr BP. – Radiocarbon, vol.46, p.1029-1058.

Roering, J.J., P.C. Almond, P.Tonkin and J. McKean – 2002 – Soil transport driven by biological processes over millennial time scales. – Geology, vol.30, p.1115-1118.

Roering, J.J., P.C. Almond, P.Tonkin and J. McKean – 2004 – Constraining climatic controls on hillslope dynamics using a coupled model for the transport of soil and tracers: application to loess-mantled hillslopes, Charwell River, South Island, New Zealand. – Journal of Geophysical Research - Earth Surface, vol.109.

Rose, W.I. and A.J. Durant – 2009 – Fine ash content of explosive eruptions. – Journal of Volcanology and Geothermal Research, vol.186, p.32-39.

Rose, W.I., G.J.S. Bluth, D.J. Schneider, G.G.J. Ernst, C.M. Riley, L.J. Henderson and R.G. McGimsey – 2001 – Observations of volcanic clouds in their first few days of atmospheric residence: the 1992 eruptions of Crater Peak, Mount Spurr Volcano, Alaska. – Journal of Geology, vol.109(6), p.677-694.

Salinger, J., W. Gray, B. Mullan and D. Wratt – 2004 – Atmospheric circulation and precipitation. – In: Freshwater of New Zealand. By: J. Harding, P. Mosley, C. Pearson and B. Sorrell (eds). – The Caxton Press, Christchurch, New Zealand.

Sarna-Wojcicki, A.M. – 2000 – Tephrochronology. – In: Quaternary geochronology: methods and applications. By: J.S. Noller, J.M. Sowers and W.R. Lettis (eds). – Washington DC: American Geophysical Union. – p. 357-377.

Schaetzl R.J. and S. Anderson – 2005 – Soils; Genesis and Geomorphology. – Cambridge University Press, New York, United States of America. – p.597-599.

Schneider, D.J., W.I. rose and L. Kelley – 1995 – Tracking of 1992 eruption clouds from Crater Peak Vent of Mount Spurr Volcano, Alaska, using AVHRR. – In:The 1992 eruptions of Crater Peak Vent, Mount Spurr Volcano, Alaska. By: T.E.C. Keith (ed). – United States Geological Survey Bulletin, vol.2139, p.27-36.

Shane, P.A.R. – 2000 – Tephrochronology: a New Zealand case study. – Earth Science Reviews, vol.49, p.223-259.

Shane, P.A.R. – 2005 – Towards a comprehensive distal andesitic tephrostratigraphic framework for New Zealand based on eruptions from Egmont volcano. – Journal of Quaternary Science, vol.20, p.45-57.

Shane, P.A.R. and J. Hoverd – 2002 – Distal record of multi-sourced tephra in Onepoto Basin, Auckland, New Zealand: implications for volcanic chronology, frequency and hazards. – Quaternary International, vol.187, p.44-53.

Shane, P.A.R., O.B. Lian, P. Augustinus, R. Chisari and H. Heijnis – 2002 – Tephrochronology and geochronology of a c. 120 kyr terrestrial record at Lake Poukawa, North Island, New Zealand. – Global and Planetary Change, vol.33, p.221-242.

Shane, P.A.R., V.C. Smith, D.J. Lowe and I.A. Nairn – 2003 – Re-identification of c. 15,700 cal yr BP tephra bed at Kaipo Bog, eastern North Island: implications for dispersal of Rotorua and Puketarata tephra beds. – New Zealand Journal of Geology and Geophysics, vol.46, p.591-596.

Shane, P.A.R., E.L. Sikes and T.P. Guilderson – 2006 – Tephra beds in deep-sea cores off northern New Zealand: implications for the history of Taupo Volcanic Zone, Mayor Island and White Island volcanoes. – Journal of Volcanoloty and Geothermal Research, vol.154, p.276-290.

Shane, P.A.R., I.A. Nairn, S.B. Martin and V.C. Smith – 2008 – Compositional heterogeneity in tephra deposits resulting from the eruption of multiple magma bodies: implications for tephrochronolgy. – Quaternary International, vol.178(1), p.44-53.

Shulmeister, J., I. Goodwin, J. Renwick, K. Harle, L. Armand, M.S. McGlone, E. Cook, J. Dodson, P.P. Hesse, P. Mayewski and M. Curran – 2004 – The Southern Hemisphere westerlies in the Australasian sector over the last glacial cycle: a synthesis. – Quaternary International, vol.118-119, p.23-53.

Shulmeister, J., C.S.M. Turney, D. Fink, R.M. Newnham and B.V. Alloway – 2006 – Developing an event stratigraphy for Australasian climate change. - Eos, Transactions American Geophysical Union, vol.87(29), p.283.

Smith, V.C., P.A.R. Shane and I.A. Nairn – 2004 – Reactivation of a rhyolitic magma body by new rhyolitic intrusion before the 15.8 ka Rotorua eruptive episode: implications for magma storage in the Okataina Volcanic Centre, New Zealand. – Journal of the Geological Society London, vol.161, p.757-773.

Smith, V.C., P.A.R. Shane, I.A. Nairn and C.M. Williams – 2006 – Geochemistry and magmatic properties of eruption episodes from Haroharo linear vent zone, Okataina Volcanic Centre, New Zealand, during the last 10 kyr. – Bulletin of Volcanology, vol.69, p.57-88.

Soons, J.M., J. Shulmeister and S. Holt – 1997 – The Holocene evolution of a well nourished gravelly barrier and logon complex, Kaitorete “Spit”, Canterbury, New Zealand. – Marine Geology, vol.138, p.69-90.

Soons, J.M., N.T. Moar, J. Shulmeister, H.D. Wilson and J.A. Carter – 2002 – Quaternary vegetation and climate changes on Banks Peninsula, South Island, New Zealand. – Global and Planetary Change, vol.33, p.301-314.

Sparks, R.J., W.H. Melhuih, J.W.A. McKee, J. Ogden and J.G. Palmer – 1995 – ^{14}C calibration in the Southern Hemisphere and the date of the last Taupo eruption: evidence from tree-ring sequences. – radiocarbon, vol.37, p.155-163.

Sparks, R.J., I.J. Graham and U. Morgenstern – 2008 – Cosmic chronometers. – In: “A Continent on the Move, New Zealand Geosciences into the 21st Century” by: Graham, I.J. (Chief editor). – Geological Society of New Zealand, Lower Hutt, New Zealand.

Speed, J., P.A.R. Shane and I.A. Nairn – 2002 – Volcanic stratigraphy and phase chemistry of the 11,900 yr BP Waiohau eruptive episode, Tarawera Volcanic Complex, New Zealand. – New Zealand Journal of geology and Geophysics, vol.45, p.395-410.

Stokes, S., D.J. Lowe and P.C. Froggatt – 1992 – Discriminant function analysis and correlation of late Quaternary rhyolitic tephra deposits from Taupo and Okataina volcanoes, New Zealand, using glass shard major element composition. – Quaternary International, vol.13-14, p.103-117.

Stout, V.M. – 1975 – Canterbury, Nelson and Westland lakes. – In: New Zealand Lakes. By: V.H. Jolly and J.M.A. Brown (eds). – Auckland University Press.

Suggate, R.P. – 1968 – The Paringa Formation, Westland, New Zealand. – New Zealand Journal of Geology and Geophysics, vol.11, p.345-355.

Suggate, R.P. – 1990 – Late Pliocene and Quaternary glaciations of New Zealand. – Quaternary Science Reviews, vol.9(2-3), p.175-197.

Suggate, R.P. and P.C. Almond – 2005 – The Last Glacial Maximum (LGM) in western South Island, New Zealand: Implications for the global LGM and MIS 2. – Quaternary Science Reviews, vol.24, p.1923-1940.

Turner, M.B., S.J. Cronin, M.S. Bebbington and T. Platz – 2008 – Developing probabilistic eruption forcasts for dormant volcanoes: a case study from Mt Taranaki, New Zealand. – Bulletin of Volcanology, vol.70, p.507-515.

Turner, M.B., M.S. Bebbington, S.J. Cronin and R.B. Stewart – 2009 – Merging eruption datasets: building and integrated Holocene eruptive record for Mt Taranaki, New Zealand. – Bulletin of Volcanology, vol.70, p.903-918.

Turney, C.S.M. and J.J. Lowe – 2001 – Tephrochronology. – In: Tracking Environmental Changes in Lake Sediments: Physical and chemical Techniques, by: W.M. Last and J.P. Smol (eds). – Kluwer Academic: Dordrecht, p.451-471.

Turney, C.S.M., J.J. Lowe, S.M. Davies, V. Hall, D.J. Lowe, S. Wastegård, W.Z. Hoek, B.V. Alloway and SCOTAV and INTIMATE members – 2004 – Tephrochronology of Last Termination sequences in Europe: a protocol for improved analytical precision and robust correlation procedures (a joint SCOTAV-INTIMATE proposal). – Journal of Quaternary Science, vol.19(2), p.111-120.

Turney, C.S.M., K. van den Burg, S. Wastegård, S.M. davies, N.J. Whitehouse, J.R. Pilcher and C. Callaghan – 2006 – North European last glacial - interglacial transition (LGIT; 15-9 ka) tephrochronology: extended limits and new events. – Journal of Quaternary Science, vol.21(4), p.335-345..

USEPA – 1999 – Innovative technology verification report: sediment sampling technology, aquatic research instruments Russian Peat Borer. – EPA/600/R-01/010 – Office of Research and Development.

Van Dam, H., A. Mertens and J. Sinkeldam – 1994 – A coded checklist and ecological indicator values of freshwater diatoms from The Netherlands. – Aquatic Ecology, vol.28, p.117-133.

Vandergoes, M.J., A.G. Hogg, D.J. Lowe, R.M. Newnham, G.H. Denton, J. Southon, F.Petchey, K. Dabell, D.J.A. Barrell, P.C. Almond, A. Allan, C.J.N. Wilson, M.S. McGlone and M. Blaauw – 2011 – Refining the age of the Kawakawa/Oruanui Tephra in New Zealand. – Poster publication GNS Science, Lower Hutt, NZ; INQUA 2011, Bern , Switzerland.

Vucetich, C.G. and R. Howarth – 1976 – Proposed definition of the Kawakawa Tephra, the c. 20,000 yrs BP marker horizon in the New Zealand region. – New Zealand Journal of Geology and Geophysics, vol.19, p.43-50.

Walker, G.P.L. – 1981 – The Waimihia and Hatepe plinian deposits from the rhyolitic Taupo Volcanic Centre. – New Zealand Journal of Geology and Geophysics, vol.20, p.179-198.

Walker, M.J.C. – 2001 – Rapid climate change during the last glacial - interglacial transition; implications for stratigraphic subdivision, correlation and dating. – Global and Planetary Change, vol.30, p.59-72.

Walker, M.J.C., S. Björck, J.J. Lowe, L.C. Cwynar, S. Johnsen, K.-L. Knudsen, B. Wohlfarth and INTIMATE-group – 1999 – Isotopic events in the GRIP ice core: a stratotype for the late Pleistocene. – Quaternary Science Reviews, vol.18, p.1143-1150.

Walker, M.J.C., S. Björck and J.J. Lowe – 2001 – Integration of ice core, marine and terrestrial records (INTIMATE) from around the North Atlantic region: an introduction. – Quaternary Science Reviews, vol.20, p.1169-1174.

Wardle, J.A. – 1983 – Disturbance and the ecology of beeches with emphasis on mountain beech. – In: The future of Tongariro National Park beech forests. By: W.B. Silvester and V. Watt (eds). – National Park Series, vol.24.

Wardle, P. – 1991 – Vegetation of New Zealand. – The Blackburn Press, New Jersey.

Wastegård, S. – 2005 – Late Quaternary tephrochronology of Sweden: a review. – Quaternary International, vol.130, p.49-62.

Wastegård, S. And S.M . Davies – 2009 – An overview of distal tephrochronology in northern Europe during the last 1000 years. – Journal of Quaternary Science, vol.24(5), p.500-512.

Weaver, S., R. Sewell and C. Dorsey – 1985 – Extinct Volcanoes: A Guide to the Geology of Banks Peninsula. – Geological Society of New Zealand; Guidebook No.7, Lower Hutt, New Zealand.

Wilmshurst, J.M. – 1997 – A late Holocene history of natural disturbance in lowland podocarp/hardwood forest, Hawke's Bay, New Zealand. – New Zealand Journal of Botany, vol.35, p.79-96.

Wilmshurst, J.M., M.S. McGlone and D.J. Charman – 2002 – Holocene vegetation and climate change in southern New Zealand: linkages between forest composition and quantitative surface moisture reconstructions from an ombrogenous bog. – Journal of Quaternary Science, vol.17(7), p.653-666.

Wilmshurst, J.M., M.S. McGlone, J.R. Leathwick and R.M. Newnham – 2007 – A pre-deforestation pollen-climate calibration model for New Zealand and quantitative temperature reconstructions for the past 18000 years. – Journal of Quaternary Science, vol.22, p.535-547.

Wilson, C.J.N. – 1993 – Stratigraphy, chronology, styles and dynamics of Late Quaternary eruptions from Taupo volcano, New Zealand. – Philosophical Transactions of the Royal Society of London, vol.A343, p.205-306.

Wilson, C.J.N. – 2001 – The 26.5 ka Oruanui eruption, New Zealand: an introduction and overview. – Journal of Volcanology and Geothermal Research, vol.112, p.133-174.

Wilson, C.J.N. and G.P.L. Walker – 1985 – The Taupo eruption, New Zealand. I. General aspects. - Philosophical Transactions of the Royal Society of London, vol.A314, p.199-228.

Wilson, C.J.N., V.R. Switsur and A.P. Ward – 1988 – A new 14C age for the Oruanui (Wairakei) eruption New Zealand. – Geology Magazine, vol.125, p.297-300.

Wilson, C.J.N., S. Blake, B.L.A. Charlier and A.N. Sutton – 2006 – The 26.5 ka Oruanui eruption, Taupo volcano, New Zealand: development, characteristics and evacuation of a large rhyolitic magma body. – Journal of Petrology, vol.47, p.34-69.

Wilson, D.D. – 1985 – Erosional and depositional trends in rivers of the Canterbury Plains, New Zealand. – New Zealand Journal of Hydrology, vol.24, p.32-44.

Wittry, D.B. – 1958 – Electron Probe Microanalyzer. – US Patent No 2916621. – Washington DC, United States of America.

Zielinski, G.A., P.A. Mayeweski, L.D. Meeker, S. Whitlow, M.S. Twickler, M. Morrison, D. Meese, R.B. Alley and A.J. Gow – 1994 – Record of volcanism since 7000 BC from the GISP2 Greenland ice core and implications for the volcano-climate system. – Science, vol.264, p.948-952.

Zielinski, G.A., P.A. Mayeweski, L.D. Meeker, K. Grönveld, M.S. Germani, S. Whitlow, M. Twickler and K. Taylor – 1997 – Volcanic aerosol records and tephrochronology of the Summit, Greenland, ice cores. – Journal of Geophysical Research, vol.102C, p.26,626-26,640.