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# VOLCANIC EMISSIONS AND DISTAL PALAEOENVIRONMENTAL IMPACTS IN NEW ZEALAND

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# VOLCANIC EMISSIONS AND DISTAL PALAEOENVIRONMENTAL IMPACTS IN NEW ZEALAND

by

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**Volcanic emissions and distal palaeoenvironmental impacts in New Zealand**

Abstract

This thesis is a palaeoenvironmental investigation into possible non-climatic effects on the environment from volcanic ash fall and toxic emissions outside the blast zone of a volcanic eruption.

These effects are determined from palynological and geochemical changes following tephra fall at a range of sites across the North Island of New Zealand which were located at increasing distances from the main volcanic source, the Taupo Volcanic Zone. These sites collectively covered a wide variety of habitats existing under different climatic regimes. The first site is a peat bog at a warm temperate, comparatively unstable coastal location, Matakana Island. The peat profile extends to 1000 yrs BP and contains the Kaharoa Tephra layer, erupted around the time of early human settlement in New Zealand. The second study site is Kaipo peat bog which, in contrast to Matakana Island, is an upland sub-alpine site existing under a harsher climatic regime with cool temperatures, strong winds and heavy rainfall. The Kaipo record covers the Holocene period up to recent times. Lake Rotoroa is the third site which is located inland, sheltered within the Waikato valley, an area of rich fertile soils and mild temperate climate. The Lake Rotoroa record extends to approximately 15,000 yrs BP including the end of the last glacial period and the Holocene. The final site investigated, Kohuora bog, is situated in an extinct late Quaternary volcanic crater within Auckland urban area, a region of warm temperate climate. This record extends from the last glacial period to the present.

Fine resolution sampling methods were employed above tephra layers preserved at each of these sites to examine the immediate short-term palaeoenvironmental impacts from volcanic tephra deposition. The methods used included pollen analysis, and the relatively new technique of Energy Dispersive X-ray Micro Analysis (EDMA) which investigated changes in sediment geochemistry to provide further information on local environmental change following tephra impact.

The use of pollen analysis together with EDMA proved beneficial in assessing overall short term environmental impacts from tephra fall. Results revealed that thicker tephra layers did not always cause extensive environmental damage, as impacts seen above the 0.5 cm thick Egmont 15 Tephra at Lake Rotoroa were among the most significant recorded at this site. Instead, the contributing factors of prevailing climate and local site factors (e.g. drainage, soils, vegetation cover and shelter) at the time of an eruption, together with local forest diversity and species sensitivity to tephra deposition, proved more important in determining the degree of tephra impact. Taxa found to be particularly sensitive to tephra deposition included *Halocarpus*, with inconsistent impacts from tephra fall on *Dacrydium* and *Metrosideros*. Duration of tephra impacts varied between sites, but broad estimates from the results showed the time taken for recovery of forest vegetation following an eruption was >100 years, with environmental stability returning after a minimum period of 50 years.

The results from Matakana Island revealed that any possible tephra impacts from deposition of the Kaharoa Tephra were obscured owing to large-scale deforestation following Polynesian settlement on the island around the time of the Kaharoa eruption. This study indicates the importance of investigating distal volcanic impacts prior to human settlement to eliminate ambiguity in interpretation of palaeoenvironmental data.

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## AUTHOR'S DECLARATION

At no time during the registration for the degree of Doctor of Philosophy has the author been registered for any other University award.

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| December 1994 | The Third Biennial U.K. Tephra Meeting, Centre for Environmental Change and Quaternary Research, Cheltenham and Gloucester College of Higher Education. |
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# Chapter One

# Introduction

## 1.0 Introduction

Volcanic eruptions have been the cause of many human catastrophes in historic times. Extensive research into proximal impacts from volcanic ejecta has been a primary concern in many regions where active volcanoes are an impending threat to the environment. Well known examples include the destruction of Pompeii caused by the eruption of Vesuvius in AD 79, and the death of 28,000 people in the town of St Pierre on Martinique Island in the Caribbean, from the eruption of Mt Pelee in 1902 (Press and Siever, 1986; Chester, 1988). Indirect effects from poisonous volcanic emissions have led to crop failures, injury to livestock and famine, as was experienced during the aftermath of the 1783 Laki eruption (Franklin, 1784; Thorarinsson, 1979). Indeed, the effects of volcanic eruptions on atmospheric circulation and climate can be severe, but probably rarely last more than 1-2 years (Stothers and Rampino, 1982; Hansen and Lacis, 1990). However, compared with these well-documented accounts of volcanic induced climatic and proximal impacts, very little research has been concerned with distal volcanic impacts on the environment.

It is now well accepted that long-distance dispersal of acid aerosols from industrial pollution has led to significant ecological damage from resultant acid rain across Europe. Ecological impacts from deposition of black acidic snow in the Cairngorm mountains, north-east Scotland, have been reported by Davies *et al.* (1984), where aerosols originated from pollution sources in the east Midlands, south Yorkshire, north-east England and Edinburgh up to 500 km away. It is therefore reasonable to suggest that similar impacts could occur from volcanic eruptions, as these are sources of acidic, sulphur-based gases and pollutants, which could also have a long-distance ecological impact.

Experimental research has been conducted to determine impacts of fine volcanic ash and aerosols travelling far from the eruptive centre (Rose, 1977; Oskarsson, 1980). Both studies suggested volcanic aerosols would have a greater impact with increasing distance from the source due to their adsorption onto fine ash particles and subsequent deposition in the environment. These studies provide an additional impetus for research into distal volcanic impacts.

Recent interest in Britain and parts of Europe has focused on distal impacts from volcanic tephra deposition during the Holocene. Research has been undertaken on Icelandic tephra layers, particularly from eruptions of Hekla, deposited in Scotland during the Holocene (Dugmore, 1989). Further research began to assess, through examination of pollen records, the possible environmental impacts from these eruptions in the remote areas of northern Scotland (Blackford *et al.*, 1992; Charman *et al.*, 1995). However, impacts from volcanic tephra deposition have not been uniformly detected in northern Scotland, and therefore are inconclusive at present (Bennett *et al.*, 1992; Birks, 1994; Charman *et al.*, 1995). Similar research was also carried out in Northern Ireland where Icelandic tephra layers are also preserved, but as yet, no conclusive evidence for volcanic impacts has been reported (Pilcher and Hall, 1992). Research in Germany has also considered possible ecological impacts from distal tephra deposition. Research focused on the Laacher See tephra (c.11,000 yrs BP) reveals no significant distal volcanic impacts (Bogaard *et al.*, 1992; Lotter and Birks, 1993). Thorarinsson (1979; 1981) has reported distal Icelandic tephra deposits over Scandinavia, which have caused some environmental damage.

However, in general, the question of distal impacts from thin tephra layers is largely unexplored. The lack of widespread evidence to date, together with an element of ambiguity in palaeoenvironmental records due to the difficulty in distinguishing volcanic from anthropogenic impacts, means this issue remains controversial. Local environmental factors such as flooding, landslides and natural fire may confuse the record, resulting in impacts on local vegetation, which could be misinterpreted as primary volcanic impact. On the other hand these hazards may also arise as a result of volcanic activity. Furthermore, any volcanic impacts on the environment may be too subtle to be detected using palynological and geochemical techniques. It is now desirable, therefore, to investigate distal volcanic impacts in an area where problems evident in the European studies can be examined more comprehensively.

An ideal location for the study of distal volcanic impacts is the North Island of New Zealand, where proximal and distal environmental impacts from volcanic eruptions have been noted (Vucetich and Pullar, 1963; McGlone, 1981; Clarkson *et al.*, 1988; Burrows, 1992; Clarkson and Clarkson, 1994; Newnham *et al.*, 1995a & b, Wilmshurst and McGlone, 1996; Wilmshurst *et al.*, 1997). The Quaternary sediments of the central

North Island include numerous tephra layers, and their stratigraphy, geochemistry and chronology are well established, especially for the late Quaternary (Froggatt and Lowe, 1990; Pillans, 1993; Wilson, 1995). The North Island also contains an abundance of relatively undisturbed late Quaternary depositional sites, in lakes and peat bogs, at varying distances from volcanic centres, where numerous tephra layers are preserved within organic sequences. These sites are also ideal for pollen analysis and, therefore, hold great potential for the assessment of vegetation impact from volcanic eruptions. Anthropogenic impacts began late in New Zealand, with the arrival of Polynesians around 1000 years BP, according to conventional views (Davidson, 1984). There is ample scope for determining distal volcanic impacts in pollen diagrams prior to 1000 yrs BP, avoiding confusion with possible human interference. This research investigates distal volcanic impacts from tephra deposition in New Zealand palaeoenvironments through examination of pollen and geochemical records from four sites in the North Island of New Zealand. Chapter two will focus in more detail on the New Zealand environment and its suitability for this investigation.

### 1.1 Aims

The fundamental aim of this project is to investigate the effect of distal volcanic tephra deposition on past environments using fine resolution palynology and geochemistry of tephric sediments from northern New Zealand. Fine resolution pollen analysis carried out immediately above tephra layers preserved in sediment cores will provide a detailed picture of vegetation changes following volcanic tephra deposition. Analysis of sediment geochemistry, using EDMA (Energy Dispersive X-ray Microanalysis), will enable the detection of possible soil and catchment disturbance, which may occur following vegetation damage and subsequent decline. The combination of geochemical and palynological analyses will provide a complete picture and clearer understanding of ecological and environmental changes following tephra deposition.

In order to investigate the effect volcanic ash deposition has on the environment, these techniques will be applied at four northern New Zealand sites with the following aims:

i) To determine whether there is a critical tephra thickness above which discernible vegetation and environmental impacts occur.

ii) To model recovery patterns of vegetation communities affected by tephra deposition, by identifying species sensitive to ash accumulation, and important pioneer species for vegetation re-establishment following tephra impact.
iii) To investigate the vegetational and environmental impacts from distal tephra fall with increasing distance from the eruptive source.
iv) To investigate whether differences in specific tephra chemistry is an important factor in determining the magnitude of damage to vegetation and the environment.

This study will aid research into volcanic risk assessment in New Zealand, providing important ramifications for further work into effects on agriculture and the natural and urban environment. The work will also contribute to the understanding of overall environmental change in northern New Zealand during the late Quaternary. Fulfilment of the aims outlined above will also demonstrate the importance of combining palynological and geochemical analyses in the investigation of distal volcanic impacts. These results may be informative in the debate over non-climatic volcanigenic extensive environmental change, which has proved to be a controversial topic in recent years in western Europe.

### 1.2 Research Strategy

Four sites in the North Island of New Zealand were investigated. Sediment cores extracted at each site contain tephra layers originating from Taupo, Tongariro, Okataina, Tuhua and Egmont Volcanic Centres (Fig. 1.1; Plate 1.1, 1.2), with tephras displaying chemical characteristics unique to each volcano. Most tephra layers preserved at each site originate from Taupo Volcanic Zone. The thickness of these macroscopic tephra layers varies at each site according to distance and direction from the source volcano.

Matakana Island study site, located in western Bay of Plenty (Fig 1.1), is a coastal dune dominated lowland environment which is environmentally unstable. The vegetation communities at this site are sensitive to constant change and re-development due to dune movement and coastal erosion, and are therefore less diverse, continually re-establishing on poorly developed recent soils. The impact of tephra deposition may have a different effect in this kind of environment than in a more environmentally stable area. The soils and vegetation of Matakana Island have also been modified following

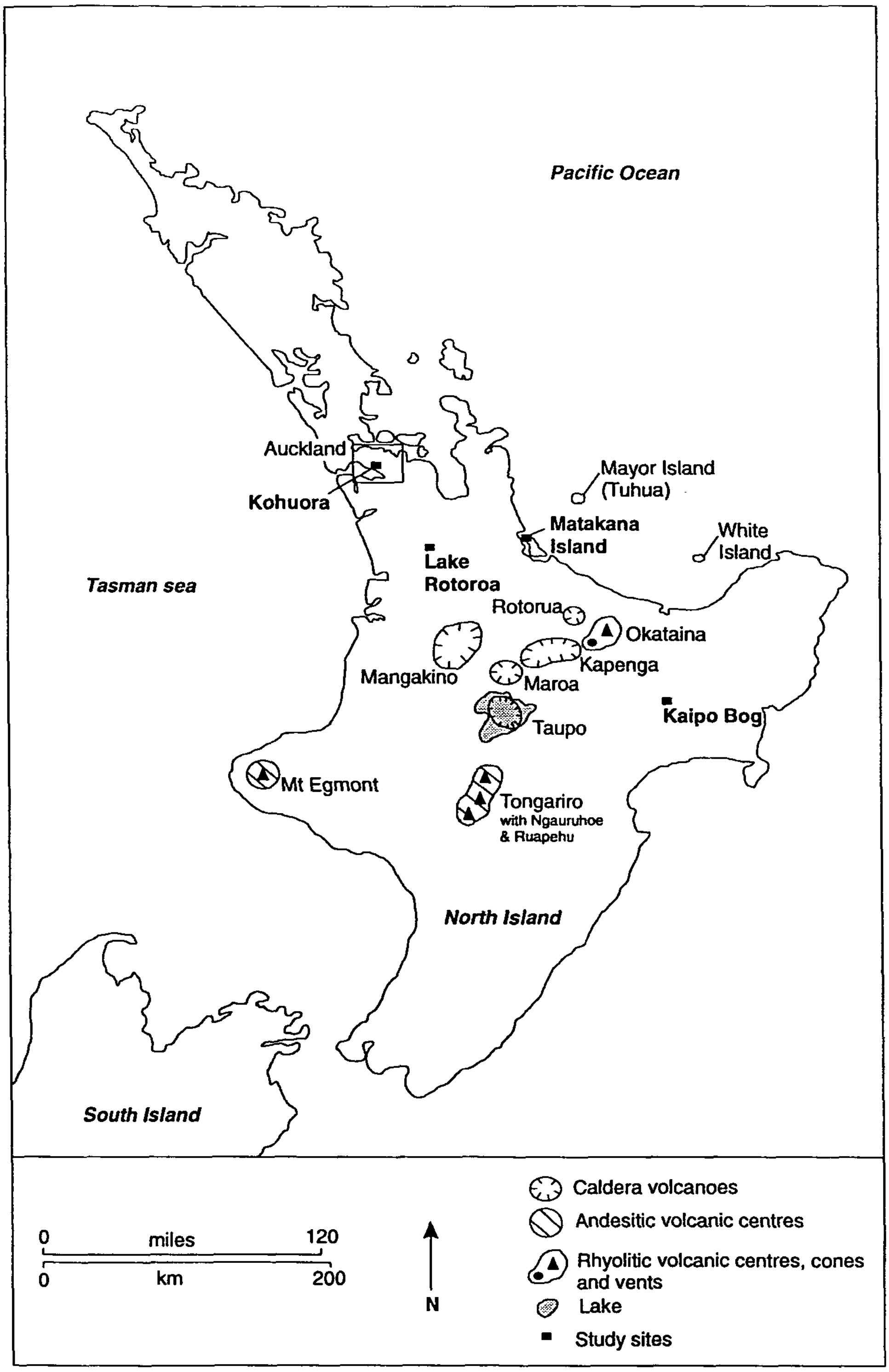



**Figure 1.1** Location of study sites and main volcanic centres in the North Island of New Zealand

**Plate 1.1** Mt Tarawera, Okataina Volcanic Centre.

**Plate 1.2a** Taupo rhyolitic volcanic centre (Lake Taupo, centre), with Tongariro, Ngauruhoe and Ruapehu forming the andesitic Tongariro Volcanic Centre in the background. Photo: Charles Cox for Promart, Promotional Art (NZ) Ltd.

**Plate 1.2b** Lake Taupo, Taupo Volcanic Centre.

settlement of Polynesians around the time of the Kaharoa eruption (665 yrs BP). This site provides the opportunity to assess whether volcanic impacts can be detected during a period where intense human activity and environmental instability have prevailed.

Kaipo bog, situated in the Urewera ranges, inland Bay of Plenty, is the closest site to Taupo. Unlike the other three localities, Kaipo is located at high altitude (1000 m a.s.l). The vegetation is hardier and tolerant of a harsher climate than that experienced in the lowlands. The effect of distal tephra deposition at Kaipo may be quite different to that which may be experienced at the other three sites, due to contrasts in vegetation, environment and climate. These comparatively harsh climatic conditions and rugged environment make Kaipo Bog an unfavourable site for human settlement. Kaipo Bog has remained free from human disturbance until the European era, and is therefore especially ideal for the investigation of possible impacts from Kaharoa Tephra fall. As Kaipo is the most proximal site to the TVZ (Taupo Volcanic Zone), and contains numerous thick (>10cm) as well as some thin tephra layers, this site will also investigate the potential maximum impacts from tephra fall on vegetation and the environment in the context of this study. As a rich suite of tephras, showing variable thickness and chemistry, is recorded at this site, an additional focus here will be the relationship between these parameters and any environmental response.

The study site at Lake Rotoroa, Hamilton, is situated in a sheltered inland area, with a mild climate and fertile alluvial soils (Fig. 1.1). Previous palynological investigations in the area reveal a history of diverse lowland forest vegetation which prevailed during most of the Holocene. The Hamilton lake sediment profile contains numerous macroscopic distal tephra layers of varying thickness and geochemistry. This site will therefore provide an insight into the effect of distal tephra deposition on an environment which has experienced long-term stability prior to human settlement, punctuated occasionally by tephra inundation. Investigations at this site will also focus on impacts observed above each tephra layer to determine how tephra thickness and specific geochemistry affects vegetation communities and the environment.

The study site at Kohuora volcanic crater, Auckland (Fig 1.1), is located towards the maximum limit of macroscopic scale deposition of many tephra layers originating from the central North Island volcanic centres. Any volcanic impacts found at this site, therefore, will generally represent the most distal recorded in this study. The site is situated within the Auckland urban area. Research carried out will be important for the assessment of the potential threat to the Auckland area from Central North Island Volcanic Centres, a hazard that has not previously been considered (Newnham, Lowe and Alloway, in press).

The four study sites chosen cover a range of different environments, from coastal to inland, upland to lowland and environmentally stable to unstable. All sites, excluding Matakana Island, contain numerous tephra layers which range in thickness and geochemistry, and were deposited before the arrival of humans. Therefore each site is ideal for investigating the fundamental aim of the project, which is to assess palaeoenvironmental impacts from distal volcanic tephra deposition using pollen and geochemical analyses. Specific site characteristics which may also influence the magnitude of distal tephra impact on the environment are summarised in Table 1.1.

**Table 1.1** Summary of study site information

| Study Site | Distance from Taupo (km) | Specific site characteristics |
|---|---|---|
| **Kaipo bog** | 70 | Nearest site to eruptive sources. Upland. Harsh climate. Hardy vegetation. |
| **Matakana Island** | 80 | Coastal, unstable environment. Area of intense human activity since 700/600 BP.. |
| **Lake Rotoroa** | 130 | Sheltered inland site. Fertile soils. Stable forest environment. |
| **Kohuora crater** | 200 | Most distal site. Lowland, mild climate. Stable environment. |

Fine resolution sampling will be employed above key tephra layers preserved at each site. Analysis of pollen records will enable detection of post-tephra vegetation changes, including determination of the species most sensitive to tephra fallout, and those which may subsequently invade following vegetation decline. Analysis of sediment geochemistry, in conjunction with palynological investigations, will provide further insight into environmental impacts associated with tephra deposition. The identification of patterns in vegetation response and changes in sediment geochemistry will aid future research into the detection of distal volcanic impacts in palaeoenvironmental records in New Zealand and elsewhere.

## 1.3 Thesis structure

The thesis is in three parts. Part 1 begins with a general introduction to the thesis, outlining the research aims and rationale, and a summary of New Zealand vegetation and of Quaternary environmental and volcanic history (this chapter). Chapter two presents evidence for proximal and distal volcanic impacts in palaeoenvironmental records from New Zealand and other parts of the world. Chapter two also reviews observations of the physiological damage to vegetation and soils, and acidification of the environment as a result of acid pollution from volcanic emissions and tephra accumulation. A brief overview of volcanic eruptions and climate cooling is included. Chapter three describes the methods employed in this study, and considers the advantages and drawbacks of using the techniques of pollen analysis and EDMA for palaeoenvironmental reconstruction.

Part two comprises four chapters (chapters 4 to 7) presenting and interpreting the results from pollen and geochemical analyses from each study site.

Part three includes general discussion (chapter 8) that integrates results from all study sites to determine the ways in which volcanic tephra fallout has affected vegetation communities and the environment as a whole. The conclusions (chapter 9) summarise these findings, explaining how the original research aims were fulfilled, and provides possible suggestions for further research.

## 1.4 Terms and abbreviations

The term 'distal volcanic impact' is referred to throughout the thesis. This concerns the alternative, possible non-climatic effects on the environment from volcanic tephra fall outside of the blast zone of a volcanic eruption, where the usual proximal volcanic hazards (e.g. lava flows, pyroclastic flows, lahars) do not operate.

*'Volcanic Centre'* refers to a collection of volcanic vents originating from the same magma source.

*'Tephra shards'* or *'Glass shards'* refer to volcanic ash particles that are microscopic in size (10-100 microns). Tephra deposits or layers are stratigraphic horizons preserved in lake sediments, peat bogs and geological sections where tephra shards and larger ash

particles (up to approximately 3mm diameter) have accumulated following a volcanic eruption.

*Cryptotephra* – a tephra layer <5mm thickness which cannot be seen by the naked eye.

*VEI* (Volcanic Explosivity Index) - represents the degree of explosivity of an eruption, determined from the height of the eruption column, having the capability to inject volcanic dust and gases into the stratosphere to potentially initiate climate cooling.

*DVI* (Dust Veil Index) - devised by Lamb (1970) to classify the magnitude of an eruption according to the volume of volcanic dust emitted. Eruptions were calibrated to a DVI of 1000 allocated to the Krakatau eruption (AD 1883), with only those eruptions emitting a significant amount of dust (DVI >100) likely to cause climate cooling.

TVZ - Taupo Volcanic Zone.

Unless otherwise specified, all dates quoted in this thesis refer to uncalibrated radiocarbon dates based on the old (Libby) $^{14}C$ half life. This is conventional in New Zealand as a long dendrochronological calibration record has yet to be constructed, and the validity of calibrating with dendrochronological records from other regions has yet to be demonstrated. BP indicates 'radiocarbon years before present' dating back from AD 1950.

The 'Polynesian era' in New Zealand is assumed to extend from approximately 1000 yrs BP, which roughly marks the beginning of human occupation of New Zealand (Davidson, 1984), to the 'European era'. The 'European era' refers to the period of extensive settlement of Europeans in the country, from 150 yrs BP.

Broad vegetation categories, referred to in this thesis, follow those from Newnham (1990) which are:

**Conifer** - includes New Zealand gymnosperm trees in the families Podocarpaceae, Araucariaceae and Cupressaceae

**Podocarp** - refers to trees in the Podocarpaceae family

**Broadleaf (hardwood)** - refers to angiosperm trees apart from *Nothofagus* (beech) species. Beech comes under a separate forest category, which is described in section 2.1. Unless otherwise stated, botanical nomenclature follows Allan (1961), Connor and Edgar (1987), Taylor (1989) and Beever *et al.* (1992).

The following sections in this chapter provide background information on New Zealand vegetation, its history and ecology, and human settlement and volcanic history since the late Quaternary.

## 1.5 New Zealand vegetation

This section provides a brief overall description of the main categories and types of vegetation in New Zealand. More detailed vegetation descriptions are found in Allan (1961).

Most New Zealand plants are evergreen and perennial. A combined total of only 10 trees and shrubs are deciduous, and none of these are dominant in the forest vegetation (McGlone, 1988). New Zealand forests fall into 2 broad categories, conifer-broadleaf forest, and *Nothofagus* (beech) forest (McGlone, 1988).

<u>Conifer-broadleaf forest</u>

These forests are typically multi-storied, with the most complex examples developing in fertile areas with a warm humid climate, in lowland to montane areas in the North Island, and lowland sites in the south (Figure 1.2).

The tallest canopy species (up to 40-60 m high) are conifers, mostly in the Podocarpaceae family, of the genera *Dacrydium*, *Podocarpus*, *Dacrycarpus*, and *Prumnopitys*, with *Agathis australis* (Araucariaceae) north of 38°S, and the angiosperms *Laurelia* and *Metrosideros*. The more continuous main canopy is largely composed of tall angiosperm trees, with some smaller podocarps. In the south, these canopy trees include species from the genera *Elaeocarpus*, *Metrosideros*, *Plagianthus*, *Quintinia* and *Weinmannia*, and are replaced northwards by *Ackama*, *Beilschmiedia*, *Knightia*, *Litsea* and *Nestegis*. The sub-canopy is generally poorly defined, consisting of young main canopy trees, with species of *Dysoxylum*, *Griselinia*, *Melicytus*, *Myrsine*, *Pittosporum*, *Pseudopanax*, *Pseudowintera*, *Schefflera*, *Coprosma*, *Paratrophis*, *Phyllocladus*, *Hoheria*, and tree ferns (*Cyathea* and *Dicksonia* species).

The diverse shrub layer includes the genera *Alseuosmia*, *Aristotelia*, *Coprosma*, *Geniostoma*, *Melicope*, *Melicytus*, *Neomyrtus*, *Pittosporum* and *Pseudopanax*. A rich diverse ground layer consists of species of fern, including *Asplenium*, *Blechnum*, *Hypolepis*, *Lasteopsis*, *Polystichum*, *Pneumatopteris* and Hymenophyllaceae, together with byrophytes and herbaceous species.

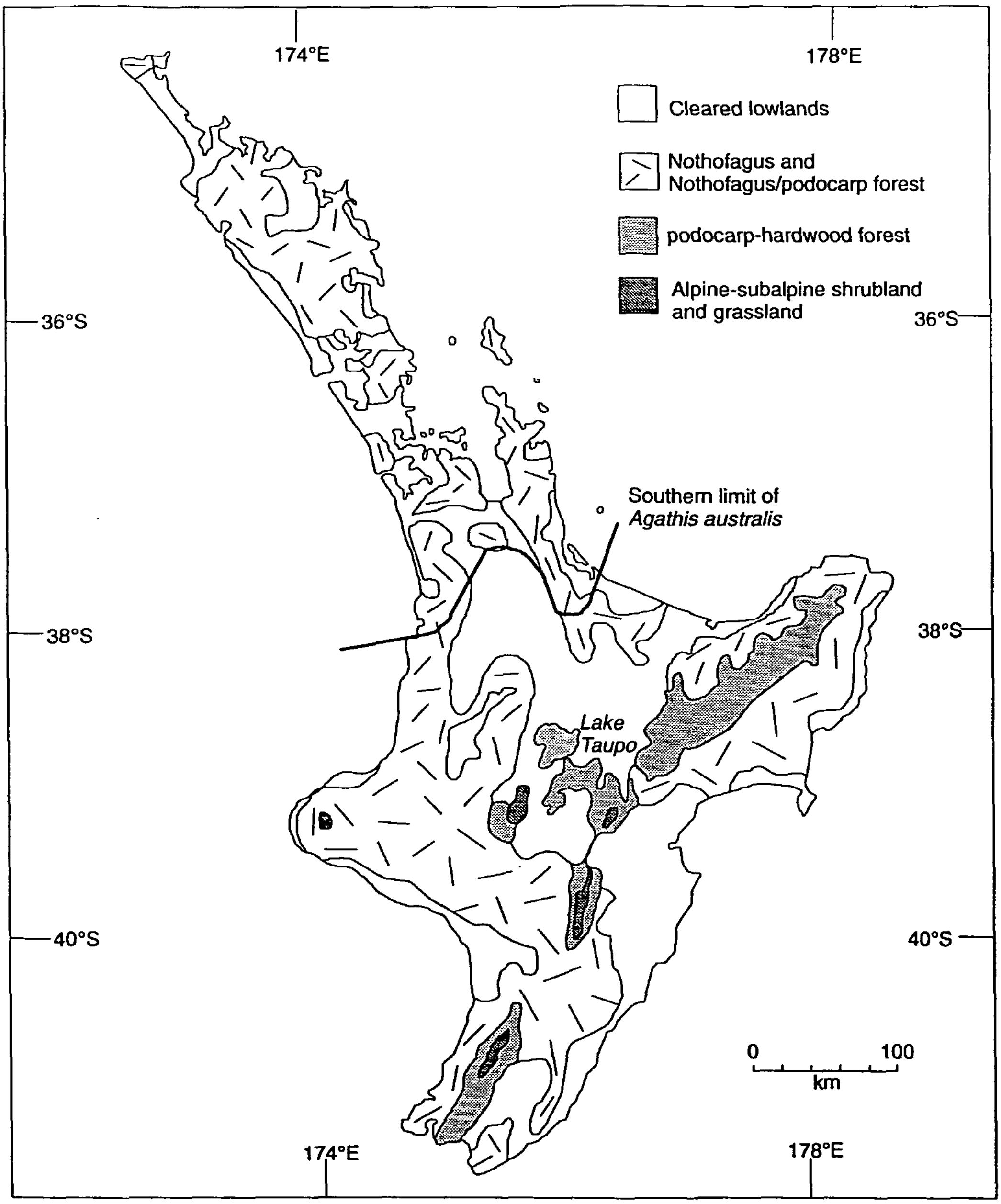



**Figure 1.2** The distribution of vegetation in the North Island of New Zealand, after McGlone (1988).

There are numerous epiphytes in the New Zealand forest, which often emerge as top canopy species (e.g. *Metrosideros robusta*, *Weinmannia racemosa*) alongside the tall conifers which are their host trees. Epiphytes include species of fern (e.g. *Asplenium*, *Anarthropteris*, *Pyrossia*) with orchids, and shrubs and herbaceous species e.g. *Astelia*, *Collospermum*, *Tupeia*. Lianes are also important canopy plants and include *Clematis*, *Freycinetia*, *Metrosideros*, *Muehlenbeckia*, *Parsonsia*, *Ripogonum*, *Rubus* and *Passiflora*.

The conifer-broadleaf forest is less diverse in cooler montane regions, and displays a more simple structure. A low main canopy usually consists of the dominant conifer species *Libocedrus bidwillii*, *Phyllocladus alpinus* and *Podocarpus hallii*, together with *Griselinia littoralis*, *Hoheria* spp., *Metrosideros umbellata* and *Weinmannia racemosa*. This grades into sub-alpine forest and shrubland, consisting of podocarp shrub species *Halocarpus biformis*, *Phyllocladus alpinus* and *Podocarpus nivalis*, along with species of *Coprosma*, *Dracophyllum*, *Hebe*, *Myrsine*, *Pseudopanax* and Asteraceae.

Differences in forest composition also occur regionally, with *Dacrycarpus dacrydioides* and *Prumnopitys taxifolia* more abundant in drier eastern districts, and *Dacrydium*, *Quintinia* and *Weinmannia* common in moist western districts. North of 38°S, vegetation communities are characterised by marked increases in *Ackama rosaefolia*, *Beilschmeidia tarire*, *Ixerba brexioides*, *Phyllocladus trichomanoides*, *Halocarpus kirkii*, *Vitex luscens* and others, especially *Agathis australis*. 38° S is the latitude which denotes the most southerly limit of some of these species (e.g. *Agathis australis*).

<u>*Nothofagus* (beech) forest</u>

New Zealand beech forests are less diverse than conifer-broadleaf forests, and thus form a simple structure. Intermixed conifer-*Nothofagus*-broadleaf forests can occur where suitable soils and climate exists. However, both *Nothofagus*, and conifer-broadleaf forests have specific soil and climate preference; hence more intimate mixtures between the two forest types do not occur.

There are four species of *Nothofagus* in New Zealand. These are *N. menziesii*, with *N. fusca*, *N. truncata* and *N. solandri*. *N. solandri* contains 2 varieties, *var.*

*solandri*, found in lowland to montane forest; and *var. cliffortioides*, found in upland to sub-alpine and southern areas. *N. menziesii* is also mostly confined to montane and sub-alpine areas, and reaches a northern limit at 37°S. In the far south it can be found at sea level, and is common in wetter cooler districts. Conversely, *N. truncata* prefers warmer areas, extending north of 38°S, and is tolerant of infertile soils. Generally, *Nothofagus* forests occupy less favourable sites for plant growth, in terms of soil type and climate. They are predominantly found in cooler southern areas and uplands, often forming timberlines (Figure 1.2).

The *Nothofagus* forest structure is simple, containing few shrub species and a sparse understorey. Species from the genera *Blechnum* dominate the ground layer, with the shrub layer composed of *Coprosma* species and *Pseudopanax* trees important in the sub-canopy. Other emergents, apart from *Nothofagus* species, may include *Dacrydium cupressinum*, *Eleaocarpus hookerianus*, *Libocedrus bidwillii*, *Metrosideros umbellatum*, *Podocarpus hallii* and *Weinmannia racemosa*. These additional species become less common as the climate becomes increasingly cooler or drier.

Swamp forests

Tall swamp forest dominates the poorly drained sites over much of North Island and western South Island. Typical northern swamp forest trees include *Agathis australis*, *Dacrycarpus dacrydioides*, *Eleaocarpus hookerianus*, *Syzygium maire*, *Laurelia novae-zelandiae* and *Libocedrus plumosa*, which vary in abundance according to substrate, soil fertility and the water table level.

The more diverse mesotrophic swamps are dominated by *Dacrycarpus dacrydioides* on peats and alluvial clays. The poorly drained acid soils are dominated by *Dacrydium cupressinum*, with small trees or shrubs of the genera *Halocarpus*, *Lepidothamnus* and *Lagarostrobos*. In areas with a higher water table, *Syzygium maire* and *Laurelia novae-zelandiae* dominate, and with increased waterlogging and soil infertility, are replaced by *Leptospermum scoparium*, *Coprosma* spp. and *Cordyline australis*, together with low-lying herbaceous vegetation.

In cooler areas and at higher altitudes, swamp forests may be composed of *Halocarpus*, or *Dracophyllum* species, with *Libocedrus bidwillii* occupying the fringes.

Mire vegetation

Mesotrophic bogs contain diverse plant communities. Important plants include *Phormium tenax*, Cyperaceae (e.g. *Carex*, *Schoenus*, *Baumea*, *Lepidosperma*), Juncaceae, *Sphagnum* moss, *Leptospermum scoparium*, *Leucopogon fasciculatus*, *Gleichenia* spp. and sometimes *Empodisma minus*.

Raised (oligotrophic) bogs are characterised by swamp plants such as *Sphagnum* moss and Restionaceae species, such as *Empodima minus* and *Sporodanthus traversii*. Drier parts of the bog may encourage growth of *Leptospermum scoparium* and *Gleichenia* ferns. Bog margins may grade into scrub and swamp forest, described above.

New Zealand aquatic plants

Species established in shallow water (0.1 - 4.5 m) include *Glossostigma*, *Myriophyllum*, *Lilaeopsis*, *Limosella*, *Potamogeton*, with *Isoetes kirkii* and *Isoetes alpinus* found in lowland and montane lakes respectively.

Tall *Myriophyllum* and *Potamogeton* grow in water depths between 1-2 m, along with Charophyta (Green algae). Tall emergent sedges (e.g. *Eleocharis* and *Baumea*) grow in most lakes, with *Scirpus*, *Typha* and *Myriophyllum* in shallower water. Plants growing around lake margins include *Polygonum decipiens* (North Island) and *Callitriche* spp. (northern South Island).

## 1.6 Late Quaternary vegetation history of the North Island of New Zealand

This section provides a brief summary of the major vegetation changes occurring in the North Island during the late Quaternary (from *c.* 120,000 years ago), based on palynological and macrofossil evidence summarised in McGlone (1985; 1988), Newnham (1990) and McGlone *et al.* (1993).

The last glacial (120,000-25,000 BP).

The evidence to date reveals that New Zealand vegetation and palaeoclimate changes during the Pleistocene are broadly analogous with those for the rest of the world. In general, most information concerning the nature of vegetation change from glacial to interglacial is derived from the last (Otiran) glaciation (100,000-10,000 BP).

The Otiran glacial exerted the greatest influence on the present distribution of New Zealand vegetation.

During the last glaciation, there were at least three major interstadials, where forest occupied most of New Zealand, separated by stadials where shrub and grassland became dominant, leaving small isolated patches of forest. During the Moerangi Interstadial, which preceded the last glacial maximum (55,000-25,000 BP), New Zealand was largely dominated by shrubland, with areas of extensive *Nothofagus* and podocarp-angiosperm forest in the Bay of Plenty and Gisborne regions in the North Island. The last glacial maximum, (25,000-15,000 BP) is the most important and most recent stadial of the Otiran glaciation, and is thought to have been a major influence on the present vegetation distribution of New Zealand.

Last glacial maximum (25,000-14,000 BP).

Glaciation in the North Island of New Zealand was minor, with cirque and small valley glaciers on the Tararua ranges in the south, and a large ice field over the Tongariro volcanic region. Pollen records indicate that grass and shrubs were the dominant vegetation communities south of 37°S during this time, with grassland dominant in the east, and shrubland in the west. The most prominent taxa were Poaceae, Apiaceae, Cyperaceae, podocarp shrubs (*Phyllocladus, Halocarpus*), *Coprosma*, *Myrsine*, *Dracophyllum*, *Hebe* and Asteraceae (shrub and herb types). Wetland plants were less common than in postglacial times, with restionaceous rushes, *Empodisma* and *Leptocarpus*, restricted to the north. Forest pollen was more abundant in the North Island, where counts of 5-65 % were recorded at some sites, although 10-30 % counts were more common. The main tree taxa were *Nothofagus* and *Libocedrus* with occasional coniferous trees. *Dacrydium cupressinum* and *Prumnopitys taxifolia* pollen was recorded at a number of sites, but was extremely low, rarely exceeding 1 %. *Nothofagus menziesii* had the highest pollen percentage of any tree taxon at certain sites. Extensive stands of forest were probably present in hilly areas of the North Island, with grass and shrubland extending over the flat and rolling lowland regions. North of 37°S, continuous forest was likely to have been more extensive (Newnham, 1992; Newnham *et al.*, 1993).

McGlone *et al.* (1993) comment that temperature depression by itself cannot explain the distribution of vegetation over New Zealand for the last glacial maximum. Temperatures were 4.5-5°C lower, which implies that areas of northern South Island and most of the North Island below 600-700 m a.s.l should have been forested. Hence drought and strong winds, natural fire in the north, and the movement of cold polar air masses over the country may have been important factors which restricted forests to isolated and sheltered areas.

Late glacial (14,000-10,000 BP).

Between 14,000 and 13,000 BP, the North Island experienced rapid and complete re-afforestation in the Waikato basin, central uplands and around the southern Ruahine Ranges. Re-afforestation prograded gradually from north to south, with early forest consisting of podocarp-hardwood trees, mainly *Prumnopitys taxifolia* and *Prumnopitys ferruginea*, with *Dacrydium cupressinum* increasing with time. *Libocedrus* (probably *L. bidwillii*) species and *Nothofagus menziesii* were also common in these forests. The late glacial podocarp-hardwood forests therefore were very different from the present day New Zealand forests. By 12,500 BP, forest had expanded throughout the whole of North Island below the present treeline, apart from the extreme south-west. In Wellington (southern North Island) grass and shrubland remained dominant until 10,000 BP, whereas *Nothofagus-Dacrydium* forest was present in Nelson (northern South Island) before 10,500 BP.

Between 10,000 and 9,300 BP, all of North Island was covered with tall podocarp-hardwood forest. From the palynological and macrofossil evidence for vegetation change, it appears that 14,000 and 10,000 BP were times of rapid climatic and vegetation change. From 14,000 to 12,000 BP climate warming progressed steadily, stabilising between 12,000-10,000 BP. Macrofossil evidence indicates the presence of cooler climate species in New Zealand forests around 12 000 BP (i.e., *Libocedrus* spp. and *Nothofagus menzeisii*), suggesting temperatures were 2°C lower than present.

The Holocene (10,000 BP to present).

During the early Holocene (10,000-7000 BP), a mild temperate climate encouraged the growth of conifer-hardwood forest throughout New Zealand, exhibiting greater species diversity than during late glacial times. In northern and western North Island there were large increases in *Dacrydium cupressinum* trees, whereas in southern North Island, palynological evidence indicates that *Nothofagus* species were abundant.

Palaeoclimate data from speleothems indicate temperatures between 10,000-7000 BP were 1-2°C warmer than at present (McGlone *et al.*, 1995). Pollen and macrofossil evidence indicate that the climate had become less windy and less frost-prone. *Ascarina lucida* and tree ferns, both highly sensitive to frost and cool climates, were abundant in western exposed areas in North and South Islands, while *Nothofagus* trees were restricted to montane and sub-alpine sites.

At around 7000 BP, further significant vegetation developments occurred in the North Island forests:

1) *Nothofagus* forest expanded over uplands in southern North Island (Ruahine ranges).

2) Numbers of some conifer-hardwood species increased, i.e., *Agathis australis*, *Libocedrus plumosa*, *Phyllocladus trichomanoides*, *Prumnopitys*, *Podocarpus*, *Knightia excelsa*, *Nestegis* and *Quintinia*.

3) *Ascarina lucida* declined.

4) *Dacrydium cupressinum* gradually declined in many western and northern areas of New Zealand.

These variations in vegetation abundance were probably associated with seasonal changes in precipitation and temperature. In northern and western regions of New Zealand, generally cooler summers, and wetter, cooler winters encouraged the expansion of *Nothofagus* trees in the uplands, and the decline in frost and drought sensitive species such as *Dacrydium* and *Ascarina*, in the lowlands. The expansion of *Nothofagus* trees reflects increasing disturbance and declining soil fertility in areas of the North Island.

Since 2500 BP, natural vegetation changes have been minimal. However, major vegetation changes after 1000 BP occurred throughout New Zealand following the arrival of the Polynesian settlers and Europeans (around 150 BP), who cleared vast areas of New Zealand forest through burning. A more detailed discussion of anthropogenic impacts on the New Zealand environment is discussed in the following section.

## 1.7 Environmental change in New Zealand Prehistory

Human settlement and associated environmental impacts began late in New Zealand compared with other parts of the world. Nevertheless, there is much debate over the timing of arrival of the first Polynesians in New Zealand, and three competing hypotheses have emerged. The conventional theory, as outlined by Davidson (1984) suggests the arrival of Polynesians in New Zealand at around 1000 yrs BP. Sutton (1987) and Kirch and Ellison (1994) advocated that Polynesian arrival occurred much earlier, especially in the North Island, where a small number of early settlers, and slow population growth, has meant that early archaeological remains are difficult to discover. The third theory suggests that the Polynesians did not arrive until 800 yrs BP in New Zealand (Coster, 1989; McFadgen, 1994; McGlone, 1989; Anderson, 1991). McGlone *et al.* (1994) suggest that the number of settlers was initially quite large (~500) with early and rapid but steady population growth. The uncertainty surrounding the number of initial settlers stems from the scarcity of radiocarbon dates between 1000-800 BP, suggesting numbers were initially small. However, many radiocarbon dates falling into this category were found to be unreliable due to contamination (Anderson, 1991). In general, dating of early Polynesian sites is difficult, as the only material available for dating left by the Polynesians is bone collagen from moa and other extinct large ground-dwelling birds, shell middens and charcoal, all of which are known to exhibit problems with accurate dating (Anderson, 1991).

In the early Polynesian culture, hunting was the main source for nutrition, with a dependency on fishing (McGlone *et al.*, 1994). Early settlers therefore colonised the coastal areas of the North and South Islands, evidence for which is presented from radiocarbon dating, with the earliest reliable dates from locations on the northern, eastern and southern coasts of New Zealand (Anderson, 1991) and also in coastal stratigraphic sections (McFadgen, 1994). Later, when population pressure and food shortages became apparent, hunting became more widespread and ventured inland into the lowland forests. Ideal sites for the Polynesians were along the coasts (Anderson, 1991; McFadgen, 1994), major estuaries, alongside large river systems, lakes and lagoons (McGlone *et al.*, 1994).

McGlone (1989) argues that massive deforestation occurred between 800-400 yrs BP, with minor disturbances prior to 750 yrs BP. Initial burning was confined to the driest fertile lowland areas around the coasts, where fire was most effective. Extensive deforestation appears to have occurred virtually simultaneously in the North and South Islands (McGlone, 1989; Anderson, 1991; McGlone *et al.*, 1994). The sites around coasts and major estuaries and rivers were cleared and burnt first, favouring areas with lighter fertile soils. Rugged areas, wetlands and dense forest were only sparsely cleared. As burning continued throughout the period between 800-400 yrs BP, deforestation would have been widespread towards the end of this period. Forests were no longer useful to the Polynesians as most hunted game had disappeared; hence burning provided areas for cultivation of fernroot, in particular bracken, which had become a major component of their nutrition.

McGlone (1989) suggests that burning and cultivation may have initiated erosion in marginal areas, although this idea has been criticised by McFadgen (1989). In particular, burning and cultivation on unstable soils (e.g. sand dunes, steeper slopes) would result in rapid soil depletion, forcing abandonment to richer more fertile sites and hence more burning and deforestation. McGlone estimates that by the time of widespread European settlement in New Zealand in the 1840s-1850s, approximately one half of the native forest had been destroyed. Evidence for the rapid depletion and scarcity of resources post-450 yrs BP stems from the concentration of Maori Pa, or fortified settlements, implying conflict over resources and the need to defend those areas still productive for the Maori people (McGlone, 1989; Anderson, 1990; McGlone *et al.*, 1994).

**1.8 Late Quaternary volcanism in New Zealand**

This section will focus briefly on the Quaternary volcanic history of North Island, New Zealand, with emphasis on late Quaternary eruptive records. Detailed tephrostratigraphic columns are presented in appendix A1 for tephras recovered from the region.

Volcanic activity in New Zealand stems from the close proximity of an obliquely converging plate boundary between the Pacific and Indo-Australian plates. Most of South Island lies on the Pacific plate and is disjointed by the Alpine fault which marks the transcurrent plate boundary, whilst North Island lies on the Indo-Australian plate and is located west of the obliquely converging plate boundary (Duncan and McDougall, 1989; Stevens, 1988; Latter, 1989).

Evidence for an extremely violent volcanic history throughout the Quaternary is clearly visible over much of North Island today. Large volcanic centres dominate several areas, with numerous and frequent eruptions known, especially for the late Quaternary. Voluminous amounts of pyroclastic material and lava flows have drastically modified the North Island landscape. Extensive research has covered all aspects of volcanism, from formation and evolution through to tephra fingerprinting and tephrochronology (e.g. Searle, 1965; Cole, 1979; Rogan, 1982; Wilson *et al.,* 1984; Cole *et al.,* 1986; Lowe, 1988; Duncan and McDougall, 1989; Smith, 1989; Froggatt and Lowe, 1990; Neall, 1992; Pillans *et al.*, 1992; Healy, 1992; Wilson, 1993; Houghton *et al.*, 1995). However, the complexity of North Island's eruptive history is still not fully understood.

### 1.8.1 Taupo Volcanic Zone (TVZ)

The main North Island volcanic centres lie in the Taupo Volcanic Zone (TVZ) which runs along a north-east to south-west transect (Figure 1.1) (Cole, 1979; Rogan, 1982; Wilson *et al.,* 1984; Wilson, 1993, Houghton *et al.*, 1995; Nairn *et al.*, 1994). The TVZ has been active since 2 Ma, based on K-Ar dating (Stipp, 1968; Wilson *et al.* 1989).

TVZ eruptive activity is dominated by caldera-related rhyolitic volcanism from Okataina, Rotorua, Taupo, Maroa, Mangakino, Whakamaru, Reporoa and Tuhua Volcanic Centres (Table 1.2).

Andesitic volcanic activity occurs in the extreme north and south of the TVZ (Tables 1.3 and 1.4). In the south, the Tongariro Volcanic Centre (TVC) includes four main andesitic volcanic massifs: Kakaramea, Pihanga, Tongariro, and Ruapehu, with small eroded centres located at Maungakatote, Hauhungatahi, a small cone at Pukeonake and four craters at Ohakune (Cole *et al.,* 1986; Healy, 1992). In the north, andesitic activity occurs from White Island and Whale Island. The TVC is very complex, as the main volcanic massifs are composed of numerous cones with extensive separate volcanic histories. Tongariro itself includes at least twelve composite cones, the youngest of which is Ngauruhoe, which is one of the most recently active volcanoes in New Zealand (Cole *et al.*, 1986). The most recent

**Table 1.2** Age span of major activity from the rhyolitic volcanic centres in the TVZ (taken from Wilson *et al.*, 1984.)

| Centre | Volcanoes in Centre | Age range of activity |
|---|---|---|
| **Okataina** | Haroharo Caldera<br>Haroharo Dome<br>Tarawera Dome | Activity occurred from 250 Ka;<br>2 phases:- 250-50 Ka Caldera forming<br>50 Ka to present Caldera infilling |
| **Tuhua** | Tuhua volcanic island | 130 - 6.3 Ka (Houghton *et al.*, 1992) |
| **Taupo** | Taupo Caldera | ~ 330 Ka - 1850 yrs BP, potentially active |
| **Rotorua** | Rotorua Caldera | ~ 140 Ka - eruption of Mamaku ignimbrite<br>140 - 22 Ka dome formation |
| **Maroa** | Maroa Caldera | 250 Ka - 14/15 Ka. Some domes formed along NNE trending belt predate 330 - 230 Ka Taupo ignimbrites. Maroa still potentially active. |
| **Kapenga** | Kapenga Caldera | 560 - 330 Ka much activity, active until 50 Ka |
| **Mangakino** | Mangakino Caldera | 1.1 Ma to ~ 500 Ka |
| **Reporoa** | Reporoa caldera | Eruption of Kaingaroa ignimbrites, Fission track age 0.24 + 0.05 Ma (Nairn *et al.*, 1994). |
| **White Island volcano** | White Island | Reported solfataric activity since 1826 AD. Occasional tephra eruptions. Very active at present with continuous geothermal activity. |

significant eruption occurring in New Zealand was from Ruapehu during 1995 and 1996. During these recent eruptions, tephra was dispersed and deposited across a wide region of North Island providing a modern analogue, albeit at a smaller scale, to past eruptions now preserved in sedimentary records.

**Table 1.3** Age range of activity of the main volcanoes in the Tongariro Volcanic Centre taken from Cole *et al.* (1986)

| Volcanic Centre | Volcanoes in Centre | Age range of activity |
|---|---|---|
| **Kakaramea massif** | Kakaramea<br>Tihia | from 220 Ka, still potentially active |
| **Pihanga** | contains several young cones and vents | < 20 Ka |
| **Tongariro** | 12 composite cones<br>youngest is Ngauruhoe | Since 260 Ka. 2 stages of activity:-<br>older lavas > 20 Ka<br>younger lavas < 20 Ka<br>Ngauruhoe 2.5 Ka to present |
| **Ruapehu** | 4 cones:-<br>Te Herenga<br>Wahianoa<br>Mangawhero<br>Whakapapa | oldest activity 230 Ka<br>- > 130 Ka<br>- 60 - 120 Ka<br>-15 - 60 Ka<br>- 15 Ka to present |

**Table 1.4 a, b** Age range of activity from smaller eroded centres (a), and satellite cones and vents (b) in the TVC. Sources: Cole *et al.* (1986) and Healy (1992).

**a. Eroded Centres**

| Volcanic centres | volcanoes in Centre | Age range of activity |
|---|---|---|
| **Maungakatote 2 cones:-** | Maungakatote<br>Maungaku | < 330 Ka |
| **Hauhungatahi** | eruptive centre eroded | possibly the oldest feature of TVC, said to be > 500 Ka (Hackett, 1985) |

**b. Satellite cones and vents**

| | | |
|---|---|---|
| **Pukeonake** | Pukeonake, southerly vent of three | active from 20/25 Ka |
| **Ohakune** | contains 4 craters and vents | active from ~ 230 Ka |

Dacitic activity in the TVZ is rare. However, at least three volcanoes are known to have a dacitic composition (Table 1.5). These are Mt Edgecumbe, located near Kawerau in the northern part of the region, Tauhara, situated in the Taupo Borough area, and Maungakakaramea and Maungaongaonga domes on opposite sides of State Highway 5 at Waiotapu.

**Table 1.5** Summary of Dacitic volcanic activity in the TVZ

| Volcano | Main activity | Age range of activity |
|---|---|---|
| **Mt Edgecumbe** | Dacitic and andesitic lava flows forming large dome | Age range not known. Tephra layer dated around 4 Ka (Lowe, pers comm.) |
| **Tuahara volcano** | Numerous dacitic lava extrusions from multiple vents | Age range not known. Activity thought to have commenced around 190 Ka (Lowe, pers comm.) |
| **Maungakakaramea** | Dacitic dome with explosion craters formed from explosive hydrothermal activity | Further eroded than Tuahara, therefore activity thought to have commenced earlier than 190 Ka |
| **Maungaongaonga** | Dacitic dome with one large crater | Also further eroded than Tuahara. Dacite dated at 159 Ka, but activity thought to have commenced prior to 190 Ka |

### 1.8.2 Egmont Volcanic Centre

The Taranaki and Wanganui districts represent another area of andesitic volcanic activity in the North Island, which commenced in the early Quaternary (Table 1.6), (Neall, 1992). The most recent eruptions in the area occurred from Egmont (Taranaki) volcano, with oldest activity from Paritutu volcano which is now greatly eroded and dissected (Pillans *et al.*, 1992; Neall, 1992). Quaternary volcanism from Kaitake, Pouakai, and Egmont volcano, from oldest to youngest respectively, is known as the Taranaki Volcanic Succession ( Neall, 1992).

**Table 1.6** Summary of eruptive history of the Taranaki volcanoes (From Neall, 1992)

| Volcanic centre | Age of last known activity |
|---|---|
| **Egmont volcano** | From 100-120 Ka<br>Last active in 1755 AD |
| **Kaitake** | Last active 575 Ka |
| **Paritutu** | Last active 1.76 Ma |
| **Pouakai** | Last active between 216 Ka and 250 Ka |

### 1.8.3 Auckland Volcanic Field

The Auckland Volcanic Field contains three distinct zones: Auckland, Southern Auckland and Ngatutura. As the latter two zones have been inactive during the late Quaternary, only the Auckland zone is considered here.

Auckland includes around 50 known eruptive centres which are all basaltic; hence eruptions were small scale and tephra dispersal was localised, in contrast with the Central North Island volcanoes. Volcanic activity in the Auckland area commenced around 140 ka (Searle, 1965; Smith, 1989, Ballance and Williams, 1992). The youngest centre, Rangitoto Island, was reported by Brothers and Golson (1959) to have commenced activity ~ AD 1200, with the most recent activity occurring around 600 yrs BP (Searle, 1965; Smith, 1989; Haywood and Kermode, 1994). Auckland's volcanoes were produced from several different eruptive styles including lava effusion and fountaining, phreatomagmatic and strombolian activity (Smith, 1989).

In conclusion, the extensive volcanic history of New Zealand has resulted in widespread transformation of the natural environment, influencing the establishment of vegetation communities and forests of the central North Island, soil development and structure, and climate. These changes will be discussed in detail in the next chapter.

## Chapter Two

## The impact of volcanic emissions on vegetation, soils and climate

### 2.0 Introduction

This chapter reviews recent literature concerning global impacts from volcanic emissions and tephra fallout. The opening section briefly summarises previous research into the impact of volcanic eruptions on global climate, followed by a more specific review of evidence for volcanic induced climate change in New Zealand. The remaining three sections of this chapter focus specifically on non-climatic volcanic impacts, discussing the short- and long-term effects of ash and toxic chemical accumulation on soils and vegetation. The theme then moves onto a review of studies into proximal and distal volcanic impacts, focusing particular attention on previous research into volcanic-induced environmental change in New Zealand.

### 2.1 Climate

#### 2.1.1 Volcanic emissions and climatic impacts

Extensive research into assessing climatic impact from volcanic eruptions has shown that large, sulphur-rich eruptions (e.g. Mt Agung, 1963; Krakatoa, 1883; Laki, 1783; Tambora, 1815) can initiate climate cooling, lasting up to 2 years (Hansen *et al.*, 1978; Hammer *et al.*, 1980; Rampino and Self, 1982; Zielinski *et al.*, 1995). Nevertheless, climate changes following some major historic eruptions were insignificant against normal background fluctuations (Sear *et al.*, 1987; Hansen and Lacis, 1990).

Occurrence of narrow growth rings in trees following some volcanic eruptions are suggested to be caused by volcanic-induced climate change (LaMarche and Hirschboeck, 1984). However, the lack of synchroneity between records from different regions may indicate response in trees to local weather disruption from volcanic aerosol/ash emissions, or physiological damage and stress from ash and toxic gas accumulation, as opposed to a global short-lived reduction in temperature of a few tenths of a degree. As a result, many of these studies cannot draw firm conclusions to show volcanic-induced climate cooling has been responsible in the past for the occurrence of narrow growth rings in trees (Baillie and Munro, 1988; Lough, 1988;

Jacoby and D'Arrigo, 1988; Briffa *et* al., 1988; Briffa *et al.*, 1990; Fayle *et al.*, 1992; Palmer and Ogden, 1992).

**2.1.2 Evidence for climatic change following New Zealand volcanic eruptions**

New Zealand palaeoclimatic data for the late Quaternary consists of fairly well documented proxy records from pollen records, South Island glacier variations, oxygen isotope data from speleothems and can be inferred from Antarctic ice core data (Burrows and Greenland, 1979; Burrows, 1979; Salinger *et al.*, 1994; Wilson *et al.*, 1979; Burrows, 1982; Wilson, 1981; Suggate, 1990; Clapperton, 1990; Gellatly, *et al.*, 1988; Gage, 1985; Denton and Hendy, 1994). Little evidence is presented in relation to New Zealand volcanism and climate.

Lowe (1993) discusses four classic New Zealand eruptions which are likely to have had a hemispheric, if not global, impact on climate. Short-lived temperature cooling has been noted from proxy records following the Rangitawa eruption, (VEI 7-8) from Whakamaru caldera at 0.35 Ma. This was reported to be due to the injection of fine ash and sulphur aerosols into the stratosphere. However, no estimates for the degree of cooling have been given. As yet, no recorded cooling has been reported following the Kawakawa eruption (VEI 7-8) from Taupo caldera at 22.6 ka.

The Taupo eruption of 1850 yrs BP (VEI 6) is probably the best-documented New Zealand eruption. It is possible that aerosols and fine ash from this eruption circled the earth, as Zielinski *et al.* (1993) attributed an acid layer in the GISP2 Greenland ice core, dated at AD 181, to the Taupo event. This date concurs with the latest averaged $^{14}C$ dates for the Taupo event of 1854 +21 yrs BP, which has been calibrated to a calendar range of AD 168-256 (Lowe, 1993). Hence, it seems possible that cooling may have occurred in the immediate aftermath of this eruption, although no temperature cooling estimates have been documented.

The eruption from Mt Tarawera in AD 1886 (VEI 5) was the largest and most dramatic New Zealand eruption during New Zealand historical times. Instrumental records reveal a small drop in average temperatures in the southern hemisphere immediately after the eruption (Lowe *pers. com.*). Self *et al.* (1981) reported a 0.2°C average temperature decrease during the period following the Tarawera eruption, between latitudes 0 - 30°S and 0 - 60°N. However, other reports indicate climate warming trends around this time (Kelly and Sear, 1982), and so Self *et al*'s results are inconclusive (Lowe, 1993). The Tarawera eruption coincided with a major ENSO ( El Nino Southern Oscillation) event which may have obscured the maximum temperature effects from Tarawera (D.J.Lowe, *pers. com.*, 1995).

In general, any climatic effects from New Zealand volcanic eruptions remain unclear, largely because development of further reliable proxy-palaeoclimatic data is still required to provide sufficient evidence in support of this.

### 2.1.3 Summary

This study investigates the possible volcanic impacts on the environment from tephra fall. Volcanic-induced climate change has been the focus of numerous earlier studies, unlike research into non-climatic distal volcanic impacts (see section 2.4). Therefore further research is required in this area to investigate the vegetational and environmental impacts from ash and toxic chemical deposition at distal locations from the eruptive source.

Research in this study is focused on volcanic impacts during the late-glacial and Holocene (i.e., the last 16,000 years), when volcanic activity was extensive in New Zealand and a reliable tephrochronology has been established. The New Zealand eruptions during this time were unlikely to have had a significant climatic impact (Lowe, 1993). Even if some of these eruptions were climatically significant, climate change and any subsequent environmental impacts would have been minor and short-lived, and assessment of these impacts would probably be beyond the scope of the methods used in this study. The opportunity is therefore provided to assess the extent of long- and short-term non-climatic distal volcanic impacts in New Zealand, which, at present, are unknown (see section 2.4.3).

## 2.2 Soils

### 2.2.1 Volcanic ejecta and its effect on soil

The influence of tephra deposition on soil formation depends primarily on the thickness and chemical properties of the tephra layers. Where tephra accumulates over a soil to a minimum depth of 60 cm, soil formation processes begin afresh on the tephra surface (Gibbs, 1968). Thin tephra deposits are considered to have little effect on vegetation and are gradually incorporated into the soil. This usually results in renewal of soil processes and properties by the addition of new minerals, and thus the temporary revival of the old soil system rather than the regeneration of a new one (Gibbs, 1968). Ash beds are ideal for soil formation owing to their loose consolidation, giving breathing space for plant roots and organisms. The fine- grained particles are easily weathered to provide minerals and nutrients.

Processes of soil formation on volcanic tephra layers are most rapid on rhyolitic ash, which also results in reduced fertility of the soil compared to those developed on andesitic or basaltic material. Gibbs summarises the main characteristics of soils derived from volcanic ash compared with other soils in New Zealand. These are:

1) Deep humic topsoil, high in calcium and nitrogen and abundant soil organisms.

2) Granular texture, good air circulation, water percolation and root penetration.

3) Contain clay (sometimes 30%). Amorphous (allophane), absorbs many humic compounds and phosphorous, molybdenum and sulphur. Retains little potassium.

4) Low bulk density.

5) Unstable under pressure. Not suitable for construction.

6) High moisture content, ideal for plant growth.

7) Sensitive to management. Properties can be altered by vegetation change. Burning, cultivation and overgrazing of vegetation may lead to rapid erosion and degradation of the soil. Well managed soils under pasture have deeper topsoil, and have fewer problems of run-off and flooding.

In New Zealand, because of these soil properties, volcanic soils have been exploited and thus depleted very quickly when cultivated, as the granular structure turns to powder soon after commencement of agricultural stress on the soil. Ugolini and Zasoski (1979), and Will (1966) report that research has shown acidity increases in pumice/tephra soils that have been dried. Other observations are volume reduction, pore size increase, water transmission increase and a reduction in water retention. Depending on persistence of drying in the soil, these changes are usually irreversible. Summer drought, for example, could cause permanent damage to these soils.

Tephra soils are usually rich in the clay minerals imogolite and allophane. These, along with iron and aluminium oxides, have weakly acidic properties. Colloids in ash-derived soils are largely composed of these clay minerals which exhibit a pH dependent charge. Because of this, and the large surface area of these soils, the colloids have high cation exchange capacities. Most volcanic soils have mild to strong acid pH; hence these soils display significant anion exchange capacity as, with decreasing pH, a marked increase in $Cl^-$ adsorption occurs while, as pH increases, nitrate adsorption increases. Thus, the high cation exchange capacity of allophanic (i.e., volcanic ash derived) soils along with their weak acid properties mean they are well buffered.

However, the high cation exchange capacity of these soils in a leached/ high rainfall environment means that as pH decreases, cation exchange sites become filled by hydrogen ions, and thus exchangeable Al levels are reduced. Allophane and imogolite clay minerals become hydrogen-saturated very rapidly. Thus, lower exchangeable Al, and the low base saturation of ash-derived soils results in rapid reduction in soil fertility (Shoji and Ono, 1978).

Magnesium is also deficient in some ash soils, especially those in New Zealand (Will, 1966). Rhyolitic tephra soils are known to be low in magnesium, and would quickly become magnesium deficient once the initial reserve was utilised. Will (1966) reported magnesium deficiency in pumice soils in New Zealand as being the main cause of spring needle tip chlorosis in young pine trees. With a slight magnesium deficiency in the soil the tips of the pine needles turn a golden yellow. Where there is severe deficiency, chlorosis sets in and extends along the needle and the tips may become necrotic. The damage to leaves appeared in spring with new growth, and seemed to occur only in *Pinus radiata* and occasionally in *Pinus contorta*. This was only observed on pumice soils, and only in young trees between 3-15 years old, with 4-year old trees which had been pruned being worst affected. One factor contributing to a reduction in magnesium is drought. The central North Island spring in 1963 was one of the driest on record, and chlorosis in young pines growing on magnesium deficient Taupo pumice soils was extensive and severe.

Further problems will arise owing to the lower availability of aluminium in ash-derived soils (Ugolini and Zasoski, 1979). Mulder *et al.* (1989) report increased acidification occurring in soils with lower levels of aluminium, as acidic inputs are usually neutralised by dissolution of aluminium, due to cation adsorption. Depletion of soil aluminium levels, due to continuous acid deposition and adsorption, will lead to reduced availability of aluminium, and a further lowering of soil pH. Mulder *et al.* note that these changes are irreversible. Hence, long-term mineral depletion and subsequent acidification of these soils may explain why some species in North Island forests of New Zealand have disappeared from areas where they once dominated (see sections 2.3.3 and 2.4.3). Conversely, addition of fresh tephra deposits may temporarily replenish the soil nutrient reservoir possibly causing a decline in species tolerant of infertile soils.

Tephra-derived soils generally are excellent for agriculture and plant growth as they are permeable, more friable and more responsive to human management than other soils formed on bedrock. Thus New Zealand volcanic soils have become favourable for food production and timber (Gibbs, 1968). Nevertheless, problems have arisen with the outbreak of a disease in livestock known as 'bush sickness'. This was normally associated with soils developed on Kaharoa (ca. 665 BP) and Taupo (1850 BP) tephras. The disease was due to a deficiency in cobalt in these soils, as Taupo and Kaharoa ashes contain very low levels of cobalt compared to other tephras. The problem was soon remedied by adding extra cobalt to these soils (Gibbs, 1968). Ash deposits are also lower than average in boron in New Zealand. Soils derived from older andesitic tephra deposits are characteristically depleted in strontium and magnesium due to leaching out or leaching to lower levels respectively (Gibbs, 1968).

It is clear from these studies that the effect of tephra deposition on soils has important consequences for future vegetation development and long-term survival. Even if the vegetation can withstand and recover from the effects of tephra accumulation and acid pollution, long-term changes and depletion of soil mineral and properties will eventually affect vegetation communities growing in the soil. Also, influx of pollutants into the soil, originally scavenged by the vegetation, may cause rapid soil acidification and subsequent vegetation decline. Soil acidification following acid pollution is discussed in the following section.

### 2.2.2 Sensitivity of soils to acid deposition

There is a general awareness that acidification and degradation of the environment can occur due to excessive pollution over a short period. As discussed in the previous section, soils affected by the addition of pollutants can become more acidic, which will have a direct effect on the vegetation. Bull (1991) assessed the environmental sensitivity of British soils to acid deposition by devising critical load maps to determine damage thresholds for ecosystems (pollution receptors) in response to acidic deposition.

Bull's definition of a critical load for a receptor-pollutant combination is the largest acid deposition load the receptor can withstand without causing long-term damage. Pollution receptors are in the form of soils, freshwater, trees, natural vegetation and crops. Soils are probably the most important receptor, as they are not renewable once depleted of their minerals. Increased acid deposition will therefore enhance leaching of the base cations essential for plant nutrition, replacing them with acidifying hydrogen ions. Bull (1991) notes that increased acidification can inhibit soil processes such as decomposition of plant material which feeds additional nutrients into the soil.

Fertile soils with a large amount of base cations and a reservoir to replace these in the from of easily weathered bedrock, will have a higher buffering capacity (high critical load) for acidification and will only become depleted after substantial and prolonged acid pollution. Conversely, easily degraded soils with few available nutrients are more easily acidified and therefore have a low critical load (Bull, 1991). This applies to soils derived from volcanic ash which have a low base saturation with nutrient levels easily depleted.

Bull notes that the rate of supply and availability of calcium and magnesium from the breakdown of soil minerals is the main factor for determining the soil buffering capacity. The type of vegetation growing in the soil will also affect the buffering capacity as trees scavenge more gaseous pollutants than grass or low lying shrubs and plants. Hence this will affect the amount of pollution deposited in the soil, as trees could almost double this, due to the large surface area from numerous leaves (Bull, 1991). This has important implications for forests affected by volcanic ash and aerosol pollution in the North Island of New Zealand. Even if the tree species can withstand pollution to a certain level, the acid input into the soil uptake of pollutants by vegetation may initiate soil acidification, resulting in long-term damage to the ecosystem as a whole.

Bull reports extensive damage occurring on blanket bogs in the Pennines from deposition of sulphur and nitrogen. Plants such as lichens and bryophytes are known to be more susceptible to gaseous $SO_2$ than others. Hence, the natural vegetation can become overwhelmed and will not continue to grow in regions affected by pollution. Cooper (1949) reported disappearance of lichens around the summit of Mt Ngauruhoe (New Zealand) following the eruption in 1945 (see section 2.3.3) possibly the result of sulphur dioxide pollution.

Smith *et al.* (1993) report that dystrophic peats are more susceptible to damage by acid deposition as, once the peat reaches 50 cm thickness, renewal of base cations by leaching of the surface layers is very limited. Surface decomposition gives short-term replenishment of minerals but this does not extend to lower levels. Hence, atmospheric input and precipitation dominate the cation exchange capacity of the peat layers and so their sensitivity to acid deposition will be high.

These investigations of soil sensitivity to non-volcanigenic acid deposition may be relevant to this study. Fine tephra particles are known to scavenge acidic volcanic aerosols during transportation (Rose, 1977; Oskarsson, 1980) and there is the possibility that deposition of distal tephra particles could result in acid loading and temporary acidification depending on the thickness of the layer, the chemistry of the volcanic emissions and the critical load capacity of the soil. As trees will absorb much of the acid pollution adhering to the tephra particles landing on leaves, such acid loading in forested areas could become quite high, compared to grass or moorland, as reported by Bull (1991).

## 2.3 Vegetation

### 2.3.1 Acid pollution effects on vegetation

Research into volcanic pollutants and their effects on vegetation reveals that some plant species are unaffected by chemicals which are usually considered phytotoxic at high levels. Other reports have shown that species can build up tolerance and adapt to harsh acidic environments. Garrec *et al.* (1977) studied the vegetation on and around Mt Etna, Sicily where degassing of fluorine in the form of HF had been measured at 30 tons per day. Large quantities of $CO_2$ and $SO_2$ are also continually emitted (25 million tons $CO_2$ per year) (Allard *et al.*, 1991; Gerlach, 1991). They recorded high levels of fluorine in vegetation proximal to the volcano (between altitudes 2450m - 700m a.s.l) which decreased with distance, but the authors did not comment on whether this actually harmed the vegetation.

LeGuern *et al.* (1988) studied the contribution of atmospheric sulphur vapour and its influence on proximal vegetation communities. Their study was also carried out on Mt Etna, where results revealed normal amounts of sulphur content in plants, but extremely high fluorine concentrations. LeGuern *et al*'s explanation was that fluorine is not as readily metabolised and therefore stored in plant leaves, whereas sulphur is an essential nutrient for plant growth and therefore utilised and eliminated. They concluded that the vegetation tolerates extensive exposure to fluorine. The authors collected plants from the slopes of Mt Etna which showed no signs of necrosis, despite their high fluorine content. Etna's slopes are populated with black pine from Austria which were planted at the beginning of this century. At that time only 20% of the trees grew to maturity because of the pollution from the volcano. However, the new generation of this species is not affected and grows as normal.

The effect of a sudden increase of a pollutant on vegetation was studied by Garrec (1982) in laboratory experiments using spruce trees. Garrec recorded a growth impediment of > 40% in spruce trees where fluorine increased above 100 ppm in the pine needles. Also, studies by Garsed and Rutter (1982) revealed acute injury to some fir and spruce trees when subjected to differing concentrations of sulphur dioxide emissions. After 67 days, classic acute injury symptoms were shown, i.e., banding and leaf tip burn. This information provides important implications for distal vegetation impacts from possible volcanic aerosol pollution. Sulphur dioxide and fluorine are both emitted in high concentrations during many eruptions and may be dispersed over long distances as aerosols. Other reports and observations written at the time of the earlier Icelandic eruptions (e.g. Laki, 1783) mention widespread environmental and ecological devastation, much of which was due to fluoride poisoning (Thorarinsson, 1979). Laboratory experiments have provided evidence that HF gas is both a mutogenic agent and a phytotoxicant. Mohammed (1977) sprayed tomato plants and maize seedlings with HF in low concentrations which induced chromosomal changes in these plants. Growths and abnormalities were also recorded in sheep, mice and cows following exposure to HF. These same effects were observed following the AD 1783 Laki eruption in Iceland, where scavenging of pollutants by ash particles resulted in widespread acid damage across Iceland and parts of Europe and Scandinavia (Thorarinsson, 1979).

The theory that volcanic tephra can accumulate acid aerosols through transportation from the source has been researched in detail by Rose (1977) and Oskarsson (1980). Experiments performed on washed and dried tephra samples of varying particle size reveal that the finer the tephra particles are, the larger the amount of acidic aerosols adsorbed. This, however, depends highly upon temperature, as maximum adsorption will occur as the eruption cloud cools to below 600°C. Hence, it can be assumed that as finer tephra particles are dispersed greater distances from the source, i.e., >200 km, the abundance of adsorbed acidic particles will also increase with distance, assuming levels of acidic aerosols remain high.

Other studies on general acid pollution, both simulated and observed in the natural environment, reveal interesting differences in magnitude of damage resulting from variations in quantity and composition of pollutants. Lal and Ambasht (1981) reported foliar damage, restricted growth rate and high accumulation of fluoride from plants exposed to airborne fluoride. Chlorophyll content of leaves was greatly reduced when exposed to high levels of fluoride, causing chlorosis and retarded plant growth, with a 32.3% reduction in individual leaf biomass and a 27% reduction in leaf area. It is possible that similar results could be found in vegetation growing in volcanic regions which emit high levels of fluoride or HF.

Reinert (1984) recorded plant responses to simulated air pollutant mixtures and observed a reduction in growth and yield, physiological and metabolic imbalances and element accumulation. The most effective and phytotoxic pollutants are ozone ($O_3$), sulphur dioxide ($SO_2$) and nitrogen dioxide ($NO_2$). As individual pollutants, Reinert revealed that damage to vegetation was minimal. In varying combinations of two or all three pollutants, the damage was extensive. However, varying degrees of damage were exhibited by different plant species. Reinert concluded that most plant species suffered damage when exposed to all three pollutants, resulting in a reduction in plant biomass and yield. If this is the case, then future volcanic eruptions may have more devastating effects on flora and fauna than in the past owing to higher combinations of gaseous pollutants already present in the atmosphere (Evans, 1984). Further addition of $SO_2$ and $NO_2$ from volcanoes could produce highly acidic conditions in the aftermath of an eruption, especially in large cities with high ozone pollution (e.g., Los Angeles).

Evans (1984) carried out a similar study to Reinert (1984), this time observing effects of acid pollution on vegetation under laboratory and normal field conditions. Results revealed simulated acid rain had caused lesions to occur on plant leaves at pH 3.4, which was the highest pH at which visible damage was observed. Also, growths, or galls, produced by abnormal cell enlargement, had occurred on several plant species, for example, pinto beans and spinach, when exposed to simulated acid rain. Evans also recorded stunted pine needles when young pine fascicles were exposed to acid rain. Lichens were also found to be extremely sensitive to pH changes when subjected to simulated rain of pH 4, as photosynthesis rates were reduced by 43%. The sensitivity of lichens to acidic conditions may possibly explain why these plants did not re-establish near the summit of Mt Ngauruhoe

**Table 2.1** Acid pollution effects on vegetation

| Pollutant | Vegetation affected | Source (volcanic, industrial, laboratory experiment) |
|---|---|---|
| **Fluoride and $SO_2$** | spruce and fir trees (leaf tip burn)<br>black pine (1st generation)<br>Fluorosis in local forest vegetation<br>birch, dock leaves, heather, crowberry, Iceland moss and clover | - lab experiment (Garrec, 1982; Garsed and Rutter, 1982)<br>- Mt Etna, Sicily (LeGuern *et al.*, 1988)<br>- Uttar Pradesh, India-industrial pollution (Lal and Ambasht, 1981)<br>- after Eldfell and Laki, Iceland (Thorarinsson, 1979) |
| **HF** | tomato plants, maize seedlings | lab experiment (Mohammed, 1977) |
| **Acid rain (pH 2-3.4)** | pinto beans, spinach, pine spp., garden beet, lichen spp.<br>summit scrub vegetation | lab experiments (Evans, 1984)<br>Poas volcano, Costa Rica (Brantley *et al.*, 1992) |
| **$O_3$ $SO_2$ $NO_2$** | apple, grape, white bean, tobacco, radish, cucumber, tomato, soybean, begonia, petunia, pea, poplar, white pine, kidney bean, grass spp. | lab experiments (Reinert, 1984) |

in New Zealand (1949) (see section 2.3.3) and similar phenomena observed in Iceland (Thorarinsson, 1979). Evans (1984) concluded that the effects of acid rain on monocultured crops is devastating as the majority of the crop would be affected, producing lower yields.

However, a forest ecosystem would be better adapted for survival as, if one species were injured, other species would compensate for this, resulting in no overall change in forest productivity.

A summary of observations of vegetation affected by acid pollution is given in Table 2.1. Some of the papers reviewed here do not concern volcanic acid pollution directly, but are relevant to this project, as they involve pollutants commonly emitted during volcanic eruptions. Therefore these studies provide an insight into the possible vegetation damage that can occur following tephra and acid aerosol deposition.

### 2.3.2 Volcanic ash accumulation and vegetation impacts

Ash accumulation can have varying effects on vegetation, and damage from unpolluted ash usually depends on thickness of the ash layer. Burnham (1994) described the effects on vegetation following the eruptions of Mt St Helens (1980) and El Chichon (1982) when vegetation was affected over 20 km and 15 km radii respectively. Ash from El Chichon reached the cities of Merida and Veracruz on the Gulf of Mexico approximately 150 km away. The most surprising observations were that proximal cocoa tree plantations (up to 12 km from the crater) withstood the initial violent eruptions, but areas with less dense forest canopy were subsequently damaged by wet ash accumulation on leaves. Burnham reports that the leaves of the cocoa trees are coriaceous (leathery) and are therefore more resistant to ash loading and pollutants. Leaves appeared to have been snapped off and torn by the burden of ash, probably exacerbated by the additional weight of water following rainfall (cf. Thorarinsson, 1979). Thus, chances of survival of ash-laden vegetation would be greatly reduced if rainfall soon followed ash deposition.

Whittaker *et al.* (1992) assessed the ecological effects of ash fall on the islands of Sertung and Panjang, situated between 3-5 km from Krakatau volcano. Examination of sediment profiles on the islands revealed thick ash layers and buried soils with evidence for considerable vegetation damage by ash accumulation during ash fall events in the 1930s and 1950s. Whittaker *et al.* (page 156) quote Dammerman's (1948) account of a visit to Sertung after ash fall on August 22nd 1930:

"whole forest had appearance of a landscape in winter or of having been destroyed by fire. The action of the fine volcanic ash, which covered the leaves of the plants, had caused them to fall off, the young twigs and buds had been killed and the lower undergrowth had for the most part been destroyed...".

Whittaker *et al.* also comment on light ash-fall events having localised effects, with a short- term loss of leaf cover due to chemical effects rather than the physical impacts alone. They also suggest possible effects on seedling and sapling growth under a disturbed forest canopy of *Timonius* trees on Sertung. Creation of light gaps in the forest canopy following volcanic-induced damage to forest dominants had increased temperatures and reduced humidity. Young trees were especially endangered following the heavy ash falls of the 1930s and 1950s, thus affecting forest recovery.

Studies by Vucetich and Pullar (1963) (see section 2.3.3) and Thorarinsson (1979) (Section 2.4.1) also discussed the effects of ash accumulation on vegetation. Thorarinsson (1979) devised critical thresholds for farm abandonment due to ash fall in Iceland from previous studies. These were as follows:

i) Lowland areas - 30-50 cm thick to cause abandonment of rural districts lasting decades.

ii) Highland areas / bordering uninhabitable - 20 cm thick for long lasting abandonment.

iii) Lowland farms - 15 cm for 1-5 yrs abandonment, 8-10 cm for short-term (<1 yr) abandonment.

This pattern of abandonment resulted from the degree of damage to vegetation and burial of soils. Ash fall also endangered livestock, as Thorarinsson noted that grazing animals were killed following consumption of ash-laden vegetation, even when the tephra had not been contaminated by toxic substances.

It is clear that the physical effects of ash deposition and accumulation on vegetation are important and can cause widespread destruction. However, acid pollution from volcanoes in the from of gas discharges, hydrothermal activity, stream acidification, and acid-laden volcanic ash particles accumulating on vegetation, have also been reported to cause stress on the environment, the full extent of which is not entirely clear. The following section reviews New Zealand literature on proximal impacts from volcanic ash and acid pollution on vegetation.

### 2.3.3 Proximal volcanic impacts on central North Island vegetation.

Previous palaeoenvironmental studies in New Zealand have shown that volcanic activity has caused significant vegetational and environmental disturbance across the North Island since the last glacial period (Nicholls, 1963; Burke, 1974; McGlone *et al.*, 1988; Clarkson *et al.*, 1988; Burrows, 1990; Clarkson, 1990; Lees and Neall, 1993; Clarkson and Clarkson, 1994). First-hand accounts of vegetation disturbance and re-establishment following the Tarawera eruption (Okataina Volcanic Centre, Figure 2.1) of 10th June 1886 revealed that regrowth began around 1889-1890, with re-sprouting from still standing trees that had been stripped of leaves and branches (Turner, 1928). Small changes in the dominant vegetation were noted, as *Arundo conspicua*, *Coriaria arborea* and *Pteridium* had invaded the lahar deposits adjacent to Lake Tarawera, whereas prior to the eruption the area was covered with dominant *Leptospermum* scrub and *Pteridium*. Vegetation succession following the eruption has been very slow over the high domes and has only developed to open scrubland (Burke, 1974; Timmins, 1983). A gradual succession of changes occurred on the lower slopes, from early colonists of lichens and mosses (Burrows, 1990), to grasses and herbaceous angiosperms, with young forest becoming established near the shores of Lake Tarawera (Turner, 1928). Clarkson and Clarkson (1983) noted that the initially *Coriaria arborea*-dominant vegetation on the lower slopes of Mt Tarawera was gradually declining due to increasing competition from *Weinmannia racemosa* and *Griselinia littoralis* some time after the Tarawera eruption.

Burrows (1990) summarised and extended the early work on vegetation re-colonisation on Mt Tarawera following the 1886 eruption. He noted that fleshy fruited woody species soon invaded once an initial vegetation mat was established and *Coriaria arborea* is today rapidly invading the gravely summit area. This species is an important colonising shrub on Tarawera and was often the first broad-leaved woody species to re-invade many moist sites on the lower slopes, following the eruption, as observed by Turner (1928). Burrows believes its delayed re-colonisation of the upper slopes and summit areas is probably due to the thin gravelly pumice soils, which are free draining, and therefore not suited to the ecological requirements of *Coriaria arborea.*

The importance of *Coriaria* as a pioneer species on Tarawera is due to its nitrogen fixing capabilities (Clarkson, 1990). Also, additional nitrogen input from leaf litter will rapidly result in nitrogen-rich soils, leading to quicker vegetation re-establishment (Burrows, 1990). Areas where *Coriaria* is absent are instead invaded by hardy shrubs such as *Leptospermum* which also colonise the early established vegetation mats of herbaceous plants, lichens and mosses. Areas where *Leptospermum* rather than *Coriaria* has invaded, exhibit much slower rates of successional change and species diversity (Clarkson, 1990; Burrows, 1990). Hence Burrows emphasises the importance of plants with nitrogen-fixation capabilities as early colonisers on volcanic material and soils, as these will no doubt lead to more rapid re-colonisation of the bared surfaces, and greater species diversity. Figure 2.2 provides a summary of vegetation succession on the eastern side of Mt Tarawera over the last 100 yrs (i.e., post 1886 eruption). It is interesting to note that *Metrosideros* species do not feature in Burrows summary, yet these plants are also considered important pioneer species on volcanic ejecta in New

Zealand (Clarkson *et al.*, 1989, Clarkson and Clarkson, 1994). Burke (1974) noted *Metrosideros* is prominent in the forests of the Rotorua district, where most soils are derived from volcanic material. It may be that competition from *Coriaria* and *Leptospermum* was vigorous and inhibited re-colonisation of *Metrosideros* here.

Other studies investigated why certain species growing prior to eruptions became absent from the area following volcanic impact (Cooper, 1949; Nicholls, 1963; Burke, 1974; Clarkson *et al.,* 1988, Clarkson, 1990; Burrows, 1990). Nicholls (1963) noted that the dense mature mixed podocarp-hardwood forest near the summit of Mt Tarawera is different from any other in the district, and proposed that the skeletal sandy-gravel soils had favoured the colonisation and persistence of *Podocarpus totara.* Similarly, Burke (1974) commented on the spread of podocarps following volcanism from Mt Tarawera. *Phyllocladus glaucus* and *Podocarpus hallii* were more extensive before the AD 1886 eruption than at present, in particular on the plateau dome where they are absent today. No clear reason has been given for this, other than local site factors.

Cooper (1949) described vegetation re-establishment on Mt Ngauruhoe (Tongariro Volcanic Centre) (Figure 2.1) after the 9th February 1949 eruption and reported a reduction in the number of lichens, despite an abundance of open areas. He suggested that recently deposited volcanic ash may have been an unfavourable base material for regrowth. Conversely, some plant species, viz. *Dracophyllum* and *Danthonia,* were apparently able to adapt to these conditions as they have long roots and *Dracophyllum* has the ability to develop roots on partly buried branches. Lichens, as well as *Coriaria*, are known to be important nitrogen fixers (Clarkson, 1990). Hence, further vegetation re-establishment and diversity on Ngauruhoe may have been inhibited due to a nitrogen deficit in the soils, as has been observed in certain areas on Mt Tarawera (Burrows, 1990).

Similar trends to those observed by Burrows (1990) and Burke (1974) on and around Mt Tarawera, were also seen to have occurred in palynological records of vegetation changes on Mt Egmont (Figure 2.1) following the Newall ash eruption (AD 1500) and Burrell lapilli eruption (AD 1600) (McGlone *et al.,* 1988). Dramatic long-term changes occurred within the forests as large numbers of the dominant trees, *Dacrydium cupressinum* and *Prumnopitys ferruginea,* appeared to have been severely damaged, possibly by leaf scorch and leaf fall with many canopy trees being killed outright. Druce (1966) analysed organic deposits found on Mt Egmont and concluded

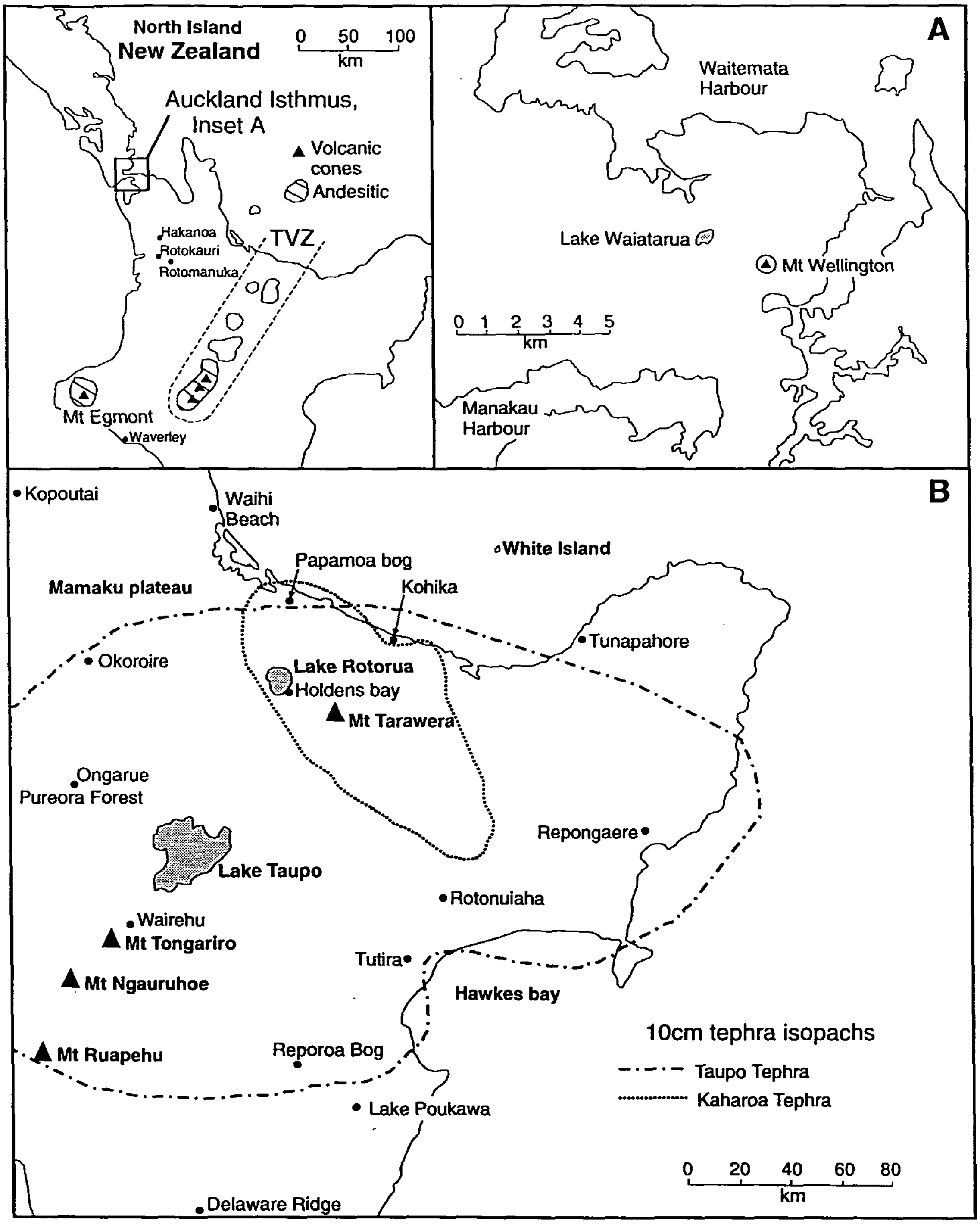



**Figure 2.1** Isopach map (10cm) showing the extent of Taupo and Kaharoa Tephra erupted from Taupo and Okataina Volcanic Centres. Sites are marked on the maps showing where proximal and distal vegetation impacts have been observed (after McGlone, 1981; Newnham and Lowe, 1991 and Wilmshurst and McGlone, 1996).

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Approximate timescale** | | 10 years | 15 years | 25-30 years | 50-70 years | 100 years | ca. 200 years (predicted future) |
| **Main growth forms** | moss-lichen* | mat herb-tufted grass | low heath shrub | tall heath (to 5m) | low broad-leaved angiosperm forest (to 15m) | moderately tall broad-leaved angiosperm forest (to 22m) | tall broad-leaved angiosperm forest (to 26m) with emergent podocarps |
| **Prominent species** | *Racomitrum lanuginosum* → | *Raoulis spp.* *Muehlenbeckia axillaris,* *Rytidosperma sp.* *Luzula sp.* mosses, lichens → | *Gaultheria spp.* *Cyathodes spp.* *Dracophyllum spp.* mosses, lichens → | *Leptospermum scoparium,* *Olearia arborescens,* *O. furfuracea,* *Coprosma robusta,* *Gaultheria spp.* *Cyathodes spp.* *Hebe sp.* some ferns → | *Weinmannia racemosa,* *Griselinia littoralis,* *Aristotelia serrata,* *Melicytus ramiflorus,* *Carpodetus serratus,* *Brachyglottis repanda,* *Pseudopanax spp.* *Coprosma spp.* many ferns → | *Weinmannia,* *Knightia excelsa,* *Beilschmiedia tawa,* *Elaeocarpus dentatus,* *Myrsine australis,* *M. salicina,* *Podocarpus hallii,* treeferns, many ground ferns → | *Weinmannia,* *Beilschmiedia,* *Elaeocarpus,* *Podocarpus hallii,* *Prumnopitys ferruginea,* *Dacrycarpus dacrydioides,* *Dacrydium cupressinum,* tree ferns, ground ferns, vascular epiphytes, vines |
| | *Cladonia spp.* → *Coriaria arborea* | mosses, lichens → *Coriaria arborea* | → *Coriaria arborea* | *Coriaria arborea* → tall heath | | | |

*Coriaria arborea* → (short circuits timing of tall shrub development by about 15-20 years)

* Initial vegetation development to this stage has occurred at progressively later dates with increasing altitude and exposure and is still occurring on parts of the summit (i.e. 100 years after the eruption).

**Figure 2.2** Vegetation development trends on the eastern side of Tarawera volcano, North Island, New Zealand, above 600 m altitude (taken from Burrows, 1990, Figure 4.11).

that many leaves found had been scorched by hot gases following the eruption of the Burrell Lapilli. Almost immediately, *Coriaria* and *Weinmannia* invaded canopy gaps, where they subsequently flourished, as noted on Mt Tarawera. These effects were virtually immediate and the resulting change in vegetation composition to *Weinmannia/Coriaria* dominance remained well into the European era.

Druce's work reveals that effects from volcanic eruptions on surrounding well established vegetation communities may be severe and long lasting. Pre-eruption vegetation (*Phyllocladus, Podocarpus,* and *Dacrydium*) which thrived on Egmont, and also Tarawera, has not returned, possibly due to vigorous competition from *Coriaria* and *Weinmannia* trees/shrubs, or changes in soil mineralogy and structure not suited to these species, or a combination of these factors. Also, a reduction in dense forest on both mountains following eruptions resulted in fewer sheltered areas for vegetation re-colonisation.

Pollen evidence presented by Lees and Neall (1993) from sites near Mt Egmont also revealed changes in soil fertility following ash deposition that resulted in a shift in vegetation and exclusion of certain species which may previously have been common in the area. However, most vegetation changes were solely due to direct volcanic impacts from blasts and hot ash affecting the emergent species in forests and creating spaces in the canopy for typical ash invading species such as *Metrosideros, Weinmannia* and *Coriaria.* Newnham and Lowe (1991) also noted that changes in soils and substrate caused by volcanic activity strongly influenced vegetation re-establishment at Lake Waiatarua, Auckland (Figure 2.1A). *Metrosideros* trees established quickly onto new lava surfaces, and rapid expansion of tall podocarps especially *Podocarpus, Dacrydium,* and *Prumnopitys taxifolia* occurred following damming of the Waiatarua valley by lavas and infilling by fresh volcanic tephra from the Mt Wellington (Maungarei) eruption(s) of ca. 9,000 BP.

Similar conclusions were reached by Clarkson *et al.* (1988) from their study of an area of forest in Pureora Conservation Park, located 50 km north-west of Taupo (Figure 2.1B), which was overthrown by strong direct blasts from the 1850 BP Taupo eruption. Analysis of macrofossils revealed differences between the present forest and the pre-eruption vegetation. Clarkson *et al.* attributed these distinct changes to the subsequent improvement of soils in the region following ash deposition, as observed on Egmont

(McGlone *et al.*, 1988; Lees and Neall, 1993) and Tarawera (Burke, 1974). Pre-eruption vegetation mostly favoured poorly drained infertile soils, and soil analysis revealed that the relic soils below the Taupo pumice were relatively infertile, with a high phosphorus retention, indicating excess weathering and a low amount of phosphorus available for plant utilisation. The authors concluded that species absent from the present-day forest were so badly damaged by the blasts that they were unable to re-sprout. Improvement of soil fertility and aeration by the addition of nutrient-rich volcanic ash made conditions less favourable for these species to re-establish themselves in the area. The impact of volcanism has permanently altered vegetation in the region and the original forest may never return.

Nicholls' (1963) research into the vegetation of the Rotorua district revealed notable differences between forests in the east and west. He suggested that this was due to long- term soil changes as ash/lapilli erupted from the Okataina Volcanic Centre possibly accumulated deeper in the east than the west zone due to prevailing wind direction. Nicholls also referred to the scattered and isolated distributions of the beeches and *Agathis australis*. He inferred that the beeches were relic species in the area, once widespread on the infertile soils of the Mamaku plateau (Figure 2.1B), with base-deficient soils deterring competition from other plants. Following the eruption of the Rotorua Tephra (13 080 ± 50 yrs BP, Froggatt and Lowe, 1990) soil fertility improved, allowing increased competition and development of the present forests, characterised by *Dacrydium cupressinum*, *Metrosideros* species and *Beilschmiedia tawa*. Although the transition from cooler to milder climate commencing ca. 15 000 yrs BP might also explain this vegetation trend, Nicholls observed that the beeches are absent from higher ground in the district where climate is suitable, but the deposition of thin tephra layers improved soil fertility, causing increased competitive pressure for these sites from other species in the area. Newnham *et al.* (1993) note that *Nothofagus* trees do not compete well under a dense forest canopy, and so the combination of these factors would have discouraged *Nothofagus* trees from these sites.

Other recent research into proximal volcanic impacts in New Zealand has been carried out on White Island volcano, situated off the Bay of Plenty coast (Figure 2.1B) (Clarkson *et al.*, 1989; and Clarkson and Clarkson, 1994). Their research has emphasised the importance of toxic fumes, acid rain and wet ash coating the leaves of the local vegetation as major causes of plant death. The toxicity of White Island emissions has been a major control over the growth of *Metrosideros excelsa*, the dominant species, and was previously observed by Oliver (1915) and Hamilton (1959) (quoted in Clarkson *et al.*, 1989). The recent studies on the island from 1976-1990 by Clarkson and Clarkson reveal that eruptions involved voluminous ash emission and extremely toxic gas discharges which lingered in the air and were virtually continuous over the period between 1976 and 1981. These toxic gases included revolatised HCl with increased amounts of absorbed compounds and elements such as HF and sulphur.

Despite this toxic environment, different phases of forest development have been observed from *Metrosideros excelsa* growth ring counts, with the oldest forest aged >180 yrs. However, owing to the recent continuing period of activity, these forests have declined by two thirds of the total original forest. *Metrosideros excelsa* is a hardy species in terms of adjusting to a harsh acidic environment and is found growing naturally in Whakarewarewa thermal area in the Rotorua district. Even so, its decline is continuing on White Island, and other hardy species associated with thermal activity, e.g. *Leptospermum* and *Kunzea,* are absent.

Studies of the vegetation in 1986 (Clarkson and Clarkson, 1994) revealed most *Metrosideros excelsa* forest was destroyed on the south-west side of the volcano. Examination of the leaves showed 'spot damage' and die-back on leaf tips and margins. These features were typical of damage by acid rain which has coalesced on leaves and literally burnt the leaves off their branches. A wet ash film on leaves, whether toxic or not, will reduce photosynthesis and other physiological processes vital to plant survival, and cause plant death. Trees and shrubs heavily laden with sulphur-bearing ash accumulating on branches, in hollows, and on leaves, will poison the plant. From 1986-1990 only seven species were reported living on the island. When weather conditions are foggy or misty, these effects are accentuated as the gases are trapped inside the thick air.

Clarkson and Clarkson (1994) comment that the White Island eruptions are atypical compared to other North island eruptions. Blasting, burning and burial of vegetation were evident on Mts Ngauruhoe and Tarawera (Cooper, 1949; Nicholls, 1963) and appeared to be the main causes of vegetation damage and death, rather than the emission of toxic fumes, wet ash accumulation and acid rain deposition, which are apparent on White Island today. However, Druce's (1966) observations of organic layers on Mt Egmont showed evidence for leaf scorch, suggesting that further research into macrofossil examination on North Island volcanoes is required in order to prove whether acid gas damage was in fact more widespread in the past. Proximal volcanic impacts reviewed in these papers are displayed in the form of a flow diagram (Fig. 2.3). The diagram shows the main vegetation changes and processes that have been reported to occur following deposition of volcanic material in the North Island of New Zealand. Taxa that are reported to be inhibited by tephra deposition are listed on the left side of the diagram, and taxa known to increase following tephra deposition are listed to the right, showing in particular, the successional changes taking place in relation to early presence of *Coriaria* shrubs.

If such varying degrees of damage can occur at proximal locations, then as volcanic ash is known to be transported over wide areas, it is indeed possible that impacts may be seen at greater distances from the source. Recent research in Britain has considered this possibility, although explicit mechanisms for distal volcanic impacts have been, at best, speculative, and the topic has been touched upon in New Zealand. This next section will discuss the possibility of distal volcanic impacts and the research completed to date.

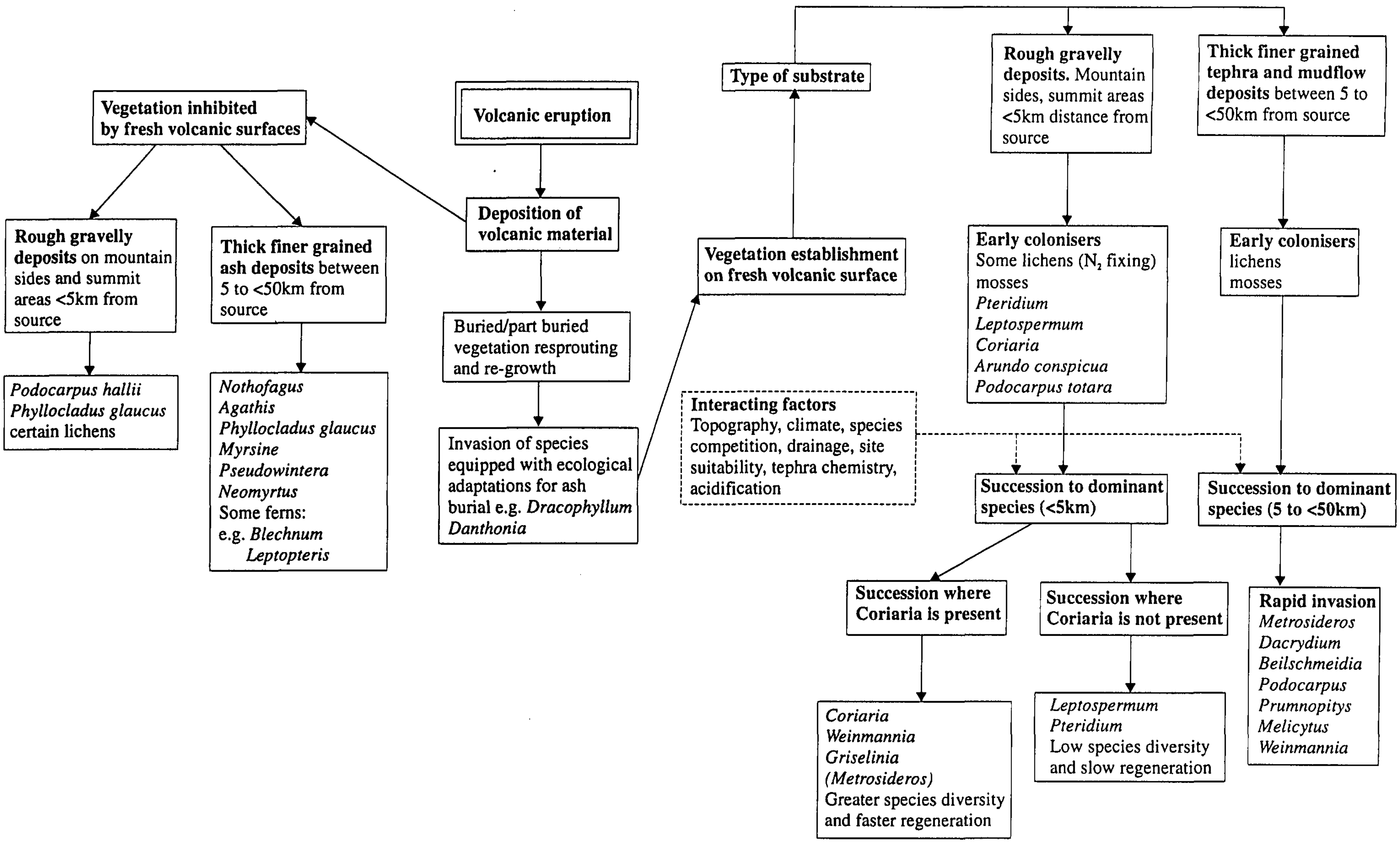



**Figure 2.3** Summary diagram reviewing the reported proximal to distal (50km) vegetation impacts following tephra fall in the North Island of New Zealand

## 2.4 Distal volcanic impacts

### 2.4.1 Distal volcanic acid pollution in Europe

Thorarinsson (1979) noted that during volcanic eruptions, solfataric activity or degassing, the damaging effect from drifting volcanic gases was normally short range. At greater distances, toxic damage is mostly caused by aerosols transported by tephra particles. Cases of fluorosis (fluorine poisoning) were reported after the Hekla eruptions of AD 1693 and AD 1845. Acute Fluorosis also occurred in AD 1970 in areas with tephra thickness as low as 0.5 - 1 mm, resulting in the death of 7000 - 8000 grazing animals in a matter of days following the eruptions (Thorarinsson, 1979). Thorarinsson also reported vegetation damage from the Eldfell (AD 1973) eruption from fine ash accumulation of 0.5 - 1mm at Myrdalur, 60 km distance from the source. Pine needles from conifers in gardens became brown and young pines were gradually killed.

Thorarinsson (1979) also mentions many reports of anomalous weather phenomena occurring shortly after the Laki eruption of AD 1783. Atmospheric conditions at the time of the eruption may have confined low-latitude aerosols to the troposphere, producing dust veils over Iceland and parts of Europe, causing dense, acidic smoggy conditions and cooler temperatures (Kington, 1992). Using historical meteorological data, Kington (1992) re-created synoptic weather maps for July 1816, following the AD 1815 Tambora eruption. Anomalous weather patterns were said to be caused by the effects from gaseous and dust output from the eruption, displacing pressure cycles, and resulting in cold wet summers and severe winters over Europe and North America (Kington, 1992). Similar events were therefore likely to have occurred following the Laki eruption. Displacement of pressure cycles, and dominance of low pressure cyclonic weather concentrates acidic aerosols and volcanic dust into the lower troposphere, thus enhancing the already unpleasant cold and wet weather conditions (Grattan and Charman, 1994).

Impacts of ash fall and toxic gas accumulation from the Laki eruption were the most severe and are well documented. Thorarinsson (1979; 1981) provides detailed accounts of damage caused in Iceland from the dry acid fog which hung in the air throughout the summer and autumn of 1783. The resulting 'Haze famine' which lasted through to 1785 caused a 24% population decline, which did not recover to pre-famine levels until the early 1800s (Vasey, 1991). The toxicity of the eruption was evident in the

Camp Century ice core in Greenland, where Hammer (1977) reports $H_2 SO_4$ aerosols reaching 100 million tons, and fluorine 5 million tons.

Thorarinsson (1979) concluded that tephra thicknesses on settlements did not exceed 3 - 4 cm but nevertheless had devastating effects. The cultivated fields turned yellow and the grass was withered to the roots. Most trees, especially birch, were also killed, shedding leaves which had shrunk and had turned black. Raindrops had burnt holes in dock leaves, and blemishes had formed on the skin of freshly shorn sheep. Hundreds of birds were also reported to have died. Large trout death tolls were also recorded in rivers and lakes 120 - 180 km away. Heather and crowberry bushes, Iceland moss (*Lichen islandicus*) and clover (*Trifolium repens*) were seriously affected.

The impacts from the Icelandic volcanoes, with some exceptions (Katla, Surtsey, Grimsvotn) appear to be unusual, although acid fog production from Mt Etna, Sicily, has also been reported, along with high acidity peaks in Greenland ice cores for other large lava flow eruptions with low explosive activity (e.g. Lanzarote, Canary Islands) (Stothers and Rampino, 1983). The effects of acid aerosol deposition are extremely severe, and, in the case of Laki, widespread, affecting most of Europe and Scandinavia.

Recent attention has been directed towards the unusual atmospheric phenomena reported in newspapers, and by Franklin (1784), following the Laki eruption, 8th June 1783 to 8th February 1784 (Thorarinsson, 1969; Thordarson and Self, 1993; Grattan and Brayshay, 1995). This eruption is considered to be one of the most climatically significant in historic times, with an estimated <1°C temperature decrease, and widespread environmental impacts, both proximal and distal as described above (Thorarinsson, 1979; Grattan and Brayshay, 1995). The Laki eruption produced 9.9 x $10^{13}$g acid gases, which was largely composed of $H_2SO_4$ (9.19 x$10^{13}$g) said to be greater than any other Holocene eruption (Devine *et al.*, 1984; Thordarson and Self, 1993; Grattan and Brayshay, 1995). The widespread acid pollution effects from this eruption were believed to be the result of volcanic aerosols being confined to the troposphere, rather than ejected and dissipated into the stratosphere, resulting in a potent thick fog which spread over Europe (Thordarson and Self, 1993; Grattan and Brayshay, in press). Unusual cold wet weather therefore prevailed over parts of Europe, whereas intense heat and violent thunderstorms were reported over Britain, with thick air dense with concentrated volcanic acidic gases (Grattan and Gilbertson, 1994). Observed impacts from the Laki eruption are summarised in Table 2.2.

**Table 2.2** Summary of unusual weather phenomena and extensive vegetation damage in Britain following the Laki 1783 eruption. Material taken from Grattan and Charman, 1994; Grattan and Pyatt, 1994; Grattan and Brayshay, 1995; Grattan *et al.*, 1996.

| Report | Region | Date | Weather | Vegetation damage |
|---|---|---|---|---|
| **Horace Walpole** | Britain | 15th July, 1783 | Unseasonable heat. constant fog. | Parched leaves. crisp turf. |
| **Sherborne Mercury** | London | 21st July, 1783 | Violent thunder and lightning | |
| " | Kent | " | Fierce winds blew from the coast, inland. | |
| " | Surrey | " | Lightning 'Violently alarming' | |
| " | Hertfordshire and Midlands | " | Sulphurous storm occurred with intense heat which increased as storm progressed. Sulphurous stench when no rain. | |
| **Cullum** | East Anglia | 23rd June, 1783 | White frost (3 am). Ice over tubs of water (3-4 am), not melted before 6 am. | Barley and oats turned brown and withered. Rye appeared mildewed. Larch, Weymouth Pine and Scotch fir-tips of leaves withered. Ash leaves withered. Cherry, peach, filbert and hazelnut 'extremely pinched'. Hypericum and hirsutum, blackthorn and sweet violet-leaves injured. |
| **Cullum** | Bury | 23rd June, 1783 | | Fig tree-leaves severely injured. |
| **Cambridge Journal** | Cambridge | 5th July, 1783 | Frost. Intense heat followed by intense cold | Grazing land (grass) and corn appeared as if dried up by the sun, turned brittle like hay. Beans turned white. |
| **Ipswich Journal** | Ipswich | 12th July, 1783 | Profuse dews, 'uncommon gloom' | Wheat, barley and oats-very yellow, leaves withered. Ears of wheat not affected. |
| **Caledonian Mercury** | Scotland (Leith) | 5th July, 1783 | Great storm, thunder and lightning. heavy rain. | Many different species of fish killed in reservoir at Leith. |

Grattan and Charman (1994) and Grattan and Pyatt (1994) conclude that the vegetation damage noted in these reports was not due to frost damage alone, but by plant poisoning from acidic aerosols, resulting in selective damage to plants according to their resistance to acid pollution. The acid damage could have occurred once the frost had melted onto leaves after frost/precipitation had scavenged volatiles from the lower atmosphere where they hung in the smoky haze. The 'acid frost' would have caused a flux of toxic chemicals onto the plants which upon melting resulted in plant necrosis.

The evidence for volcanic acid pollution in Europe provides important implications for impacts from distal tephra fallout and volcanic acid rain occurring in New Zealand. Of particular relevance is the effect of ash fall and toxic chemical accumulation on plant leaves, with further risks to grazing livestock. Changes to soil chemistry and structure must also be considered, affecting plant growth and the establishment and decline of different plant species. The following sub-sections discuss the evidence for distal volcanic impacts detected from pollen records in the British Isles, and in New Zealand. Research into distal volcanic impacts in Britain is of particular relevance to this study as many of these studies applied the same techniques in their investigations into volcanic impacts. These include fine resolution sampling above distal tephra layers to examine palynological changes in order to assess possible palaeovegetational changes immediately following ash fall. Also, palynological investigations have been used in conjunction with geochemical analysis using the EDMA technique, in order to assess possible environmental impacts on local catchment soils (Charman *et al.*, 1995). Encouraging results emerged from the British research, as environmental impacts from ash deposition were detected in palaeo records above some distal Icelandic Tephra layers analysed, despite the fact that these were cryptotephras. These studies therefore provide an important grounding for the results presented in this thesis, providing evidence to show that the techniques used can provide positive results, and that distal volcanic impacts from tephra layers <1mm in thickness can be detected in proxy palaeoenvironmental records.

### 2.4.2 Distal volcanic impacts in Britain

Research in Britain concerning distal volcanic impacts and associated environmental stress is controversial. Evidence for vegetation damage following the Laki fissure eruption in AD 1783 has been discussed in detail by Thorarinsson (1979), Grattan and Pyatt (1994), Grattan and Charman (1994) and Grattan and Brayshay (1995). However, some scientists remain sceptical about the supposed volcanic impacts in Britain from the Hekla 4 (H4) eruption in Iceland around 2310 ± 20 BC (Hall *et al.*, 1994; Birks, 1994).

The first strong evidence showing a correlation between volcanic ash deposition and vegetation decline was reported by Blackford *et al.* (1992). Pollen records from two sites in the north of Scotland revealed sharp decreases in *Pinus* frequencies directly above the Icelandic Hekla 4 tephra, erupted ca. 4000 BP. Blackford *et al.* also recorded simultaneous increases in some mire taxa at both sites, with *Erica* and *Sphagnum* increasing in abundance above the tephra layer. Blackford *et al.* concluded that there appeared to be a direct correspondence between a decline in *Pinus* pollen, and the deposition of Icelandic volcanic ash.

Blackford *et al.* suggested that volcanigenic acid precipitation and the adsorption of gases onto the tephra particles which then accumulated on the pine trees, possibly triggered their decline. They referred to reports by Thorarinsson (1979; 1981) of extensive vegetation damage occurring in Iceland and Scandinavia as a direct result of deposition of Icelandic tephra and gases. Blackford *et al.* also referred to Caput *et al.* (1978) who provided evidence that *Pinus sylvestris* was especially sensitive to pollution from acid rain. However, Blackford *et al.* also suggested that general climatic deterioration is an equally valid explanation for the pine decline, with increases in Cyperaceae and other mire taxa synchronous with decreasing levels of pine pollen, indicating a possible change to cooler, wetter conditions.

Studies in Northern Ireland, however, reveal no impact from Icelandic volcanic tephra layers on vegetation assemblages reconstructed from pollen records. No link was found between the widespread fall in *Pinus sylvestris* pollen, recorded from sites in northern Ireland, and the eruption of Hekla 4 (H4) in Iceland (Hall *et al.*, 1994). However, Hall *et al.* discussed tree ring records from Irish bog oaks at Garry Bog and sites south of Lough Neagh which showed very narrow rings over a 15 year period from 2350 BC, within the estimated dates for the H4 eruption. Yet, contrary to the oak tree ring records, oak pollen concentrations analysed around this time period do not show any evidence of decline associated with the H4 eruption (Hall *et al.*, 1994). Hall *et al.*

concluded that vegetation changes were confined to northern Scotland and may have been caused, instead, by climatic deterioration, as there is no evidence to suggest volcanic impacts on local vegetation occurred in northern Ireland at the time of the H4 eruption.

Bennett *et al.* (1992) discovered thin tephra layers with ash particles in low concentrations in a Holocene core extracted from Catta Ness, Shetland. However, no volcanic impacts were discernible in the pollen and geochemical records. Instead, environmental changes were attributed to fluctuations in human settlement, animal populations and a gradually deteriorating climate.

Further investigation into distal volcanic impacts were carried out by Charman *et al.* (1995) in the Strath of Kildonan, north-east Scotland. Results revealed no pine decline above three separate tephra layers, but complicated trends in *Pinus* pollen levels were apparent. Charman *et al.* noted vegetation changes occurred around the time of the K1 tephra deposition (7650 BP), with decline in tree and shrub pollen, and an increase in Cyperaceae. This is very similar to the vegetation responses noted by Blackford *et al.* (1992). Geochemical records revealed no evidence of increasing acidification at this time, but increasing levels of phosphorus may either have been due to presence of tephra, or a surge of nutrients released from damaged and decaying plants on the mire (Charman *et al.*, 1995). This significant vegetation change, associated with the tephra layer, is believed to have been short-lived, with no evidence for catchment disturbance (Charman *et al.*, 1995). Charman *et al.* found 2 of the 3 Icelandic tephra layers studied coincided with short-lived phases of vegetation change, with the nature of change differing in both cases, suggesting that if vegetation and sediment geochemical changes were related and influenced by tephra fall, then distal volcanic impacts were variable and thus very difficult to predict. The vegetation impacts observed also indicated that the quantity of tephra deposited was not proportional to the subsequent environmental impact recorded, suggesting other factors must be involved that may enhance the effects of volcanic tephra deposition. The most likely influencing factors are site location (i.e., exposed or sheltered), weather conditions at the time of deposition (e.g. rain, fog, high or low pressure), and soil acidity and climate (Grattan and Gilbertson, 1994).

### 2.4.3 Distal impact records from palynology and plant macrofossils in New Zealand

Little work has been completed on the distal impacts from volcanoes in New Zealand. However, a country with such a long volcanic history is an ideal location for this research.

Evidence for distal impacts from volcanic eruptions in New Zealand was reported initially by Vucetich and Pullar (1963). Their study was focused on the North Island districts of Taupo, Rotorua, Bay of Plenty and northern Hawkes Bay, and concentrated on the effects on vegetation from ash fall alone. By analysing ash deposits and vegetation history, through the analysis of plant macrofossils in ash-buried forests, they determined approximate critical depths of tephra deposits that would cause complete to partial destruction of vegetation. These depths were:

38 cm - complete destruction

30-38 cm - almost complete destruction

23-30 cm - partial destruction.

Their analysis of reports made 2 years after the Tarawera eruption of 1886 revealed that some areas of forest were seemingly not affected after suffering ash falls of 25 cm thickness. However, it is likely that these critical ash thicknesses will vary owing to individual species adaptation, volcanic tephra and gas chemistry and local site factors.

McGlone (1981) carried out further research into the effects on vegetation from distal tephra fall. He found palynological evidence for widespread fire damage following eruptions from Taupo (ca. 1850 BP) and Kaharoa (ca. 665 BP) at sites up to 150 km from the volcanic source, in the Bay of Plenty and southern Hawkes Bay regions, as well as at nearby Lake Rotorua (Figure 2.1B). Evidence for fire and vegetation damage was indicated by increases in levels of microscopic charcoal and bracken spores persisting for up to 150 yrs after the Taupo eruption. McGlone attributed the widespread fires to damage of the vegetation and canopy trees by tephra fall, stripping trees of leaves and branches, and burying low growing shrubs and seedlings. Gaps created in the forest canopy following vegetation damage increase exposure to insolation and wind, while dead trees provide dry fuel, together increasing the forest's susceptibility to fire. Also, large eruptions generate massive eruption clouds producing lightning which can initiate forest fires. The canopy gaps are soon occupied by ferns and small shrubs growing on free-draining tephra soils with low water retention. These plants would, therefore, be more vulnerable to burning in dry periods and could further increase the dry fuel stock for fire (McGlone, 1981).

McGlone also showed that small ash falls were associated with forest fires, as at Lake Poukawa (Hawkes Bay, Figure 2.1B), 150 km from Taupo, where ~35 mm of Taupo Tephra was recorded. The pollen record showed that bracken became more important, and charcoal fragments abundant. Climate was apparently drier around this time, increasing the likelihood of fire. This research showed that impacts from tephra deposition can be detected at distal locations from the volcanic source, although complete forest destruction is unlikely. McGlone commented:

> "From this it can be concluded that tephra fall as such has only a limited effect on forest, and it can be assumed that relatively thin tephra deposits (less than 600 mm thick) will not by themselves lead to deforestation" (McGlone, 1981, p84.).

More recently, evidence for widespread forest fires immediately above the Taupo Tephra has been observed in pollen records from the Hawkes Bay region (Fig. 2.1B) (Wilmshurst and McGlone, 1996; and Wilmshurst *et al.*, 1997). These fires were inferred to be caused by lightning strikes initiated by friction between the large volumes of fine ash particles in the atmosphere and volcanic gases. Extensive burning continued for up to 100 years after the Taupo eruption, possibly prolonged due to the rapid and widespread colonisation of bracken in disturbed forests. Bracken is highly combustible and therefore provides additional fuel stock for fire and increases the chances of ignition. Pollen records show vigorous forest regeneration some time after the Taupo eruption, suggesting forest vegetation was not affected by fire. Wilmshurst *et al.* (1997) concluded that sustained burning associated with Taupo Tephra deposition was therefore confined to the bracken fernlands under the disturbed forest canopies.

Wilmshurst and McGlone (1996) found the degree of forest damage following Taupo Tephra deposition was not proportional to thickness of the tephra deposit. The most severe forest disturbance related to tephra fallout was recorded at Tunapuhore (Fig. 2.1B), one of the most distal sites studied (approximately 120 km from Taupo Volcanic Centre) which received a relatively thin tephra deposit (7 cm). Forest disturbance at this site was inferred to be caused by a combination of volcanic toxicity and fire. At Repongaere swamp (Fig. 2.1B), a similar distance from Taupo but in a different direction from the vent, 17 cm of ash fell, but vegetation disturbance recorded in pollen assemblages was not as severe as that envisaged at Tunapuhore.

Newnham *et al.* (1989) recorded changes in dominant species during the period after the deposition of the Rerewhakaaitu Tephra 14,700 yrs BP at lakes in the Waikato region. These changes coincided with a warming trend and a change from sub-alpine to podocarp (temperate) forest. However, an interesting change was noted as *Prumnopitys taxifolia* became dominant over *Dacrydium cupressinum* following tephra fall. The increase in *Prumnopitys taxifolia* trees was partly explained by tolerance of this species to frosts and drier conditions, whereas *Dacrydium* thrives in moister areas. However, *Prumnopitys taxifolia* trees are also known to invade fresh alluvial soils, which in this case were also replenished by tephra deposition, and these soil changes possibly favoured the rapid growth of *Prumnopitys taxifolia* over *Dacrydium*. Hence, these trends observed at both lake sites may not be due to climate alone.

Newnham *et al.* (1989) noted, in agreement with McGlone (1981), that at these Waikato lake sites, pollen and sediments analysed above the Taupo Tephra layer (ca. 1850 yrs BP) revealed accentuated *Pteridium* peaks and increased charcoal accumulation, with little evidence for local forest disturbance. Newnham *et al.* suggested increases in bracken and charcoal possibly indicated local burning associated with tephra fallout in this area during an increasingly drier climate. Wilmshurst and McGlone (1996) suggested these trends in bracken and charcoal indicated burning was confined to the highly combustible fernlands which colonised fresh volcanic and alluvial surfaces, with forest vegetation remaining unaffected.

Further palynological investigations by Newnham *et al.* (1995a) at two tephra-bearing mires in the Western Bay of Plenty revealed evidence to suggest possible vegetation disturbance following the deposition of Taupo Tephra and Kaharoa Tephra. The most significant vegetation disturbance occurred at Papamoa Bog (Fig. 2.1B), indicated by a sharp rise in bracken spores and grass pollen immediately above the Taupo Tephra. However, charcoal levels do not rise significantly above the Taupo Tephra; hence Newnham *et al.* inferred that fire may not have been a significant cause for the post-eruption vegetation disturbance, but may instead be due to tephra impact and deposition of phytotoxic volcanic materials causing local vegetation damage and the subsequent invasion of seral taxa.

Newnham *et al.* (1995a) also note that rapid changes in the vegetation communities occurred immediately above the Kaharoa tephra layer at Papamoa Bog and Waihi Beach (Fig. 2.1B). Tree pollen declined, as levels of charcoal, bracken and other herbaceous pollen increased. These disturbances are probably associated with early Polynesian activity, which occurs at other adjacent sites in the Bay of Plenty around this time. Newnham *et al.* report that at the Waihi Beach site, bracken and charcoal levels increase immediately below the Kaharoa Tephra. However, contamination was detected at both sites, with significant numbers of adventive pollen grains from vegetation introduced to New Zealand during the European era (150 yrs BP). Hence, pinpointing any volcanic impact in the pollen records at these sites is difficult (Newnham *et al.*, 1995a).

In addition to the physical effects from volcanic eruptions on the environment, the distal impacts on the human environment are also important. Newnham *et al.* (in press) considered the distal threat from central North Island volcanoes on the city of Auckland, together with hazards of the local volcanic field itself. Many tephra layers which have originated from the central North Island volcanoes have been recovered from road cuttings, peat bogs and lake deposits around Auckland. Newnham *et al.* suggest that the greatest distal threats to the city of Auckland are from Mayor Island volcano, Okataina Volcanic Centre, Taupo, Tongariro Volcanic Centre and Mt Egmont. Owing to their distal locations, the main impacts would be from tephra fall and volcanic acid aerosols.

The recent eruptions of Ruapehu (Tongariro Volcanic Centre) in September 1995 and June 1996 caused many problems for the human population. Ash plumes from these eruptions resulted in air traffic disruption, contamination of the water supply, burial of vegetation (Plate 2.1a & b), power and communication failure and disruption to the tourism industry. Production of a huge sulphur dioxide cloud, travelling south of Ruapehu, was picked up on satellite images. The cloud travelled over Wellington and Christchurch before travelling in a northeasterly direction and extending out to sea. This volcanic fog was not considered dangerous to the public, but there was a possibility of acid rain production. Thus, even from this relatively small eruption, potential impacts from acidification are likely due to the large volume of sulphurous gases produced.

**Plate 2.1a** Mosses, lichens and grasses growing on volcanic material, Tongariro National Park.

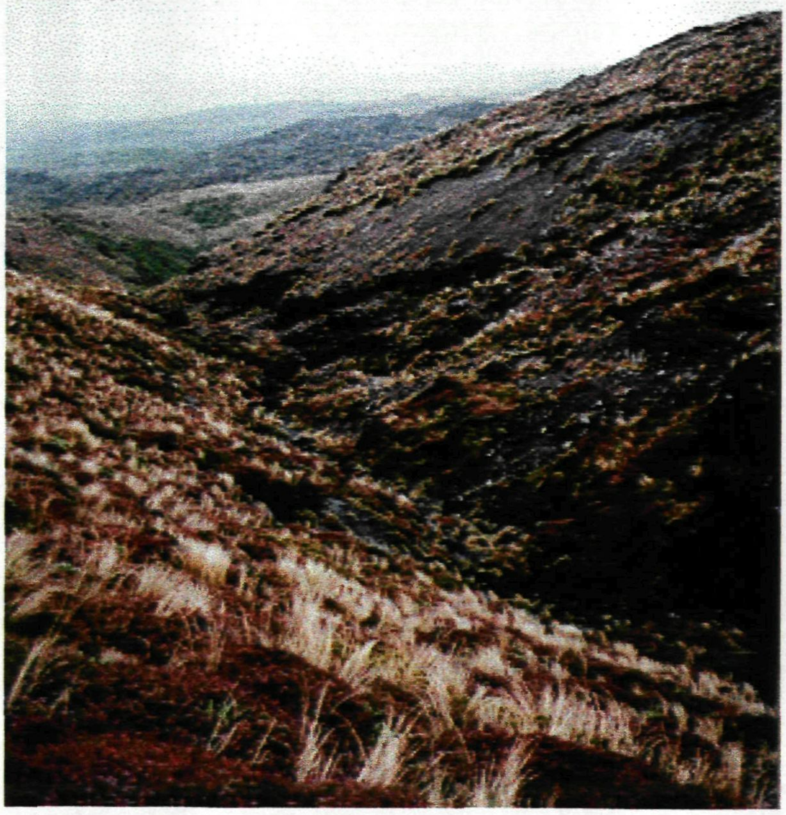


**Plate 2.1b** Vegetation partly buried by ashfall from the Ruapehu eruptions of 1995 and 1996, Tongariro National Park.

Studies were undertaken by Cronin and Hedley (1996) and Cronin *et al.* (1996) to assess the effect on agriculture from the deposition of Ruapehu ash immediately following the eruption. These reports provided evidence showing increased S and Se concentrations in soils and plants which had received thin deposits of ash between 0.5 and 15 mm. These higher S and Se concentrations were sustained for a minimum of three months following the eruption. Increases in S and Se content within soils receiving >0.5 mm ash meant that the application of sulphur fertilisers was not required, providing a major benefit to farmers, especially in the areas where the soils are naturally low in S and Se. The deposition of ash rich in S therefore reduced the problem of S deficiency in some plants. However, some soils receiving thicker ash deposits became more acidic as a result of a sudden increase and rapid oxidation of elemental S; hence careful soil management is required to assure that accelerated soil acidification does not occur after ash deposition.

**2.5 Summary**

The non-climatic, distal environmental and vegetational impacts from volcanic tephra and aerosol fallout appear to have been as significant in the past as they are today. Research summarised in this chapter has revealed natural nutrient deficiencies in tephra-derived soils which causes problems for vegetation growth and establishment. There is also evidence to show acidification occurring in marginal environments (i.e.,, those with low critical thresholds) from tephra deposition which has accumulated acid aerosols during transportation in the eruption cloud. Evidence for direct vegetation damage from tephra accumulation and associated chemical leaching is displayed in both contemporary and palaeoenvironmental studies from various parts of the world, although palaeoenvironmental research into distal volcanic impacts is still in the early stages, and conclusions reached are both speculative and tentative.

Research into proximal and distal volcanic impacts in New Zealand has revealed extensive damage to forest vegetation following tephra fallout. This is caused by the physical effects of tephra fallout and fires initiated by lightning strike associated with ash accumulation in the atmosphere. Vegetation regeneration following forest disturbance varies in response to changes in soil structure and fertility, and also local site factors (e.g. drainage, climate, altitude). Pioneer species in vegetation regeneration and succession on volcanic material is important, as establishment of nitrogen-fixing plants leads to more rapid re-colonisation and greater species diversity.

The following chapter discusses the methods employed in this thesis in order to examine volcanic impacts on the environment in New Zealand from volcanic ash and toxic chemical accumulation following volcanic eruptions during the late Quaternary.

## Chapter Three

## Methods

### 3.0 Introduction

The techniques used in this thesis have been outlined and justified briefly in Chapter one. In this chapter, the specific procedures for pollen and geochemical analysis are described in detail, together with the sampling strategies and extraction procedures employed. The first section describes and explains the fieldwork and sampling techniques employed at each study site. Section 3.2 covers dating procedures. Palynological preparation, representation and limitations, and statistical calculation and interpretations are discussed in section 3.3. The final section describes the EDMA procedure and the interpretation of results, together with the technique for carbon analysis.

### 3.1 Field sites and fieldwork

Four lake or peat sites in the North Island of New Zealand have been investigated in this study (Figure 1.1). The main focus is the investigation of tephra impacts on the environment. A fine resolution sampling strategy was employed immediately above and below tephra layers preserved within each profile to produce a detailed record of palaeoenvironmental changes following tephra deposition. Fine resolution samples were extracted at 0.5 cm intervals above and below tephra layers where possible. This was considered a suitable compromise between the need to sample at fine resolution and the need to obtain enough material for pollen and geochemical analysis at each sampling interval. Also, there are practical difficulties in physically extracting samples at <0.5 cm intervals which then increase the risk of sample contamination and overlap. Sampling of the peat sections (Matakana Island and Kaipo Bog) was undertaken in the field under difficult conditions which therefore presented further constraints, resulting in coarser 'fine resolution' sampling intervals. The nature of the sediment sampled also dictated the sampling intervals, as peat material was fibrous and difficult to extract in smaller slices and again presented the problem of obtaining sufficient material for adequate pollen counts and geochemical analysis. Fine resolution sampling intervals were therefore defined at 0.5 cm intervals in lake sediments, and 1 cm intervals in peat profiles.

A secondary consideration was the long-term record of environmental change at each site which also permits an examination of tephra impacts in their broader context. Broad interval sampling was employed at two of the sites, in addition to fine resolution sampling strategies, but time constraints restricted the study to examination of tephra impacts only at the other two sites. As long-term pollen records already exist for sites near Kaipo (McGlone, unpubl.; Newnham, unpubl.) and Lake Rotoroa (Newnham *et al.*, 1989), but not for Matakana Island and Kohuora, the latter two sites were selected for more extensive study. Cores and samples have been extracted using different techniques which are discussed individually below.

### 3.1.1 Matakana Island

The study site comprises a peat profile taken from a wetland area on Matakana Island located off the Bay of Plenty coast, North Island, New Zealand. Samples were collected by Adam Munro and Dr David Lowe from the University of Waikato, Hamilton, New Zealand. As the peat was not deep at this site (67 cm) a soil pit was excavated, and one face cleaned to expose a smooth profile. Two cm contiguous samples were taken for the entire profile to determine long-term environmental change while 1 cm contiguous slices were taken for 5 cm above and below the Kaharoa Tephra layer (44-46 cm depth) for the fine resolution tephra impact study. Three 4 cm sections of the profile were also extracted in the same way for dating at the University of Waikato radiocarbon dating laboratory, and were treated according to the procedures described in section 3.2.

### 3.1.2 Kaipo Bog, Urewera ranges

Kaipo Bog is an upland oligotrophic peat bog (1000 m a.s.l.) located in Urewera National Park. Samples were collected by the author, Dr Newnham, Dr Roland Gehrels (University of Plymouth, UK), and Dr Lowe. Fine resolution sampling was employed above and below nine macroscopic tephra layers from an exposed peat section for the tephra impact study. This exposed profile was created by erosive action from streams which feed and drain the bog. Samples were extracted using 10 $cm^3$ sample vials which were pushed into the peat above and below tephra layers. The sample vials measured approximately 1 cm in diameter, and so the sampling resolution consisted of 1 cm contiguous samples extending up to 10 cm above and below the nine tephra layers, depending on thickness of peat between the tephras.

### 3.1.3 Lake Rotoroa, Hamilton.

Three sediment cores were extracted from the lake by Dr Lowe and colleagues, using a modified Livingston piston corer operated from a dinghy. The sediment coring tubes consisted of 5 cm diameter PVC drainpipe which had been sliced vertically in half and taped firmly back together using masking tape (Munro, 1994). This process enabled easy extraction of the sediment in the laboratory. The cores were plugged with polystyrene to secure the sediment and then wrapped with cling film to keep the cores fresh and prevent dehydration. The sediment was sliced vertically in the laboratory so that the core lay in two halves. Seven 2 cm sections were taken for radiocarbon dating (section 3.2). Detailed logging of the stratigraphy and pigment changes throughout the core was undertaken by Speirs (1995).

Sub-samples from the cores were obtained using a plastic disposable syringe with the nozzle end removed, which extracted 3 $cm^3$ plugs of sediment for every 2 cm depth down the core. Fine resolution sampling was undertaken above all tephra layers at 0.5 cm intervals for 5 cm for the tephra impact study. Fine resolution sampling was also carried out below 2 tephra layers for comparison of the results for the pollen record. These samples were obtained using a scalpel and transferred to 1 $cm^3$ plastic vials using a spatula. These were sealed in plastic bags and refrigerated.

### 3.1.4 Kohuora crater, Paptoetoe, Auckland.

The 9.5 m sediment core, containing 5 tephra layers, was taken from a drained wetland marsh in a volcanic crater in south Auckland by the author, Dr David Lowe, Dr Rewi Newnham (University of Plymouth, UK) and Dr Peter de Lange (botanist with the Department of Conservation, Auckland, New Zealand) .

A site was chosen on the wetland in what appeared to be a comparatively less disturbed area in the centre of the crater basin. The 9.5 m core was extracted in 50 cm sections with a 5 cm diameter Russian corer. The stratigraphy of the sediment in each 50 cm section was recorded, then the sediment was transferred, intact, to a section of drainpipe and plugged at both ends with kitchen roll to prevent sediment loss. The core sections were wrapped securely with cling film and tape to prevent dehydration, labelled, and transported to the laboratory (University of Waikato) where they were stored at 4°C.

Sub samples of the core were taken at 10 cm intervals throughout the 9.5 cm profile, to provide a record of long term environmental change. In addition, for the tephra impact study fine resolution sampling was undertaken above and below the three tephra layers at 0.5 cm intervals for 5 cm. Fine resolution sampling for pollen analysis was also undertaken in parts of the core where tephra layers were absent, in order to gain insight into variability of vegetation trends unrelated to volcanic factors. Geochemical analysis was not performed on these samples as little variation was seen throughout the core between coarse resolution samples. Sub-samples were transferred to a 1 $cm^3$ plastic sample vial using a knife and spatula. Eleven 10 cm sections were extracted from the core for radiocarbon dating. These were placed in individual sealed plastic bags in the field.

## 3.2 Dating

### 3.2.1 Preparation of samples for radiocarbon dating

Samples were placed in beakers of distilled water to separate the sediment from any plant material, which was then put aside for analysis by P J deLange. All samples were oven-dried at 105°C overnight, and subsequently gently ground using a pestle and mortar (Munro, 1994). Samples were then submitted for dating at the University of Waikato Radiocarbon Dating Laboratory. The technique employed involves liquid scintillation counting of benzene using a Quantulus LS spectrometer (Lowe and Hogg, 1992).

### 3.2.2 The application of tephrochronology for the calculation of sedimentation rates

Tephrochronology is the study of airfall pyroclastic (tephra) deposits preserved in chronological order in sediments from lakes and bogs, representing a stratigraphic sequence of eruptive history back through time. The sources of these tephra layers are determined through analysis of the tephras minerological assemblages and glass mineral compositions which are distinguished though electron microprobe analysis. The tephras are then correlated with named proximal eruptives using their stratigraphic relationships and radiometric ages, together with their mineralogical characteristics (Lowe, 1988). The dated tephras thus provide a geological framework for palaeoenvironmental research (Lowe, 1988). All tephras reported in this study were identified by Dr David Lowe and mean ages for these tephras are those reported in Froggatt and Lowe (1990), unless otherwise specified.

Estimated sedimentation rates were based on linear interpolation between the means of tephra dates, and independent radiocarbon dates analysed and calculated for samples of sediment taken from appropriate depths within the profiles. The sedimentation rates were expressed as number of years taken per cm of sediment accumulated. As radiocarbon dated samples and mean tephra ages may have quite large standard errors, up to 100 or 200 years, some overlap of dated horizons occurs and some dated horizons can be statistically identical. Calculated sedimentation rates therefore are approximate, with the assumption that the rate has remained constant between two dated points. These estimates therefore do not account for short-term fluctuations in sediment accumulation which must nevertheless be taken into consideration during palaeoenvironmental interpretation.

Despite these limitations, the estimation of sedimentation rates is necessary in order to determine the approximate between-sample time intervals in the pollen and geochemical records. The calculation of time intervals is especially important for the fine resolution tephra impact study to establish the approximate duration of environmental changes occurring following tephra deposition. If the estimated sedimentation rates are exceptionally slow, this factor must be taken into account when assessing patterns of vegetation impact and recovery following tephra deposition.

## 3.3 Palynology

### 3.3.1 Preparation of pollen slides

Procedures for pollen extraction allow the isolation of pollen grains from a sediment by excluding as much extraneous material as possible in order to provide a 'clean' sample which can then be analysed under the microscope. The methods employed for pollen extraction follow those described by Moore *et al.* (1991). These involved using 10% NaOH for the removal of humic colloids and disaggregation of the sample sediment, followed by sieving each sample through a 180 micron sieve. Samples were washed with 10% HCL, to extract carbonates. Known quantities of *Lycopodium* spores were added to each sample during preparation in order to determine total pollen concentrations (Benninghof, 1962; Stockmarr, 1971). Acetylation using acetic anhydride and concentrated sulphuric acid in the ratio of 9:1 was carried out to remove all cellulose material.

The removal of silica from the samples by HF was not attempted, in order to permit counting of tephra-derived silicic glass shards along with pollen grains.

Glycerine jelly was used for mounting the pollen onto the microscope slides. This ensures that the grains are secured once the jelly has set, although the jelly can still be re-heated so that pollen grains can be turned. Glycerine jelly was used in preference to silicon oil for the safe transportation of slides without movement of the pollen grains. All pollen preparations were undertaken by the author at the University of Plymouth, U.K.

### 3.3.2 Pollen percentage calculations

Pollen percentages for dryland pollen taxa were calculated as a percentage of the total dryland pollen sum (250 grains counted per slide). Pollen and spores from wetland and fern taxa, and damaged pollen grains are excluded from the total land pollen sum, These taxa are expressed as a percentage of the particular group (e.g. wetland) plus the total dryland pollen. In this way, fluctuating values of local wetland and fern taxa do not affect percentage values of the dryland taxa, and overrepresentation of the local taxa is avoided (Moore *et al.*, 1991). In New Zealand palynology there are several important pollen taxa which are normally included in the total dryland pollen sum, which include species that can also grow on mires. When excessively high amounts of these taxa are encountered it is therefore prudent to exclude these from the pollen sum. An example in this study is *Leptospermum* at Kohuora. *Leptospermum* is often found growing on mires in New Zealand, and often becomes dominant in these environments causing problems in the interpretation of pollen diagrams owing to overrepresentation when included in the dryland pollen sum. *Leptospermum* was therefore excluded from the total dryland pollen sum in the Kohuora profile as high levels of this taxon were recorded at the top of the profile which obscured the record.

### 3.3.3 Counting of tephra shards and charcoal fragments

The dissemination of microscopic tephra shards around macroscopic tephra layers in sediment profiles is an important tephra impact on the environment requiring careful consideration in this study. The presence of microscopic tephra shards above macroscopic tephra layers within a sediment profile can provide evidence for post-eruption catchment disturbance and sediment inwashing following tephra deposition. The presence of microscopic tephra shards below a tephra layer possibly indicates emission of minor ash falls prior to a major eruption, such as those experienced prior to the Ruapehu eruptions of 1996 and 1997 in New Zealand. The spread of micro shards could also indicate reworking of *in situ* tephra by bioturbation. Micro-tephra impacts are likely to alter the geochemistry, structure and pH of soils and peats which in turn affect the local vegetation communities (see chapter two). The significance of micro tephra shard accumulation within sediments around macroscopic tephra layers is therefore important in assessing the magnitude and duration of post-eruption environmental instability.

The presence of charcoal fragments within sediments provides a record of past fire history for the area under analysis. The occurrence of fire is often linked with tephra deposition (Wilmshurst and McGlone, 1997; see chapter 1) and is therefore important in the study of fine resolution tephra impacts.

Tephra shards and charcoal fragments greater than 10 microns diameter were counted simultaneously with pollen counting by recording the number of tephra and charcoal fragments passing a graticule. Fragments smaller than 10 microns proved difficult to identify and count accurately. Tephra and charcoal concentrations were calculated in the same way as for total pollen concentrations using the marker spore method (Stockmarr, 1971). Results obtained from the simple counting method employed in this project gave adequate approximate levels of charcoal and tephra shards within the separate profiles which correlated well with the geochemistry record (see chapters 4-7).

In some cases it was impossible to carry out simple counting of tephra shards, owing to overlapping of particles, the very small size of particles (<10 microns) and their sheer abundance, almost completely covering the slide. Where these problems occurred, a maximum limit was set at 3000 shards per slide.

### 3.3.4 Pollen profile zonation and data analysis

Cluster analysis (CONISS) and Detrended Correspondence Analysis (DECORANA) have been carried out on pollen data to support the interpretation of vegetation changes, inferred from the pollen records.

CONISS performs stratigraphically constrained cluster analysis, grouping together samples that exhibit similar pollen content. These sample groups reflect changes in vegetation communities throughout the pollen records, thereby assisting with the placement of pollen zones. Sample clusters are determined by the calculation of incremental sum of squares from pollen percentages. Tephra counts are excluded from CONISS analysis to avoid interpretation of vegetation changes and placement of pollen zone boundaries according to presence or absence of tephra shards in the record.

DECORANA is used to provide visual representation of taxa or samples (assemblages) that display similar stratigraphic trends. The analysis is carried out on pollen percentages and produces two sets of data, taxa scores and sample scores. Taxa that are present in insignificant quantities in the pollen record (i.e., <2%) are excluded from DECORANA analysis in order to prevent cluttering and confusion of the data and allow the main vegetation trends to be distinguished clearly. Taxa scores for axes with highest eigenvalues (showing the significance of the relationship between the individuals and inferred environmental parameter) are presented as an ordination plot. Taxa clustered into groups on the ordination plot reflect closer similarity with other members of the same group than with taxa clustered in other groups on the plot. These groups represent vegetation assemblages that may be influenced by specific environmental conditions, or respond in a similar way to environmental disturbance. Sample scores for axes with highest eigenvalues are plotted on the pollen percentage diagram. Higher sample scores are derived from the overall abundance of highest scoring taxa within the sample pollen count. Dramatic changes in sample scores may reflect a rapid short-term environmental impact (e.g. tephra deposition, flooding), whereas a gradual increase or decrease in sample scores may reflect long-term changes (e.g. climate warming, declining soil fertility). Charcoal and micro-tephra counts were initially included in the analysis to help identify taxa displaying similar trends to these variables. DECORANA was performed a second time, excluding charcoal and micro-tephra counts, in order to isolate the vegetation changes occurring above the macroscopic tephra layer which were unrelated to fire damage or the abundance of microscopic tephra shards within the profile.

### 3.3.5 Taxonomy

Pollen identification and classification follows Moar (1994) for dicotyledons, and Pocknall (1981a, b, c) for the gymnosperms and identification of Poaceae (Gramineae) and Cyperaceae pollen. Identification of fern spores, including tree ferns, follow Large and Braggins (1991). The remaining fern spores were classified into the broad categories 'trilete' and 'monolete' after Newnham (1990). Pollen from New Zealand monocotyledons were identified from type slides from extensive and comprehensive reference collections at the University of Plymouth and Landcare Research in Lincoln, New Zealand.

### 3.3.6 Notes on identification of bisaccate pollen grains

Identification of bisaccate pollen grains follow Pocknall (1981a, b, c). *Prumnopitys* includes two species within this genus: *Prumnopitys ferruginea* and *Prumnopitys taxifolia.* Where distinction could not be made between pollen grains from these two species, these grains were then identified to genus level and classed as *Prumnopitys*.

*Podocarpus* trees include several species with indistinguishable pollen that is sometimes difficult to distinguish from *Prumnopitys* pollen grains. Where distinction could not be made between *Prumnopitys* and *Podocarpus* pollen, these grains were classed as 'Podocarpoid' (after Newnham, 1990).

### 3.3.7 Treatment of incomplete pollen grains

Certain pollen grains of New Zealand taxa are sometimes found in fragments that are otherwise perfectly preserved. This is usually due to the grain splitting at a point or plane of weakness. For example, *Laurelia novae zelandiae*, a monocolpate grain, easily splits along the colpus, and is rarely found with the two halves intact in fossil pollen records. In such cases each half grain encountered has been counted as half a grain to avoid over-representation of that taxon. Grains with substantially less than half their original area remaining were not counted.

**3.3.8 Classification of damaged pollen grains**

All pollen counts included frequencies of damaged pollen grains of varying condition. Damaged pollen grain counts were important in this study as large numbers of damaged grains in pollen records can indicate local catchment disturbance and inwash. Pollen grains that have accumulated in catchment soils which have then undergone erosion, will become crumpled and broken during rapid transportation, for example, via overland flow, flash floods or by high velocity catchment streams following storms. These grains are likely to have a 'worn' appearance are classified as degraded pollen grains. Counting of degraded pollen grains can therefore help identify periods of environmental instability within a catchment.

Degraded pollen grains were classed following the methods employed by Cushing (1967):

1) Crumpled - includes crumpled with exine thinned, and crumpled with exine normal. Crumpled grains are strongly folded, wrinkled or collapsed.

2) Broken - refers to grains with exines ruptured.

3) Degraded - where pollen grains have been damaged and exines had become worn and thinned, causing a loss of texture and characteristic features, giving a 'faded' appearance so that an accurate identification could not be made. These grains usually had fused structural elements, but apertures were still intact. Grains are equally 'worn' over the whole surface.

4) Corroded - refers to grains which appeared etched or pitted, with corrosion spots on the surface of the grain. If grains were only corroded, the parts remaining intact would be clear with visible structural elements.

**3.3.9 Sources of error in pollen diagram interpretation**

The main problems associated with the utilisation of pollen data to indicate plant abundance in the vegetation community, and pollen diagram interpretation are discussed individually below.

<u>Pollen representation and variations in pollen production</u>

Certain species are known to be large pollen producers, and this must be considered when analysing results from pollen counts in percentage diagrams, owing to over-representation. Examples of these are species of *Pinus* (European pollen), *Dacrydium* and *Nothofagus* spp. (New Zealand). Conversely, small pollen producers may be under-represented in diagrams, e.g. *Knightia excelsa* (New Zealand). Variations in the percentage of one taxon may influence values of other taxa (Faegri and Iverson, 1975; Moore *et al.*, 1991). This is particularly true for high percentage values from large pollen producers, where subtle changes in proportions may actually represent large shifts in the total influx of pollen (Moore *et al.*, 1991). Pollen concentrations, which display the frequencies of each taxon per unit volume of sediment, may enable each pollen type to be assessed individually, without influence from values of other pollen producers, as may occur in the percentage diagrams. However, there are other problems with pollen concentrations as these vary greatly in association with fluctuating sedimentation rates.

Pollen dispersal variations

In general, wind-pollinated plants produce large amounts of aerodynamic pollen, which can travel great distances from the plant source. These plants are often over-represented in pollen diagrams. Long-distance dispersal of pollen from the New Zealand taxa Poaceae, *Nothofagus* and species of conifer has been determined through modern pollen rain studies, which have shown the importance of *Fuscospora* pollen up to 60 km downwind from the source (Newnham, 1990). These factors must therefore be taken into consideration when interpreting pollen diagrams.

Ecological diversity within a pollen taxon

As stated in section 3.3.6, some bisaccate pollen grains from podocarp trees were identified to genus level, as the pollen from individual species in each genus could not always be distinguished. However, species in each taxon exhibit different ecological characteristics, which can create problems in interpreting palaeoenvironmental or climatic changes from fossil pollen assemblages. This problem can sometimes be reduced by inferring which species are present on the basis of their co-occurrence with other species with known ecological preferences and distinctive pollen grains, for example, *Agathis australis* and *Phyllocladus trichomanoides* growing together north of 38 S (Newnham and Lowe, 1990); *Halocarpus* and *Phyllocladus alpinus* in cooler upland areas and mires (Rogers, 1984). Newnham (1990) suggests macrofossil analysis can be used to assist in identifying likely pollen source species where applicable.

Differential pollen preservation

As some taxa are less robust than others, they may be under-represented in pollen diagrams, or may contribute disproportionately to the degraded or broken categories (section 3.3.8). Pollen from species of Cyperaceae is naturally etched, and faded, and is easily crumpled, while *Libocedrus* pollen has a weak exine which is easily torn. Grains may also vary in their resistance according to the type of sediment they are preserved in (Faegri and Iverson, 1977; Havinga, 1971). These factors require consideration when interpreting pollen records.

Pollen deposition and stratigraphic integrity

Differential pollen deposition on lake floors was investigated by Davis *et al.* (1971), who showed that pollen from plants growing closest to the lake was more abundant in shallower waters around the lake edge, whilst pollen from distal sources was more abundant in deeper water towards the middle of the lake. Hence, two rather different pollen diagrams can be produced from the same lake according to the abundance and proximity of the pollen source. It is important to be aware of this possibility when choosing core site locations for pollen studies.

Difficulty can arise in identifying local pollen influx when large volumes of pollen from other, non local sources have accumulated within the sediment analysed, for example, via inwash due to flooding, or soil erosion, or windborne pollen from distant large pollen producers. Often phases of inwash can be identified from changes in stratigraphy and identification of macrofossils (Birks, 1970). Erosion and release of pollen from older sediments may be detected by the poorer preservation of these grains (Faegri and Iverson, 1977; Moore *et al.*, 1991), or by the presence or increase in coarse material. Influxes of pollen and sediments at the sites studied in this thesis are likely to occur due to catchment disturbance and erosion as a result of possible vegetation damage following tephra fall.

Erosion hiatuses may also occur in lake and peat profiles, creating gaps in the pollen record. Tephra deposits within a peat or lake profile represent an hiatus, i.e., a break in organic sedimentation. The deposition of tephra layers is assumed to be instantaneous geologically and therefore the hiatus is minimal; however, several pollen seasons could have been lost due to disturbance associated with tephra impact such as catchment erosion and deposition, or a temporary disruption of the depositional site affecting sediment accumulation, such as a sensitive peat bog environment.

Movement of pollen grains within sediment profiles

A common occurrence in peat bogs is movement of pollen grains due to vertical water movement through the substrate, which may disrupt the pollen record. Clymo and Mackay (1987) revealed, from controlled experiments, that 25 % of pollen grains in a simulated peat profile moved 3 cm from their original position after deposition, in the unsaturated upper layers of *Sphagnum* peat. However, this problem is minimised owing to compaction of peat with depth.

Other common disturbances in sediment records are bioturbation from fauna, which will cause movement of *in situ* pollen grains. Also, drying out of a lake or peat surface may result in development of cracks and movement of pollen grains to lower levels (Faegri and Iverson, 1977; Mannion, 1980; Moore *et al.*, 1991), although such extreme events should be discernible in the palynological or sedimentological record.

## 3.4 Geochemical analysis - palaeoenvironmental applications

### 3.4.1 Introduction

Recent research into palaeoenvironmental change has used the technique of EDMA (Energy Dispersive X-ray Micro Analysis) to obtain information on the geochemistry of sedimentary sequences (Cescas *et al.*, 1968; Pyatt *et al.*, 1991; Pyatt *et al.*, 1992; Grattan, 1994; Charman *et al.*, 1995; Pyatt *et al.*, 1995; West, 1995). This technique has provided valuable insights into major environmental and other interacting processes occurring in sediment records, including changes in climate, vegetation, soils, and landuse, as well as weathering and erosion episodes (Pyatt *et al.*, 1995).

This technique is applied to identify and measure the elemental composition of sediments. The data produced show the relative frequency of the elements present in the samples analysed, which are then expressed as percentages, giving an approximate indication of the abundance of each element present in each sample. This is repeated throughout a sediment core to show the variation of elemental composition through time, from which environmental processes and changes can be inferred (e.g. phases of erosion, leaching, acidification, waterlogging). The measurement techniques are explained in more detail in section 3.4.3 to 3.4.5.

West (1997) has carried out extensive research to assess the validity of the technique for recognising signals of palaeoenvironmental change. Comparisons with 'bulk chemical' procedures revealed broadly comparable results for most of the major elements, although some uncertainty surrounds the accuracy of EDMA determinations for minor and trace elements. The EDMA technique was therefore employed in this thesis as the procedure was rapid, non- destructive and relatively simple, producing satisfactory results for the purposes of this study.

### 3.4.2 EDMA procedure

A detailed account of the physics and workings of the EDMA system can be found in Erasmus (1978), Hren *et al.* (1979), Goldstein *et al.* (1981) and Reed (1993) and will not be discussed here. However, a brief description of the procedure for measuring the geochemical content of the samples follows.

### 3.4.3 Basic operation of the EDMA system

To obtain information on the geochemical composition of a sample, quantitative analysis procedures have been employed in this thesis.

The sample is placed into the vacuum chamber of the microprobe, which is maintained under high vacuum(>$10^{-4}$ Torr), in order to create a pure environment through which the electron beam can travel with limited contact with air molecules. Situated at the top of the vacuum chamber is a tungsten filament, which is heated to 2700K in order to release the electrons, which are then positively charged and are attracted to a high negative charge between the anode (0 V) and the filament of accelerating voltage (ranging 1-40 KeV) (Goldstein *et al.*, 1992). For the purposes of this study the voltage is set to -20 KeV maximum.

Once the beam is formed, its diameter is then set in order to generate a clear image. Electron lenses are located in the vacuum chamber to focus the beam onto the sample (final beam 5 nm). The beam interacts with the sample surface to a depth of approximately 1 micron, generating different electron signals which form the image and contain information about the sample (Goldstein *et al.*, 1992). The actual image is formed by scanning the sample from point to point.

The deflection system, controlled by two scanning coils in the chamber, controls the magnification. The electron beam scans along a line on the sample surface and, once finished, the line position is displaced for the next scan, producing a rectangular raster over the specimen and on the image screen. The magnification of the sample image is the ratio of the linear size of the image screen (Cathode Ray Tube) to the linear size of the raster on the sample (Goldstein *et al.*, 1992).

The signals generated from electron bombardment of the sample are the secondary and backscatter electrons which contain information to create the image on the screen. They are collected by an Everhart-Thornley detector located next to the sample area. For quantitative analysis, the X-ray electron beams are most useful, as these contain the chemical information about the sample. These are received by the Energy Dispersive Spectrometer.

Two types of X-ray are emitted: characteristic and continuum. The characteristic X-rays are the most useful for quantitative analysis as they contain chemical information about the sample (Reed, 1993). Identification of elements occurs by comparing the atomic numbers of elements against the whole spectrum analysed. Peaks in the spectrum show the number of X-ray counts at each energy level which can be matched with the known elements. Quantitative analysis involves recording the spectrum for a pre-set time (100 seconds livetime) with the same probe current (Reed, 1993). This is important so that each sample is subjected to the same electron beam and energy.

**3.4.4 Correction procedures**

Correction procedures are required for the following phenomena (Reed, 1993):

Chromatic aberration - due to drifting accelerating voltage

Spherical abherration - where off-axis electrons display stronger energy than those closest to the beam axis

Astigmatism - Caused by imperfections in the polepieces of the final lens.

Further correction procedures are employed to account for differences in the atomic number (Z) as X-ray production varies with chemical composition of the sample. The correction procedures account for backscattering of ionised electrons producing the X-rays, which results in a loss of the beam. If not corrected, this would lead to under-representation of heavier minerals, and overrepresentation of lighter ones (Goldstein *et al.*, 1992).

Changes in absorption characteristics (A) of different elements can occur within a sample. Thus, only those X-rays that leave the sample are useful, as others that pass through the sample are absorbed with distance travelled (Goldstein *et al.*, 1992).

Differences in fluorescence of atomic nuclei (F) within the sample are caused from absorption of X-rays by one element resulting in excitation of another, so increasing the measured intensity from this element. The extent of increased X-ray intensity depends on the elements present in the sample (Goldstein *et al.*, 1992).

The magnitude of these effects will produce differences between the actual chemical composition of the sample and the recorded values. Thus ZAF corrections are employed until the results are statistically acceptable (West, 1997).

The samples were analysed using a lithium-drifted silicon EDMA detector within a Jeol 6100 Scanning Electron Microscope (SEM), connected to a Link Analytical electron microscopy data management system (eXL) equipped with a ZAF-4 program, which applied the necessary statistical correction procedures for each sample.

The machine was calibrated after 4 samples had been measured, using a Cobalt stub to check detector drift and contamination. This ensures the machine is kept at a constant level so accuracy and consistency of measurement is maintained for each sample.

### 3.4.5 Accuracy of measurements

Most authors suggest there is an overall 10% error in results according to the different characteristics of some materials (Goldstein *et al.*, 1992; Reed, 1993; Russ, 1984). This may be due to variable surface geometry and sample roughness, and to different preparation procedures (Goldstein *et al.*, 1992; West, 1997).

### 3.4.6 Sample preparation

West (1997) experimented with different sampling preparations for EDMA analysis to determine which was the most effective, and gave the most consistent and accurate results, with minimal charging and high replicability. The most favourable technique employed by West was therefore adopted for samples analysed in this project.

The method is straightforward. First, samples are air-dried until completely dehydrated. A carbon stub is then covered with a graphite adhesive layer onto which is sprinkled a small amount of sample sediment. West notes that carbon is an ideal mounting medium as it does not emit detectable X-rays, and has good electrical conductive properties. Once mounted, the sample is then coated with a layer of carbon in a vacuum chamber. This is done to reduce charging of the sample under the electron beam. The use of Duron polymide derived anti-static spray proved equally as effective in reducing sample charging, as shown by Goldstein *et al.* (1981) and Grattan (1994) and this was used for some samples analysed in this thesis. The samples are then placed in the SEM under vacuum (>$10^{-4}$ Torr). Random areas were analysed for each sample at x100 magnification for 100 seconds livetime. This was repeated 8 times for each sample. Statistical tests employed by West revealed a high replicability (>95% confidence interval) within analyses of single sampling areas, and between samples.

### 3.4.7 Presentation of results, standard error bars and profile zonation

To measure the elemental composition of the sample as a whole, the mean value was calculated from 8 analyses for each sample. The standard error of the mean was calculated to indicate the level of homogeneity of sample area measurements. The results are presented as proportional data, in the same way as pollen analysis, with each element expressed as a percentage of total elemental composition of each sample. Generally, the error bars were very small, representing high replicability between sample area measurements. However, values for some major, mobile and trace elements revealed some degree of variability, producing larger error bars. These larger error bars were included in the geochemistry diagrams to illustrate these deviations.

Chemizones within geochemical diagrams were constructed on the basis of apparent synchronous changes in elemental composition of the sediments. Similar to pollen zones, chemizones represent changing environmental conditions throughout the geochemical profile, with each chemizone considered as a litho-facies representing a distinct sedimentary environment (Grattan, 1994).

### 3.4.8 Selection of elements and interpretational possibilities

The selection of an element list to be used in the ZAF-4 quantitative analysis program may vary between sites, and between samples according to their depth in the sediment profile. These details will be covered in the results and interpretation chapters in this thesis. However, for general palaeoenvironmental research, a basic element list is recommended:

| | |
|---|---|
| Major elements | Na, K, Si, Al |
| Carbonates | Ca, Mg |
| Nutrients | P |
| Mobile elements | Fe, Mn, S |
| 'Trace' elements | Cu, Pb, Zn, Sn, As |

This classification is taken from Kemp (1976) (in West, 1997).

The presence, absence, or co-occurrence of elements provides different insights into the environmental processes prevailing in the area studied at a particular point in time. A basic summary of the processes indicated by the occurrence of each group of elements is given below, summarised from West (1997). A more detailed description of these interpretations will be given in the analysis of the sediment geochemistry for each study site.

Major elements

Generally, the occurrence of the major elements in a sample is indicative of weathering. However, the co-occurrence of Na, Mg and K may indicate a marine influence or transgression due to the chemical influence of seawater and associated solutes. Ca is also indicative of weathering, and alkalinity, as Mg and Si indicate biogenic processes, with the presence of phytoliths and diatoms. Higher Si levels can also indicate the presence of tephra particles (glass shards) within sediments as these are composed predominantly of silica. High levels of Al indicate acidification and mobilisation of elements, with a decreasing pH.

Nutrient elements

The occurrence of P represents biogenic activity, with high levels possibly indicating decomposing plant matter (Charman *et al.*, 1995). When P occurs with Fe and Mn, this represents anaerobic conditions. C (organic) indicates humus abundance, with inorganic C revealing the presence of Calcium carbonate. Procedures for carbon analysis are discussed in section 3.4.10.

Mobile elements

These represent the presence of lithospheric materials, but can also represent anaerobic conditions. Fe and Mn are acidity indicators, and higher S levels often indicate increased biogenic activity and productivity.

Trace elements

These generally indicate local anthropogenic activity, usually mining (i.e., Sn, Cu, Pb). As co-occurring with Fe and/or Mn may indicate anaerobic conditions. Cu may also represent anaerobic conditions, or the formation of sulphides.

### 3.4.9 Problems encountered with EDMA analysis in palaeoenvironmental studies

As with other palaeoenvironmental techniques (e.g. pollen analysis), there is often more than one possible explanation for the occurrence of a particular element (West, 1997), regardless of the technique used to obtain the results. This must be taken into account when interpreting the results. The presence of certain elements in association with others may provide essential clues to environmental processes occurring within the study area.

A possible problem exists with using percentage data for chemical composition of samples, rather than volumetric units, normally applied with 'bulk chemical' analysis. As mentioned in section 3.3.2, percentage data can be misleading, with the reduction in one variable creating an apparent increase in another. In pollen analysis, comparisons can be made by calculating concentrations of each variable. In this case, descriptive analysis and presentation of results with standard errors (West, 1997), should minimise these problems, and bring any apparent peaks into perspective.

### 3.4.10 Carbon analysis

Carbon analysis was carried out using a different technique to EDMA owing to obvious problems with using carbon as a mounting medium for samples and as an anti-static sample coating. Samples were prepared in the same way as for EDMA with samples dried at room temperature for ca. 72 hours, then carefully ground to a coarse powder using a pestle and mortar. A small amount of material was placed into a preweighed ceramic sample holder and weighed before analysis (within 0.0001g accuracy). The sample was then covered with ceramic fibres to avoid loss of sediment during analysis. Total Organic carbon was measured using a Shimadzu TOC 5000 Total Organic Carbon Analyser which included a SSM-5000A solid sample module, with each sample fired once at 900 C. Organic carbon content was expressed as a percentage of the total weight measured. This method was employed for sediment profiles from Kohuora, Matakana Island and Kaipo Bog. Measurement of the organic content of Rotoroa lake sediments was carried out by David Speirs at the University of Waikato as part of an MSc project. Speirs performed loss-on-ignition on dried lake samples and results are displayed in chapter 6 (Figure 6.4) with a full description of the technique used, and organic matter content for the entire sequence presented in Speirs (1995).

### 3.4.11 Behavioural trends in geochemical records

The natural balance or equilibrium state within geochemical records changes according to fluctuating environmental parameters. Butzer (1982) developed terms which describe different equilibrium states exhibited in geochemical records through time, and these terms have been adopted for geochemical interpretation in this thesis, and are discussed below.

*Static equilibrium* - represents constant, stable environmental conditions, with no external forces disturbing the equilibrium

*Steady state equilibrium* - represents fluctuations about the mean, with no net change in environmental conditions, hence no significant environmental change is inferred.

*Stable equilibrium* - this represents a sudden short-lived deviation from the norm, with conditions returning to static equilibrium after a relaxation period.

*Unstable equilibrium* - this represents a change from an old to a new stable equilibrium with an appropriate relaxation period. The new stable equilibrium occurs in the absence of any threshold.

*Metastable equilibrium* - represents a threshold separating old and new equilibrium levels. The threshold is likely to represent external forces such as changes in climate or drainage.

*Dynamic equilibrium* - represents steady state equilibrium exhibiting a long-term trend.

*Dynamic metastable equilibrium* - represents different dynamic equilibrium levels which are separated by a threshold. The establishment of the new equilibrium may indicate that significant environmental change occurred within the system.

Chapters 4 to 7 collectively form the results section of the thesis and follow this chapter. The analytical and sampling techniques outlined in this chapter have been employed and interpreted in the results. The following chapters therefore provide detailed descriptions and interpretations of pollen and geochemistry results for each study site.

## Chapter Four

## Environmental change on Matakana Island during the last 1000 yrs

### 4.0 Introduction

Matakana Island is a barrier spit island formed during a period of rapid sedimentation of Tauranga Harbour during the mid Holocene (Fig. 4.1; 4.2; Plate 4.1). The island is subjected to constant erosion and shifting dune movement, and hence supports a relatively sensitive and unstable ecosystem. Recent research indicates the lakes and wetlands in the area are of a young age (ca. 900 BP, Munro, 1994). Previous palaeoenvironmental work carried out around the western Bay of Plenty coast has generally focused on coastal erosion and sediment drift (Healy, 1980; Davies-Colley, 1976; Harray, 1977; Dahm, 1979). Recent work includes the study of Holocene evolution of the north-western area of Matakana Island (Munro, 1994) and reports on the archaeological and brief vegetation history of this area (Marshall *et al.*, 1994; Shepherd *et al.*, 1996). Palynological investigations from nearby Waihi Beach were carried out by Newnham *et al.* (1995), providing some insight into general vegetation trends in the western Bay of Plenty.

The study site chosen for this research was selected and sampled originally by Munro (1994) as part of an MSc project. This site consists of a small peat section, 66 cm deep, which contained a 2 cm thick distal tephra layer, the Kaharoa Tephra, originating from the Okataina Volcanic Centre ca. 90 km to the south-east. Most recent dates for the Kaharoa Tephra indicate eruption around ca. 700 yrs BP (Lowe and Hogg, 1992; Newnham *et al.*, 1995a;), with the most up-to-date estimate as 665 ± 15 years BP, based on 22 age determinations (Lowe *et al.*, 1998). This age agrees statistically with the age obtained from the peat profile (690 ±40 BP, Wk3426). The total areal extent of the tephra is indicated in Figure 4.1A. The Kaharoa Tephra appears to have been deposited at a critical time in New Zealand prehistory, as initial deforestation by Polynesian settlers occurred around this time (Newnham *et al.*, 1998). The shallow peat section was considered an ideal initial study site for this research as the profile was undisturbed, and included a distal tephra layer that had remained intact (Figure 4.3). Close examination of the palynological and geochemical changes have been undertaken, focusing particular attention on vegetation changes and environmental processes directly following deposition of the Kaharoa Tephra.

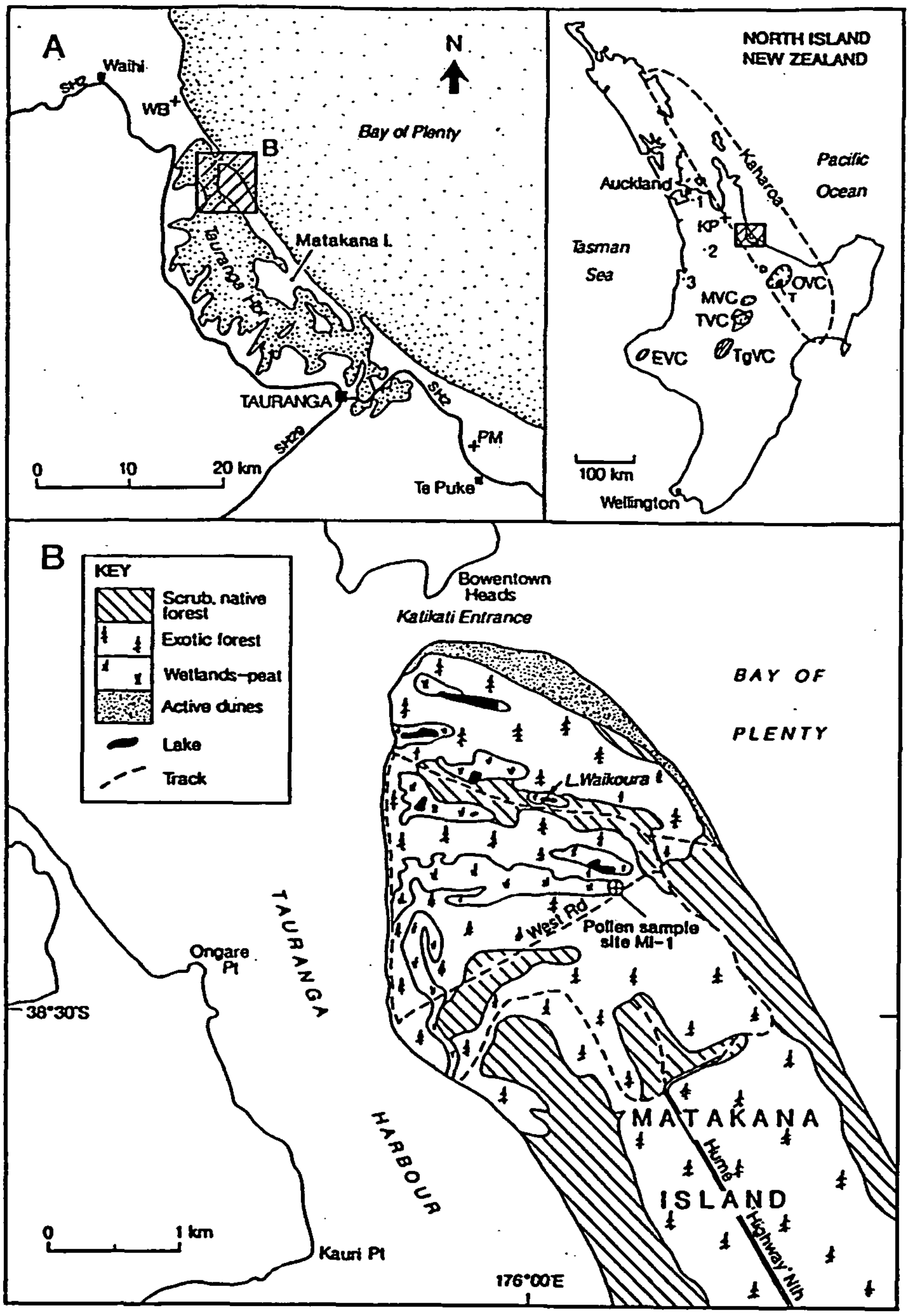



**Figure 4.1A** The location of the study site, Matakana Island, western Bay of Plenty, and a close up of the field area. The dashed line delimits the area where the Kaharoa Tephra was deposited, from Tarawera volcano (T) in the Okataina Volcanic Centre (OVC). Other volcanic centres marked on the map include Marao Volcanic Centre (MVC), Taupo Volcanic Centre (TVC), Tongariro Volcanic Centre (TgVC) and Egmont Volcanic Centre (EVC). Waihi Beach (WB), Papamoa Bog (PM) and Kopouatai Bog (KP) are referred to in the text where the Kaharoa Tephra is also preserved. Points marked 1 and 2 show the location of other field sites studied in this thesis, which are Kohuora (1) and Lake Rotoroa (2). This figure is taken directly from Giles *et al.*, (in press) hence note that point 3 is an error as this shows the location of Lake Taharoa site which was not studied in this thesis.

**Figure 4.1B** Location of pollen sampling site MI-1 and general vegetation in the north-western area of Matakana Island.

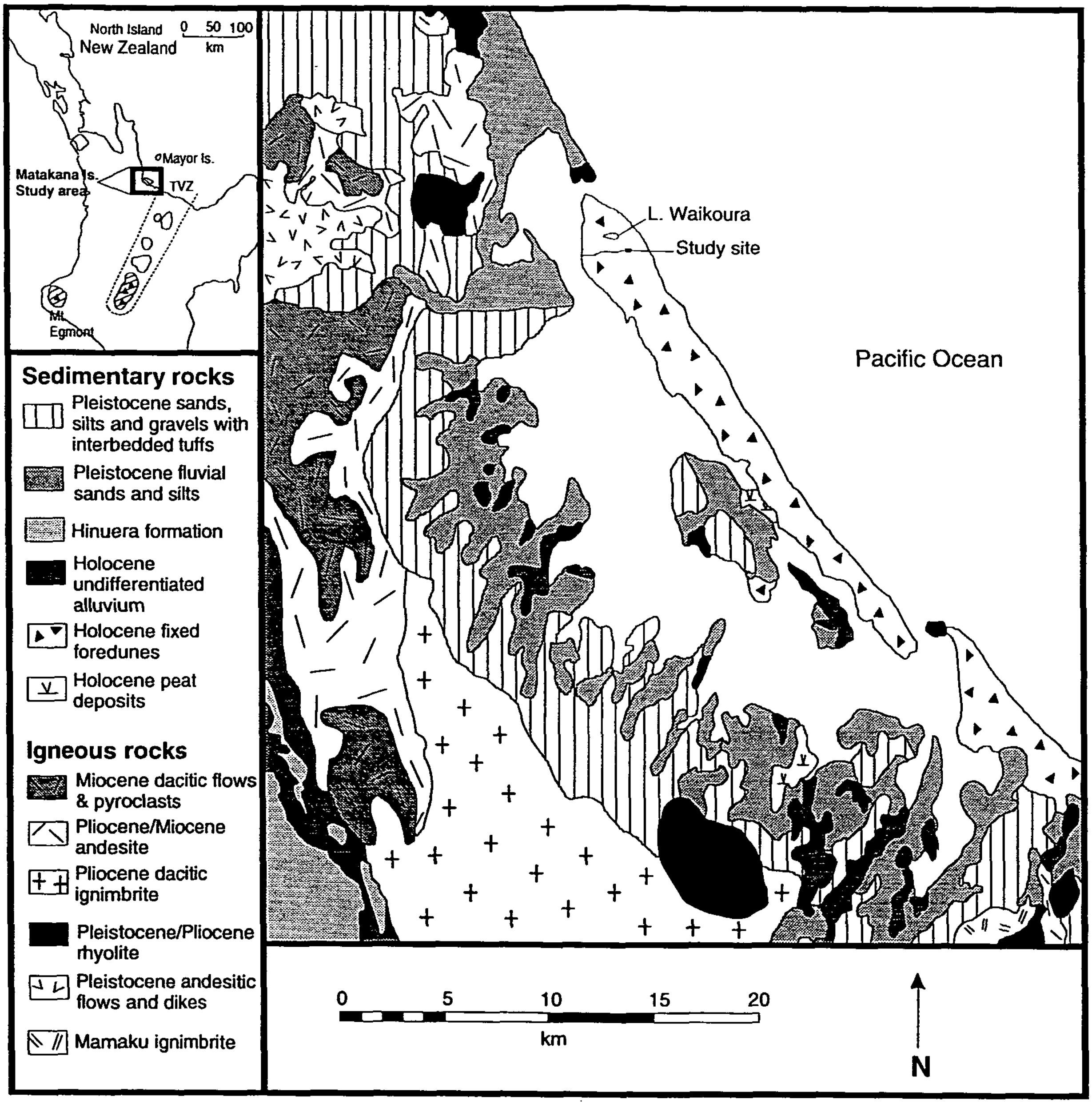



**Figure 4.2** Geology of the western Bay of Plenty (Source: New Zealand Geological Survey map 1:250 000, sheets 3 and 5).

A B

**Plate 4.1** A - Photograph showing north-west point of Matakana Island with plantation *Pinus radiata* forest.
B – Shows the north-east point of the island and the Katikati entrance to Tauranga harbour. Photos D. J. Lowe.

Palaeoenvironmental investigations at this site specifically aim to examine the possible environmental impact from distal volcanic tephra deposition on an unstable, coastal lowland environment.

### 4.1 The study area

#### 4.1.1 Geology and geomorphology

The Tauranga basin is surrounded to the west and north-west by the Kaimai range and Whakamarama plateau, to the south by the Mamaku plateau, and south-east by the Papamoa hills (Figure 4.1A) and occupies an area of ~ 570 $km^2$ (Munro, 1994). Tauranga Harbour is the dominant feature of the basin, comprising a large meso-tidal estuarine lagoon spreading over 200 $km^2$ (Munro, 1994). Rapid sedimentation of Tauranga Harbour has occurred since mid-Holocene times, with eroded rhyolitic sands from the Mamaku plateau area deposited onshore. Evidence for this is extensive, with the formation of Matakana barrier Island, Mt Maunganui Tombolo and Papamoa dune ridges.

Matakana Island is a large barrier spit island, 26 km long, and is predominantly composed of Holocene sands which accumulated during the last 6000 calendar years BP (Figure 4.1A, Figure 4.2) (Munro, 1994, Shepherd *et al.*, 1996). The island is generally divided into 2 parts. The western (inland) side is largely composed of Quaternary consolidated sediments and tephras, and reaches a maximum height of 70 m a.s.l. (Marshall *et al.* 1994). This area once formed part of a plateau which was dissected by streams during the Pleistocene, and became isolated from the mainland due to subsequent glacio-eustatic sea level rise. The eastern (ocean) side consists of Holocene sandy deposits, predominantly composed of quartz, feldspar, pumice, volcanic glass and rhyolitic rock fragments, and reaches heights of up to 20 m a.s.l. (Marshall *et al.*, 1994). The geomorphological features of the island consist of 20-30 dune ridges which are aligned parallel to the shoreline and are curved strongly westwards (inland) at the northern end of the island, displaying growth of this area during the late Holocene. The southern area of the island forms the Tauranga entrance, which prograded some 500 m between AD 1852 and 1954. Between 1954 and 1972 this area eroded back 100 m, but is currently prograding again (Healy, 1977). These previous reports demonstrate the relative instability of the island, as extensive erosion and sedimentation processes have been active throughout the Holocene, and continue to modify the island today.

### 4.1.2 Climate of the western Bay of Plenty (Table 4.1)

The western Bay of Plenty is sheltered from the predominant anticyclones and low pressure belts moving across New Zealand from the Tasman Sea due to the Kaimai Range acting as a barrier (Munro, 1994). However, the region is often affected by depressions and resultant strong north-east winds moving over the area, along with occasional tropical cyclones during November to April. The predominant winds are from the west (Healy, 1977). Matakana island receives around 1400 mm/yr rainfall (Quayle, 1984) (Table 4.1) which is largely associated with the north-easterly airstreams and depression systems.

**Table 4.1** Summary of meteorological data for Matakana Island (Taken at Takata, Matakana Island).

| | Average (yr) | Average for Feb | Average for July | Average daily range |
|---|---|---|---|---|
| **Temperature (°C)** | 15.4 | 19.5 | 10.9 | 7.0 |
| **Rain (mm)** | 1491 | 126 | 147 | - |
| **Frost (days)** | 3.3 | - | 1.9 | - |
| **Humidity (%)** | 81 | 77 | 86 | - |

### 4.1.3 Archaeological history of the area

Archaeological research on Matakana island and adjacent area is relatively limited. Excavations have been carried out at Kauri point between 1960-1963, and the Bowentown dunes in 1981 (Marshall *et al.*, 1994) (Figure 4.1B). McFadgen and Walton (1979) carried out an archaeological survey of the older area of Matakana Island. Many sites were discovered and consisted of 42 Pa (fortified settlement) sites, 25 terrace sites, 78 midden sites and 57 pit sites. These were distributed throughout the area, with Pa sites positioned along the coastline at higher levels (Marshall *et al.*, 1994). All Radiocarbon dates on shell middens presented by Shepherd *et al.* (1996) were younger than 600 cal. BP, and they concluded that first human occupation on the island probably occurred between 600 and 550 cal. BP. All these reports indicate human settlement on

Matakana Island post-dated the Kaharoa eruption (ca. 665 BP). Marshall *et al.* (1994, page 11) state:

"To date, no archaeological sites have been identified beneath intact Kaharoa tephra. But this remains a possibility."

Their own archaeological investigations around the younger part of the island also found many sites above the tephra, but none below. In some cases, shell midden were found resting on top of the Kaharoa tephra. It is clear from the evidence found that Matakana Island was not just an occasional fishing and shell fishing/hunting ground, but became reasonably heavily populated and was considered a 'bountiful homeland' (Marshall *et al.*, 1994). The abundance and availability of resources on Matakana island provided an attractive and well placed site for Maori settlement. Following human settlement on the island, almost immediate modification occurred in the form of forest clearances for gardens and other purposes (Marshall *et al.*, 1994). Palynological investigations by Shepherd *et al.* (1996) indicate a decline in tree species after 600 cal. BP coinciding with charcoal peaks and large increases in *Pteridium*, indicating invasion of these ferns following forest clearance and disturbance. Shepherd *et al.* also provided evidence to suggest that forest clearance influenced the formation of the parabolic dunes, as some very large dunes were formed or reactivated soon after human occupation.

### 4.1.4 Modern vegetation (Plate 4.2a)

The main vegetation habitats covering the north-west area of Matakana Island include wetlands, sand dunes and pine plantation forest (Beadle, 1990) (Figure 4.1B).

*Wetlands and lake margins*

Four wetland areas remain relatively intact, and 2 lakes display a wide variety of wetland and shallow water plants dominating the lake margins. These include *Schoenoplectus validus* and raupo (*Typha orientalis), Baumea, Eleocharis* and *Cyperus ustulatus*. On the wetland margins, manuka (*Leptospermum scoparium*) scrubland and willow (*Salix cinerea*) forest are common, with an understorey of *Baumea juncea*, occasional karamu (*Coprosma robusta*), mingimingi (*Leucopogon fasciculatus*), flax (*Phormium tenax*), and kiokio (*Blechnum*). Other species include sand buttercup (*Ranunculus acaulis*) and *Lilaeopsis novae zealandiae* (Beadle, 1990).

The sampling site is located near the eastern end of a large wetland (Figure 4.1B). This is presently dominated by grey willow (*Salix cinerea*), with toitoi (*Cortaderia*), gorse (*Ulex*) and bracken (*Pteridium*) scrub (Munro, 1994). There is little left of the native vegetation and the study site is now dominated by adventive species.

*Plantation forest*

The pine plantation forests are dominated by *Pinus radiata*, with local maritime pine (*Pinus pinaster*). These forests were planted around the mid 1920s, with self-sown *Pinus radiata* dating from around 1900-1910 (Giles *et al.*, in press). Indigenous species dominate the understorey, where gaps in the canopy create increased light levels, encouraging growth of sand *Coprosma* (*Coprosma acerosa*) and pingao (*Desmoschoenus spiralis*) in sand dominant areas.

Bracken (*Pteridium esculentum*), with karamu (*Coprosma robusta*) and mingimingi (*Leucopogon fasciculatus*) become dominant understorey species in the southern plantation area. Others include cabbage tree (*Cordyline australis*), turutu (*Dianella nigra*), wheki (*Dicksonia squarrosa*), manuka (*Leptospermum scoparium*) kiokio and hangehange (*Geniostoma rupestre* var. *ligustrifolium*) (Beadle, 1990).

*Sand dune vegetation*

The flat foredunes generally display a scattered vegetation cover which includes spinifex (*Spinifex sericeus*), sand *Coprosma*, *Isolepis nodosa*, *Calystegia soldanella*, *Deyeuxia billardierii* sea rocket (*Cakile* sp.) and occasional clumps of marrum grass (*Ammophila arenaria*). Nearer the sea, coastal tea tree (*Leptospermum laevigatum*) is common, and extends back to the edge of the pine plantation forest. In the lee of the foredunes, a sandfield zone supports species of sand sedge (*Carex testacea, Cyperus ustulatus*) and purple groundsel (*Senecio elegans*). Behind the sandfield zone, where there is no pine canopy, a dense mixture of sand *Coprosma* and *Muehlenbeckia complexa* or *Leptospermum laevigatum* dominates, with a ground cover of New Zealand spinach (*Tetragonia tetragonioides*) in places.

## 4.2 Stratigraphy, chronology and sampling of the study site

The stratigraphy comprises 65 cm of peat which overlies aeolian dune sands (Figure 4.3; Plate 4.2b). The Kaharoa Tephra layer is 2-3 cm thick and lies between 44-47 cm depth. The tephra layer is composed of coarse ash grading to fine ash, and is dominated by biotite (~ 85% of the magnetic fraction), which is a diagnostic mineral for this tephra (Froggatt and Lowe, 1990) (Table 4.2). The Kaharoa Tephra layer has been identified at several other sites on the island (Marshall *et al.*, 1994; Munro, 1994). Three radiocarbon dates were calculated from the peat section. The basal twiggy peat layer gave an age of 1010 ± 50 yrs BP (Wk 3427), which was corroborated by the statistically identical age of 1050 ± 70 yrs BP (Wk 2954) obtained from wood material from an identical stratigraphic position nearby (Figure 4.3) (Giles *et al.*, in press, Table 1). Peat dated between 40-44 cm depth gave an age of 690 ± 40 BP (Wk 3426). The date 430 ± 40 BP (Wk 3425) was obtained from fine black peat 20-25cm above the Kaharoa Tephra (Figure 4.3).

On the basis of the tephra and radiocarbon chronology, peat accumulation appears to be reasonably uniform and relatively fast, averaging 0.61 mm/yr. From ~1000 - 665 yrs BP (peat/sand transition to Kaharoa Tephra) the rate was ~ 0.55 mm/yr, from 665 - 430 yrs BP 0.72 mm/yr, and from 430 yrs BP to present day (assumed to be the peat surface) ~0.63 mm/yr. This last value is likely to be a minimum rate because of possible oxidation and shrinkage of the peat in recent times through drainage (Giles *et al.*, in press). Figure 4.3 displays the sampling intervals, stratigraphy and positions of radiocarbon dates in the profile.

Samples were taken at 2 cm intervals throughout the profile to provide a record of vegetation history on the island for the last 1000 years, with finer 1 cm resolution sampling undertaken 5 cm above and below the Kaharoa Tephra. The 1 cm sampling resolution was the finest sampling interval that could be undertaken in the field due to the fibrous nature of the peat creating difficulties in sample extraction. Finer resolution sampling around the Kaharoa Tephra was employed in order to provide a more detailed record of vegetation changes prior to and immediately following tephra deposition at the site.

Fifteen elements were quantitatively determined for the peat profile using the EDMA

**Table 4.2** Comparison of electron microprobe analyses of glass[1] in Kaharoa Tephra at Matakana Island with glass sampled at source (Mt Tarawera), Waihi Beach, and Kopouatai (Fig.4.1A)

| | Matakana Island[2] | Mt Tarawera[3] | Waihi Beach[4] | Kopouatai[5] |
|---|---|---|---|---|
| $SiO_2$ | 77.51 (0.19) | 78.34 (0.21) | 78.46 (0.40) | 78.22 (0.31) |
| $Al_2O_3$ | 12.81 (0.15) | 12.50 (0.12) | 12.31 (0.11) | 12.49 (0.15) |
| $TiO_2$ | 0.10 (0.03) | 0.11 (0.02) | 0.14 (0.06) | 0.13 (0.04) |
| FeO[6] | 0.88 (0.10) | 0.80 (0.08) | 0.88 (0.14) | 0.76 (0.26) |
| MgO | 0.09 (0.04) | 0.10 (0.01) | 0.10 (0.05) | 0.09 (0.13) |
| CaO | 0.53 (0.07) | 0.61 (0.05) | 0.72 (0.17) | 0.55 (0.06) |
| $Na_2O$ | 3.80 (0.09) | 3.22 (0.15) | 3.53 (0.16) | 3.42 (0.19) |
| $K_2O$ | 4.12 (0.13) | 4.21 (0.14) | 3.78 (0.15) | 4.22 (0.43) |
| Cl | 0.18 (0.03) | 0.16 (0.02) | 0.15 (0.03) | 0.14 (0.03) |
| Water[7] | 2.31 (1.29) | 3.05 (0.93) | 2.18 (1.67) | 0.93 (0.68) |
| *n* | 11 | 11 | 9 | 10 |

[1] Means and standard deviations (in parentheses) normalised to 100% loss-free. Analysed by Jeol JXA-733 Superprobe at the Analytical Facility, Victoria University of Wellington. All analyses used beam diameter 10-15 μm, current 8 nA, accel. voltage 15 kV (Froggatt 1983). Anal. 1 calculated from 11 x 2 s counts across the peak, curve integrated; anal. 2-4 calculated from 3 x 10 s counts at the peak, meaned. Analyses of $TiO_2$, MgO, and Cl were below detection in some shards; these values were omitted from the means. n = number of analyses (individual shards) in mean

[2] Core at MI-1 (U13/758083; this study)

[3] Section at [V16/177252] in Mt Tarawera crater (from Hodder *et al.* 1991)

[4] Core at [U13/702174] in Waihi Beach swamp (from Newnham *et al.* 1995b)

[5] core at [T13/380197] in Kopouatai bog (from Hodder *et al.* 1991)

[6] Total Fe as FeO

[7] Difference between original analytical total and 100

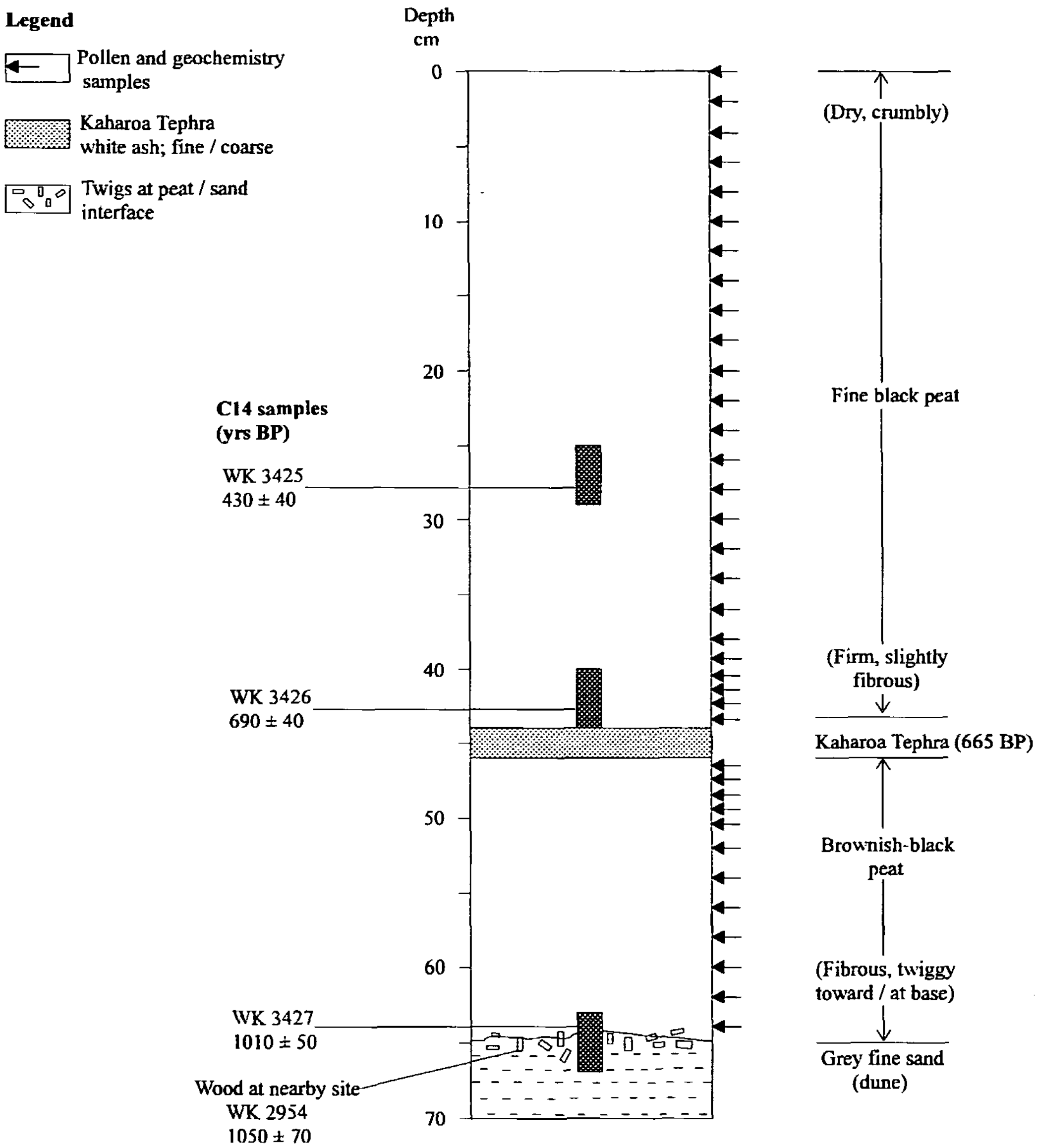



**Figure 4.3 Stratigraphy, chronology and sampling of Matakana Island peat profile**

**Plate 4.2a** Matakana Island field site vegetation, looking toward site MI-1 (in willows). Photo: D. J. Lowe.

**Plate 4.2b** Site MI-1 peat profile with arrow marking the Kaharoa Tephra layer. Photo: D. J. Lowe.

technique described in chapter 3. Only 11 of these elements were present in significant quantities, and so the remaining four are omitted from further discussion. Carbon was measured separately using the carbon analyser (chapter 3).

Results for pollen and geochemical analysis are presented in Figures 4.4 and 4.5 respectively. Results attributed to general environmental history are discussed in section 4.3 and volcanic impacts in section 4.4.

### 4.3 Pollen and geochemistry results

Results for pollen and geochemical analysis are displayed in Figures 4.4 and 4.5, with descriptions of main trends in the data presented in Tables 4.3 and 4.4.

**Table 4.3** Description of pollen changes in zones not affected by tephra fallout

| Pollen zone and date (years BP) | Depth | Description |
|---|---|---|
| **MI1 (1000-665)** | 64-46cm | *Agathis* pollen levels rise to 40%, as *Phyllocladus* steadily declines to 17%. *Prumnopitys*, *Metrosideros* and *Podocarpus* pollen fluctuates between 5-10%. *Leucopogon fasciculatus* pollen levels rise sharply at 46.5cm to 10%. *Leptospermum* pollen reaches a peak of 10% at 47.5 cm. Deteriorated pollen levels rise to 15% just below the tephra (46.5 cm). Charcoal levels reach 50% between 64-58cm, disappearing at 57 cm depth. Glass shards peak sharply just below the tephra layer to 20%. Total pollen concentration levels reach a maximum of 37,000 per $cm^3$, declining below the tephra to 20,000 per $cm^3$. |
| **MI3 (665-150)** | 40-26cm | *Agathis* pollen declines to 20%. *Dacrydium* pollen fluctuates between 15-20%. *Phyllocladus* pollen continues to decline from 15% to 5%. *Leptospermum* pollen dominates the zone, reaching 40%, declining to 10% at 26 cm. Poaceae, *Coprosma* and *Cupressus* pollen rise to 5% at the top of the zone. Cyperaceae pollen peaks at 32cm to 10%. Monolete fern spores and *Pteridium* reach 20% and 30% respectively at 26cm. Deteriorated pollen grains reach even higher levels of 70% at 26 cm, and charcoal rises dramatically to 80%. |
| **MI4 (150-0)** | 26-0cm | *Leptospermum* pollen levels peak to 20%, declining to 5% at 2 cm. *Pinus* pollen increases along with *Salix*, reaching 20% and 70% respectively at the peat surface. *Cyathea* and monolete fern spores peak to 15% at 22cm, declining to 3% at the top of the zone. *Pteridium* spores peak to 40% at 24 cm, also declining rapidly to 5% at the surface. Degraded grains rise to 55% at 22 cm depth. Charcoal levels are very high, fluctuating around 90%, before declining to 50% at the surface. Pollen concentration levels fluctuate around 30,000 per $cm^3$. |

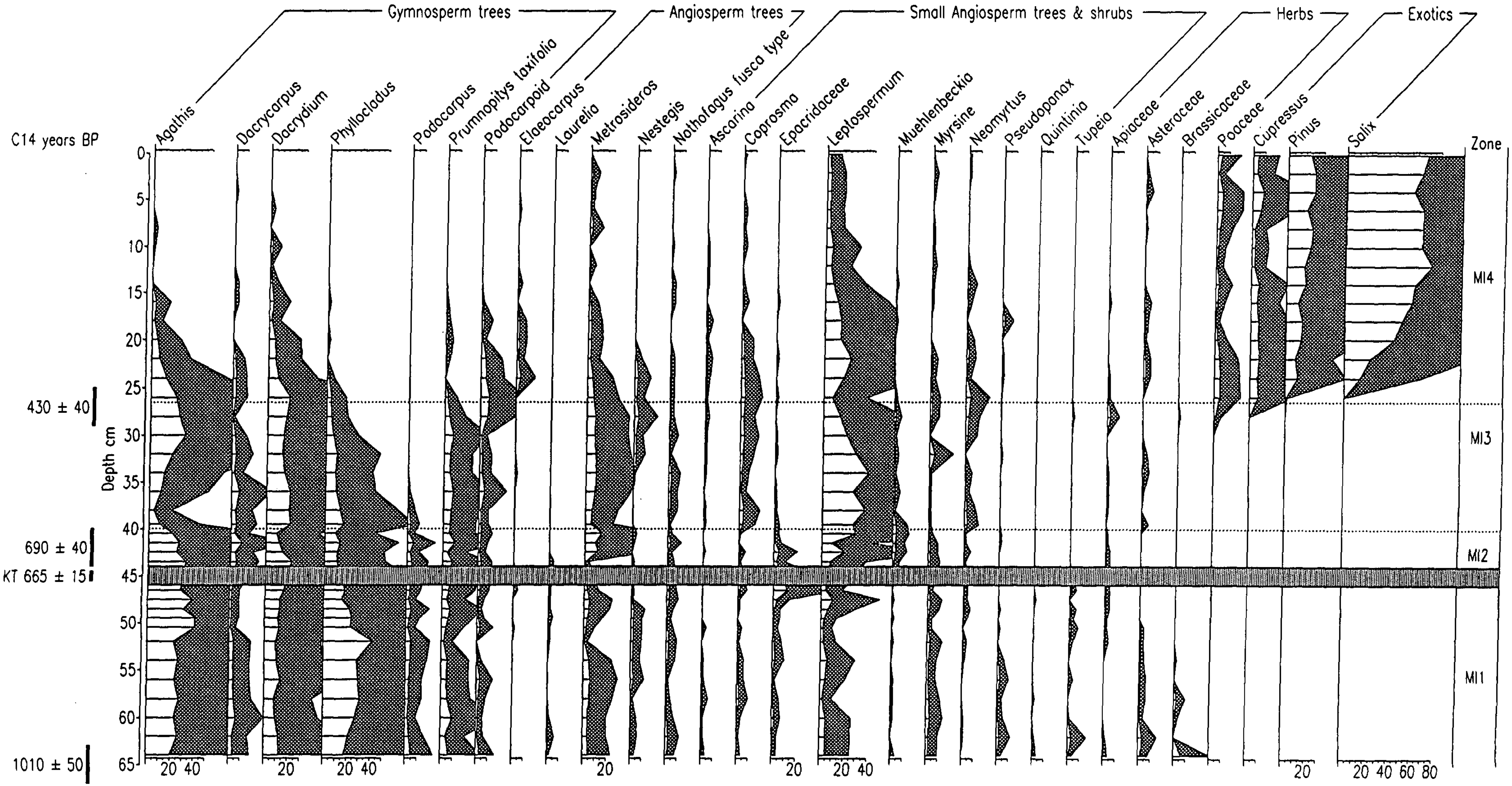
**Table 4.4** Description of changes in sediment geochemistry in non-tephric chemizones

| Chemizone and dates | Depth | Description |
|---|---|---|
| CMI1 (1000-665 BP) | 64-46cm | Na, K and Al increase to 2%, 4% and 6% respectively. C rises to 45% at 47.5cm, declining just below the tephra layer to 30%. Si increases from 10%, to 38% at 46.5 cm. Ca peaks to 40% at 48.5 cm, declining to 20%. Fe and S reach 43% and 28% respectively, declining to 15% and 10% at 46.5cm |
| CMI3 (150-0 BP) | 40-0cm | K and Al remain consistent at ca. 1% and 2.5% respectively. Na rises from 0.1% to 2% at 10 cm. Values for C reach 30% in the top 8 cm of the profile. Si fluctuates around 60%, declining to around 45% in the top 6 cm. Ca remains constant around 15%. Fe increases dramatically from 1% at 24cm, to 38% at 6cm. |

### 4.3.1 Vegetation, catchment history and human settlement on Matakana Island

At the base of pollen zone MI1 (Figure 4.4), evidence for burning is apparent, with a peak in charcoal levels and the presence of *Pteridium* spores. This is short-lived, and does not appear to have had a major effect on the local vegetation. Pollen levels from the conifer and angiosperm trees reflect dense mixed forest present on the site, with *Dacrydium* and *Phyllocladus* possibly invading the wetland fringes and low lying waterlogged pockets of ground (Newnham *et al.*, 1989), with a scattered distribution of *Nestegis* and *Weinmannia* in the forest sub-canopy. An anthropogenic cause for the charcoal peak cannot be ruled out, as the date given (~1000 BP) lies within the estimated dates for the first Maori settlers in New Zealand (Davidson, 1984). There is very little vegetation disturbance below the Kaharoa Tephra, although *Phyllocladus* pollen declines gradually. This decrease in *Phyllocladus* trees probably represents a natural ecological change in dominant species, with *Agathis* pollen increasing to highest levels as *Phyllocladus* declines. Both species prefer drier sites and are tolerant of infertile soils (Newnham *et al.*, 1989).

*Metrosideros* and *Leptospermum* pollen maintain significant levels indicating local presence of these trees around the site. *Leptospermum* is known to thrive in waterlogged areas, and can adapt to a high water table and even complete inundation for long periods (McGlone, 1988). From the moderate pollen levels counted for *Leptospermum*, it is inferred that these shrubs were present on the mire, but not growing at the pollen sampling site itself. *Fuscospora* pollen is present at very low levels, possibly indicating pockets of *Nothofagus* growing away from the site. These grains may have been blown in from the Coromandel


Gymnosperm trees
Angiosperm trees
Small Angiosperm trees & shrubs
Herbs
Exotics
C14 years BP
Agathis
Dacrycarpus
Dacrydium
Phyllocladus
Podocarpus
Prumnopitys taxifolia
Podocarpoid
Elaeocarpus
Laurelia
Metrosideros
Nestegis
Nothofagus fusca type
Ascarina
Coprosma
Epacridaceae
Leptospermum
Muehlenbeckia
Myrsine
Neomyrtus
Pseudopanax
Quintinia
Tupeia
Apiaceae
Asteraceae
Brassicaceae
Poaceae
Cupressus
Pinus
Salix
Zone
Depth cm
430 ± 40
690 ± 40
KT 665 ± 15
1010 ± 50
MI4
MI3
MI2
MI1

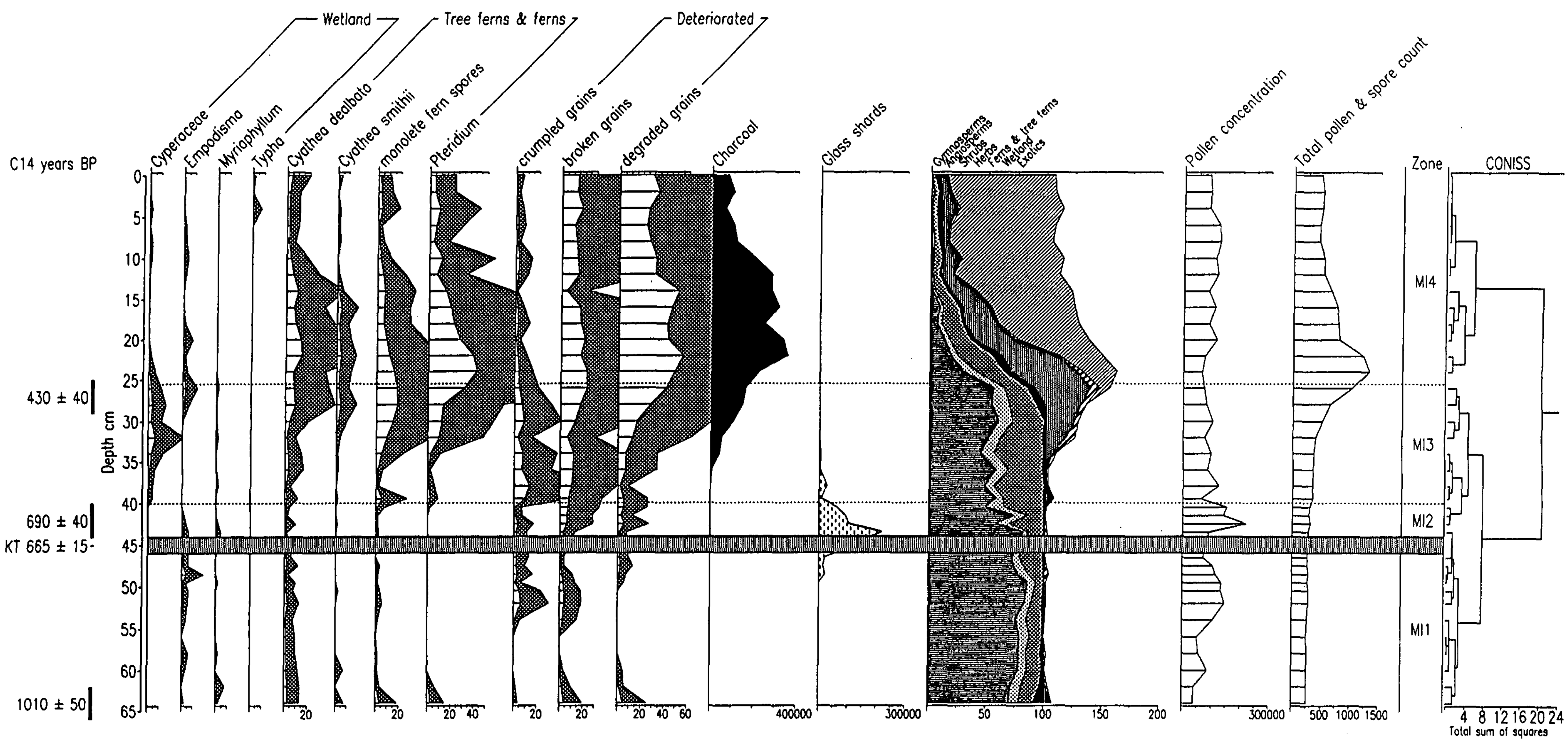



**Figure 4.4** Pollen diagram revealing changes in main taxa at site MI-1. Total pollen concentration is expressed as total number of pollen grains and spores per cm$^3$. Pollen represented as podocarpoid includes grains of *Prumnopitys* and *Podocarpus* pollen which were unable to be distinguished (see Chapter three). KT represents Kaharoa Tephra. The pollen sampling interval is indicated by the vertical spacing between bars in the 'Total pollen count per sample' curve. Charcoal and Tephra shards are expressed as number of fragments per cm$^3$.

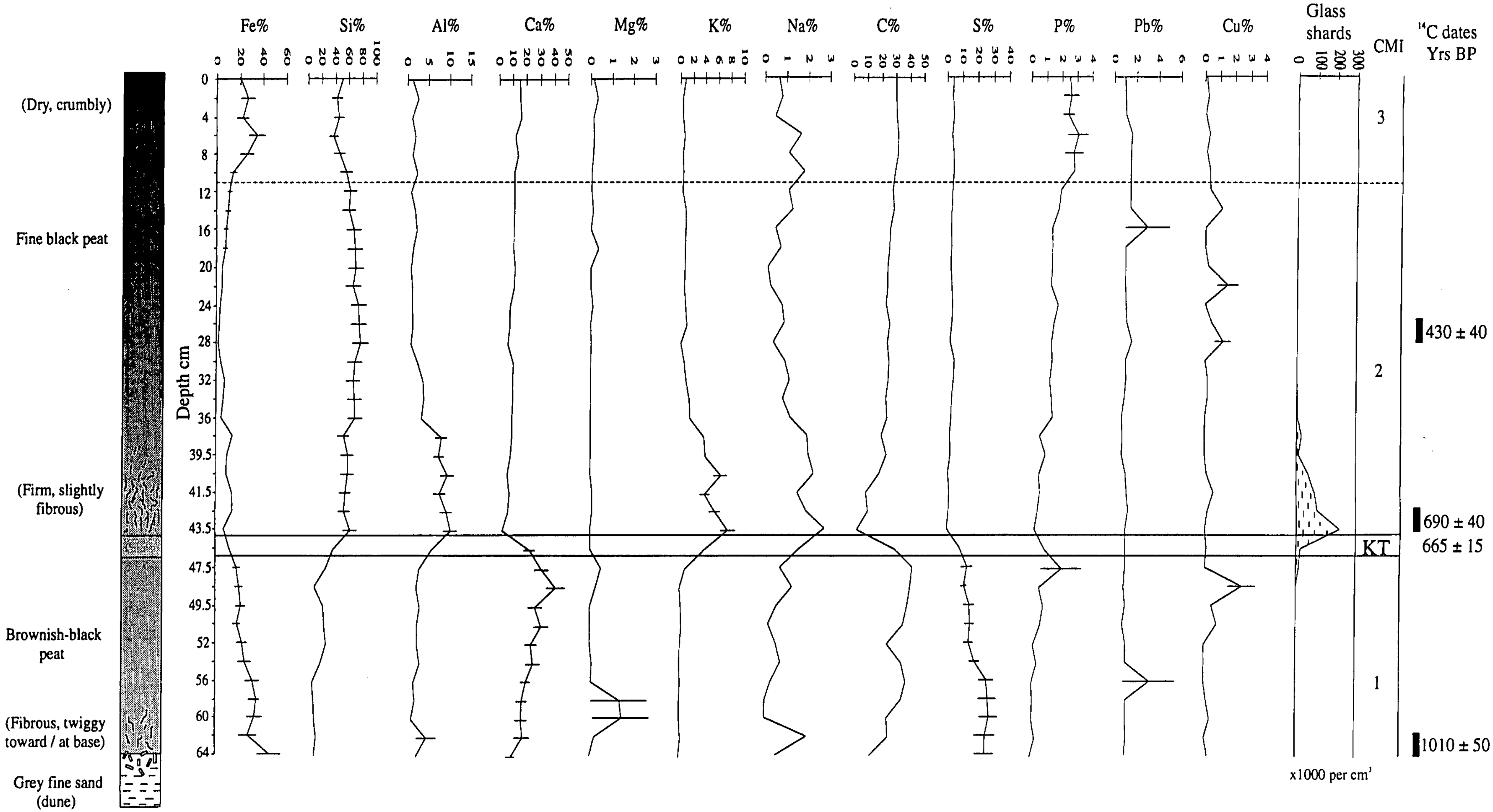



**Figure 4.5** Relative proportions of elements present in Matakana Island peat profile. Glass shards concentrations are expressed as thousands of grains per cm$^3$. CMI refers to chemizones. Solid line denotes Kaharoa Tephra layer (KT).

range, where *Nothofagus* forest is extensive (Newnham *et al.*, 1995). Overall, a relatively stable environment is inferred from the pollen diagram, with a rich mixed conifer-angiosperm forest bordering the wetland area.

The geochemical assemblages in CMI1 are in agreement with the pollen record, indicating that comparatively stable environmental conditions prevailed prior to the Kaharoa eruption. Na, K, Mg and Al are present in low proportions indicating minimal soil leaching and erosion (Bennett *et al.*, 1990, Grattan *et al.*, 1996). Na and K levels are often low in peat profiles as these elements are highly soluble and are rapidly removed from peat systems (Damman, 1978; Shotyk, 1988). Higher proportions of Fe, Ca and S are observed below the tephra layer. S is sometimes associated with sea water influence (Goldschmidt, 1954). Higher S together with Mg, which displays a small peak between 58 and 60 cm depth, may represent a short-lived marine influence at the site during a period of intense storms, causing sea water to flood into the catchment. However, the peaks observed in Mg are displayed with wide error bars, indicating significant variation in Mg measurements for these depths. Brown (1985) notes that higher S is often associated with organic matter in peats. Thus the high relative proportions of S in CMI1 could also reflect rapid decomposition of plant debris during the early stages of peat formation under mild climatic conditions. Organic C also increases throughout this zone, relating to high organic matter content, indicating the formation of well humified peat (Goldschmidt, 1954).

High levels of Fe occur in this zone as Fe trends in peats show higher concentrations towards the base and surface of peat profiles (Nauke *et al.*, 1993). Higher Fe in CMI1 is likely to be due to a higher proportion of minerogenic material present during early peat formation, due to weathering of bedrock. Clymo (1983) and Shotyk (1988) report that in early stages of peat development, dissolved and suspended mineral matter are abundant, but as peat accumulates, the rich mineral layer at the base of the profile becomes inaccessible to plants. Hence the proportion of available minerals in peats is often confined to the basal layers, with the mineral content of the peat decreasing higher up the profile. Higher Fe is also associated with groundwater influence (Chapman, 1964; Mannion, 1979), indicating possible precipitation of iron through groundwater movement within the basal layers of the peat.

Proportions of Ca are highest in this chemizone, whereas the opposite is true for Si. Increased Ca indicates low acidity (pH 6-7) and a high Cation Exchange Capacity (CEC) (McRae, 1988), revealing that peat conditions were favourable for the development of a rich and diverse vegetation cover. The presence of a relatively high proportion of Si throughout the profile is due to the coastal location of site MI-1, with possible inwashing of sand particles and volcanigenic material through surface water infiltration, and the incorporation of airborne particles into the peat from the surrounding area due to wind and coastal erosion of local dunes.

Following the initial short-lived vegetation and catchment disturbance immediately above the Kaharoa Tephra (see section 4.4), anthropogenic disturbance became significant on Matakana Island. Large-scale deforestation by Polynesians is inferred from the pollen record to have commenced 4 cm above the tephra layer, after approximately 600 years BP (pollen zone MI3). Numbers of charcoal fragments increase rapidly as local forest was burnt and cleared. *Agathis* trees were the hardest hit, with a gradual decrease in the number of *Dacrycarpus* and *Phyllocladus* trees. Taxa which typically respond to vegetation disturbance increased substantially, and included *Leptospermum* and ferns, in particular *Pteridium*, along with *Cyathea dealbata*. *Metrosideros* trees and lianes remained prominent in the area, together with an increasing abundance of *Coprosma* shrubs and Cyperaceae. These species would have invaded areas of bare ground made available by the decline in forest taxa following burning. Numbers of deteriorated pollen grains increase rapidly in pollen zone MI3 indicating a period of increased slope instability and erosion.

Evidence for increased leaching and soil erosion is envisaged from changes in mineral assemblages in the geochemical record (Fig 4.5). Increases in the relative abundance of Na, Al and K at the base of CMI2 can be partially explained by weathering and reworking of the Kaharoa Tephra layer releasing these elements into the peat. However, the higher proportions of Na and K persisting throughout most of this chemizone indicate possible erosion of soils and tephra from the surrounding catchment (Guppey and Happey-Wood, 1978; Engstrom and Wright, 1984; Bennett *et al.*, 1990) and subsequent inwashing of these elements into the peat. Higher proportions of Al, together with lower Ca, relate to increasing acidification within the catchment, caused by an increase in leaching and erosion of the surrounding catchment soils and tephra deposits, owing to local deforestation by early Polynesian settlers. Anthropogenic disturbance in the area is seen from the pollen record to have continued over a period of approximately 500 years.

High values of Si also indicate erosion of catchment soils and adjacent dunes due to local vegetation disturbance. Si may also indicate an increase in influx of plant debris such as phytoliths and crysophyte cysts (Goldschmidt, 1954; Engstrom and Wright, 1984), as much of the surrounding forest was cleared. Proportions of P rise slightly towards the top of CMI2, indicating possible nutrient inwashing from eroding soils and influx of plant matter following anthropogenic disturbance (Grattan *et al.*, 1996).

Areas studied around the Bay of Plenty coast show evidence for Maori settlement and environmental disturbance slightly earlier than inferred at Matakana Island. Palynological studies undertaken at Papamoa and Waihi Beach show peaks in *Pteridium* and charcoal levels above the Kaharoa tephra as tree pollen declines (Newnham *et al.*, 1995b). However, adventive pollen was also found at this level, which the authors suggest could have been due to contamination within the profile. Hence, no definite conclusions were drawn for either human or volcanic impact at these sites. At Kopouatai bog (Figure 4.1A), increases in bracken and charcoal commenced just below the Kaharoa tephra and were interpreted as regional human influence rather than volcanic impact (Newnham *et al.*, 1995a).

Evidence for possible downwards dislocation of microscopic particles is also seen in the Matakana Island pollen record at the base of pollen zone MI4, marked as the beginning of the European era, defined by the first appearance of adventive pollen (Figure 4.4). The European era spans the last ca. 200 years of New Zealand history, yet the peat immediately beneath MI4 is dated as 430 ± 40 BP. Either the date is an error, or adventive pollen has moved down profile, as reported for near-surface samples at Papamoa and Waihi Beach due to intense disturbance during the twentieth century (Newnham *et al.*, 1995a). In pollen zone MI4, all previously dominant native taxa decline, as mixed conifer-broadleaf forest was replaced by stands of *Salix, Pinus,* and *Cupressus* trees, with a dense cover of bracken and a small scattering of native *Leptospermum* shrubs. Charcoal levels reach highest levels yet, along with deteriorated pollen grains, indicating extensive and sustained burning in the area, which resulted in local soil degradation.

Chemical assemblages in CMI3 indicate that soil erosion and leaching within the catchment appeared to be less severe than in CMI2, as highly soluble minerals (Na, K, Al) had by now become extensively leached from the local soils and the peat acrotelm. Increases in Fe and P also indicate acidification and podsolisation of local soils as a result of sustained anthropogenic disturbance. Lower Ca also reflects prolonged acidification within the catchment, although levels increase towards the peat surface, perhaps reflecting a return to more stable conditions. Evidence for gradual environmental stability is indicated by the decline in Si in the top 10 cm of the profile, reflecting a reduction in dune and soil erosion due to stabilisation of slopes following plantation of pine forests in the area during the European era.

## 4.4 Pollen and geochemistry results immediately above Kaharoa tephra

Descriptions of the changes observed in pollen and geochemical assemblages occurring immediately above the Kaharoa Tephra layer are presented in Table 4.5, and discussed in section 4.4.1.

**Table 4.5** Description of changes in pollen and sediment geochemistry above the Kaharoa Tephra

| Pollen zone / chemizone | Depth cm | Description |
|---|---|---|
| **MI2 (665 BP)** | 44-40 | *Agathis* and *Dacrydium* pollen declines to 20% and 10% respectively at 40cm depth. Dacrycarpus and *Prumnopitys* pollen levels both exhibit peaks of 10% at 42 cm. *Metrosideros* and *Leptospermum* pollen levels peak immediately above the tephra layer at 15% and 20% respectively, with *Leptospermum* pollen rising to 30% at the top of the zone. Deteriorated pollen grains increase to 20%. Charcoal rises rapidly to 10% above 41 cm. Tephra concentrations decline sharply, from 70% to 20 % at 40 cm depth. Total pollen concentrations increase dramatically to 55,000 per $cm^3$. |
| **CMI2 (665-150 BP)** | 44-11 | Na and K peak to 2.8 and 7.5% respectively. Al also peaks at 43.5 cm to 10%. C exhibits lowest values of 5% at 43.5 cm depth, rising to 25% to the top the chemizone. Si reaches highest values of 67% at 24 cm. Ca again displays the opposite trend, with the lowest value of 3% at 43.5 cm. Fe fluctuates between 10 and 15% from 43.5 to 38 cm. |

### 4.4.1 Discussion of possible distal volcanic impacts on Matakana Island

Pollen spectra immediately following the deposition of the Kaharoa Tephra, indicate vegetation disturbance in the catchment. Changes in the established mixed conifer-angiosperm forest occur, as *Agathis* and *Dacrydium* trees decline markedly. *Agathis* and *Dacrydium* pollen curves display similar trends after tephra deposition. Initially pollen levels remain high directly above the ash layer. Shortly after, there appears to be a significant decline, which is delayed in *Agathis* trees, followed by a period of recovery to former levels in zone MI3 for both species. These short-lived declines could be attributed to a volcanic cause as they occur soon after the eruption, and are not sustained. The delayed, temporary decline in *Dacrydium* and *Agathis* may indicate these trees initially survived the tephra impact, but suffered subsequent damage due to leaching of toxic chemicals from tephra which had accumulated on branches and leaves. *Podocarpus* trees also disappeared soon after the eruption, although this is likely to be the result of increasing difficulty in identification of pollen grains due to deterioration. *Podocarpus* grains may thus be represented in figure 4.4 as podocarpoid, along with other bisaccate pollen with non-radial sac pattern, which is used when generic distinction cannot be made (see Chapter three, section 3.3.6).

*Dacrycarpus* pollen levels increased following tephra fall, indicating expansion of these trees possibly into areas formerly occupied by *Dacrydium*. Subsequently, *Dacrycarpus* trees decline to former levels as *Dacrydium* recovers into zone MI3, suggesting vigorous competition between these species around the mire margins. *Metrosideros* species, *Muehlenbeckia* lianes and *Leptospermum* shrubs also increased markedly above the tephra layer. *Metrosideros* trees thrive on fresh volcanic surfaces, as on White Island (Clarkson and Clarkson, 1994), and Rangitoto Island, Auckland, and therefore may have benefited from fresh tephra deposition at Matakana Island.

*Laurelia*, *Quintinia*, and the epiphytic shrub *Tupeia antarctica* were growing in proximity to the site before the tephra was deposited, indicated by low pollen levels in MI1, but apparently disappeared immediately after the eruption. These taxa may have been striving to become established in the area, but the deposition of acid-laden tephra may have inflicted severe stress on these plants, causing their death in the catchment. The disappearance of *Tupeia* may be related to damage to host plants (e.g. *Agathis*, *Dacrydium*) as a result of tephra accumulation. Similarly Epacridaceae (mostly *Leucopogon fasciculatus*) increases distinctly immediately below the Kaharoa Tephra, but subsequently declines in zone MI2, suggesting possible plant damage by tephra deposition. Rapid invasion by *Leptospermum* may have resulted in increased competition for fresh ground surfaces, a factor which may also have contributed to the decline in *Leucopogon fasciculatus*. McGlone (1988) notes that *Leptospermum* invades most rapidly over sites with a lower water table (i.e.,, less waterlogged) and low ground cover. Thus, it seems likely that *Leptospermum* would have spread to the slightly drier sites that may have become available following the decline in *Agathis* and *Dacrydium* trees. The prolific seeding of *Leptospermum* would have created difficulty for other species (e.g. *Leucopogon fasciculatus*) to become established in the area.

It is clear from figures 4.4 and 4.5 that significant changes in vegetation communities and catchment occurred shortly after the Kaharoa eruption; however, the interpretations are put forward with caution and cannot yet be attributed to a volcanic cause. The immediate disappearance of *Tupeia* and the gradual decline in *Leucopogon fasciculatus* could be connected with the deposition of tephra. Immediate and dramatic increases in *Leptospermum* scrub, along with *Metrosideros* and *Muehlenbeckia* suggests subsequent invasion of canopy openings and bared surfaces following the gradual decline in former vegetation which occupied these sites (i.e.,, *Phyllocladus, Dacrydium, Agathis, Tupeia* and *Leucopogon fasciculatus*). These decreases in formerly abundant vegetation may have been initiated by possible acid damage to plants, or tephra accumulation on plant leaves interfering with vital mechanical processes for plant survival (i.e.,, photosynthesis, evapotranspiration, respiration).

It is interesting that total pollen concentrations reach their highest values in zone MI2, suggesting vegetation was flourishing soon after the Kaharoa eruption. However, an increase in pollen concentrations may be caused by drying of the peat bog through the addition of the 2 cm thick tephra layer, resulting in slower peat accumulation for the immediate period following the eruption. A short-lived reduction in the rate of peat accumulation, together with increased pollen influx from deteriorated pollen grains washed in from the catchment, could explain the temporary peak in pollen concentrations soon after tephra deposition.

Changes observed in vegetation assemblages following tephra fall cannot be attributed unequivocally to a volcanic cause. An alternative explanation concerns the timing of the arrival of Polynesians on the island. As stated above, Marshall *et al.* (1994) estimate their arrival around 600 yrs ago. As discussed in Chapter one, large-scale burning and clearance of the New Zealand landscape by the Polynesians is believed to have had a significant impact on the New Zealand environment from around 450 BP (McGlone, 1989, Anderson, 1992). Early settlers on Matakana island may have had little impact on the vegetation, as abundant food sources were available through fishing and hunting. Expansion of the island's population over a few decades would have triggered the need for land clearance and cultivation. The second charcoal peak in figure 4.4 (zone MI2-3) may therefore be misleading as an indicator for the commencement of the Polynesian era at this site, and the gradual decline in *Agathis* and *Dacrydium* trees in zone MI2 may indicate Polynesian forest clearance. Despite this, Marshall *et al.* (1994) indicate, from their archaeological findings, that burning and clearance of land commenced almost immediately with the arrival of the Polynesians on Matakana Island.

Nevertheless it can be argued that the vegetation changes envisaged in pollen zone MI2 could be the result of volcanic rather than human impact, as charcoal and bracken levels do not appear directly above the tephra layer, but a further 4 cm above. The subsequent disturbance, presumed to be the result of Polynesian activity, may be superimposed on a longer term volcanic impact on the vegetation. Hence the extent of damage caused from the deposition of the Kaharoa Tephra remains unclear. The distribution of tephra shards around the main Kaharoa Tephra layer indicates some disturbance within the profile. The spread of shards above the layer may point to increased run-off or wind erosion in the area as *Agathis* and *Dacrydium* trees begin to decline, possibly creating gaps in the forest canopy and bared ground surfaces. Hence the shards may have been washed or blown in from the catchment, along with increased levels of deteriorated pollen grains, which also suggests catchment erosion. Higher values of Na, K, Al and Si in the geochemical record (CMI2) suggests erosion of soils and adjacent dunes following disturbance of the local vegetation. The lower levels of C above the tephra layer support these conclusions, indicating a higher proportion of minerogenic material, and a reduction in organic matter within the peat in the lower half of CMI2. The increase in minerogenic material indicates that sedimentation had occurred from erosion of surrounding soils and dunes, with the presence of glass shards derived from the Kaharoa Tephra layer also increasing the mineral content of the peat.

The geochemistry of the peat changes significantly above the Kaharoa Tephra layer with increases in Si, Na, Al and K. These elements are all present in the Kaharoa Tephra and were probably incorporated into the peat through weathering of the tephra layer. It is impossible to pinpoint specific ash-fall induced environmental changes from the results presented here, as there are no specific geochemical changes that can be attributed to volcanic impact prior to the commencement of anthropogenic deforestation in the area. The elemental changes in CMI2 reveal unstable environmental conditions, with the sudden decline in Ca indicating an increase in peat acidity. It is clear from the results presented in Figure 4.5 that local soil and dune erosion was active in the area for some time as a result of anthropogenic and possible volcanic impacts.

Tephra shards are found almost to the top of zone MI3, which may be the result of burning and clearance by early Polynesian settlers causing continued erosion in the area. Tephra shards have also spread below the main tephra layer. This dissemination may be the result of the irregular surface of the peat bog on which the ash was deposited, with the tephra being physically reworked to accumulate in hollows created by uneven vegetation cover. Glass shards would then have been displaced below the main tephra deposit and become compressed into the peat following subsequent sedimentation and compaction. Minor bioturbation and possible infiltration through root channels following deposition may also have contributed to the downward spread of shards in the profile.

### 4.5 Summary

Table 4.6 provides a summary of vegetation and catchment geochemistry change on Matakana Island. The pollen and geochemical records display close affinity with one another, revealing a period of environmental disturbance commencing soon after the deposition of the Kaharoa Tephra. A major difficulty in interpretation of the pollen and geochemical records is the fact that clear differentiation cannot be made between human-induced and volcanic-induced environmental disturbance at this site. Changes observed in the pollen record immediately above the tephra layer could indicate damage to vegetation from ash and toxic chemical deposition. These changes occurred below the assumed level of human-induced environmental disturbance and vegetation burning, which appeared to commence 4 cm above the Kaharoa Tephra layer (Fig. 4.4).

Human or volcanic impact signals in the geochemical record are blurred owing to the geochemistry of the Kaharoa Tephra, composed predominantly of Si, Na, Al and K, with minor amounts of Fe and Ca, all of which are important elements in palaeoenvironmental interpretation and reconstruction. Thus the increase in the relative abundances of Si, Na, Al and K immediately above the tephra are likely to be due to weathering of the tephra layer, and the subsequent incorporation of these elements into the peat. These higher levels continue throughout the most part of chemizone CMI2, indicating soil erosion and leaching processes within the catchment, together with increasing acidification of soils and peat, indicated by the sudden decline in Ca levels and rise in Al. These geochemical changes are synchronous with the abrupt rise in the number of microscopic charcoal fragments, and the decline in dominant forest vegetation, displayed in pollen zone MI3. These changes in the geochemical and palynological records indicate large-scale deforestation of the local area by early Polynesian settlers, leading to soil instability and subsequent erosion of newly exposed bared surfaces.

The similarity between the pollen and geochemistry records becomes less obvious between 30-10 cm depth. The pollen record reveals a period of intensive deforestation, likely to be due to settlement of Polynesians on the island, which continue into the European era. Local erosion is also apparent, with high levels of degraded and broken pollen grains. However, in the geochemical record, the erosion indicators Al, Na and K all decline to former low levels above 30 cm, even though the most intensive phase of deforestation and environmental disturbance occurs above this depth in the pollen record. This may indicate that these minerals had by now been mobilised and leached from local soils, with the majority being lost to soil drainage water and groundwater flow.

Within the top 10 cm of the profile a slight return to more stable environmental conditions is envisaged from the geochemical record, as Ca rises gradually towards the peat surface, indicating less acidic conditions, and Si levels fall in the top 8 cm possibly indicating a reduction in local dune and soil erosion. The reliability of geochemical data for palaeoenvironmental interpretation in the surface layer of the peat is limited due to natural oxidising conditions which can cause an apparent enrichment of minerals, in particular Fe, in the top few cm of the profile (Goldschmidt, 1954; Mackereth, 1966; Shotyk, 1988). In the pollen record, a reduction in the number of broken and degraded pollen grains, and microscopic charcoal fragments from 10 cm depth also indicates environmental conditions were gradually becoming more stable owing to a reduction in runoff and soil erosion, as envisaged from the geochemical record. The increasing

**Table 4.6** Summary of main vegetation changes occurring on Matakana Island over 1000 yr timespan. Age of pollen zone MI4 based on appearance of adventive pollen rather than Wk-3425.

| **Yrs BP** | **Dominant pollen taxa and geochemical elements** | **Vegetation and Environment** |
|---|---|---|
| 0-150 | *Salix, Pinus, Pteridium*<br>C, Fe, Si, Ca, Na | European era. Abundant charcoal and damaged pollen grains indicate extensive burning of native species. reduced soil erosion and leaching, environment stabilises at a new equilibrium, chemical assemblages represent an acidified environment. |
| 150-665 | *Leptospermum (Agathis)*<br>Na, K, Al, Si | Recovery of *Agathis* and *Dacrydium*. Polynesian era - sustained burning, *Pteridium* and Cyperaceae become established. Long term soil instability, leaching and erosion. peat acidification. |
| Immediate post Kaharoa eruption | *Leptospermum, Agathis*<br>Na, K, Al, Si | Possible volcanically induced disturbance. Local disappearance of *Tupeia, Quintinia*, Epacridaceae. Decline of *Agathis* and *Dacrydium*. Invasion by seral species. Reworking of Kaharoa Tephra layer, soil erosion and leaching commences, leading to inwashing of tephra, soil and dune sediments into the peat. |
| 665-1000 | *Phyllocladus, Agathis*<br>Fe, Ca, C, Si, S | Dominant northern conifer-angiosperm forest. Stable environment. Peat formation and humification processes occurring. High CEC of soils and peat due to abundant elements and low acidity (pH 6-7). |

number of *Pinus* and *Salix* pollen grains indicates expansion of *Salix* around the wetland, and the establishment of local pine plantation forest during the early 1900s, increasing interception and evapotranspiration and stabilising the soil.

## 4.6 Conclusions

Owing to the uncertainty surrounding the commencement of Polynesian activity on Matakana Island, there is insufficient evidence to confirm that vegetation and geochemical changes occurring immediately above the Kaharoa Tephra can be attributed unequivocally to a volcanic cause. This problem has also been found at Papamoa and Kopouatai bogs where possible vegetation responses to Kaharoa Tephra deposition have been obscured by likely human impact (Newnham *et al.*, 1995a; Newnham *et al.*, 1995b). Research on volcanic impacts in the northern hemisphere has also encountered problems in distinguishing volcanic from human impacts above tephra layers in palaeoenvironmental records. Bennett *et al.* (1992) attributed environmental changes following the deposition of thin Icelandic tephra layers in the Shetland Islands, Northern Scotland, to fluctuations in human settlement, animal populations and climate. Similar palaeoenvironmental investigations were undertaken by Charman *et al.* (1995) in northern Scotland, who also found anthropogenic disturbance was responsible for vegetation changes above one of three Icelandic tephra layers studied, therefore obscuring any evidence for possible volcanic impacts. These problems accentuate the importance and validity of focusing research into distal volcanic impacts on palaeoenvironmental records which extend beyond the period of human settlement, both in New Zealand, and northern Britain.

Blurring of the geochemical record has obscured the signal for commencement of extensive local erosion on Matakana Island. Weathering of the tephra layer is partially responsible for increases in Na, K, Al and Si within the peat, but also represents local soil leaching and erosion. Hence the usefulness of geochemical analysis in this case is limited. However, the synchroneity of broad signals for environmental change shown in both records indicates the potential importance of using pollen analysis together with geochemistry, to produce palaeoenvironmental records that can provide firm evidence to support conclusions which would otherwise be speculative when using either technique separately.

In order to examine pollen and geochemical records to detect a clear unambiguous vegetational and environmental response to volcanic impact, it is necessary to examine records which extend beyond the period of Polynesian settlement in New Zealand. The following chapters will analyse pollen and geochemical records from sites in the North Island which pre-date the human era, to determine possible tephra impacts on palaeovegetation communities. Comparison of these records with pollen and geochemical data from Matakana Island may provide important evidence linking environmental and vegetational changes at this site to volcanic impact from tephra fall as opposed to human-induced environmental change.

## Chapter five

## Kaipo Bog, Urewera National Park

### 5.0 Introduction

Kaipo Bog is situated 70 km east-north-east of Taupo, in the Urewera National Park, inland Bay of Plenty (Fig. 5.1). The bog site is 1000 m a.s.l and local vegetation is largely composed of hardy species which can tolerate high winds and rainfall, and cool temperatures (Plate 5.1). Kaipo Bog is therefore different from the other lowland, warm temperate sites studied in chapters 4, 6 and 7. This chapter will investigate the palaeoenvironmental impacts from distal volcanic tephra deposition on the sensitive ecosystem of Kaipo Bog existing under a harsher climatic regime. Long-term environmental change will not be examined at this site as other studies within the area have previously covered this (McGlone, Unpublished; Newnham, *et al.*, 1998; see chapter three); therefore, investigations at Kaipo Bog focus on volcanic impacts. The bog is the most proximal site to the TVZ studied in this thesis, therefore providing the opportunity also to assess the potential maximum impacts from the deposition of tephra.

Samples collected for pollen and geochemical analysis were extracted from an exposed peat profile located in a woody copse near the western margin of the bog (Fig. 5.1). The profile contained numerous tephra layers of variable thickness, nine of which were deposited during the Holocene. These nine tephra layers have been selected for the investigation of volcanic impacts at this site.

### 5.1 The study area

Kaipo Bog is located in the south western segment of Urewera National Park. To the south of Kaipo Bog lies Lake Waikareiti (4 $km^2$) which is north-east of the larger Lake Waikaremoana (56 $km^2$) formed by an earthquake-induced landslide which dammed the Waikaretaheke River ca. 2200 BP (Read *et al.*, 1991). Kaipo Bog lies in a basin of low relief approximately 1000m a.s.l, 400m higher than Lake Waikaremoana. It is unclear how the basin was formed, but it is generally thought to be due to earthquake activity faulting and deforming the underlying soft Miocene rock formations (Rogers, 1984). Erosion and subsequent silting of the basin occurred towards the end of the last glacial, as warmer climatic conditions and increased water movement eroded surrounding unforested slopes of Miocene rock. Silting and increased run-off may have caused waterlogging of the basin, creating conditions that were largely unfavourable

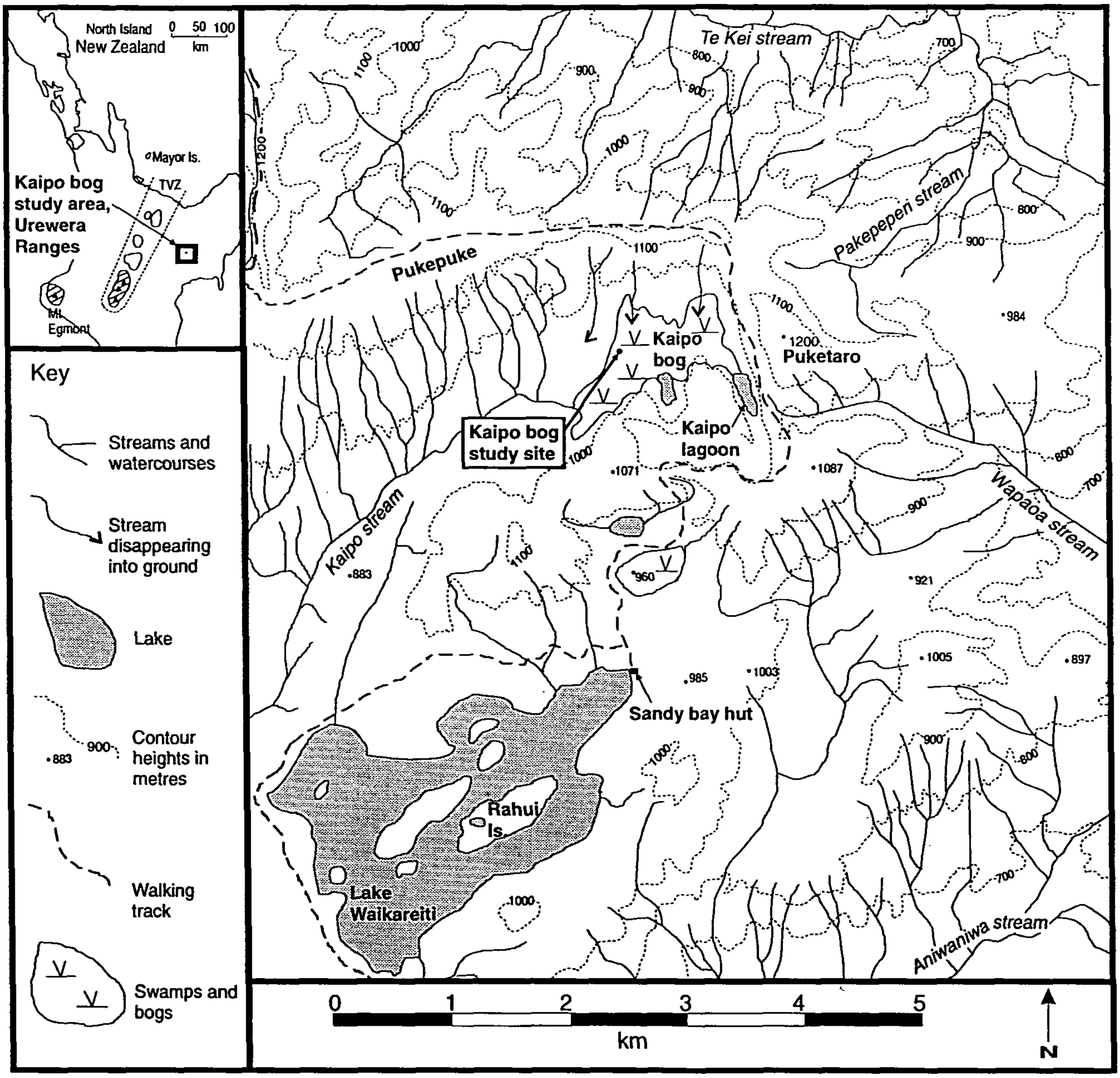



**Figure 5.1** Kaipo Bog study site location, Urewera National Park, North Island, New Zealand. (Source: New Zealand Topographical map 290,1:50 000, sheet W17\18).

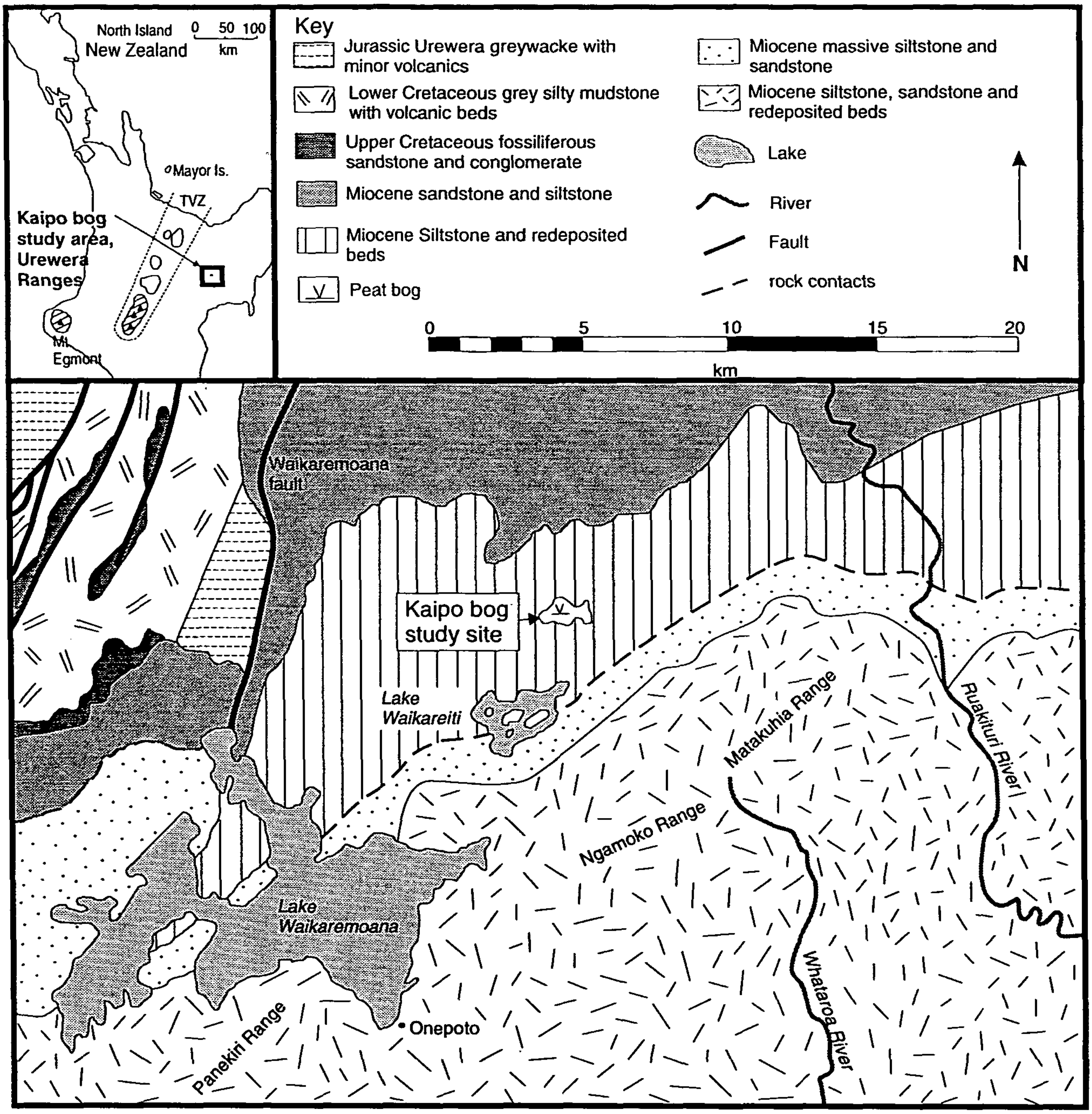



**Figure 5.2** Geology of Kaipo bog and adjacent area (Source: New Zealand Geological Survey map 1:250 000, sheet 8).

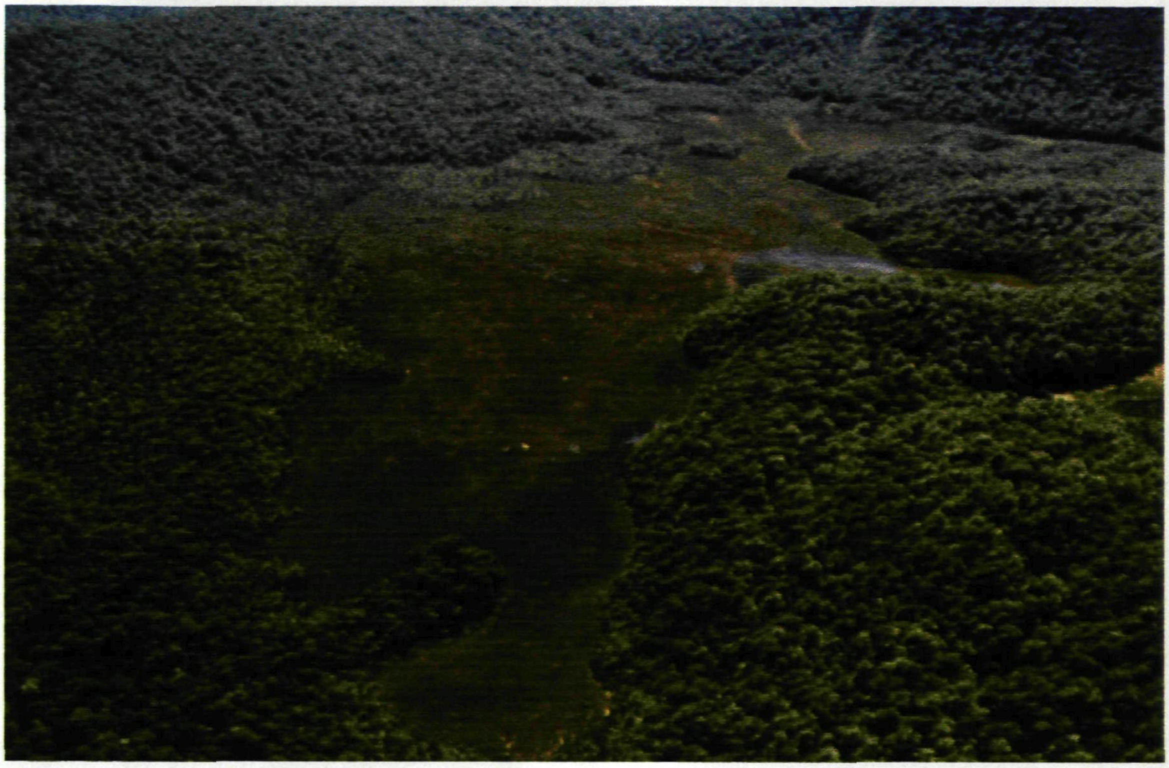


**Plate 5.1a** Kaipo Bog and surrounding *Nothofagus* forest, Urewera National Park. The peat section is located in the area to the bottom left of the photo where the forest has encroached onto the bog. Grey/blue patches show areas of standing water. Photo: Dr Chris Ward.

**Plate 5.1b** View across Kaipo Bog showing local vegetation and surrounding *Nothofagus* forest. Photo: R. M. Newnham

for vegetation establishment (Rogers, 1984). The colonisation of peat-forming flora in this hostile environment then commenced. Inception of the bog is thought to have been around 11 500 years BP, with bog development interrupted by silting following erosion of slopes which were sparsely vegetated and thus unstable at this time (Rogers, 1984). The underlying geology of Kaipo Bog and adjacent area is displayed in Figure 5.2.

Kaipo Bog is described as ombrotrophic, receiving moisture direct from rainfall. However, water also drains from the Pukepuke ridge to the north of the bog (Figure 5.1). Only a small percentage of surface water is derived from this slope, and is largely concentrated in stream channels (Rogers, 1984). Kaipo Bog covers an area of 73 ha, and has a catchment area of approximately 330 ha.

### 5.2 Climate

The climate of the Kaipo Bog/Urewera area is generally described as cool to mild, and wet. Onepoto, located at the southern end of Lake Waikaremoana, and nearby Mautaketake point, are the nearest sites to Kaipo where meteorological data have been recorded (Figure 5.2; Table 5.1). As the altitude of these sites are 500m lower than Kaipo,

**Table 5.1** Climate data for Lake Waikaremoana, from data recorded between 1951-1980 taken from New Zealand Meteorological Service (1990).

| | Mean (yr) | Mean summer (Feb) | Mean winter (Jul) |
|---|---|---|---|
| Maximum Temperature (C) | - | 20.5 | 8.9 |
| Minimum Temperature (C) | - | 11.7 | 3.1 |
| Rain (mm) | 2062 | 251 | 239 |
| Ground frost (days) | 38.2 | - | - |
| Wind speed (knots) | 6.5 | | |

these data represent only approximate climatic conditions for Kaipo Bog. Mean temperatures at Kaipo are therefore likely to be several degrees cooler, with greater wind speeds, higher rainfall and more frequent frosts. Predominant strong winds are from the north and north-west, with an average of 4.3 days of gale force winds which are likely to occur in spring and autumn and are especially damaging to local vegetation (Rogers, 1984).

**5.3 Vegetation history**

Prior to this work the postglacial vegetation history of this area was known only in broad outline, and based on 10 pollen samples from the Kaipo section (Rogers, 1984). Re-afforestation of the Lake Waikaremoana area and adjacent slopes to Kaipo Bog occurred shortly after the last glacial, around 13 000 to 14 000 years ago. Early post-glacial forest was largely composed of sub-alpine scrubland, dominated by *Phyllocladus alpinus* and *Halocarpus* shrubs, together with Asteraceae and grasses (Rogers, 1984, McGlone, unpubl.). Podocarp forest developed at lower altitudes, dominated by *Prumnopitys taxifolia* and *Podocarpus totara*, with *Dacrydium cupressinum* and *Libocedrus* and some angiosperms. By 9000 years BP *Dacrydium* became dominant in lower altitude forest, while *Halocarpus*, *Podocarpus hallii*, *Pseudopanax* spp. and *Dracophyllum* spp. increased in abundance. *Nothofagus* forest developed between 8800 and 3200 BP initially dominated *by N. fusca*, with *N. menziesii* and *Phyllocladus* spp becoming increasingly common.

The mire vegetation record is unclear as considerable fluctuations in the water table were possible, and so the bog was unstable. Initially the mire was dominated by sedge, which was then replaced by *Empodisma*, *Gleichenia* and *Sphagnum* spp. A short phase of sedge domination occurred before returning to former co-dominance of *Gleichenia* and *Empodisma*, together with *Hebe odora*, *Dracophyllum* spp, *Phyllocladus alpinus* and *N. menziesii* along the fringes of the mire.

**5.4 Present vegetation (Plate 5.1)**

Forest surrounding Kaipo Bog at ca. 1000 m a.s.l. consists of dominant *Nothofagus menziesii* and *N. fusca.* Kaipo Bog consists of three broad vegetation zones, a scrub zone around the margins of the bog, a herbaceous zone and an area of water colonised by rushes. The scrub zone is colonised by woody plants 1-3 m high, dominated largely by *Halocarpus* and *Phyllocladus asplenifolius var alpinus*, together with *Dracophyllum* spp., *Coprosma parviflora* and *Myrsine divaricata.* Plants growing in the herbaceous zone include *Empodisma minor* forming hummocks across the bog, separated by water channels. *Gleichenia* is also common on the mire, with Sphagnum spp, *Oreobolus pectinus*, several species of moss, including *Dicranoloma billardierii* and *Campylopus cristatum*. The lichen *Cladia retipora* is also present. Bordering the water is the sedge *Schoenus brevifolius* (Green, unpubl.).

At lower altitudes (<900 m) beech trees are less abundant, and are limited to scattered small groves. Lowland-montane taxa become more common within the forest between lakes Waikareiti and Waikaremoana (ca. 900 - 500 m a.s.l.), with podocarp-hardwood forest dominant around Lake Waikaremoana. These forests are principally composed of *Prumnopitys taxifolia, Podocarpus totara, Dacrydium cupressinum* and *Libocedrus*, together with a variety of hardwood species and tree ferns (Rogers, 1984).

**5.5 Stratigraphy and chronology of Kaipo peat profile**

The stratigraphy of the peat profile is displayed in detail in Figure 5.3 and Plate 5.2. The profile is located at the section of a waterfall, where fluvial action from streams draining the bog and adjacent area has eroded the peat, exposing a section 4.4 m high. The tephra layers preserved in the Kaipo Bog profile range in thickness from 2 cm (Kaharoa Tephra, 665 years BP) to 28 cm (Waimihia Tephra, 3280 years BP) and their specific chemistry is displayed in Table 5.2. Evidence for dissemination of tephra shards is displayed in the pollen and geochemical records. As these macroscopic tephra layers indicate primary airfall tephra, dissemination of glass shards above and below the layers is probably the result of post-depositional movement and accumulation of shards through weathering of the tephra layer and inwash from the surface of catchment soils.

Estimated sedimentation rates are variable, ranging from 1.68 mm/yr (above Konini Tephra) to 0.023 mm/yr (above Tuhua Tephra) with a mean rate of 0.297 mm/yr for the entire profile. A record of the changes in estimated sedimentation rates in the top 2 m of the profile is displayed in Table 5.3. Approximate sample ages have also been determined and are presented alongside fine resolution pollen diagrams.

Overall, the estimated sedimentation rates for this profile are slow, with thin layers of peat between the tephra layers perhaps indicating that peat formation was interrupted or diminished following ash deposition, with drainage and bog hydrology possibly affected by tephra fall. Slow sedimentation rates make it difficult to determine tephra impacts on the local environment over a short-term fine resolution timescale above all nine tephra layers. However, sedimentation rates were more rapid following

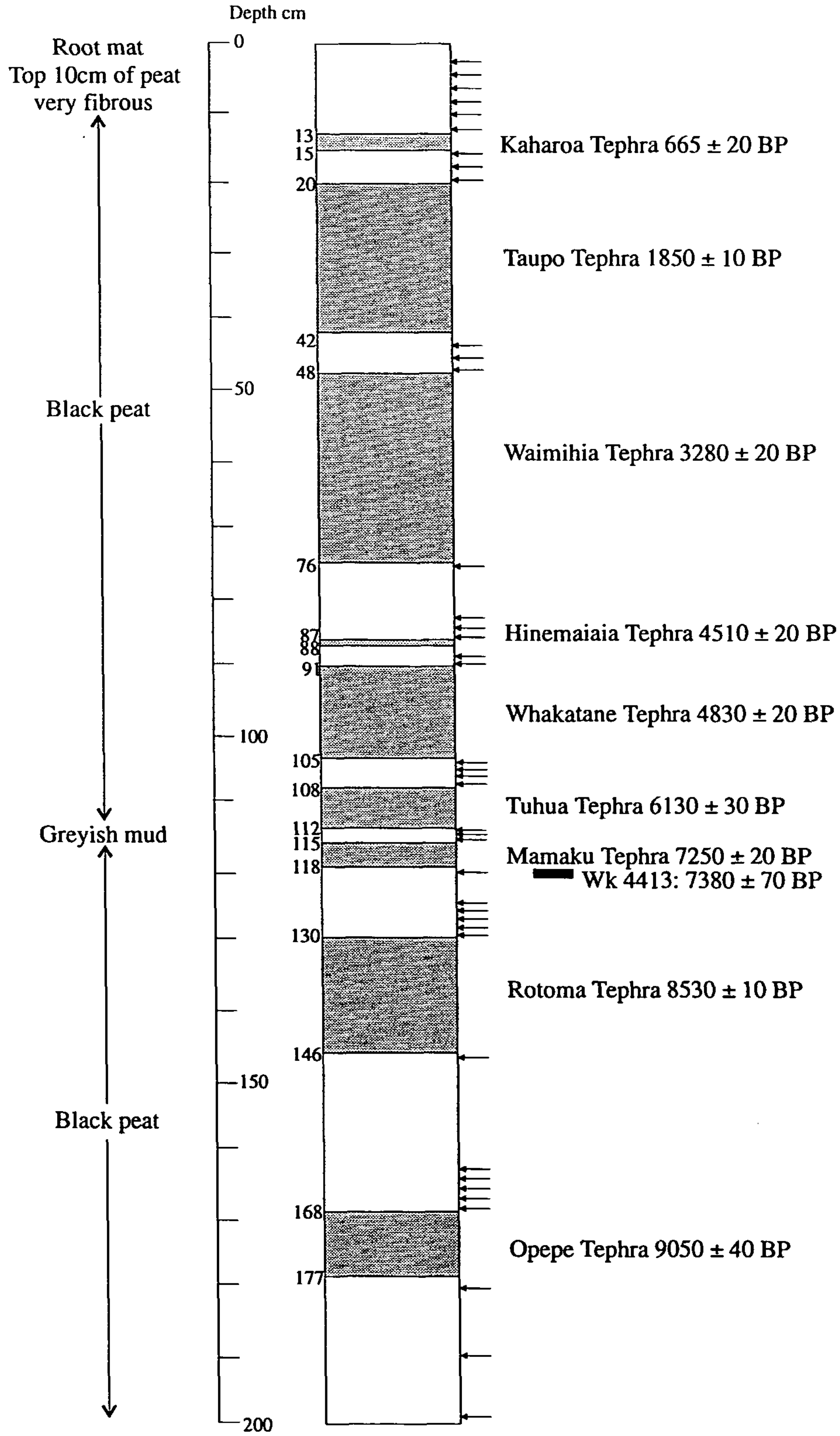



**Figure 5.3** Stratigraphy and sampling of Kaipo peat profile

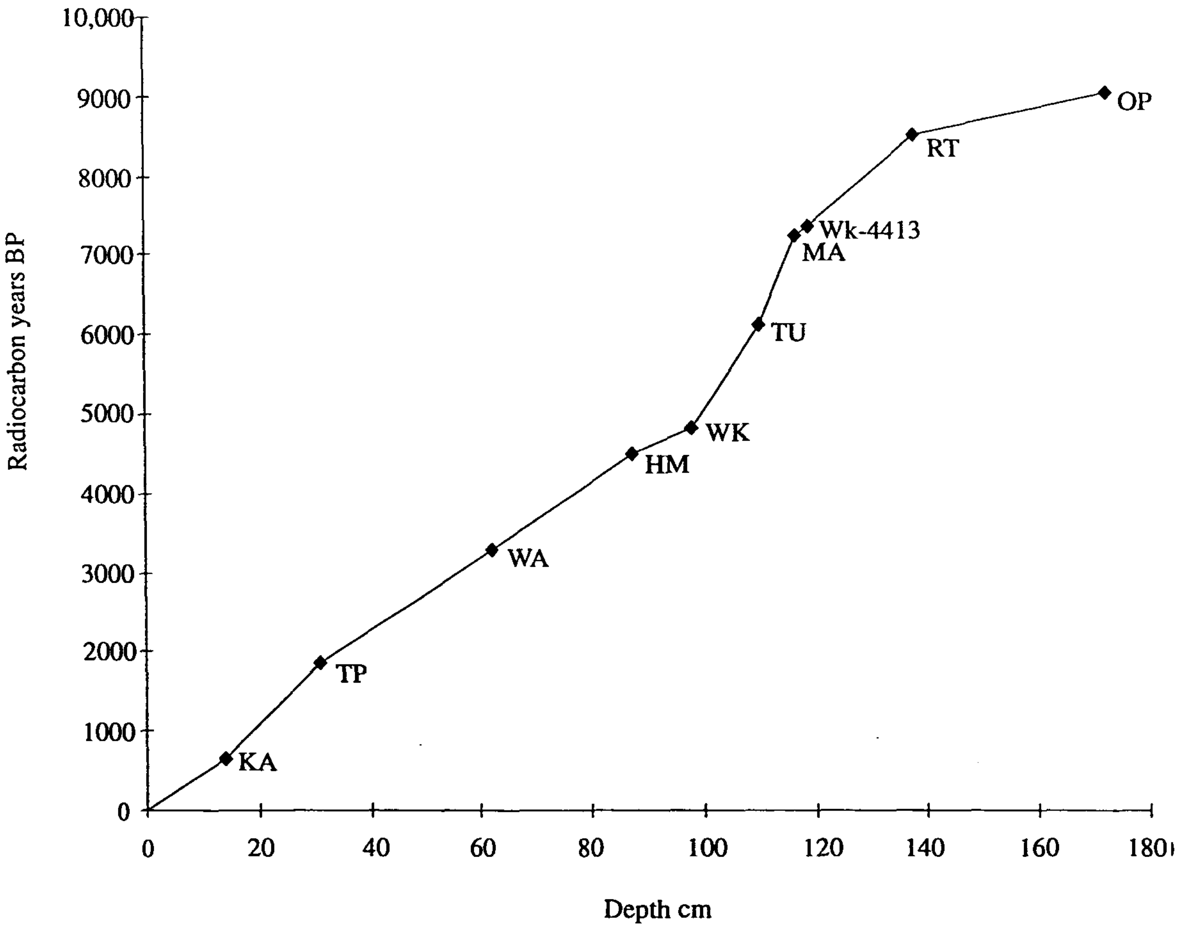



**Figure 5.4** Age depth curve for the Kaipo bog profile. Tephra ages are taken from Lowe and Hogg (1986) and Froggatt and Lowe (1990). Explanation of character codes for tephra layers are given in Figure 7.3. Wk-4413 denotes radiocarbon dated peat extracted immediately beneath the Mamaku Tephra.


**Plate 5.2** Kaipo peat profile with tephra layers labelled.

**Table 5.2** Stratigraphy, chronology and geochemistry of tephra layers preserved in the Kaipo peat profile. Tephra ages and geochemistry taken from Lowe and Hogg (1986), Lowe (1986), Lowe (1988), Froggatt and Lowe (1990), Lowe and Hogg (1992), Stokes *et al.* (1992) and Giles *et al.* (in press).

| Tephra and age (yrs BP) | Source volcano | Distance from source | Key chemical constituents[1] | Depth/thickness of tephra layer | Depth above tephra layer sampling commenced | Fine resolution sample timescale |
|---|---|---|---|---|---|---|
| Opepe 9050 ± 40 | Taupo | 100 km | Si (76.51) Na (3.86) Fe (1.73) Mg (0.2) Al (13.01) K (3.86) Ca (1.41) Ti (0.18) | 168 - 177 cm | | 24 yrs |
| Rotoma 8530 ± 10 | Okataina | 90 km | Si (78.63) Na (3.76) Fe (0.87) Mg (0.12) Al (12.33) K (3.37) Ca (0.71) Ti (0.1) | 130 - 146 cm | immediately above tephra layer | 106 yrs |
| Mamaku 7250 ± 20 | Okataina | 90 km | Si (78.87) Na (3.8) Fe (0.87) Ti (0.12) Al (12.05) K (3.38) Ca (0.69) Mg (0.1) | 115 - 118 cm | | 373 yrs |
| Tuhua 6130 ± 30 | Tuhua (Mayor Is.) | 200 km | Si (75.4) Fe (5.65) K (3.94) Ca (0.24) Al (9.43) Na (4.86) Ti (0.29) Mg (0.02) | 108 - 112 cm | | 325 yrs |
| Whakatane 4830 ± 20 | Okataina | 90 km | Si (78.41) Na (3.77) Fe (0.78) Ti (0.12) Al (12.41) K (3.62) Ca (0.67) Mg (0.1) | 91 - 105 cm | | 106 yrs |
| Hinemaiaia 4510 ± 20 | Taupo | 100 km | Si (76.9) Na (3.75) Fe (1.6) Ti (0.19) Al (12.99) K (2.99) Ca (1.3) Mg (0.17) | 87 - 88 cm | immediately above tephra layer | 112 yrs |
| Waimihia 3280 ± 20 | Taupo | 100 km | Si (74.88) Na (4.1) Fe (1.67) Ti (0.19) Al (12.68) K (2.85) Ca (1.25) Mg (0.17) | 48 - 76 cm | | 238 yrs |
| Taupo 1850 ± 10 | Taupo | 100 km | Si (76.43) Na (3.97) Fe (1.81) Ti (0.23) Al (13.05) K (2.84) Ca (1.31) Mg (0.22) | 20 - 42 cm | | 237 yrs |
| Kaharoa 665 ± 20 | Okataina | 90 km | Si (77.51) K (4.12) Fe (0.88) Ti (0.1) Al (12.81) Na (3.8) Ca (0.53) Mg (0.09) | 13 - 15 cm | | 51 years |

[1] Numbers in parentheses are mean percentages

the Opepe and Kaharoa eruptions hence investigation of vegetation impacts over a more detailed timescale was achievable above these two tephra layers.

**Table 5.3** Estimated sedimentation rates between tephra layers preserved in the profile

| Depth interval between tephra layers (cm) | Radiocarbon dates of tephra layers (years BP) | Time interval between tephra layers (years BP) | Estimated sedimentation rate (mm/yr) |
|---|---|---|---|
| 0-13 | 0 to 665 | 665 | 0.210 |
| 15-20 | 665 to 1850 ± 10 | 1185 | 0.042 |
| 42-48 | 1850 ± 10 to 3280 ± 20 | 1430 | 0.042 |
| 76-87 | 3280 ± 20 to 4510 ± 20 | 1230 | 0.089 |
| 88-91 | 4510 ± 20 to 4830 ± 20 | 320 | 0.093 |
| 105-108 | 4830 ± 20 to 6130 ± 30 | 1300 | 0.023 |
| 112-115 | 6130 ± 30 to 7250 ± 20 | 1120 | 0.026 |
| 118-130 | 7250 ± 20 to 8530 ± 10 | 1280 | 0.094 |
| 146-168 | 8530 ± 10 to 9050 ± 40 | 520 | 0.420 |

## 5.6 Methodology

The top 2 m of the profile contain the nine Holocene tephras analysed in this study. Holocene tephra layers were chosen for analysis in order to compare tephra impacts observed at this site with those recorded at the three other study sites investigated in this thesis, where many of the same Holocene tephra layers were preserved and analysed.

Surface debris was removed using a spade so a 'clean' section was visible from which samples for pollen and geochemical analysis were extracted. Conditions in the field were very difficult and extremely wet owing to continual fluvial activity around the sampling site. Owing to these problems, the most effective sampling method involved pressing 1cm diameter plastic sample vials into the peat above the tephra layers, collecting contiguous samples at 1 cm intervals where possible of approximately 2 $cm^3$ of sediment inside the vial which was then secured with a screw-top lid. The 1 cm sampling resolution was the highest

resolution achievable owing to the nature of the sediment (largely fibrous peat dissected by tree roots). Samples were taken above all nine tephra layers as close as possible to the tephra layer, continuing over a depth of 6 cm above the tephra layers where sufficient sediment was available. Samples were also taken immediately below each tephra layer for analysis to represent pollen and geochemical assemblages prior to the eruptions.

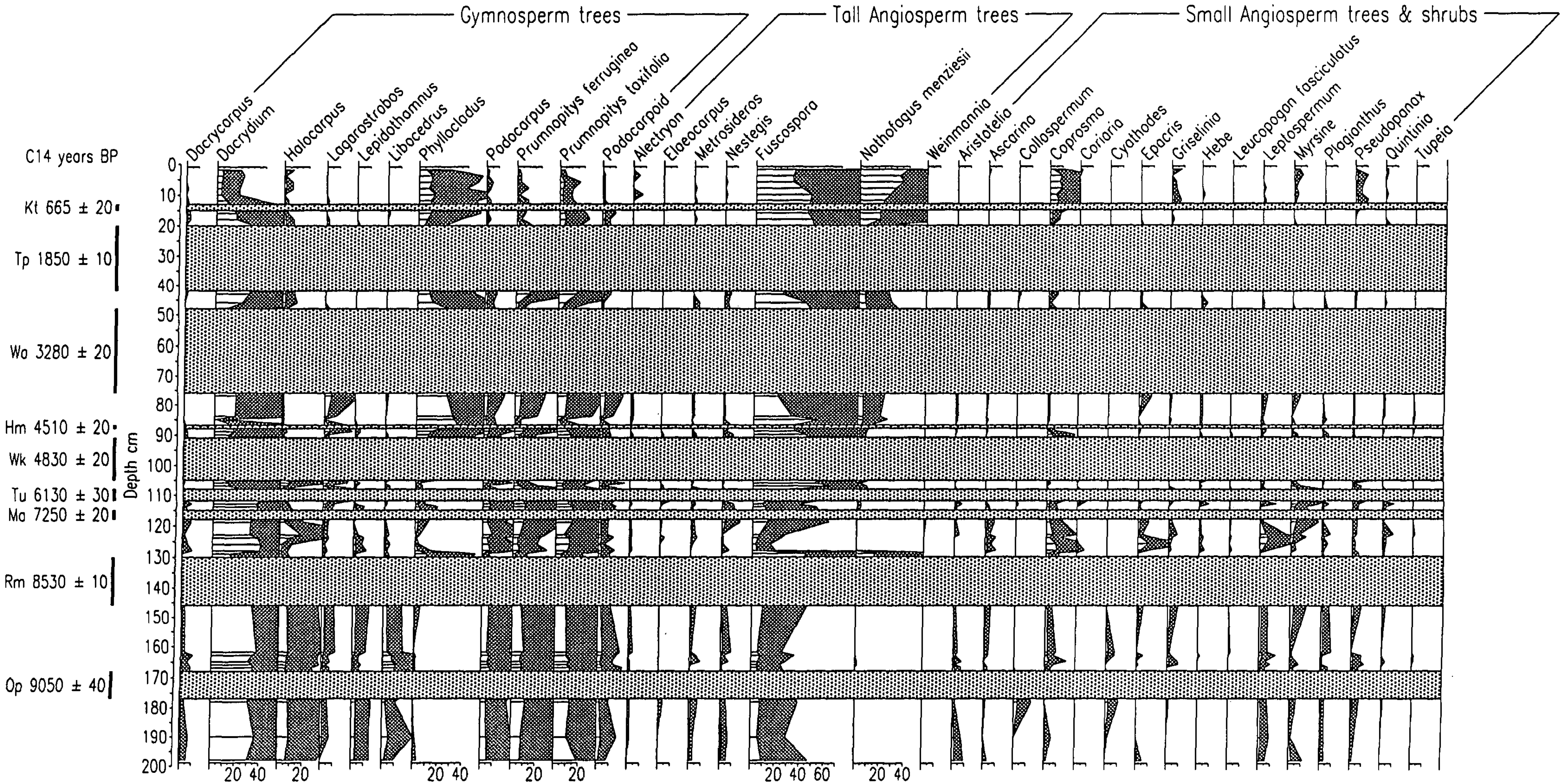
The total dryland pollen sum included taxa from Gymnosperm trees, Angiosperm trees and shrubs, and herbs. *Leptospermum* was included in the pollen sum as it was not abundant at this site.

DECORANA was carried out on all fine resolution samples. Sample scores were displayed stratigraphically against pollen changes in Figure 5.5, and in the form of a biplot in

Figure 5.21 as a relationship was found between samples occurring immediately above tephra layers. Biplots of taxa scores immediately above individual tephra layers were included where a significant relationship between vegetation responding to tephra impact was shown.

### 5.7 Results from pollen, geochemical and statistical analyses

Descriptions of palynological and geochemical changes following the nine Holocene volcanic eruptions investigated are presented in Tables 5.4 to 5.7, and displayed in Figures 5.5 and 5.6.



Gymnosperm trees
Tall Angiosperm trees
Small Angiosperm trees & shrubs
C14 years BP
Kt 665 ± 20
Tp 1850 ± 10
Wa 3280 ± 20
Hm 4510 ± 20
Wk 4830 ± 20
Tu 6130 ± 30
Ma 7250 ± 20
Rm 8530 ± 10
Op 9050 ± 40
Depth cm
Dacrycarpus
Dacrydium
Halocarpus
Lagarostrobos
Lepidothamnus
Libocedrus
Phyllocladus
Podocarpus
Prumnopitys ferruginea
Prumnopitys taxifolia
Podocarpoid
Alectryon
Elaeocarpus
Metrosideros
Nestegis
Fuscospora
Nothofagus menziesii
Weinmannia
Aristotelia
Ascarina
Collospermum
Coprosma
Coriaria
Cyathodes
Epacris
Griselinia
Hebe
Leucopogon fasciculatus
Leptospermum
Myrsine
Plagianthus
Pseudopanax
Quintinia
Tupeia
0
10
20
30
40
50
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80
90
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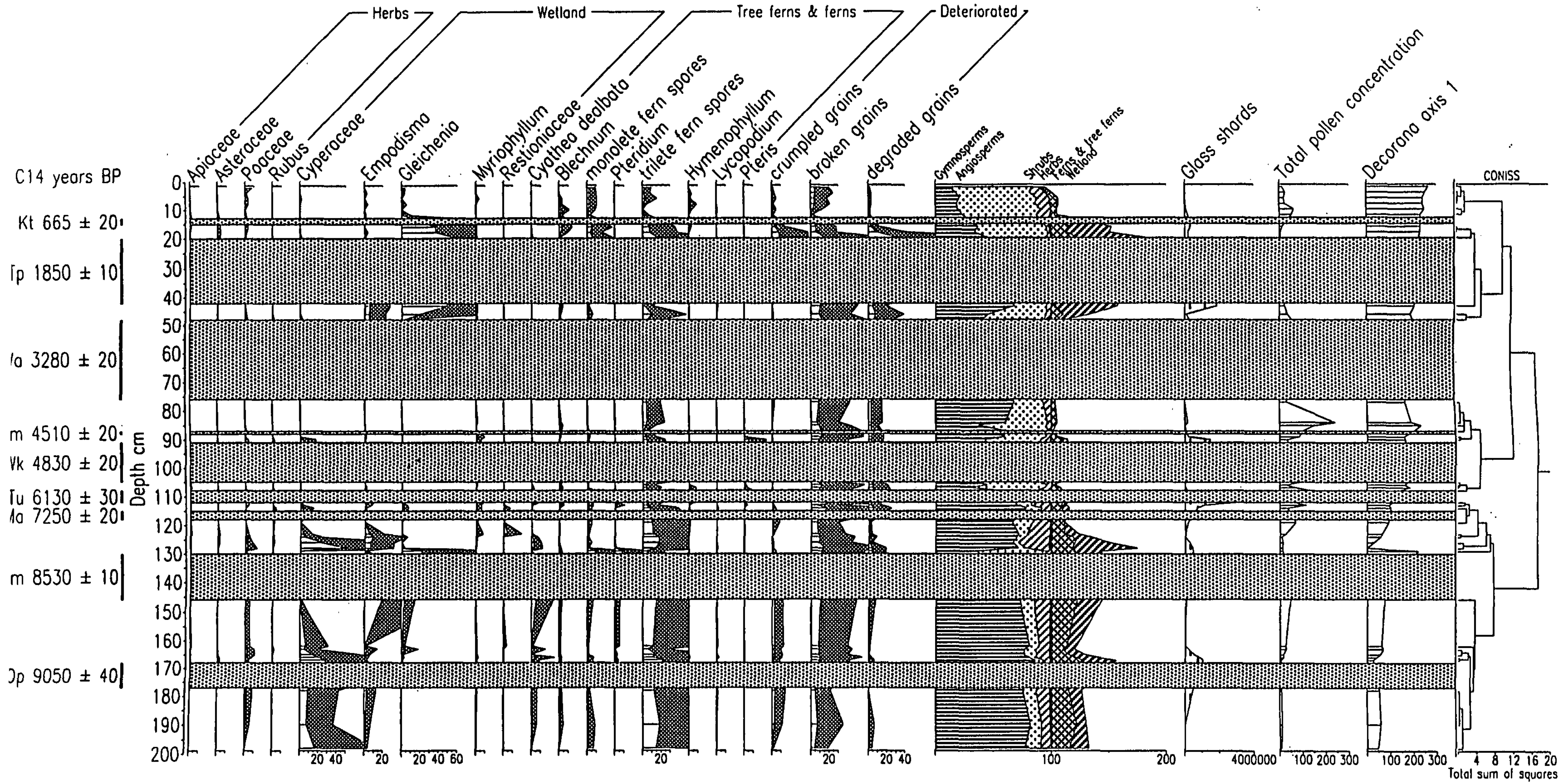



**Figure 5.5** Pollen diagram displaying changes in taxa for all samples analysed in the Kaipo bog peat profile. Charcoal and Tephra shards are expressed as number of fragments per $cm^3$ sediment analysed. Stippled curves represent x 5 magnification of pollen percentages.

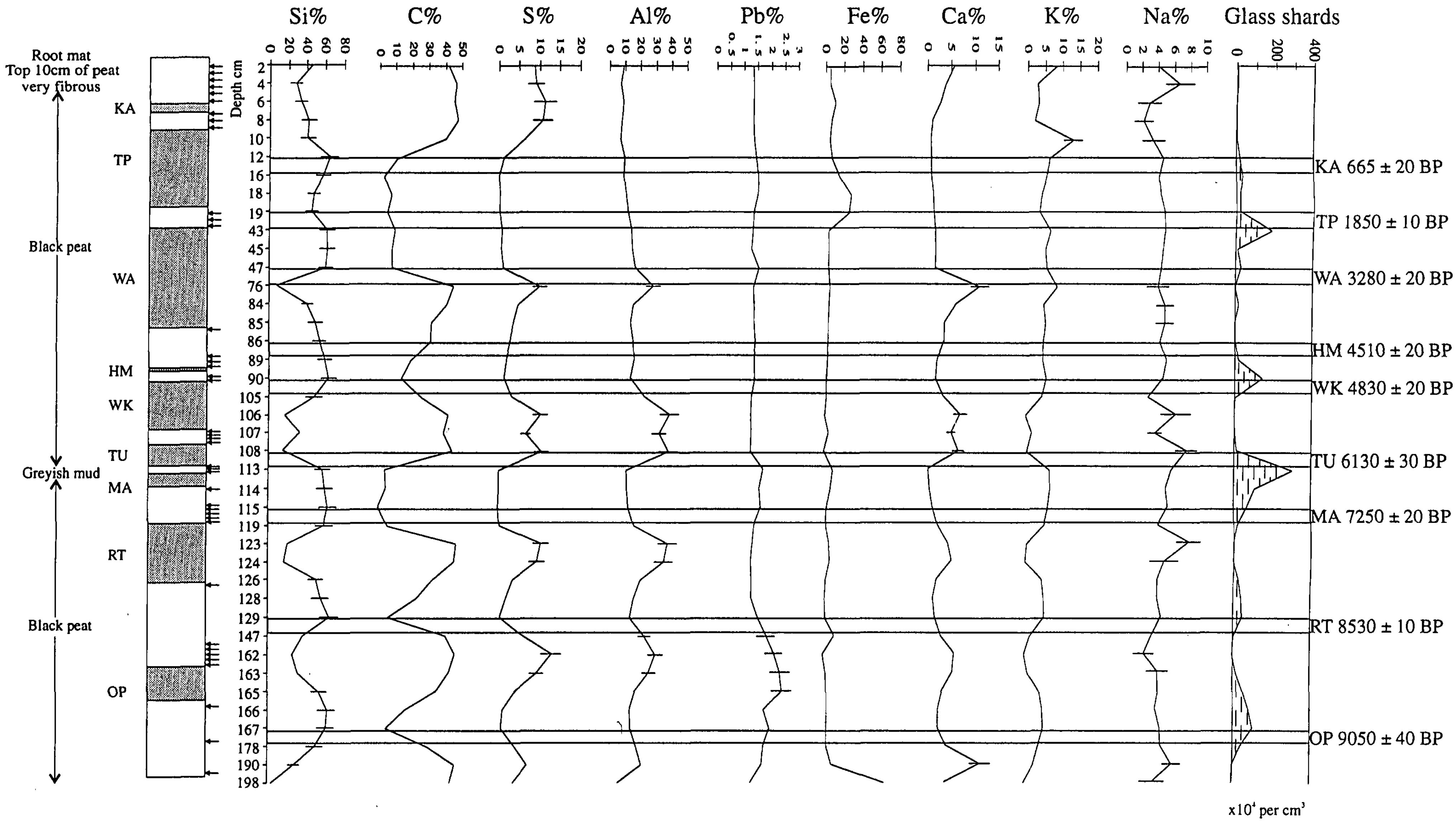



**Figure 5.6** Geochemical changes above and below nine tephra layers analysed in the Kaipo bog profile. Tephra ages taken from Lowe and Hogg (1986) and Froggatt and Lowe (1990). Short horizontal bars are error bars calculated to ± 2 standard deviations.

**Table 5.4** Description of changes in peat geochemistry following early- to mid-Holocene volcanic eruptions.

| **Tephra layer age and depth** | **Geochemical changes prior to tephra fall** | **Geochemical changes immediately following tephra fall** |
|---|---|---|
| Opepe 9050<br>168-177 cm | Geochemical assemblages are highly variable, exhibiting unstable equilibrium. Si and C display opposite trends, with Si rising from 5-40%, and C falling from 45-25%. S fluctuates between 5-10% and Al from 10-20%. Fe declines from 70-5%. Ca peaks to 12% at 190cm, falling to 4% at 178 cm. K rises to 5% below the tephra layer, Na fluctuates between 4-6%. | Si remains high at 60%, declining to 20% at 162cm. C falls to 5% at 167cm, increasing to 50% at 162cm. S falls to 2% above the tephra, increasing to 15%. Al rises from 10 to 27%. Ca rises to 5% at 162 cm. K peaks to 7% above the tephra, while Na falls from 7% to 3% at 162 cm. |
| Rotoma 8530 BP<br>130-146 cm | Si and C are present at 35% and 37% respectively below the tephra layer. S falls to 6%, and Al to 20%. Fe rises to 17%. Ca, K and Na exhibit low levels of <4%. | Si peaks to 60%, as C falls to 4% above the tephra. Si then declines to 18% as C rises to 47% at 125cm. S and Al increase to 11% and 40% respectively at 123 cm. Fe and Ca fluctuate between 2-6%. K peaks to 7% above the tephra. Na rises to 8% at 123 cm. |
| Mamaku 7250 BP<br>115-118 cm | Si levels are high at 60%, while C declines to 5%. Al is present at 15%, and K at 5%. Na, Ca, Fe and S are present at low levels below 4%. | **Geochemical changes above Mamaku and below Tuhua**<br>Si increases to 65% above the tephra, falling to 58%. C falls to zero, increasing again to 4%. Al falls to 10%. Fe rises from 2-5%. K and Na increase slightly to 7% and 6% respectively. |
| Tuhua 6130 BP<br>108-112 cm | | Si declines to 18% as C increases to 45% above the tephra. S and Al rise to 12% and 42% respectively. Ca rises to 7%, and Na peaks to 8% at 108 cm, falling to 6% at 106cm. K and Fe are low at 3%. |

**Table 5.5 Description of pollen changes following early to mid Holocene volcanic eruptions**

| Tephra layer, age and depth | Pollen changes prior to tephra fall | Pollen changes immediately following tephra fall |
|---|---|---|
| Opepe 9050 BP 168-177 cm | *Dacrydium* pollen is dominant, reaching 30-35%, together with abundant *Prumnopitys taxifolia* (15-20%) and *P. ferruginea* which increases to 12% at 178cm. *Halocarpus* and *Fuscospora* pollen levels fluctuate between 5-8% and 5-10% respectively. Cyperaceae pollen declines slightly from 15 to 10%. Trilete ferns spores fluctuate between 15-20%. Glass shards increase to 500,000 at 178 cm. Total pollen concentrations remain consistent between 80,000 to 100,000. | *Dacrydium* and *Prumnopitys taxifolia* pollen levels remain at pre-eruption levels. *Halocarpus* and *Fuscospora* decline to 4% at 167cm. *Prumnopitys ferruginea* declines to 7%. Major increases occur in *Libocedrus* and *Podocarpus*, reaching 10% and 8% respectively at 167cm. Cyperaceae pollen and trilete fern spores increase dramatically to 25% and 20% respectively, and damaged grains rise to 10% above the tephra layer. Glass shards peak to 1,000,000. Total pollen concentrations increase to 300,000 at 164 cm. |
| Rotoma 8530 BP 130-146 cm | *Dacrydium* remains dominant at 35%. *Halocarpus*, *Prumnopitys ferruginea* and *P. taxifolia* are less abundant at 5%, 6% and 10% respectively. *Nothofagus* and *Podocarpus* are present at 10% and 5% respectively. *Empodisma* pollen peaks to 15%, and trilete spores rise to 13%. Broken grains reach 10% below the tephra, with glass shards present at 50,000, and total pollen levels peaking to 440,000. | *Dacrydium* pollen falls to 15%. *Halocarpus*, *Podocarpus*, *Prumnopitys ferruginea* and *P. taxifolia* all decline to <2%. *Empodisma* and trilete spores decline to 1% and 3% respectively at 129 cm. Increases are seen in *Phyllocladus* pollen, rising to 8% at 129cm, with *Fuscospora* and *N. menziesii* rising to 43% and 15% respectively. *Coprosma* rises to 10% at 128cm. Cyperaceae peaks to 50% at 128cm, and *Gleichenia* rises to 20% at 129cm. Monolete fern spores and *Pteridium* increase to 7% and broken grains to 20%. Glass shards are abundant at 500,000. Total pollen declines to 150,000. |
| Mamaku 7250 BP 115-118 cm | *Dacrydium* remains dominant at 32%, together with *Prumnopitys ferruginea*, reaching 7%, with *P. taxifolia* and *Fuscospora* both reaching 13%. Trilete ferns spores are present at 8%, and broken grains at 5%. Glass shards rise to 10,000, and total pollen concentrations reach 60,000. | **Pollen changes above Mamaku and below Tuhua Tephras** *Dacrydium* pollen increases to 36% immediately above the tephra layer. *Podocarpus* and *Prumnopitys ferruginea* increase to 6% and 10% respectively, falling to pre-eruption levels at 112cm. Broken and degraded grains rise to 17% and 5% respectively above the tephra layer, with broken grains increasing further to 25%. A gradual decline occurs in *Prumnopitys taxifolia*, falling from 13% at 114 cm to 8% at 112 cm. Trilete ferns spores decline to 5%. Glass shards increase from 70,000 at 114 cm to 300,000 at 112 cm. Total pollen concentrations reach 120,000 at 113 cm. |
| Tuhua 6130 BP 108-112 cm | | *Dacrydium* declines immediately to 20%, falling to 10% at 105cm. *Podocarpus* declines to 1%. *Prumnopitys ferruginea* and *P. taxifolia* gradually decline to 2% and 5% respectively between 108 and 105 cm depth. *Myrsine* declines from 5% to <1%. A gradual increase is seen in *Halocarpus*, reaching 10% at 106cm. *Fuscospora* increases dramatically, peaking to 65% at 107cm. Broken and degraded grains reach 13% and 5% respectively. Glass shards fall to 10,000. Total pollen concentrations peak at 108cm to 120,000, falling to 25,000 at 106 cm. |

**Table 5.6** Description of pollen changes following mid to late Holocene volcanic eruptions.

| Tephra layer, age and depth | Pollen changes prior to tephra fall | Pollen changes immediately following tephra fall |
|---|---|---|
| Whakatane 4830 BP 91-105 cm | *Fuscospora* pollen dominates, reaching 55%. *Dacrydium* and *Prumnopitys taxifolia* pollen levels reach 8% and 5% respectively. *Halocarpus*, *Lagarostrobos*, *Phyllocladus* and *Podocarpus* pollen levels are present at 3-4%. Trilete fern spores reach 5%. | *Fuscospora* pollen declines to 45%, together with *Halocarpus* and *Lagarostrobos* to <1%. *Dacrydium* rises to 15-20%, together with *Phyllocladus* and *Prumnopitys taxifolia*, both increasing to 10%. *P. ferruginea* increases gradually to 10% at 89cm. Glass shards peak to 150,000 at 90cm and total pollen concentrations increase to 80,000 at 89 cm. |
| Hinemaiaia 4510 BP 87-88 cm | *Fuscospora* pollen is dominant at 30%. *Phyllocladus* and *Prumnopitys* spp. reach 10% and *Dacrydium* is present at 15%. Broken grains rise to 12%. Pollen concentrations increase to 80,000. | *Phyllocladus* pollen increases to 30%. *Dacrydium* declines to 12% and *Prumnopitys* to <2%. Pollen concentrations rise to 100,000. |
| Waimihia 3280 BP 48-76 cm | *Phyllocladus* pollen is dominant, reaching 25%, together with *Dacrydium* and *Fuscospora* both reaching 20%. *Prumnopitys taxifolia* pollen rises to 8% and *Lagarostrobos*, *Prumnopitys ferruginea* and *Nothofagus menziesii* all reach 5%. | *Dacrydium* declines to 10%, together with *Lagarostrobos*, *Podocarpus Prumnopitys ferruginea* and *P. taxifolia*. *Phyllocladus* pollen declines to 13% at 46cm. *Fuscospora* increases to 40%. Increases also occur in *N. menziesii* to 7%, with a gradual increase in *Gleichenia* to 40% at 43cm. Glass shards increase from 50,000 to 1,750,000 at 43cm. |
| Taupo 1850 BP 20-42 cm | *Dacrydium* pollen dominates, reaching 30%. *Fuscospora* falls to 20%. *Phyllocladus*, *Prumnopitys ferruginea* and *P. taxifolia* are abundant at 10%, 12% and 15% respectively. Wetland vegetation increases with *Empodisma* present at 5% and *Gleichenia* rising to 45%. Glass shards peak to 180,000 at 43 cm. | *Dacrydium* exhibits a delayed decline to 15% at 18cm. *Phyllocladus*, *Prumnopitys ferruginea* and *P. taxifolia* all decline to <4% and *Empodisma* to <1%. *Fuscospora* increases to 48%, with a delayed increase in *N. menziesii* to 15% at 18cm. *Gleichenia* increases to 60% and large increases are seen in fern spores to between 5-15%. Deteriorated pollen grains increase, with degraded grains peaking to 30%. Total pollen concentrations are low at 10,000. |
| Kaharoa 665 BP 13-15 cm | *Fuscospora* is common at 40%, with *N. menziesii* and *Dacrydium* at 15%. *Phyllocladus* is present at 8%. *Gleichenia* reaches 40%, with monolete and trilete ferns spores reaching 5-6%. Glass shards peak to 350,000, and total pollen levels increase to 100,000. | *Dacrydium* declines to 6%, together with declines in *Gleichenia* and fern spores to <2%. *Nothofagus menziesii* and *Coprosma* increase to 20% and 5% respectively. Minor increases are seen in *Griselinia*, *Myrsine* and *Pseudopanax*. Total pollen concentrations increase to 500,000. |

**Table 5.7** Geochemical changes following mid to late Holocene tephra deposition.

| Tephra layer, age and depth | Geochemical changes prior to tephra fall | Geochemical changes following tephra fall |
|---|---|---|
| Whakatane 4830<br>91-105 cm | Si rises to 45%, with C and Al abundant at 20% and 15% respectively. Fe is consistent at 5%. Na, K, Ca and S are present at low levels <4%. | Si increases to 60% as C and Al levels fall to 12% and 8% respectively. Na and K increase slightly to 5% and 6% respectively. Ca and S fall to <2%. |
| Waimihia 3280<br>48-76 cm | Si levels fall to 10% as C and S increase to 45% and 10% respectively, and Al peaks to 23%. Ca and K also peak to 10% and 7% respectively. Na and Fe reach 5%. | **Geochemical changes above Waimihia and below Taupo Tephra.**<br>Si peaks to 60% as C, S and Al fall to 7%, 1% and 11% respectively. Ca falls rapidly to 1.5%, and K declines slightly to 5%. These levels are maintained to immediately below the Taupo Tephra layer. |
| Taupo 1850 BP<br>20-42 cm | | Si is abundant at 43%. Levels of C and Al fall slightly to 6% and 10% respectively. Fe peaks to 22%. Na, K and Ca remain below 4%. |
| Kaharoa 665 BP<br>13-15 cm | Si rises to 57%. C and Al remain low at 5% and 10% respectively. Fe falls to 13%, and K rises slightly to 5%. Na, Ca and S remain below 4%. | Si increases to 60%, together with a slight increase in C to 10%. Al remains consistent at 10%. Fe falls to 5%. K remains at 5% and Na, Ca and S levels are low at <4%. |

## 5.8 Early to mid Holocene volcanic impacts

Sedimentation rates were comparatively rapid following the Opepe eruption and each 1 cm sample above the tephra layer represented approximately 24 years of peat growth (Fig. 5.7). The deposition of the 9 cm Opepe Tephra layer appeared to have affected the adjacent forest and local mire vegetation. The slight decline in *Halocarpus* suggests possible sensitivity to tephra accumulation and associated toxic chemical leaching. The increased availability of drier sites encouraged the invasion of seral vegetation such as *Coprosma*, Cyperaceae, *Pteridium* and ferns. *Pteridium* in particular grows best on well drained soils, and can tolerate acidic conditions. Increases in *Dacrycarpus*, *Libocedrus*, *Podocarpus*, *Griselinia*, *Cyathea dealbata* and *C. smithii* were also recorded above the Opepe Tephra. *Dacrycarpus*, *Griselinia* and *Cyathea* species prefer warmer, moist conditions than those experienced at Kaipo Bog, and so pollen from these taxa are likely to have derived from lower altitude forests around Lake Waikaremoana. These increases may reflect expansion of these taxa at lower altitudes following volcanic induced forest disturbance.

Increases in seral and forest vegetation may have occurred in response to forest disturbance following the Opepe eruption. Significant declines in the lower altitude forest species *Prumnopitys ferruginea*, and a reduction in the number of local *Halocarpus* and *Nothofagus fusca* trees and shrubs, together with slight declines in *Collospermum*,

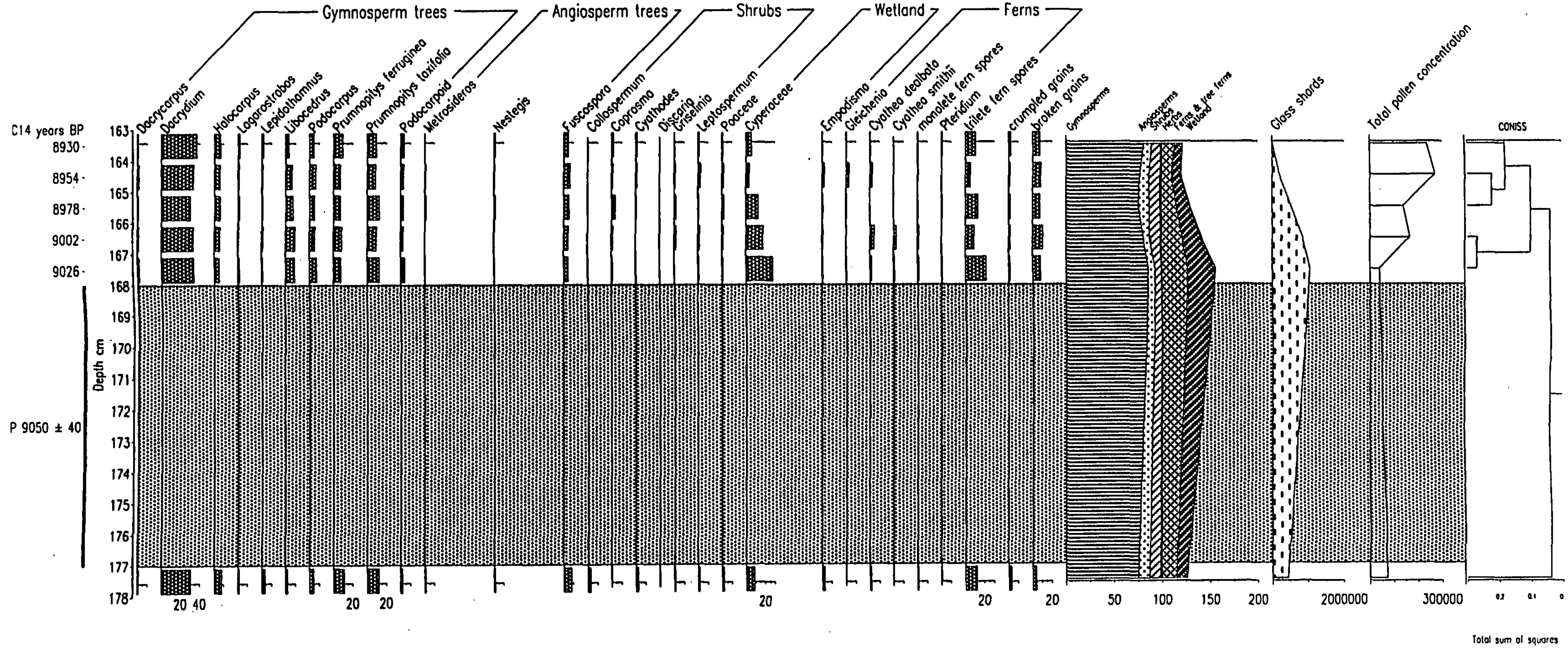



**Figure 5.7** Fine resolution pollen diagram displaying changes in main taxa above and below Opepe Tephra. Glass shards are expressed as number of fragments per cm$^3$ sediment analysed.

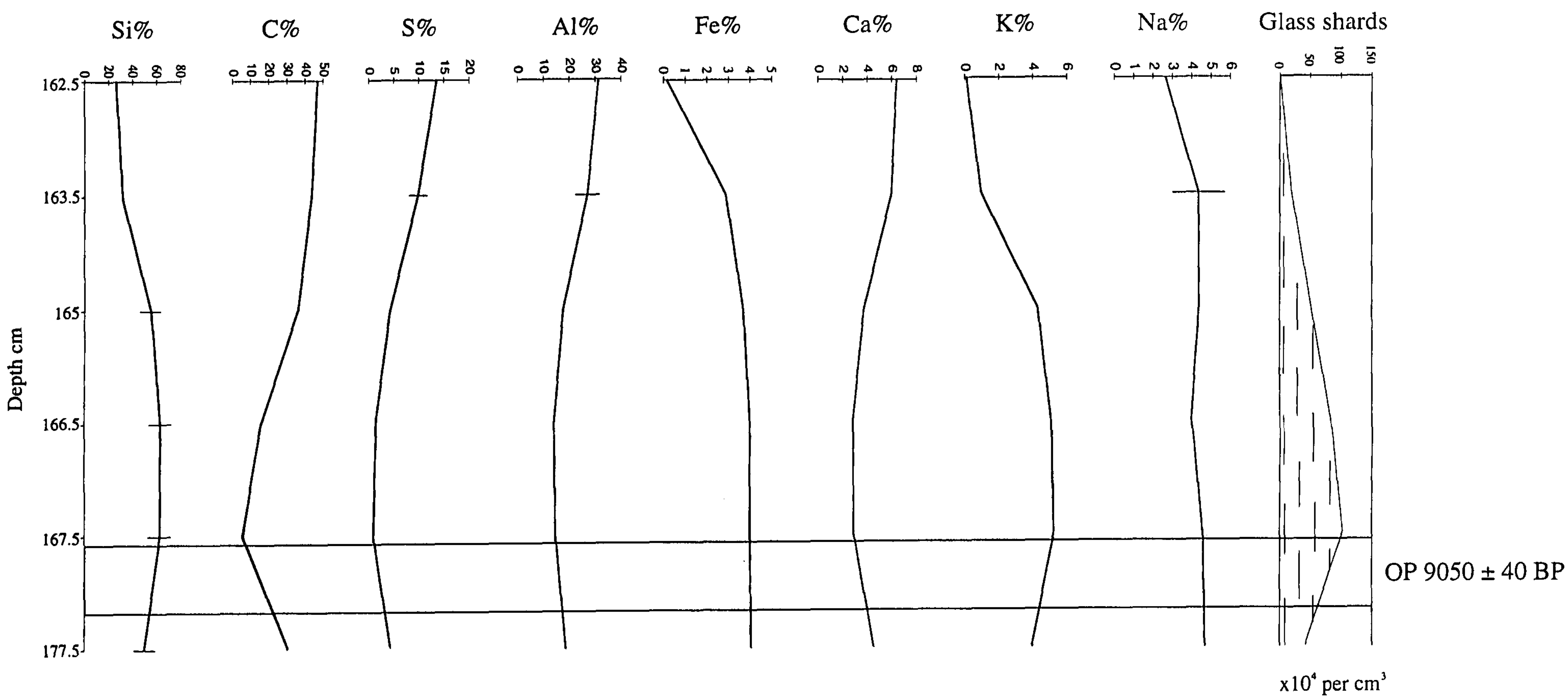



**Figure 5.8** Fine resolution geochemistry, Opepe Tephra

*Cyathodes* and *Lepidothamnus* possibly indicate damage to vegetation from tephra and acid aerosol accumulation. These taxa were likely to have been particularly sensitive to the effects of ash accumulation and associated toxic chemical leaching. *Halocarpus* shrubs were probably the tallest plants growing in their specific niche, and therefore more susceptible to damage from tephra fall as they were exposed and unprotected. *Nothofagus fusca* trees were not abundant within the catchment at this time (ca. 9000 BP). Pollen assemblages indicate local forest was dominated by *Prumnopitys taxifolia*, *Libocedrus* and *Podocarpus* trees, together with *Halocarpus* and *Phyllocladus*, and *Dacrydium* and *Prumnopitys ferruginea* common at lower altitudes, in agreement with vegetation trends reported by Rogers (1984). Competitive pressure for canopy space and light from these forest taxa may be the cause of the slight decline in *N. fusca* trees following forest disturbance, as *Fuscospora* species do not compete well within established forests (Newnham *et al.*, 1993). The decline in *Collospermum*, an epiphytic shrub, may have been in response to the death of or damage to its host.

Increases in broken pollen grains and the high concentration of glass shards immediately above the macroscopic Opepe Tephra layer indicate influx of tephric material via increased surface run-off and erosion of topsoils from the catchment following vegetation disturbance. A reduction in total pollen concentrations occurs immediately above the tephra layer, which suggests sedimentation rates temporarily increased as opposed to a decline in pollen production, as massive forest destruction was not evident from the palynological changes in Figure 5.7. Increases in sedimentation rates would have had a 'diluting' effect on the pollen signal, resulting in lower overall pollen concentrations, as seen below the Opepe Tephra. Higher pollen concentrations were observed in these sections of the profile where estimated sedimentation rates were slow (e.g. >100 years per cm between Hinemaiaia and Waimihia Tephra layers).

Evidence for increased sedimentation from the catchment is displayed in the geochemistry record (Fig. 5.8). High Si levels, together with increases in Na and K, and lower C and S levels, reflect an increase in minerogenic material in the peat and very low levels of organic matter. These geochemical changes indicate tephra inwash from soil surfaces and possible slope instability which may have led to short-term local soil erosion. These changes appeared to have continued up to approximately 72 years after the eruption.

Sedimentation rates following the Rotoma eruption were much slower. As a result, each 1 cm sample represents 106 years environmental history (Fig. 5.9). This time resolution is not sufficient for detecting the duration and magnitude of volcanic impacts

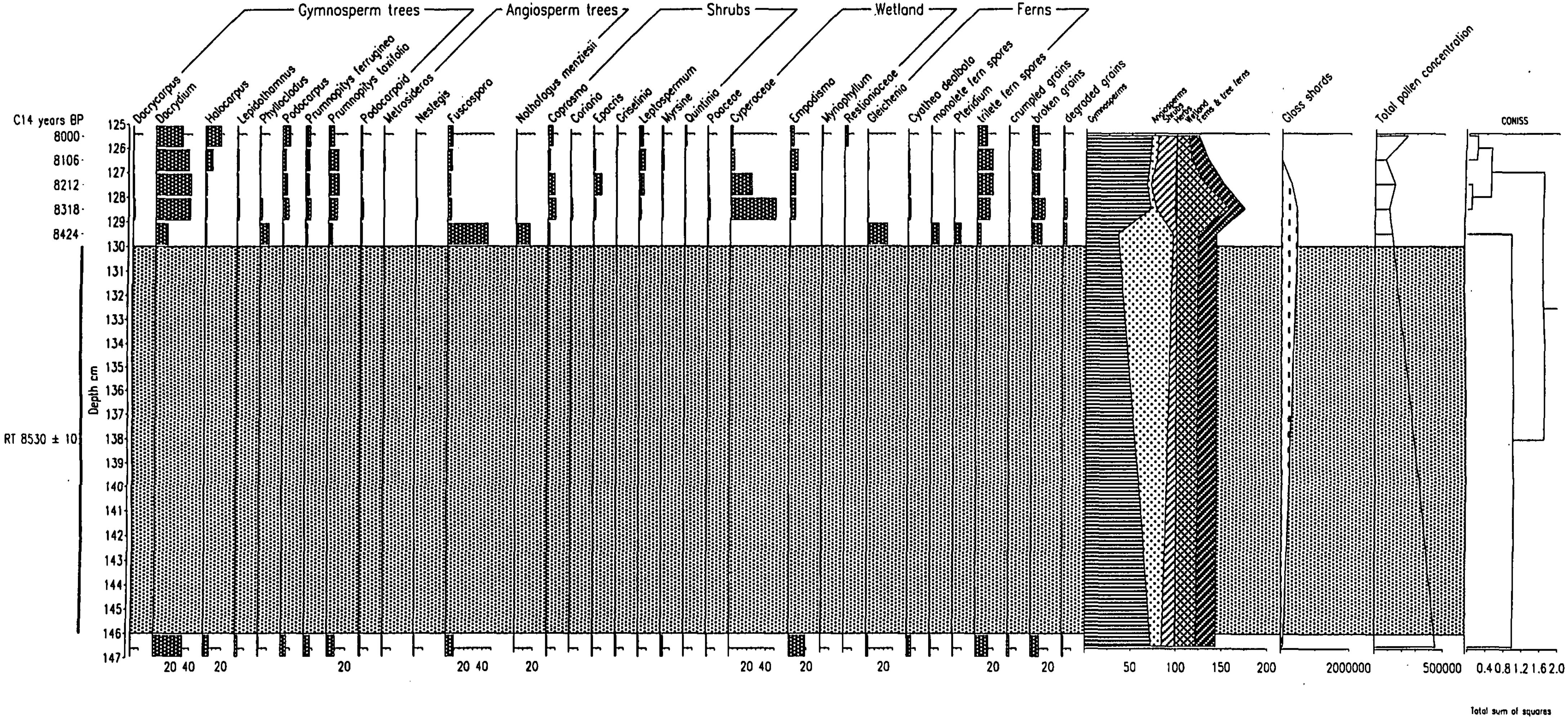



**Figure 5.9** Fine resolution pollen diagram displaying changes in main taxa above and below Rotoma Tephra. Glass shards are expressed as number of fragments per $cm^3$ sediment analysed.

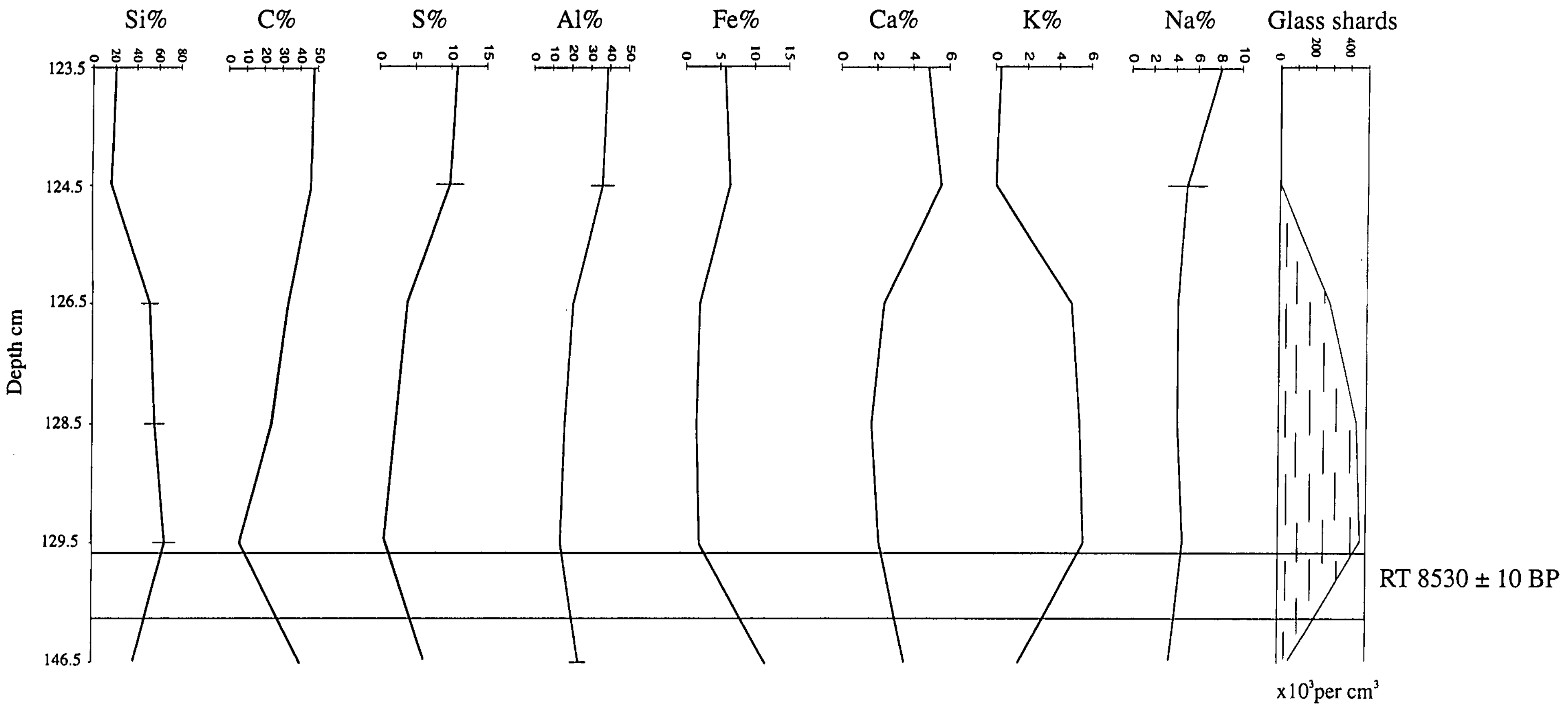
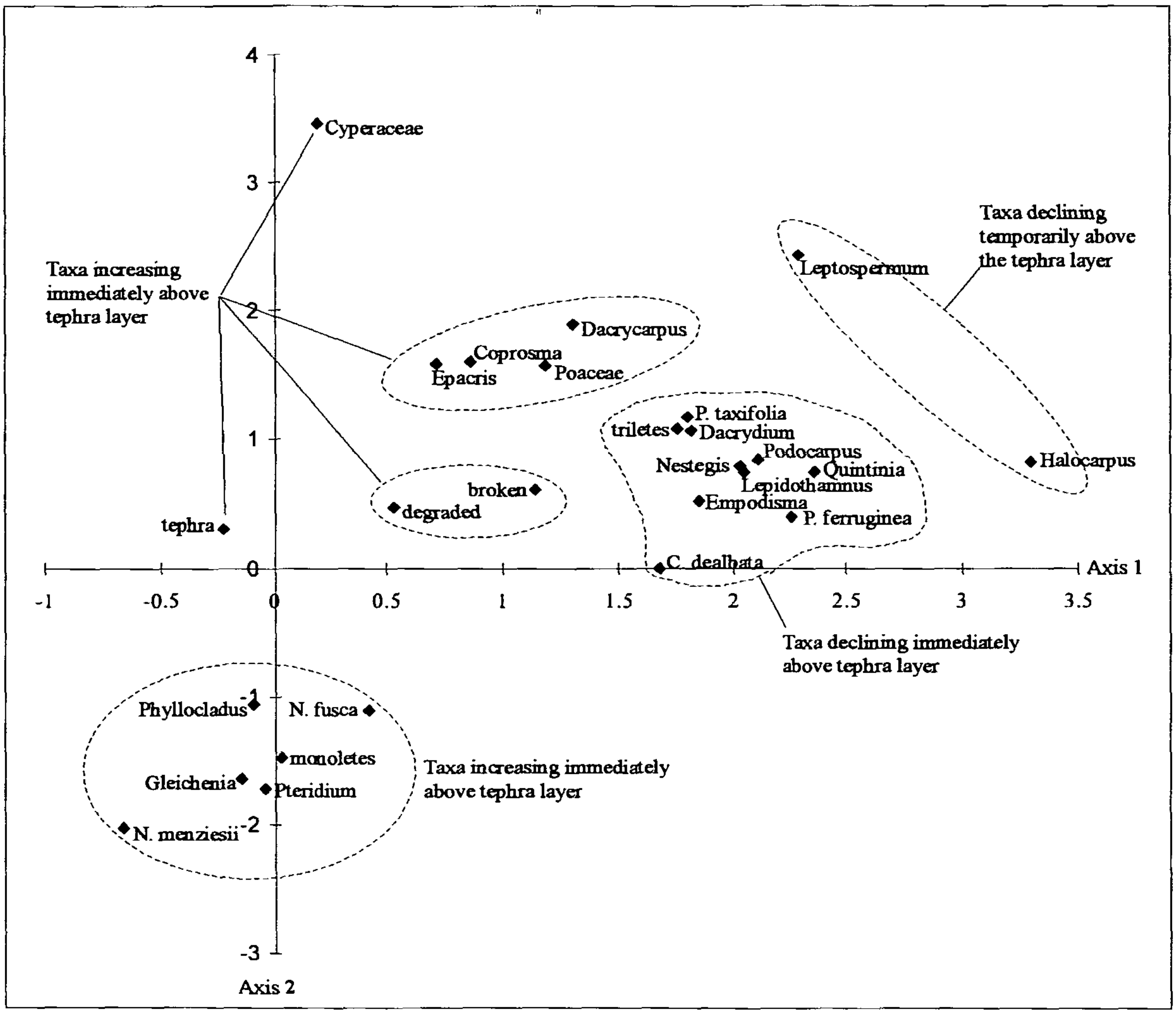



**Figure 5.10** Fine resolution geochemistry, Rotoma Tephra




Eigenvalues Axis 1 = 0.45 Axis 2 = 0.04

**Figure 5.11 A biplot of pollen taxon associations in spectra surrounding the Rotoma Tephra layer at Kaipo Bog, determined from DECORANA.**

which are obscured against overall environmental changes occurring during this period. However, pollen and geochemical assemblages immediately above the tephra layer (130-129 cm, Figs. 5.9 and 5.10) represent vegetation communities and geochemical changes present during the first ca. 106 years after the eruption. Despite the poor time resolution, the impact of Rotoma tephra fall on local vegetation communities and the ambient forest was significant. Detrended correspondence analysis was undertaken on the palynological data, the results of which are illustrated by means of a biplot of taxa scores, distributed along axes 1 and 2 of the DECORANA output (Fig. 5.11). Clear distinctions are evident between those taxa increasing and those which declined following tephra impact. Palynological data displayed in Figure 5.9 reveals a marked decline in *Dacrydium* trees, together with less severe decreases in the number of *Podocarpus*, *Prumnopitys ferruginea* and *P. taxifolia* trees. *Halocarpus*, *Lagarostrobos*, *Lepidothamnus*, *Libocedrus* and *Cyathea dealbata*, present in low numbers prior to the eruption, also declined. Disturbance within the ambient forest gave rise to significant expansion of beech forest, dominated principally by *Nothofagus fusca* trees, and *N. menziesii*.

Mire vegetation was also affected as *Empodisma* declined significantly, indicating possible damage by tephra fall and sensitivity to acid aerosol leaching, creating the opportunity for the expansion of *Gleichenia*. *Gleichenia* is currently found growing on hummocks formed by thick clumps of *Empodisma minor* across Kaipo Bog (Green, unpublished). It can therefore be inferred that *Gleichenia* prefers drier sites, whereas *Empodisma* favours wetter habitats and grows in water saturated areas of peat bogs (Newnham *et al.*, 1995). The decline in *Empodisma* and increase in *Gleichenia* probably occurred indirectly as a result of tephra accumulation, which raised the surface of the bog, creating a greater proportion of drier sites which encouraged the expansion of species such as *Gleichenia* and other fern taxa favouring drier conditions , for example, *Pteridium*. The increase in *Pteridium*, together with monolete fern spores, may also indicate invasion of exposed ground following forest disturbance. The increase in *Phyllocladus*, likely to be the sub-alpine shrub species *P. alpinus* which is common in the area today, probably indicates invasion onto mire margins that were formerly dominated by *Halocarpus* shrubs prior to the eruption. The changes in vegetation following the Rotoma eruption were significant but short-lived, with pre-eruption forest and mire vegetation recovering to former levels within ca. 106 years, which is the maximum estimate for the time encompassed by the pollen sample.

A high concentration of glass shards immediately above the tephra layer coincides with a significant increase in Si, together with minor increases in Na and K, and significant reductions in C and S (Fig. 5.10). These changes indicate inwashing of minerogenic tephra-derived material from the catchment, resulting in a higher ratio of minerogenic to organic matter within the peat. High but declining levels of these elements and glass shards continued up to ca. 300 years after the eruption, indicating local slope and soil instability following significant volcanic induced vegetation disturbance. Pollen concentration levels also declined, probably reflecting an overall reduction in pollen production following significant podocarp forest destruction envisaged from pollen changes in Figure 5.9. Total pollen concentrations were also likely to have been diluted following the short-lived increase in sedimentation onto the surface of the mire following catchment disturbance.

The Mamaku eruption resulted in the deposition of a 3 cm thick tephra layer at Kaipo. Peat accumulation was very slow above the tephra layer, with each 1 cm peat sample encompassing ca. 373 years of environmental history. This time resolution is too broad to detect short-term vegetational and environmental impacts from tephra fall, especially from a relatively thin tephra layer in comparison to the Opepe and Rotoma Tephras discussed previously. Hence, fine resolution pollen and geochemical diagrams have not been produced. Changes in vegetation assemblages above the tephra layer indicate expansion of conifer-angiosperm forest, with gradual long-term declines in *Halocarpus*, *Prumnopitys taxifolia* and *Myrsine*. These changes probably reflect climate warming and environmental stability, resulting in forest expansion and increasing competitive pressure between forest taxa. The geochemical record (Fig 5.6) shows higher Si, Na and K levels and lower C, S and Al, corresponding with an increasing proportion of glass shards within the peat (Fig. 5.5). These changes reflect inwashing of tephric material from the catchment, and possible dissemination of shards within the peat from the Tuhua tephra layer which lies 3 cm above the Mamaku Tephra in the profile.

Each sample above the Tuhua Tephra layer encompasses ca. 325 years of environmental history, and so the magnitude and duration of volcanic impacts on local forest and the catchment cannot be determined. Following the Tuhua eruption, palynological assemblages indicate a significant decline in *Dacrydium* trees within the lower altitude forest, and a rapid increase in local populations of *Nothofagus fusca* trees (Fig. 5.5). A gradual decline also occurred in *Podocarpus*, *Prumnopitys ferruginea*, *P. taxifolia* and *Myrsine* trees. These changes could have been initiated by damage to vegetation following tephra and acid aerosol accumulation, although declines were gradual and occurred over an estimated period of 1300 years. Other factors, in particular climate change, were likely to have contributed to the overall change in forest composition. From 7000 years BP *Nothofagus* forest expanded in upland areas of the North Island, as frost and drought sensitive *Ascarina* and *Dacrydium* trees declined in response to cooler climatic conditions (McGlone *et al.*, 1995).

It can be inferred from pollen assemblages above Mamaku and Tuhua Tephra layers that the total area of the mire had decreased as forest encroached onto mire margins. Pollen levels from mire vegetation, such as *Gleichenia*, *Empodisma* and other Restionaceae taxa, were low at the sampling site above the Mamaku Tephra, and were virtually absent following the Tuhua eruption. These changes may have resulted indirectly from long-term volcanic activity, in addition to climate change as conditions became progressively cooler and drier during the mid Holocene (Salinger *et al.*, 1993). Between 9050 and 6130 year BP, 32 cm of tephra had been deposited on the surface of Kaipo Bog, plus the additional short-lived periods of sediment influx from catchment soils which had become unstable following volcanic induced vegetation disturbance. Tephra accumulation and inwash of eroded topsoils would have gradually raised the surface of the bog, resulting in the exposure of mire margins above the water table. Drainage then improved, creating drier sites that rapidly became colonised by *N. fusca* trees. The fringes of the mire therefore became too dry for wetland vegetation to survive, resulting in the decline of mire taxa, and the overall shrinkage of the total mire area.

### 5.9 Mid to late Holocene volcanic impacts

Each sample above the Whakatane Tephra encompasses approximately 160 years of environmental history, and so short-term volcanic impacts cannot be determined. Following the Whakatane eruption, podocarp forest increased in the area as *N. fusca* trees declined but continued to remain dominant within the local forest (Fig. 5.12). Mire vegetation also increased slightly, with the expansion of *Coprosma*, Cyperaceae and *Myriophyllum*. *Phyllocladus* probably colonised the mire fringes, invading areas formerly occupied by *Halocarpus* shrubs which declined following tephra fall. *Nothofagus* trees dominated the forest canopy, and were thus exposed to damage from tephra accumulation and associated toxic chemical leaching. Tephra accumulation therefore probably caused the decline in *N. fusca* trees, creating opportunities for the expansion of podocarp trees within the damaged forest, and expansion of the mire following forest die-back. These changes were sustained up to ca. 320 years after the Whakatane eruption.

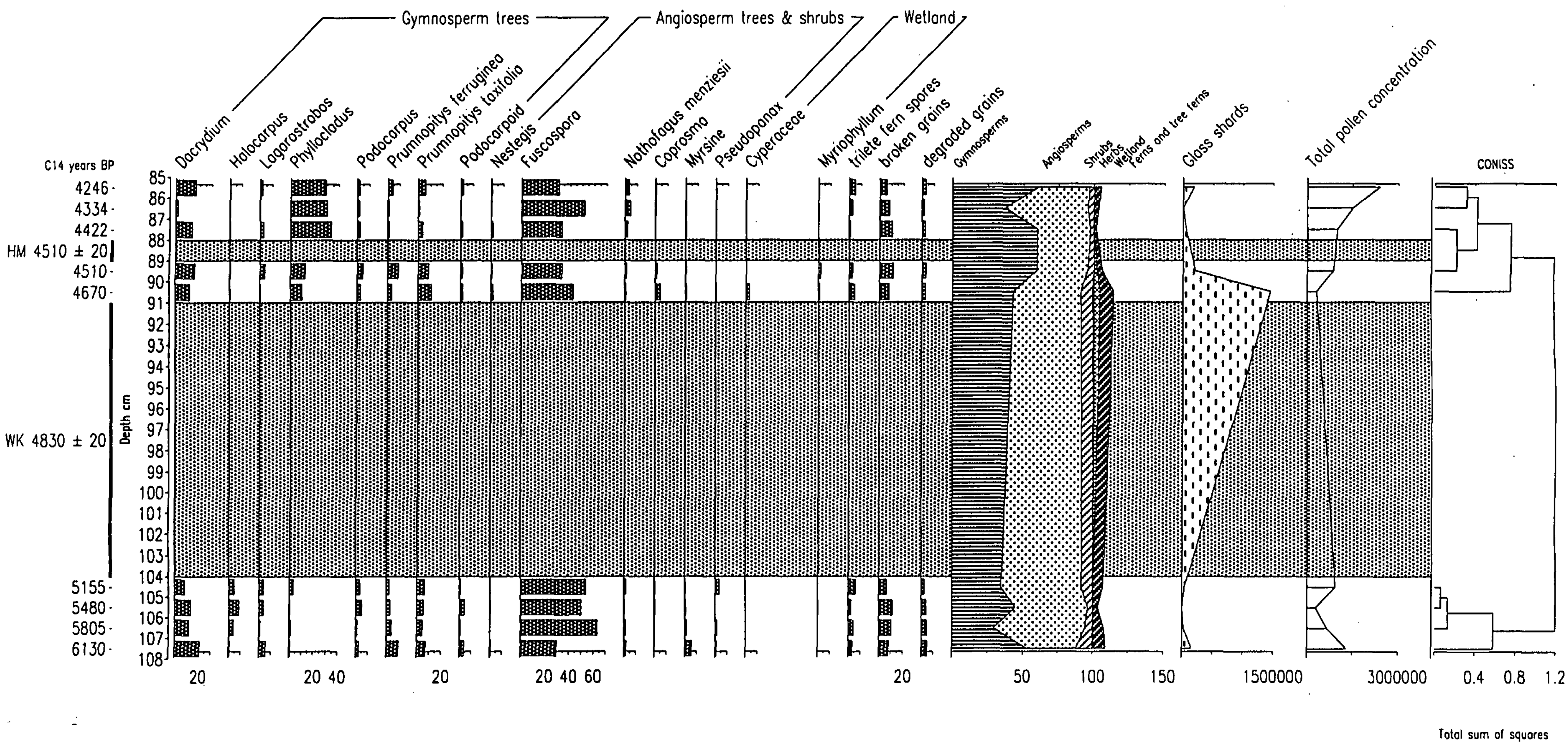



**Figure 5.12** Fine resolution pollen diagram displaying changes in main taxa above and below Whakatane Tephra. Glass shards are expressed as number of fragments per cm$^3$ sediment analysed.

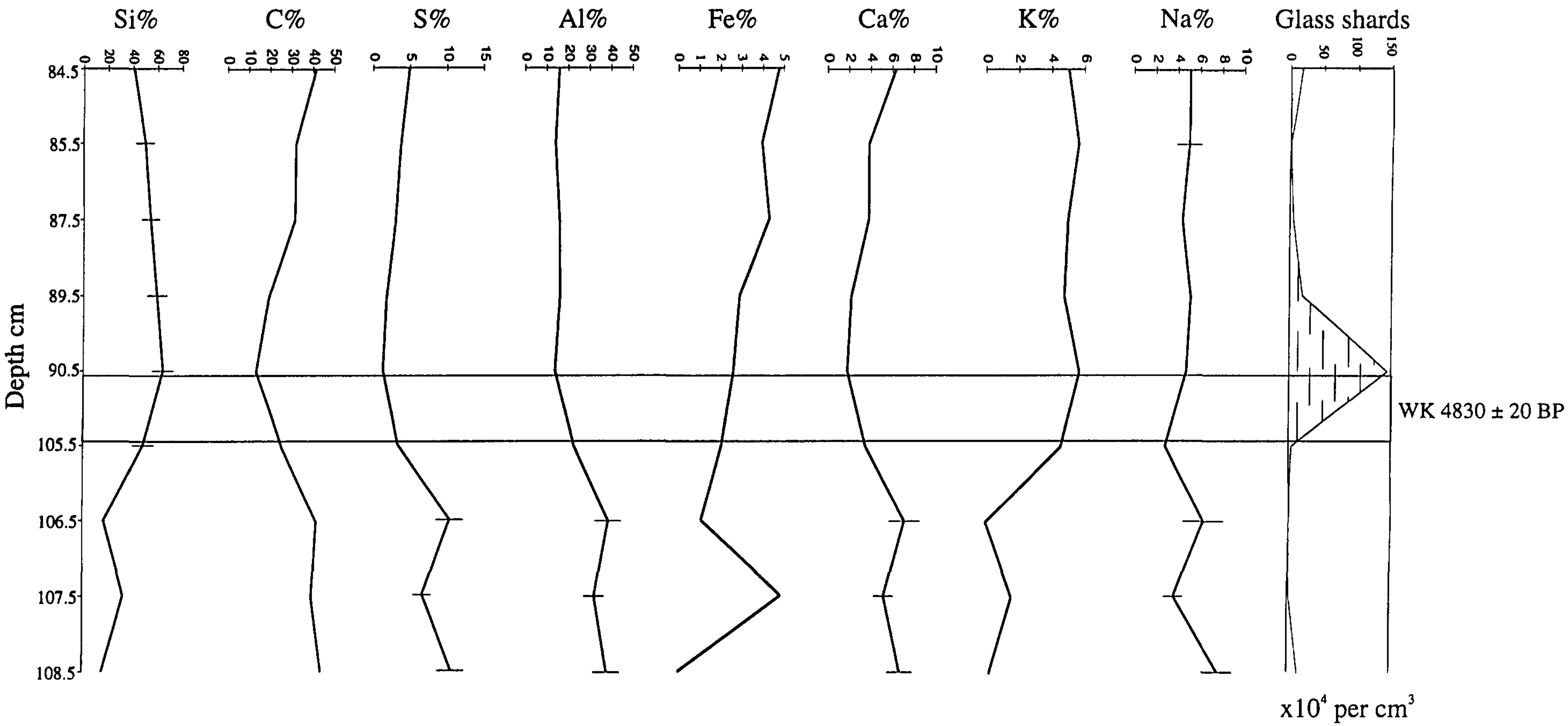



**Figure 5.13** Fine resolution geochemistry, Whakatane Tephra

Geochemical observations reveal a high proportion of minerogenic material within peat sediment immediately above the tephra layer, consisting largely of tephra-derived material washed into the basin from the surface of catchment soils. Evidence is shown in Figure 5.13 as glass shards exhibit a peak, coinciding with a large increase in Si and small increases in Na and K above the tephra layer. Organic matter content of the peat is minimal at this depth, indicated by low levels of C and S, suggesting rapid influx of minerogenic material onto the mire. Higher levels of minerogenic material in the peat were sustained up to and immediately following the deposition of the Hinemaiaia Tephra (4510 BP). The decline in pollen concentrations (Fig. 5.12) probably resulted from a combination of reduced pollen production following damage to forest vegetation, together with the sudden short-lived increase in sedimentation rates which diluted the pollen signal.

Changes in vegetation assemblages following the Hinemaiaia eruption are likely to reflect climate change as opposed to volcanic impact, as the climate was becoming cooler during the mid Holocene, with *Phyllocladus alpinus* trees becoming increasingly common in the area (Fig. 5.12) (Rogers, 1984; Salinger *al al.*, 1993; McGlone *et al.*, 1995). The sample immediately above the tephra layer represents 112 years of environmental history, and short-term volcanic impacts following this eruption are not detected within this broad time resolution.

Changes in ambient and lower altitude forest vegetation were detected following deposition of the Waimihia Tephra (Fig. 5.14). Sedimentation rates were slow above the tephra layer, with 1 cm of peat encompassing ca. 238 years of environmental history. Significant declines occurred in *Dacrydium*, *Lagarostrobos* and *Prumnopitys*, together with a slight decrease in the number of *Podocarpus* trees. Re-establishment of beech forest occurred, with increases in fern and mire taxa following forest disturbance. *Gleichenia*, *Coprosma* and *Empodisma* increased, expanding within mire margins, following the decline in *Phyllocladus alpinus* and forest die-back. *Nothofagus fusca* trees increased significantly above the tephra layer, and may have benefited from improved drainage following deposition of the 28 cm thick tephra layer. Vegetation disturbance and improved drainage within mire margins would have created the opportunity for the expansion of low-lying fern taxa. Despite the broad time resolution, volcanic impacts are discernible within this long-term record.

The geochemical record reveals a high ratio of minerogenic to organic material within the peat above the Waimihia Tephra layer, with low C and S levels and increases in Si (Fig. 5.15). A slight increase in glass shards and deteriorated pollen grains reflects the

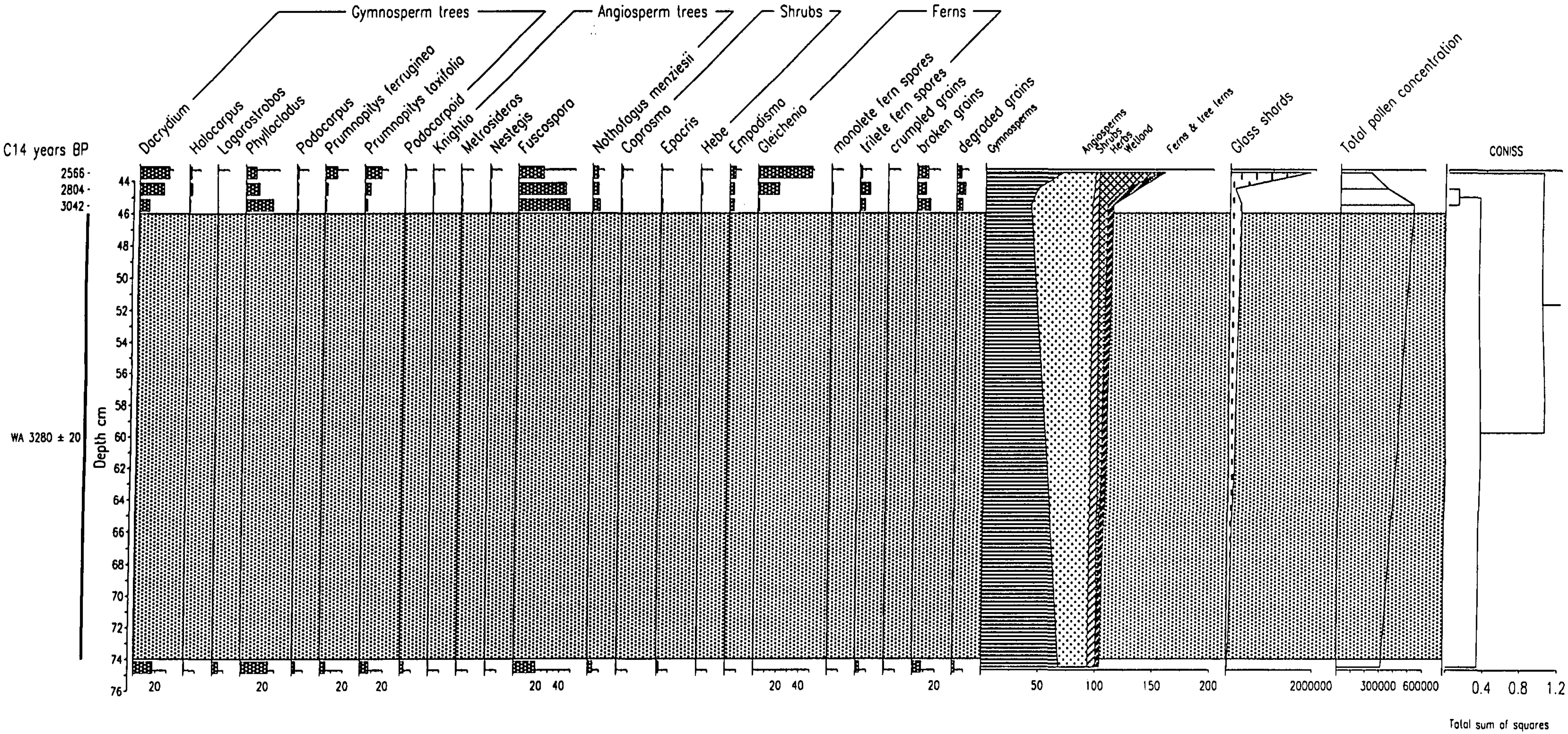



**Figure 5.14** Fine resolution pollen diagram displaying changes in main taxa above and below Waimihia Tephra. Glass shards are expressed as number of fragments per $cm^3$ sediment analysed.

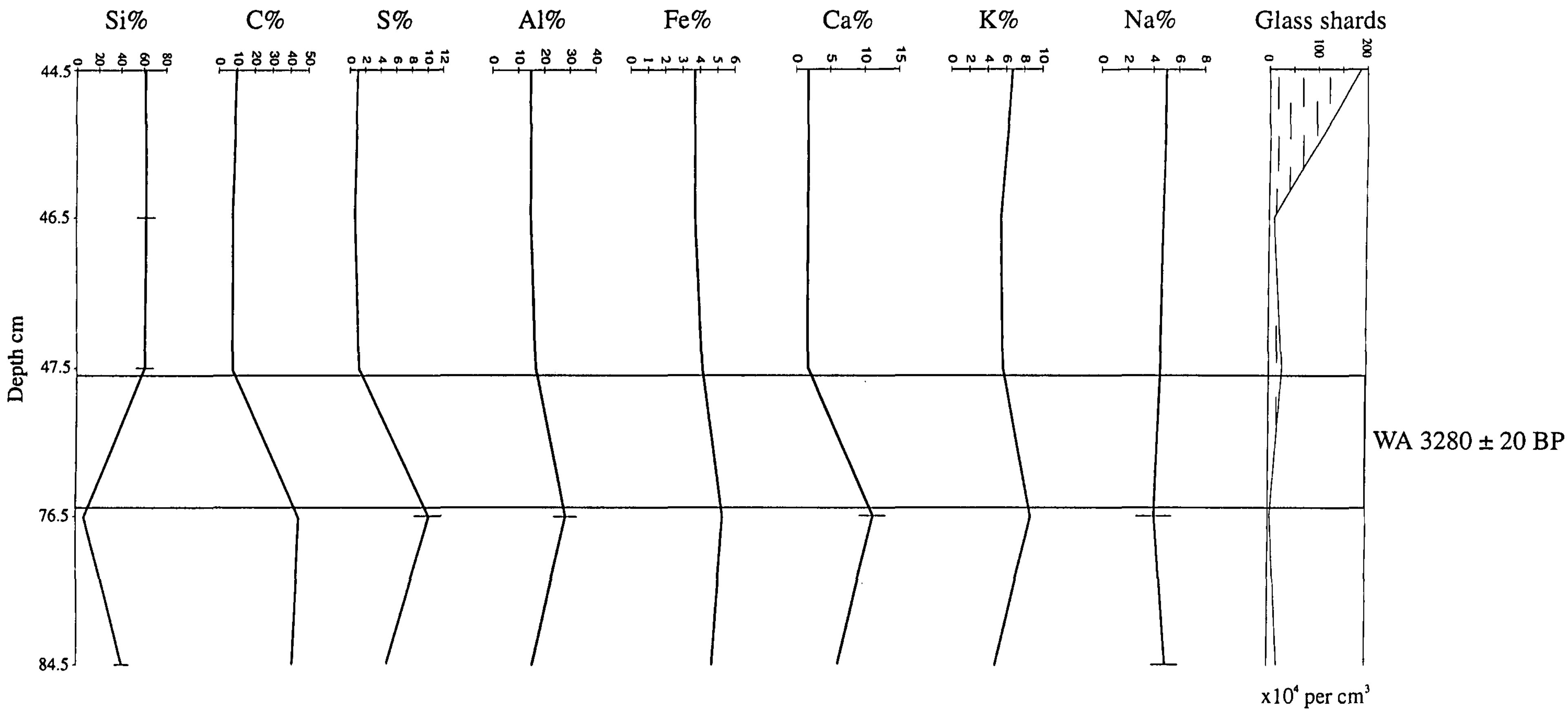



**Figure 5.15** Fine resolution geochemistry, Waimihia Tephra

influx of tephra-derived, and soil-derived material from the catchment via surface run-off and soil weathering processes. There appears to be no strong evidence to suggest large-scale environmental impacts occurred within the catchment following tephra fall and forest disturbance. The apparent low magnitude of environmental impacts following the Waimihia eruption may be due to slow peat accumulation rates above this tephra layer, obscuring the volcanic impact signal within the geochemical record against long-term environmental changes.

Sedimentation rates following the Taupo eruption remained slow, with each 1 cm section of peat accumulating over an estimated 237-year period. Despite the broad timescale, volcanic impacts are discernible above the Taupo Tephra layer in the palynological and geochemical records (Figures 5.16 and 5.17). Impacts on local and lower altitude forest, and mire vegetation occurring after the Taupo eruption are similar to those recorded following Waimihia Tephra fall. *Phyllocladus*, *Prumnopitys ferruginea* and *P. taxifolia* trees declined significantly, while *Nothofagus fusca* forest increased, together with ferns and *Gleichenia*. These changes possibly suggest *Prumnopitys* and *Phyllocladus* trees were exposed to tephra accumulation and associated toxic chemical leaching which damaged these trees, as these taxa were likely to have been the tallest within their niche. The expansion of beech forest and ferns may have been initiated by subsequent drainage improvement following the deposition of the 22 cm thick Taupo Tephra layer.

The wetland species *Empodisma*, which was relatively common in the area prior to the Taupo eruption, disappears above the Taupo Tephra layer as *Gleichenia* exhibits a significant increase. These changes also reflect drainage improvement following tephra accumulation, which temporarily raised the bog surface above the water table, creating drier sites and favouring the expansion of *Gleichenia*. *Empodisma* plants grow in waterlogged habitats; however, the reduced availability of suitable marshy sites following tephra deposition resulted in the subsequent decline in these plants on the mire. A decline in *Empodisma* and the expansion of *Gleichenia* also occurred following the deposition of the Rotoma Tephra at this site.

Evidence for catchment disturbance and soil erosion is envisaged from the pollen and geochemical records. Deteriorated pollen grains increased substantially immediately above the tephra layer, coinciding with high relative proportions of Fe, indicating erosion of soil surfaces and subsequent sedimentation onto the surface of the mire. Higher Fe levels are sustained up to ca. 474 years, and Si levels increased steadily, suggesting prolonged catchment disturbance resulting in the influx of soil and tephra-derived sediments into the

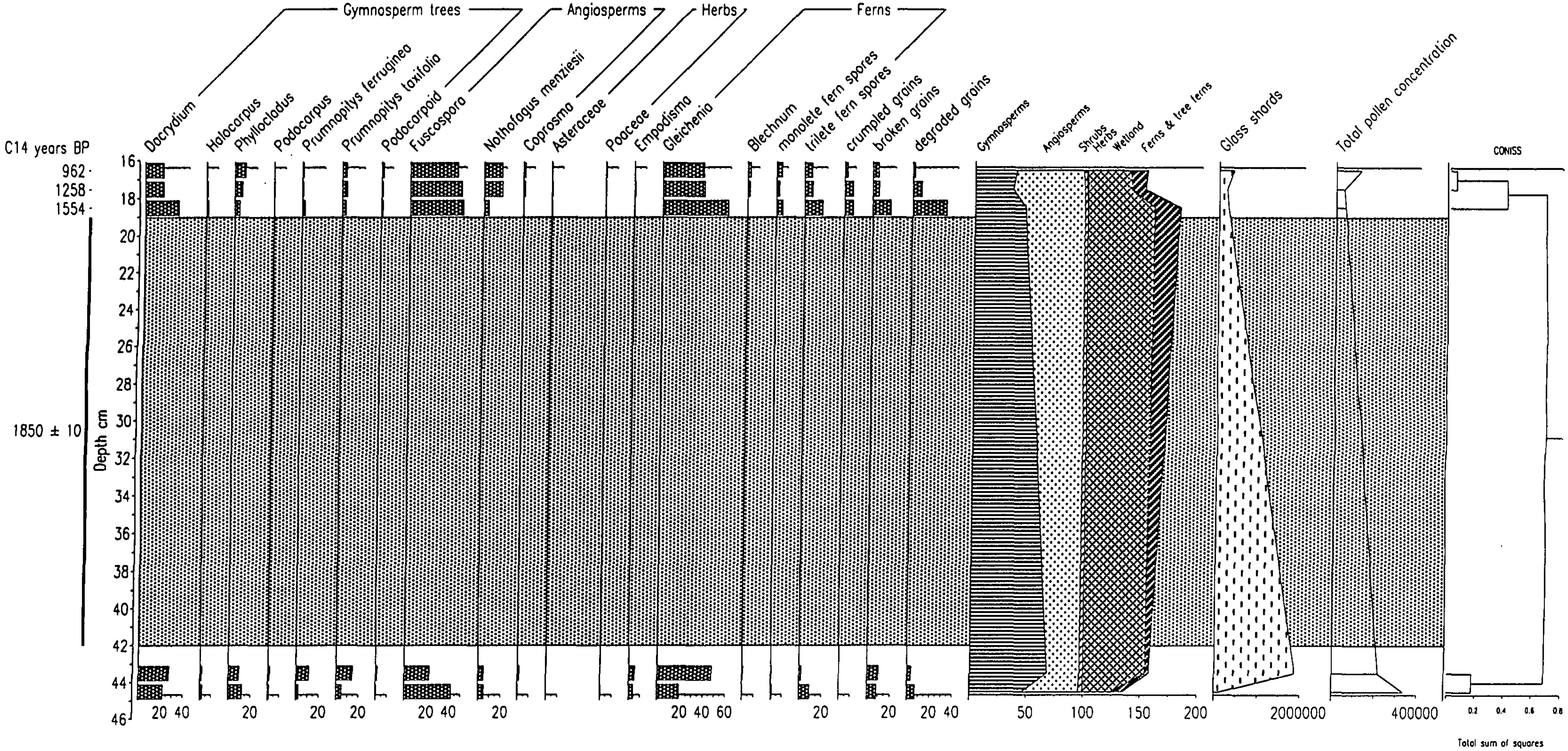



**Figure 5.16** Fine resolution pollen diagram displaying changes in main taxa above and below Taupo Tephra. Glass shards are expressed as number of fragments per $cm^3$ sediment analysed.

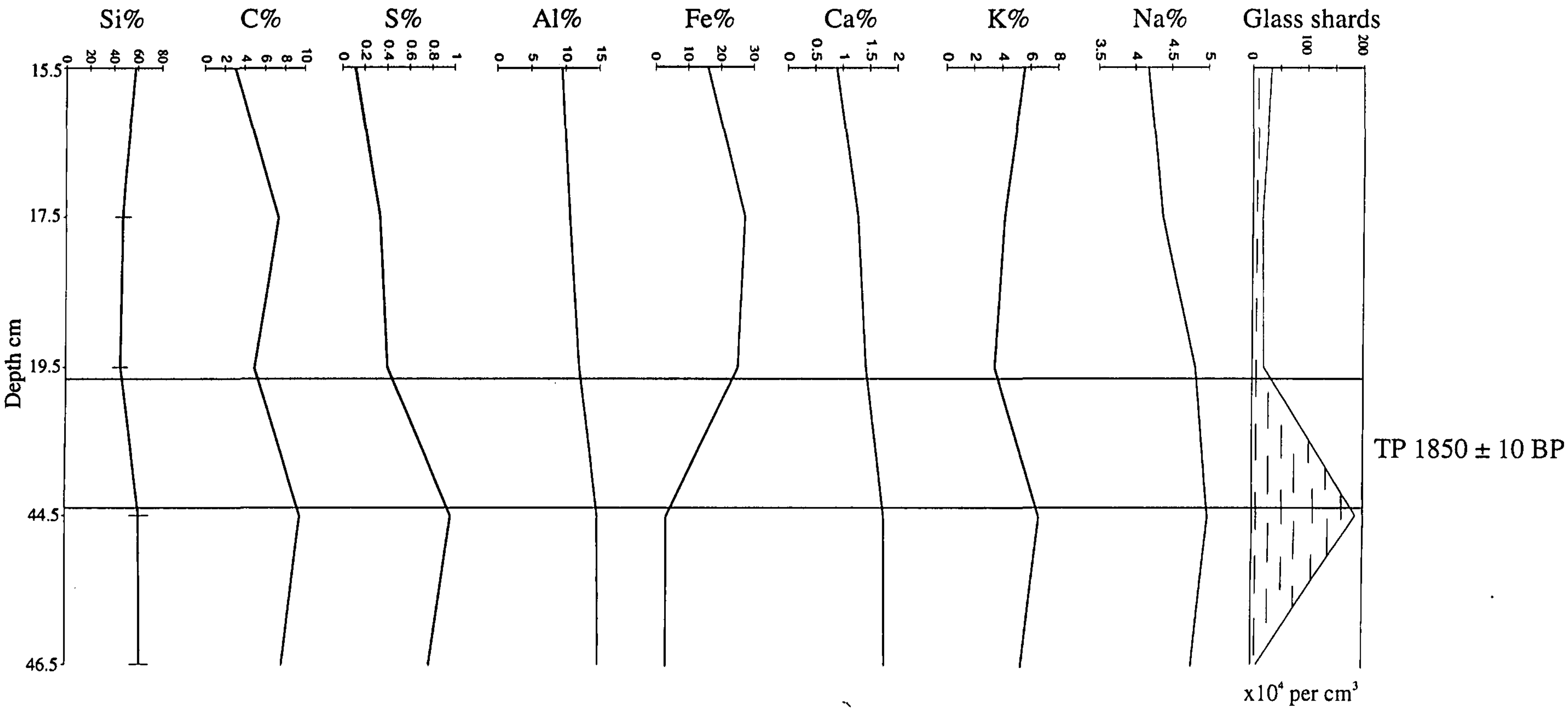



**Figure 5.17** Fine resolution geochemistry, Taupo Tephra

basin. The concentration of glass shards was high above the macroscopic tephra layer, but were lower than below the tephra layer. The accumulation of microscopic tephra below the main layer may have derived from small ash falls representing the early stages of the eruption. These ash falls possibly occurred over a few months or years before the main eruptive phase which resulted in the deposition of the macroscopic tephra layer. Small ash falls from Ruapehu volcano were reported in news bulletins, and occurred some months before the main Ruapehu eruptions in 1995 and 1996. Therefore it is possible that small pre-eruption ash falls could have preceded large Holocene eruptions by several months, resulting in the possible dispersal and deposition of microscopic tephra shards at distal locations, depending on wind strength and direction at the time of ash emission.

Vegetation changes following the Kaharoa eruption were discernible in the pollen and geochemical records (Figs. 5.18 and 5.19). Rapid peat accumulation rates resulted in a between-sample time-resolution of 51 years, and so a more detailed record of short-term environmental impacts could be established. A significant decline in *Dacrydium* trees occurred in the lower altitude forest, while *Nothofagus fusca* trees remained dominant locally, together with an increasing number of *Nothofagus menziesii* trees. *Coprosma*, *Pseudopanax* and *Griselinia* trees and shrubs also increased slightly within the catchment. A significant decline in *Gleichenia* occurred indicating this taxon was no longer growing close to the study site following deposition of the Kaharoa Tephra. These changes may have occurred as a direct result of tephra deposition, which improved drainage, providing suitable drier sites which encouraged the invasion of beech trees. Palynological evidence therefore suggests that beech forest had encroached onto the fringes of the mire as local forest expanded, resulting in a decline in the total area of the mire following tephra deposition. Low-lying mire vegetation remained absent from the study site up to the top of the profile, as beech forest prevailed within the catchment.

Elemental assemblages within the geochemical record (Fig. 5.19) indicate a return to static equilibrium levels within the peat profile and local catchment. Organic material is abundant, while Si and Al levels are low, indicating influx of minerogenic material from the surrounding catchment had declined following the stabilisation of slopes and expansion of beech forest. A short-lived peak in K occurs at 10 cm depth in the profile. It is unlikely that this peak is associated with inwash of tephra-derived material, as Si declines, and glass shard concentrations are not particularly high at this depth. It is equally unlikely that the peak in K represents local soil erosion, as Na, Al and Si levels are low. The peak may be an artefact of the natural distribution of K within peat. K is readily leached from living and

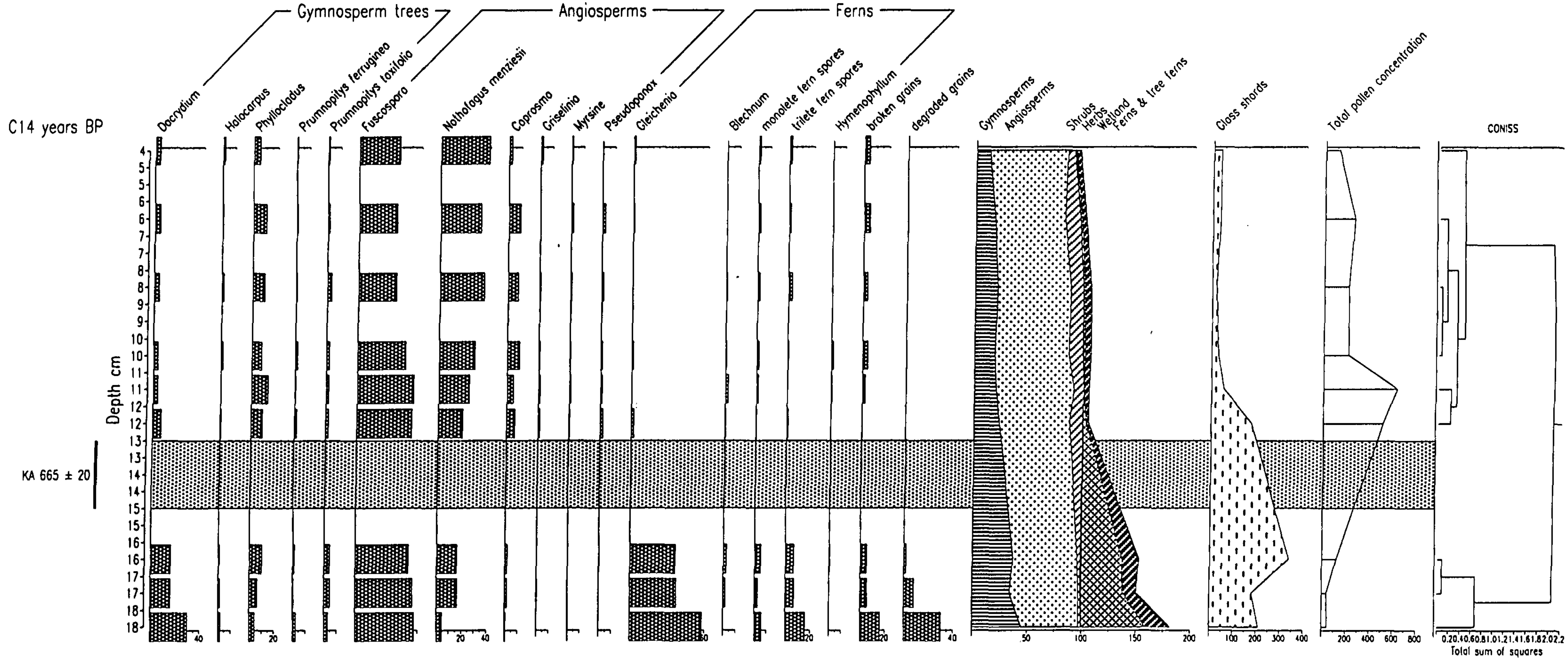



**Figure 5.18** Fine resolution pollen diagram displaying changes in main taxa above and below Kaharoa Tephra. Glass shards are expressed as number of fragments per $cm^3$ sediment analysed.

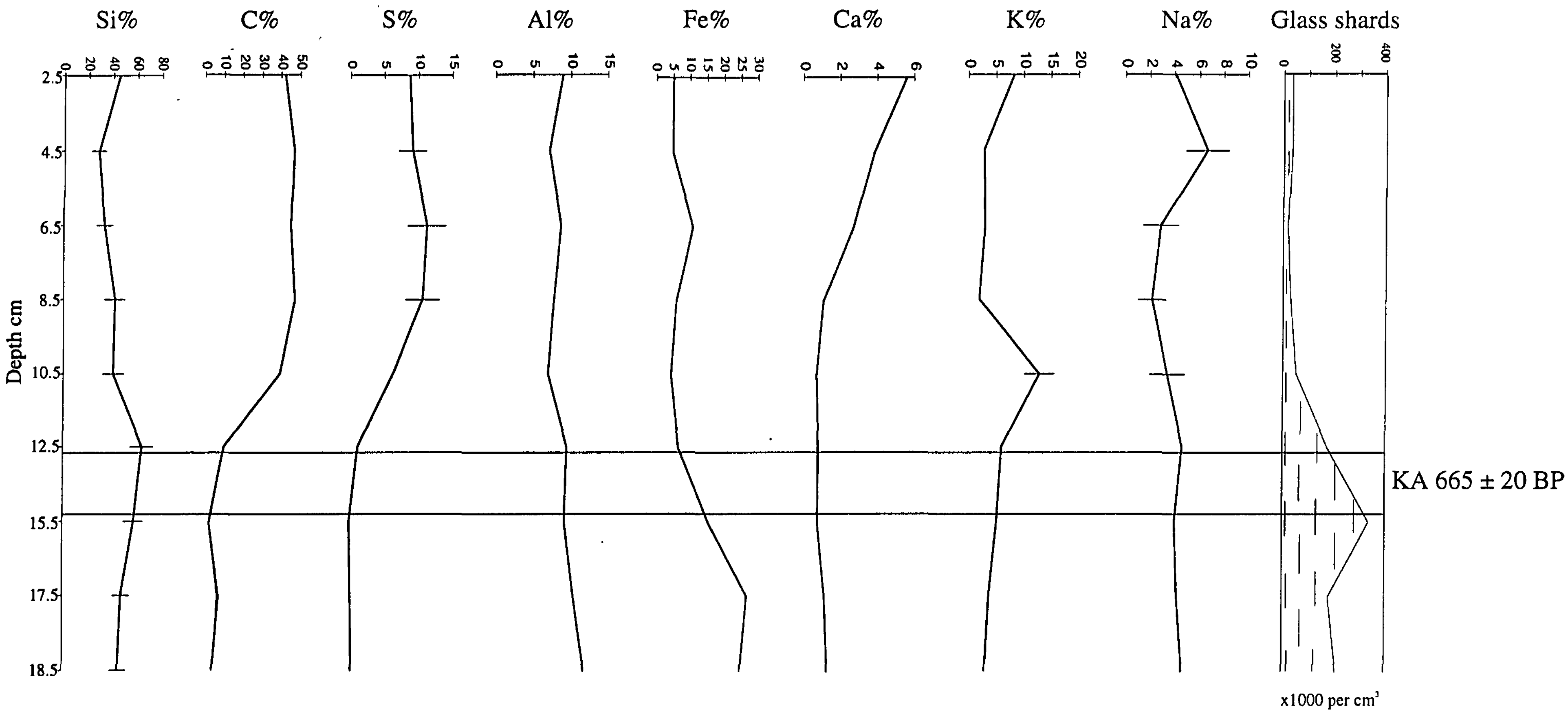



**Figure 5.19** Fine resolution geochemistry, Kaharoa Tephra

dead plant material and is often found to be highly concentrated in the surface horizons of peat deposits, usually in the top 5 cm (Damman, 1978). As the top 10 cm of the Kaipo profile contains abundant dead and living plant material, K may therefore have been leached from decomposing plant matter, and accumulated at the base of the active peat layer.

The concentration of glass shards is slightly higher below the tephra layer reflecting the possible accumulation of microscopic tephra shards from pre-eruption ash falls. The Kaharoa Tephra layer is a thin deposit reaching 2 cm thickness. As environmental stability prevailed following the eruption, very little influx of tephra-derived material occurred, and so glass shard concentrations were therefore lower above the tephra layer.

It is interesting to note that no deforestation signal is recorded in the pollen record above the Kaharoa Tephra. The harsh climatic and environmental conditions at Kaipo Bog make this site unattractive for human inhabitation. It is unlikely, therefore, that local vegetation disturbances above the Kaharoa Tephra could be attributed to anthropogenic impact, unlike those recorded above the Kaharoa Tephra at Matakana Island (Chapter 4). However, pollen studies by Newnham *et al.* (1998) at nearby Lake Waikaremoana show evidence for human disturbance in the area. Their results show a significant increase in charcoal fragments and *Pteridium* spores at ca. 375 years BP, suggesting forest clearance by burning. However, tree pollen levels do not decline significantly, in contrast with other pollen diagrams illustrating anthropogenic forest clearances in New Zealand. Newnham *et al.* therefore suggest that evidence for forest clearances in the Waikaremoana profile may reflect regional rather than local disturbance. These disturbances were not detected in the pollen record at Kaipo Bog. Also, adventive pollen is absent from the top of the Kaipo profile, in contrast with the Waikaremoana record which displays increases in *Cupressus, Pinus* and *Salix* pollen in the top 5 cm. It can therefore be concluded that the uppermost samples from Kaipo pre-date Polynesian and European deforestation, and that the last ca. 400 years are missing from the Kaipo record.

### 5.10 Summary and conclusions

Despite the slow peat accumulation rates above many of the tephra layers within the peat profile, volcanic impacts on local vegetation and the environment are discernible within the pollen and geochemical records. An overall summary of vegetation and environmental impacts following tephra deposition at Kaipo Bog are displayed in Table 5.8.

Detrended correspondence analysis (DECORANA) was carried out for the entire core to detect significant differences in local vegetation communities following tephra fall.

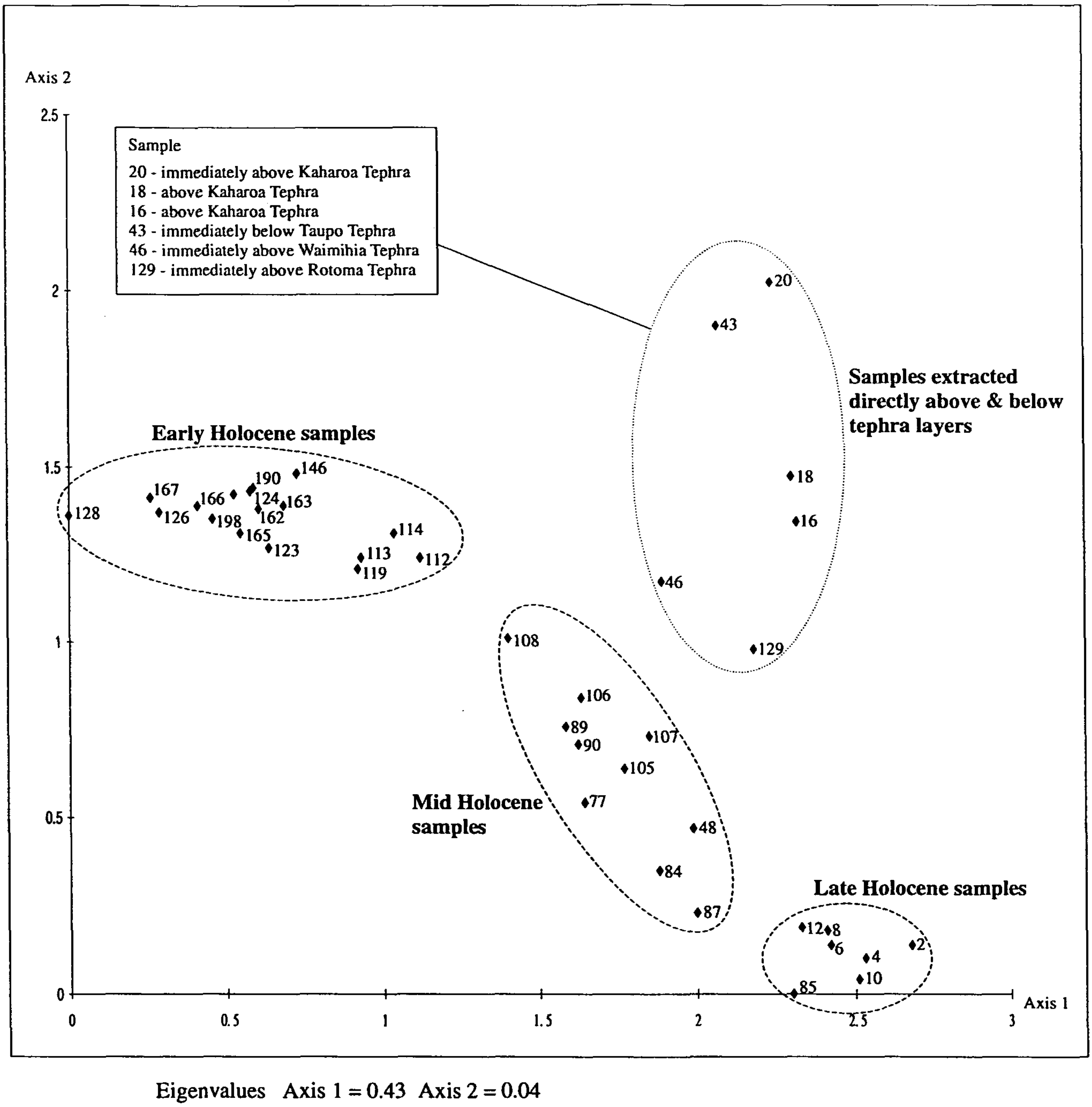



**Figure 5.20** Biplot of Decorana samples cores for the Kaipo Bog profile. Sample numbers represent depth extracted (cm). Sample groupings were manually interpolated and labelled.

The results are presented as a biplot of sample scores plotted against DECORANA axes 1 and 2 (Figure 5.20). The plot displays a curvilinear distribution of samples reflecting changes in forest composition in response to climate change during the Holocene. Samples deviating from the curvilinear distribution are grouped together by a dotted line. These samples, with the exception of the sample at 43 cm, are located immediately above Kaharoa, Waimihia and Rotoma tephra layers, suggesting volcanic tephra fall was the most important factor influencing local vegetation change following these eruptions. Similar changes in forest composition occurred above these tephra layers as beech forest became dominant, and podocarp trees declined. However, it is unclear why the sample at 43 cm, located immediately below the Taupo tephra, has been included in this group, as vegetation assemblages were dominated by podocarp trees and *Gleichenia*, with a lower proportion of beech trees present in the ambient forest. These vegetation communities may therefore be influenced by other factors such as local natural drainage improvement during increasingly drier climatic conditions from approximately 2000 BP (Salinger *et al.*, 1993), which also occurs following tephra accumulation.

The conclusions reached following this investigation into the effect of volcanic tephra fall at Kaipo Bog are listed below:

*1)* The deposition of thick tephra layers (>8 cm) at this site resulted in vegetational and environmental changes which were detected in the pollen and geochemistry records, even where between sample time resolutions were in excess of 200 years (i.e., above Waimihia and Taupo Tephra layers). It can therefore be inferred that volcanic tephra fall caused significant damage to local forest and mire vegetation, leading to subsequent slope instability and soil erosion.

*2)* Damage to local vegetation is detected following six of the nine eruptions investigated. Taxa most frequently affected were *Halocarpus*, *Prumnopitys ferruginea*, *Dacrydium*, *Podocarpus* and *Prumnopitys taxifolia*. These taxa were probably especially sensitive to volcanic tephra accumulation and associated toxic chemical leaching, perhaps due to their specific structure and physiological characteristics. These are taxa that were emergent above the main forest canopy, or grew on the exposed bog and hence were unprotected against damage from tephra fall.

*3)* Taxa most commonly increasing following tephra fall included *Nothofagus* spp., *Phyllocladus*, *Gleichenia* and other ferns (including *Pteridium*), *Coprosma* and Cyperaceae. The accumulation of thick tephra layers, and subsequent vegetation damage, created canopy gaps within the forest, and drier ground surfaces within mire margins, encouraging the expansion of these taxa.

*4)* Tephra deposition resulted in drier ground conditions across the bog which was inferred to be the primary reason for the decline in *Empodisma,* and rapid increases in *Gleichenia* and *Pteridium* following the Rotoma, Opepe and Taupo eruptions.

*5)* Tephra deposition appeared to be responsible for the decline in *Halocarpus* shrubs within mire margins following early- to mid-Holocene eruptions. These shrubs were then replaced by *Phyllocladus*, which became temporarily dominant, benefiting from reduced competitive pressure from *Halocarpus*, and possibly preferring drier ground surfaces which resulted from tephra accumulation.

*6)* Volcanic-induced vegetation disturbance was not discernible following Tuhua, Mamaku and Hinemaiaia eruptions, which deposited tephra layers <4 cm in thickness. However, short-term impacts may have been obscured by long-term environmental change, as between-sample time-resolutions were broad (>100 years per cm) owing to slow peat accumulation rates above these thinner tephra layers. Environmental changes were detected in the pollen and geochemistry records above the 2cm thick Kaharoa Tephra layer, as the between-sample time-resolution was considerably higher (ca. 51 years per cm).

*7)* Higher concentrations of glass shards and deteriorated pollen grains, together with lower pollen concentrations, were observed within the peat immediately above the Opepe, Rotoma, Mamaku, Whakatane and Waimihia Tephra layers. These increases coincided with higher relative proportions of Si and occasional increases in Na and K, and lower levels of C and S in the geochemistry record. These changes indicate that catchment instability occurred as a result of vegetation disturbance, initiating increased surface run-off and soil erosion, and resulting in the influx of sediment onto the surface of the mire. Reduced pollen concentrations were likely to be due to vegetation destruction following tephra fall causing a fall in overall pollen production, together with increased sedimentation rates which diluted the pollen signal.

*8)* Dissemination of tephra shards below some of the macroscopic tephra layers (Kaharoa, Taupo, Tuhua and Opepe) probably results from distal deposition of microscopic tephra shards from pre-eruption ash emissions, dispersed by strong east winds. However post-depositional movement of tephra shards down profile cannot be ruled out.

The environmental impacts from tephra deposition at Kaipo Bog were significant and severe, and were detected in the palaeoenvironmental records despite slow peat accumulation rates and poor time resolutions. As Kaipo Bog is an ecosystem surviving under harsh climatic conditions, local vegetation communities were probably more sensitive to impacts from tephra fall as some species may have been struggling to survive locally where cooler temperatures prevailed, especially during the late Holocene (e.g. *Dacrydium cupressinum*). Also, vegetation communities may have suffered greater damage due to the close proximity of the site to the TVZ, resulting in the deposition of thicker tephra layers. The following chapter investigates volcanic impacts at a more distal location at Lake Rotoroa, Hamilton, where a warm temperate climate prevails. Palaeoenvironmental investigations at Lake Rotoroa will determine whether volcanic impacts can still be detected following tephra fall at greater distances from the TVZ, at a site which possesses climatic and environmental attributes that are most favourable for forest establishment.

**Table 5.8** Summary of vegetational and environmental changes following tephra fall at Kaipo Bog

| Tephra layer | Taxa declining | Taxa increasing | Elements declining | Elements increasing | Peat accumulation rate (per cm) | Explanation of environmental change |
|---|---|---|---|---|---|---|
| Opepe | *Halocarpus*<br>*Lepidothamnus* (distal)<br>*Prumnopitys ferruginea*<br>*Fuscospora*<br>*Collospermum*<br>*Cyathodes* | *Dacrycarpus*<br>*Libocedrus*<br>*Podocarpus*<br>*Coprosma*<br>*Griselinia*<br>Cyperaceae<br>*Cyathea smithii*<br>*C. dealbata*<br>*Pteridium*<br>triletes<br>broken grains | C, S, Al, Ca | K, Si | 24 years | Tephra deposition dried the site, encouraging invasion of seral vegetation following the decline of *Halocarpus* around bog margins. Damage to forest vegetation from tephra accumulation and associated toxic chemical leaching. Forest disturbance caused local slope instability, topsoil erosion and tephra in-wash from the catchment. Local disturbance continued for approximately 72 years after the eruption. |
| Rotoma | *Dacrydium*<br>*Halocarpus*<br>*Lagarostrobos*<br>*Lepidothamnus*<br>*Libocedrus*<br>*Podocarpus*<br>*Prumnopitys ferruginea*<br>*P. taxifolia*<br>*Empodisma*<br>*Cyathea dealbata*<br>triletes | *Phyllocladus*<br>*Fuscospora*<br>*N. menziesii*<br>*Coprosma*<br>Cyperaceae<br>*Gleichenia*<br>monoletes<br>*Pteridium*<br>broken grains | C, S, Al, Ca | Si, K, Na | 106 years | Significant damage to local podocarp forest occurred, making way for the rapid expansion of beech forest. Mire vegetation was also affected, with the decline of *Empodisma*, and the expansion of *Gleichenia* indicating tephra deposition had resulted in drier conditions across the bog. Drier mire margins encouraged the expansion of *Phyllocladus* shrubs and *Pteridium*. Vegetation disturbance initiated local slope instability, topsoil erosion and influx of tephra-derived material onto the mire from the catchment. |

| | | | | | | |
|---|---|---|---|---|---|---|
| Whakatane | *Halocarpus*<br>*Lagarostrobos*<br>*Fuscospora*<br>*Pseudopanax* | *Dacrydium*<br>*Phyllocladus*<br>*Prumnopitys*<br>*ferruginea*<br>*P. taxifolia*<br>*Coprosma*<br>Cyperaceae<br>*Myriophyllum* | C, S, Al, Ca | Si, K, Na | 160 years | Beech forest declined after the eruption, as these trees were dominant and exposed to the damaging effects of tephra accumulation. Podocarp forest then expanded within the catchment. Mire vegetation also increased. *Halocarpus* shrubs declined, making way for the expansion of *Phyllocladus*. Tephra and local topsoil inwash from the catchment occurred following forest disturbance. |
| Waimihia | *Dacrydium*<br>*Lagarostrobos*<br>*Phyllocladus*<br>(delayed)<br>*Podocarpus*<br>*Prumnopitys*<br>*ferruginea*<br>*P. taxifolia* | *Fuscospora*<br>*N. menziesii*<br>*Coprosma*<br>*Hebe*<br>*Empodisma*<br>*Gleichenia*<br>monoletes<br>triletes<br>*Metrosideros*<br>(slight)<br>*Nestegis* (slight) | C, S, Al, Ca, K | Si, Na | 238 years | Podocarp forest declined significantly following damage by tephra fall, encouraging the re-establishment of beech dominant forest. Possible expansion of mire margins occurred as mire taxa increased, probably due to forest die-back, with ferns invading forest margins and canopy gaps. Forest disturbance caused slope instability and increased inwash of topsoil and tephra-derived material onto the mire. |
| Taupo | *Phyllocladus*<br>*Prumnopitys*<br>*ferruginea*<br>*P. taxifolia*<br>*Empodisma* | *Fuscospora*<br>*N. menziesii*<br>(delayed)<br>monoletes<br>triletes<br>*Gleichenia* | C, Al, K, Si | Fe, | 237 years | Podocarp forest suffered damage from tephra fall and subsequently declined, resulting in the rapid expansion of beech forest. Drying of the bog from the deposition of tephra initiated the decline in *Empodisma* and increase in *Gleichenia*. Soil leaching and erosion occurred following forest disturbance and slope instability. |
| Kaharoa | *Dacrydium*<br>*Gleichenia*<br>*Blechnum*<br>monoletes<br>triletes | *Nothofagus*<br>*menziesii*<br>*Coprosma*<br>*Griselinia* (slight)<br>*Myrsine* (slight)<br>*Pseudopanax*<br>(slight) | Fe | Si, C, S, K, Na | 51 years | *Dacrydium* trees declined in the area while beech forest remained dominant and *N. menziesii* trees increased. Possible shrinkage of the mire occurred as mire taxa declined significantly, indicating forest now dominated the site, encroaching across mire margins. Geochemical assemblages indicate catchment stability, as little minerogenic material is present above the tephra layer. |

**Chapter 6**

**Lake Rotoroa, Hamilton**

## 6.0 Introduction

During the Quaternary the Waikato region has undergone extensive modification due to the deposition of vast quantities of volcanic tephra and ignimbrite throughout the area. During the last 15,000 years the main volcanic threat to the Waikato has been from the Taupo Volcanic Zone and to a lesser extent from Mt Egmont (see chapter two). Extensive ecological and palaeoenvironmental research in the Waikato and adjacent Rotorua areas has provided an insight into proximal volcanic impacts on vegetation communities of the past and present (Burke, 1974; Burrows, 1990; Clarkson, 1990; see chapter two). However, little is known about the extent to which forests of the region were affected by distal volcanic tephra fallout.

In order to examine distal volcanic impacts on palaeoenvironments in more detail, the study site at Lake Rotoroa, situated in Hamilton urban area (population ca. 100 000), has been chosen for investigation (Fig. 6.1; Plate 6.1). The area represents a sheltered lowland environment supporting rich diverse forest since the end of the last glacial period and throughout the Holocene, until the period of deforestation following human settlement. The site was considered for this study primarily owing to the long palaeoenvironmental record encompassed by three sediment cores extracted from the lake, extending back to the last glacial. The sediment cores contain tephra layers originating from different eruptive centres which are rhyolitic to andesitic. As a result the tephra layers display contrasting geochemistry which could have affected the local environment and vegetation communities quite differently. This site also presents an opportunity to examine tephra impacts during the last glacial, when the area was largely unforested, and the late glacial, when forest was becoming established, as well as during the Holocene.

## 6.1 The study area

Hamilton Basin is an oval-shaped depression approximately 80 km long and >40 km wide, almost completely surrounded by ranges up to 300 m high (McCraw, 1967; Selby and

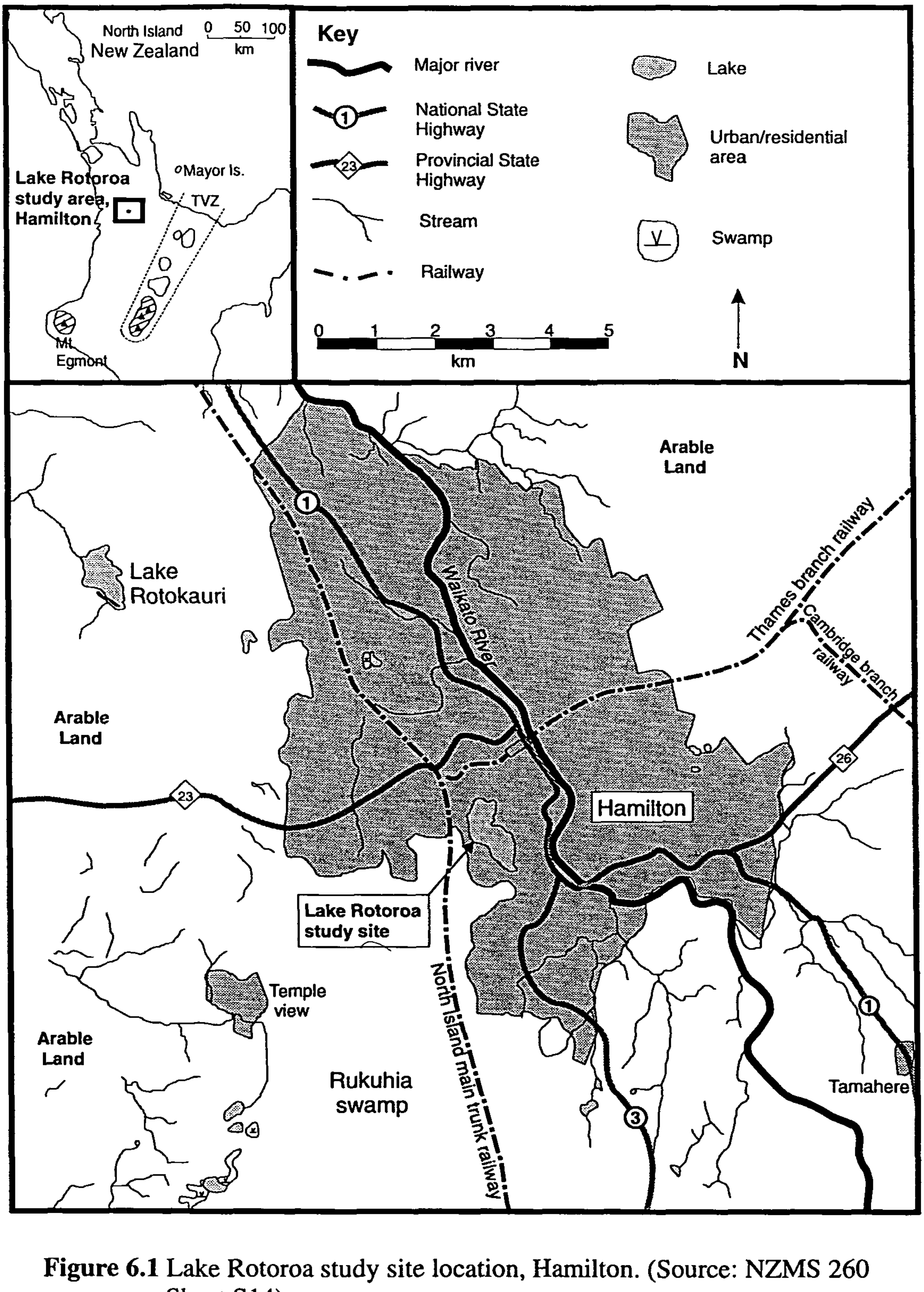



**Figure 6.1** Lake Rotoroa study site location, Hamilton. (Source: NZMS 260 Sheet S14).

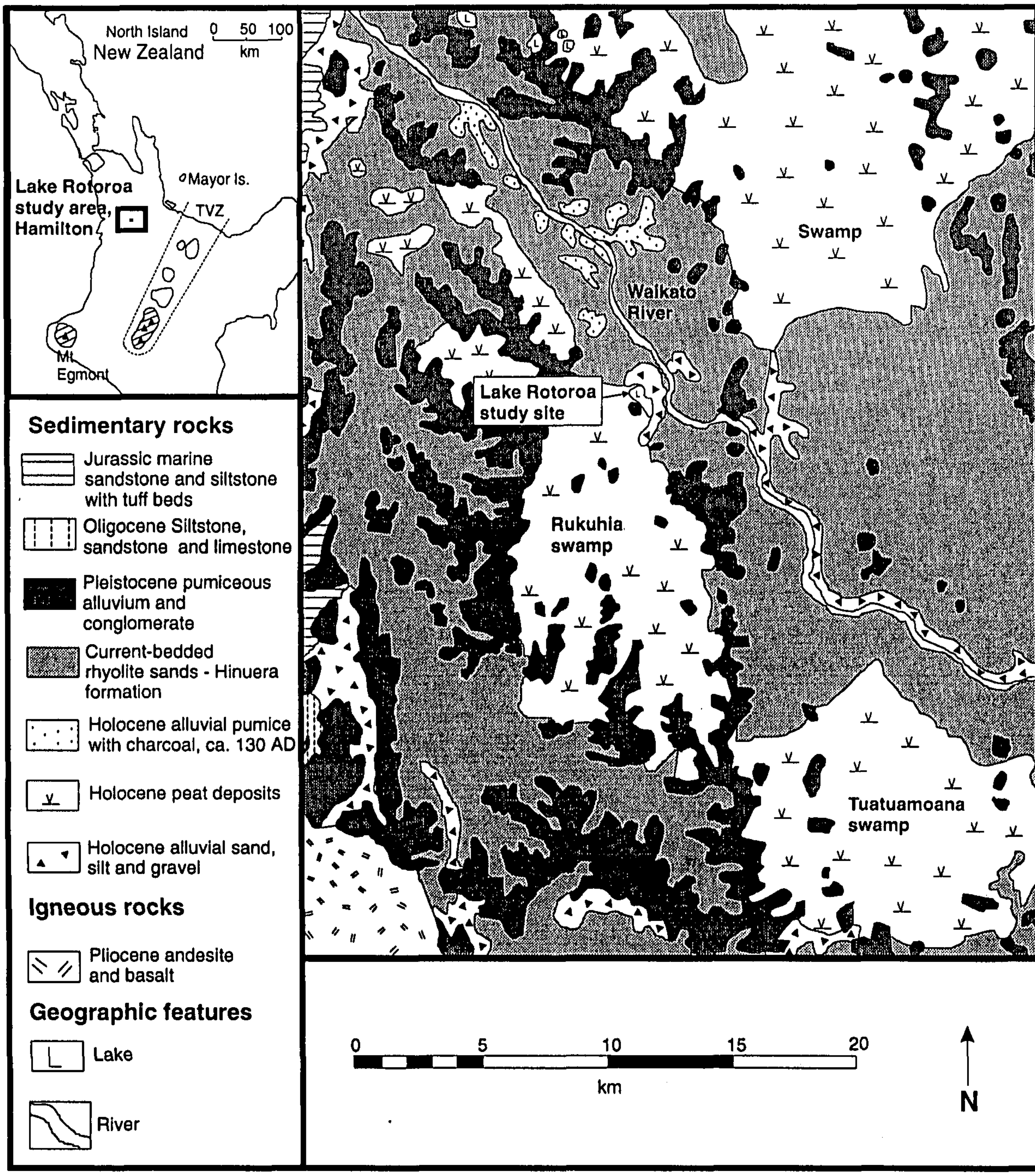



**Figure 6.2** Geology of the Hamilton area (Source: New Zealand Geological Survey map 1:250 000, sheet 4).

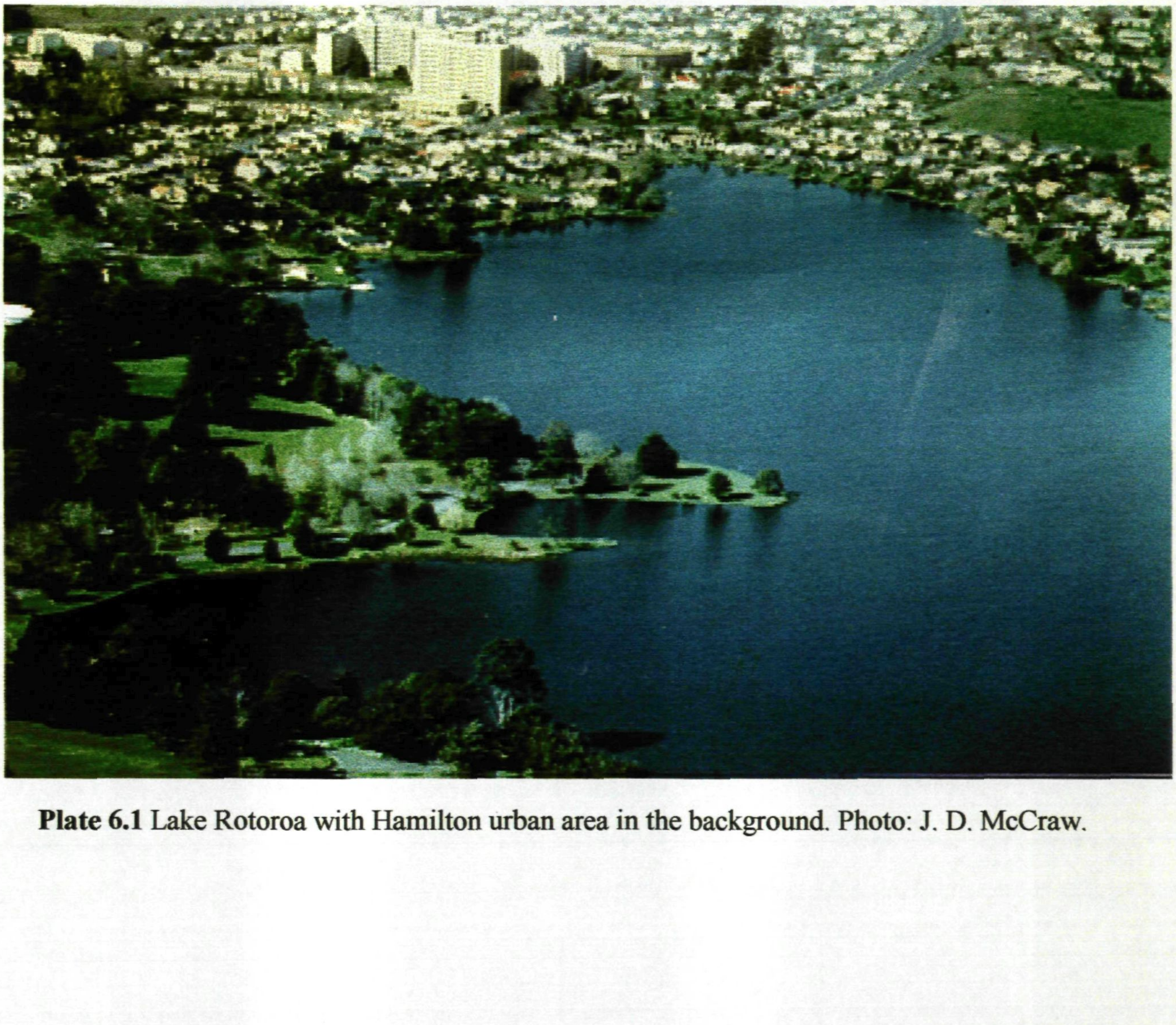


**Plate 6.1** Lake Rotoroa with Hamilton urban area in the background. Photo: J. D. McCraw.

Lowe, 1992). The ranges west and east of the basin are composed of Triassic and Jurassic greywacke sandstone, siltstones and conglomerates, overlain by Tertiary coal measures, sandstones, siltstones and limestones (Fig. 6.2). In some areas Plio-Pleistocene basaltic lava sheets and scoria mounds have been deposited over these sedimentary rocks (Selby and Lowe, 1992).

The geomorphology of the Hamilton area has largely been determined by movements of the Waikato river (Fig. 6.1). The most important geomorphological feature formed by the river is the Waikato alluvial fan. This is composed of current bedded sands and gravels, ignimbrite, andesite, greywacke and pumice together with large quantities of quartz sand collectively known as the Hinuera formation (McCraw, 1967). The most active sedimentation period occurred during the height of the last glacial, between 19,000 and 17,000 years BP. Sedimentation was significantly reduced by the end of the glacial period, ceasing around the time of re-afforestation and climatic amelioration from 15,000 years BP (Selby and Lowe, 1992). Deposition of the Hinuera formation sediments created dammed valleys and lakes in the embayments of hills which protruded through the Hinuera surface. Hamilton Lake is one of many in the area that were formed in this way (Selby and Lowe, 1992). It is a small shallow lake, with an area of 54 ha and a mean depth of 2.4 m (Speirs, 1995). A palaeolimnological study by Speirs (1995) revealed the lake was formed by 16,870 ± 270 years BP (Fig. 6.3), during the final stages of deposition of the Hinuera formation.

## 6.2 Climate

Hamilton basin is sheltered from the prevailing westerlies by the adjacent ranges. As a result the Waikato region experiences warm humid summers, mild winters and a moderate rainfall with winter maximum (Table 6.1). Winds are predominantly SW to NW, with greatest wind speeds in spring, and a smaller maximum in late autumn (de Lisle, 1967). Generally rainfall is spread evenly throughout the year, with occasional droughts in summer, and occasional flooding following days of persistent heavy rain.

**Table 6.1** Summary of climate data for the Hamilton area taken from the New Zealand meteorological Survey Bulletin.

| | Average (yr) | Average summer (Feb) | Average winter (Jul) | Average daily range |
|---|---|---|---|---|
| Temperature °C | 13.4 | 18.6 | 8.1 | 11.6 |
| Rain (mm) | 1214 | 89 | 129 | - |
| Ground frost (days) | 63.1 | 0.2 | 14.6 | - |
| Humidity (%) | 84 | 82 | 90 | - |

## 6.3 Vegetation history

Vegetation history for the Hamilton / Waikato area has been determined from palynological investigations of lake and peat bog cores in the region (McGlone *et al.*, 1984; Newnham *et al.*, 1989). Prior to 15 000 years BP the Waikato region was dominated by shrub and grassland and thus was largely unforested. Palynological studies from lakes in the Hamilton / Waikato area reveal peaks in Poaceae, *Phyllocladus*, *Halocarpus*, *Coprosma*, and increasing tree taxa, mostly *Libocedrus* and *Nothofagus*, between 18 000 to 14 000 years BP. From around 14 500 years BP rapid expansion of podocarp-hardwood forest occurred in the region during the climatic amelioration following the late glacial, which is synchronous with forest expansion in other parts of central North Island (McGlone and Topping, 1977; McGlone *et al.*, 1984).

Late glacial and early postglacial forests were dominated by *Prumnopitys taxifolia*, and also *Nothofagus menziesii*, although the latter species subsequently declined after ca. 13,000 years BP as the climate became warmer and wetter, and *Dacrydium cupressinum* became common. From 11,000 years BP angiosperm trees increased in abundance throughout the region, in particular *Metrosideros*, *Nestegis*, *Knightia* and *Quintinia*, and *Ascarina*. Tree ferns and *Dacrydium* trees became more common, indicating mild and moist climatic conditions prevailed during the early post-glacial.

Within early- to mid-Holocene forests *Ascarina* declined in the region (from ca. 9000 BP), thought to be due to a combination of increased drought and frost frequency. From 5500 years BP the climate had become drier than in the early post-glacial period. *Dacrydium* decreased in abundance, while *Agathis* and *Phyllocladus* increased along with microscopic charcoal, indicating that forest fires became more frequent across the region.

*Agathis* had become common in the Waikato area from 3000 years BP, reaching highest levels around 1000 years BP. Polynesian settlement and deforestation occurred after approximately 1000 years BP, with maximum environmental impact occurring between approximately 800-400 years BP (McGlone, 1988). Forests of the Waikato area are sparse today. *Nothofagus truncata* is found approximately 50-750 m a.s.l. often growing together with *Agathis* and *Phyllocladus* in drier areas and on ridges (Clayton-Greene, 1975). *Agathis* trees are generally found growing on the Waikato ranges, Kaimai ranges in the east, and the greywacke ranges of central and western Waikato, often together with *Phyllocladus trichomanoides* as both species have similar ecological requirements. Other *Phyllocladus* species are also found in the area today. *N. fusca* and *N. menziesii* are found growing at altitudes > 650 m (Clayton-Greene, 1975).

**6.4 Stratigraphy and Chronology of lake sediment cores**

The three lake sediment cores RCA1, RCA2 and RCA3 were extracted from the southern part of Hamilton lake (N.Z.M.S. 260 514 107753) by a team from Waikato University, New Zealand using a Livingston Piston Corer (Speirs, 1995). These three cores overlap and cumulatively reach a depth of 340 cm, which is the point of gradation from lacustrine sediment to underlying Hinuera formation sediment (Fig 6.3). Detailed palaeolimnological studies were carried out on these cores by David Speirs at Waikato University, where changes in lake production, sedimentation sources and colour changes were noted carefully (Speirs, 1995; Fig. 6.3).

Thirteen macroscopic tephra layers have been preserved in these cores. Ages and chemistry of the tephra layers included in the analysis are described in detail in Lowe (1988), Froggatt and Lowe (1990), and Table 6.2. These tephra layers, together with eight radiocarbon dates, provide an excellent time framework for palaeoenvironmental research at this site. Sedimentation rates, determined from $^{14}C$ dates and tephra ages, average 0.2 mm/yr for the entire sequence, with a range of 0.02 to 3.2 mm/yr (Table 6.3). Hence sedimentation of Lake Rotoroa has varied considerably throughout the last 16,000 years (Fig. 6.4).

**Table 6.2** Geochemistry of tephra layers investigated in cores RCA1, 2 and 3. Results are expressed as mean percentages, with numbers in parentheses representing 1 standard deviation of the mean. Data taken from Froggatt and Lowe (1990).

| Tephra layer | $SiO_2$ | $Al_2O_3$ | $TiO_2$ | FeO | MgO | CaO | $Na_2O$ | $K_2O$ | $Cr_2O_3$ | MnO | NiO | Cl | Water | Number of analyses performed |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Taupo (1850 ± 10) | 76.43 (0.64) | 13.05 (0.23) | 0.23 (0.05) | 1.81 (0.19) | 0.22 (0.05) | 1.31 (0.16) | 3.97 (0.31) | 2.84 (0.17) | | | | 0.14 (0.03) | 3.21 (1.83) | 10 |
| Tuhua (6130 ± 30) | 75.4 (0.38) | 9.43 (0.26) | 0.29 (0.05) | 5.65 (0.33) | 0.02 (0.01) | 0.24 (0.04) | 4.86 (0.31) | 3.94 (0.42) | | | | 0.17 (0.06) | 0.73 (1.16) | 16 |
| Mamaku (7250 ± 20) | 78.87 (0.5) | 12.05 (0.17) | 0.12 (0.02) | 0.87 (0.07) | 0.1 (0.02) | 0.69 (0.1) | 3.8 (0.2) | 3.38 (0.43) | | | | 0.12 (0.02) | 1.13 (1.4) | 14 |
| Rotoma (8530 ± 10) | 78.63 (0.16) | 12.33 (0.1) | 0.1 (0.05) | 0.87 (0.07) | 0.12 (0.02) | 0.71 (0.07) | 3.76 (0.06) | 3.37 (0.09) | | | | 0.11 (0.05) | 0.7 (0.43) | 10 |
| Opepe (9050 ± 40) | 76.51 (0.4) | 13.01 (0.32) | 0.18 (0.03) | 1.73 (0.06) | 0.2 (0.02) | 1.41 (0.12) | 3.86 (0.28) | 2.94 (0.13) | | | | 0.16 (0.03) | 6.33 (3.9) | 7 |
| Mangamate (9985) | 0.1 (0.07) | 2.68 (0.56) | 8 (5.5) | 80.21 (4.67) | 2 (0.72) | 0.1 (0.01) | | | 0.27 (0.11) | 0.33 (0.07) | 0.06 (0.06) | | | 5 |
| Waiohau (11850 ± 60) | 78.61 (0.3) | 12.35 (0.13) | 0.13 (0.03) | 0.92 (0.08) | 0.14 (0.01) | 0.89 (0.04) | 3.6 (0.28) | 3.26 (0.1) | | | | 0.1 (0.03) | 4.99 (3) | 10 |
| Rotorua (13080 ± 50) | 78.34 (0.58) | 12.68 (0.32) | 0.21 (0.05) | 1.26 (0.05) | 0.2 (0.08) | 1.2 (0.33) | 3.55 (0.29) | 3.19 (0.44) | | | | 0.14 (0.03) | 7.07 (1.71) | 10 |
| Rerewhakaaitu (14700 ± 110) | 78.34 (0.41) | 12.41 (0.18) | 0.14 (0.04) | 1 (0.13) | 0.13 (0.03) | 0.88 (0.07) | 3.42 (0.34) | 3.56 (0.34) | | | | 0.12 (0.03) | 3.38 (2.12) | 12 |
| Egmont 15[1] (14650 ± 200) | 49.2 | 31.47 | 0.04 | 0.64 | 0.08 | 14.66 | 3.05 | 0.19 | | | | | | 2 |

[1] Results for Egmont 15 Tephra calculated as averages from two separate analyses of Egmont 15 Tephra shards. Both analyses were undertaken on plagioclase feldspar shards present in Egmont 15 Tephra. Data obtained from Lowe (1987), pp 137-138.

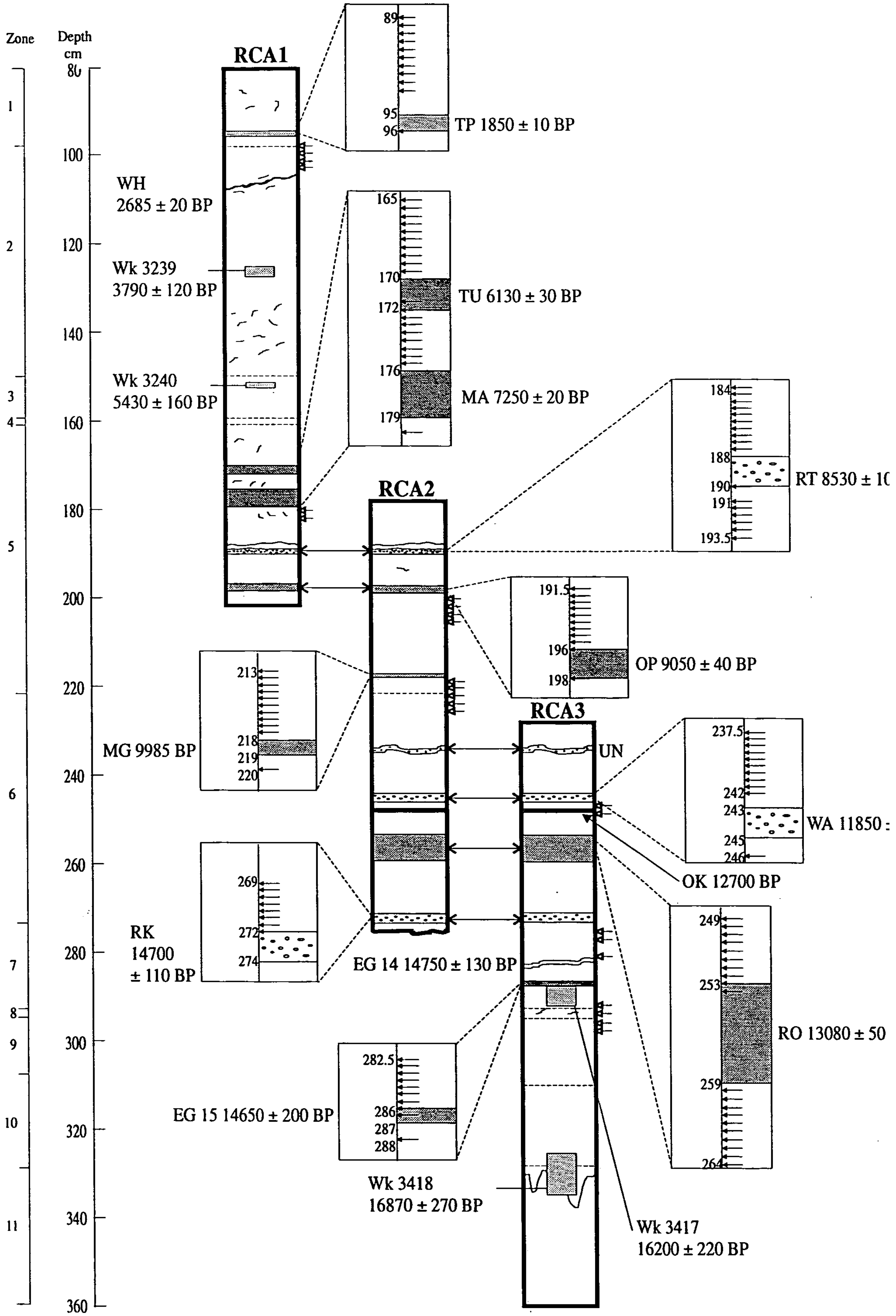
**Table 6.3** Average sedimentation rates for Lake Rotoroa.

| Depth interval of dated points (cm) and tephra layers | Radiocarbon date (years BP) | Time interval (radiocarbon years ) | Calculated sedimentation rate (mm/yr) |
|---|---|---|---|
| 11 - 65 | 810 ± 180 to 1450 ± 130 | 640 | 0.84 |
| 65 - 95 (Tp) | 1450 ± 130 to 1850 ± 10 | 400 | 0.75 |
| 95 - 108 (Wo) | 1850 ± 50 to 2685 ± 20 | 835 | 0.14 |
| 108 - 124 | 2685 ± 20 to 3790 ± 120 | 1105 | 0.15 |
| 124 - 155 | 3790 ± 120 to 5430 ± 160 | 1640 | 0.19 |
| 155 - 170 (Tu) | 5430 ± 160 to 6130 ± 30 | 700 | 0.20 |
| 170 - 176 (Ma) | 6130 ± 30 to 7250 ± 20 | 1120 | 0.05 |
| 176 - 188 (Rt) | 7250 ± 20 to 8530 ± 10 | 1280 | 0.09 |
| 188 - 196 (Op) | 8530 ± 10 to 9050 ± 40 | 520 | 0.15 |
| 196 - 218 (Mn) | 9050 ± 40 to 9985 | 935 | 0.23 |
| 218 - 243 (Wh) | 9985 to 11850 ± 60 | 1865 | 0.13 |
| 243 - 246 (Ok) | 11850 ± 60 to 12700 ± 200 | 850 | 0.03 |
| 246 - 253 (Rr) | 12700 ± 200 to 13080 ± 60 | 380 | 0.18 |
| 253 - 272 (Rk) | 13080 ± 60 to 14700 ± 110 | 1620 | 0.12 |
| 272 - 282 (Eg14) | 14700 ± 110 to 14750 ± 130 | 50 | 2.00 |
| 282 - 286 (Eg15) | 14750 ± 130 to 14930 ± 200 | 180 | 0.22 |
| 286 - 310 | 14930 ± 200 to 16200 ± 220 | 1270 | 0.18 |

## 6.5 Methodology

Of the 13 macroscopic tephra layers, 10 were chosen for volcanic impacts analysis. The tephras excluded from the analysis were very thin (i.e., < 1 cm) and intermittent (Whakaipo, at 109 cm depth, and Egmont 14 at 282 cm depth), or unidentified (at 233.5 cm depth). Fine resolution pollen and geochemical analysis was carried out above the tephra layers in order to provide a detailed examination of the impacts of distal tephra fallout on local vegetation communities and the environment. As the late-Quaternary vegetation history of Waikato is well established from previous palynological studies (see section 6.3), it was considered unnecessary to produce a similar detailed record at Lake Rotoroa. As a result, coarse sampling of the Rotoroa cores was not employed at this site. Samples for pollen and geochemical analysis were taken at 0.5 cm intervals for 5 cm above all 10 tephra layers. Samples were also taken at 0.5 cm intervals below Rotoma, Tuhua and Rotorua Tephras in order to produce and compare fine resolution records in sections of the core where tephra fall had not affected local vegetation. Below the remaining tephra layers, samples were taken at 2 cm intervals to provide a broad picture of vegetation communities flourishing in the area immediately prior to tephra deposition (Fig 6.3).

Approximate ages have also been calculated for each sample in the entire sequence, and these are presented in fine resolution pollen diagrams. Owing to the very


Zone
Depth cm
RCA1
RCA2
RCA3
TP 1850 ± 10 BP
WH
2685 ± 20 BP
Wk 3239
3790 ± 120 BP
TU 6130 ± 30 BP
Wk 3240
5430 ± 160 BP
MA 7250 ± 20 BP
RT 8530 ± 10
OP 9050 ± 40 BP
MG 9985 BP
UN
WA 11850
OK 12700 BP
RK
14700
± 110 BP
EG 14 14750 ± 130 BP
RO 13080 ± 50
EG 15 14650 ± 200 BP
Wk 3418
16870 ± 270 BP
Wk 3417
16200 ± 220 BP

## Key

Zones:

1- Sediment texture very firm.
Colour olive-black (5Y 3/1)

2 - Sediment becomes sticky, remaining firm, gradually less sticky and organic, and increasingly clayey. Colour grades from 2.5Y 2/1 to 2.5 Y 3/2, from black to brownish-black

3 - sediment texture remains firm and clayey. Colour more yellow (2.5 Y 4/2)

4 - Colour olive-black (5Y 3/1)

5 - Sediment remains constant, colour constant 5Y 4/2

6 - Gradual colour changes to 5Y 3/2, at 225cm to a darker 5Y 2/2, darkening to 5Y 2/1 below Okupata, and to green (5Y 3/2) below Rotorua

7 - Below Rerewhakaaitu, sediments become dark greyish-brown (2.5Y 4/3). Below EG 14 sediment is olive-black gyttja (7.5Y 2/2)

8 - Pale sediment band (5Y 4/3)

9 - Three 0.5cm light yellow sediment bands (5Y 7/4) with black background sediments (7.5Y 2/1)

10 - Dark green-grey sediment (10GY 3/1) - (10GY 2/1)

11 - Colour 10Y 4/2. grading darker (10GY 3/1), then into Hinuera formation fine sand-mud (10Y 6/2 - 10Y 6/1) at 348cm

Plant remains within lake sediment. Leaf/root material

Fine resolution sampling employed above and below tephra layer, 0.5cm resolution

Sampling below tephra layers, 2cm resolution

TP - Taupo Tephra

TU - Tuhua Tephra

MA - Mamaku Tephra

RT - Rotoma Tephra

OP - Opepe Tephra

MG - Mangamate Tephra

UN - Unidentified tephra

WA - Waiohau Tephra

OK - Okupata Tephra

RO - Rotorua Tephra

RK - Rerewhakaaitu Tephra

EG 14 - Egmont 14 Tephra

EG 15 - Egmont 15 Tephra

**Figure 6.3** Stratigraphy and chronology of lake sediment cores RCA1, RCA2, and RCA3 extracted from Lake Rotoroa, Hamilton. Radiocarbon ages prefixed Wk were dated at the University of Waikato Radiocarbon Dating Laboratory. Tephra ages are taken from Lowe (1988) and Froggatt and Lowe (1990). Dashed lines across core correspond to zone labels reflecting changes in sediment texture and colour.

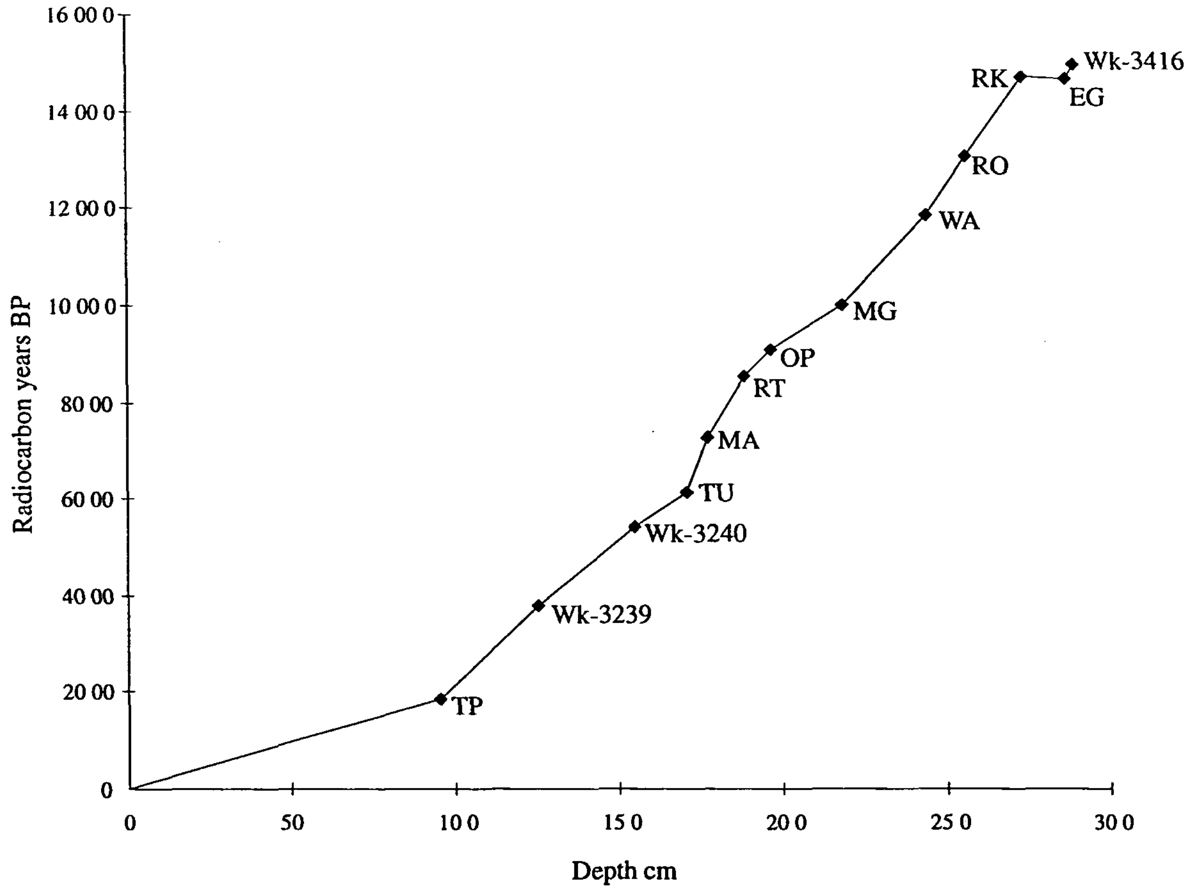



**Figure 6.4** Age-depth curve for the Lake Rotoroa sediment core. Tephra ages are taken from Froggatt and Lowe (1990) and Speirs (1995). Explanation of character codes for tephra layers are given in Figure 6.3. Ages with label prefixes Wk denote radiocarbon dated sediments extracted from the lake core.

slow sedimentation rates found above some tephras, it was not always possible to determine short-term tephra-impacts. However, above Taupo, Egmont 15, Mangamate and Tuhua Tephra layers sedimentation rates were more rapid, ranging from 7 to 29 years per 0.5 cm, permitting some insight into short-term environmental changes.

*Leptospermum* has been included in the pollen sum as it is present in relatively low proportions, and so problems of over-representation were not encountered at this site. This is common practice for lake sites.

DECORANA and cluster analyses were carried out on fine resolution pollen samples above each tephra layer. The DECORANA analysis was carried out twice on these samples in the same way as described in chapter 5. Biplots of DECORANA taxa scores are presented where these are considered to be instructive: that is, for samples analysed above Egmont 15, Rerewhakaaitu, Mangamate, Opepe, Tuhua and Taupo Tephra layers.

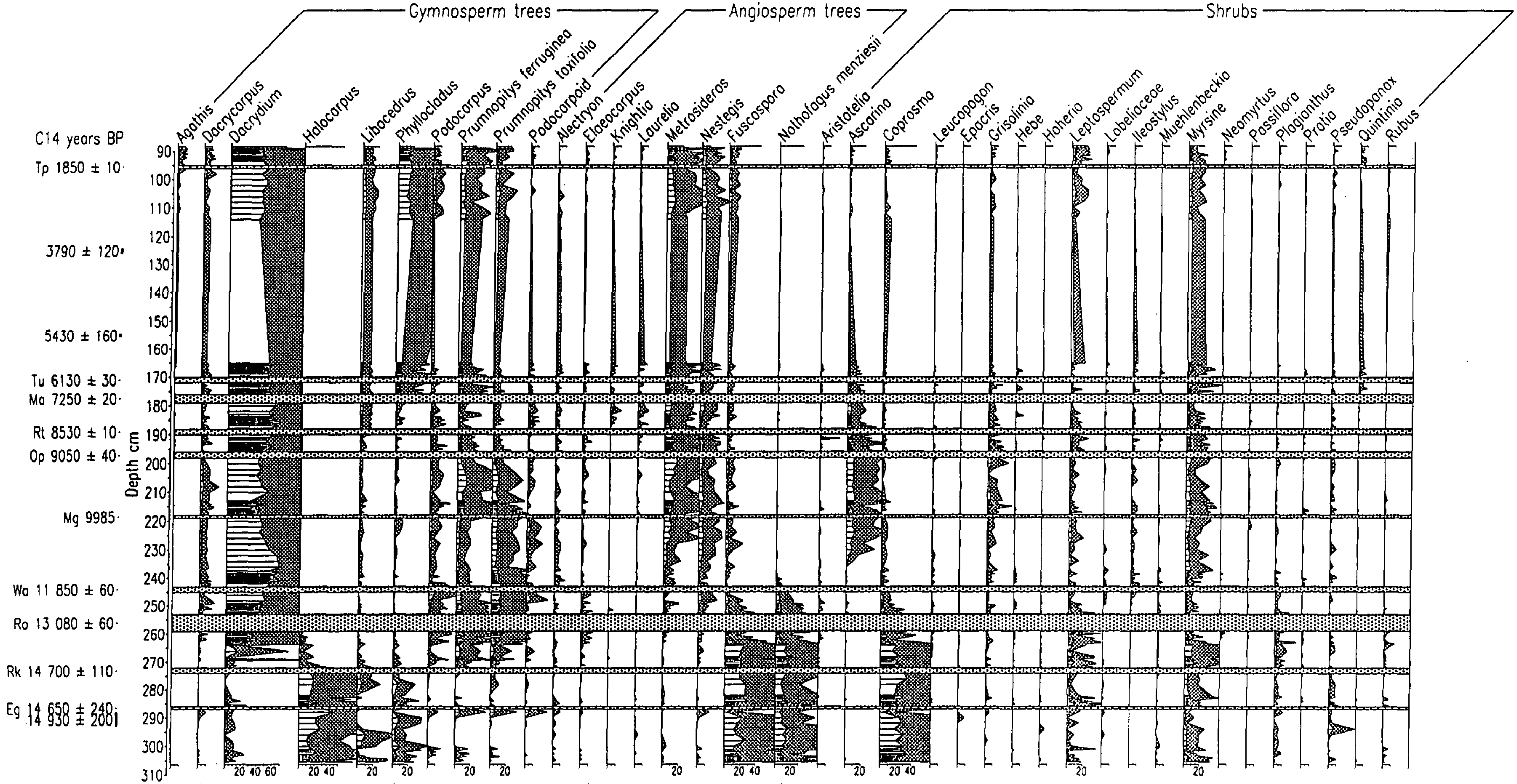
Sixteen elements were quantitatively determined using EDMA in order to reconstruct geochemical changes throughout the record, but only 9 of these were present in significant magnitude to be included for discussion in this chapter. Results for all samples analysed are presented in Figure 6.5. Percentage of organic matter was analysed by David Speirs at the University of Waikato using the 'loss-on-ignition' technique for the entire sequence. These results are displayed in Figure 6.6.

### 6.6 Results

In this section, changes in pollen assemblages and lake sediment geochemistry above and below each tephra layer are presented in chronological order. Pollen and geochemical diagrams displaying results from all 10 tephra layers are shown in Figures 6.5 and 6.7. Organic matter content for the entire sequence is displayed in Figure 6.6, and a summary of tephra chemistry and key information is displayed in Table 6.4.

**Table 6.4** Summary of tephra chemistry and key information in cores RCA1, 2, and 3.

| Tephra and age (yrs BP) | Source volcano | Distance from source | Key chemical constituents in decreasing abundance | Depth/thickness of tephra layer | Depth above tephra layer sampling commenced | Fine resolution sample timescale |
|---|---|---|---|---|---|---|
| Egmont 15 (14 650 ± 200) | Egmont | 200km | | 286-287cm | 0.5cm below tephra/lake sediment boundary | 29 years |
| Rerewhakaaitu (14 700 ± 110) | Okataina | 120km | Si, Al, K, Na, Fe, Ca | 272-274cm | immediately above tephra layer | 62 years |
| Rotorua (13 080 ± 50) | Taupo | 100km | Si, Al, Na, K, Fe, Ca | 253-259cm | 0.5cm below tephra/lake sediment boundary | 77 years |
| Waiohau (11 850 ± 60) | Okataina | 120km | Si, Al, Na, K, Fe, Ca | 243-245cm | 1cm | 78 years to first sample, then every 39 years |
| Mangamate (9985) | Tongariro | 120km | Fe, Ti, Al, Mg | 218-219cm | 0.5cm | 23 years |
| Opepe (9050 ± 40) | Taupo | 100km | Si, Al, Na, K, Fe, Ca | 196-198cm | Immediately above tephra layer | 43 years |
| Rotoma (8530 ± 10) | Okataina | 120km | Si, Al, Na, K, Fe | 188-190cm | 0.5cm | 71 years |
| Mamaku (7250 ± 20) | Okataina | 120km | Si, Al, K, Na, Fe | 176-179cm | 0.5cm | 140 years |
| Tuhua (6130 ± 30) | Tuhua | 100km | Si, Al, Fe, Na, K | 170-172cm | 0.5cm | 24 years |
| Taupo (1850 ± 10 ) | Taupo | 100km | Si, Al, Na, K, Fe, Ca | 95-96cm | 1.5cm | 24 years to first sample, then every 8 years |


Gymnosperm trees
Angiosperm trees
Shrubs
Agathis
Dacrycarpus
Dacrydium
Halocarpus
Libocedrus
Phyllocladus
Podocarpus
Prumnopitys ferruginea
Prumnopitys taxifolia
Podocarpoid
Alectryon
Elaeocarpus
Knightia
Laurelia
Metrosideros
Nestegis
Fuscospora
Nothofagus menziesii
Aristotelia
Ascarina
Coprosma
Leucopogon
Epacris
Grisolinia
Hebe
Hoheria
Leptospermum
Lobeliaceae
Ileostylus
Muehlenbeckia
Myrsine
Neomyrtus
Passiflora
Plagianthus
Pratia
Pseudopanax
Quintinia
Rubus
C14 years BP
Tp 1850 ± 10
3790 ± 120
5430 ± 160
Tu 6130 ± 30
Ma 7250 ± 20
Rt 8530 ± 10
Op 9050 ± 40
Mg 9985
Wa 11 850 ± 60
Ro 13 080 ± 60
Rk 14 700 ± 110
Eg 14 650 ± 240
14 930 ± 200
Depth cm
90
100
110
120
130
140
150
160
170
180
190
200
210
220
230
240
250
260
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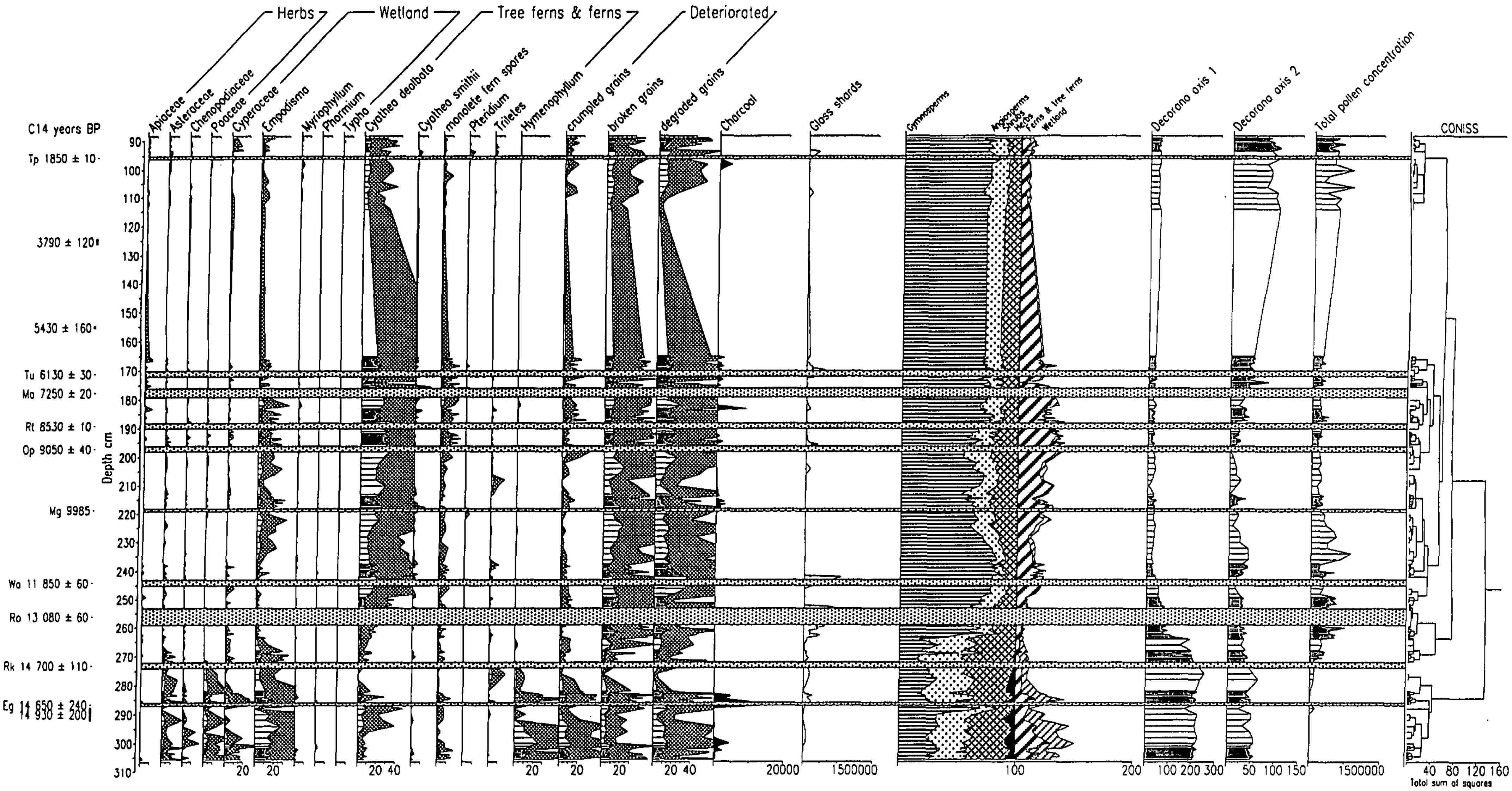



**Figure 6.5** Pollen diagram displaying changes in taxa for all samples analysed in lake sediment cores RCA 1, 2 and 3. Charcoal and tephra shards are expressed as number of fragments per $cm^3$ sediment analysed. Stippled curves represent x 5 magnification of pollen percentages.

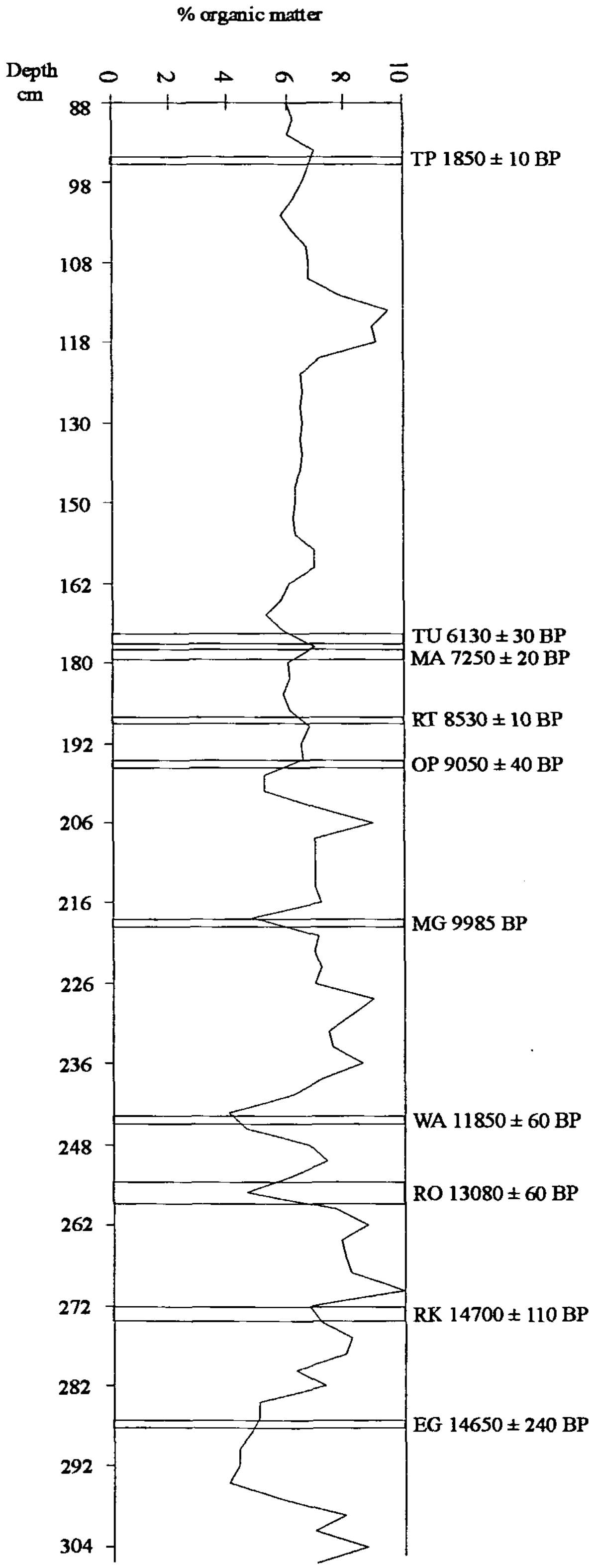



**Figure 6.6** Measurement of % organic matter in Rotoroa cores: sampling interval every 2cm where possible.

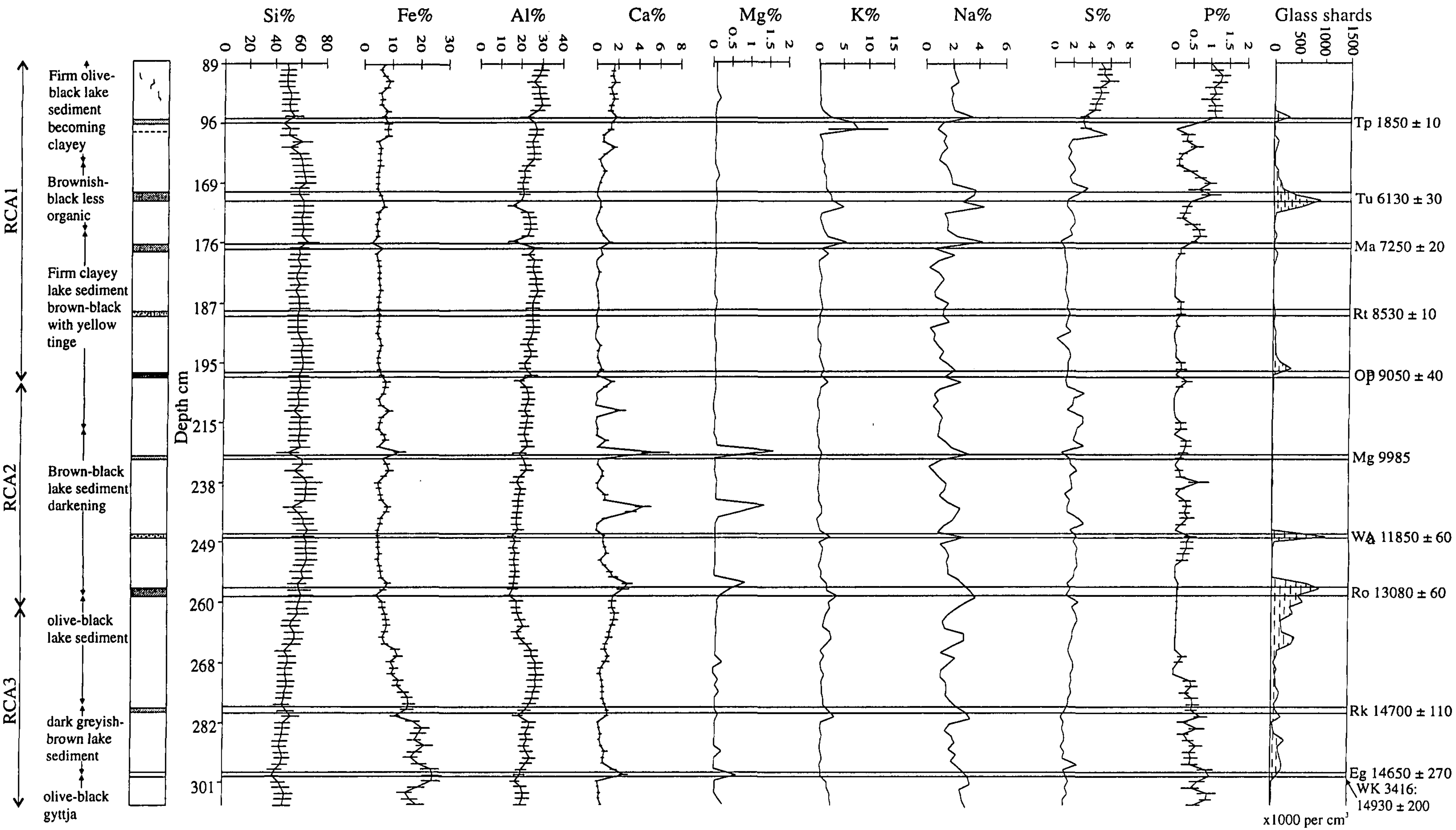



**Figure 6.7** Comparison of geochemical changes above and below 10 tephra layers analysed in the three Rotoroa cores. WK 3416 is the prefix label for the radiocarbon date taken for sediments immediately below the Egmont 15 Tephra layer. Tephra ages taken from Lowe (1988) and Froggatt and Lowe (1990).

**Table 6.5** Description of geochemistry changes around Egmont 15 and Rerewhakaaitu Tephras.

| Tephra layer | Geochemical changes |
|---|---|
| Egmont 15<br>286-287 cm | Na rises gradually to 4% at 286cm, and Fe increases to 25% at 286.5cm. Ca peaks to 3% at 287cm depth. S levels reach 3% at 285.5cm from consistent levels of 1.5%. Organic matter increases slightly from 4% to 5% at 286cm. Si remains high, fluctuating between 40-45%. Al declines slightly around the tephra layer, falling from 25% to 21% at 286.5cm. |
| Rerewhakaaitu<br>272-274 cm | Na, K and Ca increase to 3.5%, 3.8% and 1.2% respectively at 272.5cm depth. Si fluctuates around 50%. The mobile elements Fe and Al, along with S, decline within the tephra sediment, with Al falling from 28% to 20%, Fe falling from 15% to 12% and S from 2% to 1% at 272.5cm. Organic matter peaks to 10% at 270cm. |

**Table 6.6** Description of pollen results above and below Last glacial tephras

| Tephra layer and depth | Pollen changes prior to tephra fall | Pollen changes following tephra fall |
|---|---|---|
| Egmont 15<br>286-287 cm | *Halocarpus* is dominant peaking to 45% at 288cm. *Fuscospora* peaks to 20% at 290cm, declining to 5% below the tephra along with *N. menziesii*. *Coprosma* declines to 5%. *Podocarpus*, *Prumnopitys ferruginea* and *Prumnopitys taxifolia*, rise to 3%, 8% and 6% respectively. *Phyllocladus* declines to <1% at 288cm. *Empodisma* pollen fluctuates between 20-25%, disappearing at 288cm. *Cyathea dealbata* spores remain at 10%. Glass shards reach 60-90%, falling to 25% at 288cm. | *Halocarpus* declines to 5% at 285.5cm. *Podocarpus*, *Prumnopitys ferruginea* and *Prumnopitys taxifolia* all decline to <1%. *Nothofagus fusca* and *N. menziesii* pollen increases to 20% and 8% respectively. *Coprosma* rises to 25%, and *Leptospermum* and *Myrsine* increase to 12% and 5% above 286cm. Cyperaceae and *Empodisma* increase to 7% and 15% and *Hymenophyllum* peaks to 10% above 285cm. Charcoal levels reach 60% within the tephra sediment, declining to 15% at 284.5cm. Glass shards remain at 90%. |
| Rerewhakaaitu<br>272-274 cm | Highest pollen levels are shown for *Halocarpus*, *Coprosma*, *Nothofagus fusca* and *Nothofagus menziesii* reaching 15%, 20%, 30% and 10% respectively at 276cm depth. Libocedrus and *Phyllocladus* are present, reaching 5% at 278cm, declining to <3% at 276cm. *Empodisma* pollen declines to 5% at 276cm depth. Glass shards increase below the tephra to 50%. | *Halocarpus* declines significantly to <5%. Poaceae pollen, *Hymenophyllum* and Trilete fern spores disappear. *Coprosma* pollen falls to 15% at 269cm. Podocarps increase with *Podocarpus*, *Prumnopitys ferruginea* and *P. taxifolia* peaking at 5%, 10% and 7% respectively at 269cm. *Nothofagus menziesii* pollen rises to 22% at 268.5cm. *Leptospermum* and *Myrsine* increase significantly to 7% and 15% respectively. Glass shards rise to 40% at 272cm, declining to 12% at 268cm. |

**Table 6.7** Description of geochemical changes around late glacial Tephra layers

| Tephra layer and depth | Description of geochemical changes |
|---|---|
| Rotorua tephra 253-259 cm | Na rises slightly from 2 to 3.5%, and K from 1 to 4% at 258cm depth. Mg and Ca levels reach 1% and 3% respectively at 253cm. S levels fall from approximately 2.5% to 1.5% at 253cm. Organic matter falls to 4.5% at 254cm. Al values fall slightly from 18% to 15% at 258cm depth. Si levels fluctuate around 60%. |
| Waiohau Tephra 243-245 cm | K, and Na increase to 2% immediately above the tephra layer (242cm). Mg, Ca and Fe exhibit delayed increases at 239cm, with Ca and Mg peaking to 1.5% and 5% respectively at 240cm. Fe rises gradually from 5% to 10% at 240cm depth. Al declines from 20% to 16%. Organic matter falls to 4% at 242cm. Si remains consistently high around 60%. |

**Table 6.8** Description of pollen changes above and below late glacial tephra layers

| Tephra layer and depth | Pollen changes prior to tephra fall | Pollen changes following tephra fall |
|---|---|---|
| Rotorua 253-259 cm | *Dacrydium* becomes dominant, reaching 40% at 262cm. *Podocarpus*, *Prumnopitys ferruginea* and *P. taxifolia* increase to 7%, 10% and 12% respectively. *Leptospermum* pollen fluctuates between 5-10%. *Fuscospora*, *N. menziesii* and *Coprosma* all fall to between 5 - 8% at 259cm. Glass shards fluctuate around 30%, rising to 60% at 259cm depth. | Only subtle changes occur in pollen assemblages above the Rotorua tephra. *Dacrydium* pollen continues to increase, reaching 35% at 249cm. *Coprosma* pollen declines to 2%, while *Cyathea dealbata* increases to 7%. Glass shards peak to 80% at 253 cm, falling rapidly and disappearing at 251cm depth. |
| Waiohau 243-245 cm | Podocarp pollen levels are dominated by *Dacrydium* which rises to 50% at 245cm depth. *Podocarpus*, *Prumnopitys ferruginea* and *P. taxifolia* reach 8%, 5% and 10% respectively below the tephra layer. *Cyathea dealbata* spores reach 15% at 245cm. Degraded grains increase from 5% to 30%, along with glass shards, rising to 30% at 245cm. | *Dacrydium* peaks to 65% at 241cm and *Cyathea dealbata* spores rise to 20% at 240cm. *Metrosideros* and *Myrsine* pollen levels increase gradually to 4% and 7% respectively at 237.5cm. *Prumnopitys ferruginea* and *Elaeocarpus* pollen declines to 3% and <1% respectively. Glass shards peak to 80% at 242cm, subsequently disappearing at 241.5cm. |

**Table 6.9** Description of geochemical changes around Holocene tephra layers

| Tephra layer/depth | Geochemical changes |
|---|---|
| Mangamate 218-219 cm | Fe exhibits the highest increase, rising from 6 % to 12% at 218cm, together with Ca rising from 0.5 to 5%. Mg and K increase from <0.5% to 1.5 and 1% respectively, and Na rises from 0.5% to 3% at 218cm. Al declines from 25% to 20%, together with Si, falling by 10% to 50% at this depth. S levels fall from 2.5% to 1%, with Organic matter also declining to 4.8% at 218cm. |
| Opepe 196-198 cm | Na, K, Ca and Fe all increase immediately below the tephra layer, with Na and K rising to 2.5% and 2% respectively at 198cm. Ca rises from 0.5 to 1.5% at this depth, and Fe increases from 6 to 8% at 198cm depth, declining to 4% at 195cm. Al declines from 25% to 20% at 198cm. Si levels are high, fluctuating around 60%. |
| Rotoma 188-190 cm | Na and K both rise from 0.5 to 1.5% and 1% respectively above the tephra. Values for Si and Al remain consistent around 60% and 25% respectively, and are the most abundant elements present in the lake sediments at this level. |
| Mamaku 176-179 cm | Na and K rise from 1% below the tephra layer to 4% and 6% respectively at 175.5cm. Fe, Al and S decline briefly at 175.5cm, from 7% to 3%, and from 28% to 15% respectively. S exhibits a short-lived fall in values from 1.5% to 0.8% at 175.5cm. Si remains dominant fluctuating between 60 and 70%. |
| Tuhua 170-172 cm | Na and K peak below the tephra layer, to 4% and 5% respectively. Fe also increases to 7% at 172.5cm. Al declines below the tephra layer to 17%. S increases to 4% above the tephra. Si remains abundant at 60%. |
| Taupo 95-96 cm | Na increases from 1% to 3.5% at 93.5cm. K rises significantly from 0.1% to 8% between 96-100cm depth. S falls to 4% above 100cm. Al levels decline briefly from 30 to 25%. Si remains abundant, fluctuating between 45 and 50%. |

**Table 6.10** Description of pollen changes above and below Holocene tephra layers

| Tephra layer and depth | Pollen changes prior to tephra fall | Pollen changes following tephra fall |
|---|---|---|
| Mangamate 217-218 cm | *Dacrydium* pollen remains dominant, fluctuating between 45-50%. *P. ferruginea* and *P. taxifolia* pollen reaches 3% and 7% respectively at 220cm. *Metrosideros* and *Ascarina* rise to 7% below the tephra layer, and *Nestegis* and *Myrsine* increase to 5% at 220 cm depth. *Cyathea dealbata* spores fall slightly to 15% below the tephra. Glass shards increase to 10%. | *Dacrydium* pollen peaks briefly to 50% at 214.5cm, declining to 30% at 213cm. *Ascarina* pollen reaches 10% immediately above the tephra, falling to 4% at 215cm. *Cyathea dealbata* spores fluctuate between 15-20%. *P. ferruginea* and *P. taxifolia* rise to 10% at 217.5cm. *Metrosideros*, *Myrsine* and *Griselinia* pollen levels reach 13%, 7% and 5% respectively at 215cm. *Nestegis* pollen falls to 2% at 216cm. Charcoal fragments reach 2% at 217.5cm. |
| Opepe 196-198 cm | *Dacrydium* pollen fluctuates around 40%. *Ascarina* pollen remains abundant at 10%. *Metrosideros* and *Myrsine* pollen reach 14% and 5% respectively at 198cm. *Cyathea dealbata* spores increase to 30%. Glass shards peak at 204cm to 50% before disappearing at 202cm, rising again to 10% below the tephra. | *Dacrydium* pollen increases from 40% to 52% at 194.5cm. *Leptospermum* peaks to 5% at 191cm depth. Degraded grains peak above the tephra to 22% at 195cm. *Metrosideros* declines to 7% at 194.5cm, rising again to 12% at 192cm. *Ascarina* pollen declines to 5% between 195.5 and 194cm, increasing briefly to 10% at 193cm depth. Glass shards peak to 70% at 195.5cm. |
| Rotoma 188-190 cm | *Dacrydium* pollen fluctuates between 43-55%. *Metrosideros* rises to 14% at 192cm. *Ascarina* pollen falls to 7% at 190cm. *Cyathea dealbata* spores fluctuate between 23-30%. Glass shards peak to 25%, falling to 2% below the tephra layer. | *Dacrydium* pollen fluctuates between 55 - 60%. *Metrosideros* pollen falls from 10% to 5% at 184cm. *Cyathea dealbata* spores decline from 30% at 187.5cm, to 12% at 187cm. Glass shards exhibit a peak at 187.5cm to 20%, declining to <1% above 185.5cm depth. |
| Mamaku 176-179 cm | *Dacrydium* pollen levels remain at 55-60%. *Metrosideros* and *Nestegis* pollen levels are consistent at 7% and 5% respectively. Empodisma pollen exhibits a peak to 5% at 182cm. *Cyathea dealbata* fluctuates between 15-20%. Peaks occur in charcoal fragments and glass shards at 183cm, reaching 4% and 40% respectively. | **Pollen changes above Mamaku Tephra and Below Tuhua Tephra** *Dacrydium* pollen falls to 40% at 175cm. *Phyllocladus* pollen increases to 12% at 172cm, with *Nestegis* peaking to 6%. *Prumnopitys ferruginea* and *Myrsine* increase to 10% at 173.5cm. Trends for *Cyathea dealbata*, broken and degraded grains decline to zero at 174cm, increasing again to 18%, 7% and 20% respectively. Glass shards rise to 25% immediately above the tephra layer, falling to 0% at 174 cm, increasing to 80% at 172cm. |
| Tuhua 170-172 cm | | *Dacrydium* pollen and *Cyathea dealbata* spores remain abundant, fluctuating around 55%, and 20% respectively. *Prumnopitys ferruginea* increases temporarily immediately above the tephra to 7%. *Myrsine* pollen increases to 7% at 167cm. Glass shards peak to 80% immediately above the tephra layer, falling gradually to 10% at 166cm, rising to 25% at 165cm. |
| Taupo 95-96 cm | *Dacrydium* declines slightly, fluctuating between 40 and 45%. *Phyllocladus* pollen is abundant at 15-18% below the tephra layer. *Metrosideros* pollen declines from 10% to 5% at 96cm. *Cyathea dealbata* also declined to 5%. | *Dacrydium* pollen continues to fluctuate around 40% and *Phyllocladus* pollen fluctuates around 15%. *Prumnopitys ferruginea* pollen rises to 7%. *Metrosideros* and *Nestegis* pollen also increases at 93.5cm to 10% and 5% respectively. Glass shards exhibit a peak at 93.5cm to 35%. |

## 6.7 Discussion

*Volcanic impacts during the last glacial*

Prior to the Egmont 15 eruption, vegetation growing in the Lake Rotoroa area was characteristic of cooler climatic conditions, with *Halocarpus*, *Phyllocladus* (*P. alpinus*?) and *Nothofagus* species abundant at the site. Podocarp tree taxa appear in low numbers prior to the eruption, probably surviving in sheltered areas with a more favourable microclimate.

During the period between 16,870 to 14,700 years BP, sedimentation rates were comparatively high at Lake Rotoroa (Table 6.3) with basal lake sediments derived from lacustrine and fluvial sources (Speirs, 1995). Fluvial sediments originated from erosion of the Hinuera formation, which is largely composed of eroded and reworked tephra deposits. Increased levels of glass shards present in the lower 50 cm section of the core may therefore represent allocthonous input into the lake. A sparse low-lying vegetation cover would have increased soil susceptibility to run-off and erosion, also contributing to higher sedimentation rates.

Local burning occurred in the area following the Egmont 15 eruption indicated by the presence of charcoal fragments within and above the tephra layer (Fig. 6.8). Declines in podocarp trees *Podocarpus*, *Prumnopitys ferruginea*, *P. taxifolia*, *Halocarpus*, together with *Nestegis* and *Cyathea dealbata*, occurred immediately following tephra fall, coinciding with the appearance of charcoal, suggesting damage from tephra accumulation and fire were responsible. Local burning was perhaps initiated by lightning strike caused by ash accumulation in the atmosphere (Wilmshurst and McGlone, 1996). Damage to trees was particularly significant following the Egmont 15 eruption, suggesting that the vegetation was already under considerable stress during the harsh climatic conditions which prevailed at this time. Frost, wind and possibly drought had probably already weakened these trees, resulting in their inability to withstand additional stress from tephra accumulation and chemical leaching. Subsequent seral succession occurred, with increases in vegetation which typically invade following forest disturbance, in particular, *Leptospermum*, Asteraceae, Poaceae, Cyperaceae, *Coprosma* and ferns. The decline in podocarps, and increase in seral taxa was sustained for approximately 170 years, suggesting impacts from volcanic tephra accumulation and

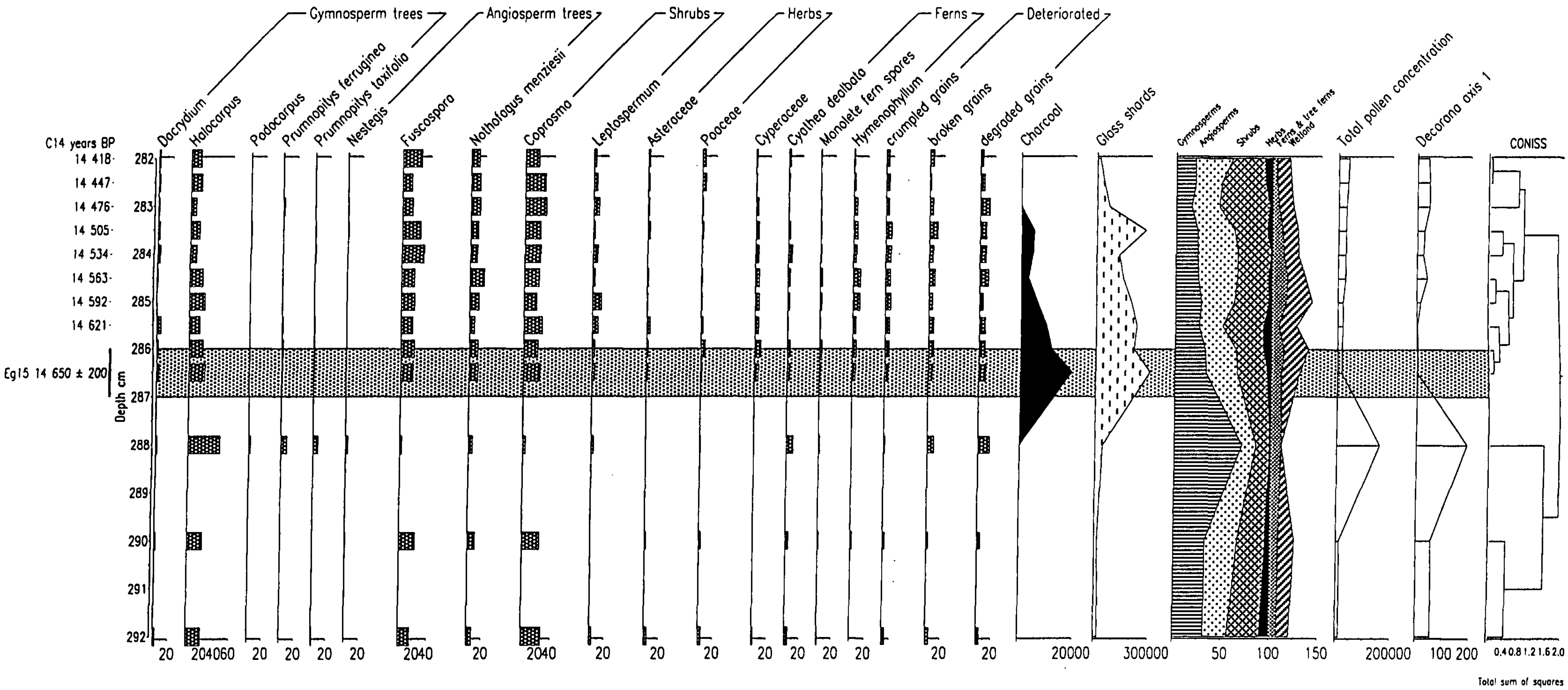



**Figure 6.8** Fine resolution pollen diagram displaying changes in main taxa above and below Egmont 15 Tephra. Charcoal fragments and glass shards are expressed as number of fragments per cm³ sediment analysed.

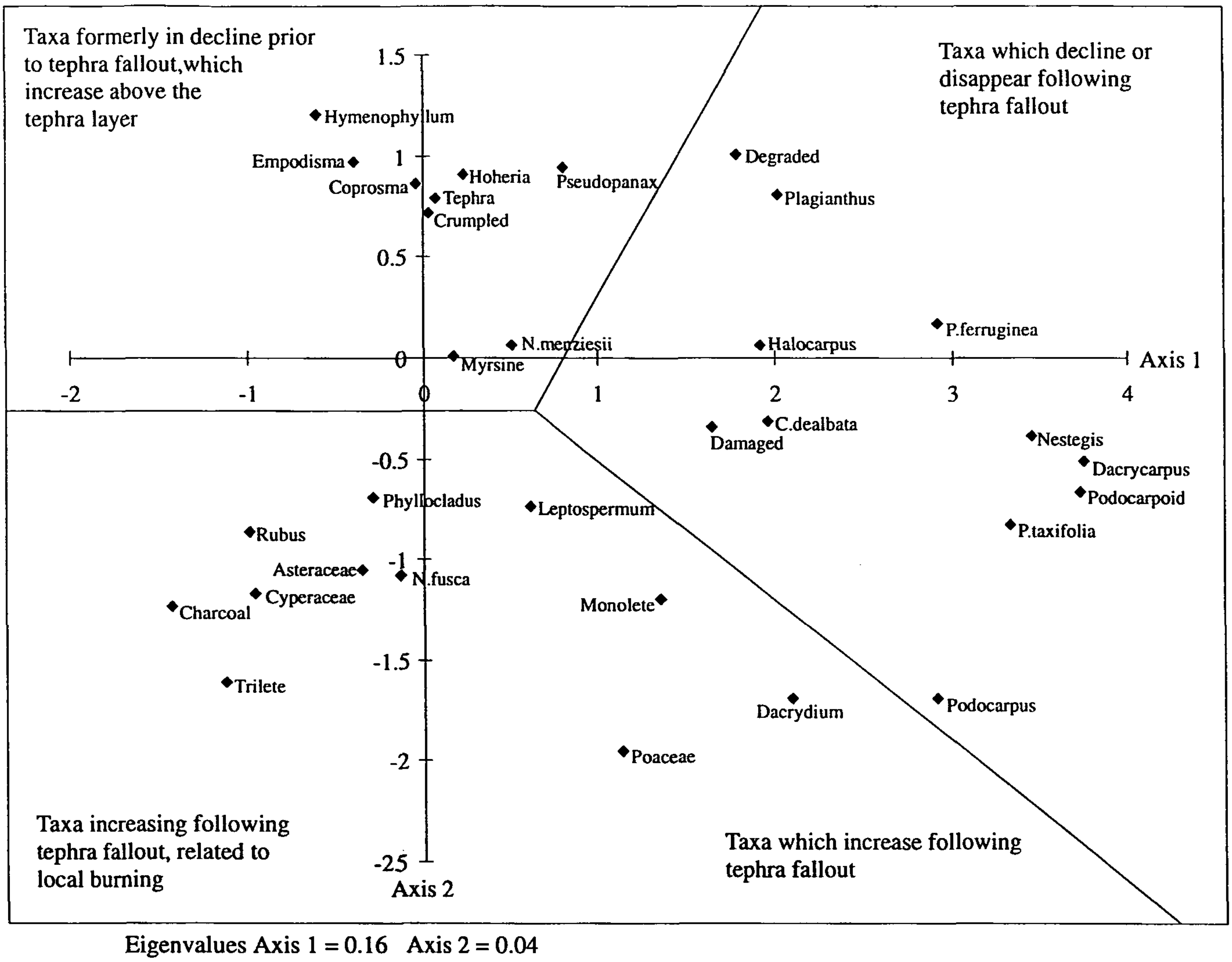



**Figure 6.9** A biplot of pollen taxon associations in spectra surrounding the Egmont 15 Tephra layer at Lake Rotoroa.

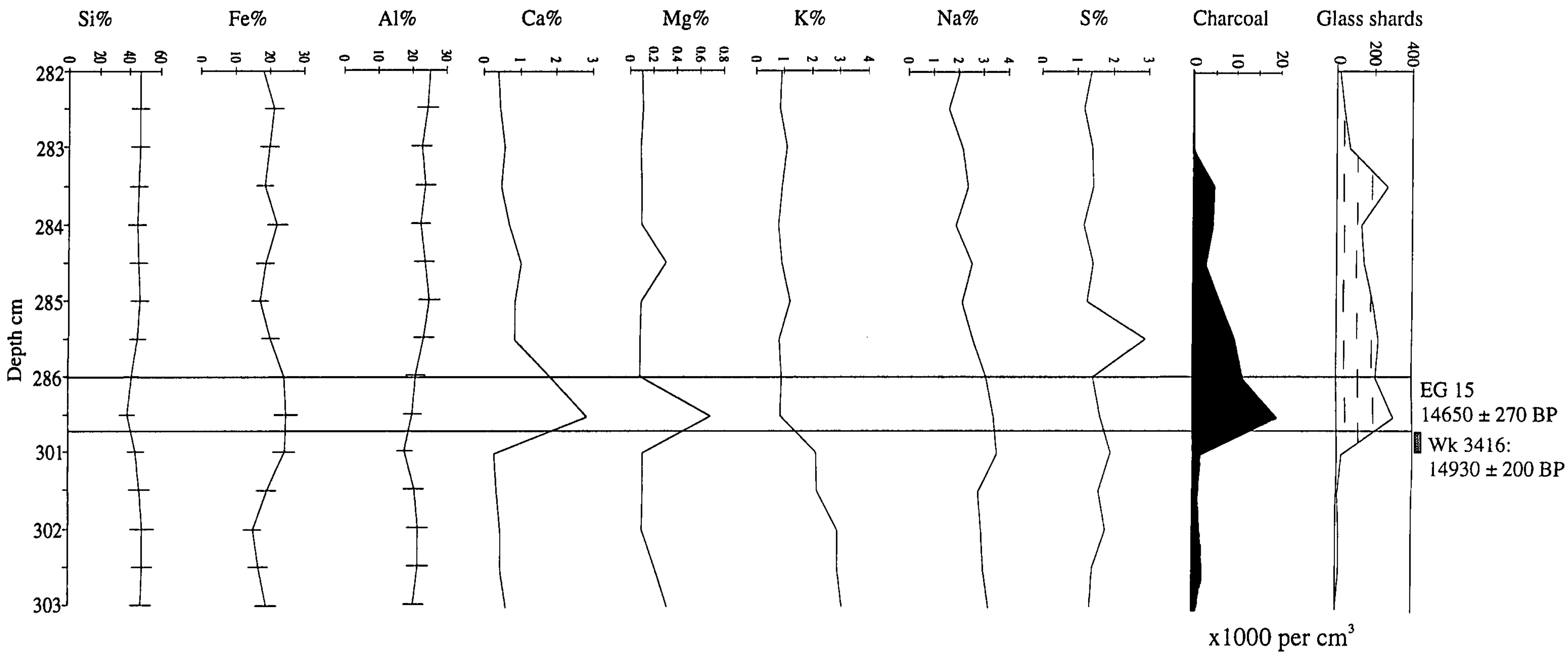



**Figure 6.10** Fine resolution sampling taken at 0.5cm intervals displaying changes in lake sediment geochemistry above Egmont 15 Tephra. Short horizontal lines indicate error bars calculated to 2 standard deviations.

associated burning were responsible for long-term changes in forest structure and development towards the end of the last glacial period.

Impacts from tephra fall and fire following Egmont tephra deposition were discernible from statistical analysis of palynological data (Fig. 6.8). A stratigraphic plot of sample scores for DECORANA axes 1 is also displayed in Figure 6.8. Higher sample scores for axis 1 reflect high taxa scores from species that are abundant prior to tephra fallout (e.g. *Halocarpus*, *Prumnopitys ferruginea*, *P. taxifolia*, *Podocarpus*, *Nestegis*). Sample scores above the tephra layer reach lowest values, as high-scoring taxa had significantly declined, and lower scoring individuals became more common (i.e., *Leptospermum*, Cyperaceae, *Hymenophyllum*, Charcoal). Results for cluster analysis (CONISS) reveal vegetation assemblages for samples within and immediately above the tephra layer (285.5 cm, 286 cm, 286.5 cm) are similar, and are clearly distinguished from those prior to tephra fallout, indicating a change in local vegetation following tephra deposition.

The configuration of taxa scores plotted on the first two DECORANA axes (Fig. 6.9) are closely related to vegetation response following tephra fallout. Taxa that decline or increase following tephra fallout have been grouped together accordingly, indicating that volcanic impact following the Egmont eruption was significant at Lake Rotoroa, and of sufficient magnitude to be determined from statistical analyses.

Lake sediment chemistry was also affected by the deposition of Egmont 15 Tephra. Minor enrichments in Na, Fe, Mg and Ca occur in lake sediments intermixed within the macroscopic tephra layer (Fig. 6.10). Microscopic tephra shards increase above the tephra layer and were likely to have been incorporated into the lake following soil surface run-off. Shards are disseminated below the layer, possibly due to mixing and leaching of soluble elements (i.e., Na, K). Background Si and Al levels are high, and hence are not significantly affected by the deposition of tephra in the local area. Si and Al are the most abundant elements in lake sediments, with Si often enhanced in lakes due to increased biological activity (Pennington, 1982). Organic matter content is lower owing to incorporation of minerogenic tephra-derived sediments, resulting in a higher ratio of minerogenic to organic material around the macroscopic tephra layer.

A peak in S occurs 0.5 cm above the tephra layer, which spans an estimated 28 years of sedimentation, suggesting lake chemistry and biological productivity was affected by Egmont 15 Tephra deposition. Leaching of toxic elements from the tephra may have initiated the formation of algal blooms, reducing light penetration within the lake for other flora and fauna. It is clear that the impact of tephra fall on lake chemistry is quite pronounced, but is relatively short-lived, as conditions appeared to return to pre-eruption stability after ca. 28 years.

Vegetation characteristic of a cooler climate still dominated the local area prior to the Rerewhakaaitu eruption (Fig. 6.11). Vegetation cover remained relatively sparse, with patchy *Nothofagus* forest and low-lying shrub, herb and fern taxa common in the area. The frequency of glass shards remains consistently high owing to local erosion of the Hinuera formation and continued fluvial input into the lake, so that sedimentation rates remain comparatively high at this time (Speirs, 1995; Table 6.3).

It is difficult to determine the extent to which deposition of the Rerewhakaaitu Tephra affected local vegetation assemblages as each fine resolution sample represents approximately 62 years of sedimentation (Fig. 6.11). The sample taken at 272 cm, immediately above the tephra layer, provides the only possible indication of vegetation assemblages. It is therefore unlikely that the prolonged changes in vegetation illustrated in Figure 6.11 were entirely due to volcanic impact. Other factors were likely to have contributed to long term changes, and volcanic impacts appear to be short-lived, and of little significance overall, as shown in the biplot of taxa scores (Figure 6.12). A decline in *Halocarpus* and gradual decrease in *Coprosma* trees may partially be explained by climatic amelioration. However, their decline may have been initiated or accelerated by tephra accumulation and leaching of toxic chemicals, causing damage to leaf structure, inhibiting the physiological processes required for plant growth and survival. The additional stress on these plants possibly caused their rapid decline after the eruption. Poaceae and *Hymenophyllum* ferns also declined as forest taxa became more common in the area. Gradual increases in podocarp-angiosperm forest taxa occurred following the eruption, in particular *Dacrydium*, together with minor increases in *Alectryon*, *Cyathea dealbata* and *Rubus*. These changes are comparable with those recorded by Newnham *et al.* (1989), indicating re-afforestation in the Waikato area commenced soon after

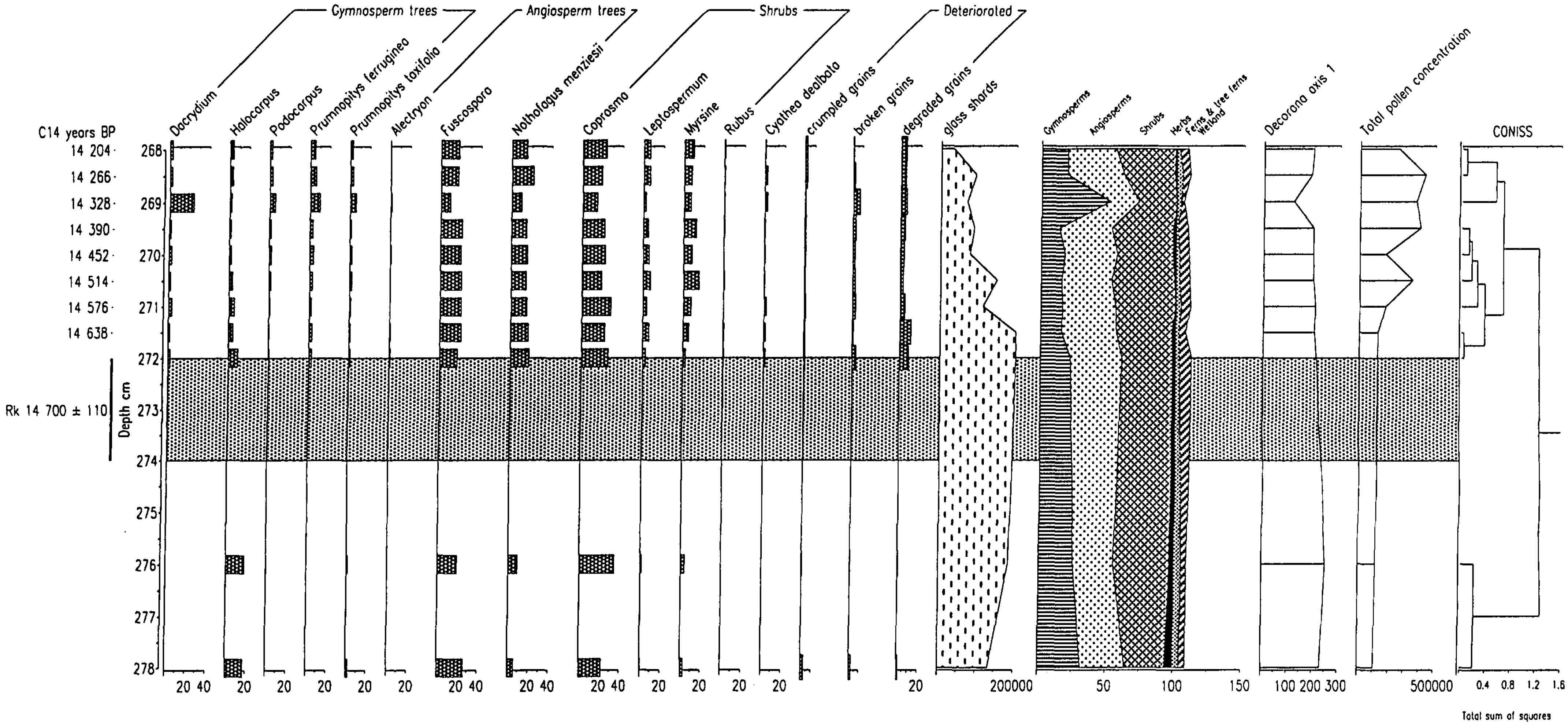



**Figure 6.11** Fine resolution pollen diagram displaying changes in main taxa above and below Rerewhakaaitu Tephra. Glass shards are expressed as number of fragments per cm³ sediment analysed.

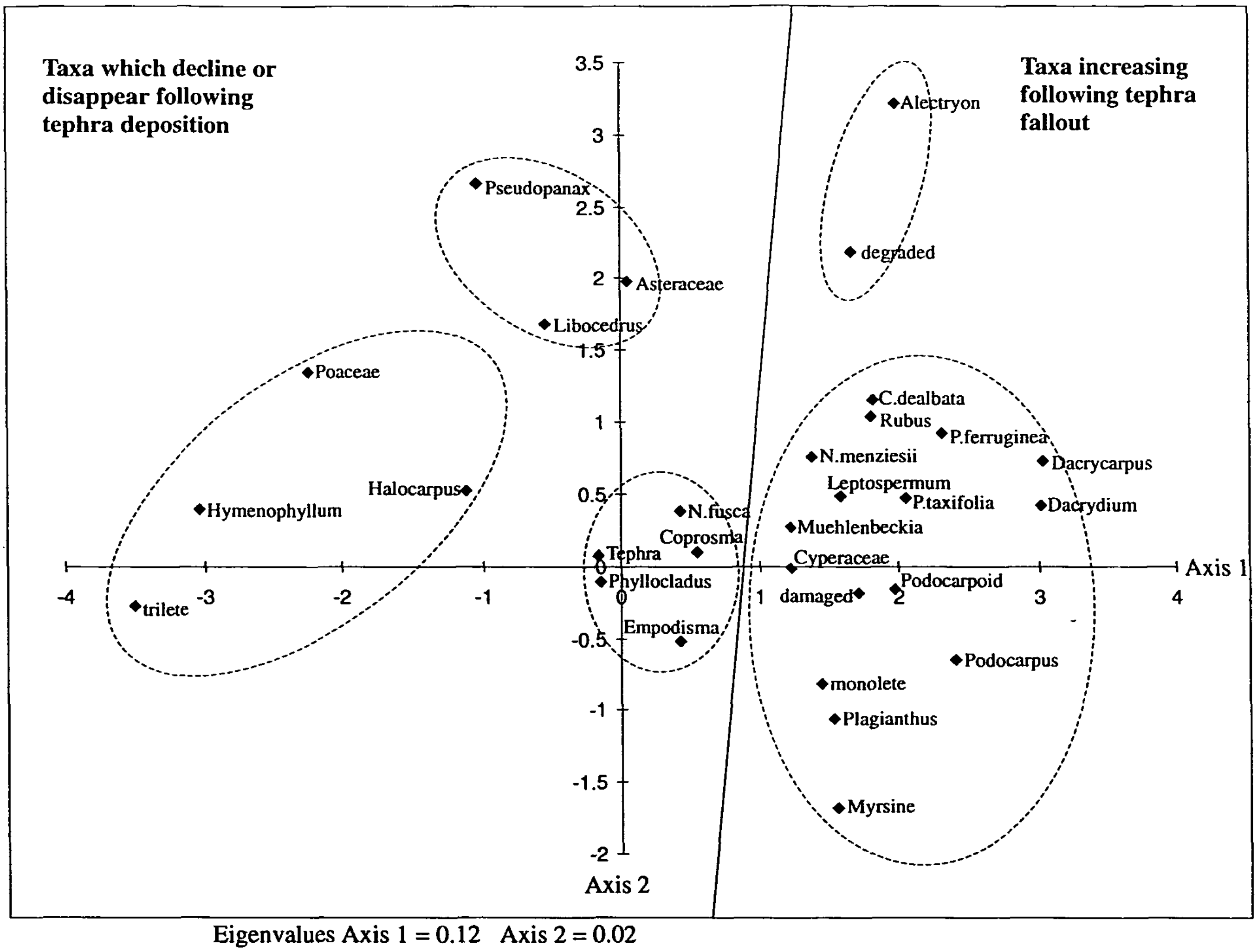



**Figure 6.12** A biplot of pollen taxon associations in spectra surrounding the Rerewhakaaitu Tephra layer at Lake Rotoroa

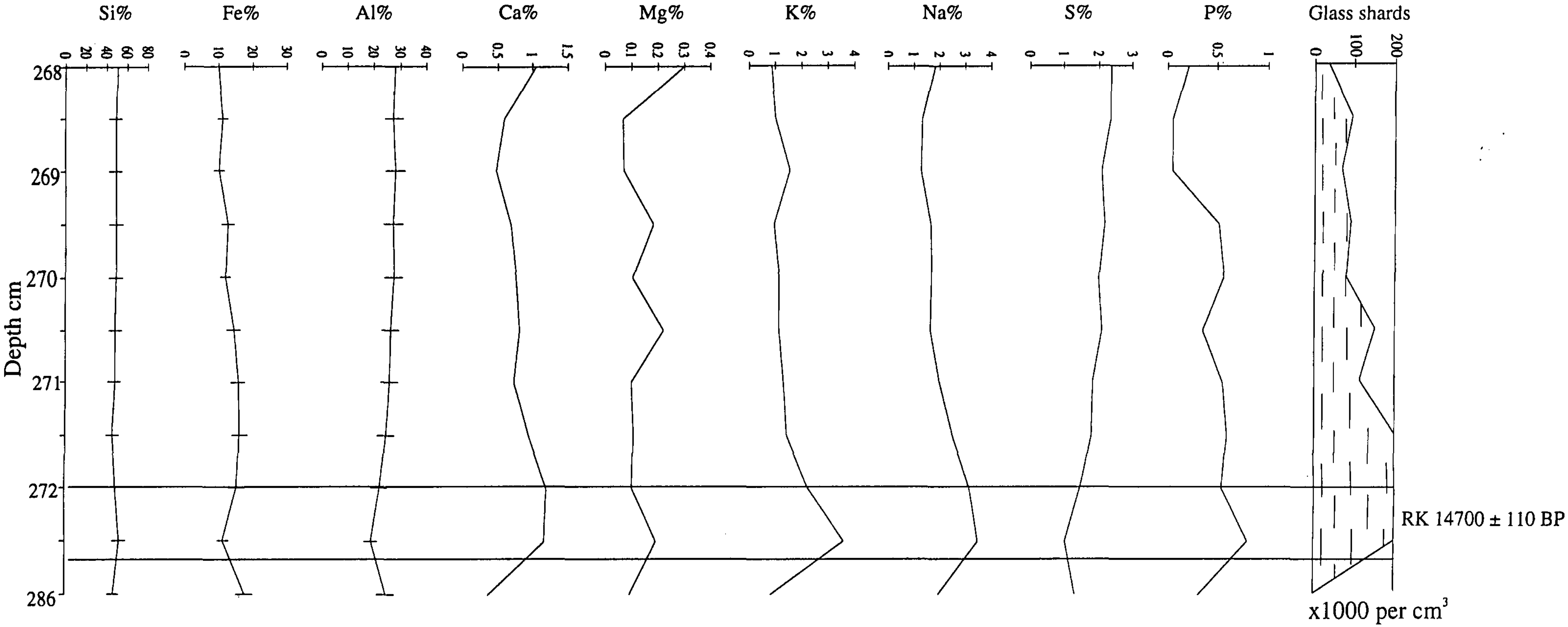



**Figure 6.13** Fine resolution sampling taken at 0.5cm intervals displaying changes in lake sediment geochemistry above Rerewhakaaitu Tephra. Short horizontal lines indicate error bars calculated to 2 standard deviations.

deposition of the Rerewhakaaitu Tephra. *Nothofagus menziesii* trees were still prominent in the area, as pollen levels remain too high to represent a distal source. Newnham *et al.* (1989) noted that *N. menziesii* remained abundant in the area until 13,000 years BP, indicating temperatures were up to 3° C cooler than present.

Evidence for gradual climate warming can be seen from the stratigraphic plots of DECORANA samples scores (Fig. 6.11). Higher sample scores on DECORANA axis 1 below the tephra layer are derived from taxa characteristic of cooler climatic conditions (i.e., *Halocarpus*, *Libocedrus*), while low-scoring taxa characteristic of a milder wetter climate become more abundant above the tephra layer (i.e.,, *Dacrydium*, *Prumnopitys ferruginea*). Cluster analysis (Fig. 6.11) shows samples immediately above the tephra are clustered together, reflecting a significant change in local vegetation assemblages following tephra deposition. Climate change appears to have strongly influenced the distribution of taxa scores plotted on the first two axes from the DECORANA output (Fig. 6.12).

The geochemical record shows increases in Na, K and Ca at the base of the macroscopic tephra layer (Fig. 6.13) indicating a higher proportion of these elements within tephra-rich lake sediments, than in allogenic material within lake sediments derived from weathering of catchment soils. High levels of Si and Al are also present within the Rerewhakaaitu Tephra (Table 6.3). However, levels of these elements remain consistent within and above the tephra layer, which suggests the Si and Al content of lake and tephra sediments are similar. Large reservoirs of Si and Al occur in lake sediments, and so minor fluctuations in these elements following tephra fall are not detected against normal background levels (Engstrom and Wright, 1987). Microscopic tephra shards present above the main tephra layer probably derived from inwashing from soil surfaces soon after tephra deposition, together with continued influx of eroded sediments from the Hinuera formation. The peak in organic matter at 270 cm (Fig. 6.6) reflects input of plant detritus due to the increase in vegetation density around the lake margins as climate improved.

*Volcanic impacts during the late glacial*

Podocarp forest had become well established in the area prior to the Rotorua eruption and was dominated principally by *Dacrydium* together with *Prumnopitys* *taxifolia* and a scattered distribution of *Podocarpus* and *Prumnopitys ferruginea* trees. Tephra shards remain abundant below the Rotoma Tephra layer, although less so than below the Rerewhakaaitu and Egmont tephras, indicating falling sedimentation rates during rapid re-afforestation and subsequent stabilisation of slopes in the area.

The samples within and immediately above the Rotorua Tephra (253 cm, Figure 6.14) can be assumed to represent vegetation communities present around the site immediately following the eruption. *Halocarpus* completely disappears, possibly indicating damage from tephra fall eliminated the remaining *Halocarpus* shrubs, which were already under pressure following competition from expanding forest taxa, and were declining in response to climate change. A substantial amount of ash accumulated around the lake following the Rotorua eruption, forming a tephra layer 6 cm thick. This amount of ash and associated toxic chemicals is likely to have caused severe damage to a sparse, declining population of *Halocarpus* shrubs. The continued decline in *Myrsine* following the Rotorua eruption may also indicate some damage to these trees from tephra accumulation, as pollen levels exhibit a sudden temporary decrease above the tephra layer, increasing again after ca. 77 years. *Elaeocarpus* and *Podocarpus* trees also declined, indicating possible initial damage from tephra fall. However, increased competitive pressure from expanding forest taxa (i.e.,, *Dacrydium*, *Cyathea dealbata*, *Metrosideros*, *Griselinia*) probably caused their sustained (ca. 180 yr) decline.

By ca. 13 000 years BP, podocarp-angiosperm forest had become well established, rather than merely surviving in sheltered niches as was the situation for earlier tephra falls. Forest vegetation had become more resilient to volcanic tephra accumulation and associated chemical and gas emissions. Trees that were affected by tephra fallout following the Rotorua eruption (i.e.,, *Elaeocarpus* and *Prumnopitys ferruginea*) were uncommon in the area at this time. These taxa were probably mostly represented by juveniles that were more sensitive to damage from volcanic tephra accumulation. The long time interval between fine resolution samples (77 years) creates difficulty in determining the duration of possible tephra impact on local vegetation. Damage from tephra accumulation may have initiated the vegetation changes described above, which were sustained due to climate change and competitive pressure from expanding forest taxa.

Statistical analyses reveal the main external influences on local vegetation trends

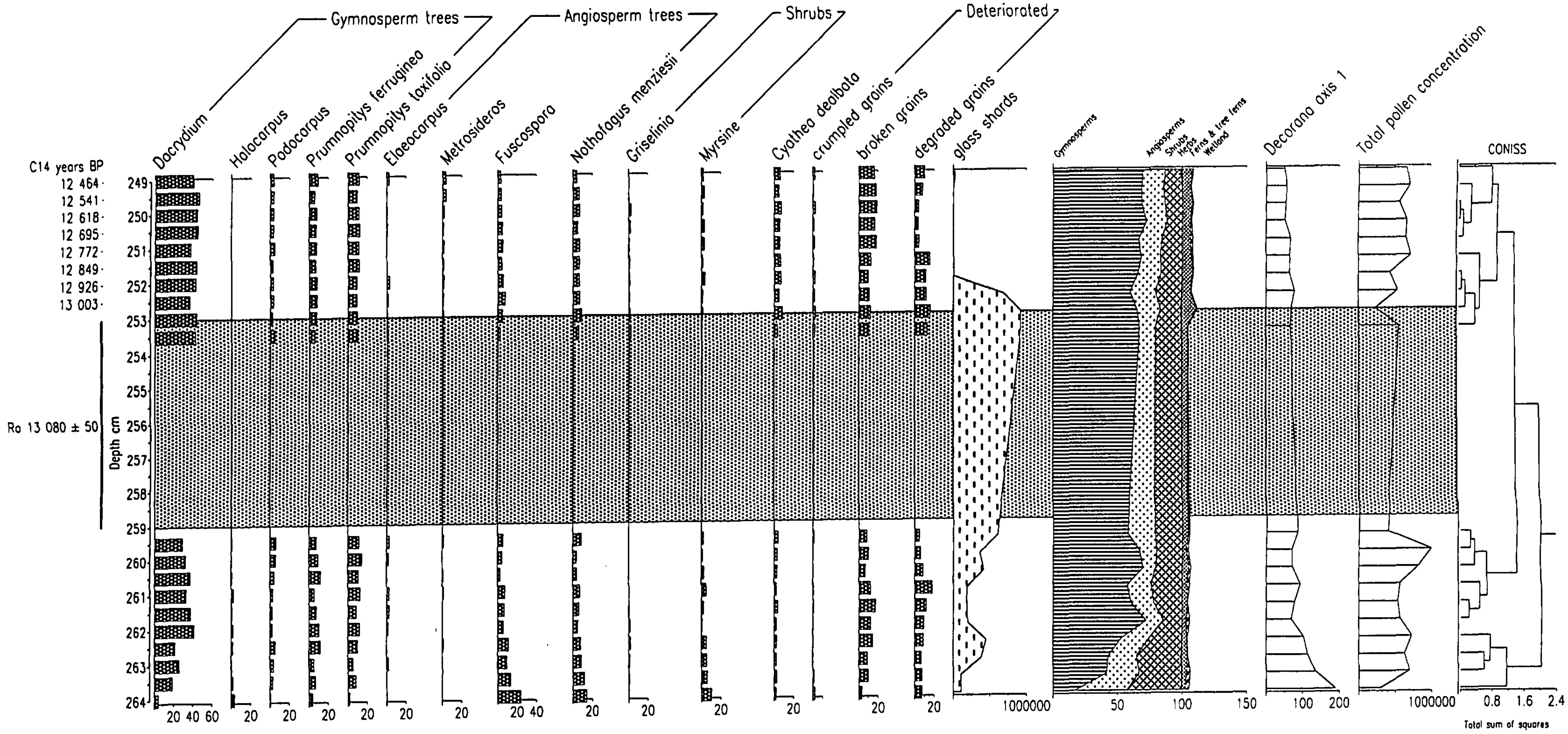



**Figure 6.14** Fine resolution pollen diagram displaying changes in main taxa above and below Rotorua Tephra. Glass shards are expressed as number of fragments per $cm^3$ sediment analysed.

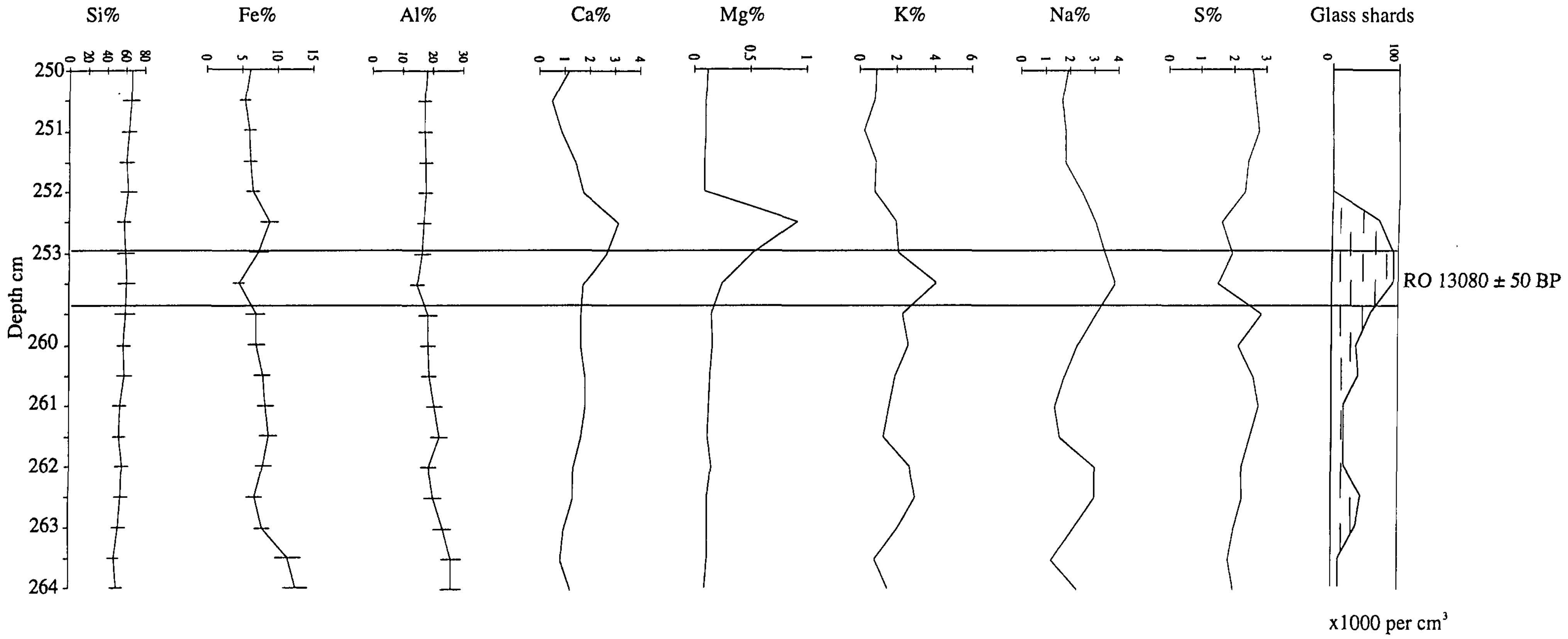



**Figure 6.15** Fine resolution sampling taken at 0.5cm intervals displaying changes in lake sediment geochemistry above and below Rotorua Tephra. Short horizontal lines indicate error bars calculated to 2 standard deviations.

were likely to have been due to a combination of climate, competitive pressure, and volcanic impact. Stratigraphic plots of sample scores for DECORANA axis 1 (Fig. 6.14) show high-scoring cool climate vegetation contributing to sample scores (i.e., *Halocarpus*, *Nothofagus menziesii*) which declined considerably above the tephra layer, while warm temperate vegetation (low-scoring taxa) became more common (i.e., *Dacrydium*, *P. ferruginea*). No clear distinction is observed between taxa increasing or decreasing above the tephra layer; hence it can be concluded from these results that volcanic impacts were important, but the influence of climate change possibly had a greater effect on local vegetation changes.

Tephra shards are particularly abundant immediately above the tephra layer, accumulating in the lake via inwash from surrounding slopes and soil surfaces. The influx of tephra shards continued for approximately 180 years, and is likely to be related to the thickness of the tephra deposit (6 cm), with soil surface layers becoming enriched in tephric material. Continued weathering of soils under stable environmental conditions resulted in the long-term influx of tephra shards into the lake. The geochemical record displays slight increases in K, Mg and Ca within and immediately above the tephra layer. These increases reflect the high proportion of clastic tephra material derived from primary airfall deposition, and secondary deposition following weathering of the tephra layer and subsequent inwashing from soil surface horizons (Fig. 6.15). Na increases below the tephra layer indicating downwards leaching of this element. Fe levels are lower within the tephra-rich sediments at the base of the macroscopic tephra layer as the Rotorua Tephra contains low relative proportions of iron (Table 6.2). A greater proportion of minerogenic material together with lower organic matter probably caused the temporary reduction in S, relating to an overall reduction in biological productivity. The magnitude of tephra-induced geochemical change is likely to be underestimated here, owing to the poor time resolution between samples. Therefore, initial impacts from tephra fall on lake sediment geochemistry were probably obscured by long-term geochemical changes.

Difficulties were encountered in determining the impact of tephra fall on vegetation following the Waiohau eruption. Fine resolution sampling commenced 1 cm above the tephra layer, ca. 78 years after the eruption. Short-term volcanic impacts in the palynological and geochemical records were not discernible at this sampling interval as the tephra layer was relatively thin (2 cm); hence impacts were probably subtle and obscured by long-term environmental changes.

*Volcanic impacts during the Holocene*

Local podocarp-hardwood forest had become more diverse prior to the Mangamate eruption (ca. 9985 BP). Angiosperm trees and shrubs became established in the area, in particular, *Ascarina*, *Metrosideros*, *Nestegis* and *Myrsine*. These changes are synchronous with those recorded at nearby Waikato lake sites by Newnham *et al.* (1989), with the expansion of *Dacrydium* and *Ascarina* trees indicating warmer temperatures and increased precipitation in the Waikato region.

A sustained decline in *Phyllocladus* trees and shrubs commences within ca. 23 years after the Mangamate eruption (Fig. 6.16). The coincident appearance of charcoal fragments, suggests these trees suffered fire damage at this time. It is unlikely that dry and windy conditions initiated local burning as a period of wetter climatic conditions prevailed between 10 000 and 8000 years BP (Salinger *et al.*, 1993). It is therefore reasonable to suggest that burning was probably initiated by lightning strike, resulting from the generation of electrical charges from volcanic ash and gas accumulation in the atmosphere. *Nestegis* trees also declined following the eruption, although this is very gradual (over a 160-year period), with these trees recovering towards the top of the diagram. The decline in *Nestegis* is likely to be related to increased competitive pressure. *Prumnopitys ferruginea*, *P. taxifolia* and *Ascarina* became more common after the eruption, together with minor increases in *Elaeocarpus* and *Cyathea smithii*, and these taxa were possibly invading canopy gaps created following vegetation damage by fire. These trees, shrubs and tree ferns may have also benefited from improved soil fertility and structure following tephra deposition, especially *P. taxifolia* which prefers mineral-rich fertile soils (Wardle, 1990). Increases in *P. taxifolia* have been recorded following tephra deposition at other sites in the North Island (Chapter 7; Newnham *et al.*, 1989; Newnham and Lowe, 1991). Gradual increases in *Podocarpus*, *Metrosideros*, *Griselinia* and *Myrsine* trees also occurred, possibly indicating increased availability of drier ground

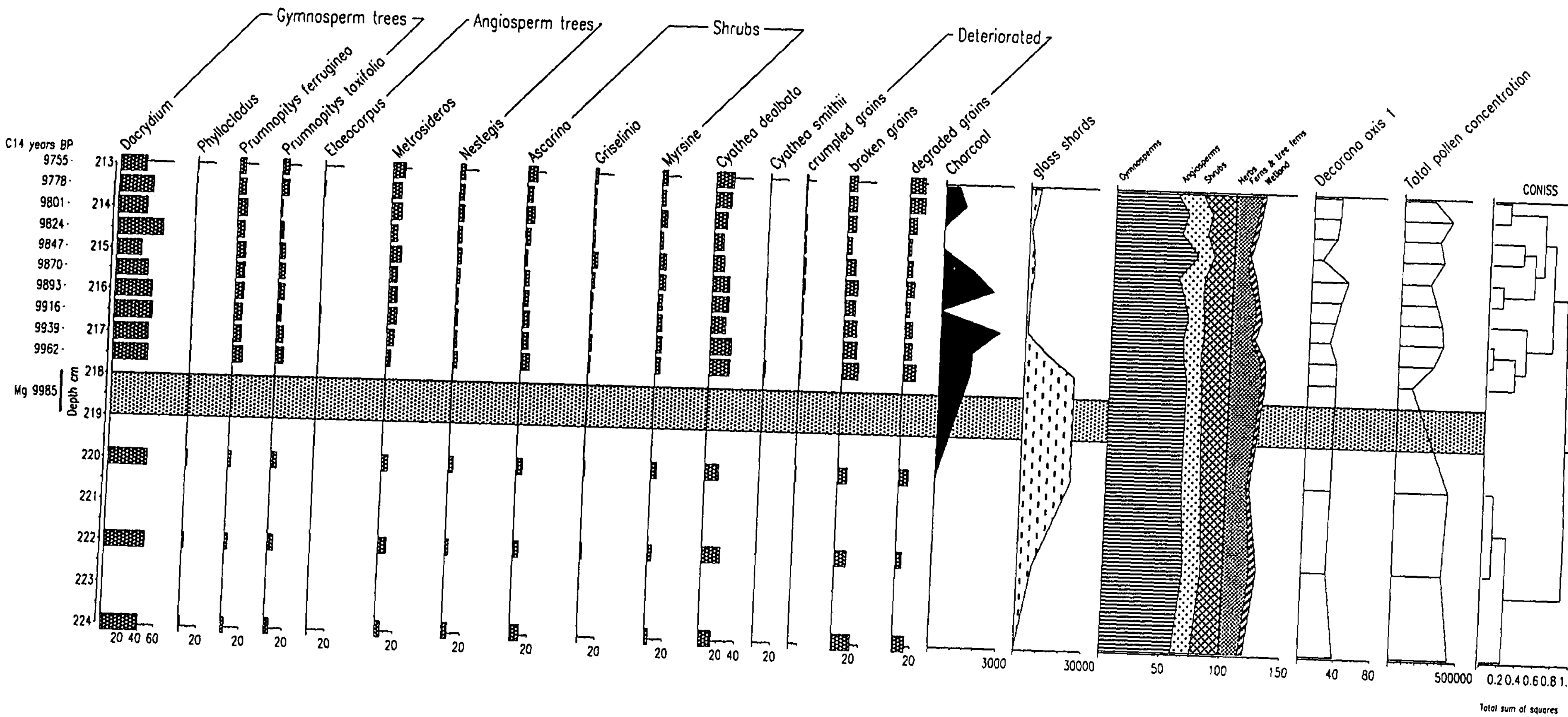
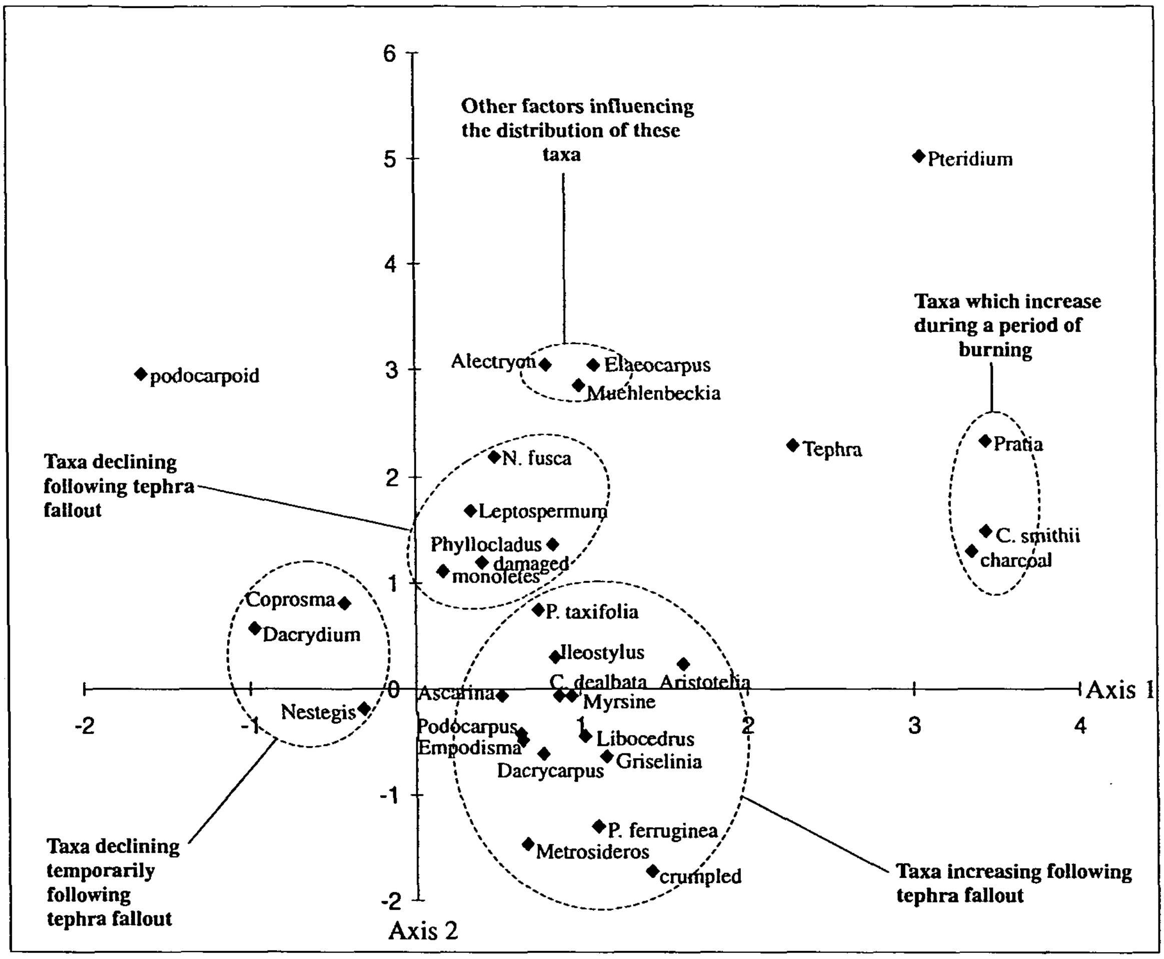



**Figure 6.16** Fine resolution pollen diagram displaying changes in main taxa above and below Mangamate Tephra. Charcoal and Glass shards are expressed as number of fragments per $cm^3$ sediment analysed.




Eigenvalues Axis 1 = 0.04, Axis 2 = 0.02

**Figure 6.17** A biplot of taxon associations in spectra surrounding the Mangamate Tephra layer at Lake Rotoroa.

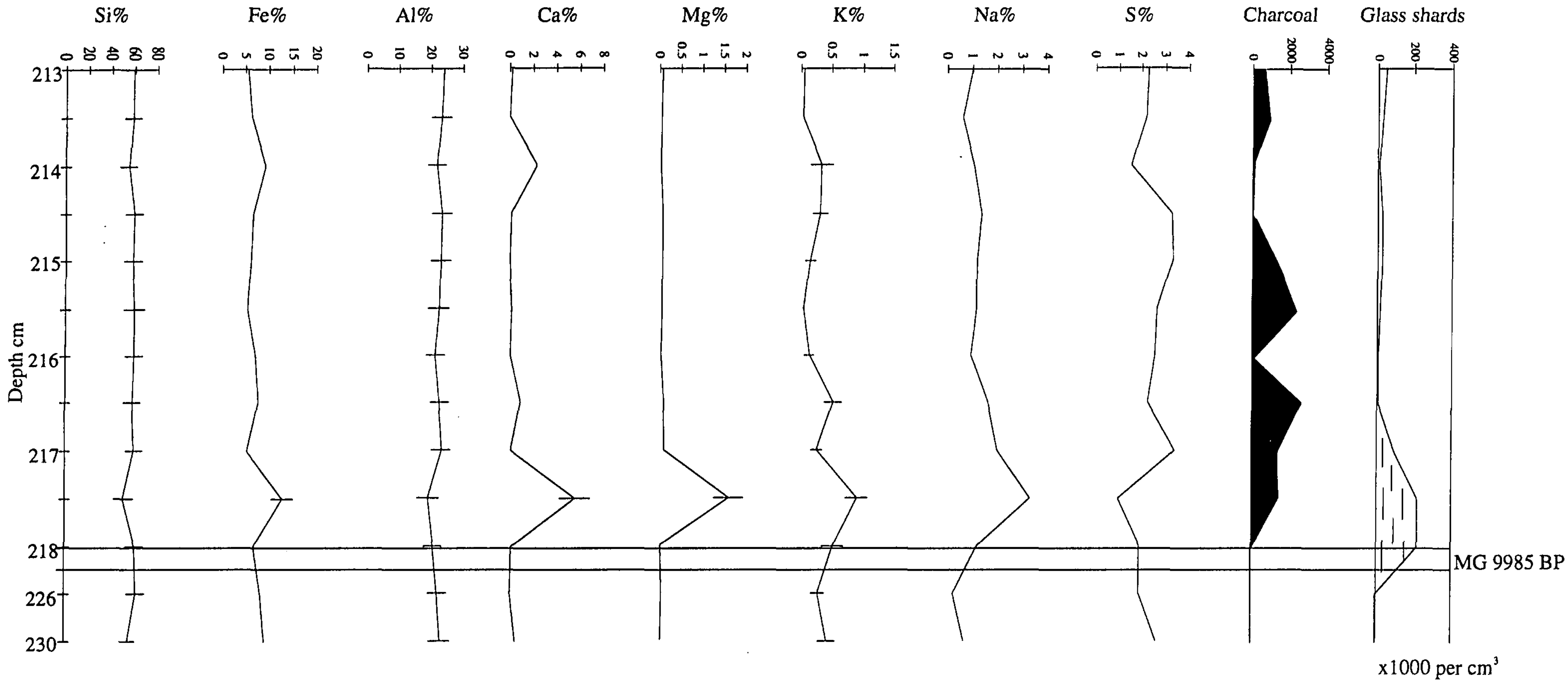



**Figure 6.18** Fine resolution sampling taken at 0.5cm intervals displaying lake sediment geochemistry above Mangamate Tephra. Short horizontal lines indicate error bars calculated to 2 standard deviations.

for colonisation following tephra accumulation, resulting in improved soil drainage and fertility.

DECORANA results show no clear distinction between species declining or increasing above the tephra layer (Fig. 6.17). The Mangamate tephra layer was very thin at this site (1 cm) and was deposited during a period of extensive forest expansion and comparative environmental stability. These factors may explain why any volcanic impacts were subtle and of low magnitude. Cluster analysis (CONISS, Fig. 6.16) distinguishes between vegetation assemblages before and after the tephra, indicating volcanic impacts were discernible at this timescale despite a very thin tephra deposit.

The geochemistry record (Fig. 6.18) displays short-lived peaks in Na, K, Mg, Ca, and Fe 0.5 cm above the tephra layer, ca. 23 years after the eruption. Na, K and Ca are not present in the andesitic Mangamate Tephra; hence, higher levels of these elements indicate increased soil erosion, probably in response to vegetation disturbance following volcanic impact and burning. Topsoils enriched in Fe, derived from the deposition of highly iron-rich Mangamate Tephra (see Table 6.2) would have contributed to higher Fe levels observed at 217.5 cm depth. Accumulation of these elements resulted from the influx of clastic eroded soil material. Lower Si and Al may be misleading as this may merely reflect the problems of proportional representation of data, with lower levels of these elements compensating for increases in others.

Local vegetation impacts following the Opepe eruption were negligible (Fig. 6.19). The forest was able to withstand and/or recover rapidly from the impact of ash fall and associated toxic chemical damage, possibly due to a warm temperate climate providing the most favourable conditions for recovery and regeneration of damaged vegetation following minor disturbance.

*Metrosideros* trees and lianes decline immediately above the Opepe Tephra layer suggesting possible damage from tephra fall. They were increasing in abundance prior to the eruption. Previous studies have suggested that *Metrosideros* species are particularly sensitive to toxic chemical leaching derived from tephra which accumulated on leaves and branches (Clarkson and Clarkson, 1993; Newnham *et al.* 1995; Wilmshurst and McGlone, 1996). It is therefore possible that these trees and lianes were initially adversely affected by tephra accumulation, with their sustained decline due to competitive pressure from the expansion of *Dacrydium* and *Leptospermum* trees and

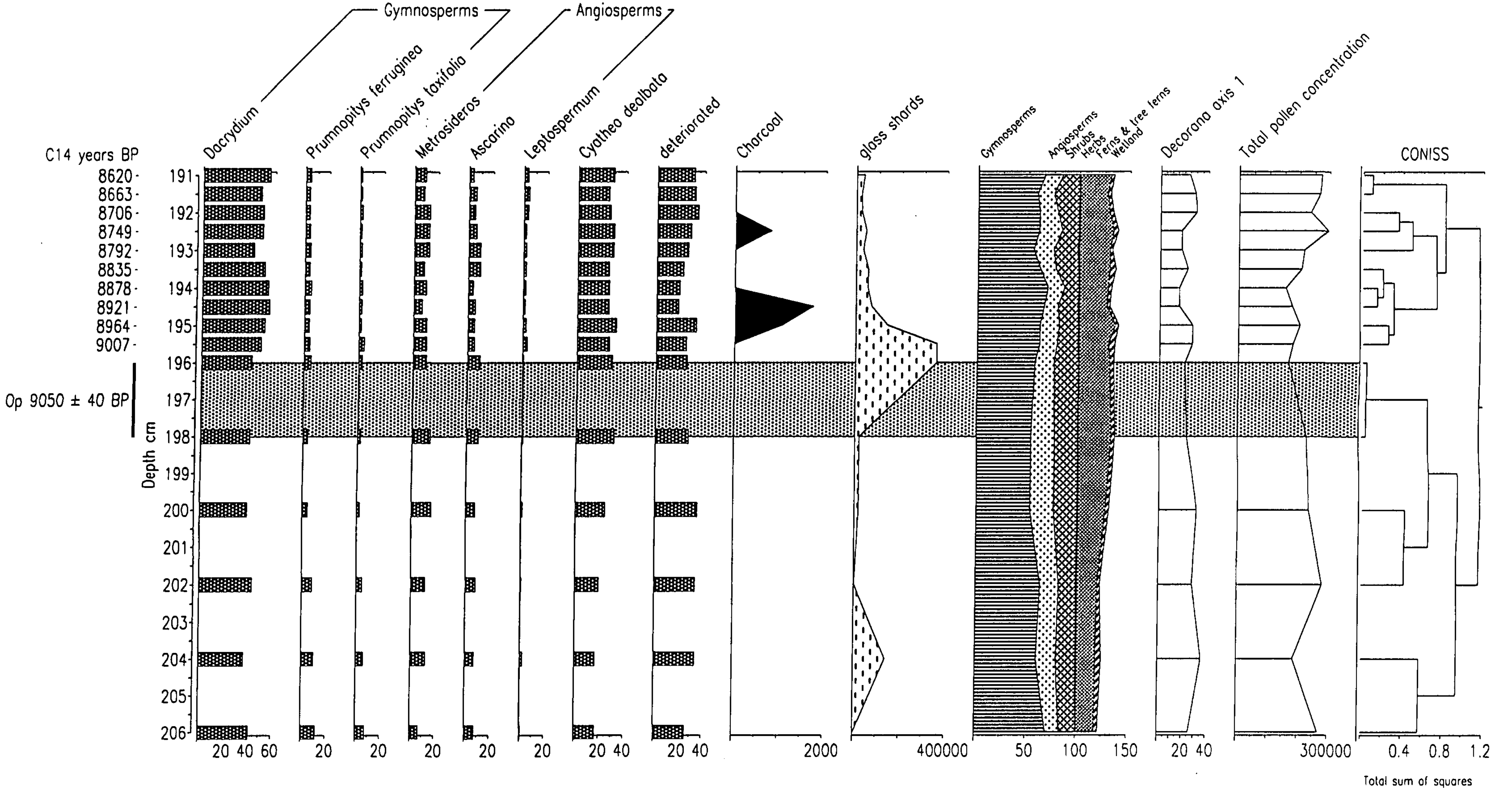



**Figure 6.19** Fine resolution pollen diagram displaying changes in main taxa above and below Opepe Tephra. Charcoal and Tephra shards are expressed as number of fragments per $cm^3$ sediment analysed.

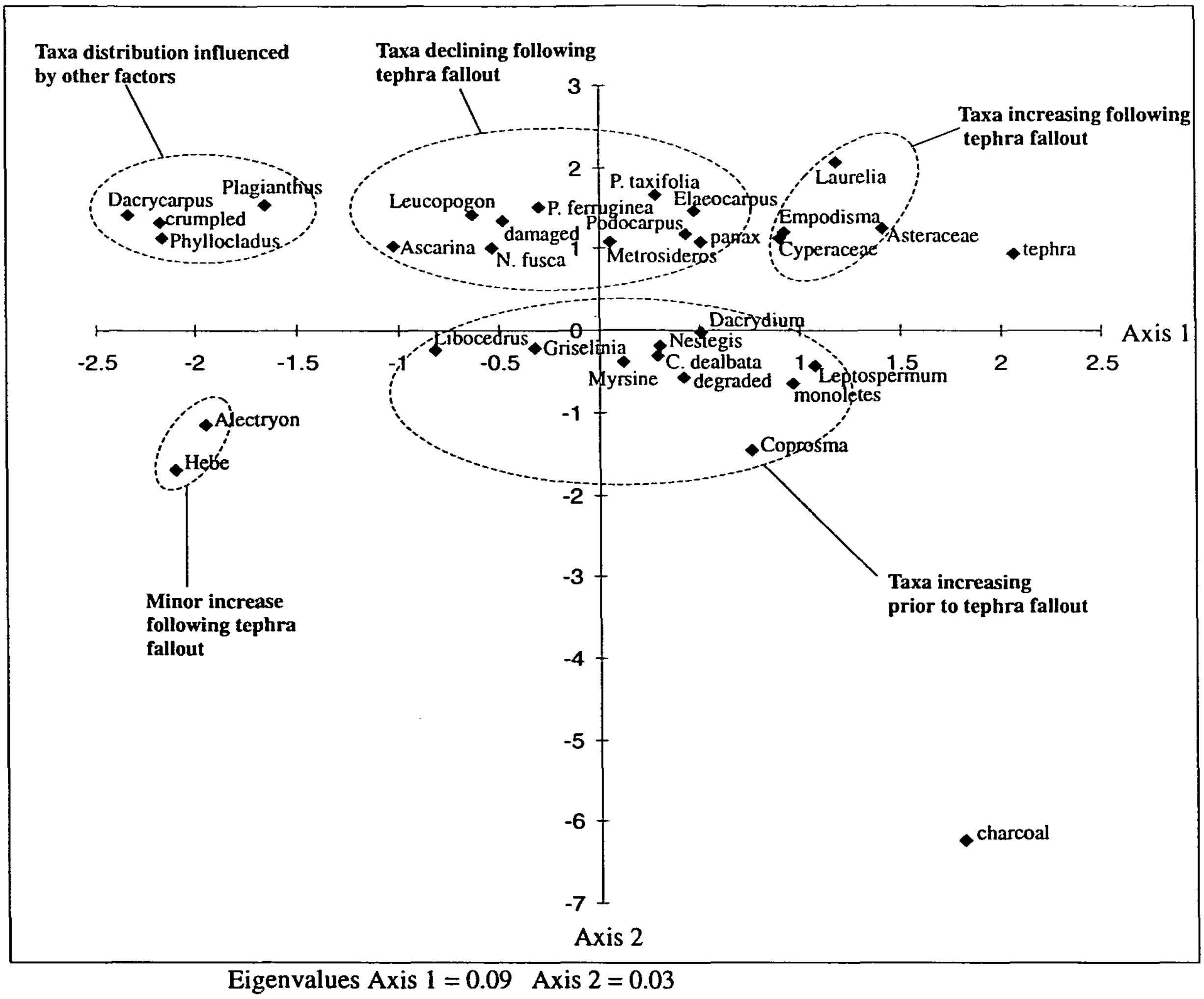



**Figure 6.20** A biplot of pollen taxon associations in spectra surrounding the Opepe Tephra layer at Lake Rotoroa.

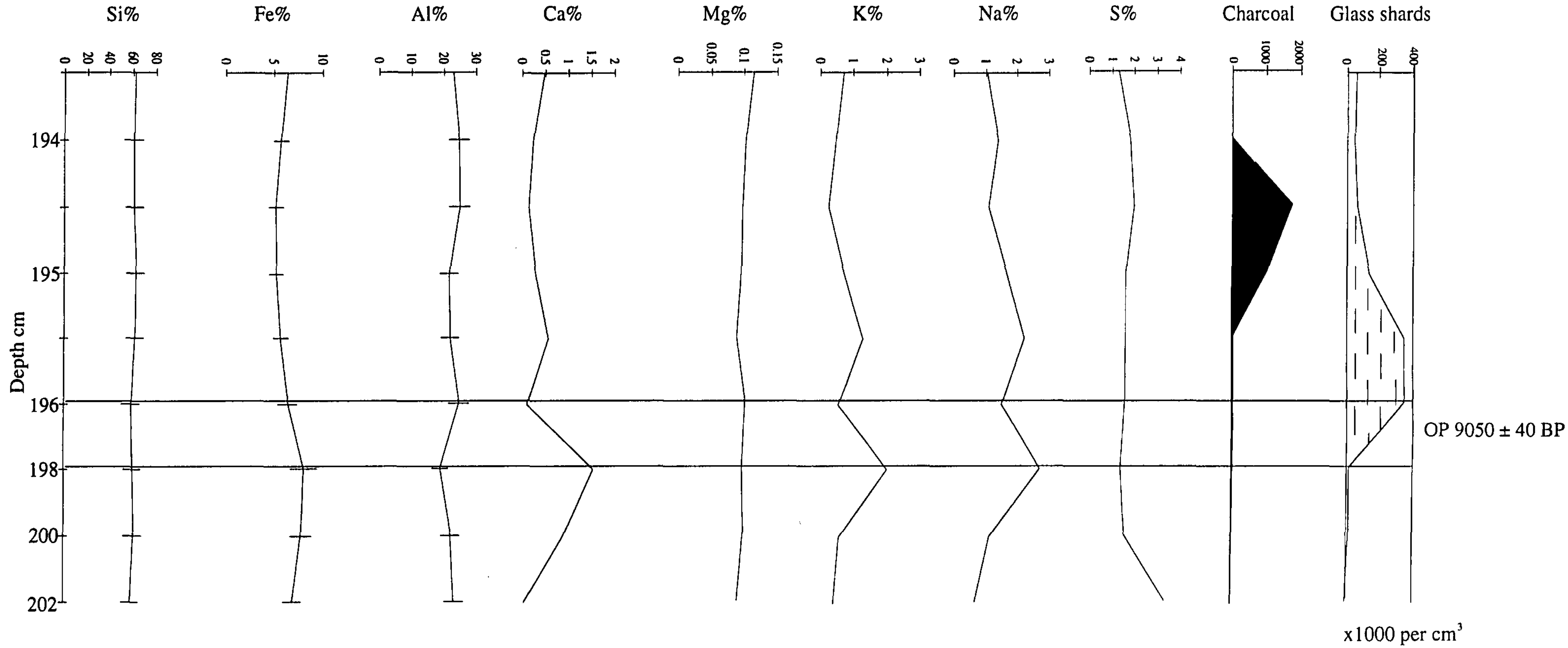



**Figure 6.21** Fine resolution sampling taken at 0.5cm intervals displaying changes in lake sediment geochemistry above Opepe Tephra. Short horizontal lines indicate standard error bars calculated to 2 standard deviations.

shrubs after the eruption. A delayed decline in *Ascarina* trees ca. 43 years after the eruption probably results from reduced light penetration to lower forest tiers following the increase in *Dacrydium* trees. *Ascarina* trees were likely to have become abundant within the sub-canopy as they favour sheltered moist conditions for growth (Wardle, 1990).

Statistical analyses reveal little change in vegetation assemblages following the Opepe eruption, inferred by a very weak eigenvalue for DECORANA axis 1 of 0.05. Cluster analysis (Fig. 6.20) shows the sample immediately above the tephra layer (196 cm) is closely related to those below, which also suggests local vegetation was not significantly affected by tephra fallout.

Lake sediment geochemistry changes (Fig. 6.21) occur at the base of the tephra layer, with slight increases in Na, K, Ca and Fe and lower Al reflecting the abundance of tephric material within the lake at this time. Organic matter remains higher around the tephra layer. These changes are also likely to reflect local environmental change, with erosion of the adjacent Rukuhia peat bog occurring at this time, resulting in an increase in allocthonous minerogenic and organic peat material into the lake (Lowe and Green, 1992; Speirs, 1995).

It is also difficult to determine volcanic-induced vegetational and geochemical impacts following the Rotoma and Mamaku eruptions. Fine resolution sampling at 0.5 cm intervals above these tephra layers nevertheless span ca. 71 years and 140 years sedimentation respectively, making it difficult to determine the extent and duration of volcanic impacts. DECORANA and cluster analyses show no evidence to suggest vegetation response in association with Rotoma and Mamaku Tephra deposition, and it can therefore be inferred that volcanic-induced changes within the pollen and geochemical records are not discernible at this sampling resolution.

*Phyllocladus*, *Nestegis*, *Metrosideros* and *Cyathea dealbata* began to increase in abundance prior to the Tuhua eruption (Fig. 6.22). Decreases in pollen and spore levels for these taxa within the tephra layer suggest possible damage to these taxa due to tephra and toxic chemical accumulation. These changes were of low magnitude however, with long-term trends for these taxa after the eruption fluctuating at pre-eruption levels. *Dacrydium* trees also declined prior to the eruption, slightly earlier than the aforementioned taxa. *Dacrydium* pollen levels were fluctuating considerably over long

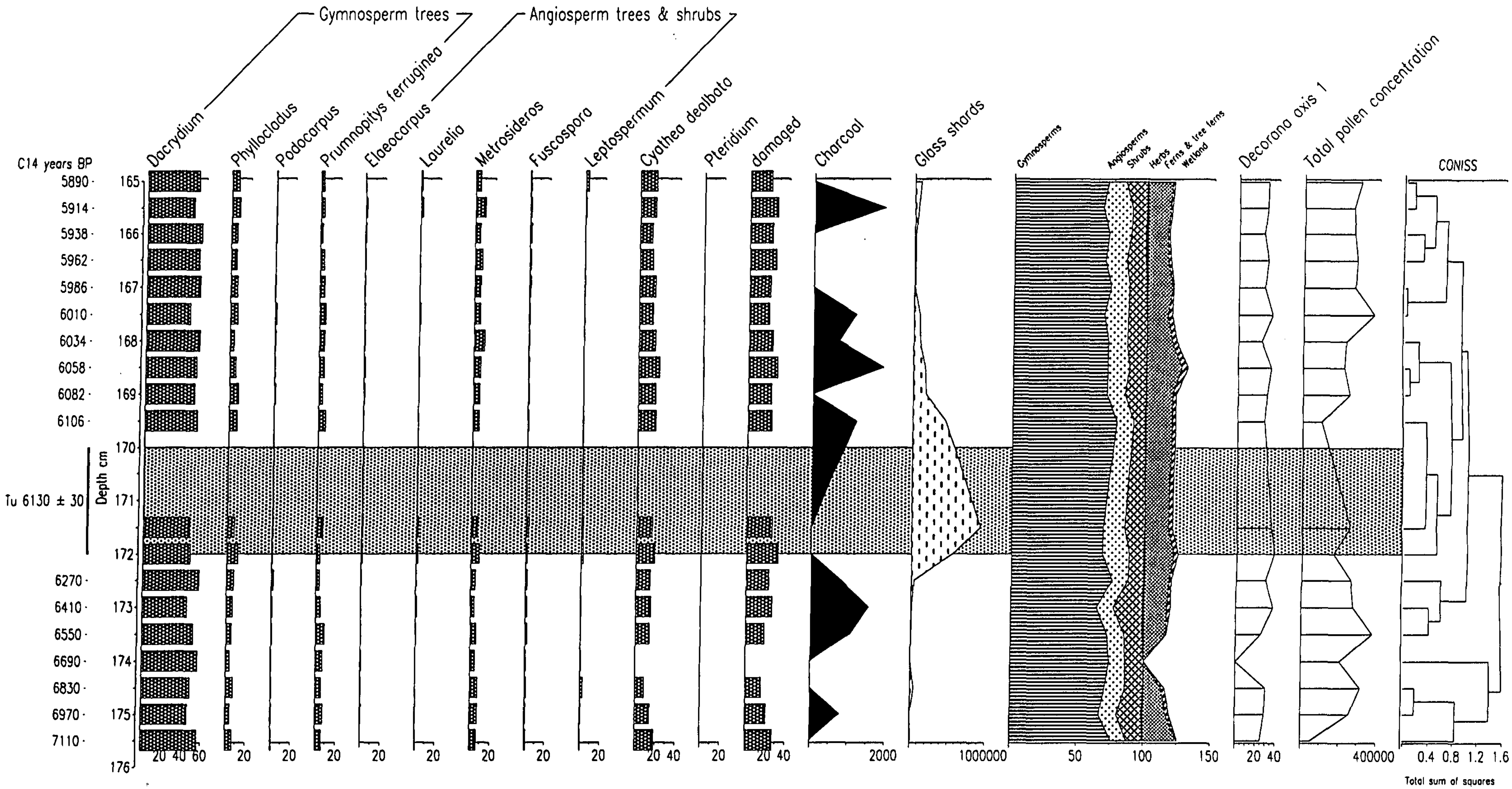
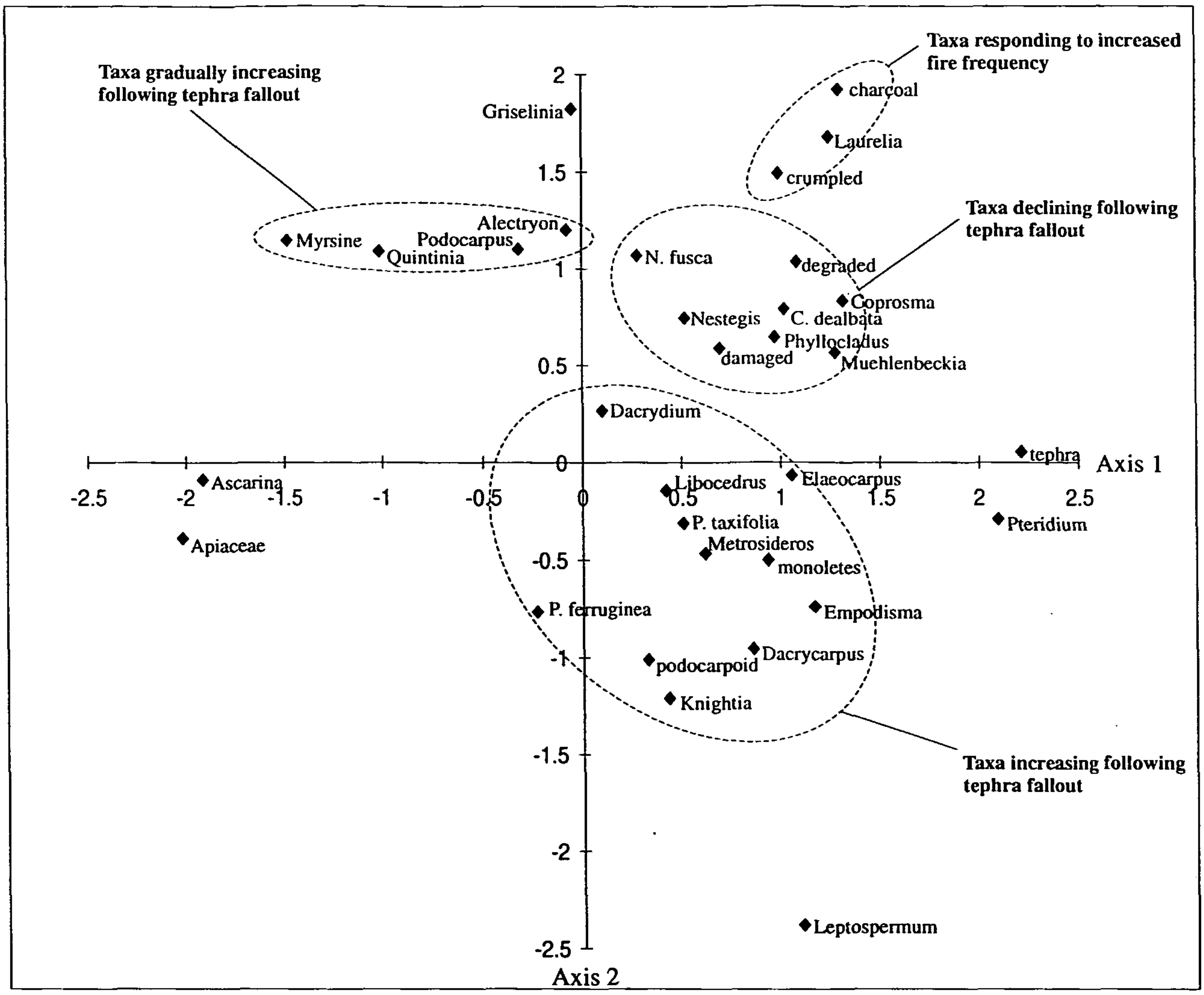



**Figure 6.22** Fine resolution pollen diagram displaying changes in main taxa above and below Tuhua Tephra. Charcoal and Tephra shards are expressed as number of fragments per cm$^3$ sediment analysed.




Eigenvalues Axis 1 = 0.12, Axis 2 = 0.02

**Figure 6.23** A biplot of taxon associations in spectra surrounding the Tuhua Tephra layer at Lake Rotoroa.

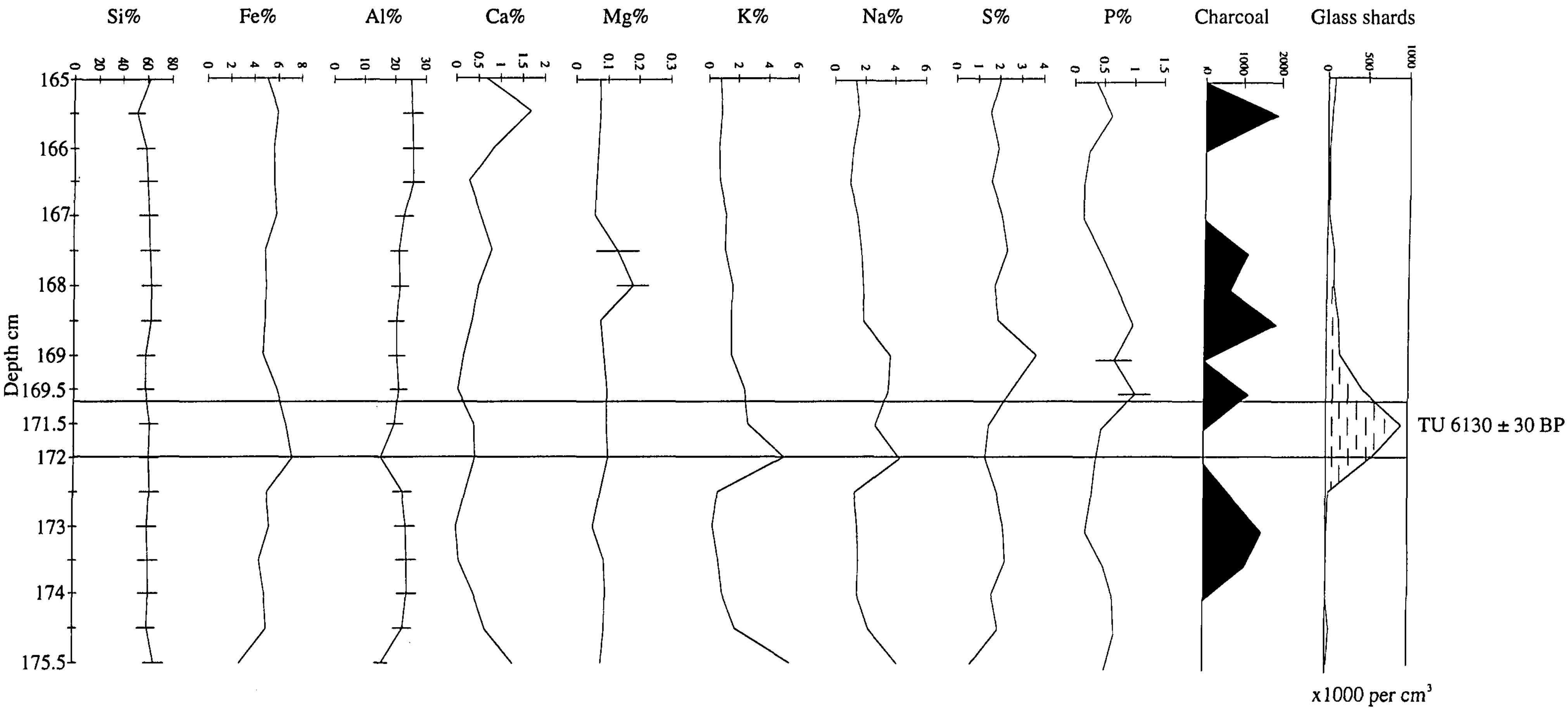



**Figure 6.24** Fine resolution sampling taken at 0.5cm intervals displaying changes in lake sediment geochemistry above and below Tuhua Tephra. Short horizontal lines indicate error bars calculated to 2 standard deviations.

time periods of approximately 140 years duration (the estimated time interval between each pollen sample) possibly in response to climate change. Low levels of microscopic charcoal fragments are present up to 3 cm above the tephra layer, providing evidence for sustained burning in the area up to ca. 72 years after the eruption. Burning within the catchment continued during drier climatic conditions, estimated to have commenced after 6000 years BP (McGlone *et al.*, 1993), with fire damage possibly responsible for slight temporary decline in *Podocarpus, Elaeocarpus, Laurelia, Nothofagus,* and *Leptospermum.*

Volcanic-induced vegetation changes following Tuhua Tephra fall were not discernible from DECORANA analysis (Figs. 6.22; 6.23). Cluster analysis (Fig. 6.22) reveals samples immediately above, below and within the tephra sediment are closely related, suggesting low-magnitude volcanic impacts were obscured by long-term vegetation changes.

Geochemical changes are most pronounced at the base of the tephra layer with increases in Fe, K and Na due to the abundance of tephric material enriched in these elements (Fig. 6.24). Changes also occur above the Tuhua Tephra layer, with increases in the relative concentrations of P and S 1-2 cm above the Tuhua tephra, incorporating ca. 96 years of sedimentation. These changes possibly represent nutrient inwashing from the surrounding catchment following decomposition of plant detritus, derived from vegetation damaged by fire.

During the long time interval between Tuhua and Taupo eruptions (approximately 4200 years) climatic conditions changed, which in turn affected local vegetation. Drier climatic conditions are envisaged from the pollen assemblages below the Taupo Tephra layer (Fig. 6.25) as *Dacrydium* trees decreased significantly, along with a considerable reduction in local presence of *Ascarina* and *Cyathea dealbata*, with *Phyllocladus* trees now thriving at this site. *Phyllocladus* may favour periods of lower precipitation, and typically colonise areas of drier ground (Newnham *et al.*, 1989; Wardle, 1990). *Metrosideros*, *Nestegis* and *Myrsine* trees and shrubs were less common than during the early Holocene (10,000 - 8000 years BP) when precipitation levels and temperatures were considered to be greater than present (McGlone *et al.*, 1993; Salinger *et al.*, 1993).

A number of changes occur in local vegetation assemblages following the Taupo

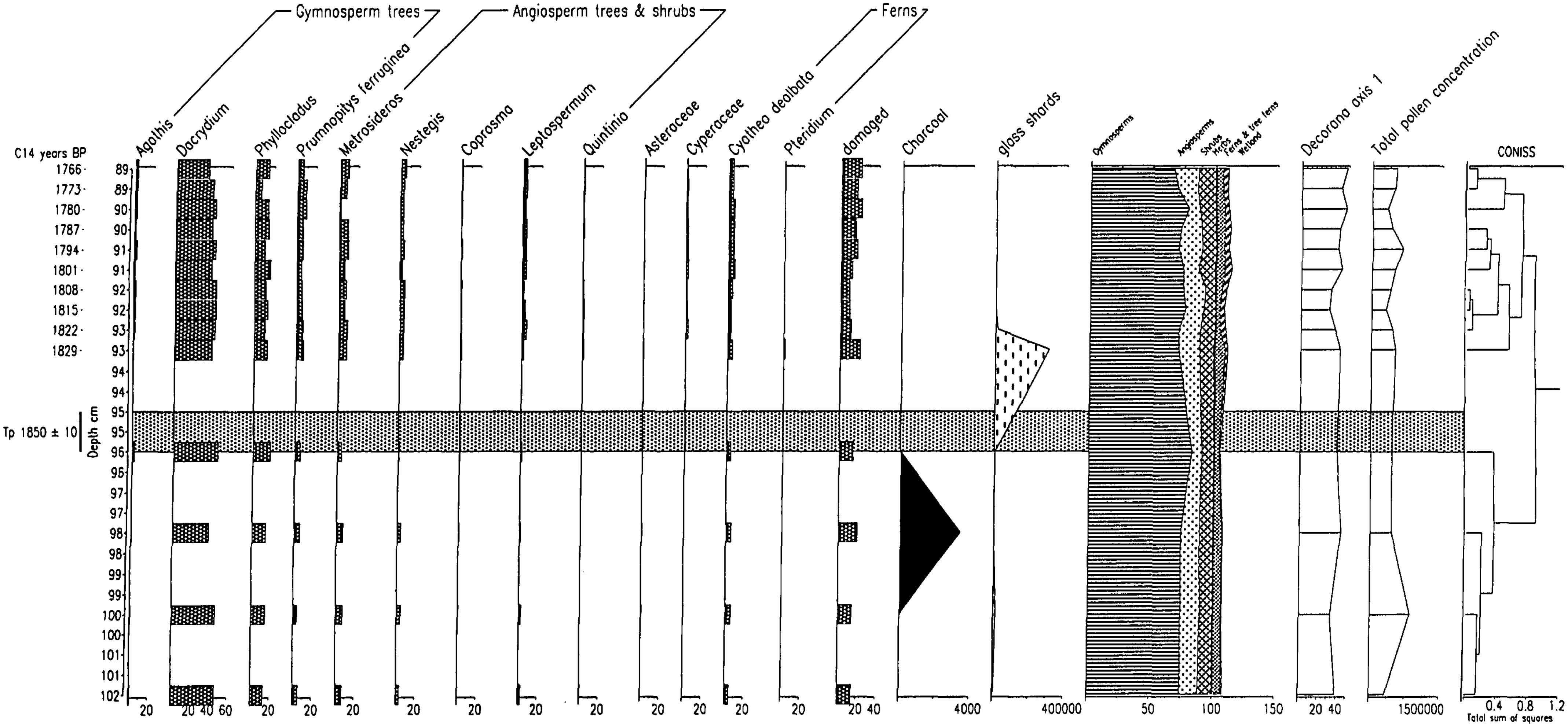
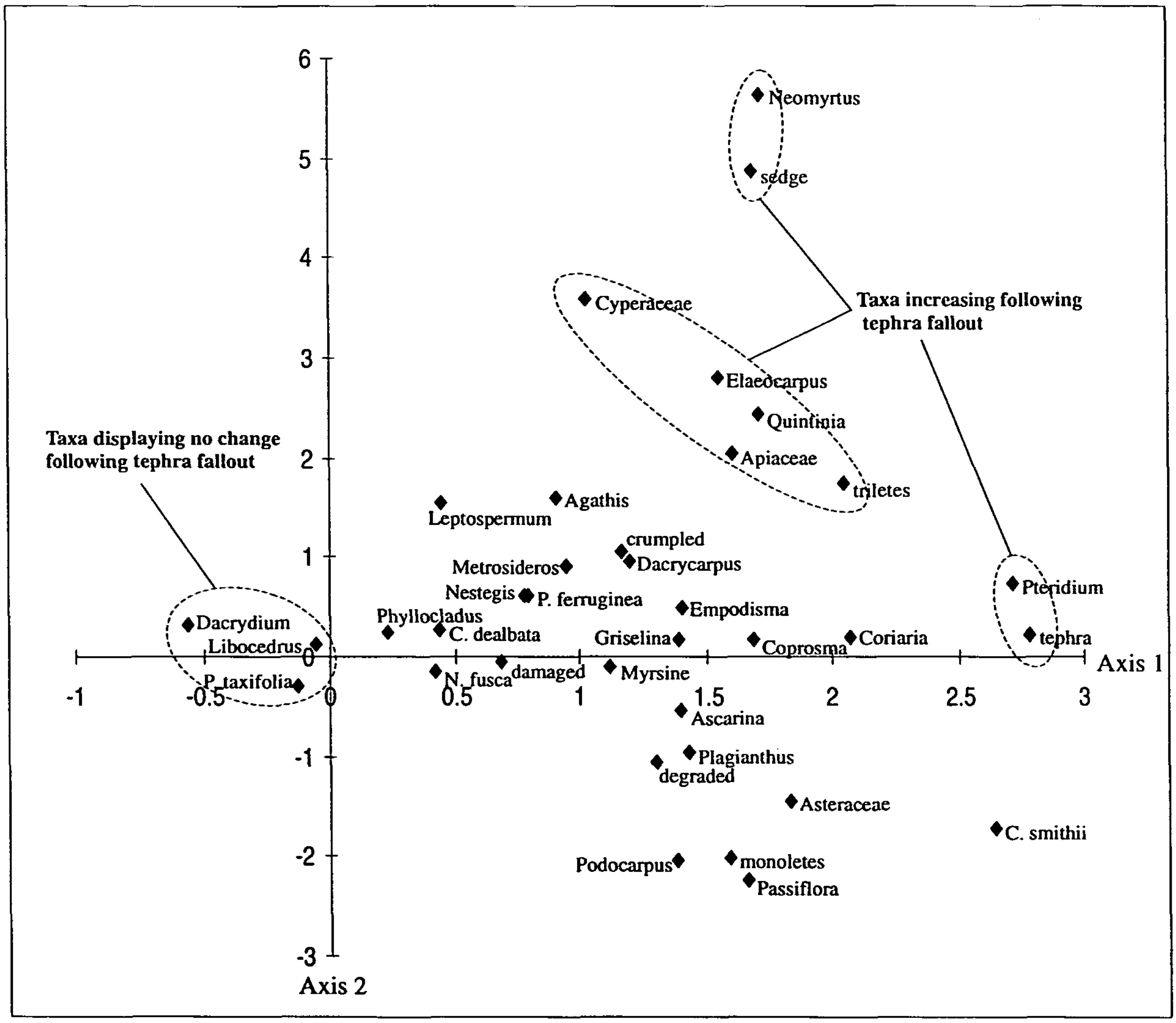



**Figure 6.25** Fine resolution pollen diagram displaying changes in main taxa above and below Taupo Tephra. Charcoal and Tephra shards are expressed as number of fragments per cm$^3$ sediment analysed.




Eigenvalues Axis 1 = 0.16 Axis 2 = 0.02

**Figure 6.26** A biplot of pollen taxon associations in spectra surrounding the Taupo Tephra layer at Lake Rotoroa.

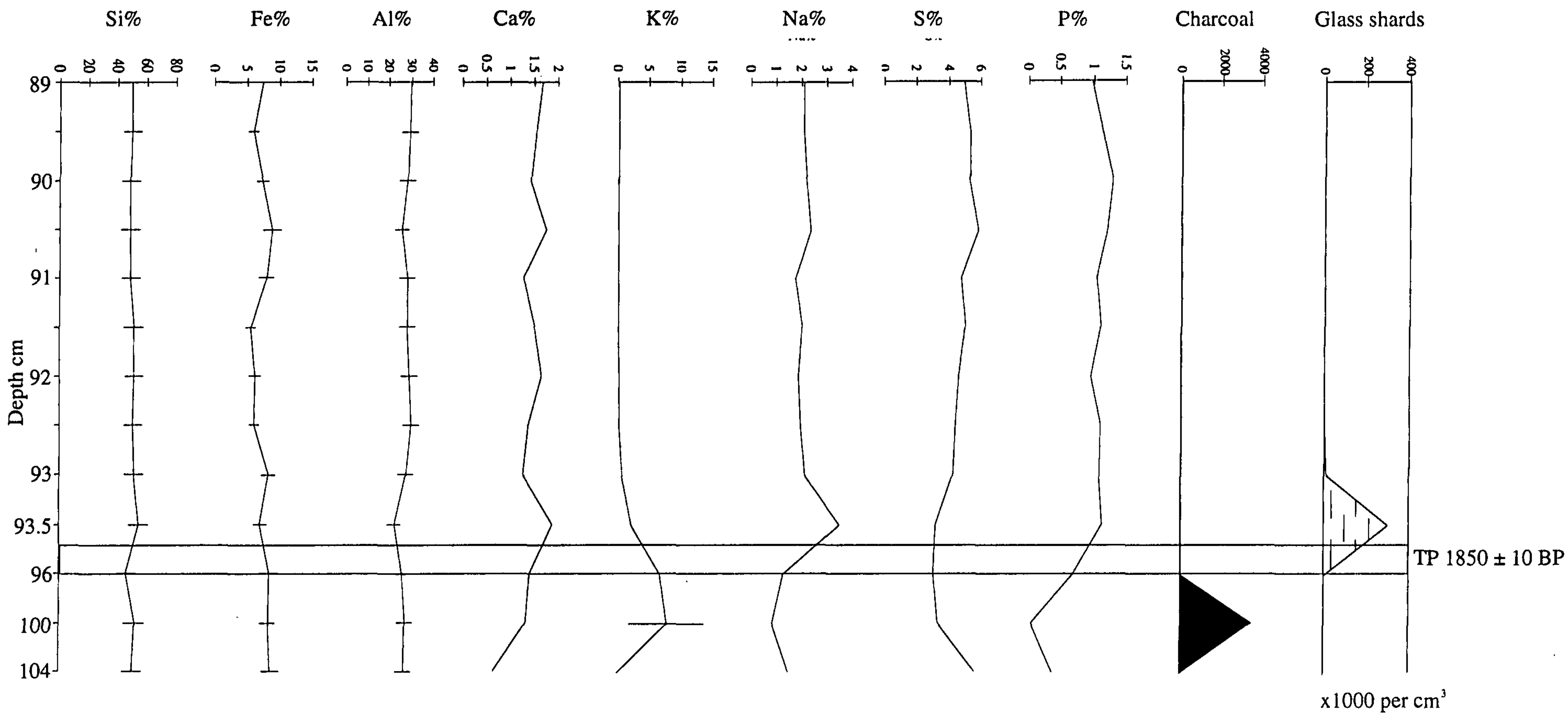



**Figure 6.27** Fine resolution sampling taken at 0.5cm intervals displaying changes in lake sediment geochemistry above Taupo Tephra. Short horizontal lines indicate error bars calculated to 2 standard deviations.

eruption, which could be attributed to volcanic tephra deposition. Each fine resolution sample above the tephra represents ca. 7 years sedimentation. Unfortunately the closest possible sample to the tephra layer was extracted at 93.5 cm (1.5 cm above) as the tephra layer was slanted and tephra fragments had disseminated around the main layer. This sample encompasses 21 years of environmental history. *Prumnopitys ferruginea*, *Metrosideros* and *Nestegis* trees increased during this time and possibly benefited from soil improvement following the incorporation of tephra derived minerals. Taxa which typically respond to forest disturbance such as Apiaceae, Asteraceae, *Coprosma*, *Leptospermum*, *Quintinia*, *Cyathea smithii*, *Pteridium* and Cyperaceae also increased. Evidence for forest disturbance is envisaged from pollen trends as *Dacrydium* and *Phyllocladus* trees decline slightly above the Taupo Tephra (5% reduction in pollen levels). These main canopy trees may have been exposed to damage from tephra accumulation and associated toxic chemical leaching, initiating their decline in the area. The decrease in abundance of *Dacrydium* and *Phyllocladus* trees is sustained to the top of Figure 6.25, covering an estimated time period of 84 years. Their sustained decline reflects competition between forest species due to invasion of seral taxa, and expansion of *Prumnopitys ferruginea*, *Metrosideros* and *Nestegis* trees.

These vegetation changes following Taupo Tephra fall are similar to those reported by McGlone (1981) and Wilmshurst and McGlone (1996), who recorded declines in forest taxa and subsequent seral succession in pollen records from many sites around central North Island and the Hawkes Bay region. However, increased fire frequency occurred at all sites where sedimentation was rapid enough to detect short-term volcanic impacts following Taupo Tephra deposition. Fire outbreaks continued for at least 100 years after the Taupo eruption, contributing to forest destruction and encouraging the invasion of seral taxa. Initially, post-eruption fires were most likely to have been caused by lightning strike from eruption clouds, with fire spreading through exposed damaged forest canopies (Wilmshurst and McGlone, 1996). In the Lake Rotoroa record there was no evidence to suggest burning had occurred following the Taupo eruption. Forest vegetation at Lake Rotoroa may have escaped post-eruption burning as damage to vegetation was probably not severe enough to provide sufficient fuel stock for fire. Also, the prevailing westerly winds concentrated eruption clouds to the east and north-east of Taupo (McDowall, 1995), increasing the chances of lightning strikes and forest fire occurrence in these areas. The 10 cm isopach limit of the Taupo Tephra is strongly skewed to the east and north-east direction from the vent (Wilmshurst and McGlone, 1996), suggesting forests in these areas were likely to have been severely affected as a result of tephra accumulation and chemical damage. Lake Rotoroa is located approximately 100 km to the north west of the vent and was therefore likely to have escaped severe damage from eruption plumes, gas discharges and lightning strikes.

DECORANA analysis reveals no specific relationship between vegetation responding to Taupo Tephra deposition (Fig. 6.26). However, cluster analysis reveals samples immediately above the Taupo Tephra are grouped together (Fig. 6.25) showing similar changes in pollen assemblages after tephra fall. The peak in tephra shards corresponds with increases in deteriorated pollen grains, indicating local catchment disturbance as dominant forest taxa declined and low-lying seral vegetation became established.

The geochemical changes displayed in Figure 6.27 are likely to represent a combination of tephra impact and local environmental change. Increased concentrations of Na indicate an abundance of clastic tephra-derived material entering the lake, corresponding with a higher frequency of microscopic tephra shards. However, elevated K levels below the tephra could indicate downwards leaching of tephra-derived elements, and also increased soil leaching in the catchment. Above 93 cm lower K levels suggest local soils had by now become depleted in potassium. Sustained higher concentrations of P and Ca in the lake sediments are likely to have derived from local soils where minerals, nutrients and organic matter had been lost through increased leaching and erosion during the late Holocene. Al concentrations are also much higher in this section of the core, indicating the gradual acidification of local soils as Al is mobilised below a pH of 5 (Engstrom and Wright, 1987). A gradual reduction in species diversity followed, resulting in invasion of seral taxa and forest trees tolerant of drier, infertile and/or acidic soils (i.e., *Phyllocladus*, *Agathis*, *Leptospermum*, Cyperaceae).

### 6.8 Summary and conclusions

Sedimentation rates were mostly very slow throughout the Rotoroa profile. In many cases the finest possible sampling resolution (0.5 cm) represents time intervals that were probably too long to detect volcanic impacts. The finest between-sample time-resolution was 7 years per 0.5 cm above the Taupo Tephra, although samples were extracted from 1.5 cm above the tephra layer, which represented vegetation changes occurring ca. 21 years after the eruption. However, it was possible to extract samples at the tephra/lake sediment interface above Egmont 15, Rerewhakaaitu, Rotorua and Opepe Tephra layers. These samples detected environmental changes immediately after these eruptions, although impacts were partially obscured by long-term vegetational and environmental changes contributing to the pollen spectrum and elemental assemblages within each 0.5 cm sample. Despite these problems, analysis of tephra impacts following specific eruptions at this site produced results which supported the thesis aims. These findings are listed below.

1) The detailed and accurate chronology established at this site using dated tephra horizons and independent radiocarbon dates illustrates that short-term sedimentation rates can be highly variable . Therefore it is important in studies of short-term environmental change to establish an approximate between-sample time interval in fine resolution records. Using the detailed chronology, it became apparent that time intervals ranged from 7 years to 140 years per 0.5 cm sample in different parts of the Rotoroa cores. Hence, it was not always possible to determine whether fine resolution samples indicated short-lived vegetation and environmental change attributable to tephra fall, or alternatively displayed changes occurring over a much longer timescale that were unrelated to tephra impact.

2) The magnitude of tephra impacts on vegetation assemblages at this site were not proportional to thickness of the tephra deposits, or related to specific tephra chemistry. However, specific tephra chemistry influenced changes in the lake sediment geochemical record. These changes were due to short-term inwashing of tephra shards from soil surfaces, and erosion of tephric material integrated within upper horizons of catchment soils. Short-term increases in tephra-derived material resulted in a higher ratio of minerogenic to organic material in the lake sediment. Tephra deposition uniquely influenced biological productivity within the lake following the Egmont 15 eruption, resulting in a temporary increase in sulphur production.

3) The degree of climate stability and the stage of forest development largely determined the magnitude of tephra impact observed at Lake Rotoroa. Volcanic tephra impacts on poorly developed podocarp forest were significant during the last glacial and early post-

glacial period as trees were already struggling to survive under harsh climatic conditions. Additional stress on trees following tephra and toxic chemical accumulation weakened and damaged trees, triggering their decline. In contrast, during the Holocene, volcanic impacts were minimal as podocarp-hardwood forest had become well established following climatic amelioration and environmental stability. Hence local forest was well buffered against possible damage from tephra fall.

4) Initial tephra impacts on vegetation assemblages could be detected in pollen records up to ca. 20-30 years after some eruptions at this site. Following a decline in tephra-damaged vegetation, the subsequent invasion of canopy gaps by expanding taxa increased competitive pressure within the forest, resulting in the sustained decline in tephra-damaged taxa (e.g., 180-year decline in damaged taxa following Rotorua Tephra deposition). Tephra impacts on lake sediment geochemistry were short-lived. The maximum duration of impacts observed in the geochemical record at this site was 77 years, which resulted from the deposition of the 6 cm thick Rotorua Tephra. Episodes of catchment erosion or nutrient inwashing were displayed in geochemical records and coincided with sustained vegetation disturbance following Taupo, Tuhua, Mangamate and Egmont 15 eruptions. Between-sample time resolutions above these tephra layers are the shortest for the entire profile, ranging from 7 years (Taupo) to 28 years (Egmont 15); hence, short-term volcanic impacts were detected even though the tephra layers were only 1 cm thick.

5) Microscopic charcoal peaks were present above Egmont 15, Mangamate and Tuhua Tephra layers, indicating that volcanic-induced burning was an additional factor responsible for sustained forest damage at this site following these eruptions.

6) Taxa that consistently declined following tephra fall were *Halocarpus* (above Egmont 15, Rerewhakaaitu and Rotorua Tephra layers), and *Phyllocladus* (above Mangamate, Tuhua and Taupo Tephras). Damage by tephra accumulation and associated toxic chemical leaching, and volcanic-induced burning together with climate change, were responsible for the decline in *Halocarpus* and *Phyllocladus* shrubs. *Phyllocladus* trees suffered volcanic-induced burning following the Mangamate and Tuhua eruptions. Taxa that consistently increased following tephra impacts were species that typically invade following forest disturbance: for example, Asteraceae, Cyperaceae, *Leptospermum* and *Pteridium*. *Griselinia* increased above the Mangamate and Rotorua Tephra layers; these

shrubs often colonise fresh volcanic substrates, and are able to coppice freely following damage to branches by tephra accumulation (Wilmshurst and McGlone, 1996).

7) Taxa displaying inconsistent responses to tephra fall are numerous and are presented in Table 6.7. These changes are the result of a combination of factors. Firstly, changes in forest structure may result in a particular species becoming dominant within the forest canopy and thus exposed to the harmful effects from tephra accumulation. These changes are highlighted by the decline in *Metrosideros* trees and lianes above the Opepe tephra, which became prominent in the forest canopy prior to the eruption. This taxon had previously increased following the preceding Rotorua and Mangamate eruptions. The age of trees will also determine the extent of damage caused by tephra accumulation. Trees become weakened with age and are more susceptible to damage from high winds and disease. The additional stress on older trees from tephra and toxic chemical accumulation may initiate long-term decline. The sustained decline in *Dacrydium* trees after the Taupo eruption may have been due to an abundance of older *Dacrydium* trees present in the forest during the late Holocene, which were unable to recover from the damaging effects from tephra fall. Inconsistent responses to tephra deposition shown by other taxa may be the result of climate change and competition from taxa expanding and invading following tephra induced forest disturbance.

8) Elements that most commonly increased in lake sediments above the macroscopic tephra layers were Na, K and Ca, due to their natural enrichment within the tephras. Tephra impact had no effect on background concentrations of Al and Si in Lake Rotoroa sediments, indicating Si and Al concentrations in tephra layers and ambient lake sediments were very similar.

The next chapter focuses on volcanic impacts following tephra fall at Kohuora crater, Auckland. Investigations at this site will assess the most distal volcanic impacts recorded in this thesis as Kohuora is the furthest study site from the TVZ.

**Table 6.11** Summary of vegetation and environmental changes following tephra fall at Lake Rotoroa

| Tephra layer | Taxa declining | Taxa increasing | Elements declining | Elements increasing | Timescale (5cm above tephra) | Explanation of environmental change |
|---|---|---|---|---|---|---|
| **Egmont 15** | *Halocarpus*<br>*Podocarpus*<br>*Prumnopitys ferruginea*<br>*Prumnopitys taxifolia*<br>*Nestegis*<br>*Cyathea dealbata* | *Leptospermum*<br>Asteraceae<br>Poaceae<br>Cyperaceae<br>*Hymenophyllum*<br>*Coprosma*<br>*Dacrydium*<br>*Myrsine*<br>charcoal | Si, Al | S, Na, Mg, Ca, Fe | 174 years | Damage to vegetation initiated by tephra fallout, sustained due to harsh climate and continued burning in the catchment. Possible evidence for lake pollution displayed in the geochemical record, due to tephra deposition, initiating increased biological productivity and possible formation of algal blooms. |
| **Rerewhakaaitu** | *Halocarpus*<br>*Coprosma* (gradual)<br>Poaceae (gradual)<br>*Hymenophyllum* (gradual) | *Dacrydium*<br>*Leptospermum*<br>*Myrsine*<br>*Alectryon*<br>*Rubus*<br>*C. dealbata* | Fe, Al, S at base of tephra layer | Na, K, Ca, Si at base of tephra layer | 496 years | Decline in vegetation typical of a cooler climate immediately after tephra fall due to a combination of volcanic impact and climate amelioration. Downwards dislocation of tephra shards displayed in pollen and geochemical records. Time resolution too long (0.5cm=62years) to detect inwash of shards after eruption |
| **Rotorua** | *Halocarpus*<br>*Elaeocarpus*<br>*Myrsine*<br>*Podocarpus* | *Dacrydium*<br>*Metrosideros* (gradual)<br>*C. dealbata*<br>*Griselinia*<br>*Plagianthus* | S, Al, Fe | Na, K, Mg, Ca | 616 years | Volcanic induced vegetation decline, sustained for 180 yrs due to increasing competition from expanding forest vegetation under a warmer climate. Tephra deposition and inwashing from catchment influenced lake chemistry for ca. 77 yrs. |

| | | | | | | |
|---|---|---|---|---|---|---|
| **Mangamate** | *Phyllocladus*<br>*Nestegis* (gradual) | *P. ferruginea*<br>*P. taxifolia*<br>*Elaeocarpus*<br>*C. smithii*<br>*Podocarpus* (gradual)<br>*Metrosideros* (gradual)<br>*Griselinia* (gradual)<br>*Myrsine* (gradual)<br>charcoal | Si, Al, S | Na, K,<br>Mg, Ca, Fe | 230 years | Minimal volcanic impact on vegetation. Many taxa increasing could have benefited from tephra fallout improving local soils, but climatic amelioration is a more likely factor. Burning probably initiated decline in *Phyllocladus*, and could have been caused by lightning strike from eruption cloud. Lake geochemical record shows tephra inwash and catchment erosion 23 yrs after eruption. |
| **Opepe** | *Metrosideros*<br>*Ascarina* (delayed) | all gradual increases in<br>*Dacrydium*<br>*Leptospermum*<br>*Libocedrus*<br>*Alectryon*<br>monoletes | Al at base of tephra layer | Na, K, Ca, Fe at base of tephra layer | 387 years | Maximum temperatures and precipitation at this time favour the expansion of warm temperate podocarp-hardwood forest. Volcanic induced decline in taxa due to tephra accumulation and toxic chemical leaching. Minimal impact on lake geochemistry. |
| **Tuhua** | *Phyllocladus*<br>*Nestegis*<br>*Metrosideros*<br>*C. dealbata*<br>*Podocarpus*<br>*Elaeocarpus*<br>*Laurelia*<br>*N. fusca* | *Pteridium*<br>*P. ferruginea*<br>charcoal | Ca, Al | Fe, Na, K<br>P and S delayed | 240 years | Burning likely to have caused decline in taxa, may have been initiated by lightning strike from eruption cloud. evidence for tephra inwash up to 24 yrs after eruption, with inwash of nutrient elements due to decomposition of damaged taxa, and soil erosion. |
| **Taupo** | *Podocarpus*<br>*Dacrydium*<br>*Phyllocladus* | *P. ferruginea*<br>*Metrosideros*<br>*Nestegis*<br>*Coprosma*<br>*Leptospermum*<br>*Quintinia*<br>*C. smithii*<br>*Pteridium*<br>Cyperaceae<br>Apiaceae<br>Asteraceae | Al, S | Na, P, Ca, K | 84 years | Vegetation and geochemical changes reflecting impact from tephra deposition, causing soil acidification and vegetation damage. Changes also related to drier climatic conditions and increasing soil infertility. |

# Chapter Seven

## Kohuora crater, Papatoetoe, Auckland

### 7.0 Introduction

Macroscopic rhyolitic tephra layers from the Taupo volcanic zone have been discovered at many sites in urban Auckland (Kermode, 1989; Moore, 1989; Newnham and Lowe, 1991). However, the extent to which distal tephra deposition during the Holocene has affected forests in the Auckland region is unknown. The Auckland field site is the most distal study site from the TVZ investigated in this thesis, and is located within the Auckland volcanic field (Figs. 7.1, 7.2). Previous volcanic risk assessments for the city of Auckland have focused on the threat from Auckland's ca. 50 volcanoes. Late Quaternary and Holocene activity from the Auckland volcanic field was characterised by small-scale effusive or mildly explosive eruptions producing localised pyroclastic surges, wet and dry ash fall, lapilli, bombs and lava flows, which today present a potential hazard to the city and its population (ca. 1,000,000) (Searle, 1981; Allen and Smith, 1994). However, the potential threat of distal ash fall from high-magnitude central North Island volcanic eruptions has not been considered until recently. Newnham *et al.* (in press) discuss this previously unrecognised threat to the city of Auckland and stress that further research is required to investigate the possible impacts that are likely to occur following distal ash deposition.

This chapter focuses on the extent to which long-distance ash dispersal has affected Auckland's natural environment. This research will aid investigations into the potential hazard Auckland faces from the Central North Island volcanic field, providing important ramifications for further research into volcanic risk assessment in the Auckland metropolitan area today. The site chosen for this study is an ancient volcanic crater, Kohuora, located in the Papatoetoe area in the southern part of the city, close to Auckland International Airport (Fig. 7.1). The crater has been infilled with thick lake and peat deposits producing a useful site for palaeoenvironmental studies. Palynological and geochemical analyses have been undertaken to determine the vegetation and environmental history of the area since the late glacial, with fine resolution sampling employed above and below the tephra layers to focus in

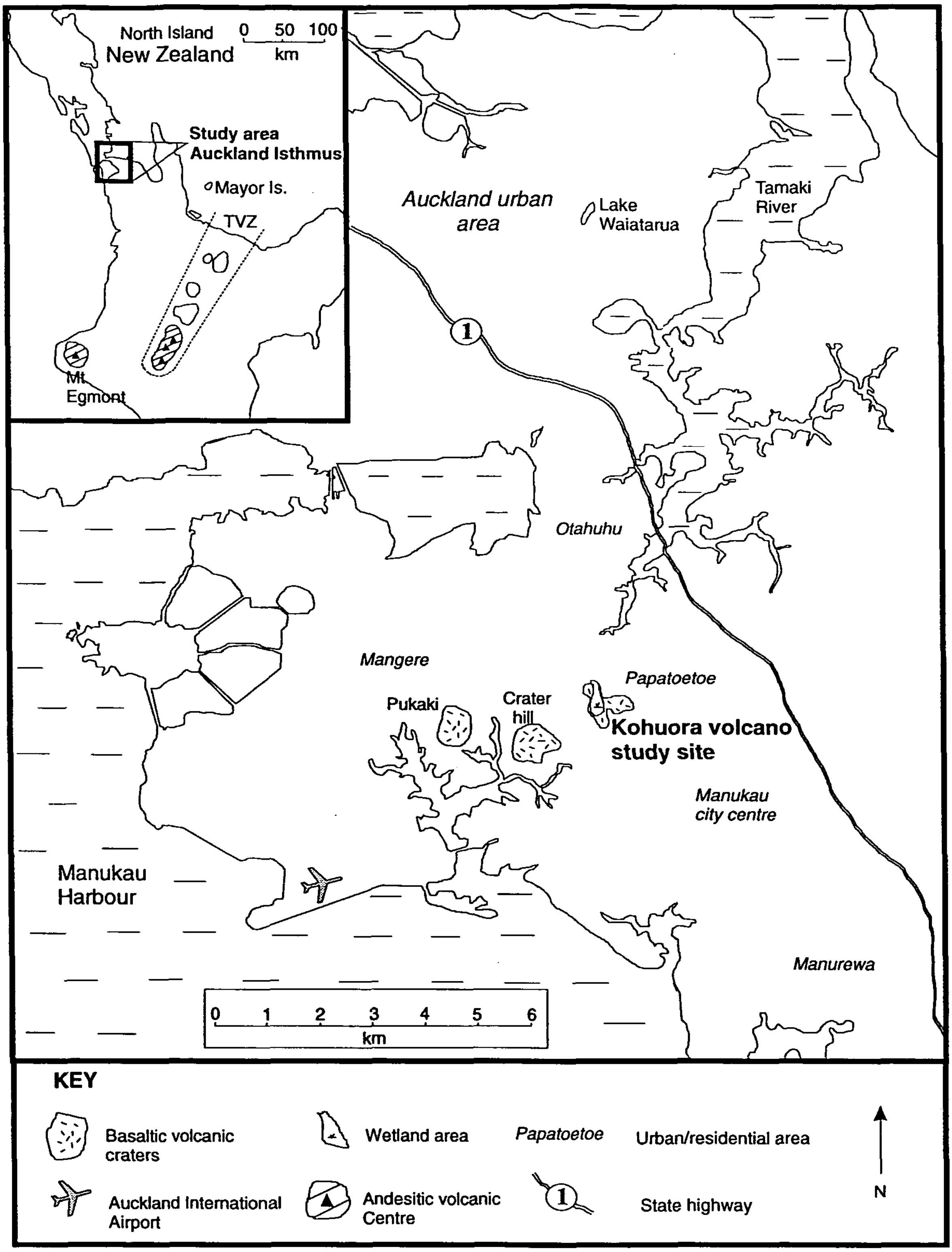



**Figure 7.1** Kohuora volcano study site location, South Auckland urban area (source: New Zealand Topographical Map, 1:250 000, sheet 260)

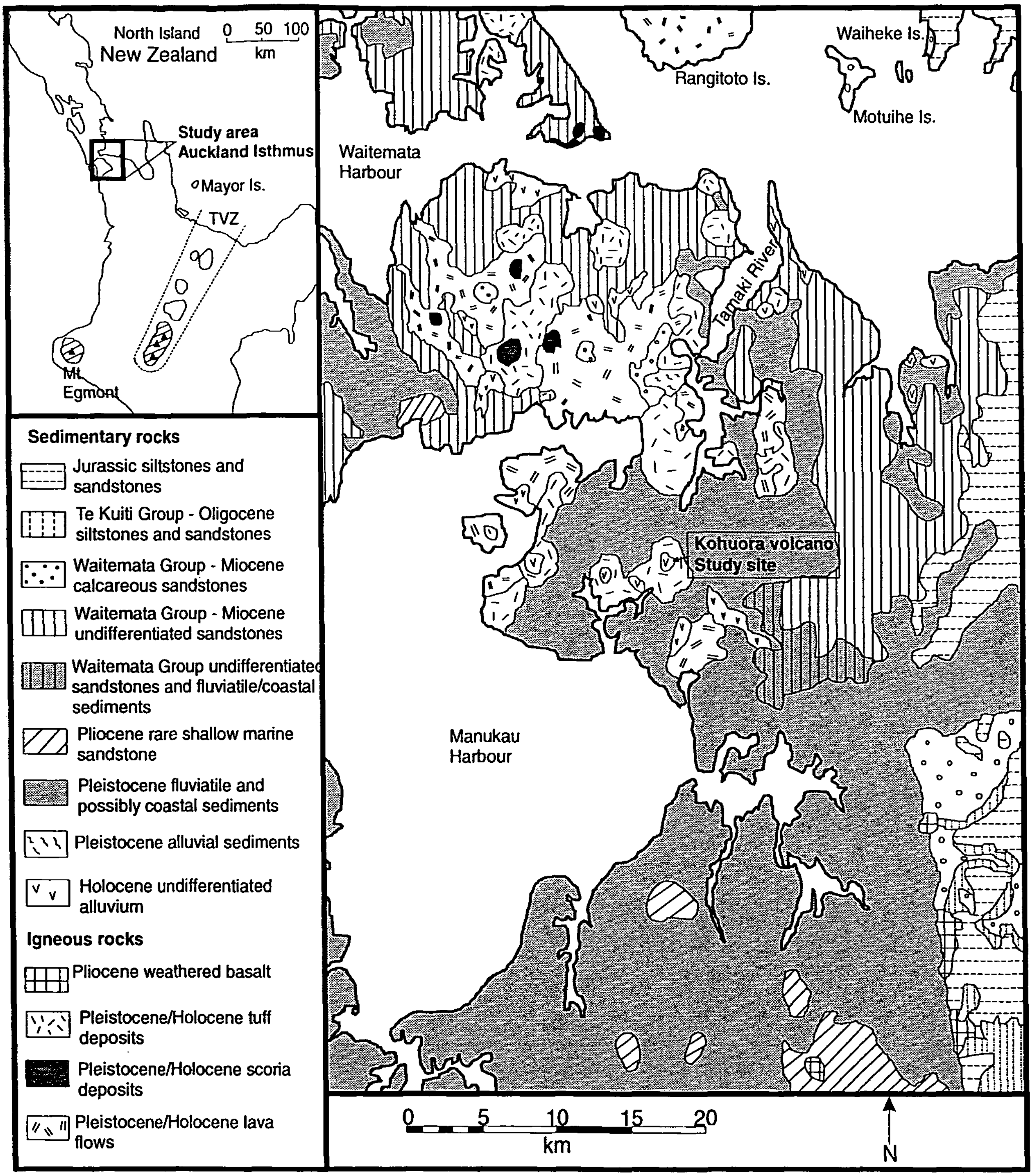



**Figure 7.2** Geology of the Auckland area (source: New Zealand Geological survey map, 1:250 000, sheet 3).

particular on changes in vegetation assemblages and environmental processes prior to, and immediately following, distal tephra deposition.

### 7.1 The study area

During Plio-Pleistocene times, the south Auckland area was inundated with pumiceous sediments originating from the central volcanic plateau, deposited unconformably on Miocene sedimentary rocks (Kermode, 1989) (Figure 7.1 inset). Glacio-eustatic sea level fluctuations during the last 1.8 million years formed a number of coastal terraces at Northland and Auckland coastlines. Drowned river valleys formed as a result of postglacial sea level rise from >100 m below the present level around 20,000 years BP (Ballance and Williams, 1990).

Basaltic lavas and ash deposits from Auckland's ca. 50 volcanoes have covered a large proportion of the Plio-Pleistocene sediments over the last 150,000 years, producing 4.1 $km^3$ volcanic material over an area of 360 $km^2$ (Searle, 1965; Allen and Smith, 1994). The most recent eruption occurred on Rangitoto Island, dated at around 700 years BP (Robertson, 1986; Allen and Smith, 1994).

### 7.2 Geological setting and volcanic history of Kohuora volcano

Kohuora volcano, a small tuff ring-crater complex is located in Papatoetoe, South Auckland (Fig. 7.2). The Papatoetoe area is low lying, with a gently sloping topography. Kohuora crater floor is 5 m a.s.l, with the top of the tuff ring reaching 33 m a.s.l (Gadd, 1987). Kohuora volcano, together with nearby Crater Hill and Pukaki, form the Papatoetoe volcanic group where activity ranged from wholly phreatic to magmatophreatic (Searle, 1965; Rout, 1990). Searle (1965; 1981) notes that Kohuora was once a collection of explosion pits, which perhaps indicates more than one explosive eruption. These pits have been greatly modified by erosion, and Kohuora volcano appears today as a V-shaped depression formed by explosive volcanic activity which has produced the basaltic tuff-ring surrounding the crater. The volcano is $^{14}$C-dated at 29,000 ± 700 BP (Allen and Smith, 1994) with the adjacent Crater Hill dating to 29,700 ± 2000 BP (Allen and Smith, 1994). Pukaki is undated, but this volcano was probably formed around the same time as Kohuora and Crater Hill (Rout, 1990). Tuff deposited in the Papatoetoe region covers approximately 2 square miles, forming a collection of ridges and depressions over the area.

### 7.3 Vegetation history of Auckland

Relatively little is known about the vegetation history of the Auckland area. Only small remnants of native forest have survived the period of extensive deforestation during the last 1000 years. Palynological studies at Lake Waiatarua represent the only on-land site where palynological investigations have been undertaken in the Auckland region (Newnham and Lowe, 1991) (Fig. 7.1), providing an insight into the nature of the vegetation assemblages flourishing in the region prior to human settlement back to 12,000 years BP. Evidence from the pollen record suggests local forests were composed of mixed podocarp and angiosperm trees, with an abundance of tree ferns (Newnham and Lowe, 1991). The Kohuora study expands on this single record.

*Ascarina* expanded its range during the early Holocene (9 ka) and declined in the mid Holocene. *Agathis* becomes increasingly common, expanding over the area from around 6000 BP along with *Libocedrus* and *Phyllocladus*. These changes are analogous with those occurring to the north and south of Auckland, indicating the vegetation was responding to regionally extensive environmental factors (Newnham and Lowe, 1991). Extensive deforestation of the Auckland Isthmus occurred following the arrival of Polynesians around 1000 years BP (Davidson, 1984). Former forests were replaced largely by bracken, grass and scrub vegetation. Sweet potato cultivation was probably practised throughout the area (Newnham and Lowe, 1991).

### 7.4 Local vegetation at Kohuora crater (Plate 7.1a and b)

The wetland area within Kohuora crater has undergone extensive disturbance in recent years due to local residential development and industrial waste disposal. Apart from occasional patches of relatively undisturbed wetland, nothing remains of former vegetation.

A mesic-eutrophic wetland system has established within the crater, dominated by *Paspalum distachum*, with co-associates *Galium palustre*, *Hydrocotle novae-zelandiae* (*sensu stricto*), *Carex virgata*, *Agrostis stolonifera* and *Glyceris flutens* (P. J. deLange *pers.*

**Plate 7.1a** Kohuora field site area with drainage channel to the left.

**Plate 7.1b** Kohuora crater field site vegetation

*com.*). Species present within the general area include *Carex maorica*, *Schoenipectus validus*, *Baumea teretifolia* (rare), *B. rubigenosa* (rare), *Ranunculus repens* and *Salix cinirea* (willow).

### 7.5 Stratigraphy and chronology of Kohuora sediment core (Fig. 7.3)

The core was extracted from the crater in 50 cm sections using a Russian corer (see chapter 3) reaching 950 cm depth. The top 300 cm of sediment is largely composed of peat deposits, grading downwards into lake sediment, which in turn overlies volcanic tuff. Four macroscopic tephra layers are present in the core, and have been identified through major element analysis of constituent glass shards using the electron microprobe by D. J Lowe at Waikato University, New Zealand (Table 7.1). The Tuhua and Rotoma Tephra layers are 3 cm thick, and the Rotorua Tephra is 2 cm thick. The lowermost thin tephra layer (0.5 cm) located at 948 cm depth has been tentatively identified as Rotoaira Lapilli owing to its andesitic geochemistry, and its estimated approximate age of 13,700 BP (Lowe, 1988; Donoghue *et al.*, 1995), which is virtually identical to the $^{14}C$ date of 13,640 ± 170 BP for basal sediments between 940 – 950 cm depth. These macroscopic tephra layers are assumed to indicate primary tephra fall at the time of the eruption, where large ash clouds spread from the volcanic source, resulting in the gradual settling of ash and the deposition of tephra layers over the region.

A total of 11 samples were extracted from the profile for dating at the University of Waikato radiocarbon dating laboratory (Fig. 7.3). There were 2 minor age inversions, at 442 cm and 470 cm with dates of 6480 ± 78 BP and 6210 ± 78 BP respectively, and at 860 cm and 940 cm which gave dates of 13,700 ±130 BP and 13,640 ± 170 BP respectively (see figure 7.4). However, these differences are insignificant at the 2 s.d. level. One major discrepancy is the date of the Rotoma Tephra (8500 ± 10 BP) which lies between the two dates at 420 cm and 470 cm. Owing to these problems, sedimentation rates (Table 7.2) have been estimated using estimated ages for the tephra layers from Froggatt and Lowe (1990). All dates have been plotted against depth to give a visual representation of fluctuations in sedimentation rates throughout the core (Fig. 7.4). Sedimentation rates vary considerably throughout the profile. The estimate for the top 40 cm is likely to be a minimum rate due to

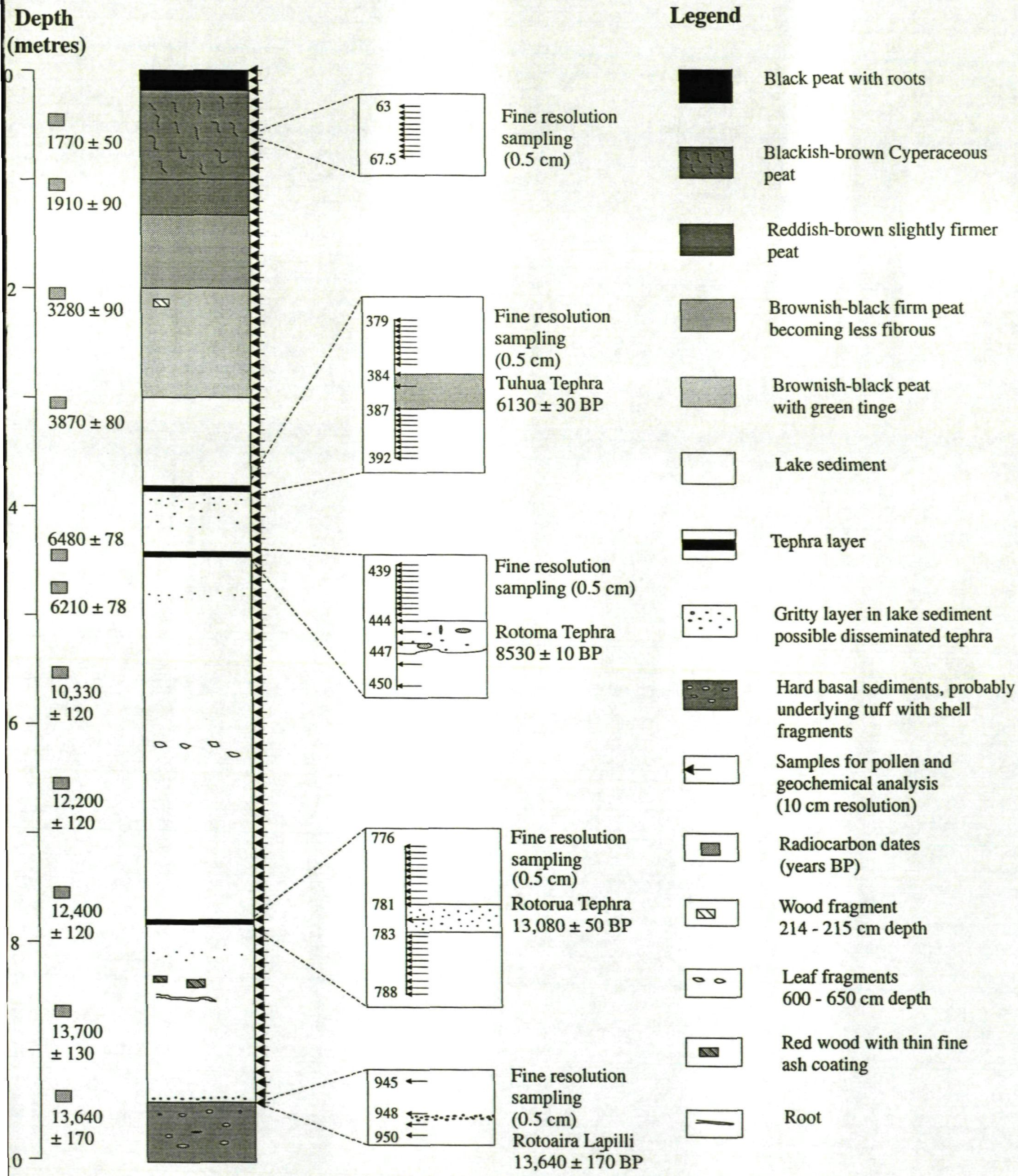



**Figure 7.3** Stratigraphy, chronology and sampling of Kohuora sediment profile

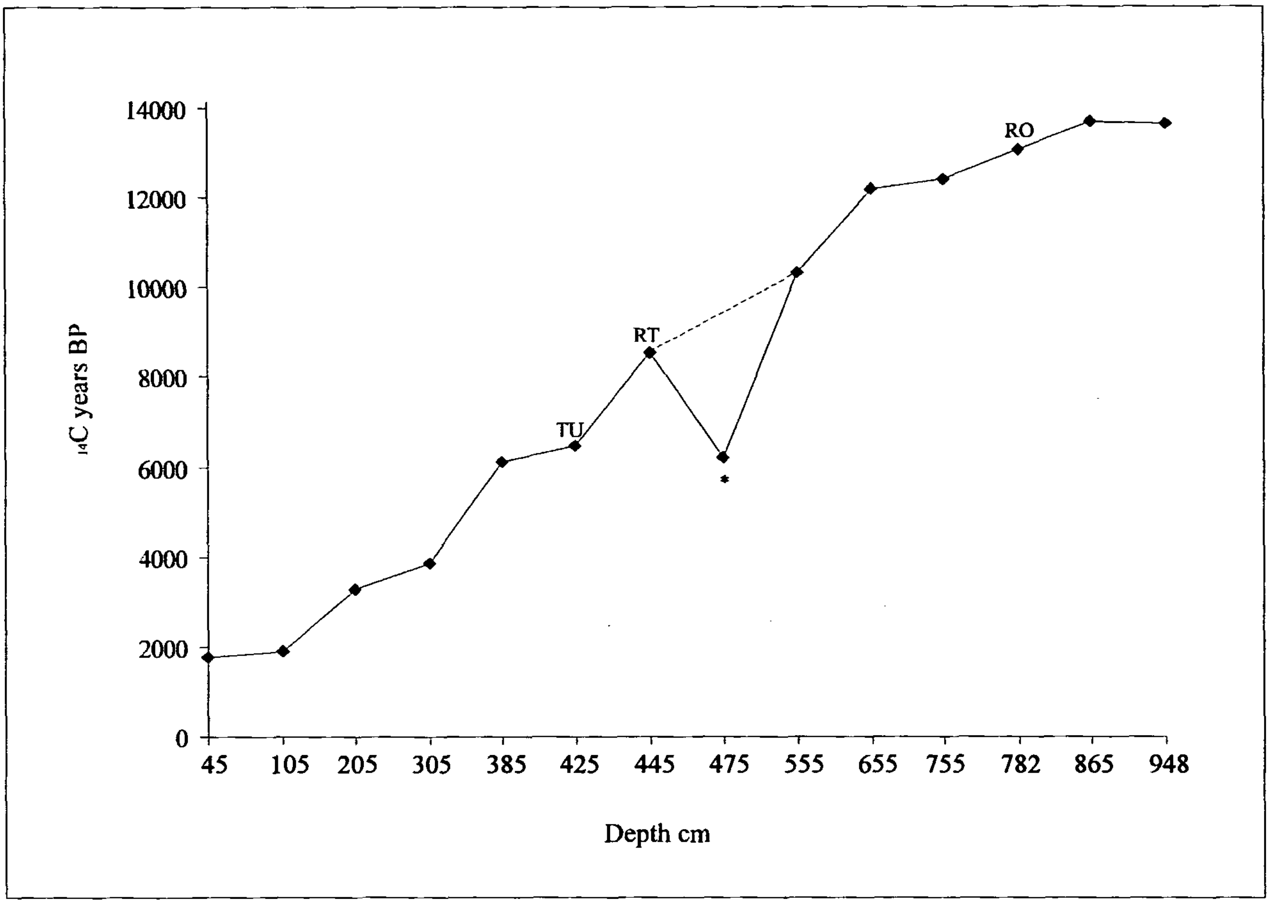



**Figure 7.4** Age-depth curve for Kohuora sediment core, based on tephrochronology radiocarbon dating. TU marks Tuhua Tephra, RT marks Rotoma Tephra and RO marks Rotorua Tephra. * indicates radiocarbon date inversion.

oxidation and shrinkage of the peat in recent times through construction of drainage channels. There is also the possibility that the top section of the profile is missing as the peat has been cut at this site for commercial purposes.

**Table 7.1** Electron microprobe analysis of glass shards from Rotorua, Rotoma and Tuhua tephra layers sampled from Lake Rotomanuka, near Hamilton, North Island, New Zealand. Taken from Lowe (1988).

| Element | Rotorua Tephra, Okataina 13,080 ± 50 BP | Rotoma Tephra, Okataina 8530 ± 10 BP | Tuhua Tephra, Mayor Island 6130 ± 30 BP |
|---|---|---|---|
| $SiO_2$ | 77.57 (0.58) | 78.63 (0.16) | 75.40 (0.38) |
| $AlO_3$ | 12.68 (0.32) | 12.33 (0.10) | 9.43 (0.26) |
| $TiO_2$ | 0.21 (0.05) | 0.10 (0.05) | 0.29 (0.05) |
| FeO | 1.26 (0.09) | 0.87 (0.07) | 5.65 (0.33) |
| MgO | 0.20 (0.08) | 0.12 (0.02) | 0.02 (0.01) |
| CaO | 1.20 (0.33) | 0.71 (0.07) | 0.24 (0.04) |
| $Na_2O$ | 3.55 (0.29) | 3.76 (0.06) | 4.86 (0.31) |
| $K_2O$ | 3.19 (0.44) | 3.37 (0.09) | 3.94 (0.42) |
| n | 10 | 10 | 16 |

n = number of analyses in mean; numbers in parentheses = 1 standard deviation

**Table 7.2** Radiocarbon dates and estimated sedimentation rates for Kohuora profile

| Depth (cm) | $^{14}C$ date (years BP) | Estimated sedimentation rate (cm/year) |
|---|---|---|
| 0 - 40 | 0 - 1770 ± 80 | 0.023 |
| 40 - 100 | 1770 - 1910 ± 90 | 0.43 |
| 100 - 200 | 1910 - 3280 ± 90 | 0.073 |
| 200 - 300 | 3280 - 3870 ± 80 | 0.17 |
| 300 - 384 | 3870 - 6130 ± 30* (Tuhua Tephra) | 0.037 |
| 384 - 444 | 6130 - 8530 ± 10* (Rotoma Tephra) | 0.027 |
| 444 - 550 | 8530 - 10,330 ± 120 | 0.059 |
| 550 - 650 | 10,330 - 12,200 ± 120 | 0.053 |
| 650 - 750 | 12,200 - 12,410 ± 130 | 0.48 |
| 750 - 781 | 12,410 - 13,080 ± 50* (Rotorua Tephra) | 0.046 |
| 781 - 948 | 13,080 - 13,640 ± 170 | 0.3 |

* Dates for tephra layers taken from Froggatt and Lowe (1990).

### 7.6 Methodology

Samples for pollen and geochemical analysis were taken at 10 cm intervals throughout the core to provide a complete record of environmental change occurring throughout the sequence. In addition, Fine resolution sampling was employed above each tephra layer at 0.5 cm intervals in order to examine in detail any possible changes in vegetation and environmental impacts immediately following tephra fallout over a shorter timescale. This fine resolution sampling strategy was also employed below Tuhua and Rotoma tephras in order to investigate vegetational and environmental changes over the same fine resolution timescale prior to tephra fall. Sampling at 0.5 cm intervals created detailed time resolutions which varied from 11 years, 21 years and 14 years per 0.5 cm above Rotorua, Rotoma and Tuhua Tephras respectively.

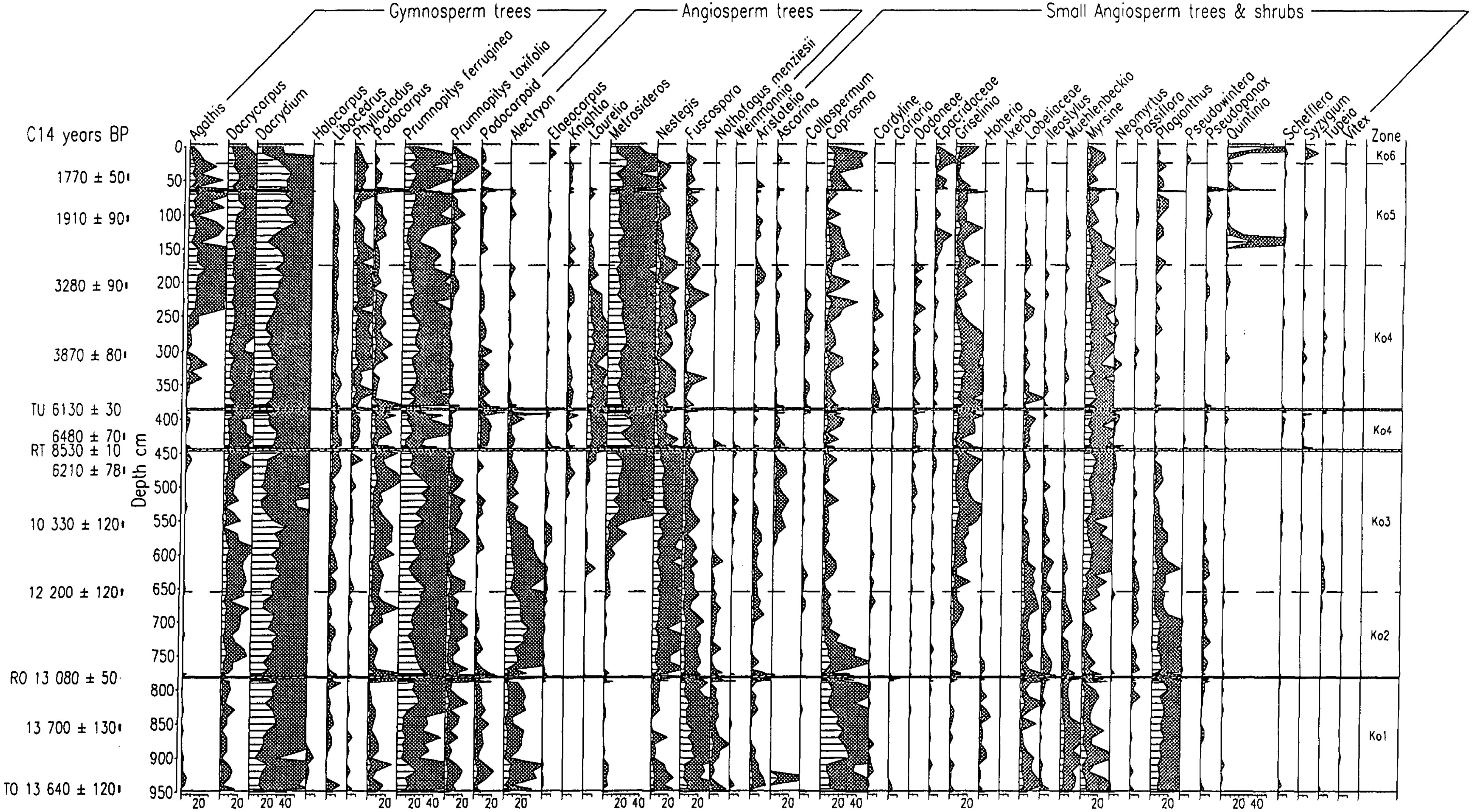
*Leptospermum* pollen is over-represented in the record, indicating local on-site pollen influx and is therefore excluded from the dryland pollen sum.

DECORANA and cluster analyses were carried out on pollen taxa for the entire sequence, and again for the fine resolution pollen changes above each tephra layer. These analyses excluded tephra shards and charcoal counts in order to isolate specific vegetational trends and changes occurring throughout the sequence. In addition DECORANA was carried out on fine resolution pollen samples including tephra shards and charcoal in order to examine any taxa trends closely resembling those of tephra and charcoal in the pollen record.

Fifteen elements have been quantitatively determined. Geochemical analysis revealed only 8 of these elements were present in significant proportions throughout the sediment profile, and so the remaining 7 elements were omitted from the diagrams and further discussion.

**7.7 Results**

Results for the full sequence of pollen and geochemical changes are displayed in Figures 7.5 and 7.6 respectively, with full descriptions presented in Tables 7.3 and 7.4. Pollen and geochemistry results for fine resolution sampling above tephra layers are described in Table 7.5 and displayed in Figures 7.7 and 7.9 (Rotorua), 7.10 and 7.12 (Rotoma) and 7.13 and 7.15 (Tuhua).


Gymnosperm trees
Angiosperm trees
Small Angiosperm trees & shrubs
C14 years BP
Agathis
Dacrycarpus
Dacrydium
Halocarpus
Libocedrus
Phyllocladus
Podocarpus
Prumnopitys ferruginea
Prumnopitys taxifolia
Podocarpoid
Alectryon
Elaeocarpus
Knightia
Laurelia
Metrosideros
Nestegis
Fuscospora
Nothofagus menziesii
Weinmannia
Aristotelia
Ascarina
Callospermum
Coprosma
Cordyline
Coriaria
Dodoneae
Epacridaceae
Griselinia
Hoheria
Ixerba
Lobeliaceae
Ileostylus
Muehlenbeckia
Myrsine
Neomyrtus
Passiflora
Plagianthus
Pseudowintera
Pseudopanax
Quintinia
Schefflera
Syzygium
Tupeia
Vitex
Zone
1770 ± 50
1910 ± 90
3280 ± 90
3870 ± 80
TU 6130 ± 30
6480 ± 70
RT 8530 ± 10
6210 ± 78
10 330 ± 120
12 200 ± 120
RO 13 080 ± 50
13 700 ± 130
TO 13 640 ± 120
Depth cm
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
750
800
850
900
950
Ko6
Ko5
Ko4
Ko4
Ko3
Ko2
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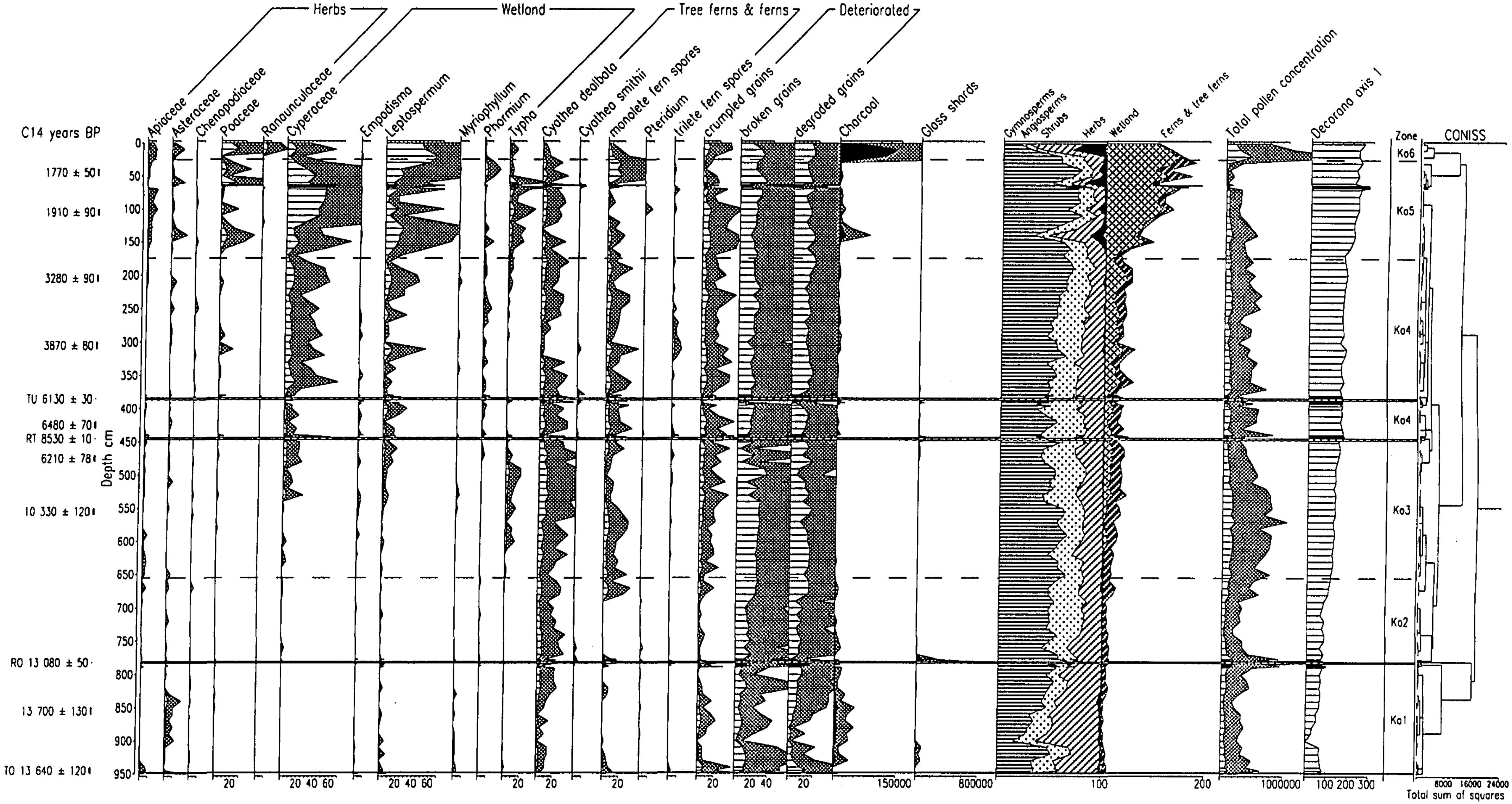



**Figure 7.5** Pollen diagram revealing changes in main taxa for the complete sediment profile from Kohuora crater. Charcoal and glass shards are expressed as number of fragments per cm$^3$ sediment. Stippled curves represent x 5 magnification of pollen percentages.

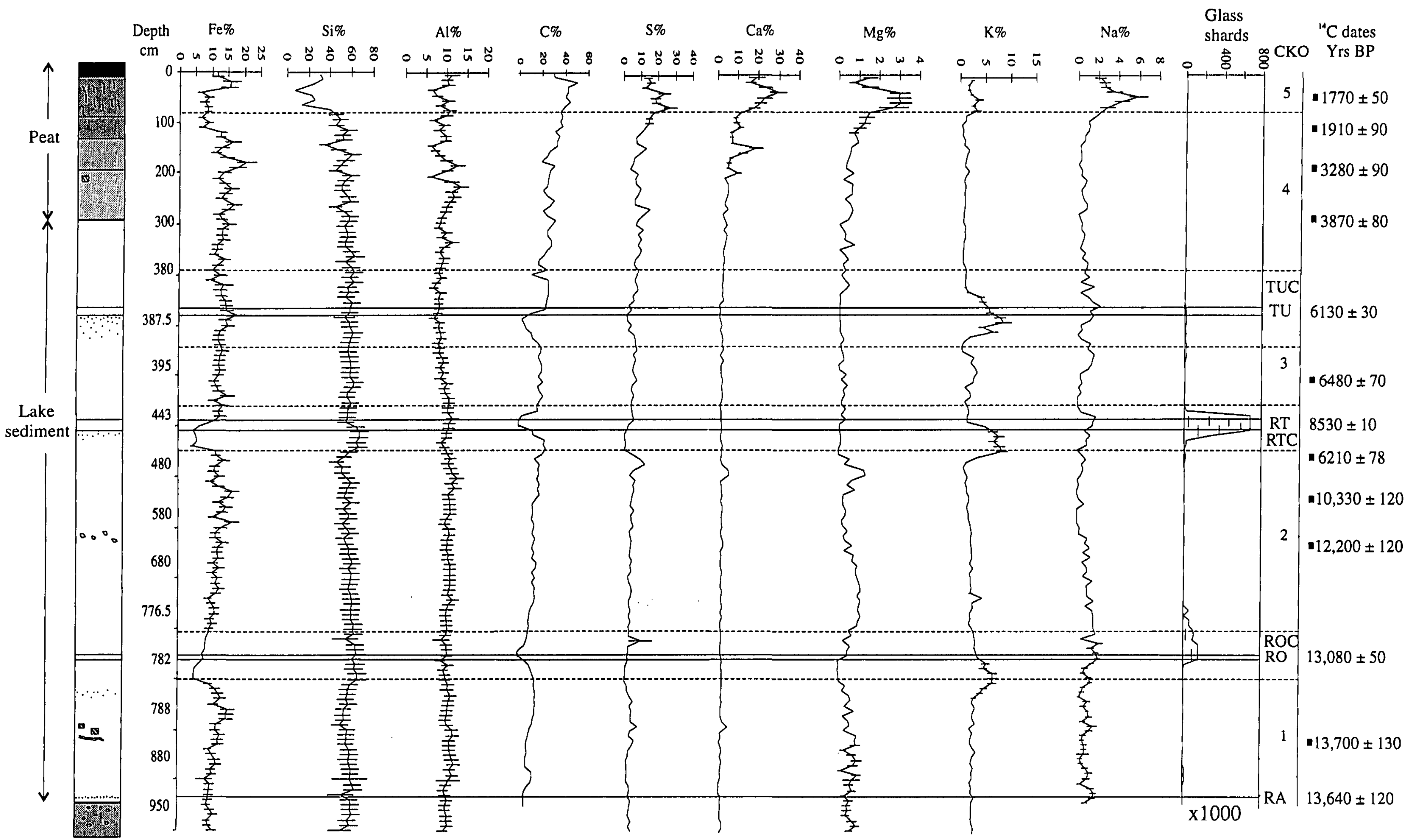



**Figure 7.6** Relative proportions of elements present in Kohuora sediment core. CKO refers to chemizones which are numbered or identified by character codes. TUC marks Tuhua Tephra Chemizone, RTC marks Rotoma Tephra Chemizone, and ROC marks Rotorua Tephra Chemizone. Solid boundaries with character labels denote visible (macroscopic) Tephra layers, Tuhua Tephra (TU), Rotoma Tephra (RT), Rotorua Tephra (RO) and Rotoaira Tephra (RA). Short horizontal lines represent standard error bars calculated to ± 2 standard deviations. Glass shards are expressed in thousands per $cm^3$.

**Table 7.3** Description of pollen results (Fig. 7.5)

| Pollen zone | Depth (cm) | Description |
|---|---|---|
| **KO1** | 948-783 | Lowermost spectra largely dominated by small angiosperm tree and shrub pollen, comprising 60% tdlp sum. Trees: *Dacrydium* pollen is abundant, peaking to 30% at 790cm. *Prumnopitys ferruginea* present at 20%, *Podocarpus* and *Prumnopitys taxifolia* increase to 10% above 790cm. *Fuscospora* pollen declines throughout the zone. Shrubs: *Coprosma* and *Plagianthus* pollen is abundant. Deteriorated pollen grains increase. Charcoal levels reach 20% at 850cm. |
| **KO2** | 783-655 | Trees: Podocarp pollen becomes abundant with *Dacrydium* and *Prumnopitys ferruginea* both increasing to 30%. *Podocarpus* and *Prumnopitys taxifolia* pollen declines above 776cm to 5%. *Alectryon* peaks to 30% at 710cm, declining to 10% at 655cm. *Nothofagus* pollen types fall to <5%. Tree ferns: Tree fern spores are present at 5%. Broken and degraded pollen increases to 25% above 660cm. Charcoal fragments reach 5% at 760cm. |
| **KO3** | 655-447 | Trees: *Dacrydium* pollen levels peak to 40% at 560cm, declining to <30%. *Prumnopitys ferruginea* pollen declines to 10% at 620cm. *Metrosideros* pollen and minor levels of Ascarina pollen appears in this zone, with *Metrosideros* rising to 15% at 460cm. Shrubs: *Myrsine* pollen increases immediately below the Rotoma Tephra. *Griselinia* pollen is present at 10% at 530cm. Tree ferns: *Cyathea dealbata* peaks to 15%, declining below the tephra layer. Deteriorated pollen fluctuates, but remains high between 20-35%. |
| **KO4** | 447-175 | Trees: *Dacrycarpus* pollen exhibits a short-lived peak to 10% at 410cm. *Agathis* pollen appears at 340cm, increasing rapidly to 20% at 180cm. *Dacrydium* pollen remains abundant while *Prumnopitys ferruginea* pollen declines to 5% at 175cm. *Alectryon* pollen declines to <1% above 390cm. *Metrosideros* pollen remains abundant at 10%. Shrubs: *Griselinia* and *Myrsine* pollen increases to 10% and 13% respectively. Wetland: *Leptospermum* and Cyperaceae increase to 10% and 12% respectively. Deteriorated pollen abundant at 20%. Charcoal fragments feature sporadically, reaching 3% between 320-260cm. |
| **KO5** | 175-25 | Trees: *Dacrycarpus* pollen is abundant at 10%-15%, *Dacrydium* peaks to 40% at 110cm. Shrubs: *Quintinia* displays a sudden peak at 160cm to 20%. Herbs: Poaceae pollen displays a short-lived increase to 15% at 60cm. Wetland: *Leptospermum* and Cyperaceae pollen rises to 30% and 60% respectively. *Typha* pollen reaches 10%. Deteriorated pollen declines. Charcoal fragments peak to 20% at 140cm, and 15% at 40cm. |
| **KO6** | 25-0 | Shrub and Herb pollen comprises 90% of tdlp sum. Shrubs/wetland: *Quintinia* and *Leptospermum* are dominant, with *Leptospermum* pollen peaking to 65%, falling to 45% at the peat surface while *Quintinia* peaks to 25%. Herbs: Poaceae and Ranunculaceae pollen rises to 8% and 3% respectively. Deteriorated pollen levels are <15%. Charcoal fragments reach 50% at 10cm, falling to 30% at the surface. |

**Table 7.4** Description of Geochemistry results (Fig. 7.6)

| Chemizone | Depth (cm) | Description |
|---|---|---|
| **CKO1** | 950-785 | Si and Al are the dominant elements and fluctuate between 45-53%, and 10-12% respectively. Ca peaks at 788 cm depth to 6%. K remains consistent at 2.5 %. P exhibits a small peak at 900 cm to 1.3%. Mobile elements S and Fe display similar trends, rising to 6-8%, and 13-15% respectively from 820 to 786 cm. |
| **CKO2** | 779-460 | Major elements K and Na fall from 4-2%, and 1.5-0.8% respectively. Si is the dominant element present at highest levels of 65% at 779 cm. Ca and Al remain at 3% and 8-10% respectively. S is present between 5-7%, displaying a sudden peak to 10% at 777.5 cm. Fe falls from 16% to 12% at 475 cm. C rises from 12% to 20% at the top of the zone. |
| **CKO3** | 440-389.5 | K and Na fluctuate between 0.5-3%, and 0.1-1.5% respectively. Si remains dominant at 50-55%, and Ca is consistent at 3%. Al falls gradually from 10% to 8% at 389.5 cm depth. S and Fe exhibit similar trends with S increasing from 5 - 8%, and Fe from 11 - 14% at the top of the chemizone. C fluctuates around 20%. |
| **CKO4** | 380.5-80 | Na, K and Mg are present below 2% throughout. Si is the dominant element, falling gradually from 60-40%, displaying a lowest value of 32% at 140 cm depth. Ca exhibits a sudden peak at 140 cm to 18%, falling to 6-10% at the top of the chemizone. S increases erratically from 5-15%. Fe rises to 20%, declining to 8% at 80 cm. C rises from 18% to 38% at 80cm. |
| **CKO5** | 80-0 | K and Na peak to 3.8% and 5.8% respectively at 40 cm. Mg increases from 1.2 to 3% between 30-50 cm. Si declines to lowest core values of 8% at 30 cm, rising again to 30% at 0 cm. Ca exhibits a sharp increase to 29% at 30 cm, declining to 18% at the peat surface. Al fluctuates between 7-11%. S peaks to 26% at 60 cm, falling to 14% at the peat surface. Fe values rise to 16% at 20 cm, falling to 12% at 0 cm. C peaks to 50% at 20cm. |

**Table 7.5** Pollen and geochemical changes immediately following and during tephra deposition at Kohuora crater

| Tephra | Depth (cm) | Pollen changes | Geochemical changes | Remarks |
|---|---|---|---|---|
| **Rotorua** | 781-783 | Significant increase: *Prumnopitys ferruginea*, *Coprosma*<br>Significant decrease: *Dacrydium*, *Podocarpus*, *Prumnopitys taxifolia* | Significant increase: Na<br>K (temporary)<br>Significant decrease: Mg, Fe, S,<br>C (temporary) | Degraded pollen declines gradually.<br>Charcoal present at 779-778cm.<br>C rises sharply after initial decline.<br>K declines gradually above tephra layer. |
| **Rotoma** | 444-447 | Significant increase: *Metrosideros*, *Griselinia*, Cyperaceae<br>Significant decrease: *Dacrydium*, *Prumnopitys ferruginea* | Significant increase: K (temporary)<br>Na, Si<br>Significant decrease: S,<br>Al, C, Fe (temporary) | K initially high within tephra layer, declines rapidly above tephra.<br>Al, C, Fe low within/above tephra, gradually increasing above. |
| **Tuhua** | 384-387 | Significant increase: *Podocarpus*, *Griselinia*, *Myrsine*, Laurelia<br>Significant decrease: *Dacrydium*, *Prumnopitys ferruginea*, *Metrosideros* | Significant increase: Na, K (temporary)<br>C, Fe | Broken pollen levels decline, while degraded grains peak at 381.5cm.<br>Charcoal present peak sharply at 385cm.<br>Na and K increase within/immediately above the tephra, declining thereafter. |

## 7.8 Vegetation and catchment history

*Late glacial (13,640 to 10,330 years BP)*

Pollen spectra at the base of zone KO1 (950 - 945 cm, Fig. 7.5) reveal a transition from a relative abundance of shrub and herb vegetation, characterised by *Coprosma*, *Plagianthus*, *Myrsine* and Asteraceae, to the expansion of podocarp-hardwood forest around Kohuora crater. Forest vegetation is characterised by *Dacrycarpus*, *Dacrydium*, *Prumnopitys ferruginea*, *Alectryon*, *Nestegis*, and *Cyathea dealbata*. *Fuscospora* pollen was probably derived from distal sources. The expansion of podocarp-hardwood forest may be in response to the changing climate at this time. These basal sediments are dated at 13 640 ± 120 BP, suggesting the base of zone KO1 falls within the period of transition from full glacial to full interglacial conditions, occurring between 14 000 - 8000 BP (Burrows, 1979). From 14 000 BP expansion of podocarp forest was widespread over northern and central North Island (McGlone, 1983; Newnham *et al*., 1989; Newnham and Lowe, 1991; McGlone *et al.*, 1993). Previous palynological studies in the Firth of Thames and Northland indicate that podocarp-hardwood forest was already established throughout the region around 14,000 BP (Pocknall *et al.*, 1989; Newnham, 1992).

Microscopic charcoal fragments are present immediately below the Rotoaira Tephra layer, indicating an episode of burning had occurred in the area prior to that eruption. This also could have been responsible for the observed vegetation changes at the base of the profile. Evidence for sustained burning of the local vegetation is indicated by the abundance of microscopic charcoal fragments, with lower levels podocarp-hardwood forest pollen, and higher levels in *Nothofagus fusca*-type, *Coprosma* and *Myrsine* shrubs, and Asteraceae, previously in decline. These latter shrubs it seems recovered temporarily, probably invading canopy gaps created following damage to trees by fire. Newnham (1992) notes that these taxa are opportunists, which can invade rapidly into areas where light penetrates through the forest canopy, following the death of tall canopy and emergent trees. Evidence for frequent late glacial forest fires has also been found in pollen records from Trig Road (Newnham *et al.*, 1993) and Otakairangi swamp (Newnham, 1992) in the Northland region.

Sustained burning in the local area may have triggered catchment erosion and inwashing of topsoil and organic matter into the lake Evidence for erosion is supported to some extent by the increase in occurrence of crumpled, broken and degraded pollen grains in the lower section of zone KO1. Chemical assemblages in chemizone CKO1 (Fig 7.6) initially indicate predominantly stable environmental conditions. Na, K, Ca, Si, Al and Mg display steady-state equilibrium, suggesting minimal soil leaching and mechanical weathering. As the trend in S closely resembles that of Fe, S may therefore reflect some influx of ferrous sulphides into the lake (Mackereth, 1966). Fe has possibly been incorporated into the lake sediments by its presence on sediment particles as an oxide coating, or in a dissolved form as humic/fulvic acid complexes from the soil during normal leaching processes under stable environmental conditions (Mackereth, 1966; Jones and Bowser, 1978; Engstrom and Wright, 1984). However, Fe displays dynamic equilibrium with a steadily increasing trend. This may indicate an increase in soil leaching and erosion, initiated by local vegetation disturbance through sustained burning in the catchment. Burning may have altered the chemical properties of the soil, possibly causing some iron enrichment in Fe in lake sediments derived from inwashing of burnt topsoil from the catchment. The period of burning appears to have continued almost to the time of the Rotorua eruption 13,300 BP. A slight increase in local erosion owing to vegetation damage by fire may have been responsible for the higher sedimentation rates estimated for zone KO1.

Pollen assemblages appear to indicate swamp forest dominated the site, with *Dacrydium* and *Coprosma* in particular, and lower numbers of *Dacrycarpus* trees all growing in marshy areas and shallow lake margins. These trees prefer moister conditions and may be sensitive to drought (Newnham *et al.*, 1989). *Prumnopitys ferruginea* probably grew on the higher ground around the Kohuora tuff ring. A decline in *P. ferruginea* is envisaged from the pollen data, probably due to periodic burning over drier areas surrounding the crater. *Prumnopitys ferruginea* and *Dacrydium* trees probably originally flourished at this site owing to its sheltered location. *Nothofagus* trees may have been growing in more exposed areas and less favourable sites at distal locations from Kohuora, partly because they can adapt to these conditions, but also because they do not compete well in areas where forest cover is already established (Newnham, 1992). Influx of pollen from *Nothofagus* species probably originated from beech stands in the Waitakere and Hunua ranges.

Above the Rotorua tephra layer, *Prumnopitys ferruginea* trees became prominent in the area, while *Dacrydium* remained dominant in the main canopy, and *Alectryon, Nestegis, Myrsine,* Lobeliaceae and *Cyathea dealbata* became abundant. The apparent increase in diversity within the local forest may have been the result of periodic burning on a smaller scale, indicated by low levels of microscopic charcoal fragments, encouraging the establishment and growth of angiosperm saplings due to increased light infiltration and canopy space.

Increases in *Coprosma* and *Dacrydium*, and to a lesser extent *Dacrycarpus*, between 13,000 to 12,000 years BP may indicate expansion of marshy lake margins due to a shallowing of the lake, possibly due to infilling by organic matter from the forest. The expansion of tall forest trees could also suggest an increase in precipitation, with the expansion of *Dacrydium* in North Island forests in response to a change to warmer, wetter conditions around 12,000 years BP (Newnham *et al.*, 1989). Higher Si levels displayed in the geochemical record may be partially due to the incorporation of plant-derived silica within lake sediments (Grattan *et al.*, 1996), as the forest cover surrounding the lake increases in density. High levels of Si, together with moderate Al, could also reflect the influx of clastic silicate minerals (Engstrom and Wright, 1988), derived from continual weathering of local catchment rocks and soils around Kohuora crater during increasingly mild and moist climatic conditions.

A sudden increase in forest diversity is recorded at sites in the Waikato region from 11 000 BP (Newnham *et al.*, 1989) and other pollen sites in the North Island from 10 000 BP (McGlone and Topping, 1977, Mildenhall, 1979). However, this appears to occur much earlier at Kohuora, perhaps due to the northerly location of this site, where the climate may have been slightly milder, and also due to its low-lying relatively sheltered position, encouraging forest expansion in the area.

The rise in the number of damaged pollen grains may indicate increased overland flow and sediment inwashing during a period of higher precipitation. Increases in the proportions of distal pollen represents the rapid expansion of forest throughout the Auckland region.

*Holocene vegetation and catchment history (10 330 - top of core)*

Vegetation changes at Kohuora during the early Holocene (10 330 - 8500 BP) appear to be analogous with those reported by Newnham and Lowe (1991) at Lake Waiatarua. *Dacrydium* trees declined while *Metrosideros, Ascarina, Nestegis, Myrsine* trees and *Cyathea dealbata* tree ferns exhibit marked increases in numbers at both sites. These changes in forest taxa may therefore represent a regional vegetation response to climate change, as *Metrosideros* species and *Ascarina* are known to flourish in areas where a warm, moist and relatively frost-free climate prevails (McGlone *et al.*, 1993). Newnham and Lowe (1991) suggest these changes represent a climate that was possibly warmer than at present, allowing these taxa to expand across the region. Similar vegetation changes have been reported from other North Island pollen sites, in particular the expansion of *Ascarina* during the early Holocene (McGlone and Moar, 1977; Moar and Mildenhall, 1988). Newnham and Lowe (1991) note that *Ascarina* was never common in the Auckland region, as shown by low pollen levels at Waiatarua (7%) and Kohuora (4-5%), and have suggested that *Ascarina* pollen was derived from long-distance dispersal, perhaps from the Hunua and Waitakere ranges to the west and south of Auckland (fig. 7.1).

Turning to the geochemistry record, Si exhibits dynamic equilibrium with a downwards trend, possibly reflecting lower overall erosion within the catchment as local forest increases in density, stabilising soils on surrounding slopes. Fe and S exhibit similar trends, displaying dynamic equilibrium with an upwards trend. S displays a sudden peak at 777.5 cm depth. This may represent a period of increased biological productivity in the lake, and a gradual increase in influx of organic material, indicated by a steady increase in C. However, caution must be employed in the interpretation of the peak in S as the error bars represent a large deviation about the mean, indicating variability in sample measurements. Fe increases, possibly due to the incorporation of ferrous sulphides in the lake sediments. The production of humic acids from rapid breakdown of organic matter under a dense forest canopy may also have contributed to higher Fe levels, and is not associated with erosion of local soils in this case as Na and K remain very low throughout CKO2 and CKO3. Hence it can be inferred from these chemical assemblages that environmental stability prevailed in the local catchment.

*Dacrydium* trees become dominant at Kohuora once again around 8000 yrs BP, immediately below the Rotoma tephra, which is synchronous with rises in *Dacrydium* at Lake Waiatarua and at Waikato pollen sites (Newnham and Lowe, 1991; Newnham *et al.*, 1989). The increase in *Dacrydium* at Kohuora is likely to be in response to a period of maximum warmth and wetness, reflecting climatic optimum conditions which were reported by Burrows (1979) to have prevailed around 8000 years BP. *Metrosideros* trees are most abundant at this time, with increases in *Laurelia, Myrsine* and *Griselinia,* and a short-lived rise in the prevalence of *Alectryon* trees, suggesting well established diverse forest thrived at this site from 8500 years BP.

Between 8000 - 6000 BP, gradual vegetation changes indicate a possible decrease in soil fertility, and hydroseral succession infilling the lake, indicated by the transition from lake sediments to organic peat above 300 cm depth, and an increase in wetland plants (e.g. *Leptospermum*, *Coprosma*, Cyperaceae and *Phormium*). *Prumnopitys ferruginea*, *Myrsine* and *Griselinia* trees decline, while *Dacrycarpus*, *Dacrydium*, *Agathis* and *Phyllocladus* increase, indicating perhaps that swamp forest and wetland taxa dominated the lower ground in the crater, while *Agathis* and *Phyllocladus* became established on higher, dry ground where soils were more likely to have become impoverished over time. *Agathis* trees can tolerate poor soils and frequent disturbance (McGlone, *et al.*, 1993) and, together with *Phyllocladus*, favour drier sites (Newnham *et al.*, 1989). These changes are comparable to those recorded at Lake Waiatarua during the Holocene, reflecting the expansion of these trees throughout the Auckland region, perhaps due to a drier overall climate (Newnham and Lowe, 1991).

Levels of Na and K remain low throughout CKO4 which would appear to indicate that environmental conditions remained stable. However, this contradicts other evidence from the mineral assemblages which indicates increasing environmental instability around Kohuora crater. Increases in Ca, Fe, Al and Mg reveal a possible increase in leaching and erosion of local soils (Mackereth, 1966), leading to a decline in soil fertility. High values of S indicate nutrient inwashing from the catchment, and an increase in organic matter content, biological activity and humification (Pyatt *et al.*, 1995). The abundance of organic matter and plant detritus subsequently led to infilling of the lake, initiating the accumulation of peat deposits in the crater.

Above the lake/peat transition at 300 cm depth, wetland taxa increase substantially (Fig. 7.5), indicating the establishment of the wetland area over the crater floor. A peak in microscopic charcoal fragments coincides with a sudden reduction in *Agathis* and *Dacrydium* trees at 140 cm. These changes may indicate drier, windier conditions, with these trees, especially *Dacrydium*, becoming susceptible to windthrow, providing fuel stock for fire. Also, temporary drying of the bog surface and/or margins may have increased the frequency and spread of local fires. Following the period of burning, *Dacrydium* and *Dacrycarpus* trees recover, reflecting local presence around wetland margins on marshy waterlogged soils. *Agathis* and *Phyllocladus* trees continue to decline, possibly as a result of the expanding wetland area which may have forced these trees to retreat to higher dry ground further from the core site.

Rapid invasion of shrub and herb taxa follow, with short-lived peaks in *Quintinia*, Poaceae and Asteraceae, which probably invaded patches of burnt ground formerly occupied by *Agathis and Phyllocladus* trees. The cause of this extensive burning is unclear, but is unlikely to reflect early anthropogenic disturbance from the arrival of Polynesians in the area, as the top of the zone is dated at 1770 ± 50 BP. The occurrence of *Pinus* pollen from 140 cm depth indicates disturbance of the peat causing downwards dislocation of pollen and charcoal to lower levels. There also appears to be no clear anthropogenic deforestation signal in the dominant tall tree taxa, as tree pollen levels remain relatively consistent to the top of KO5, showing no sharp decline until the base of zone KO6. The burning towards the top of the zone could have been caused by lightning strikes. There is evidence elsewhere in New Zealand to suggest the climate became increasingly windy (McGlone *et al.*, 1993) which would have encouraged the spread of natural fires.

The large charcoal peak at the top of the profile indicates sustained extensive burning in the area since around 1770 BP. *Dacrydium*, *Dacrycarpus*, *Agathis* and *Prumnopitys ferruginea* trees declined, coinciding with increasing charcoal levels from 30 cm depth to the peat surface. *Leptospermum* shrubs appear to be abundant close to the coring site from approximately 1000 years BP, indicated by high pollen levels. *Leptospermum* is a large pollen producer and can grow in abundance at wetland sites, and over-representation in pollen records is common (McGlone, 1988). Herbaceous plants become abundant in the top 30 cm of the profile, reflecting the replacement of dense forest with grasses, herbs and low-lying shrubs. *Quintinia* also increases in abundance, reflecting local presence at Kohuora to recent times. *Quintinia* appears in conjunction with high charcoal levels, which is also seen in zone KO5, suggesting its ability to invade rapidly on charred surfaces following recent fires.

The European impact signal is missing, and Polynesian impact is unclear at this site owing to extensive disturbance of the peat in recent years. This would explain why there are very few pollen grains from adventive taxa present in the top 10 cm of the record. The elemental changes in CKO5 reveal sustained disturbance within the catchment. Na, K, Mg, Fe and Ca levels are high, representing inwashing of these elements from disturbed catchment soils. Si and Al levels are low, representing reduced influx of alumino-silicates, as Al had by now been leached from local soils. However, this could also be the result of increasing acidity within the peat, as Al becomes mobilised above pH 5 (Bache, 1986). Thus, the palaeoenvironmental significance of Al becomes less valuable, owing to ambiguity in the interpretation. K is often present in high proportions in the surface layers of peat profiles as it is an essential nutrient for all living plants (Clymo, 1983; Shotyk, 1988), and so the high proportions of this element in surface layers is probably due to a natural surface enrichment. Its occurrence with Na provides further evidence for local catchment disturbance. Higher Fe is often observed in surface horizons of peat profiles due to active soil-plant circulation, and oxidising conditions resulting in the apparent iron enrichment (Markert and Thornton, 1990). Higher Fe and P observed in surface peat sediments by Grattan *et al.* (1996) have been interpreted to be the result of prolonged acidification and exploitation of local soils and the influx of nutrients due to anthropogenic disturbance and deforestation.

## 7.9 Volcanic impacts

*Rotorua Tephra*

Changes in vegetation assemblages following the deposition of the Rotorua tephra (Fig. 7.7 and Fig 7.8) show some similarity with those at other pollen sites following tephra fallout (Clarkson *et al.*, 1988; Clarkson, 1990; Lees and Neall, 1994; Wilmshurst and McGlone, 1996). Increases in herbs and scrub vegetation have been recorded as large forest canopy trees are damaged during an eruption, allowing increased light intensity to the forest floor (McGlone *et al.*, 1988; Wilmshurst and McGlone, 1996). Fine resolution sampling above the tephra layer has produced a detailed picture of vegetation change over a shorter timescale, with each 0.5 cm sample representing approximately 11 years of post-eruption environmental history (Fig. 7.7). Vegetation changes observed at Kohuora reveal a decline in the podocarps *Prumnopitys taxifolia, Podocarpus* and *Dacrydium*, and *Muehlenbeckia* lianes, which was sustained for approximately 100 years, while *Prumnopitys ferruginea* trees appear to increase significantly immediately above the Rotorua tephra, along with slight increases in *Nestegis* and *Alectryon* trees, and monolete fern spores.

Prior to the eruption, previously dominant vegetation included *Dacrydium* together with *Prumnopitys ferruginea*. Clarkson *et al.* (1988) reported that forest vegetation at Pureora (Fig. 2.1) prior to the Taupo eruption consisted of emergent tall *Dacrydium*, with a main canopy of *Prumnopitys ferruginea* trees. Assuming a similar forest structure had

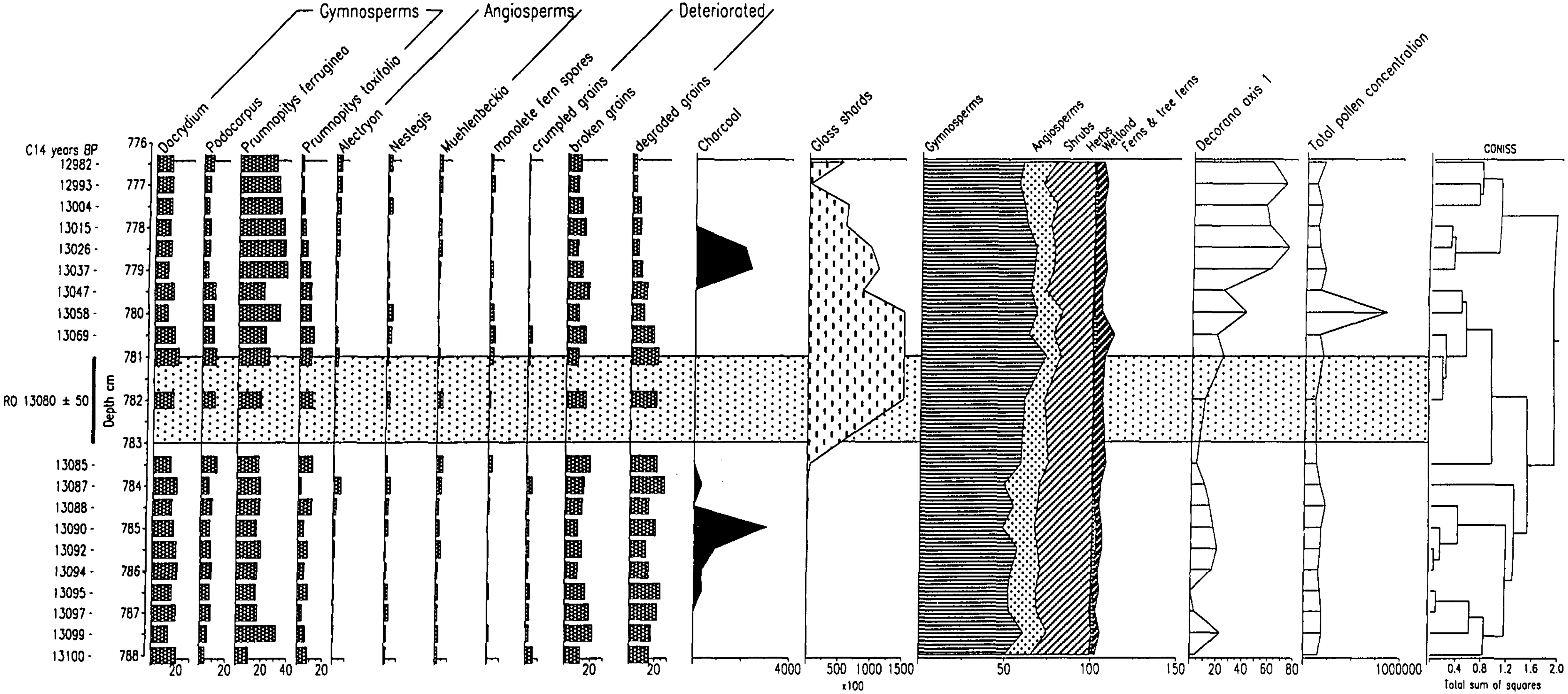
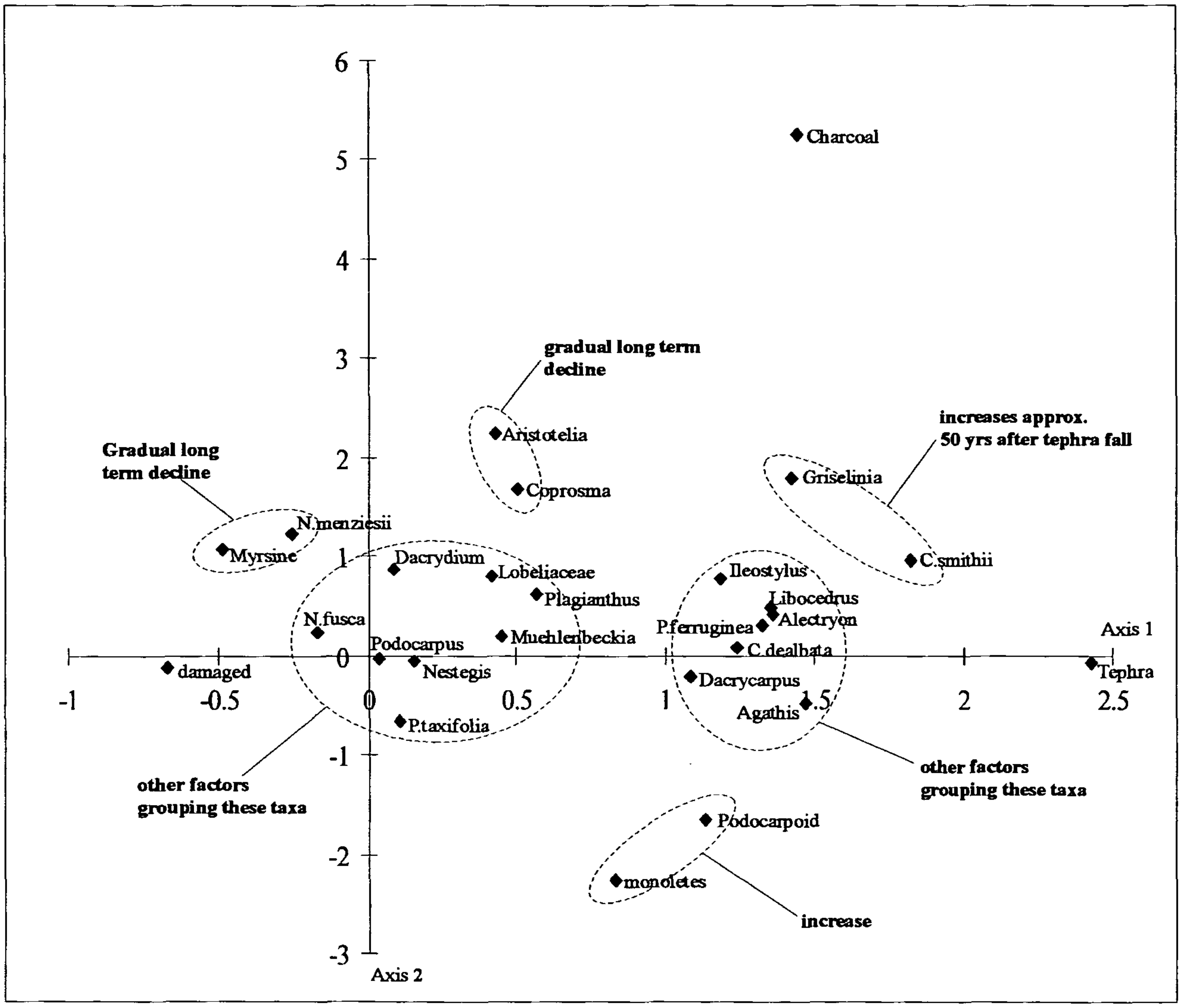



**Figure 7.7** Fine resolution pollen diagram displaying changes in main taxa above and below Rotorua Tephra. Charcoal and glass shards are expressed as number of fragments per cm$^3$ sediment analysed.




Eigenvalues: Axis 1= 0.27 Axis 2 = 0.03

**Figure 7.8** A biplot of pollen taxon associations, determined from DECORANA, in spectra surrounding the Rotorua Tephra layer at Kohuora crater, Auckland.

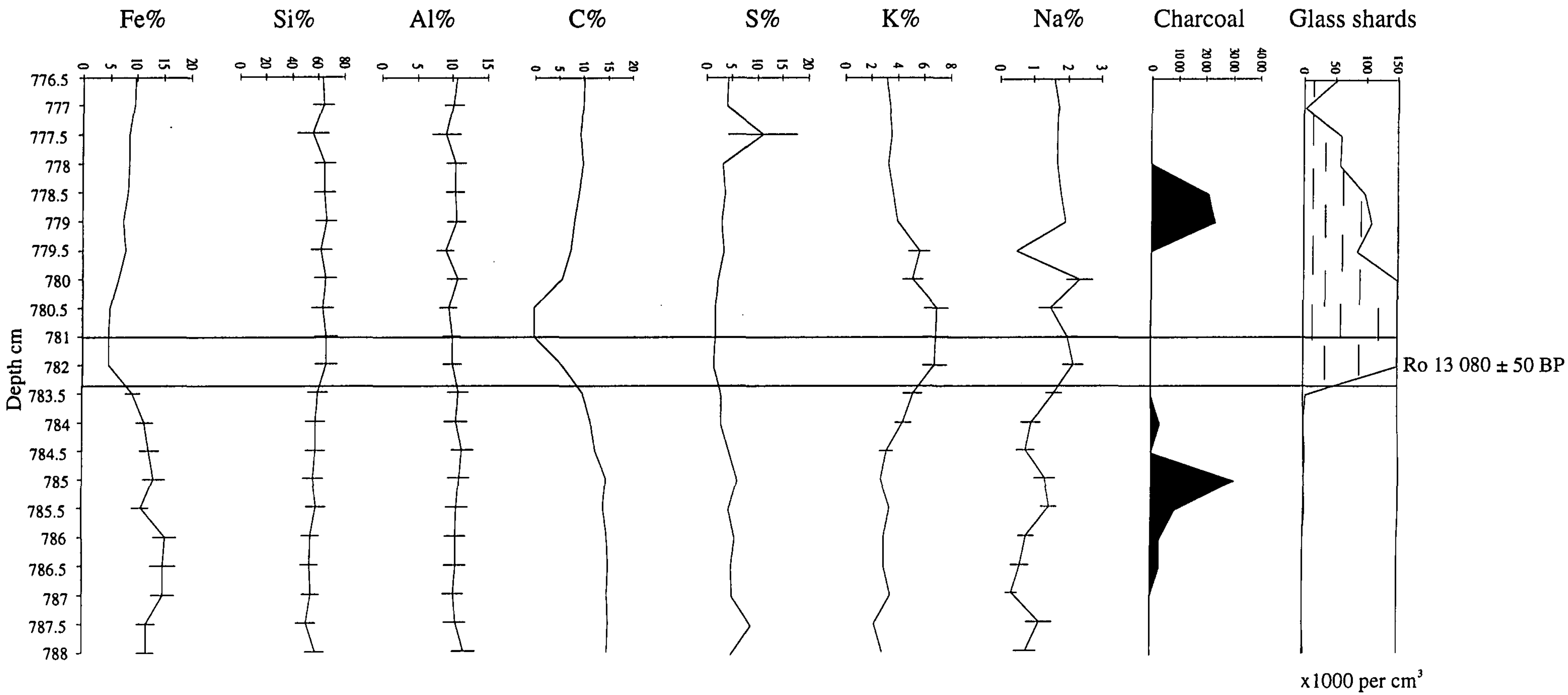



**Figure 7.9** Fine resolution sampling and geochemical analysis taken at 0.5cm intervals where possible, displaying changes in lake sediment geochemistry above and below Rotorua Tephra. Short horizontal lines indicate error bars calculated to 2 standard deviations.

become established at Kohuora, *Dacrydium* trees may have sheltered the lower canopy of *Prumnopitys ferruginea* trees from damage by tephra fall and toxic chemicals. Lees and Neall (1994) suggested that *Dacrydium* trees suffered the most damage following the eruption of the Burrell Ash from Mt Egmont (470 ± 50 years BP), owing to their tall stature rising above the lower forest canopy. Defoliation of *Dacrydium* and other podocarp trees following damage from tephra accumulation would have opened up the forest allowing light to penetrate the main canopy and forest floor, encouraging the expansion of ferns and new *Nestegis*, *Alectryon* and *Prumnopitys ferruginea* saplings. The decline in *Podocarpus* and *Prumnopitys taxifolia* may reflect sensitivity to ash accumulation and toxic chemical leaching, and also competitive pressure from expanding *Prumnopitys ferruginea* trees. *Muehlenbeckia* lianes may have suffered inadvertently through the decline of podocarp host trees or from tephra accumulation if they too were exposed above the main forest canopy, and had perhaps become established in the crown of tall podocarps such as *Dacrydium* and *Prumnopitys taxifolia.*

An additional factor that is likely to have encouraged expansion of Prumnopitys ferruginea is the immediate effect tephra accumulation has on the soil and ground surface. The deposition of 3 cm of Rotorua tephra at Kohuora would have improved drainage and soil aeration, and provided a potential deeper rooting medium (Clarkson *et al.*, 1988). This would have encouraged expansion of *Prumnopitys ferruginea*, which generally prefers drier sites (Newnham *et al.*, 1989), creating an ideal substrate for the germination and establishment of new *Prumnopitys ferruginea* saplings. Also, replenishment of the soil by the addition of mineral rich tephra, and breakdown of organic matter from damaged trees and foliage will have provided a temporary abundant mineral and nutrient supply to the topsoil, ideal for vegetation regeneration. In contrast, *Dacrydium* trees thrive in poorly drained areas (Clarkson *et al.*, 1988) and may be susceptible to drought (Newnham *et al.*, 1989).

The impact of tephra accumulation on catchment soils is reflected in lake sediment geochemistry (Fig. 7.9), which shows evidence for soil nutrient replenishment. The major elements Na, K and Si, increase above and below the Rotorua tephra. High Si levels are displayed in the Rotorua Tephra chemizone due to the incorporation and dissemination of tephra shards within the lake sediments above and below the main tephra layer. Na and K are known to be easily leached and eroded from sediments (Mackereth, 1966; Engstrom and Wright, 1988); hence, higher levels may also be due to leaching and weathering of these elements from the tephra deposit.

A marked reduction in the relative proportions of Fe, S and Mg occurs. A higher proportion of minerogenic material and lower organic material is envisaged as C levels fall immediately above the tephra layer, reflecting the incorporation of tephra shards washed into the lake from the surrounding catchment. This would account for lower S values, reflecting a reduction in the ratio of organic to minerogenic material, and in biological productivity in the lake for approximately 30 years after the eruption. Fe values are greatly reduced compared to levels displayed in CKO1 sediments. Fe is present in the tephra in low quantities (1.26%); hence, low Fe levels indicate influx of tephra shards from the surface of catchment soils. These geochemical trends appear to show that the Rotorua Tephra was also relatively poor in iron compared to the natural soils of the Kohuora catchment.

Cluster and ordination analyses carried out on fine resolution pollen samples above and below the tephra layer show no obvious immediate impact on local vegetation assemblages following tephra fallout. Cluster analysis (CONISS Fig. 7.7) reveals the four samples within and immediately above the tephra are more closely related to those below 783 cm, indicating that the volcanic-induced vegetation changes observed and described above are subtle, and therefore not of significant magnitude to be differentiated from pre-eruption vegetation assemblages. The plot of taxa scores on the first two DECORANA axes (Fig. 7.8) confirms this statement as taxa groupings have been influenced by factors other than tephra fallout, the most likely of these being climate, soil fertility and drainage. The stratigraphic plot of DECORANA axis 1 sample scores (Fig. 7.7) shows a gradual increasing trend which is likely to reflect warmer temperatures, indicated by the replacement of taxa typical of a cooler climate with warm-temperate vegetation.

*Rotoma Tephra*

The deposition of the Rotoma tephra has a different impact on the local vegetation at Kohuora to that of the Rotorua Tephra. As mentioned earlier, *Metrosideros* trees appear to expand immediately above the tephra, while *Dacrydium* and *Prumnopitys ferruginea* decline quite significantly, along with a slight decline in *Prumnopitys taxifolia*. Increases are seen in shrub and herb taxa (Cyperaceae, Poaceae, ferns) with sub-canopy trees *Griselinia, Ascarina, Neomyrtus, Knightia, Elaeocarpus, Pseudopanax* and *Syzygium* also increasing. These changes reflect the effect of tephra on mature and well established forest, with increasing competition among trees for canopy space and light. The pollen record reveals that the podocarps did not recover to pre-eruption dominance for approximately 80 years. As the podocarps are mostly tall forest trees, emerging from a dense forest canopy, they may have initially accumulated a large proportion of the tephra deposited over the area, while the main forest canopy and sub-canopy trees were relatively well protected. The podocarps could then have become weakened, or perhaps shed their leaves, allowing increased light penetration to the forest floor, and the subsequent invasion of sub-canopy trees, shrubs, ferns and herbs. *Prumnopitys ferruginea* trees were already in decline prior to the Rotoma eruption, but the deposition of tephra appears to have accentuated this. This is likely to be due to accumulation of wet ash damaging leaves of trees, which were possibly already weakened by disease, or struggling to compete and survive in an expanding forest with increasing species diversity.

A rise in shrub and herb taxa is often seen in pollen records following volcanic-induced vegetation disturbance. *Griselinia,* Cyperaceae, ferns and grasses increase at a number of sites where the ca. 1850 BP Taupo tephra had been deposited (Clarkson *et al.*, 1988; Wilmshurst and McGlone, 1996) and following eruptions on Mt Egmont (McGlone *et al.*, 1988) owing to the infiltration of light through the damaged forest canopy. *Griselinia* is able to tolerate shady conditions and can invade and expand in the understorey vegetation following minimal disturbance, as seen on Mt Tarawera (Clarkson, 1990). This small tree can also regenerate from basal stem sprouts (Burrows, 1994); hence, increases in *Griselinia* pollen seen above the Rotoma tephra could be due to enhanced flowering from new shoots perhaps following damage to branches by tephra accumulation.

Cluster analysis carried out on fine resolution pollen samples reveals the three samples immediately above the tephra layer are closely related, and are differentiated from those below the tephra (Fig. 7.10). This suggests changes had occurred in the local vegetation following, and possibly as a result of the deposition of the Rotoma Tephra at

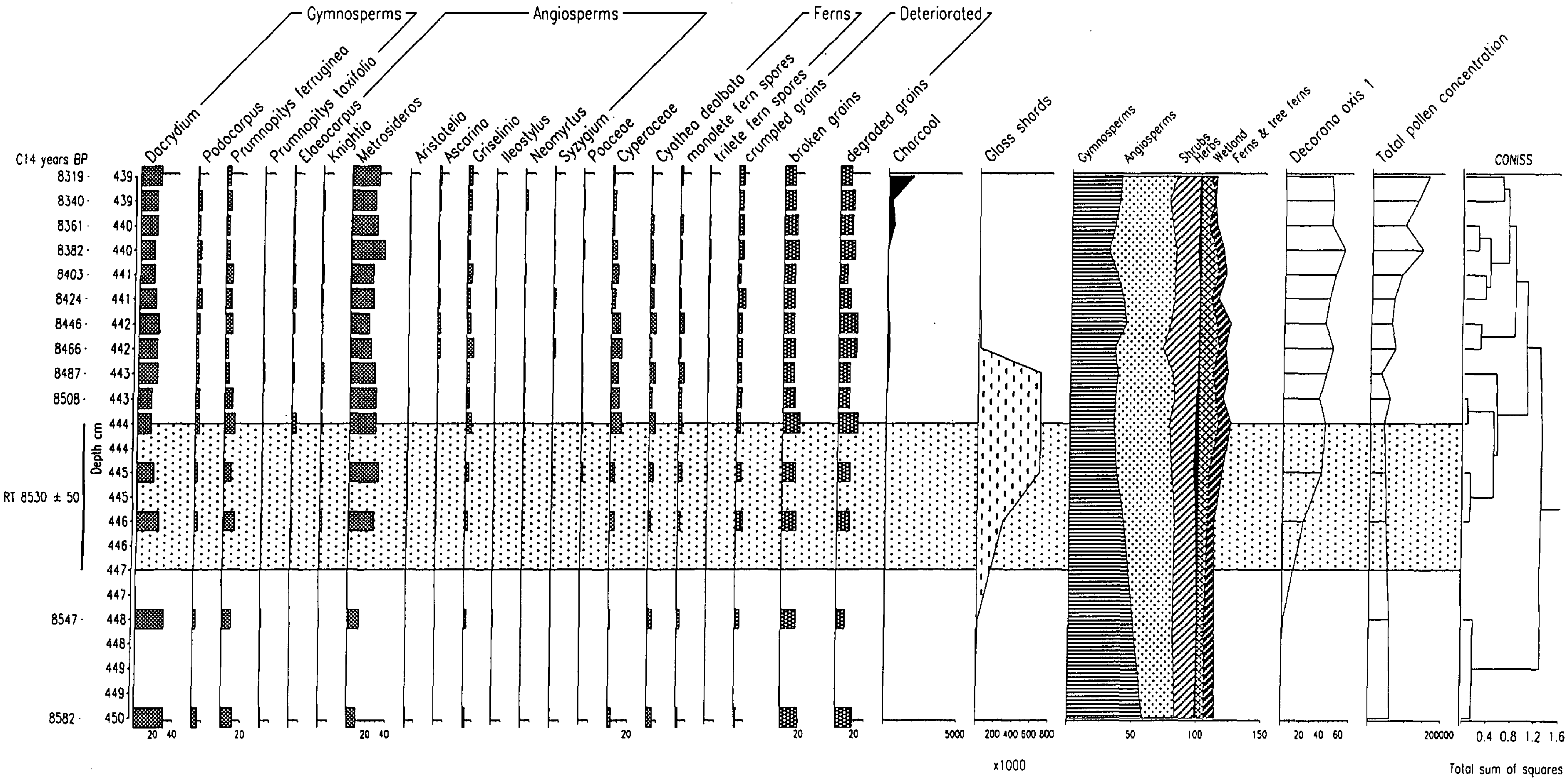



**Figure 7.10** Fine resolution pollen diagram displaying changes in main taxa above and below Rotoma Tephra. Charcoal and Glass shards are expressed as number of fragments per cm³ sediment analysed.

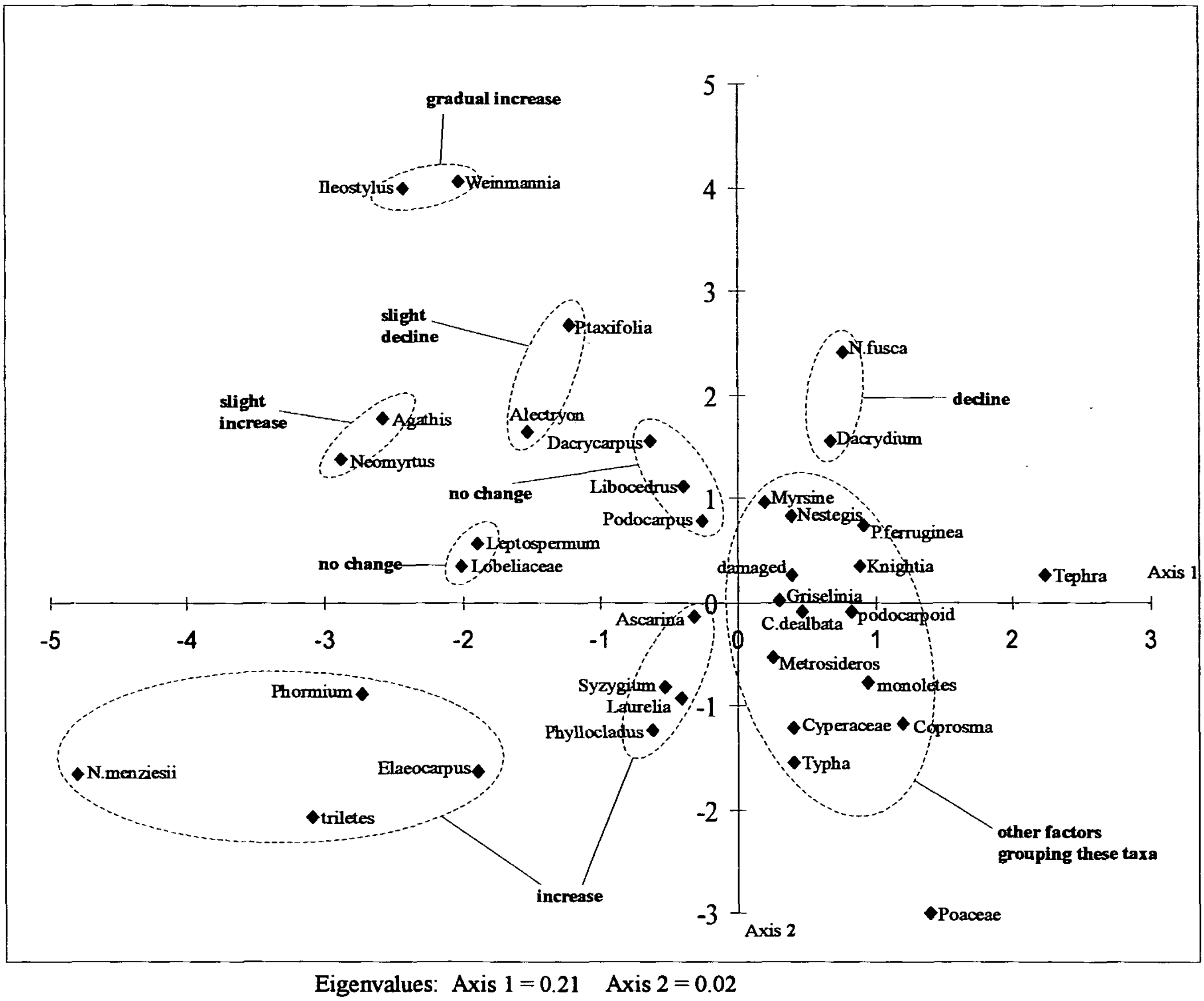



**Figure 7.11** A biplot of pollen taxon associations, determined by DECORANA, in spectra surrounding the Rotoma Tephra layer at Kohuora crater, Auckland.

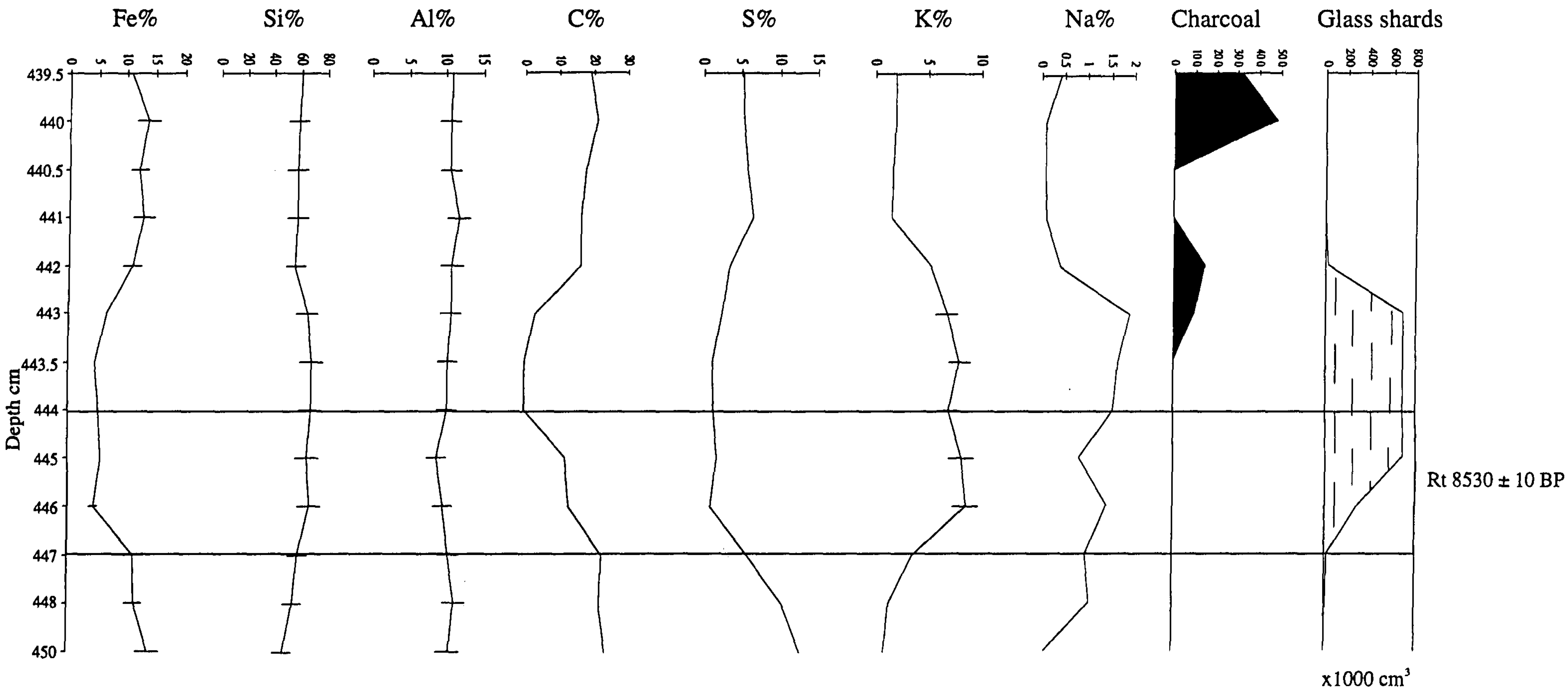



**Figure 7.12** Fine resolution sampling and geochemical analysis displaying changes in lake sediment geochemistry above and below Rotoma Tephra. Short horizontal lines indicate srror bars calculated to 2 standard deviations.

Kohuora. DECORANA axis 1 (sample scores) reflects these changes, possibly superimposed on an overall trend reflecting optimum climatic conditions for forest development, as species diversity increases after the eruption during the period of maximum forest expansion in New Zealand between 10,000 and 8,000 years BP.

The ordination plot (Fig. 7.11) shows a significant clustering of taxa towards the centre of the plot, with no clear grouping. Species in the largest group all responded differently after the eruption, therefore suggesting the clustering is due to other environmental factors. Taxa that appear to increase following tephra deposition are clustered in separate groups, indicating other environmental factors have had greater influence on these species than the deposition of the Rotoma Tephra.

The geochemistry assemblages show higher proportions of Na, K, and Si in response to Rotoma Tephra deposition (Fig. 7.12). As seen from Table 7.2, the Rotoma Tephra is largely composed of Si, Al, Na and K. Higher concentrations of these elements are therefore due to release of these minerals through weathering of the tephra layer, and incorporation of tephra shards above the macroscopic tephra layer due to inwashing from adjacent soil surfaces. Evidence for dissemination of tephra shards is displayed in Fig. 7.12 as shards were encountered in pollen slides above and below the tephra layer. Despite the high concentration of Al in the Rotoma Tephra (12.33%) Al levels around the tephra layer are low compared to the rest of the profile. Lower Al may indicate a reduction in the influx of aluminosilicates from the catchment, as the majority of sediment washed into the lake from the surrounding catchment would have been largely composed of tephra shards for a short period following the Rotoma eruption. The surrounding soils and sediments were probably relatively enriched in Al compared to the Rotoma Tephra; hence normal soil leaching processes provided a higher proportion of Al to the lake sediments.

Carbon is greatly depleted within and above the tephra, indicating that the lake sediments contained very high proportions of minerogenic, tephra-derived material, in relation to organic matter (Fig. 7.12). Lower S levels support this statement, reflecting lower biological productivity and lower proportion of plant detritus. Lower S, C and Fe levels appear to have been sustained for approximately 40 years after the eruption. Fe is relatively depleted in the Rotoma Tephra, with only 0.87% iron concentration (Table 7.2).

Fe levels increase again at the top of the chemizone indicating most of the tephra shards had become incorporated into the main matrix of the soils or washed into the lake and accumulated in the basal sediments.

*Tuhua Tephra*

The Tuhua Tephra appears to have had a limited effect on local forest vegetation (Figs. 7.13 and 7.14). Minor increases are seen in *Podocarpus, Cordyline, Griselinia* and *Myrsine*, with a very slight decrease in *Knightia* (Fig. 7.13). *Metrosideros* trees decline above the tephra layer, possibly due to damage to foliage from tephra accumulation and associated toxic chemical leaching, as has been reported on White Island (Clarkson *et al.*, 1989; Clarkson, 1990; Clarkson and Clarkson, 1994). These were the dominant canopy trees prior to the Tuhua eruption, and were therefore relatively unprotected against the damaging effects of tephra and toxic chemical accumulation. That *Metrosideros* trees declined following the Tuhua eruption, and not the Rotoma eruption could be due to differences in forest structure. *Metrosideros* pollen levels below the Tuhua Tephra reached ca. 20% suggesting these trees were prominent within the main forest canopy, whereas below the Rotoma Tephra, *Metrosideros* pollen levels were lower (ca. 10%) indicating *Metrosideros* trees were less prominent within the forest, and these were probably confined to the sub-canopy. *Metrosideros* trees may have been sheltered under a dense podocarp forest canopy following the Rotoma eruption, therefore escaping damage. The slight increases in *Podocarpus, Griselinia, Cordyline, Myrsine* and the delayed rise in *Prumnopitys ferruginea* following the Tuhua eruption could reflect regeneration of new saplings in canopy gaps made available by the decline in *Metrosideros* trees and lianes. Trees that declined following the eruption did not recover to pre-eruption abundance for approximately 95 years, with *Metrosideros* trees never fully recovering to former dominance.

Minor changes occur in the geochemical record in response to Tuhua Tephra fall. The major elements Na, K and Si increase around the tephra layer. Table 7.2 displays the chemistry of this tephra, and shows Na, K and Si are present in high concentrations. Leaching and weathering of the tephra layer within the lake sediments, and from the surrounding catchment soils has caused dissemination of tephra shards around the main body

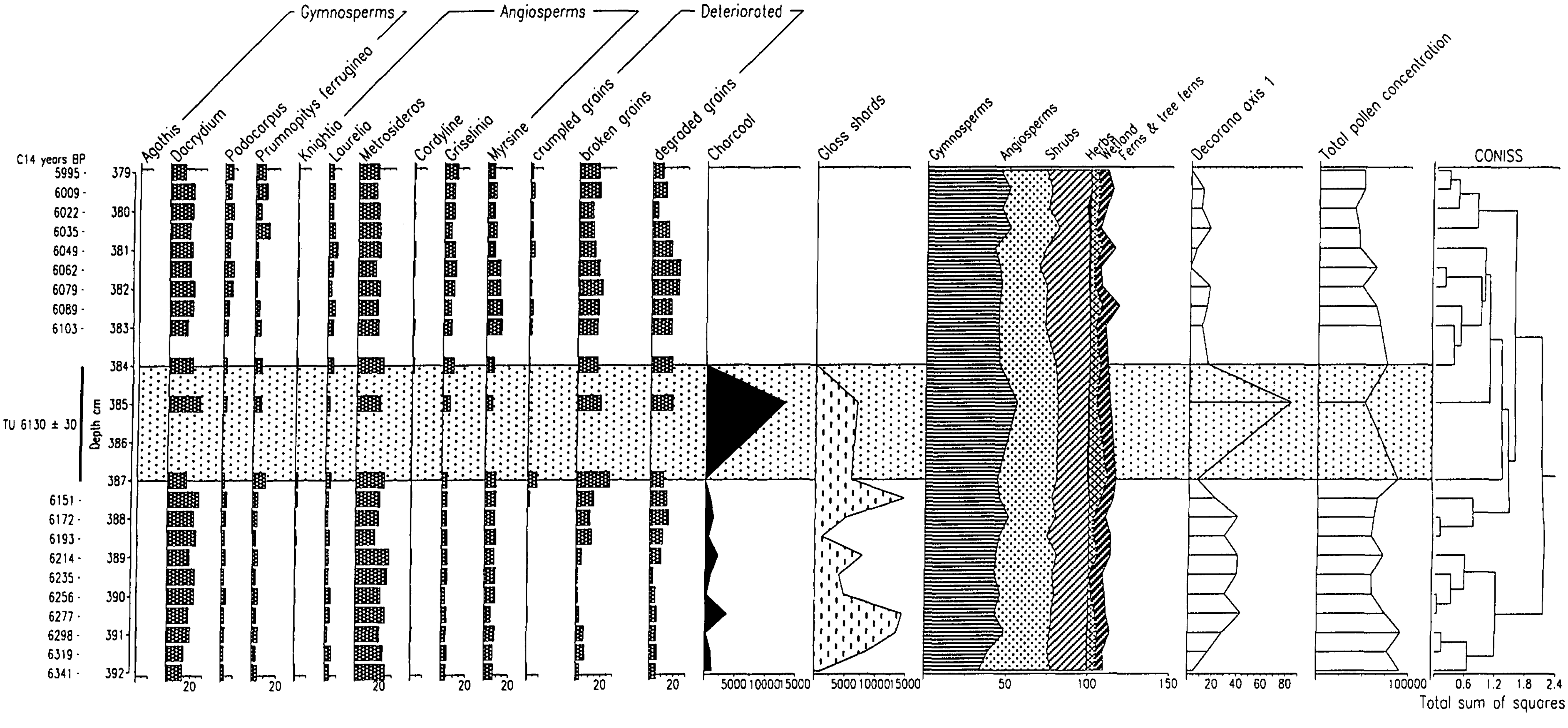
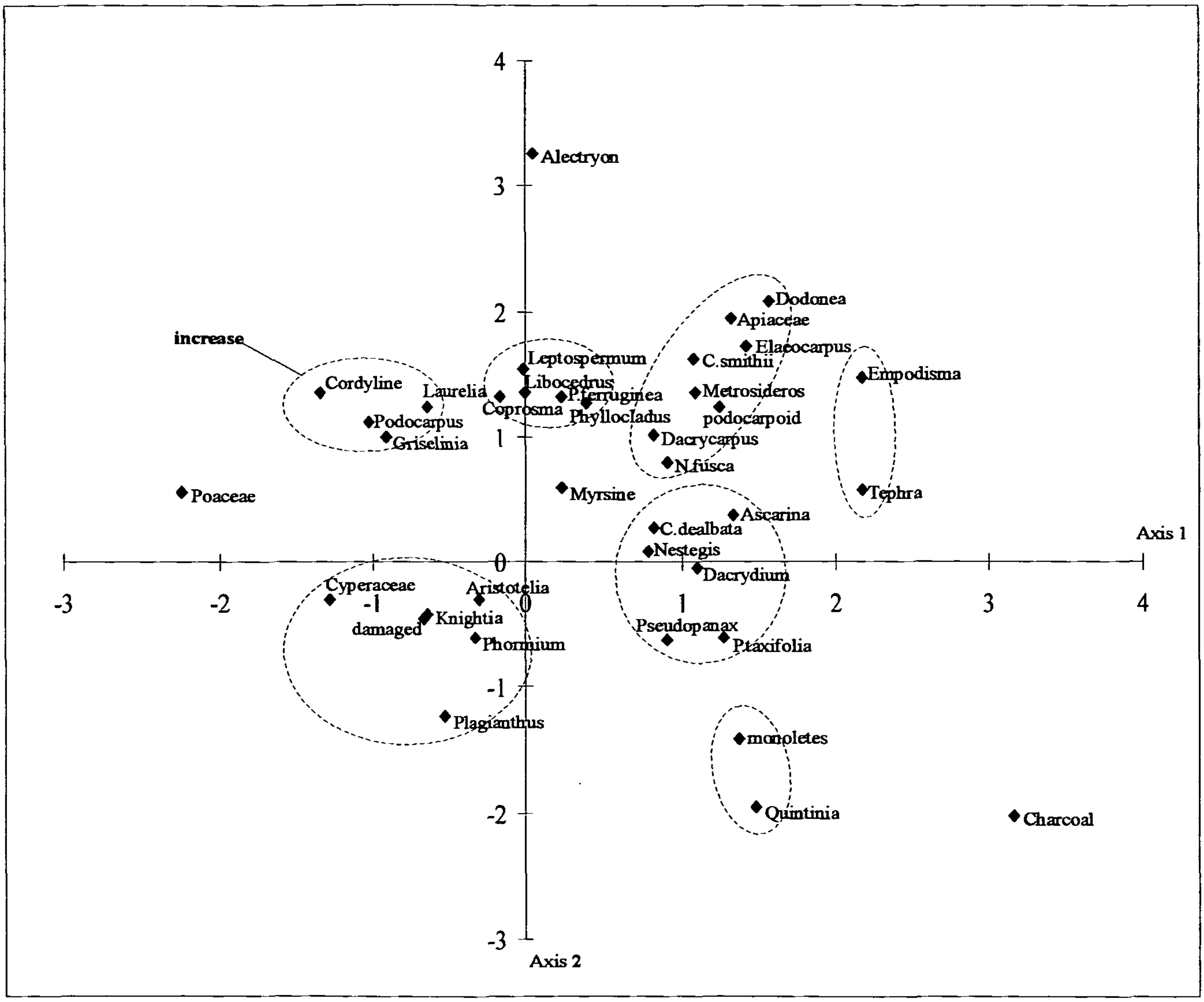



**Figure 7.13** Fine resolution pollen diagram displaying changes in main taxa aboe and below Tuhua Tephra. Charcoal and glass shards are expressed as number of fragments per cm$^3$ sediment analysed.




Eigenvalues: Axis 1 = 0.12 Axis 2 = 0.03

**Figure 7.14** A biplot of taxon associations, determined by DECORANA, in spectra surrounding the Tuhua Tephra layer at Kohuora crater, Auckland. Main groups have not been labelled as taxa orientation is related to factors other than volcanic tephra fall.

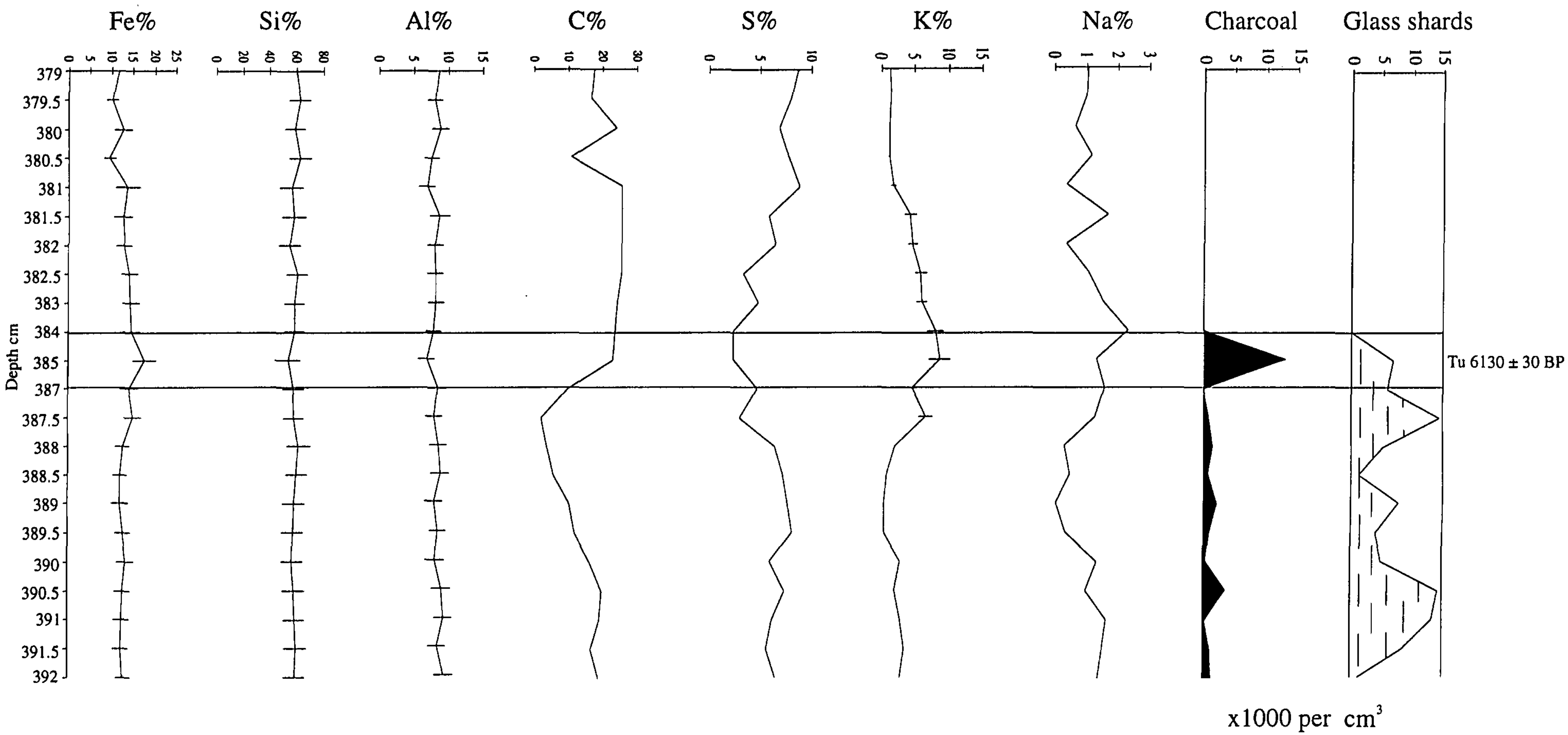



**Figure 7.15** Fine resolution sampling and geochemical analysis taken at 0.5cm intervals where possible, displaying changes in lake sediment geochemistry above and below Tuhua Tephra. Short horizontal lines indicate error bars calculated to 2 standard deviations.

of the tephra layer.

The Tuhua Tephra contains a higher proportion of iron than the Rotoma and Rotorua Tephras (Table 7.2). Hence Fe levels are slightly higher in the Tuhua Tephra Chemizone due to tephra influx. C declines immediately below the tephra layer, reflecting a higher proportion of minerogenic, tephra-derived material within the sediment profile resulting in an apparent reduction in organic matter. Increased minerogenic material at this level may suggest pre-eruption ash fall from minor blasts which were precursors to the main Tuhua eruption. Minor emissions of ash occurred prior to the Ruapehu eruption of AD 1995 (Chapter 8, section 8.1); hence, similar emissions could have occurred prior to the Tuhua eruption. Alternatively, higher levels of minerogenic material may indicate reworking of earlier tephric sediments from the catchment. Levels of tephra shards show a greater abundance of tephra-derived minerogenic material below the main tephra layer (Fig. 7.13), in agreement with the geochemical record (Fig. 7.15). Levels of S increase towards the top of the chemizone indicating a return to higher levels of biological productivity and a higher proportion of organic matter as influx of tephra-derived material declines. Deposition of the tephra appears to have affected lake chemistry and productivity for approximately 50 years after the eruption.

Cluster analysis of fine resolution pollen samples (Fig. 7.13) reveals the three samples above the Tuhua tephra are closely related, and are differentiated from those below the tephra layer, indicating changes had occurred within the local vegetation communities following the eruption. However, the ordination plot (Fig. 7.14) reveals these changes were influenced by factors other than tephra fallout. *Cordyline*, *Podocarpus*, *Laurelia* and *Griselinia* increase above the Tuhua Tephra and have been clustered together. Other taxa which also increased have been clustered with other species which decline or show no change. This again suggests factors such as climate or soil fertility and drainage probably had a greater influence on the distribution and relative abundance of taxa represented in the pollen diagram.

*Possible volcanic impacts from Rotoaira Tephra deposition*

The Rotoaira Tephra layer occurs between 948 and 948.5 cm, at the base of pollen zone KO1. Pollen changes in zone KO1 (Fig. 7.5) have been discussed in section 7.8; however, the possibility of environmental changes following deposition of the Rotoaira Tephra at Kohuora has not been considered. Changes in local vegetation assemblages occur immediately above the thin andesitic tephra layer (0.5 cm). The pollen record extends to a depth of 950cm, with two pollen samples analysed below the tephra. The dominant taxa vary significantly between 949 and 950 cm, and the record does not extend far enough below the tephra in order to determine the dominant vegetation communities prior to the eruption. Similarly, the limited record of geochemical change below the Rotoaira Tephra (fig. 7.6) creates problems for determining the extent of environmental impact following tephra deposition. Hence it is unclear whether local vegetation and environmental changes observed above the tephra layer are related to volcanic impact from tephra fall. The vegetation changes observed at the base of the profile have therefore been attributed to local burning and perhaps climate change.

**7.10 Summary and conclusions**

A complete summary of vegetation and catchment changes following Rotorua, Rotoma and Tuhua eruptions are displayed in Table 7.6, together with estimates of duration of impact.

Fine resolution pollen and numerical analyses indicate that the impact of volcanic tephra fallout on local vegetation assemblages at Kohuora were subtle in relation to the major effect of a gradual changing climate during the late glacial and Holocene. Clustering of species on the ordination plots (Figs 7.8, 7.11, 7.14) show other factors were likely to have influenced the local vegetation; such factors might include fire, drainage, soil fertility and structure, aspect and altitude, as well as competitive interactions between different species.

Soil fertility, drainage and structure, and the balance of species competition, can be altered by tephra deposition, which may be considered as an indirect volcanic impact on vegetation. The geochemical record shows that the impact of tephra deposition on lake sediment chemistry, which is largely influenced by local catchment and soil geochemistry due to the input of allogenic material from adjacent slopes, is sustained for up to 50 years following an eruption (Fig. 7.6). Short-term changes in soil structure and fertility were likely to have had an important effect on forest regeneration, and the establishment and invasion of new species within the forest surrounding Kohuora crater. It is clear from these results that volcanic tephra fallout can initiate forest disturbance both directly and indirectly, with the effects observed in the pollen record for up to 100 years after the eruption (Figs. 7.7, 7.10, 7.13).

The response of *Dacrydium* trees to tephra fallout was a consistent decrease in abundance above all three tephra layers. These trees are tall, long-lived, slow-growing forest emergents and were likely to have suffered from physiological damage from tephra fallout as they were exposed above the main forest canopy and received little protection from tephra deposition and associated toxic chemical accumulation. *Griselinia* trees increased in abundance following Rotoma and Tuhua eruptions. *Griselinia* is specially adapted to withstand volcanic impacts, as it has the ability to resprout from basal stems following damage from tephra fallout. It is highly tolerant of shady conditions and is therefore able to regenerate rapidly under a dense forest canopy (Clarkson, 1990).

Species such as *Knightia* and *Metrosideros* declined following the Tuhua eruption, but increased after Rotoma Tephra deposition. *Metrosideros* trees were hit harder following the Tuhua eruption as they formed a significant part of the canopy and were exposed to the damaging effects of tephra accumulation and associated chemical leaching. *Prumnopitys ferruginea* declined following the Rotoma and Tuhua eruptions, but increased after Rotorua, again probably due to the degree of shelter these trees received according to their dominance within the forest canopy. Many other taxa showed no change following tephra fallout, but randomly declined following one particular eruption (e.g. *Podocarpus* after Rotoma eruption; see Table 7.5). This is most likely to be related to a combination of forest structure, competition from opportunist species, age of trees, climate, and possibly sensitivity of species to specific tephra chemistry and gases.

These findings have important implications for the possible extent of volcanic hazards from the central North Island volcanoes on the Auckland urban area today. Forest damage from tephra fall and associated toxic chemicals was detected in these

**Table 7.6** Summary of volcanic impacts at Kohuora

| Tephra Layer | Increases in geochemical elements and vegetation | Decline in geochemical elements and vegetation | Approximate duration of impact following tephra fall |
|---|---|---|---|
| Rotorua Tephra (13,080 BP) | Higher proportions of Na, K, Si<br><br>*Prumnopitys ferruginea* (significant increase)<br><br>Asteraceae<br>Monolete fern spores | Lower proportions of Fe, S, Mg, C<br><br>*Podocarpus*<br>*Prumnopitys taxifolia*<br>*Fuscospora*<br>*Aristotelia*<br>*Muehlenbeckia*<br>*Ileostylus*<br>*Dacrydium* | Vegetation - 100 yrs<br><br>Geochemistry - 30 yrs |
| Rotoma Tephra (8500 BP) | Higher Na, K, Si<br><br>*Metrosideros*<br>*Elaeocarpus*<br>*Griselinia*<br>Cyperaceae<br>monolete fern spores<br>trilete fern spores<br>Minor increases:<br>*Ascarina*<br>*Neomyrtus*<br>*Syzygium*<br>Poaceae<br>*Knightia*<br>*Laurelia* | Lower Fe, Al, C, S, Mg<br><br>*Dacrydium*<br>*Prumnopitys ferruginea*<br>*Myrsine*<br>*Nestegis* | Vegetation - 80 yrs<br><br>Geochemistry - 40 yrs |
| Tuhua Tephra (6130 BP) | Higher Fe, K, Na<br><br>*Griselinia*<br>Laurelia<br>*Podocarpus*<br>Minor increases:<br>*Cordyline*<br>*Myrsine* | Lower Si, C, S<br><br>*Knightia*<br>*Metrosideros*<br>*Prumnopitys ferruginea*<br>*Dacrydium* | Vegetation - 95 yrs<br><br>Geochemistry - 55 yrs |

palaeoenvironmental records, and clearly shows that the potential hazard from these distant (>200 km) volcanoes should be included in volcanic hazard risk assessments for Auckland city. The central North Island volcanoes pose a different threat to the city to those from the local volcanic field, as the main impacts will be from ash accumulation and associated toxic chemical leaching. The results presented in this chapter indicate that these impacts can be severe and long lived, imposing a serious threat to local agriculture, vegetation, soils, and freshwater flora and fauna, as well as to the quality of Auckland's water supplies. The abundance of toxic gases and fine volcanic ash settling from the atmosphere may also affect air quality, exacerbating Auckland's air pollution levels in certain meteorological conditions (Newnham *et al.*, in press), which may have serious implications for people with respiratory diseases such as hay fever and asthma (Cronin and Hedley, 1996). Ash accumulation in the atmosphere will affect air traffic to and from Auckland International Airport, as occurred following the Ruapehu eruptions of 1995 and 1996, with reduced air quality also. The weight of ash accumulation is also likely to cause damage to power and communication lines, leaving the city, and possibly many parts of the North Island, without power during and after a significant eruption. In highlighting these problems, it is therefore clear that a re-evaluation of volcanic hazards in Auckland is necessary, to include the potential dangers from the central North Island volcanic field.

In relation to the specific aims of the project (chapter 1), analyses from the present chapter have gone part way towards addressing these problems, the results of which are listed below:

i) In determining a critical tephra thickness above which discernible impacts occur, pollen and geochemical analysis at Kohuora has shown that vegetational and environmental impacts are observed up to 200 km from the volcanic source. Also, distal tephra deposition of 2-3 cm thickness results in vegetational and environmental change lasting up to 100 years and 50 years respectively.

ii) No consistent recovery patterns emerged in vegetation communities affected by tephra fall, as impacts varied following each eruption. However, *Dacrydium* trees appeared to be sensitive to ash accumulation, exhibiting a marked decline above each tephra layer. *Griselinia* trees displayed significant increases above Rotoma and Tuhua Tephras, owing to special ecological adaptations for regeneration following tephra accumulation.

iii) Tephras preserved in the Kohuora profile originated from Okataina and Tuhua volcanic centres and exhibited distinct tephra chemistry. Deposition of these tephra layers affected catchment soils and lake/peat geochemistry differently, for example, sediments immediately above and below Tuhua Tephra were iron rich, compared to sediments around Rotoma and Rotorua Tephras. Difficulties were faced in attempting to establish the effect of different tephra chemistry on vegetation following tephra fall. The magnitude of impact varied following each eruption, according to forest structure, with main canopy species suffering the most.

In conclusion, the results presented from pollen and geochemical analysis at Kohuora crater reveal impacts on local vegetation, catchment soils and lake chemistry and biological productivity, as a result of volcanic tephra fallout, superimposed over the continued influence of a gradual change in climate from the late glacial to late Holocene.

The following chapter provides a synthesis of volcanic impacts from all sites analysed in this thesis, and assesses the criteria by which volcanic impacts can be determined from palaeoenvironmental records.

# Chapter 8

# Synthesis

## 8.0 Introduction

Research undertaken in this thesis has sought to examine the impact of distal volcanic tephra fall on palaeoenvironments over the last ca. 15,000 years. Palynological and geochemical investigations were undertaken on samples from above and below macroscopic tephra layers in sediment profiles at the four study sites in North Island. The degree and nature of vegetational and environmental disturbance relating to tephra fall varied according to thickness of ash fall, local site characteristics, climate and forest resilience. This chapter provides a synthesis of these results, by discussing the main findings of this research and addressing the project aims. These findings are then compared with those from previous research into volcanic impacts in New Zealand and world-wide. The discussion then focuses on the general research problems, and then specific problems encountered at each site.

## 8.1 Volcanic impacts and achievement of project aims

Volcanic-induced impacts detected above macroscopic tephra layers at the sites studied in this thesis varied greatly between sites, and according to the prevailing environmental conditions at the time of the eruption. The magnitude of the impacts differ between deposits of late glacial age and those of Holocene age, when forests had developed to their maximum extent in the North Island of New Zealand. Climate and forest resilience therefore had a significant effect on the magnitude of volcanic impact.

In order to assess whether volcanic impacts were discernible in fine resolution pollen and geochemistry records, the results should meet at least two of the following criteria, which are related to the main aims of this study (Chapter one):

1) Notable changes to pollen taxa that appear to be directly related to the tephra layer but are of a greater magnitude than the natural ("background") variation exhibited in that taxon previously;

2) Notable changes to sediment chemistry that appear to be directly related to the tephra layer but are of a greater magnitude than the natural variation exhibited previously;

3) Cluster analysis dendrogram of pollen assemblages showing a significant divide at the tephra layer;
4) Clustering of DECORANA taxa scores for taxa that show a similar pattern of behaviour after the tephra that differs from their behaviour before the tephra;
5) Clustering of DECORANA sample scores for samples that show a similar pattern of behaviour after tephra that differs from their behaviour before the tephra layer.

The discussion will focus on each aim of the project following the criteria outlined above.

### 8.1.1 Critical tephra thickness

The first aim of the project was to consider whether there was a critical tephra thickness above which discernible impacts occurred. Tephra layers analysed from various sediment records ranged in thickness from 0.5 cm (Egmont-15 Tephra, Lake Rotoroa) to 28 cm (Waimihia Tephra, Kaipo Bog). Tephra impacts were observed above all tephra layers where between-sample time resolutions were sufficiently fine enough to detect short-lived volcanic impacts. These time resolutions varied because of fluctuating sedimentation rates. Samples extracted immediately above thicker (> 3 cm) tephra layers generally displayed volcanic impact even when between-sample time resolutions were very broad. For example, weak impact signals were evident above Rotorua and Rerewhakaaitu Tephras in the Lake Rotoroa core, where sediment accumulation rates were 77 yrs and 62 yrs per cm, respectively. Weak impact signals were also evident above Taupo and Waimihia Tephras in the Kaipo profile where peat accumulation rates were 238 yrs per cm. Volcanic impacts could still be detected, however, despite these broad time intervals. In the Kaipo profile, the Taupo and Waimihia Tephra layers are 23 cm and 28 cm thick, respectively, and their deposition caused severe environmental impacts that were obvious in the pollen and geochemical records. The deposition of the thinner Rotorua and Rerewhakaaitu Tephra layers (6 cm and 2 cm respectively) resulted in subtle environmental impacts being detected. Such detection was nevertheless important, because they were matched to some degree by concomitant long-term environmental changes. Volcanic impacts therefore may have been more severe than those envisaged from these records.

One of the thinnest tephra deposits, the 0.5 cm thick Egmont-15 Tephra in the Rotoroa core, caused subtle short-lived volcanic impacts which were detected in the pollen and geochemical records. The time resolution was just 29 yrs per 0.5 cm sample, producing a detailed record. However, deposition of the 1 cm thick Hinemaiaia Tephra in the Kaipo profile had no apparent impact on the local environment, although sedimentation rates were exceptionally slow above this tephra layer, resulting in broad between-sample time intervals of 88 years per cm. Volcanic impacts were absent in palaeo records above the Mamaku (3 cm) and Tuhua (4 cm) Tephra layers in the Kaipo profile. This apparent lack of impact is probably the result of slow sedimentation rates and broad between-sample time intervals ( > 320 yrs per cm) that obscured short-lived volcanic impacts. Volcanic impacts were also not seen above the Mamaku (3 cm) and Rotoma (2 cm) Tephras in the Rotoroa core, probably because of inadequate sampling resolution (sedimentation rates > 70 yrs per 0.5 cm).

From these results it is not possible to recognise a critical tephra thickness above which tephra impacts were discernible. All tephras closely analysed, with the exception of those mentioned above revealing no apparent tephra impact, showed some impact, despite the large range in thickness. The minimum tephra thickness analysed in this study was 0.5 cm; layers less than this were not available for analysis in this project. Efforts were made to attempt to find traces of the Taupo Tephra layer in the Kohuora core. However, as mentioned earlier in this chapter, extensive disturbance of the upper 1 m section of the Kohuora profile meant that these efforts were foiled, and microscopic traces of the Taupo Tephra were not discovered. However, it was necessary to investigate the extent of environmental impacts from macroscopic tephra fall at various sites within varying distances from the volcanic sources in New Zealand, which has been accomplished in this thesis. It is now known that tephra layers of 0.5 cm thickness can initiate environmental disturbances sustained for up to 170 yrs. This contrasts with earlier research, based on observational evidence at proximal sites following the 1886 Tarawera eruption, which indicated that ash fall of 23 – 30 cm would cause partial damage to forest vegetation (Vucetich and Pullar, 1963; see chapter two). Further research is now required to determine whether environmental impacts can be detected following the deposition of tephra layers < 0.5 cm in thickness in New Zealand.

### 8.1.2 Recovery patterns of vegetation communities affected by tephra fall

This aim involved the determination of which species were sensitive to tephra accumulation, to model their recovery patterns, and to identify species that were not affected or appeared to thrive following tephra impact, and were important pioneer species for vegetation re-establishment. New Zealand forests can tolerate quite high levels of toxic volcanic emissions and ash accumulation under stable environmental and climatic conditions, such as those experienced at Lake Rotoroa during the early Holocene. Most New Zealand trees are evergreen with strong leaves, which tend to have a leathery texture. This enables these trees to withstand diurnal and seasonal temperature ranges, and to be resilient against storm damage and frost to some extent, while some species remain relatively unscathed following fire, for example, *Cordyline australis* (Wardle, 1990). Extensive, long-term damage to vegetation from tephra accumulation and phytotoxic chemical leaching would only occur following prolonged exposure to these elements from very thick tephra deposits, or during times where forest vegetation is already weakened, perhaps following fire/storm damage, disease, age, or harsh climatic conditions (McGlone, 1981).

The results presented here show that individual taxa may respond differently to tephra fall, depending on several important factors. Therefore, in addressing the second aim of this thesis, it is first necessary to consider external factors, which are likely to affect the magnitude of volcanic-induced vegetation and environmental impacts. These contributing factors are:

1) Climate
2) Season
3) Forest dynamics (structure, age, and species competition)
4) Susceptibility of the vegetation to burning
6) Long-term vegetation or environmental trends that existed prior to a volcanic eruption

1) Climate

Climate change is one of the most powerful factors influencing vegetation distribution and environmental change. With the exception of the severe impacts associated with thick Holocene tephras at Kaipo Bog, vegetation impacts and changes in sediment geochemistry appear to have been most severe during the late glacial as the environment responded to a changing climate.

The only taxon that consistently exhibited a marked decline following tephra deposition was *Halocarpus*. This shrub appears to be particularly sensitive to ash deposition, but its decline was also likely to have been related to climate change during the late glacial. *Halocarpus* declined immediately above the Egmont-15, Rerewhakaaitu and Rotorua Tephras in the Lake Rotoroa core, and immediately above the Opepe, Rotoma and Whakatane Tephra layers in the Kaipo peat profile. At Kaipo Bog, *Halocarpus* was growing under cool, harsh, windy and very wet climatic conditions. This species is able to adapt and grow under these conditions (Wardle, 1990), but probably received little canopy shelter from harsh cold winds and frequent frosts. In the more open exposed vegetation communities of the late glacial period, further pressure from ash accumulation and associated toxic chemical leaching would have inflicted additional stress on these shrubs in the form of damage to leaves and branches from accumulated ash, and possible acid burns to leaves.

At Lake Rotoroa, *Halocarpus* was common around the site during the late glacial period; hence *Halocarpus* probably suffered due to a combination of changing climatic conditions and the additional impact from tephra fall and toxic chemical accumulation. However, these impacts continued up to the early Holocene when climatic conditions had become warmer and wetter around the time of the Opepe eruption (9050 ± 40 BP). These shrubs were already declining because of the gradual climatic amelioration encouraging rapid podocarp-hardwood forest expansion in the area. Further stress from increased competitive pressure within the expanding forest, climate change and impact from tephra deposition resulted in the decline of *Halocarpus* at Lake Rotoroa.

Other taxa also suffered at Lake Rotoroa following the deposition of the Egmont-15 Tephra (14,650 ± 200 BP). These included *Podocarpus*, *Prumnopitys* spp., *Nestegis* and *Cyathea dealbata*, which grow best under warm moist climatic conditions, and were thus probably already weakened by frequent frosts, possible drought and strong cold winds which were likely to have prevailed around the time of this eruption (McGlone *et al.*, 1993). These taxa do not consistently decline following tephra fall. *Prumnopitys* spp. increased following the Mangamate, Taupo and Tuhua eruptions at Lake Rotoroa, and immediately following the Rotorua eruption at Kohuora. In these situations climatic conditions were better suited to *Prumnopitys* and these trees therefore were able to compete effectively in the post-tephra environment.

2) Season

It is conceivable that an eruption occurring at a crucial stage in the growing season may have a more damaging effect on certain species, and this may have contributed to the inconsistency in species response to tephra fall. However, it is difficult to determine here whether forest taxa suffered more damage from tephra fall at certain times of the year.

A large eruption occurring during spring time, when trees are flowering, seeds are germinating, new saplings are emerging across the forest floor and trees are sprouting new shoots, could be quite damaging to the forest. New saplings may be buried by ash and suffer damage due to toxic chemical leaching, and new shoots and flowers may be damaged and broken off due to the weight of ash accumulation. Disturbance of these processes of spring forest rejuvenation and reproduction would therefore set back forest development and expansion for one year, or longer.

Some taxa flower periodically, not annually, or exhibit variations in flowering intensity with alternate sparse/prolific flowering years, for example, *Nothofagus* spp., *Cordyline*, and *Phormium* (Wardle, 1990). When these taxa are damaged by tephra and toxic chemical accumulation, their chances of reproduction are limited or even destroyed until the next time they flower. These taxa are therefore at a competitive disadvantage against other taxa, which often benefit from tephra fall and forest disturbance (e.g. *Myrsine, Cyathea dealbata*, *Griselinia*, *Leptospermum, Pteridium* and other ferns). These impacts are therefore likely to be evident from pollen diagrams. Declines in *Nothofagus* trees at Kohuora following the Rotorua eruption, at Lake Rotoroa following the Tuhua eruption, and at Kaipo Bog following the Opepe and Whakatane eruptions, may have been caused by tephra-induced damage to these trees during flowering years, inhibiting further expansion within the forest. *Nothofagus* typically has mast years where pollen productivity is particularly high, separated by up to 7 years of low pollen production (Newnham, 1990). Therefore an eruption occurring during a mast year may damage these trees, reducing flowering and pollen production, possible resulting in a decline in further regeneration of *Nothofagus* within the forest. *Nothofagus* trees do not compete well under a well established forest canopy (Newnham, 1990) and these trees are therefore further disadvantaged.

Taxa flowering outside the main spring flowering season (e.g. *Metrosideros fulgens, Pseudopanax arboreus*) may have escaped extensive damage provided the tephra was deposited in spring, and therefore would benefit from a decline in regeneration of damaged trees, and subsequently flourish and expand within the forest. These processes may have initiated the increase in *Pseudopanax* following the Kaharoa Tephra deposition at Kaipo Bog.

An eruption occurring during winter months may cause greater damage to forest vegetation, as cooler climatic conditions, frosts and possibly snow, may have weakened trees less tolerant to frost, for example, *Prumnopitys ferruginea* (Kaipo and Kohuora profiles), *Agathis australis* (Matakana Island). Tephra impact may therefore be extremely damaging to these trees at this time of year.

3) Forest dynamics

Specific examples of taxa which displayed inconsistent responses to tephra impact include *Dacrydium*, *Prumnopitys* spp., *Nothofagus* spp., *Metrosideros* spp., *Podocarpus* spp., *Phyllocladus* spp., *Elaeocarpus*, *Laurelia*, *Knightia*, *Myrsine*, *Ascarina*, *Pseudopanax*, fern and tree fern species and several lianes and epiphitic shrubs. Some of these inconsistencies in vegetation responses may have been related to the age and structure of the forest, the physiological structure of each species, and the population size of individual species within the forest. The most striking change in vegetation noted at Lake Rotoroa was the increase in *Dacrydium* trees which occurred above three late-glacial tephra layers, i.e., Egmont 15, Rerewhakaaitu, Rotorua; and the early Holocene Opepe Tephra (9050 ± 40 BP). At Kohuora crater (see chapter five), *Dacrydium* trees consistently declined following tephra deposition in all cases. *Dacrydium* trees are tall and willowy, and often emerge above the main forest canopy, exposing them to tephra accumulation, associated toxic chemical damage, and gas emissions. As the Kohuora study site is located furthest from the Taupo and Okataina, tephra deposits may have accumulated toxic chemicals as they travelled a greater distance within the eruption cloud, in comparison to those deposits from more proximal study sites (i.e., Lake Rotoroa, Kaipo Bog). Therefore, *Dacrydium* trees may have suffered at Kohuora due to increased toxic chemical leaching from these tephra deposits. *Dacrydium* trees increased above each late-glacial tephra layer, and the Holocene Opepe Tephra at Lake Rotoroa. These changes were more likely to reflect the natural expansion of *Dacrydium* as a result of increasingly favourable environmental conditions, rather than any physiological advantages of this species, or changes in forest dynamics.

The structure of the forest is important in terms of vegetation re-establishment following tephra impact. Often, the tallest taxa within an assemblage suffered the most damage, including *Dacrydium* as mentioned above, and *Halocarpus*, which was one of the taller shrubs growing on Kaipo Bog, and around Lake Rotoroa during the late-glacial. Semi-dominant main forest canopy species also suffered damage from tephra and presumably toxic chemical accumulation. These species include *Prumnopitys ferruginea*, *P. taxifolia*, *Agathis australis*, *Libocedrus*, *Podocarpus*, *Elaeocarpus*, *Nothofagus* spp and *Metrosideros*. Their dominance within the forest is also important, because the more trees there are in the forest canopy, the greater their likelihood of exposure to tephra accumulation, lightning strike and acid damage from toxic gas emissions and chemical leaching often associated with tephra fall. Possible examples where dominant forest canopy taxa have suffered damage following tephra fall are *Dacrydium* and *Agathis* trees, which declined after Kaharoa Tephra deposition at Matakana Island; *Metrosideros* trees, which declined following Tuhua tephra deposition at Kohuora; and *Nothofagus* trees which declined following Rotoma deposition at Kaipo Bog.

Some tall emergent species and dominant main canopy taxa are often the oldest trees within a forest, because they are slow-growing and long-lived, having become established over hundreds of years. Typical examples include *Dacrydium cupressinum* (600-1200 years), *Agathis australis* (600-1700 years), *Prumnopitys taxifolia* (1400 years), *Halocarpus* (1000 years), *Libocedrus* (720 years), *Metrosideros umbellata* (400 - >1000 years), *Nothofagus fusca* and *Nothofagus menziesii* trees (450-600 years) (Wardle, 1963; 1971;

1984; 1990; Smith *et al.*, 1985; Ahmed and Ogden, 1987; Norton *et al.*, 1988). Older trees are more susceptible to damage from tephra accumulation and associated toxic chemical leaching because they become weakened and brittle with age. Forests that are dominated largely by an individual species, rather than by several different species, are then likely to suffer greater damage as these trees age. Marked declines in *Dacrydium* trees, which were dominant at Kohuora prior to the Rotoma and Tuhua eruptions, may possibly reflect tephra-induced impacts affecting older trees in particular. *Dacrydium* had been long established within the area since the Rotorua eruption (13,080 BP), suggesting mature forest development and perhaps a higher proportion of older emergents which were more susceptible to damage from tephra fall. Significant reductions in the number of *Nothofagus fusca* trees immediately following the deposition of the Whakatane Tephra were displayed in the pollen record from Kaipo Bog. These trees had dominated the ambient forest since ca. 6130 yrs BP; hence many of these may have been approaching their maximum lifespan at the time of this eruption. Expansion of seral taxa occurs within forests that have suffered disturbance due to damage to older trees. Increases in *Pteridium*, together with the increased number of fallen trees and dead plant material littering the forest floor, magnifies the risk of further damage from forest fire.

Some species occasionally benefited from the tephra-induced decline of a dominant canopy taxon. These species were often already present within the forest, but were not significant, and may have occupied the forest sub-canopy, or were juveniles that were struggling to penetrate the main canopy. Competitive pressure within the forest is therefore an important factor affecting the decline and increase of forest taxa, especially following forest disturbance. Sub-canopy taxa were probably protected from the potentially damaging effects of tephra fall to some degree by the dominant main canopy species and emergents, which in turn suffered and declined. Examples include the rapid expansion of *Metrosideros* trees following damage to *Dacrydium* trees after deposition of the Rotoma Tephra at Kohuora. *Phyllocladus* shrubs also increased dramatically following deposition of Rotoma and Whakatane Tephras at Kaipo Bog.

Seral vegetation almost always increased following tephra-induced forest disturbance. Seral vegetation includes ferns, Asteraceae, Apiaceae, Cyperaceae, *Leptospermum* and grasses. These are opportunists which colonise rapidly and can grow on a variety of substrates. These taxa rapidly expand across the forest floor into canopy gaps created where emergent species and main canopy trees have been damaged, struck by lightning, stripped of leaves, or killed outright by physical damage from tephra fall. Other opportunist taxa, which were often seen to thrive following damage to forests by tephra fall, are *Griselinia* and *Coprosma*. *Alectryon* also increased significantly above Rerewhakaaitu and Opepe Tephras at Lake Rotoroa. In every tephra sequence analysed in this study, at least one seral taxon, or one or more of the above-mentioned opportunist species, expanded within the tephra-damaged forests.

4) Forest susceptibility to burning following tephra deposition

Evidence for burning is displayed in pollen records above the Tuhua Tephra layer at Kohuora and Lake Rotoroa. Charcoal peaks also occurred above Mamaku, Opepe, Mangamate and Egmont 15 Tephras in the Rotoroa core. Previous studies have shown that burning is often associated with tephra fall and is thought to be due to a greater frequency of lightning strikes, due to electrical charges and sparks generated by ash and volcanic gases in the atmosphere (McGlone, 1980; Newnham *et al.*, 1995; Wilmshurst and McGlone, 1996; 1997). Lightning can trigger forest fires by striking and igniting taller trees. The fire can then spread to the main canopy trees and across wide areas of the forest especially during periods when strong winds prevail.

Forest susceptibility to burning is dependent largely on local site characteristics and a combination of other factors including climate, season, the availability of fuel stock (i.e., fallen trees and the abundance of dead plant matter across the forest floor), and the age and type of vegetation. Forests in drier areas are more susceptible to burning than swamp forests or mires. No evidence for burning was detected in the Kaipo Bog profile, despite large volumes of ash deposition, and the relative proximity of the site to the TVZ. Kaipo Bog and the surrounding area receive a high volume of rainfall in excess of 2200 mm per annum, and several streams and watercourses flow through the area (see Figure 5.1). The risk of forest fire in this extremely wet upland area is therefore minimal.

Kohuora and Lake Rotoroa are much drier sites, both receiving < 1300 mm rainfall per annum today. The warm-temperate humid climate at these sites during the late glacial and Holocene created ideal conditions for the establishment of forest vegetation, and these factors, together with the availability of adequately fertile soils, enabled forests to develop to maturity. As a result, many long-lived species survived to their maximum age range, such as *Dacrydium* trees in forests of the Waikato region (Newnham *et al.*, 1989). As the tall forest dominants age, they become susceptible to windthrow, and are easily ignited by lightning strikes and often trigger forest fires (McGlone, 1980; Wilmshurst and McGlone, 1996). For example, burning is evident at Lake Rotoroa and Kohuora following the deposition of the Tuhua Tephra. Around the time of the Tuhua eruption (ca. 6130 yrs BP) the climate was changing, becoming drier and windier (McGlone *et al.* 1993; Salinger *et al.*, 1993). Forests had become established over thousands of years and were therefore likely to contain large populations of older dominants, many of which may have died but remained standing above the canopy, or had fallen and lain on the forest floor, increasing the risk of fire. The Tuhua eruption therefore possibly occurred during the summer season, perhaps during a period of drought, because forests at Kohuora and Rotoroa would have been highly susceptible to burning at this time.

Fire was also evident in the Rotoroa pollen record following the deposition of Egmont 15 Tephra. This eruption occurred during late-glacial times when the climate was as much as three degrees cooler than today, drier and windier. Forests were establishing and relatively sparse at this time and therefore they may have been more open to strong winds. Under these conditions forest fires could have spread easily, and the risk of ignition was high.

*Phyllocladus* trees appeared to suffer damage from volcanic-induced burning, as decline in *Phyllocladus* pollen coincided with charcoal peaks above Mangamate and Opepe Tephra layers in the Lake Rotoroa profile. These trees prefer drier sites (Wardle, 1990) which therefore increased the risk of ignition from lightning strikes and subsequent forest fire associated with tephra fall.

5) Long-term vegetational and environmental trends

Recovery patterns in vegetation assemblages and the environment following tephra deposition are sometimes related to long-term trends occurring prior to an eruption. Taxa that exhibited a gradual decline prior to an eruption often disappeared or displayed a marked decrease following tephra fall. A clear example is *Halocarpus*, previously mentioned, which declined rapidly following deposition of the Rerewhakaaitu and Rotorua tephra layers at Lake Rotoroa. Other examples include the decline in *Phyllocladus* pollen above the Kaharoa Tephra at Matakana Island, and above the Waimihia Tephra at Kaipo. *Prumnopitys ferruginea* and *Dacrydium* pollen also exhibited marked decreases in the Kohuora core above the Rotoma and Rotorua tephras. The rapid decrease in these taxa following tephra deposition is likely to be related to long-term trends, because these trees were in decline prior to the eruptions. These examples of long-term decline may have been the result of climate change, changes in soil fertility and drainage, disease or increased competitive pressure from other taxa expanding within the forest. For taxa already in a weakened state, or struggling to survive following climatic or environmental changes, the impact from instantaneous tephra fall and subsequent toxic chemical leaching would have inflicted further stress and perhaps accelerated their decline.

Other taxa, present in low numbers prior to an eruption, completely disappeared following tephra deposition. The apparent extinction of *Tupeia*, *Quintinia* and *Laurelia* at Matakana Island following the Kaharoa eruption are examples. Many other species which were present in low numbers prior to tephra fall, disappeared temporarily but recovered some years later, for example the temporary declines in *Elaeocarpus* and *Agathis* following Rotoma tephra fall at Kohuora; the decline in *Elaeocarpus* at Rotoroa following the Rotoma eruption; the decline in *Leucopogon fasciculatus* and *Alectryon* at Kaipo following the Mamaku eruption. These taxa were likely to have been struggling to become established at these sites owing to competitive pressure from other species already established and expanding within the forest. The impact of tephra fall appeared to have a serious impact on these taxa, which probably suffered damage from tephra accumulation and associated toxic chemical leaching, and could no longer compete for space and light in the forest, resulting in their subsequent temporary or permanent decline from the site.

This pattern of tephra fall exacerbating long-term trends is not universal, however. In the Kaipo profile, *Nothofagus fusca* trees exhibited a gradual decline prior to the Waimihia and Taupo eruptions, but increased dramatically following tephra fall. It is unclear why these trees responded in this way, but it could possibly be related to changes in soil fertility and drainage as these tephra deposits were greater than 20 cm in thickness. Fresh volcanic substrate provides a deeper rooting medium, creating ideal conditions for seedling establishment. It is also possible that the surface of the bog was raised following tephra deposition, lowering the water table, and therefore creating additional sites suitable for the expansion of *Nothofagus fusca*.

Taxa that were increasing prior to an eruption exhibited inconsistent responses to tephra deposition. *Dacrydium* trees were expanding in the ambient forest at Kohuora, but declined immediately following Rotoma Tephra deposition. *Dacrydium* trees also declined following deposition of the Taupo and Tuhua Tephra layers at Kaipo Bog, despite expansion of these trees immediately prior to these eruptions. Similarly, *Coprosma* trees were increasing prior to the Rerewhakaaitu eruption at Lake Rotoroa, but also declined following tephra deposition. Conversely, *Coprosma* trees were seen to increase above Opepe, Rotoma, Whakatane, Waimihia and Kaharoa tephras at Kaipo Bog. Similarly, *Dacrydium* trees, which increased around Lake Rotoroa prior to the Rotorua, Waiohau and Rotoma eruptions, rapidly expanded around the lake immediately following deposition of these tephras. *Nothofagus fusca* trees declined following the deposition of Whakatane Tephra at Kaipo, despite former increases in these trees prior to this. These trees also increased at Kaipo following the Waimihia and Taupo eruptions, as discussed earlier.

The inconsistency of vegetation response to tephra fall is probably due to a combination of changes in soil chemistry and drainage, and the extent to which trees were sheltered from tephra and acid damage. As mentioned earlier in this chapter, the magnitude of damage to vegetation following tephra fall could be related to the degree of dominance of a taxon within the upper forest tiers. Dominant canopy trees and tall emergents are likely to suffer the most damage as they are more exposed to tephra accumulation and toxic gas discharge than vegetation occupying the lower forest tiers (e.g. the decline in *Metrosideros* and *Dacrydium* trees at Kohuora). Changes in soil chemistry are evident in the geochemical records following tephra fall. These changes would have had a direct impact on local vegetation assemblages because fresh volcanic surfaces favour the expansion of taxa which prefer well drained fertile soils, for example *Prumnopitys taxifolia* (Wardle, 1990). Other species that were previously thriving in the area on nutrient deficient soils may have then struggled against greater species competition as soils improved. Such changes may have occurred at Kaipo, initiating the decline in taxa such as *Phyllocladus* and *Nothofagus fusca*.

Decline in *Dacrydium* trees following tephra deposition could possibly be a result of improvements in soil drainage and fertility due to tephra accumulation. *Dacrydium* trees are known to thrive under moist conditions and are tolerant of infertile soils (Wardle, 1990). As these trees are also likely to suffer greater damage owing to their tall stature and longevity, further changes in soils and drainage contribute to their decline. It is difficult to explain why *Dacrydium* trees do not appear to have been affected by tephra deposition at Lake Rotoroa. Perhaps the sheltered site location in the Waikato lowlands and favourable climatic and drainage conditions enabled these trees to thrive at this site. These trees were probably more suitably adapted to survive tephra impact as optimum environmental conditions encouraged their growth and survival at Lake Rotoroa.

Changes in soil chemistry and drainage are important as they have a direct effect on local vegetation assemblages. At Kaipo Bog, fluctuations in populations of *Gleichenia* and *Empodisma* were strongly related to changes in drainage following tephra impact. *Empodisma* grows in stands of water across peat bogs, whereas *Gleichenia* forms hummocks raised above the water level. Evidence for drainage improvement following tephra fall was displayed above the Rotoma Tephra layer in the Kaipo Bog profile. A large increase in *Gleichenia* coincided with a rapid decline in *Empodisma*, suggesting drying of the bog surface following the deposition of the 16 cm thick tephra layer. *Nothofagus fusca* and *N. menziesii* trees also thrived at this site following the Rotoma eruption, probably benefiting from improved drainage around the mire margins which encouraged their expansion.

In conclusion, the recovery patterns of vegetation communities affected by tephra deposition are complex and vary according to individual site characteristics - hydrology, morphology, climate, soil structure and fertility - and the physiognomic, age structure and adaptability of the local vegetation community. It is therefore difficult to determine specific species that exhibited particular sensitivity to tephra deposition. As outlined above, almost all species showed some sensitivity to tephra deposition following certain eruptions, despite often showing no response, or even expanding, above other tephra layers at the different sites studied. Table 8.1 illustrates the principal consistent vegetation responses exhibited following tephra fall at all four study sites.

**Table 8.1** Summary of the main vegetation impacts following tephra fall at all four study sites

**a) Pollen taxa that mainly declined following tephra fall**

| Pollen declining | Comments |
|---|---|
| ***Halocarpus*** | Appears to be particularly sensitive to tephra deposition. Declined following Egmont 15, Rerewhakaaitu and Rotorua tephra fall at Lake Rotoroa, and following Opepe, Rotoma and Whakatane tephra fall at Kaipo Bog. |
| ***Dacrydium*** | Often appeared to suffer damage from tephra fall as pollen levels declined following Kaharoa Tephra deposition at Matakana Island, above Rotorua, Rotoma and Tuhua tephra layers at Kohuora, above Taupo Tephra at Lake Rotoroa, and above Rotoma, Waimihia and Kaharoa tephra layers at Kaipo Bog |

**b) Pollen taxa that often increased following tephra fall**

| Pollen increasing | Comments |
|---|---|
| **Seral vegetation types:**<br>***Leptospermum***<br>***Pteridium***<br>**Asteraceae**<br>**Apiaceae**<br>**Cyperaceae**<br>**ferns**<br>**some tree ferns**<br>**(*Cyathea smithii*)** | At least one or more of these taxa increased after tephra deposition at all study sites in response to forest disturbance. |
| ***Griselinia*** | Increased following Rotoma and Tuhua tephra deposition at Kohuora, above Rotorua and Mangamate tephra layers at Lake Rotoroa, and above Opepe and Kaharoa tephra layers at Kaipo Bog. *Griselinia* is specially adapted to thrive on volcanic surfaces and has nitrogen-fixing capabilities. |
| ***Alectryon*** | Fossil pollen not usually preserved in large quantities. High pollen levels from this taxon were found at Lake Rotoroa. *Alectryon* was seen to increase following deposition of Rerewhakaaitu and Opepe Tephras. |
| ***Coprosma* (also a seral shrub)** | *Coprosma* is a similar taxon to *Leptospermum* as it can grow on a variety of different substrates and is often found growing on or near mire environments. Often invaded following tephra fall in conjunction with increases in seral vegetation. Increased above Egmont 15 and Taupo tephra layers at Lake Rotoroa, and above Opepe, Whakatane and Waimihia tephra layers at Kaipo. |

### 8.1.3 Tephra impacts with increasing distance from the volcanic source

Tephra fall at Kaipo Bog was the most severe encountered in this study, which was to be expected as this site received the thickest deposits of tephra. Kaipo Bog was also the most proximal site to the TVZ, located only 70 km to the east of Taupo. DECORANA revealed significant differences in sample scores from pollen samples extracted immediately above Kaharoa, Taupo, Waimihia and Rotoma tephra layers (Fig. 5.14), indicating that the magnitude of volcanic-induced forest disturbance was substantial, and significant enough to stand out against background environmental changes.

Matakana Island was located only 80 km away from the source of the Kaharoa Tephra, Mt Tarawera, and impacts appeared to be of low magnitude but complex. However, the problems of separating human-induced from volcanic-induced impacts at this site meant that an unambiguous assessment of volcanic impacts could not be made (Giles *et al.*, in press). Also, only one relatively thin (2 cm) tephra layer (Kaharoa) was preserved at this site. Comparison of distal impacts at this site with those from the other study sites could, therefore, not be made.

Volcanic impacts recorded at Lake Rotoroa ( 130 km from Taupo) were relatively insignificant in comparison with those recorded at Kaipo Bog, although imprecision in sampling related to slow sedimentation rates resulted in blurring of tephra-impacts against on-going environmental changes.

Kohuora was the most distal site studied in this thesis, located >200 km from Taupo. Despite this distance, the volcanic impacts on the local environment and vegetation assemblages were significant. Sedimentation rates were fairly rapid at this site; hence it was possible to sample at high resolution and to assess the approximate duration of impacts above each tephra layer preserved in the core. These varied between 80-100 years for the recovery of vegetation assemblages, and between 30-55 years for lake sediment geochemistry, to return to pre-eruption levels. These impacts were subtle, but vegetation changes were of significant magnitude to be detected in DECORANA results. Plots of taxa scores (Figs. 7.8 and 7.11) showed grouping of taxa that either increased or decreased following tephra fall.

These distal impacts from tephra fall are subtle, yet they appear to trigger long-term vegetation changes within the disturbed forest lasting up to 100 years at distances greater than 200 km from the eruptive source. At more proximal locations, i.e., Lake Rotoroa and Kaipo Bog, the time taken for vegetation recovery and the return to stable environmental conditions was up to 200 years and 70 years, respectively, in the most severe cases. In conclusion, the impact from distal tephra fall on vegetation communities and the environment as a whole is significant, with the after-effects lasting over several decades. Presently, volcanic hazard assessments in New Zealand focus on the proximal risk from the TVZ. The potential distal hazard from the TVZ is perhaps not as severe, but is still important, as ash fall poses a threat to local agriculture and livestock and affects export of produce. Cereal, fruit and wine harvests could be severely damaged by ash fall and livestock could be affected by chemical poisoning through consumption of ash-laden vegetation. If the hazard from distal ash accumulation and associated toxic chemical leaching is acknowledged, then measures can be taken to reduce or even prevent any damage occurring. The threat from distal tephra fall must therefore be considered as a potential hazard and included in contemporary environmental impact assessments in New Zealand.

### 8.1.4 Differences in tephra chemical composition

Specific tephra chemical composition did not vary greatly between tephra deposits at each site. Two tephra layers that show some variation in chemical composition from the main suite of tephras are Tuhua and Mangamate tephras as these originated from different source volcanoes, Mayor Island and Tongariro, respectively. The Mangamate Tephra was preserved only at Lake Rotoroa, forming a tephra layer of 1 cm thickness. Subtle, low-magnitude impacts were detected within the pollen and geochemical records, which were short-lived, because pre-eruption environmental stability returned after ca. 23 years. The main impact appears to have been to *Phyllocladus* shrubs (probably *Phyllocladus alpinus)*, whose population became extremely sparse following tephra deposition. The only noticeable differences in impacts from Mangamate Tephra fall compared with those of the other tephra layers was the change in sediment geochemistry. The Mangamate Tephra contains a high proportion of iron, and local soils and lake sediments became slightly enriched in iron. In an acidified environment with strong leaching, the deposition of iron-enriched tephra could have intensified the acidic conditions through iron accumulation in soils. At Lake Rotoroa, the deposition of Mangamate Tephra occurred at a time of forest expansion in response to optimum climatic conditions during the early Holocene. These stable environmental conditions probably contributed to the minimal level of impact detected following the Mangamate eruption (see earlier discussion).

The Tuhua Tephra is preserved in sediment profiles at Kaipo Bog, Kohuora crater, and Lake Rotoroa. Volcanic impacts recorded in the pollen profiles from Kohuora and Lake Rotoroa were subtle and comparable in magnitude to impacts recorded above other tephra layers preserved in these profiles. Sedimentation rates were extremely slow above the Tuhua Tephra at Kaipo Bog, hence immediate volcanic impacts could not be assessed. There is some evidence to suggest that deposition of the Tuhua Tephra triggered acidic conditions in the soils at Kohuora, as inwash of glass shards and increased iron content was apparent up to 55 years after the eruption. Seral vegetation became more common, and increases in taxa that are tolerant of infertile soils, such as *Dacrydium*, *Agathis* and *Phyllocladus*, together with *Coprosma* and *Leptospermum*, suggest that soils were becoming less fertile. *Metrosideros* pollen levels decline markedly above the Tuhua Tephra layer and did not recover to former levels. These trees may have been sensitive to the higher proportions of iron within the tephra, which resulted in the temporary enrichment of iron within local soils. *Metrosideros* pollen increased significantly above the Rotoma Tephra at Kohuora, which contained much lower proportions of Fe. As discussed earlier, these trees became dominant in the local area prior to the Tuhua eruption and possibly suffered greater damage as they formed the main forest canopy and were exposed to the harmful effects of tephra fall and associated toxic chemical leaching and gas discharge. The appearance of charcoal fragments in association with the deposition of the Tuhua Tephra could indicate that local burning may have caused significant damage to *Metrosideros* trees. The explanation for the decline in *Metrosideros* is speculative because there is insufficient evidence available from these palaeo-records to determine the exact cause of the decline. However, it is likely that these trees declined in response to atypical characteristics of the Tuhua Tephra, because these trees do not exhibit such dramatic decreases in numbers following tephra fall at any other site.

At Lake Rotoroa, burning occurred following deposition of the Tuhua Tephra, although vegetational and environmental disturbances were not severe and did not lead to long-term environmental change.

### 8.1.5 Comparison of results with previous research into volcanic or tephra-fall impacts

Investigations into the impact of distal tephra fall on vegetation communities and the environment in this thesis have produced results that are comparable to other palaeoenvironmental studies in New Zealand. However, these earlier studies revealed burning was often associated with Taupo Tephra deposition at many sites in central and eastern parts of the North Island, although some burning may be related to ignimbrite emplacement rather than tephra-fall (McGlone, 1980; Newnham *et al.* 1995a; Newnham *et al.*, 1995b; Wilmshurst and McGlone, 1996, Wilmshurst *et al.*, 1997). Results from pollen records in this study showed no evidence for forest fire following the deposition of the Taupo Tephra at Lake Rotoroa and at Kaipo Bog, although evidence for vegetation and catchment disturbance is evident at both sites. These differences are likely to be due to individual site characteristics, because Kaipo Bog and the surrounding catchment receives high annual rainfall, and so forest fire in the region is rare. The sheltered nature of the Lake Rotoroa site, and perhaps a lack of fuel stock within the local forest, may have prevented the spread of fires associated with tephra fall following the Taupo eruption. However, sites where other volcanic impact investigations have taken place were largely situated around the eastern coast of the North Island, from the southern Hawkes Bay region through to the western Bay of Plenty (Fig. 2.3). These areas are dry, receiving low annual rainfall resulting in frequent summer droughts. These sites are therefore more susceptible to burning than those in northern and western areas of New Zealand which receive higher levels of rainfall per annum (Salinger 1994). Most of the previous evidence for post-tephra burning relates to studies of the late Holocene, a time of drier climate. However, analysis of palaeo-records in this thesis spanning a longer interval, revealed that the occurrence of forest fire in association with tephra fall was relatively uncommon.

Previous tephra impact studies revealed *Pteridium* increases following tephra impact and forest fire (McGlone, 1980; Newnham *et* al., 1995a; Wilmshurst and McGlone, 1996; Wilmshurst *et al.*, 1997). As the *Pteridium* fern is a very dry and brittle plant, it is highly combustible. *Pteridium* expands rapidly across patches of ground made available through forest disturbance, therefore providing additional fuel stock for forest fires. McGlone (1980) suggested that forest fires related to tephra impact were likely to have been sustained due to the provision of an additional fuel source through the expansion of highly combustible *Pteridium* ferns within the damage forest. *Pteridium* expansion therefore probably increased the likelihood of sustained forest fire following Taupo Tephra fall at study sites in central and eastern parts of the North Island (Wilmshurst and McGlone, 1996). *Pteridium* increases were uncommon following tephra-fall-induced forest disturbances at the sites studied in this thesis, therefore reducing the risk of more extensive damage to forests through sustained burning. Minor increases in *Pteridium* were displayed in spore records following Tuhua Tephra deposition and local forest fire at Lake Rotoroa (Figure 6.4). It is possible that small patches of *Pteridium*, which occurred approximately 50 years after initial volcanic-induced forest disturbance and fire, provided additional fuel stock which may have increased or encouraged sustained burning and forest disturbance within the local area.

Some comparisons can be made between vegetation responses and recovery following tephra fall at study sites in this thesis with those from other sites in the North Island. Detailed studies by Wilmshurst *et al.* (1997) and Wilmshurst and McGlone (1996) into palaeoenvironmental impacts from tephra fall revealed that dominant main forest canopy species and emergents often declined following tephra deposition, particularly *Dacrydium* and *Prumnopitys* species. These trees declined following Waimihia and Rotoma tephra deposition at Kaipo Bog, and above Rotorua, Rotoma and Tuhua tephra layers at Kohuora. These impacts, although variable and inconsistent between sites and different tephra layers, suggest taller, long-lived trees are more susceptible to damage from tephra fall and toxic chemical fallout than trees and shrubs that occupy lower forest tiers. These smaller trees are sheltered by the main forest canopy from direct atmospheric impact. The threat to lower canopy trees is therefore likely to come from the indirect impacts from tephra fall, either through changes in soil chemistry and structure, changes in drainage, forest fire, or from competitive pressure from expanding seral vegetation.

The level of impact of distal tephra fall on *Metrosideros* was seen to be inconsistent and variable from fine resolution pollen records at Matakana Island, Kohuora and Lake Rotoroa. This taxon includes tree species and lianes encompassing a range of potential habitats. It is therefore likely that there will be inconsistencies in the response of *Metrosideros* to tephra impact. *Metrosideros* exhibited marked declines following the deposition of Tuhua Tephra at Kohuora and Rotoroa, and after deposition of the Opepe Tephra at Rotoroa, and yet increased following other eruptions (i.e., deposition of Rotoma at Kohuora, Kaharoa at Matakana Island, and Rotorua, Mangamate and Taupo at Lake Rotoroa). *Metrosideros* trees declined following deposition of the Taupo Tephra at Papamoa Bog (Newnham *et al.*, 1995) after Taupo Tephra fall at Repongaere Swamp and Tunapahore (Wilmshurst and McGlone, 1996) and following various eruptions on White Island (Clarkson and Clarkson, 1994; Clarkson 1994).

The evidence presented in this thesis, and in the studies described above, indicates that some *Metrosideros* species are highly sensitive to the impact of tephra accumulation through the harmful effects associated with toxic chemical leaching from tephra deposits, i.e., leaf scorch and burning through wet ash coating leaves. Where *Metrosideros* appeared to be somewhat protected and sheltered by larger dominant canopy trees (e.g. *Dacrydium*, *Prumnopitys* spp.), no impacts were recorded, or increases were seen in *Metrosideros* pollen levels, indicating expansion of these trees into canopy gaps created following the decline in damaged canopy taxa. Hence, whether *Metrosideros* spp. decline or increase following tephra deposition is dependent largely on forest structure, as a dense forest canopy of taller podocarp and angiosperm trees will provide the necessary shelter for *Metrosideros* spp. to survive tephra impacts and subsequently expand following the decline in damaged canopy species.

The impact of tephra fall on vegetation assemblages appears to be significant at distal sites where impacts were expected to be minimal. Impacts recorded at Kohuora, >200 km from Taupo, appeared to be more significant than those recorded at Lake Rotoroa and Matakana Island 130 km and 80 km from the Taupo respectively, where tephra layers comparable in thickness to those at Kohuora were deposited (i.e., 2-3 cm). Similar results were reported by Wilmshurst and McGlone (1996) as the greatest forest disturbance following Taupo Tephra deposition was recorded at Tunapahore, one of the most distal sites from the eruptive source, which also received a relatively thin deposit of ash (7 cm). However, other palynological studies by Wilmshurst *et al.* (1997) revealed no evidence for vegetation disturbance following the distal deposition of thin tephra layers found in sediment cores, despite fine-resolution sampling (0.5-1 cm intervals).

Volcanic-induced damage to vegetation following distal deposition of thin (< 8 cm) tephra layers is not uncommon, as many similar reports revealed extensive damage to crops and livestock at distal locations throughout Iceland and parts of Europe following the AD 1783 Laki eruption in Iceland (Grattan *et al.* 1994; Blackford *et al.*, 1992), and following distal deposition of the Laacher See Tephra in Germany (Lotter and Birks, 1993). Rose (1977) and Oskarsson (1980) reported that adsorption of toxic chemicals onto glass shards occurred during transportation of ash within the eruption cloud (see chapter two). It is therefore possible that the distal impacts recorded in pollen records in this thesis, and in European and New Zealand palaeoenvironmental studies, are the result of an increase in toxicity of tephra deposits through chemical adsorption with increasing distance from the eruptive source.

## 8.2 Problems encountered

The most significant problem encountered was generally slow (i.e., >50 years per 0.5 cm) and variable sedimentation rates which affected the detection of volcanic impacts within the palynological and geochemical records. This problem therefore demonstrates the need to sample at very high resolutions and to have accurate estimates of sediment accumulation rates in order to overcome difficulties in interpretation of palaeorecords for distal volcanic impact assessments.

Slow rates of sedimentation were apparent in cores from Lake Rotoroa, with variable and slow peat accumulation rates encountered in the Kaipo peat profile. Despite fine resolution sampling undertaken above tephra layers, in some cases the time resolutions were too broad. Thus any short-term volcanic impacts were likely to be obscured by long-term vegetational and environmental changes. Sedimentation rates were especially slow above Rotoma, Waiohau and Mamaku Tephras in the Rotoroa cores, and were estimated as 71 years, 78 years and 140 years, respectively, per 0.5 cm. As a result, investigations into volcanic impacts following these eruptions were not completed. Similarly, potential impacts were not investigated above Mamaku and Tuhua Tephra layers in the Kaipo profile where peat accumulation rates were estimated as 373 years and 325 years per centimetre, respectively. Although slow accumulation rates were also encountered above other tephra layers within the Kaipo profile, the tephra deposits are thick (>10 cm) and the impact of tephra fall on local vegetation was sufficiently severe to be evident in samples taken immediately above them. However, it was not possible to detect the precise magnitude of volcanic impact alone, or the time taken for the forest to recover, because of the relatively coarse temporal resolution of samples. Hence changes observed within the pollen and geochemical records were interpreted as minimum impacts, with the true potential impact from tephra deposition possibly much greater.

Interpretation of geochemical records proved difficult as high levels of certain elements could have been caused by a number of different processes. Si, Al, Na and K are all important elements present in tephra layers, yet in palaeoenvironmental research increased proportions of these elements in lake or peat sediments may indicate catchment erosion or suggest acidification of local soils. Higher levels of Si, Al, Na and K above tephra layers have been associated with inwash of tephra-derived glass shards from soil surfaces within the catchment immediately following tephra deposition. However, elevated levels of these elements often continued over a period of approximately 40 years or more, suggesting sustained soil erosion occurred following damage to local vegetation from tephra impact. Evidence for catchment erosion following tephra fall is illustrated in the fine-resolution pollen diagrams, with increases in deteriorated pollen grains and tephra shards probably derived from eroded catchment topsoils.

Glass shard counts occasionally remained low immediately above some macroscopic tephra layers, yet Si, Na, K and Al increased (e.g. above Tūhua Tephra, Kohuora; above Mamaku Tephra, Rotoroa). These element increases were therefore likely to have been the result of catchment erosion of topsoils, rather than extensive erosion and tephra inwash, as low shard counts suggest tephra presence was minimal above the macroscopic layers. Thus in these instances normal background levels of catchment erosion can be clearly identified and distinguished from increased levels of tephra inwash associated with volcanic-induced catchment disturbance.

Glass shard counts sometimes reached higher concentrations below macroscopic tephra layers than above. Microscopic glass shards, and pollen grains, are likely to migrate downwards to a slight degree due to compaction of sediments within the profile and downwards throughflow of moisture, as sedimentation processes continue through time. Bioturbation would also encourage downwards migration of pollen grains and glass shards (Lowe, 1988). In addition, the uneven topography of peat bog surfaces will result in accumulation of micro-shards in small hollows and dips following instantaneous tephra deposition. Micro-shard counts below macro-tephra layers may also indicate early eruption phases occurring over a period of several months to years prior to the main eruptive blast. These precursor emissions of ash and gases are quite common: they were observed several months before the AD 1995 and 1996 eruptions of Mt Ruapehu. Tephra from these ash clouds carried by prevailing winds can be deposited some distance from the volcanic source. These processes are likely to have occurred prior to, or in the initial stages of the Taupo and Tuhua eruptions, and possibly Rotorua and Rerewhakaaitu eruptions, resulting in high counts of micro-shards below these macroscopic tephra layers in sediment profiles from Kaipo Bog and Lake Rotoroa.

There are some difficulties in distinguishing volcanic impacts from anthropogenic disturbance. This problem is of particular relevance to only the youngest deposits because human settlement in New Zealand is dated from ca. 700 BP at the earliest (Newnham *et al.* 1998). The difficulty in interpretation was evident at one site, Matakana Island in particular (Chapter Four), although serious anthropogenic disturbance within the top metre of the Kohuora core caused difficulties in locating the Taupo Tephra and determining any possible environmental impacts associated with its deposition. The Matakana Island peat profile contains the Kaharoa Tephra layer (665 years BP) which was erupted within the timeframe of regional human settlement (ca. 700 BP, Newnham *et al.* 1998). Evidence for environmental disturbance was displayed within the pollen and geochemical records immediately above the Kaharoa Tephra layer, with further, more severe disturbance displayed a few centimetres above the tephra which were sustained. It was unclear whether the initial low magnitude disturbances immediately above the tephra layer were due to the impact of tephra accumulation and associated toxic chemicals, or early settlers on the island causing minor disturbances (e.g. clearance of small areas for building shelters, damage to young trees/undergrowth in the forest during hunting).

The vegetation changes recorded in the Matakana profile are complex and do not appear to be comparable to any other post-tephra sequences in this thesis. For example, vegetation changes above the Kaharoa Tephra at Kaipo Bog show marked and sustained declines in *Dacrydium*, *Prumnopitys taxifolia*, *Gleichenia* and other fern taxa, while *Phyllocladus*, *Nothofagus menziesii*, *Coprosma* and *Griselinia* increase. No Polynesian deforestation signal is apparent from these data, and pollen trends in the Kaipo record are less complex than those displayed in the Matakana profile. An explanation for these complexities in the Matakana record was presented in Chapter 4 and published in Giles *et al.* (in press), which suggested that the initial vegetation changes immediately above the tephra layer (i.e., between ca. 44 - 43 cm) may have occurred as a result of tephra impact, although the possibility of anthropogenic impact from early Polynesian settlers cannot be ruled out.

Vegetational and environmental investigations above other relatively thin (i.e., <3cm) Holocene tephra layers pre-dating the Polynesian era from the three other study sites do not exhibit such complex changes. Short-lived vegetation changes recorded immediately above these tephra layers were likely to have been caused by the deposition of tephra and associated toxic chemicals, as human impacts could be discounted. Given the strong evidence for anthropogenic forest clearances in the region around the time of the Kaharoa eruption, together with the benefit of similar tephra investigations in this thesis which pre-date the Polynesian era for comparison, it is likely that the complex vegetation changes above the Kaharoa Tephra layer in the Matakana profile were primarily due to disturbance from early Polynesian settlers, which were perhaps strengthened or exacerbated by tephra impacts.

The Matakana Island study demonstrates the difficulty in distinguishing volcanic impacts from human impacts. However, this problem did not affect investigations at the other three sites as all tephra layers preserved in the sediment profiles predated the Polynesian era, with the exception of the Kaharoa Tephra at Kaipo Bog. Human impacts could therefore be discounted when assessing environmental disturbance from tephra fall, which was a great advantage for this study. This advantage is not shared in most European tephra-impact studies, which have attempted to investigate environmental impacts above tephra layers from eruptions occurring within the timeframe of human settlement across Europe (Blackford *et al.* 1994; Grattan *et al.* 1995). These investigations are constrained by an inability to distinguish unequivocally between human and tephra impacts, especially when taking into account long-term environmental factors and climatic changes which must also be distinguished from tephra impacts in palaeoenvironmental records.

**8.3 Summary**

Research undertaken in this thesis, to determine the impact of distal tephra fall on vegetation and the environment in New Zealand, has sought to provide explanations and answers to the fundamental aims of the project outlined in Chapter One. Results have shown that distal tephra fall can cause varying degrees of damage to forests between 70 to >200 km from eruptive sources. Palaeoenvironmental records presented in this thesis have illustrated that damage to vegetation and subsequent environmental instability occurred as a result of distal tephra deposition and associated toxic chemical leaching. The evidence presented has revealed that distal volcanic impacts were widespread in New Zealand following many volcanic eruptions occurring since the late glacial, and were not confined to the Taupo eruption on which many previous reports have focused. Table 8.2 provides a summary of tephra impacts investigated in this study.

Results have clearly shown that the magnitude of impacts were not proportional to tephra thickness, nor strictly related to distance from the eruptive sources. Impacts inferred from pollen assemblages were variable and unpredictable, and often obscured owing to problems of slow sedimentation rates in records. Impacts were seen to vary greatly depending on prevailing climate, site characteristics, individual species sensitivity to ash accumulation and toxicity, and forest structure and age.

The following chapter provides the conclusions reached from the analysis of results presented in this thesis, and recommendations for further research.

**Table 8.2** A summary of tephra impact criteria and impact ratings for tephras analysed. These ratings are as follows:
0 = No discernible impact, 1 = Minor impact or equivocal impact, 2 = Moderate impact, 3 = Major unequivocal impact

| **Site** | **Tephra** | **Age (yrs BP)** | **Distance from source (km)** | **Thickness (cm)** | **Dryland vegetation** | **Impact rating** | **Criteria** |
|---|---|---|---|---|---|---|---|
| Matakana Island | Kaharoa | 665±15 | 80 | 2 | Podocarp-hardwood forest | 1 | Pollen changes immediately above tephra are very minor and it is unclear whether they are directly related to deposition of tephra layer<br>Clustering of samples immediately above tephra layer.<br>Changes in geochemistry immediately above the tephra layer, but unclear whether they are directly related to tephra layer. |
| Kaipo Bog | Kaharoa | 665±15 | 80 | 1.5 | Montane beech forest with local wetland vegetation | 2 | Pollen changes directly related to tephra layer.<br>Cluster analysis shows clustering of samples immediately above tephra layer.<br>Decorana sample scores show distinctive changes in pollen samples immediately above the tephra layer related to its fall. |
| Kaipo Bog | Taupo | 1850±10 | 90 | 22 | Montane beech forest and local wetland vegetation | 1 | Pollen changes may be related to tephra layer.<br>Cluster analysis shows clustering of samples immediately above tephra layer. |
| Kaipo Bog | Waimihia | 3280±20 | 90 | 28 | Montane beech forest and local wetland vegetation | 3 | Pollen changes directly related to tephra layer.<br>Cluster analysis shows clustering of samples immediately above the tephra layer.<br>Decorana sample scores show distinctive overall pollen changes within the sample related to tephra fall. |
| Kaipo Bog | Hinemaiaia | 4510±20 | 90 | 1 | Montane beech forest and local wetland vegetation | 0 | No changes directly related to the tephra layer were detected |
| Kaipo Bog | Whakatane | 4830±20 | 80 | 14 | Montane beech forest and local wetland vegetation | 3 | Pollen changes directly related to the tephra layer.<br>Cluster analysis shows clustering of samples immediately above the tephra layer.<br>Decorana taxa scores show distinctive changes in taxa behaviour related to tephra fall.<br>Changes in sediment geochemistry directly related to the tephra layer. |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Kaipo Bog | Tuhua | 6130±30 | 200 | 4 | Montane beech forest and local wetland vegetation | 0 | Pollen changes occurred above the tephra layer, but were not directly related to tephra fall. |
| Kaipo Bog | Mamaku | 7250±20 | 80 | 3 | Montane beech forest and local wetland vegetation | 0 | Pollen changes occurred above the tephra layer, but were not directly related to tephra fall. |
| Kaipo Bog | Rotoma | 8530±10 | 80 | 16 | Montane beech forest and local wetland vegetation | 3 | Pollen changes directly related to the tephra layer.<br>Decorana taxa scores show distinctive changes in taxa behaviour related to tephra fall.<br>Decorana sample scores show distinctive overall pollen changes within the sample related to tephra fall.<br>Changes in sediment geochemistry directly related to the tephra layer. |
| Kaipo Bog | Opepe | 9050±40 | 90 | 9 | Montane beech forest and local wetland vegetation | 2 | Pollen changes directly related to the tephra layer.<br>Cluster analysis shows clustering of samples immediately above the tephra layer.<br>Changes in sediment geochemistry directly related to the tephra layer. |
| Lake Rotoroa | Taupo | 1850±10 | 100 | 1 | Lowland podocarp-hardwood forest | 1 | Pollen changes directly related to tephra layer.<br>Geochemistry changes directly related to tephra layer. |
| Lake Rotoroa | Tuhua | 6130±30 | 100 | 2 | Lowland podocarp-hardwood forest | 1 | Pollen changes directly related to tephra layer.<br>Decorana taxa scores show some changes in taxa related to tephra fall.<br>Geochemistry changes directly related to tephra layer. |
| Lake Rotoroa | Mamaku | 7250±20 | 120 | 3 | Lowland podocarp-hardwood forest | 0 | No distinct changes in pollen and geochemistry records which can be directly linked to tephra layer. |
| Lake Rotoroa | Rotoma | 8530±10 | 120 | 2 | Lowland podocarp-hardwood forest | 0 | No distinct changes in pollen and geochemistry records which can be directly linked to tephra layer. |
| Lake Rotoroa | Opepe | 9050±40 | 100 | 2 | Lowland podocarp-hardwood forest | 1 | Pollen changes may be related to tephra layer.<br>Decorana taxa scores show some changes in taxa related to tephra fall.<br>Geochemistry changes directly related to tephra layer. |
| Lake Rotoroa | Mangamate | 9985 | 120 | 1 | Lowland podocarp-hardwood forest | 1 | Pollen changes directly related to tephra layer.<br>Cluster analysis shows clustering of samples immediately above the tephra layer.<br>Geochemistry changes directly related to tephra layer. |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Lake Rotoroa | Waiohau | 11,850±60 | 120 | 2 | Lowland podocarp-hardwood forest | 0 | Pollen changes were not directly related to tephra layer. |
| Lake Rotoroa | Rotorua | 13,080±50 | 100 | 6 | Lowland podocarp-hardwood forest | 2 | Pollen changes directly related to tephra layer.<br>Cluster analysis shows clustering of samples immediately above the tephra layer.<br>Geochemistry changes may be related to tephra layer. |
| Lake Rotoroa | Rerewhakaaitu | 14,700±110 | 120 | 2 | Lowland podocarp-hardwood forest | 1 | Pollen changes immediately above tephra layer may be directly related to tephra fall.<br>Cluster analysis shows clustering of samples immediately above the tephra layer.<br>Decorana taxa scores show distinctive changes in taxa related to tephra fall.<br>Geochemistry changes possibly related to tephra impact. |
| Lake Rotoroa | Egmont-15 | 14,650±200 | 200 | 1 | Lowland podocarp-hardwood forest | 3 | Pollen changes directly related to the tephra layer.<br>Cluster analysis shows clustering of samples immediately above the tephra layer.<br>Decorana taxa scores show distinctive changes in taxa related to tephra fall.<br>Changes in sediment geochemistry directly related to the tephra layer. |
| Kohuora | Tuhua | 6130±30 | 150 | 3 | Lowland podocarp-hardwood forest | 1 | Pollen changes directly related to tephra layer.<br>Geochemistry changes directly related to tephra layer. |
| Kohuora | Rotoma | 8530±10 | 200 | 3 | Lowland podocarp-hardwood forest | 2 | Pollen changes directly related to tephra layer.<br>Decorana taxa scores show some changes in taxa related to tephra fall.<br>Geochemistry changes directly related to tephra layer. |
| Kohuora | Rotorua | 13,080±50 | 200 | 2 | Lowland podocarp-hardwood forest | 1 | Pollen changes directly related to tephra layer.<br>Decorana taxa scores show some changes in taxa related to tephra layer.<br>Geochemistry changes directly related to tephra layer. |

## Chapter 9

## Conclusions

Investigations were undertaken to assess the distal palaeoenvironmental impacts from volcanic tephra deposition, through pollen and geochemical analysis of sediment cores extracted from four study sites in the North Island of New Zealand. Fine-resolution pollen analysis immediately above tephra layers within these cores, generally, provided an adequate method for the reconstruction and assessment of vegetation impacts immediately following tephra fall. However, in some cases, where estimated sedimentation rates were slow (i.e., >50 years per 0.5 cm), the 0.5 cm fine resolution sampling was insufficient to detect short-term tephra impacts. EDMA techniques were used to assess fine resolution changes in sediment geochemistry and to detect possible environmental instability and erosion following tephra impact. Geochemical analysis through the use of EDMA was less successful, because results produced were not sensitive enough to differentiate between normal mechanical erosional processes occurring within the catchment soils and the impacts resulting from tephra deposition. However, the detection of increases in deteriorated pollen grains within the pollen record provided further evidence for environmental degradation and instability. The geochemical data were therefore used to support the pollen evidence for palaeoenvironmental change, and in that context proved useful for the assessment of tephra-induced environmental impacts.

Conclusions reached from this research are related to the fundamental aims of the project which are outlined in chapter one.

1) From this research, the critical tephra thickness, above which discernible vegetational and environmental impacts occurred, could not be determined. The results have shown that, in many cases, the deposition of thick tephra layers (>3 cm) did not always result in significant environmental and vegetational disturbance, yet the deposition of some of the thinner tephra layers caused considerable damage. In the Rotoroa core, notable vegetational and environmental disturbances were detected above the 0.5 cm thick Egmont 15 Tephra layer, (impact rating = 3), whereas no disturbance was detected above the 3 cm thick Mamaku Tephra (impact rating = 0). Low impact ratings were also allocated to other thick tephra

layers, for example the 22 cm thick Taupo Tephra layer at Kaipo allocated an impact rating of 1, the 4 cm thick Tuhua Tephra layer at Kaipo, allocated an impact rating of 0. However, problems of sampling resolution and slow sedimentation at some sites, especially Rotoroa and Kaipo Bog, created difficulty in assessing the magnitude of short-term tephra impacts. It is not known whether tephra layers < 0.5 cm thick could have caused environmental disturbance, as thinner tephra layers were not identified in any profiles analysed in this thesis. These results suggest that the concept of a critical tephra thickness, although undoubtedly important for volcanic hazards assessment in areas proximal to the volcano, may be less useful in investigations of distal impacts.

2) Recovery patterns of vegetation affected by tephra fall varied between sites and individual species. Factors that strongly influenced these variations included prevailing climatic conditions, individual site characteristics (e.g. drainage / soil moisture), season of year during which the eruption occurred, and forest structure and age. The impact of tephra fall on individual species therefore was inconsistent. However, taxa that were particularly sensitive to ash deposition included *Halocarpus*, *Dacrydium* and *Metrosideros*. The inconsistent impact of tephra fall on *Metrosideros* and *Dacrydium* is attributed to variations in the degree of shelter these taxa received from other forest canopy trees.

3) No evidence for total forest destruction was detected following tephra fall, even at Kaipo Bog, 70 km away from the TVZ, where tephra thickness exceeded 20 cm. Instead, damage to the forest canopy probably occurred in patches, as tall emergent trees and older, less robust individuals were likely to have been stripped of leaves and upper branches, while many main canopy trees may have escaped severe damage. Taxa that typically increased within these disturbed forests included:

Seral vegetation - *Leptospermum*
Asteraceae
Apiaceae
Cyperaceae

Tree ferns \ ferns

*Griselinia*

*Coprosma*

Non seral vegetation - *Alectryon*

4) Results presented in this thesis revealed that the magnitude of vegetational and environmental impacts was not strictly related to the proximity of the site to the volcanic source. Tephra impacts were illustrated in pollen and geochemical records at Kohuora, located > 200 km from the TVZ. These impacts were significant enough to be detected from numerical analyses of pollen data using DECORANA and CONISS. At Lake Rotoroa, 130 km away from the TVZ, tephra layers varied between 0.5 cm and 6 cm in thickness. Impacts detected above the 0.5 cm tephra layer were among the most significant recorded at this site. Generally however, tephra impacts at Lake Rotoroa were subtle, and in some cases negligible, although slow sedimentation rates and less-than-optimal sampling resolutions meant that possible tephra-caused impacts were indiscernible from background levels of environmental changes. Matakana Island, located 80 km away from the TVZ, received a 2 cm thick tephra layer which produced subtle impacts within the local forest and environment, although results were ambiguous owing to possible human disturbance at the time of the Kaharoa eruption. Kaipo Bog, 70 km away from the TVZ, received very thick tephra deposits which had significant impacts on the local vegetation assemblages and the environment.

5) The duration of tephra impacts varied between sites. At more proximal locations, i.e., Lake Rotoroa and Kaipo Bog, full recovery of vegetation following tephra-induced damage took up to 200 years, with environmental stability returning after a maximum of approximately 70 years. The time taken for recovery of vegetation following tephra impact at Matakana Island cannot be determined owing to the impact of anthropogenic disturbance occurring shortly after the Kaharoa eruption (665 years BP). At Kohuora, the time taken for the recovery of vegetation following tephra impact was approximately 100 years, with

environmental stability occurring after approximately 50 years.These are broad estimates constrained by the generally slow and variable sedimentation rates at these sites.

6) Analysis of results presented in this study revealed that chemical composition of the tephra did not have a definitive effect on the magnitude or duration of volcanic impacts at any of the study sites. However, it is reasonable to suggest that specific tephra chemistry could be important to some taxa which declined following the deposition of specific tephra layers (e.g. *Metrosideros* decline above Tuhua Tephra at Kohuora and Lake Rotoroa). However, it may not be possible to determine these impacts from palaeoenvironmental records, because many different factors occurring in conjunction with tephra impacts are likely to have contributed to vegetation decline.

*Limitations and recommendations for further research*

The research presented in this thesis has shown that impacts on the vegetation and environment are significant, with the return to environmental and vegetational stability occurring over considerable periods of time. The risk of environmental damage from distal tephra deposition should therefore be considered in contemporary volcanic hazard assessments in New Zealand. Damage to crops and livestock, as well as to the natural environment, is likely to occur following deposition of even very thin tephra layers. It is therefore important to consider ways in which damage to agriculture, water supplies, lifelines and other societal resources as well as to the natural environment from distal tephra fall and associated toxic chemical leaching can be avoided or minimised. The detection, at Kohuora, of tephra layers from the TVZ and environmental changes resulting from them, indicate that the Auckland urban area is at greater risk from non-local rhyolitic volcanic eruptions than was previously thought.

The main limitation in the assessment of distal volcanic impacts in this study was that in many cases, the sampling resolution (0.5 cm intervals) was insufficient to detect short-term palaeoenvironmental changes in the records analysed because of very slow sedimentation rates. It is therefore prudent to assess these possible problems in future palaeoenvironmental investigations where fine resolution sampling methods are needed.

Previous palaeovegetational research into proximal volcanic impacts in New Zealand has used palynological data together with plant macrofossil analyses to try to determine the cause of damage to vegetation following volcanic eruptions (Druce, 1966; Clarkson *et al.* 1988). Analysis of plant macrofossils in these studies showed evidence for burning and charring of leaves of specific plant species, through acid damage from toxic chemicals associated with tephra deposition and volcanic gas emissions. The use of plant macrofossil analyses (if present) in conjunction with pollen and geochemical analyses would be extremely useful for future studies, in order to provide further evidence for the cause of vegetation decline following tephra impacts.

Further research is required in order to assess impacts on the environment from distal microscopic tephra fall. Palynological studies in Britain (and elsewhere) have shown that declines in vegetation were associated with the deposition of microscopic tephra layers originating from Icelandic eruptions. Research in this thesis has shown that distal tephra layers 0.5 cm thick have caused quite significant damage to vegetation and triggered environmental instability. It is therefore possible that even thinner tephra deposits could still pose a threat to the environment, and further palaeoenvironmental research is required to assess the magnitude and significance of these impacts. A further implication from this work is that it may not be possible to distinguish anthropogenic impacts from distal volcanic impacts using palaeoecological methods alone, unless human presence can be discounted.

Contemporary laboratory investigations, involving the exposure of taxa such as *Metrosideros* to different chemical combinations within tephra deposits, could be undertaken under simulated climatic conditions. These experiments could then assess how these elements affect plant growth and morphology directly from atmospheric input, or indirectly through uptake from soils. It is likely that the deposition of tephra enriched in iron could trigger or intensify acidification processes, resulting in vegetation decline, soil degradation and erosion and environmental instability.

**References**

Allan, H. H. 1961: *Flora of New Zealand, Volume 1* Government Printer, Wellington.

Allard, P., Carbonelle, J., Dajlevic, D., Le Bronec, J., Morel, P., Robe, M. C., Maurenas, J. M., Faivre-Pierret, R., Martin, D., Sabroux, J. C., and Zettwoog, P., 1991: Eruptive and diffuse emissions of $CO_2$ from Mt Etna. *Nature 351*, 387-391.

Anderson, A., 1991: The chronology of colonisation in New Zealand. *Antiquity 65*, 767-795.

Anderson, A., 1995: Current approaches in east Polynesian colonisation research. *The Journal of the Polynesian Society 104*, 110-132.

Angell, J. K., and Korshover, J., 1985: Surface temperature changes following the six major volcanic episodes between 1780-1980. *Journal of Climate and Applied Meteorology 24*, 937-951.

Bache, B. W. 1986: Aluminium mobilisation in soils and waters. *Journal of the Geological Society 143 (4)*, 699-706.

Baillie, M. G. L., 1994: Dendrochronology raises questions about the nature of the AD 536 dust veil event. *The Holocene 4*, 212-217.

Baillie, M. G. L. and Munro, M. A. R., 1988: Irish tree rings, Santorini and volcanic dust veils. *Nature 322*, 344-346.

Baldwin, B., Pollack, J. B., Summers, A., and Toon, O. B., 1976: Stratospheric aerosols and climatic change. *Nature 263*: 551-555.

Ballance, P. F. and Williams, P. W., 1992: The Geomorphology and Auckland and Northland. In Soons, J. M. and Selby, M. J. (eds) *Landforms of New Zealand, Second edition.* Longman Paul. 210-233

Beadle, S., 1990: An account of the vegetation and flora of the north-western end of Matakana Island, Tauranga Harbour. *Rotorua Botanical Society Newsletter 19*, 24-35.

Beever, J. E., Allison, K., and Child, J., 1992: *The mosses of New Zealand (second edition).* Dunedin, University of Otago Press, 214 pp.

Bennett, K. D., Boreham, S., Sharp, M. J., and Switsur, V. R., 1992: Holocene history of environment, vegetation and human settlement on Catta Ness, Lunnasting, Shetland. *Journal of Ecology 80*, 241-273.

Benninghof, W. S., 1962: Calculations os pollen and spore density in sediments by addition of exotic pollen in known quantities. *Pollen et spores 4*, 332-333.

Betzer, P. R., Cardner, K. L., Duce, R. A., Merrill, J. T., Tindale, N. W., Uematsu, M., Costello, D. K., Young, R. W., Feely, A., Breland, J. A., Bernstein, R. E., and Greco, A. M., 1988: Long range transport of giant mineral aerosol particles. *Nature 336*, 568-571.

Birks, H. J. B., 1970: Inwashed pollen spectra at Loch Fada, Isle of Skye. *New Phytologist 69*, 807-820.

Birks, H. J. B., 1994: Did Icelandic volcanic eruptions influence the post-glacial vegetational history of the British Isles? *Trends in Ecology and Evolution 9*, 312-314.

Birrell, K. S., 1962: Surface acidity of subsoils derived from volcanic ash deposits. *New Zealand Journal of Science 5*, 453-462.

Blackford, J. J., Edwards, K. J., Dugmore, A. J., Cook, G. T., and Buckland, P., 1992: Hekla 4: Icelandic volcanic ash and the mid Holocene Scots Pine decline in northern Scotland. *The Holocene 2*, 260-265.

Bogaard, P. V. D., Schminke, H. U., Freundt, A., and Park, C., 1992: Evolution of complex eruptions: the late Quaternary Laacher See case history. In, D. A. Hardy, J. Keller, V. P. Galanopoulos, N. C. Flemming and T. H. Druitt (eds) *Thera and the Aegean world Volume two, Earth Sciences*. Proceedings of the third international congress, Santorini Greece. London: The Thera Foundation. 128-145

Bradley, R. S., 1973: Recent freezing level changes and climatic deterioration in the Canadian Arctic Archipelago. *Nature 243*, 398-399.

Bradley, R. S., and England, J., 1978: Volcanic dust influence on glacier mass balance at high latitude. *Nature 271*, 726-738.

Brantley, S. L., Rowe, G. L., Konikow, L. F., and Ward, E. S., 1992: Toxic waters of Poas Volcano. *National Geographic Research and Exploration 8*, 328-337.

Bray, J. R., 1974a: Volcanism and glaciation during the past 40 millenia. *Nature 252*, 679-680.

Bray, J. R., 1974b: Glacial advance relative to volcanic activity since 1500 AD. *Nature 248*, 42-43.

Bray, J. R., 1976: Volcanic triggering of glaciation. *Nature 260*, 414-415.

Bray, J. R., 1979: Surface albedo increase following massive Pleistocene explosive eruptions in western North America. *Quaternary Research 12*, 204-241.

Briffa, K. R., Bartholin, T. S., Eckstein, D., Jones, P. D., Karlen, W., Schweingruber, F. H., and Zetterburg, P., 1990: A 1400-year tree ring record of summer temperatures in fennoscandia. *Nature 346*, 434-439.

Briffa, K. R., and Jones, P. D., 1992: The climate of Europe during the 1810's with special reference to 1816. In Harington, C. R (ed) *The year without a summer* Ottawa. Canadian Museum of Nature. 372-392

Briffa, K. R., Jones, P. D., and Schweingruber, F. H., 1988: Summer temperatures over Europe: A reconstruction from 1750 AD based on maximum latewood density indices of conifers. *Quaternary Research 30*, 36-52.

Briggs, R. M., Itaya, T., Lowe, D. J., and Keane, A. J., 1989: Ages of the Pliocene-Pleistocene Alexandra and Ngatutura volcanics, western North Island, New Zealand, and some geological implications. *New Zealand Journal of Geology and Geophysics 32*: 417-427.

Brothers, R. N., and Golson, J., 1959: Geological and archaeological interpretation of a section in Rangitoto ash on Motutapu Island, Auckland. *New Zealand Journal of Geology and Geophysics 2*, 569-577.

Brown, K. A. 1985: Sulphur distribution and metabolism in waterlogged peat. *Soil Biology and Biochemistry 17*, 39-45.

Bryson, R. A., and Goodman, B. M., 1980: Volcanic activity and climatic changes. *Science 207*, 1041-1044.

Bull, K., 1991: Critical load maps for the U.K. *NERC News July*, 31-32.

Burgess, C., 1989: Volcanoes. *Current Archaeology 117*, 325-329.

Burke, W. D., 1974: Regeneration of Podocarps in a central North Island forest. *New Zealand Journal of Botany 12*, 9-26.

Burke, K., and Francis, P., 1985: Climatic effects of volcanic eruptions. *Nature 314*, p136.

Burnham, R. J., 1994: Plant deposition in modern volcanic environments. *Transactions of the Royal Society of Edinburgh, Earth Sciences 84*, 275-281.

Burrows, C. J., 1979: A chronology for cool-climate episodes in the southern hemisphere 12, 000-1 000 yr BP. *Palaeogeography, Palaeoclimatology, Paleoecology 27*, 287-347.

Burrows, C. J., and Greenland, D. E., 1979: An analysis of the evidence for climatic change in New Zealand in the last thousand yrs: evidence from diverse natural phenomena and from instrumental records. *Journal of the Royal Society of New Zealand 9*, 321-373.

Burrows, C. J., 1982: On New Zealand climate within the last 1000 years. *New Zealand Journal of Archaeology 4*, 157-167.

Burrows, C. J., 1990: Vegetation development on volcanic ejecta. In Burrows, C. J. (ed) *Processes of Vegetation Change*. Unwin Hymen. London, 123-145.

Caput, C., Belot, Y., Auclair, D., and Delcourt, N., 1978: Absorption of sulphur dioxide by pine needles leading to acute injury. *Environmental Pollution 16*, 3-15.

Cescas, M. P., Edward, H. T., and Lawrence, J. G., 1968: The Electron Microprobe X-ray analyser and its use in soil investigations. *Advances in Agronomy 20*, 153-198.

Challis, G. A., 1978: The late mobile phase: igneous activity. In: Suggate, R. P., Stevens, G. R., Te Punga, M. T. (eds) *The Geology of New Zealand*. Government printer, Wellington. 2 vols, 628-667.

Chapman, S. B., 1964: The ecology of Coom Rigg Moss, Northumberland, II. The chemistry of peat profiles and the development of the bog system. *Journal of Ecology 52*, 315-321.

Charman, D. J., 1992: The effects of acetylation on fossil *Pinus* pollen and *Sphagnum* spores discovered during routine pollen analysis. *Review of Palaeobotany and Palynology 72*, 159-164.

Charman, D. J., West, S., Kelly, A. and Grattan, J. P., 1995: Environmental response to tephra deposition in the Strath of Kildonan, northern Scotland. *Journal of Archaeological Science*, *22*, 799-809.

Chester, D. K., 1988: Volcanoes and climate: recent volcanological perspectives. *Progress in Physical Geography 12*, 1-35.

Chia-Hsi, W., Da-fu, Q., Zheng-fang, L., Xu-ping, G., Shu-yu, T., Ru-gui, P., 1982: Selection of plants resistant, absorptive and sensitive to air pollutants. In Unsworth, M. H. and Ormrod, D. P. (eds) *Effects of gaseous air pollution in agriculture and Horticulture* London. Butterworth, 478.

Christensen, E. R. and Chien, N. K. 1981: Fluxes of Arsenic, Lead, Zinc and Cadmium to Green Bay and Lake Michigan sediments. *Environmental Science and Technology 15*, 553-558.

Clapperton, C. M., 1990: Quaternary glaciations and the southern hemisphere: an overview *Quaternary Science Reviews 9*: 299-304.

Clarkson, B. D., 1990: A review of vegetation development following recent (<450 yrs) volcanic disturbance in North Island, New Zealand. *New Zealand Journal of Ecology 14*, 59-71.

Clarkson, B. D. and Clarkson, B. R., 1983: Mt Tarawera 2. Rates of change on the high domes. *New Zealand Journal of Ecology 6*, 107-119.

Clarkson, B. D. and Clarkson, B. R., 1994: Vegetation decline following recent eruptions on White Island, Bay of Plenty, New Zealand. *New Zealand Journal of Botany 32*, 21-36.

Clarkson, B. R., Patel., R. N. and Clarkson, B. D., 1988: Composition and structure of forest overwhelmed at Pureora, central North Island, New Zealand, during the Taupo eruption (c. AD 130). *Journal of the Royal Society of New Zealand 8*, 417-436.

Clayton-Greene, K. A., 1975: The distribution of *Nothofagus* in the Rotorua district. *New Zealand Journal of Botany, 13*, 125-131.

Clarkson, B. D., Clarkson, B. R and Smale, M. C., 1989: Vegetation destruction and recovery following recent eruptions on White Island, Bay of Plenty, New Zealand. *New Zealand Geological Survey Bulletin 103*, 137-138.

Clymo, R. S., 1983: Peat. In Gore, A. J. P. (ed) *Mires: swamp, Bog, Fen and Moor*, Elsevier Scientific Publishing Company, Amsterdam, 159-224.

Clymo, R. S., and Mackay, D., 1987: Upwash and downwash of pollen and spores in the unsaturated surface layer of *Sphagnum*-dominated peat. *New Phytologist 105*, 175-183.

Cole, J. W. and Nairn, I. A., 1975: General volcanic history of North Island. *Catalogue of the Active volcanoes of the world including Solfatara fields Part XXII*. Decker, R.W. (ed). 1-59.

Cole, J. W., Graham, I. J., Hackett, W. R. and Houghton, B. F., 1986: Volcanology and Petrology of the quaternary composite volcanoes of Tongariro volcanic centre Taupo volcanic Zone. *Bulletin of the Royal Society of New Zealand 23*, 224-250.

Connor, H. E., and Edgar, E., 1987: Name changes in the indigenous New Zealand flora 1960-1986 and nomina nova IV, 1983-1986. *New Zealand Journal of Botany 25*, 115-170.

Cooper, R., 1949: The effect of the recent eruption on the plants of Ngauruhoe. *Records of the Auckland Institute and Museum 3*, 381-385.

Coster, J., 1989: Dates from the dunes: a sequence from the Aupouri peninsula, Northland New Zealand. *New Zealand Journal of Archaeology 11*, 51-75.

Cowgill, U. M. and Hutchinson, G. E. 1970: Chemistry and Mineralogy of the sediments and their source materials. *Transactions of the American Philosophical Society 60*, 37-101.

Cronin, S. J. and Hedley, M. J. 1996 An explosive new player in the fertiliser market? *WISPAS: a newsletter about water in the soil - plant - atmosphere system, 63.* HortResearch.

Cronin, S. J., Hedley, M. J. and Neall, V. E. 1996: Estimates of elemental deposition rates and impact on soil and pasture chemical composition *Impact of October 1995 Ruapehu ash fall on soil fertility,* Massey University publication

Cullum, Rev. Sir John., 1783: Of a remarkable frost on the 23rd June, 1783. *Philosophical Transactions of the Royal Society. Abridged Volume 15*, 1781-1785, 604.

Cushing, E. J., 1967: Evidence for differential pollen preservation in late Quaternary sediments in Minnesota. *Review of Palaeobotany and Palynology 4*, 87-101.

Dahm, J., 1983: *The geomorphic development, bathymetric stability and sediment dynamics of Tauranga Harbour.* Unpublished MSc thesis, Library, University of Waikato, Hamilton, New Zealand.

Damman, A, W. H., 1978: Distribution and movement of elements in ombrotrophic peat bogs. *Oikos 30*, 480-495.

Davidson, J., 1984: *The Prehistory of New Zealand.* Auckland. Longman Paul.

Davis, M. B., Brubaker, L. B., and Beiswenger, J. M., 1971: Pollen grains in lake sediments: pollen percentages in surface sediments from southern Michigan. *Quaternary Research 1*, 450-467.

Davies, T. D., Abrams, P. W., Tranter, M., Blackwood, I., Brimblecombe, P., Vincent, C. E. 1984: Black acidic snow in the remote Scottish highlands. *Nature 312*, 58-61.

Davies-Colley, R. J., 1976: *Sediment dynamics of Tauranga Harbour and the Tauranga inlet.* Unpublished MSc thsis, Library, University of Waikato, New Zealand

Denton, G. H., and Hendy, C. H., 1994: Younger Dryas age advance of Franz Josef glacier in the southern Alps of New Zealand. *Science 264*, 1434-1437.

Devine, J. D., Sigurdsson, H., Davies, A. N. and Self, S., 1984: Estimates of sulphur and chlorine yield to the atmosphere from volcanic eruptions and potential climatic effects. *Journal of Geophysical Research 89*, 6309-6325.

Donoghue, S. L., Neall, V. E. and Palmer, A. S. 1995: Stratigraphy and chronology of late Quaternary andesitic tephra deposits, Tongariro Volcanic Centre, New Zealand *Journal of the Royal Society of New Zealand* 25: 115-206

Donoghue, S. L. and Neall, V. E. 1996: Tephrostratigraphic studies at Tongariro Volcanic Centre, New Zealand: an overview *Quaternary International* 34-36: 13-20

Druce, A. P., 1966: Tree-ring dating of recent volcanic ash and lapilli, Mt Egmont. *New Zealand Journal of Botany 4*, 3-41.

Dugmore, A.J., 1989: Icelandic volcanic ash in Scotland. *Scottish Geographical Magazine 105*, 168-172.

Duncan, R. A. and McDougall, I., 1989: volcanic time space relationships. In Johnson, R. W. (ed) *Intraplate volcanism in Australia and New Zealand.* Cambridge University Press.

Duncan, A. R., 1970: *The petrology and petrochemistry of andesite and dacite volcanoes in eastern Bay of Plenty, New Zealand.* Unpublished PhD thesis, Victoria University of Wellington.

Durand, P., Neal, C., Jeffery, H. A., Ryland, G. P. and Neal, M., 1994: Major, minor and trace element budjets in the Plynlimon afforested catchments (Wales): general trends, and effects of felling and climate variations. *Journal of Hydrology 157*, 139-156.

Edwards, K. J., Buckland, P. C., Blackford, J. J., Dugmore, A. J. and Sadler, J. P. 1994: The impact of tephra: proximal and distal studies of Icelandic eruptions In: Stotter. J. and Wilhelm, F. (eds) *Environmental change in Iceland* Munchener Geographische Abhandlungen. B12: 79-99

Engstrom, D. R. and Wright, H. E. 1984: Chemical stratigraphy of lake sediments as a record of environmental change. In Haworth, E. Y. and Lund, J. W. G. (eds) *Lake Sediments and Environmental History*, Leicester University Press, Leicester, 11-67.

Erasmus, D. A., 1978: *Electron Probe Microanalysis in Biology*. Chapman & Hall Ltd. London.

Evans, L. S., 1984: Acidic precipitation effects on terrestrial vegetation. *Annual Review of Phytopathology 22*, 397-442.

Faegri, K. & Iverson, J., 1975: *Textbook of Pollen Analysis*, Wiley and Sons. Chichester.

Fayle, D. C., Bentley, C. V., and Scott, P. A., 1992: How did treeline white spruce at Churchill, Manitoba, resond to conditions around 1816. In Harington, C. R (ed*) The Year Without a Summer*, Ottawa, Canadian Museum of Nature. 281-291.

Fiacco, R. J., Thordarson, T., Germani, M. S., Self, S., Palais, J. M., Whitlow, S. and Grootes, P. M., 1994: Atmospheric aerosol loading and transport due to the 1783-84 Laki eruption in Iceland, interpreted from ash particles and acidity in the GISP2 ice core. *Quaternary Research 42*, 231-239.

Franklin, B., 1784: Meteorological imaginations and conjectures. *Memoirs, Manchester Lierary and Philosophical Society 2*, 373-377.

Froggatt, P. C. and Lowe, D. J., 1990: A review of late Quaternary Silicic and sone other tephra formations from New Zealand: their stratigraphy, nomenclature, distribution volume and age'. *New Zealand Journal of Geology and Geophysics 33*, 89-109.

Gage, M., 1985: Glaciation in New Zealand - the first century of research. *Quaternary Science Reviews 4*, 189-214.

Gandrud, B. W. and Lazrus, A. L., 1981: Filter measurements of stratospheric sulphate and chlorine in the eruption plume of Mt St Helens. *Science 211*, 826-827.

Garrec, J. P., 1982: Studies of fluoride pollution impact on coniferous forests. In Unsworth, M. H. and Ormrod, D. P. (eds) *Effects of gaseous air pollution in Agriculture and horticulture*, London, Butterworth, 476-477.

Garsed, S. G. and Rutter, A. J., 1982: The relative sensitivities of conifer populations to $SO_2$ in screening tests with different concentrations of sulphur dioxide. *Effects of gaseous air pollution in agriculture and horticulture*, London, Butterworth, 474-478.

Gellatly, A. F., Chinn, T. G. H., and Rothlisberger, F., 1988: Holocene glacier variations in New Zealand: A review. *Quaternary Science Reviews 7*, 227-242.

Gerlach, T. M., 1991: Etna's Greenhouse pump. *Nature 351*, 352-353.

Gibbs, H. S., 1968: Volcanic ash soils in New Zealand. *New Zealand DSIR Information Series 65*.

Giles, T. M., Newnham, R. M., Lowe, D. J., and Munro, A. J., in press: Impact of tephra fall and environmental change: a 1000 year record from Matakana Island, Bay of Plenty, New Zealand. *Proceedings of the Geologists Association, Special Publication: Volcanoes in the Quaternary.*

Glooschenko, W. A., 1986: Monitoring the atmospheric deposition of metals by use of bog vegetation and peat profiles. In Nriagu, J. O. (ed) *Toxic Metals in the Atmosphere*, Wiley - Interscience, New York, 507-533.

Glooschenko, W. A. and Benedetti, A. D. 1983: Atmospheric deposition of iron from mining activities in northern Ontario. *The Science of the Total Environment 32*, 73-79.

Goldschmidt, V. M., 1958: *Geochemistry*, Oxford University Press, London.

Goldstein, J. I., Newbury, D. E., Echlin, P., Joy, D. C., Fiori, C. and Lifshin, E., 1981: *Scanning Electron Microscopey and X-ray Microanalysis*. Plenum Press, New York.

Gordon, J. E., 1980: Recent climatic trends and local glacier margin fluctuations in west Greenland. *Nature 284*, 157-159.

Grattan, J. P., 1994: *The impact of Icelandic volcanic eruptions upon the ancient settlement and environment of northern Britain.* Unpublished PhD Thesis, University of Sheffield.

Grattan, J. P., in press: The response of marginal societies and ecosystems in Britain to Icelandic volcanic eruptions. *On the Edge*, Mills and Coles (eds). Oxbow.

Grattan, J. P. and Brayshay, M., 1995: An amazing and portentous summer: Environmental and social responses in Britain to the 1783 eruption of an Iceland volcano. *Geographical Journal 161 (2):* 125-134.

Grattan, J. and Charman, D. J., 1994: Non-climatic factors and the environmental impact of volcanic volatiles: implications of the Laki fissure eruption of AD 1783 *The Holocene 4*, 101-106.

Grattan, J. P. and Gilbertson, D. D., 1994: Acid loading from Icelandic tephra falling on acidified ecosystems as a key to understanding archaeological and environmental stress in northern and western Britain. *Journal of Archaeological Science 21*, 221-235.

Grattan, J. P. and Pyatt, F. B., 1994: Acid damage to vegetation following the Laki fissure eruption in 1783 - an historical review. *The Science of the Total Environment 151*, 241-247.

Green, M. R., 1994: *The Holocene palaeolimnology and developmental history of lake Taharoa (Kawhia), North Island, New Zealand.* Unpublished Msc Thesis, University of Waikato.

Green, T. G. A., Lake Waikaeiti and its Islands. *Unpublished information bulletin for the Urewera National Park.*

Guppey, S. F. and Happey-Wood, C. M., 1978: Chemistry of sediments from two linked lakes in North Wales. *Freshwater Biology 8*, 401-413.

Hackett, W. R., 1985: *Geology and petrology of Ruapehu volcano and related vents.* Unpublished PhD thesis, Victoria University of Wellington.

Hall, V. A., Pilcher, J. R. and McCormac, F. G., 1994: Icelandic volcanic ash and the mid Holocene Scots pine decline (*Pinus sylvestris*) in the north of Ireland: no correlation. *The Holocene 4*, 79-83.

Hammer, C. U., 1977: Past volcanism revealed by Greenland ice sheet impurities. *Nature 270*, 482-486.

Hammer, C. U., Clausen, H. B. and Dansgaard, W., 1980: Greenland ice sheet evidence of post-glacial and its climatic impact. *Nature 288*, 230-235.

Handler, P., 1986: Stratospheric aerosols and the Indian Monsoon. *Journal of Geophysical Research 91*, 14475-14490.

Handler, P. and O'Neil, B., 1987: Simultaneity of response of Atlantic Ocean tropical cyclones and Indian monsoons. *Journal of Geophysical Research 92*, 14621- 14630.

Handler, P. and Andsager, K., 1990: Volcanic aerosols, El Nino and the southern oscillation. *International Journal of Climatology 10*, 413-412.

Hansen, J. E., Wang, W. and Lacis A. A., 1978: Mount Agung eruption provides test of global climatic perturbation. *Science 199*, 1065-1068.

Hansen, J. E., and Lacis, A. A., 1990: Sun and dust versus greenhouse gases: an assessment of their relative roles in global climate change. *Nature 346*, 713-719.

Harray, K. G., 1977: *Beach erosion and sediments at Waihi Beach.* Unpublished MSc thesis, Library, University of Waikato, Hamilton, New Zealand.

Harris, W. F., 1963: Palaeo-ecological evidence from pollen and spores. *Proceedings of New Zealand Ecological Society 10*, 38-44.

Havinga, A. J., 1964: Investigation into the differential corrosion susceptibility of pollen and spores. *Pollen et Spores 6*, 621-635.

Haywood, B. W., and Kermode, L. O., 1994: How many volcanoes in Auckland and how old is Rangitoto? *Geological Society of New Zealand 104*, 36-39.

Healy, J., 1977: Progradation at the entrance, Tauranga Harbour, Bay of Plenty. *New Zealand Geographer 33*, 90-92.

Healy, J., 1980: Erosion and sediment drift on the Bay of plenty coast. *Soil and Water August*, 12-15.

Healy, J., 1992: Central Volcanic Region. In Soons, J. M. and Selby, M. J. (eds) *Landforms of New Zealand. Second edition*, Longman Paul. 256-287.

Horrocks, M. and Ogden, J. in press: The effects of the Taupo Pumice eruption of c. 1718 BP on the vegetation of Mt Hauhungatahi, central North Island, New Zealand *Journal of Biogeography*

Houghton, B. F., Wilson, C. J. N., McWilliams, M. O., Lanphere, M. A., Weaver, S. D., Briggs, R. M., and Pringle, M. S., 1995: Chronology and dynamics of a large silicic magmatic system: Central Taupo Volcanic Zone, New Zealand. *Geology 23*, 13-16.

Hren, J. J., Goldstein, J. I., & Joy, D. C., (eds) 1979: *Introduction to Analytical Electron Microscopey*, Plenun Press. New York.

Jones, B. F. and Bowser, C. J., 1978: The mineralogy and related chemistry of lake sediments. In Lerman, A. (ed) *Lakes: Chemistry, Geology, Physics*, Springer-Verlag, New York, 179-235.

Jones, R. L. & Cundill, P. R., 1982: Introduction to Pollen Analysis. *British Geomorphological Research Group, Technical Bulletin No. 22.*

Jacoby, G. C., and D'Arrigo, R., 1989: Reconstructed northern hemisphere annual temperature since 1671 based on high latitude tree ring data from North America. *Climatic Change 14*, 35-59.

Jacoby, G. C., and D'Arrigo, R., 1992: Spatial patterns of tree groeth anomalies from the North American boreal treeline in the early 1800's, including the year 1816. In Harington, C. R. (ed) *The year without a summer*,Ottawa, Canadian Museum of Nature. 255-266.

Kear, D., 1960: Sheet 4 - Hamilton. Geological map of New Zealand 1: 250 000. New Zealand Department of Scientific and Industrial Research.

Kelly, P. M. and Sear, C. B., 1984: Climatic impact of explosive volcanic eruptions. *Nature 311*, 740-743.

Kermode, L. O., 1988: *Volcanic landscape: a guide to the Auckland volcanic field.* New Zealand Geological Survey, DSIR.. Lower Hutt, New Zealand.

Kerr, R. A., 1981: Mt St Helens and a climatic quandary. *Science 211*, 371-374.

Kington, J. A., 1992: Weather patterns over Europe in 1816. In Harington, C. R (ed) *The year without a summer*, Ottawa. Canadian Museum of Nature. 358-372.

Kirch, P. V. and Ellison, P., 1994: Palaeoenvironmental evidence for human colonisation of remote oceanic islands. *Antiquity 68*, 310-21.

Koerner, R. M., 1977: Devon Island ice cap: Core stratigraphy and palaeoclimate. *Science 196*, 15-18.

Kovach, W. L., 1995: Multivariate Data Analysis In: D. Maddy and J. S. Brew (Eds) Statistical Modelling of Quaternary Science Data. *Quaternary Research Association, Technical Guide No. 5.* 1-35.

Lal, B. and Ambasht, R. S., 1981: Impairment of Chlorophyll content in leaves of *Diospyros melanoxylon* by fluoride pollution. *Water, air and soil pollution 16*, 361-365.

LaMarche, V. C. and Hirschboeck, K., 1984: Frost rings in trees as records of major volcanic eruptions. *Nature 307*, 121-126.

Lamb, H. H., 1970: Volcanic dust in the atmosphere; with a chronology and assesment of its meteorological significance. *Philosophical Transactions of the Royal Society of London A266*, 425-533.

Lamb, H. H., 1977: *Climate, Past, Present and Future, volume 2*, Methuen. London.

Lambert, R. A., 1970: *Pollen analysis of a peat profile from the Hamilton basin, New Zealand.* Unpublished Msc Thesis, University of Auckland, Auckland, New Zealand

Large, M. F. and Braggins, J. E. 1991: Spore Atlas of New Zealand ferns and fern allies. *New Zealand Journal of Botany SS,* 1-167.

Latter, J. H., 1989: Geological setting of New Zealand: regional setting. In Johnson, R .W. (ed) *Intraplate volcanism in Australia and New Zealand*, Cambridge University Press. 213-229.

Lees, C. M. and Neall, V. E., 1993: Vegetation response to volcanic eruptions on Egmont volcano, New Zealand, during the last 1500 years. *Journal of the Royal Society of New Zealand 23*, 91-127.

LeGuern, F., Faivre-Pierret. and Garrec, J. P., 1988: Atmospheric contribution of volcanic sulphur vapour and its influence on the surrounding vegetation. *Journal of Volcanology and Geothermal Research 35*, 173-178.

Le Roy Laduire, E., 1972: *Times of Feast, Times of Famine*, George, Allen and Unwin, 71.

Lotter, A. F. and Birks, H. J. B., 1993: The impact of the Laacher See Tephra on terrestrial and aquatic ecosystems in the Black Forest, southern Germany. *Journal of Quaternary Science 8*, 263-276.

Lough, J.M., 1992: Climate in 1816 and 1811-20 as reconstructed from weatern North American tree ring chronologies. In: Harington, C.R. (ed) *The year without a summer* Ottawa. Canadian Museum of Nature. 97-115.

Lowe, D. J. 1986: Revision of the age and stratigraphic relationships of Hinemaiaia Tephra and Whakatane Ash, North Island, New Zealand, using distal occurrences in organic deposits. *New Zealand Journal of Geology and Geophysics 29*: 61 - 73.

Lowe, D. J. 1987: Studies on late Quaternary tephras in the Waikato and other regions in northern North Island, New Zealand, based on distal deposits in lake sediments and peats. *Unpublished PhD Thesis* University of Waikato, Hamilton, New Zealand

Lowe, D. J. 1988: Late Quaternary volcanism in New Zealand: towards an integrated record using distal airfall tephras in lakes and bogs. *Journal of Quaternary Science 3*: 111-120.

Lowe, D.J., 1993: Explosive volcanism and climatic change a New Zealand perspective. *Climatic impact of explosive volcanism* IGBP pages - INQUA COT meeting, Tokyo, Japan.

Lowe, D.J., pers Comm, 1995: Lecture notes.

Lowe, D. J., and Hogg, A. G. 1986: Tephrostratigraphy and chronology of the Kaipo Lagoon, an 11,500 year - old montane peat bog in Urewera National Park, Neew Zealand. *Journal of the Royal Society of New Zealand 16*: 25 - 41.

Lowe, D. J., and Green, J. D., 1992: Lakes. In: Soons, J. M. and Selby, M. J. (eds), *Landforms of New Zealand* (second edition) Auckland: Longman Paul, 107-143.

Lowe, D.J., and Hogg, A.G., 1992: Application of new technology liquid scintillation spectrometry to radiocarbon dating of tephra deposits, New Zealand. *Quaternary International 13/14*: 135-142.

Lowe, D. J., McFadgen, B. G., Higham, T. F. G., Hogg, A. G., Froggatt, P. C. and Nairn, I. A., 1998: Radiocarbon age of the Kaharoa Tephra, a key marker for late-Holocene stratigraphy and archaeology in New Zealand. *The Holocene 8,* 499-507

Mackereth, F. J. H., 1965: Chemical investigation of lake sediments and their interpretation. *Proceedings of the Royal Society of London 161, B,* 295-309.

Mackereth, F. J. H., 1966: Some chemical observations on Post-Glacial lake sediments. *Philosophical Transactions of the Royal Society of London 250, B,* 165-214.

Mannion, A. M., 1979: Chemical Analyses of a peat profile from Threepwood Moss, south-east Scotland. *Chemosphere 4,* 223-242.

Mannion, A. M., 1980: *Pollen Analysis: A Technique in Palaeo-Environmental Reconstruction* Geographical Papers, Department of Geography, University of Reading.

Markert, B. and Thornton, I., 1990: Multi-element analysis of an English peat-bog soil. *Water, Air and Soil Pollution 43,* 113-123.

Marshall, Y., Paama, M., Samuels, M., Sutton, D. and Taikato, T., 1994: Archaeological survey of Matakana Island forest compartment 3, stands 2-4, compartment 12, stands 1-5, compartment 14, stand 2 and compartment 20, stands 1-5. Final report.' Auckland Uniservices LTD, University of Auckland 107 pp.

McCraw, J. D., 1967: The surface features and soil pattern of the Hamilton basin. *Earth Science Journal 1,* 59-74.

McDowall, R.M., 1995: Effects of Taupo eruption endure in fish communities. *NIWA Water and Atmosphere 3(2):* 22-23.

McFadgen, B.G. and Walton, A.J., 1981: Report of Archeaological survey of Matakana and Rangiwaea Islands, Bay of Plenty. *Report to the New Zealand Historic Places Trust Wellington,* September 1981.

McFadgen, B.G., 1994: Coastal stratigraphic evidence for human setllement. In: Sutton D G (ed) *The Origins of the First New Zealanders.* Auckland University Press. Chapter 9: 195-207.

McGlone, M. S., Unpublished: Pollen diagrams from Kaipo Bog, Urewera National Park. New Zealand.

McGlone, M.S., 1981: Forest fire following Holocene tephra fall. *Proceedings of tephra workshop, June 30th-July 1st 1980* Victoria university of Wellington Howarth R, Froggatt P, Vucetich C G and Collen J D (eds).

McGlone, M. S. 1983: Holocene pollen diagrams, Lake Rotorua, North Island, New Zealand. *Journal of the Royal Society of New Zealand 13,* 53-65.

McGlone, M. S., 1988: New Zealand. In: Huntley, B. and Webb, T. (eds) *Handbook of Vegetation Science 7. Vegetation History.* Kluwer Academic Publishers, Dordrecht, 557-599.

McGlone, M. S., 1989: The Polynesian settlement of New Zealand in relation to environmental and biotic changes. *New Zealand Journal of Ecology (supplement), 12,* 115-129.

McGlone, M. S., and Moar, N. T., 1977: The *Ascarina* decline and postglacial climatic change. *New Zealand Journal of Botany 15,* 485-489.

McGlone, M. S., and Topping, W. W., 1977: Aranuian (post-glacial) pollen diagrams from the Tongariro region, North Island, New Zealand. *New Zealand Journal of Botany 15,* 749-760.

McGlone, M. S., Nelson, C. S. and Todd, A. J. 1984: Vegetation history and environmental significance of pre-peat and surficial peat deposits at Ohinewai, Lower Waikato lowland *Journal of the Royal Society of New Zealand 14*: 233-244

McGlone, M.S., Neall ,V.E. and Clarkson, B.D., 1988: The effect of recent volcanic events and climatic changes on the vegetation of Mt Egmont, New Zealand. *New Zealand Journal of Botany 26*: 123-144.

McGlone, M.S., Salinger, M.J. and Moar, N.T., 1993: Palaeovegetation studies of New Zealand's climate since the last galcial maximum. In: Wright Jr, H.E., Kutzbach, J.E., Webb III, T., Ruddiman, W.F., Street-Perrott, F.A., and Bartlein, P.J. (eds) *Global Climates Since the Last Glacial Maximum* Chapter 12: 294-317. University of Minnesota Press.

McGlone, M.S., Anderson, A.J. and Holdaway, R.N., 1994: An ecological approach to the Polynesian settlement of New Zealand. In: Sutton D G (ed) *The Origins of the First New Zealanders.* Auckland University Press. Chapter 7: 136-163.

McRae, S. G., 1988: *Practical Pedology: studying soils in the field,* John Wiley and Sons, Chichester.

Mildenhall, D. C. 1979: Holocene pollen diagrams from Pauatahanui inlet, Porirua, New Zealand. *New Zealand Journal of Geology and Geophysics 22,* 585-591.

Miles, M.K. and Gildersleeves, P.B., 1978: Volcanic dust changes in northern hemisphere temperature. *Nature 271*: 735-736.

Moar, N.T., 1994: *Pollen grains of New Zealand dicoteledonous plants.* Government Printer. Wellington.

Moar, N. T., and Mildenhall, D. C., 1988: Pollen assemblages from late Quaternary deposits in Canterbury. Appendix in Brown, L. J. and Wilson, D. D. *Stratigraphy of the late Quaternary Deposits of the Northern Canterbury Plains, New Zealand. New Zealand journal of Geology and Geophysics 31*, 331-335.

Moore, C. L., 1989: *Rhyolitic tephra in the Auckland region.* Unpublished B.Sc. Hons thesis, University of Auckland.

Moore, L.B, and Edgar, E., 1976: *Flora of New Zealand, Volume II* Government Printer Wellington.

Moore, P.D., Webb, J.A. and Collinson, M.E., 1990: *Pollen Analysis* Blackwell Scientific Publications, London.

Mukherjee, B.K., Indira, K. and Dani, K.K., 1987: Low-latitude volcanic eruptions and their effects on Sri Lankan rainfall during the north-east monsoon. *Journal of Climatology 7*: 145 -155.

Mulder, J., Van Breemen, N. and Eijck, H.C., 1989: Depletion of soil aluminium by acid deposition and implications for acid neutralisation. *Nature 337*: 247-249.

Munro, A.J., 1994: *Holocene evolution and palaeolimnology of a barrier spit, north-western Matakana Island, Bay of Plenty, New Zealand.* Unpublished Msc Thesis, University of Waikato.

Nauke, W., Heathwaite, A. L., Eggelsmann, R. and Schuch, M., 1993: Mire Chemistry. In Heathwaite, A. L. and Gottlich, K. H. (eds) *Mires: processes, Exploitation and Conservation*, John Wiley and Sons, Chichester, 263-309.

Neall, V.E., 1992: Landforms of Taranaki and the Wanganui lowlands. In: Soons, J M and Selby, M J (eds) *Landforms of New Zealand. Second edition.* Longman Paul. 287-308.

Newall, R.E., and Self, S., 1982: The volcanic explosivity index (VEI) an estimate of explosive magnitude for all volcanism. *Journal of Geophysical Research 87 (C2)*: 1231-1238.

Newnham, R.M., 1990: *Late Quaternary Palynological Investigations into the History of Vegetation and Climate in Northern New Zealand.* Unpublished Ph.D thesis, University of Auckland.

Newnham, R.M., Lowe, D.J. and Green, J.D., 1989: Palynology, vegetation and climate of the Waikato lowlands, North Island, New Zealand, since 18 000 yrs ago. *Journal of the Royal Society of New Zealand* 19 (2): 127-150.

Newnham, R.M., Lowe, D.J., 1990: 'Holocene vegetaion and volcanic activity, Auckland Isthmus, New Zealand.' *Journal of Quaternary Science 6 (3)*: 177-193.

Newnham, R. M., Ogden, J., and Mildenhall, D. 1993: A vegetation history of the far North of New Zealand during the late Otira (last) glaciation. *Quaternary Research, 39*: 361 - 372.

Newnham, R.M., Lowe, D.J. and Wigley, G.N.A., 1995: Late Holocene palynology and palaeovegetation of tephra-bearing mires at Papamoa and Waihi Beach, western Bay of Plenty, North Island, New Zealand. *Journal of the Royal Society of New Zealand 25, 2*: 283-300.

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

Newnham, R. M., Lowe, D. J. and Matthews, B. W., 1998: A late-Holocene and prehistoric record of environmental change from Lake Waikaremoana, New Zealand. *The Holocene 8,* 443-454.

Newnham, R. M., Lowe, D. J. and Alloway, B, V. in press. 'Volcanic hazards in Auckland New Zealand: implications from the late Quaternary central North Island record' *Proceedings of the Geologists Association, special publication: Volcanoes in the Quaternary.*

Nicholls, J.L., 1963: Vulcanicity and indigenous vegetation in the Rotorua district. *Proceedings of the New Zealand Ecological society 10*: 58-65.

Nicholls, N., 1988: Low latitude volcanic eruptions and the El Nino southern oscillation. *Journal of Climatology 8*: 91-95.

Nicholls, N., 1990: Low latitude volcanic eruptions and the El Nino southern oscillation: a reply. *International Journal of Climatology 10*: 425-429.

Ninkovitch, D. and Donn, W.L., 1976: Explosive Cenozoic volcanism and climatic implications. *Science 194*: 899-906.

Norton, D.A. 1982: Australasia. In: *Climate from Tree rings* M.K. Hughes (ed). Proceedings of the second international workshop on global dendroclimatology, University of East Anglia. Cambridge University Press. 223 p.

Norton, D. A., Herbert, J. W., and Beveridge, A. E., 1988: The ecology of *Dacrydium Cupressinum*: a review. *New Zealand Journal of Botany 26,* 37-62.

Norton, D.A., Briffa, K.B. and Salinger, M.J., 1989: Reconstruction of New Zealand summer temperatures to 1730 AD using dendroclimatic techniques. *International Journal of Climatology 9*: 613-644.

Norton, D.A. & Palmer, J.G., 1992: Dendroclimatic evidence from Australasia. In: Bradley R.S. & Jones, P.D. (eds) *Climate Since AD 1500.* Routledge. 153-169.

Ogden, J., Newnham, R. M., Palmer, J. G., Serra, R. G., and Mitchell, N. D. 1993: Climatic implications of macro- and micro-fossil assemblages from late Pleistocene deposits in northern New Zealand. *Quaternary Research, 39*: 107-119.

Ogden, J., Wilson, A. T., Hendy, C. H., Hogg, A. G., and Newnham, R. M. 1992: The late Quaternary history of Kauri (*Agathis australis*) in New Zealand and its climatic significance. *Journal of biogeography, 19*: 611-621.

Oskarsson, N., 1980: 'The interaction between volcanic gases and tephra: Fluorine adhering to tephra of the 1970 Hekla eruption.' *Journal of Volcanology and Geothermal Research 8*: 251-266.

Palmer, J. & Ogden, J., 1992: Tree ring chronologies from Endemic Australian and New Zealand conifers 1800-30. In: Harrington (ed) *1816: The Year Without a Summer.* Ottawa. Canadian Museum of Nature: 510-515.

Pennington, W. 1981: Records of a lake's life in time: the sediments. *Hydrobiologia 79,* 197-219.

Pennington, W., Haworth, E. Y., Bonny, A. P. and Lishman, J. P., 1972: Lake sediments in northern Scotland. *Philosophical Transactions of the Royal Society of London 264, B*, 191-294.

Phadtare, N. R. in press: Tephra-linked palynology in quest of the floristic effects of volcanic-ash fall. *Review of Palaeobotany and Palynology.*

Pickrill, R. A., Nelson, C. S., Stoffers, P. and Craig, G. G. P. 1991: Influence of late Holocene pyroclastic eruptions on the sedimentary geochemistry of Lake Rotoiti, North Island, New Zealand. *Journal of Palaeolimnology, 6*: 173 - 192.

Pilcher, J.R., and Hall, V.A., 1992: Towards a tephrochronology for the north of Ireland. *The Holocene 2 (3)*: 255-259.

Pillans, B., Pullar, W.A., Selby, M.J. and Soons, J.M., 1992: The age and development of the New Zealand landscape. In: Soons, J M and Selby, M J (eds) *Landforms of New Zealand. Second edition.* Longman Paul. 31-63.

Pocknall, D.T., 1981: Pollen morphology of New Zealand species of *Dacrydium* Solander *Podocarpus* L'Heritier, and *Dacrycarpus* Endlicher (Podocarpaceae*). New Zealand Journal of Botany 19*: 67-95.

Pocknall, D.T., 1981: Pollen morphology of *Phyllocladus* L. C. et A. Rich. *New Zealand Journal of Botany 19*: 259-266.

Pocknall, D.T., 1981: Pollen morphology of New Zealand species of *Libocedrus* Endlicher (Cupressaceae) and *Agathis* Salisbury (Araucariaceae*). New Zealand Journal of Botany 19*: 267-272.

Pocknall, D. T., Gregory, M. R., and Greig, D. A., 1989: Palynology of core 80/20 and its implications to understanding Holocene sea-level changes in the Firth of Thames, New Zealand. *Journal of the Royal Society of new Zealand 19,* 171-179.

Pollack, J.B., Toon, O.B., Sagan, C., Summers, A., Baldwin, B., and Van Camp, W., 1976: Volcanic explosions and climatic change: A theoretical assessment. *Journal of Geophysical Research 81 (6)*: 1071-1083.

Porter, S. C., 1981: Recent glacier variations and colcanic eruptions. *Nature 291*: 139-141.

Press, F., and Seiver, R. 1989: *Earth* fourth edition. W.H Freeman and co. New York.

Pyatt, F. B., Beaumont, E. H., Buckland, P. C., Lacy, D. and Storey, D. M., 1991: An examination of the moblisation of elements from the skin and bone of the bog body Lindow II and a comparison with Lindow III. *Environmental Geochemistry and Health 13(3):* 153-159.

Pyatt, F. B., Lacy, D., Beattie, R. C. and Pyatt, A. J., 1992: Element content of Thalli of Xanthoria Parietina obtained from three different types of sub-strata. *Environment and Ecology 10(3):* 682-692.

Pyatt, F. B., Grattan, J. P., Lacy, D., Gilbertson, D. D. and Brayshay, B. A., 1995: Studies of Loch-sediment chemistry and soil history from a 10,000+ year old core from Loch Hellisdale, South Uist, Outer Hebrides. *Scottish Geographical Magazine 111*: 106-102.

Pyle, D.M., 1989: Ice core acidity peaks, retarded tree growth and putative eruptions. *Archaeometry 31*: 88-91.

Quayle, A.M., 1984: The climate and weather of the Bay of Plenty region. *New Zealand Meteorological service Miscellaneous Publication 2nd Edition, 155 (1)*:56p.

Rampino, M.R. and Self, S., 1982: Historic eruptions of Tanbora (1815), Krakatau (1883), and Agung (1963), their stratospheric aerosols and climatic impact. *Quaternary Research 18*: 127-143.

Rampino, M. R. and Self, S., 1984: Sulphur-rich volcanic eruptions and stratospheric aerosols *Nature 310*: 677-679.

Rampino, M. R., Self, S. and Farebridge, I. W., 1982: Can rapid climatic change cause volcanic eruptions? *Science 206*: 826-829.

Reed, S. J. B., 1993: *Electron Microprobe Analysis. Second Edition* Cambridge University Press.

Read, S. A. L., Beetham, R. D., and Riley, P. B. 1991: Lake Waikaremoana barrier - A large landslide dam in New Zealand, In: *Landslides* Bell (ed). Balkema, Rotterdam. 1481-1487.

Reinert, R.A., 1984: Plant responses to air pollution mixtures. *Annual Review of Phytopathology 22*: 421-442.

Robertson, 1986: A Palaeomagnetic study of Rangitoto Island, Auckland, New Zealand. *New Zealand Journal of Geology and Geophysics 29,* 405-411.

Robock, A., 1981: The Mt St Helens volcanic eruption of 18th may 1980: Minimal climatic effect. *Science 212*: 1383-1384.

Rogan, M., 1982: A geophysical study of the Taupo volcanic Zone, New Zealand. *Journal of Geophysical Research 87*: 4073-4088.

Rogers, N. B. 1984: The vegetation and history of Kaipo and other natural peatland clearings, Urewera National Park, New Zealand. *Unpublished Msc Thesis, University of Waikato.*

Roscow, W. B., 1978: Cloud microphysics: Analysis of the clouds of earth, Venus, Mars and Jupiter. *Icarus 36*: 1-50.

Rose, W. I., 1977: Scavenging of volcanic aerosol by ash: atmosheric and volcanological implications. *Geology 5*: 621-624.

Rout, D. 1991: *A geophysical and volcanological study of the Wiri and Papatoetoe volcanoes, Auckland.* Unpublished MSc thesis, University of Auckland.

Rudd, J. W. M., Kelly, C. A. and Furutani, A., 1986: The role of sulfate reduction in the long term accumulation of organic and inorganic sulfur in lake sediments. *Limnology and Oceanography 31*, 1281-1291.

Russ, J.C., 1984: *Fundamentals of Energy Dispersive X-Ray Analaysis* Butterworths & Co. Ltd. London.

Salinger, J., 1994: New Zealand climate in the last 25,000 years. *Palaeoclimates and climate modelling workshop proceedings:* 15-16.

Sear, C. B., Kelley, P. M., Jones, P. D., and Goodess, C. M., 1987: Global surface temperature responses to major volcanic eruptions. *Nature 330*: 365-367.

Searle, E. J., 1965: Tour G- Auckland volcanic district. *New Zealand volcanology Northland, Coromandel, Auckland* Kermode L O, Thompson B N (eds) New Zealand DSIR series 49.

Searle, E. J. 1981: *City of Volcanoes: a geology of Auckland.* 2nd edition, Longman Paul, Auckland, New Zealand.

Selby, M. J. and Lowe, D. J., 1992: The middle Waikato basin and hills. In: Soons, J M and Selby, M J (eds) *Landforms of New Zealand. Second edition.* Longman Paul. 233-256.

Self, S., Rampino, M. R., Barbera, J. J., 1981: The possible effects of large 19th Century and 20th Century volcanic eruptions on zonal and hemispheric surface temperatures. *Journal of Volcanology and geothermal research, 11 (1),* 41-60.

Shepherd, M. J., McFadgen, B. G., Betts, H. D., and Sutton, D. G. 1996: Formation, landforms and palaeoenvironment of Matakana Island and implications for archaeology. *Science and Research Series 102*: 80pp.

Shoji, S. & Ono, T., 1978: Physical and chemical properties and clay mineralogy of andosols from Kitakami, Japan. *Soils Science 126*: 297-312.

Shotyk, W., 1988: Review of the inorganic geochemistry of peats and peatland waters. *Earth-Science Reviews 25*, 95-176.

Simkin, T., 1994: Distant effects of volcanism - how big and how often. *Science 264*: 913-914.

Smith, I. E. M., 1989: North Island. In: Johnson, R W (ed) *Intraplate volcanism in Australia and New Zealand.* Cambridge University Press: 157-162.

Smith, C. M. S., Cresser, M. S. and Mitchell, R. D. J., 1993: Sensitivity to acid deposition of dystrophic peat in Great Britain. *Ambio 22(1):* 22-26.

Speirs, D. A., 1995: *The Palaeolimnology of Lake Rotorua (Hamilton lake) North Island New Zealand: Sedimentology, fossil pigments, Cladocera and Chironomidae.* Unpublished MSc thesis, University of Waikato.

Stevens, G., 1988: A new Land. In: Stevens, G, McGlone, M, and McCullough, B (eds) *Prehistoric New Zealand* Heinemann Reed: 71-82.

Stipp, J. J., 1968: *The geochronology and petrogenesis of the Cenozoic volcanics of North Island, New Zealand.* Unpublished PhD thesis, Australian National University Canberra.

Stockmarr, J., 1971: Tablets with spores used in absolute pollen analysis. *Pollen and Spores 13(4)*: 165-621.

Stokes, S., Lowe, D. J. and Froggatt, P. C. 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, 13\14.* 103 - 117.

Stommel, H. and Stommel, E., 1979: The year without a summer. *Scientific American 240*: 134-140.

Stothers, R. B. and Rampino, M. R., 1983: Historic volcanism, European dry fogs and Greenland ice precipitation. 1500 BC-AD 1500. *Science 222*: 411-413.

Suggate, R.P., 1990: Late Pliocene and Quaternary glaciations of New Zealand. *Quaternary Science Reviews 9*: 175-197.

Sutton, D. G., 1987: A pardigmatic shift in Polynesian Prehistory: implications for New Zealand. *New Zealand Journal of Archaeology 9*: 135-155.

Sutton, D.G., 1994: Conclusion: Origins. In: Sutton D G (ed) *The Origins of the First New Zealanders.* Auckland University Press. Chapter 13: 243-258.

Taylor, P., 1989: *The genus Utricularia - a taxonomic monograph* Kew Bulletin International Series XIV, London. Her Majesty's stationary office.

Thorarinsson, S., 1969: The Lakagigar eruption of 1783. *Bulletin Volcanologique 33(3):* 910-929.

Thorarinsson, S., 1979: On the damage caused by volcanic eruptions with special reference to tephra and gases. In: Payson and Sheets (eds) *Volcanic Activity and Human Ecology* Academic Press: 125-159.

Thorarinsson, S., 1981: Greetings from Iceland. Ash falls and volcanic aerosols in Scandinavia. *Geographiska Annaler 63 A (3-4):* 109-118.

Thordarson, T. and Self, S., 1993: The Laki [Scaftar fires] and Grimsvotn eruptions in 1783 -85, Iceland. *Bulletin Volcanologique 55*: 233-263.

Timmins, S. M., 1983: Mt Tarawera: 1 - Vegetation types and successional trends. *New Zealand Journal of Ecology 6:* 99-105.

Turner, E. P., 1928: Breif account of the re-establishment of vegetationof Tarawera Mountain since the eruption of 1886. *Royal society of New Zealand Transactions and Proceedings 59*: 60-66.

Ugolini, F. C. & Zasoski, R. J., 1979: Soils derived from tephra. In: Sheets, P. D. & Grayson, D. K. (eds) *Volcanic Activity and Human Ecology*. Academic Press. Orlando, Florida. Chapter 4: 83-124.

Vasey, D. E., 1991: Population, Agriculture and Famine: Iceland, 1784-1785. *Human Ecology 19 (3)*: 323-350.

Vucetich, C. G. and Pullar, W. A., 1963: Ash beds and soils in the Rotorua district. *Proceedings of the New Zealand Ecological Society 10*: 2-9.

Wardle, P., 1991: *Vegetation of New Zealand*. Cambridge, Cambridge University Press.

Watters, W. A., 1978: The late mobile phase: igneous activity. In: Suggate, R P, Stevens, G R, Te Punga M T (eds) *The Geology of New Zealand*. Government printer, Wellington. 628-647.

West, S. 1997: *Geochemical and Palynological Signals for Palaeoenvironmental Change in South-west England*. Unpublished PhD Thesis, University of Plymouth.

White, G., 1789: *The Natural History of Selborne* Reprinted 1977. London: Penguin.

Whittaker, R. J., Walden, J. and Hill, J., 1992: Post-1883 ash fall on Panjang and Sertung and its ecological impact. *Geojournal 28 (2):* 153-171.

Will, G. M., 1966: Magnesium deficiency, the cause of spring needle tip chlorosis in young pines on pumice soils. *New Zealand Journal of Forestry Science 11*: 88-94.

Wilmshurst, J., 1995: A blast from the past. The Taupo eruption landscaped the central North Island. *New Zealand Science monthly 6*: 6-9.

Wilmshurst, J. M. and McGlone, M. S. 1996: Forest disturbance in the central North Island, New Zealand, following the 1850 BP Taupo eruption. *The Holocene 6 (4):* 399-411.

Wilmshurst, J. M., 1997: The impact of human settlement on vegetation and soil stability in Hawke's Bay, New Zealand. *New Zealand Journal of Botany, 35*: 97-111.

Wilmshurst, J. M., McGlone, M. S. and Partridge, T. R. 1997: A late Holocene history of natural disturbance in lowland podocarp/hardwood forest, Hawkes Bay, New Zealand *New Zealand Journal of Botany, 35*: 79-96

Wilson, A. T, Hendy, C. H. and Reynolds, C. P., 1979: Short-term climate change and New Zealand temperatures during the last millennium. *Nature 279*: 315-317.

Wilson, A. T., 1981: Isotope evidence for past climatic and environmental change. In: R. I. Rotberg and T. K. Rotob (Eds.) *Climate and History.* Princeton University Press. 241-259.

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 A 343*: 205-306.

Wilson, C. J. N., Rogan, A. M., Smith, I. E. M., Northey, D. J., Nairn, I. A. and Houghton, B. F., 1984: Caldera volcanoes of the Taupo Volcanic Zone, New Zealand. *Journal of Geophysica Research 89, B10*: 8463-8484.

Zielinski, G. A., German, M. S., Larsen, G., Baillie, M.G. L., Whitlow, S., Twickler, M. S. and Taylor, K., 1995: Evidence of the Eldgja (Icelnad) eruption in the GISP2 ice core: relationship to eruption processes and climatic conditions in the tenth century. *The Holocene 5, 2*: 129-140.