A 2000 year history of vegetation and landscape change in Hawke's Bay, North Island, New Zealand.

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For
my Sweet FA and Secret PA
(Alan and Mary)
for all your love and support
while I've been chained to assorted instruments of science

ABSTRACT

Sediment cores from four lakes in the Tutira and Putere districts of Hawke's Bay, North Island, New Zealand, are analysed for the remains of pollen, charcoal, tephra and erosion pulses to reconstruct a 2000 year history of vegetation and landscape change. The Hawke's Bay region is disturbed frequently by earthquakes, volcanic eruptions, cyclonic storms, droughts and fire. This thesis determines how the vegetation and soil stability have responded to some of these disturbances, through detailed palaeoecological investigations of lake sediment cores. Studies of surface pollen and differential pollen and spore preservation were undertaken to enhance the interpretations made from the palaeoecological record. Because New Zealand has only been settled by Polynesians relatively recently, the effects of natural disturbance on the vegetation and landscape can be assessed under similar climatic conditions to the present, but in the absence of cultural change. The effects of human settlement on a previously uninhabited landscape are assessed and compared with previously occurring natural disturbances.

Over the 2000 years investigated, the pollen records show three distinct types of vegetation were present in Hawke's Bay. These are summarised below, together with the principal conclusions drawn from the analyses:

(1) Pre-deforestation vegetation: 1850 to 600 BP

Frequent disturbance caused ongoing changes in the composition of the lowland podocarp-hardwood forests of Hawke's Bay. Natural fires have not previously been considered as a primary cause of forest disturbance in the North Island during the late Holocene, but the results show forests were disturbed frequently by lightning-strike fires associated with cyclic and episodic droughts, and with volcanic eruptions. Despite the frequency of these fires and the low specific adaptation to fire in the New Zealand flora, full and relatively rapid forest redevelopment occurred after each fire episode indicating a degree of tolerance to fire. The 1850 BP Taupo eruption was the largest single disturbance event during this period, but full forest redevelopment occurred within *c.* 200 years. Storms and erosion producing events caused no measurable changes in pollen composition.

(2) Polynesian deforestation: 600 BP

Widespread deforestation occurred in Hawke's Bay *c.*600 BP as a result of Polynesian settlement, after which bracken became the dominant vegetation type until it was cleared by European settlers in AD 1840-1870. Polynesian deforestation was the largest and most sustained disturbance to have occurred in Hawke's Bay since the end of the last glaciation. Polynesian deforestation may have coincided with or followed a severe, prolonged drought. Droughts and the increased frequency and scale of both intentional and accidental fires, invoked widespread and rapid forest clearance. Throughout the Polynesian period soil erosion was minimised, partly because of the deeply penetrating bracken rhizomes which maintained the strength of the soil structure and the dense fern canopy which protected the soils from raindrop impact. Despite the rapid clearance of large areas of forest, the landscape and bracken/shrubland vegetation remained relatively stable for 500 years.

(3) European settlement: AD 1870

Since European settlement in AD 1870, erosion caused by intense rainstorms is the most significant and frequently occurring type of disturbance in Hawke's Bay. Erosion occurred more often during the European period when the catchments were under grassland, compared with both the forest and bracken/shrubland vegetation phases. These results agree with contemporary studies of landslide erosion under similar vegetation types. In the European section of the cores, there is approximately six times more erosion pulse sediment than there is in the forested period, and about two to four times more than in the Polynesian period. Since pasture became the dominant vegetation type, the soft-rock hill country of the Tutira and Putere districts has become more vulnerable to erosion and landslides.

The pollen and spore content of surface samples (mosses, soils and surface lake sediments) was analysed to help define the different sources of pollen and spores in the ancient lake sediments. Surface lake sediment pollen spectra represent an amalgamation of both contemporaneous and secondary inwashed pollen and spores of mixed age. The bracken and tree fern spores in the surface sediments were highly corroded but the pollen was well preserved. In contrast, pollen and spores in mosses were well preserved and almost entirely derived from local, contemporaneous source plants. Soils contained a lower diversity of mixed aged pollen and spores which were highly corroded, except for the most resistant types such as tree fern spores. These variations in pollen and spore preservation are attributed to their different sources in the catchment. In the surface lake sediments most of the bracken spores were derived from stored spores in the soils; most of the pollen was derived from the contemporaneous plants; and corroded tree fern spores were presumed to have been eroded from river bank sediments.

Differential pollen and spore preservation analyses were used to determine relationships between the category of preservation and type of deposit. Results indicate corroded bracken spores are strongly associated with inwashed soils. In lake basins that receive inwashed soils, these soils can continue to supply old, corroded bracken spores to the pollen spectra, even though the fern may be absent or scarce in the catchment. Differential preservation analysis allows the proportion of these corroded bracken spores to be estimated and removed from the pollen sum, permitting a more accurate representation of this fern spore in the fossil pollen record.

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CHAPTER 1

INTRODUCTION

Many areas of New Zealand are disturbed at varying intervals by earthquakes, volcanic eruptions, cyclonic storms, fires and droughts. Understanding the response and subsequent regeneration of contemporary forests to these types of disturbances is often made difficult by anthropogenic changes. This thesis aims to assess the environmental effects of some of these natural disturbances that occurred before human settlement, through detailed palaeoecological investigations of lake sediment cores. New Zealand was first settled by Polynesians *c.* 900-800 BP (McGlone *et al.* 1994) and being one of the most recently settled, large landmasses it provides an ideal opportunity to examine vegetation responses to natural disturbance under similar climatic conditions to the present, but in the absence of cultural change. In addition, the environmental effects of initial human settlement can also be assessed in relation to previous disturbances.

In this thesis, four sediment cores from four lake catchments in the Tutira and Putere districts of Hawke's Bay, North Island are analysed for pollen, and evidence of past disturbances including charcoal, tephras and erosion pulses (rapidly inwashed catchment material). The Hawke's Bay region is used for this study because it was forested until recent Polynesian settlement (McGlone, 1978), and experiences frequent natural disturbance. The study area has a high rainfall variability and experiences intense rainstorms, floods and droughts. The rocks, cover beds and soils of the steep hill-country in Hawke's Bay are inherently unstable.

When storm- or earthquake-induced erosion occurs in the study catchments, minerogenic material is transported from the slopes and riverbeds to the lake basin, where the rapidly inwashed sediment is preserved in the lake sediments as a discrete pulse. Forest fires ignited by lightning-strike are also common and leave charcoal fragments in the lake sediments. Many of the Holocene eruptions from volcanoes in the North Island Central Volcanic Zone (Figure 2.1) have dispersed tephras as far as Hawke's Bay during the last 2000 years BP (Eden *et al.* 1993). Tephra deposits from some of these eruptions found in the lake sediments can be as identified and dated.

In the past, many other types of disturbance such as windthrow, earthquakes, and attack by insects and pathogens could have caused forest disturbance in the study catchments but did not leave a signature in the pollen or sediment record. Therefore, the disturbances recognised and discussed in this thesis are limited to the types of disturbance that leave a clear signature in the sediment record (e.g., tephra, charcoal fragments, erosion pulses) which can be interpreted along with changes in the pollen data.

The term vegetation disturbance is used in this thesis to describe "a discrete, punctuated killing, displacement, or damaging of one or more individuals (or colonies) that directly or indirectly creates an opportunity for new individuals (or colonies) to become established" following the definition of Sousa (1984: 356). Sousa (1984) suggests that disturbance can be seen as lying near to one extreme of the continuum of natural perturbations affecting the organisms.

Chapter 2 introduces the study area, and provides physiographic details of the lake catchments. Sections are included on local climate and the types of natural disturbance the study sites experience. The pre-Polynesian, pre-European and present-day vegetation of the sites are outlined, together with successional pathways from cleared land to lowland podocarp-hardwood forest typical of the region. These provide a context for the palynological discussions in Chapter 5. For the same reason, a section on the importance of *Pteridium esculentum* (bracken) after disturbance is provided in Chapter 2.

The methods employed in the collection, preparation and analysis of the lake sediment cores and samples are presented in Chapter 3. Justification of the pollen sums used, and the layout of the pollen diagrams are also given here.

In Chapter 4, surface samples of moss cushions and soils are pollen analysed and compared with the pollen spectra from surface lake sediments to identify the different sources of pollen and spores in the ancient lake sediments. As there are numerous erosion pulses in the lake sediment cores analysed in Chapter 5, there is a risk of inwash of non-contemporary pollen and spores. The results from Chapter 4 are used to help interpret the fossil pollen records in Chapter 5, particularly to differentiate between real disturbance-induced vegetation changes and spurious signals produced by inwashed secondary pollen and spores.

The main thrust of this thesis is presented in Chapter 5, where the pollen-based vegetation history of Hawke's Bay is documented from *c.* 2000 BP to the present. Tephra deposits from the 1850 BP Taupo eruption recorded at the base of the sediment cores, provide the temporal limits for this study. The extent to which the vegetation and landscape were altered by volcanic eruptions, storms and fires is discussed. Particular attention is given to the review of vegetation change at Tutira and Putere after the explosive 1850 BP Taupo eruption, as this was the largest natural disturbance to affect these catchments during the period studied. These vegetation changes are compared with those recorded from other pollen sites in the central North Island, to assess the distal effects of this eruption on the North Island forests. This work contributes to the current understanding of volcanic disturbance on the native lowland forests of New Zealand, particularly in terms of the extent of damage, and speed of revegetation after such an event.

In Chapter 5, vegetation changes generated by Polynesian settlement are also considered in detail, adding to the current debates on the timing, extent and sequence of deforestation (McGlone *et al.* 1994), and the influence of such large-scale change on soil stability (Grant, 1994). The effects of European settlement on landscape stability and erosion are discussed. The environmental impact of *c.*150 years of European settlement are compared with those caused by Polynesian deforestation. The frequency of erosion-producing events in the lake catchments during the three major periods studied i.e., forest, Polynesian and European are compared, particularly in light of the current concerns regarding soil erosion in Hawke's Bay (e.g., Trustrum & Page, 1992; Marden & Rowan, 1993; Page *et al.* 1994a; Page *et al.* 1994b). Data from modern pollen rain studies in New Zealand lowland podocarp/hardwood forests are used to help interpret the pre-clearance fossil pollen assemblages in Chapter 5. Data from other studies were used, as most of the lowland podocarp-hardwood forest in the study area has been cleared and exact modern analogues for this type of vegetation are not available from the Tutira and Putere catchments.

In Chapter 6, differential preservation analyses of the pollen and spores contained in the sediment cores are used to separate the reworked and contemporaneous components of the pollen spectra. The pollen and spores in the surface samples analysed in Chapter 4 are also examined for differential preservation to help separate secondary from contemporary sources. The results from both the surface and fossil pollen preservation analyses are used to enhance the understanding of the fossil pollen records in Chapter 5. Experimental studies of pollen and spore preservation overseas have identified differential rates of decay in different types of deposits (e.g., Sangster & Dale, 1961, 1964; Cushing, 1964; Havinga, 1964, 1984). However, differential preservation of palynomorphs has only been considered in a few Holocene palynological studies in New Zealand (e.g., Pocknall, 1980; McGlone, 1983a) and these mostly refer to the over-representation and corroded state of tree fern spores in inwashed sediments. Other New Zealand palaeoecological studies have not analysed in detail the effects of differential pollen and spore preservation on fossil pollen spectra, therefore the approach presented in this thesis is an exploratory one in the New Zealand context.

A summary of the conclusions from the palaeoecological studies, surface pollen analyses and differential preservation are presented in Chapter 7.

CHAPTER 2

STUDY AREA: PHYSIOGRAPHY AND VEGETATION

STUDY AREA

Catchment physiography

The study sites are lake catchments in the Tutira and Putere districts, Hawke's Bay, North Island, New Zealand (Figure 2.1). Tutira (39° 13' S, 176° 54' E) has a more lowland and coastal situation than Putere (38° 57' S, 177° 2' E), and the two sites are about 35 km apart. The catchments consist of sandstone and siltstone interbedded with limestone and conglomerates of Pliocene and early Pleistocene age, mantled with tephra from the 1850 BP Taupo eruption (Lowe, 1987). The two sites are typical of the soft rock hill country in Hawke's Bay. There are three lakes at the Tutira site, Lakes Tutira, Waikopiro and Orakai, and for the purposes of this study, cores were collected from the first two of these lakes (Figure 2.2). Similarly, there are three lakes at the Putere site, Lakes Rotonuiaha, Rotongaio and Rotoroa, and cores were collected from the first two of these lakes for this study (Figure 2.3).

In the Tutira district, Lake Tutira (1.8 km^2) lies at the southern end of an elongated catchment (32 km^2) that rises to a maximum altitude of 494 m above sea level (Figure 2.2 and Plate 2.1). Lake Tutira is 150 m above sea level and has a maximum depth of 42 m. The main inflow is from Papakiri Stream which enters the northern end of the lake as Sandy Creek. The lake is also drained at its northern end by Mahiaruhe Stream which lies less than 100 m to the west of the inlet (Figure 2.2).

The smaller adjacent Lake Waikopiro (0.11 km^2) has a saucer-shaped basin, a maximum depth of 16 m, and a relatively small catchment consisting of steep hills to the south of the basin (Figure 2.2 and Plate 2.1). The lake has no inflowing streams but during periods of high lake levels, water overflows from Lake Tutira to Lake Waikopiro. Lakes Tutira and Waikopiro formed *c.* 6500 BP (Eden *et al.* 1993) after landslide debris blocked Papakiri Stream which previously flowed to the south (Adams, 1981). The former meandering

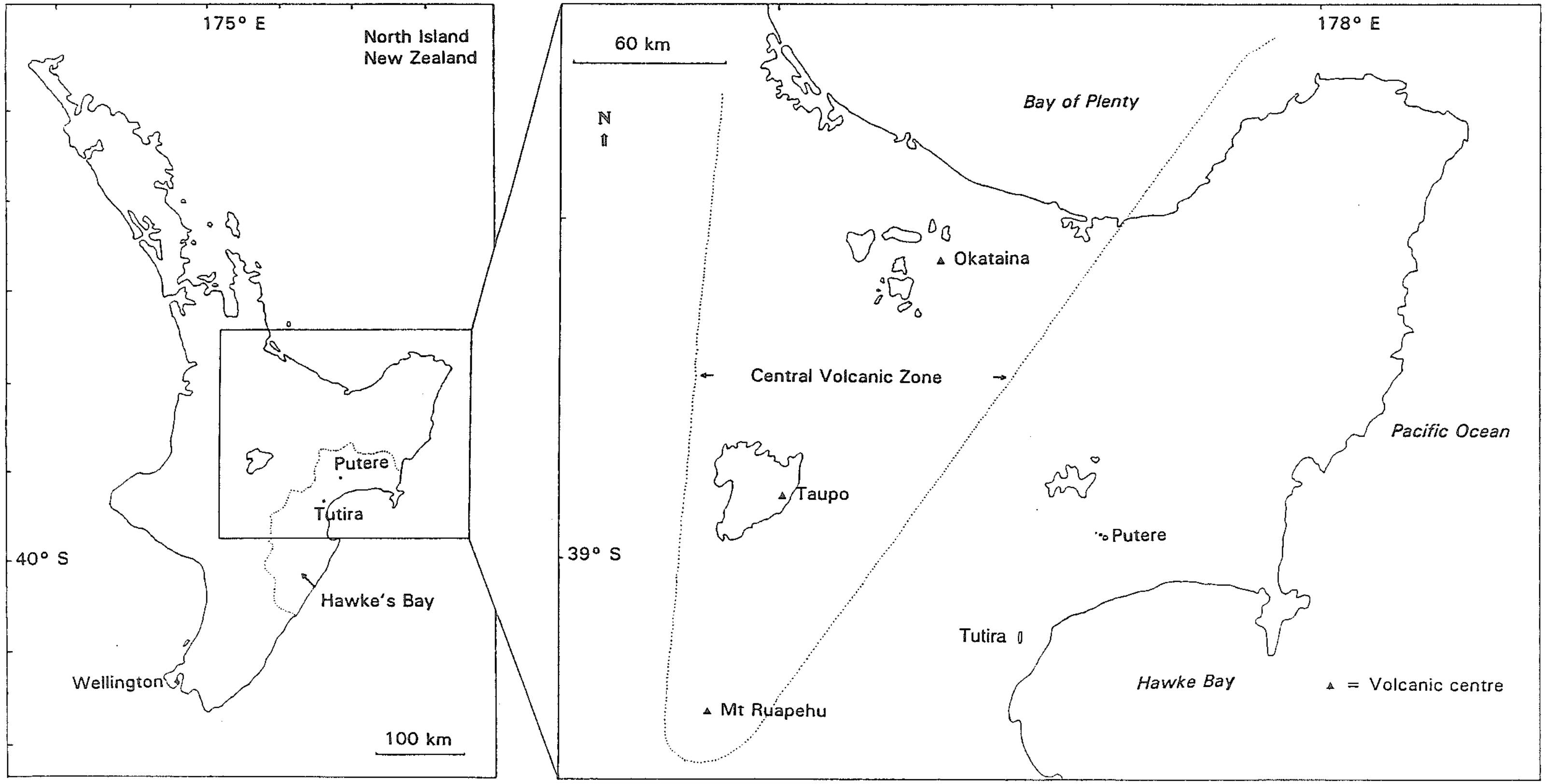


Figure 2.1. Location of study sites, showing the Hawke's Bay region and the limit of the Central Volcanic Zone.

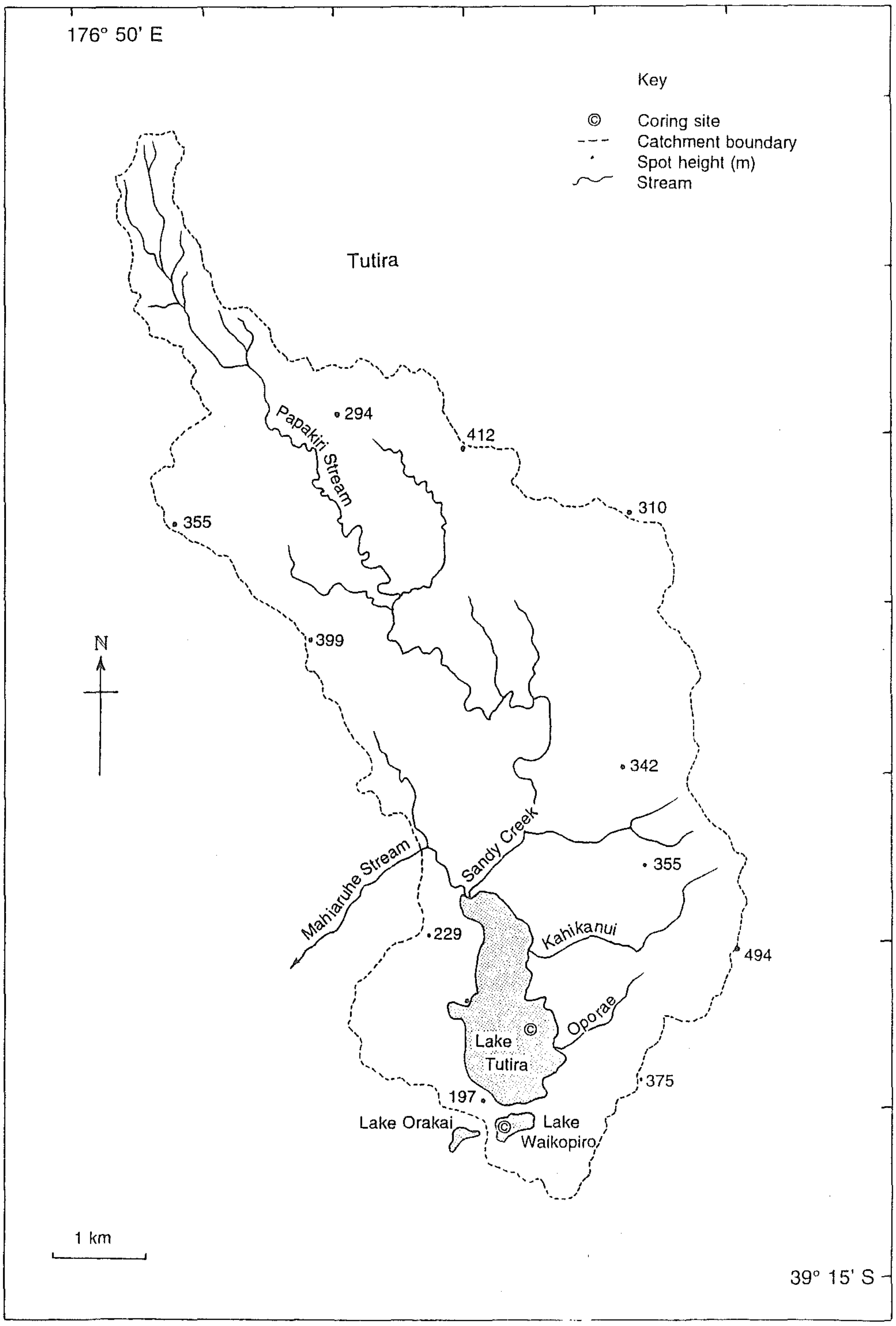


Figure 2.2. Catchment areas of Lakes Tutira and Waikopiro, showing coring sites.

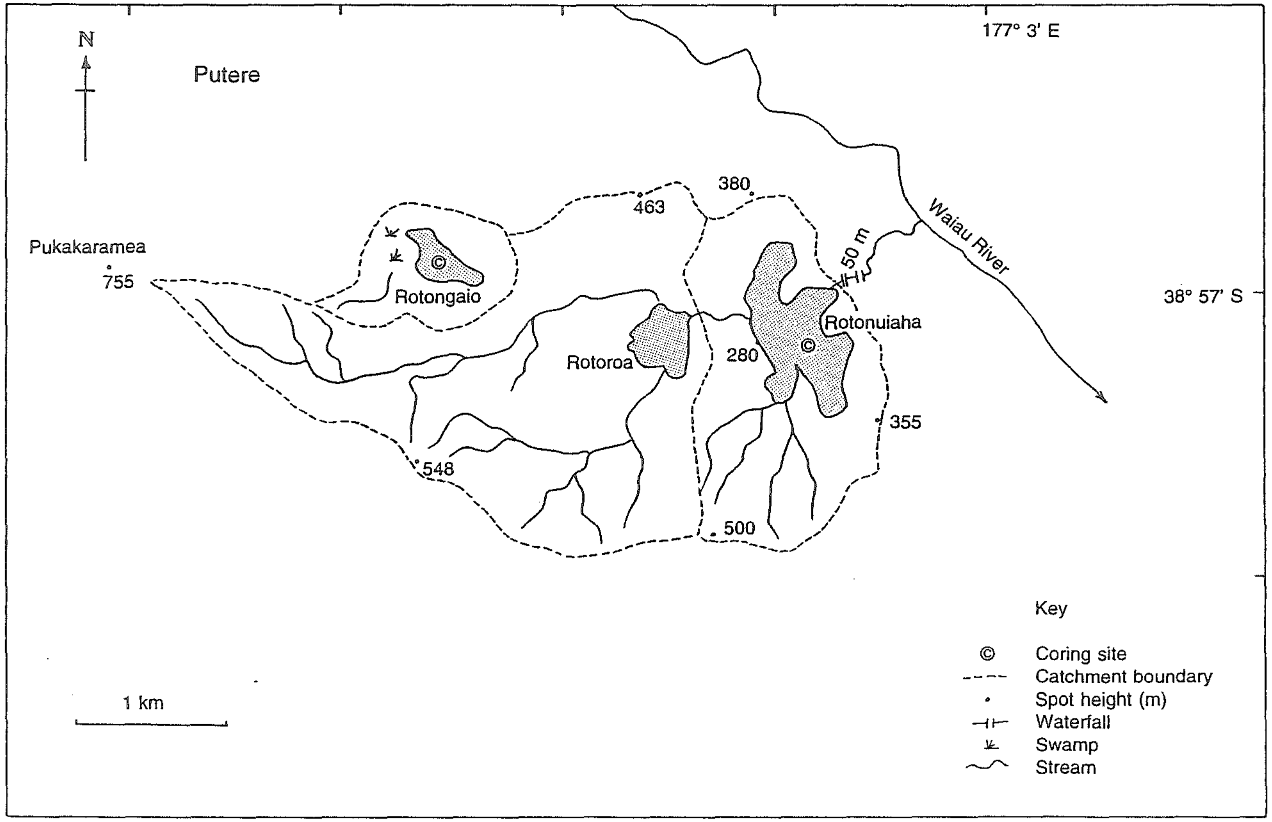


Figure 2.3. Catchment areas of Lakes Rotongaio, Rotoroa and Rotonuiaha showing coring sites.

valley of Papakiri Stream is visible in the bathymetric maps of the Lake Tutira basin (Grant, 1966; Guthrie-Smith, 1969:17; Irwin, 1978).

Lake Rotonuiaha is the largest (0.44 km^2) of the three lakes in the Putere district, and has a maximum depth of 30 m. The landslide-damned lakes at Putere are perched above the Waiau River. The catchment covers a smaller and more gently sloping area (2 km^2) than Lake Tutira but rises to 500 m above sea level (Figure 2.3 and Plate 2.2). The outlet from Lake Rotonuiaha consists of a waterfall at the eastern shore (Figure 2.3 and Plate 2.2) which drains into the Waiau River. On the western side of Lake Rotonuiaha, a small stream drains from Lake Rotoroa. At times of high rainfall and erosion in the steeper Rotoroa catchment, silty water from Lake Rotoroa is transported to Lake Rotonuiaha, giving the lake a muddy appearance.

Lake Rotongaio (0.94 km^2) is the smallest of the lakes at Putere, and has a maximum depth of *c.* 5 m. The Rotongaio catchment (0.5 km^2) consists of a small area to the east of steep but stable mudstone/sandstone hills; the remainder lies predominantly to the west and is relatively flat (Plate 2.2). There are no major inflows to Lake Rotongaio; instead the lake is fed by seepage and the margins are surrounded by dense swamp communities.

Climate

The following Hawke's Bay climate statistics are based on Thompson (1987) and Tomlinson (1976). Tutira has warm, dry summers and moderate winter temperatures, and a mean annual rainfall of *c.* 1400 mm/yr (Figures 2.4 and 2.5). The inland and higher site of Putere has a cooler and wetter hill climate, with a mean annual rainfall of *c.* 2000 mm/yr. The daily range of temperature on the east side of the mountain ranges in Hawke's Bay varies from about 8°C at the coast to over 12°C in sheltered inland areas (Figure 2.6). The axial ranges shelter Hawke's Bay from the prevailing westerly winds (Figure 2.7). Orography largely controls the direction of local winds, that tend to channel along river valleys. Predominant wind directions in central and southern Hawke's Bay (Tutira) are from the west or south-west compared to the northern districts (Putere) where north or north-west winds are most frequent (Thompson, 1987).

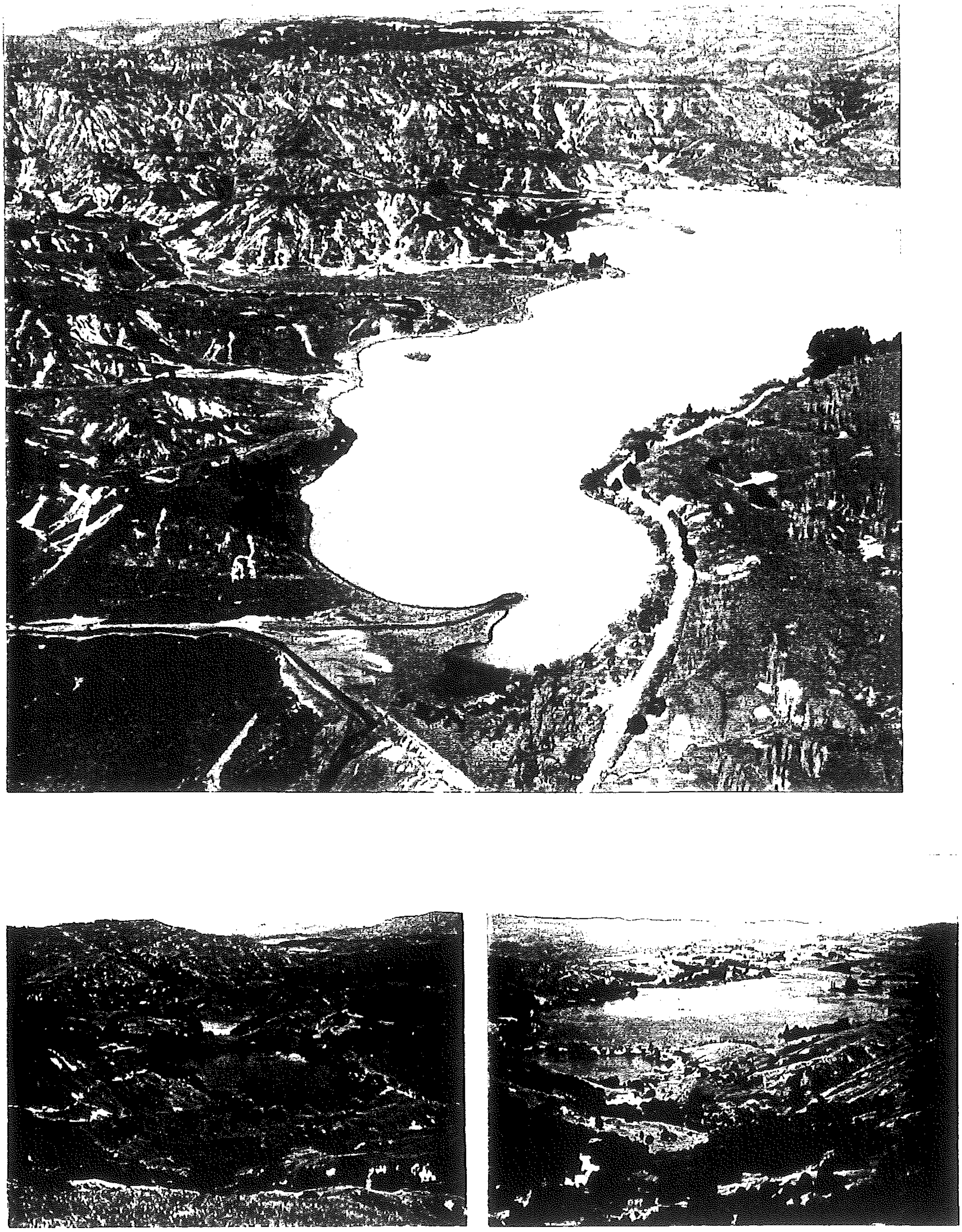
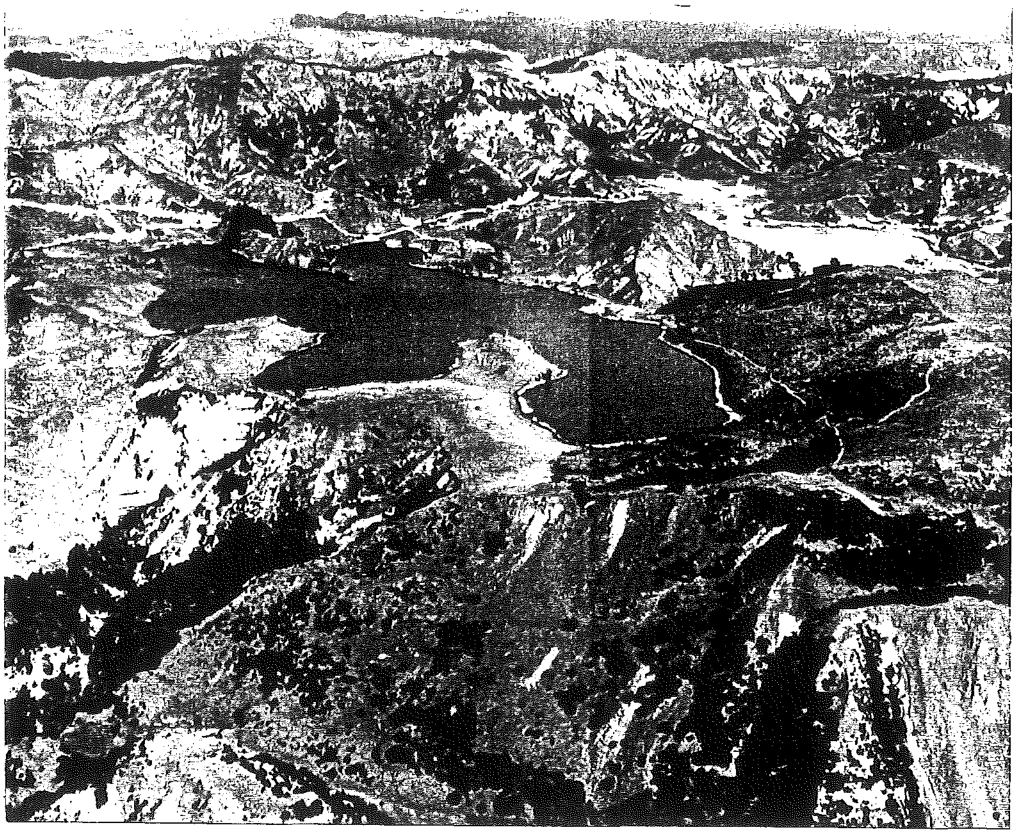
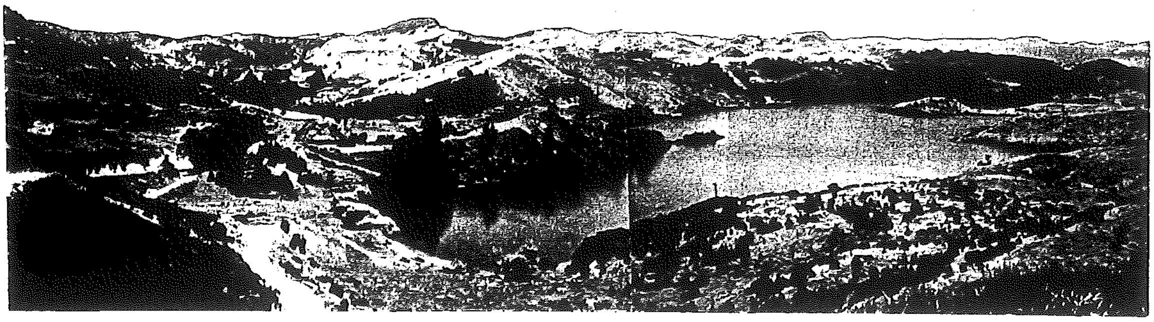


Plate 2.1. Lake Tutira (top - oblique aerial, and bottom right - looking north) and Lake Waikopiro (bottom left - looking east).





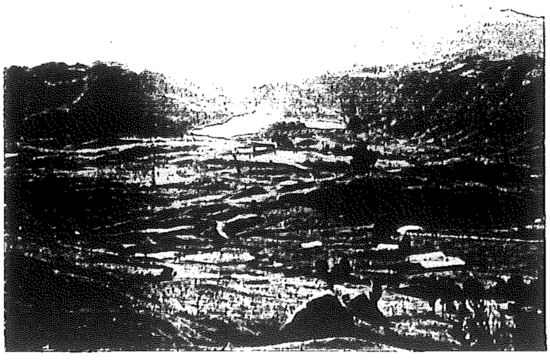


Plate 2.2. Lake Rotonuiaha (top - oblique aerial and middle - looking north-west) and Lake Rotongaio (bottom - looking east).

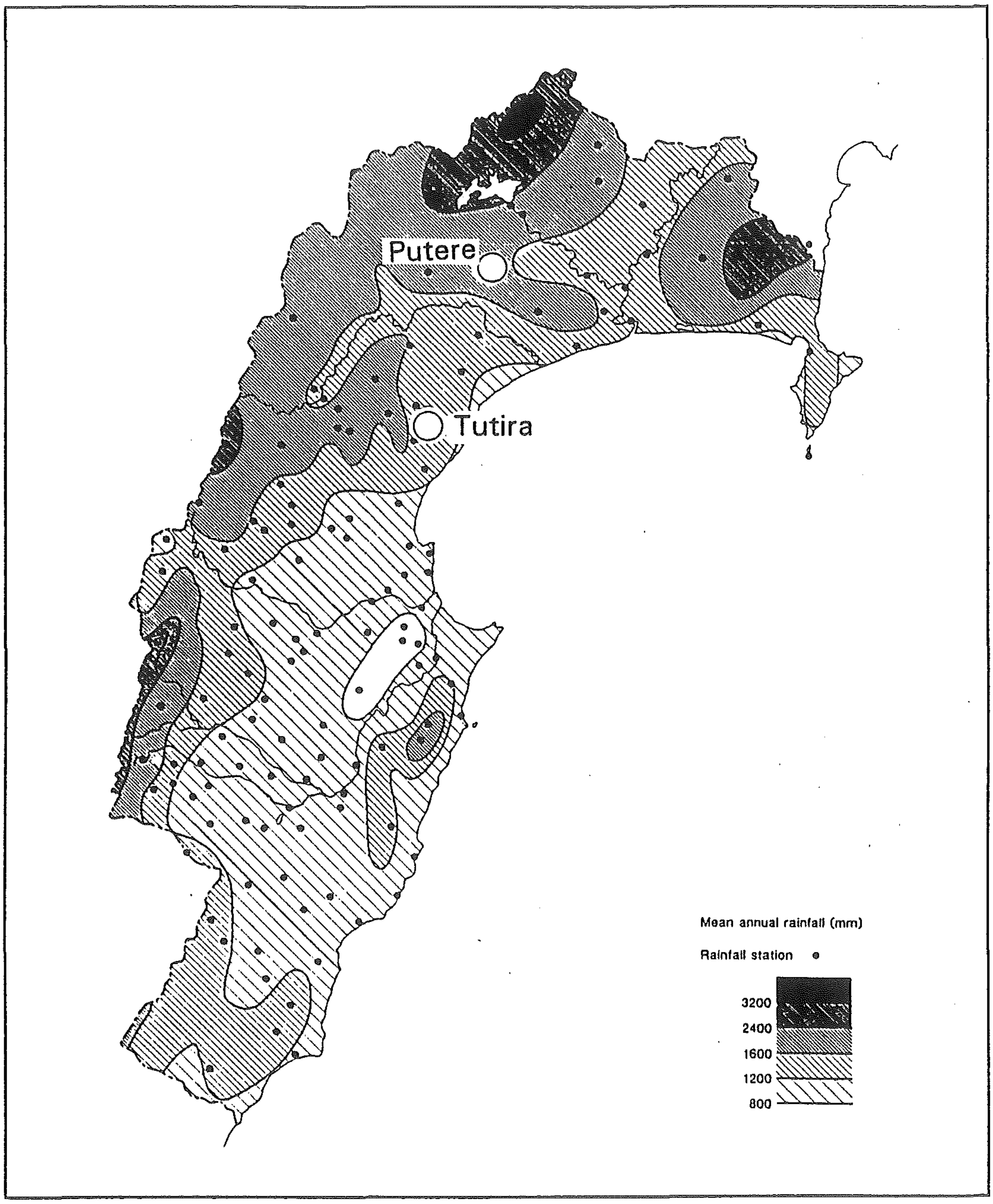
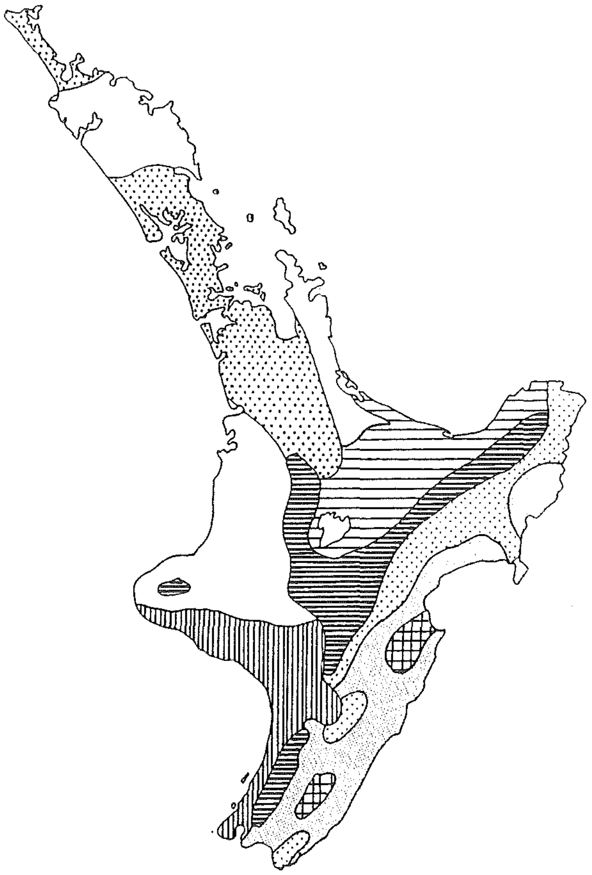


Figure 2.4. Mean annual rainfall in Hawke's Bay; from Thompson, 1987.



A	░	Warm humid summers, mild winters. Annual rainfall 1000 mm to 1500 mm with maximum in winter. Prevailing wind S.W., but occasional strong gales and heavy rains from E. or N.E. from Auckland northwards and Coromandel.
A2	☐	Similar to A, but much wetter. Rainfall 1500 mm to 2400 mm.
B	▤	Sunny rather sheltered areas which receive rains of very high intensity at times from N.E. and N. Very warm summers and mild winters. Annual rainfall 1000 mm to 1800 mm with winter maximum.
C	░	Very warm summers, day temperatures occasionally rise above 32°C with dry foehn N.W. winds. Annual rainfall 1000 mm to 1500 mm; marked decrease in amount and reliability of rain in spring and summer. Moderate winter temperatures with maximum rainfall in this season.
CO	▦	Drier than type C; rainfall 600 mm to 1000 mm.
C2	░	Cooler and wetter hill climates. Very heavy rains at times from S. and S.E.; annual rainfall mainly 1500 mm to 2000 mm.
D	▥	W. to N.W. winds prevail with relatively frequent gales. Annual rainfall 900 mm to 1300 mm. Rainfall reliable and evenly distributed throughout the year. Warm summers, mild winters.
H	▤	High rainfall; mountain climates

Figure 2.5. Climatic Zones of the North Island; from Tomlinson, 1976.

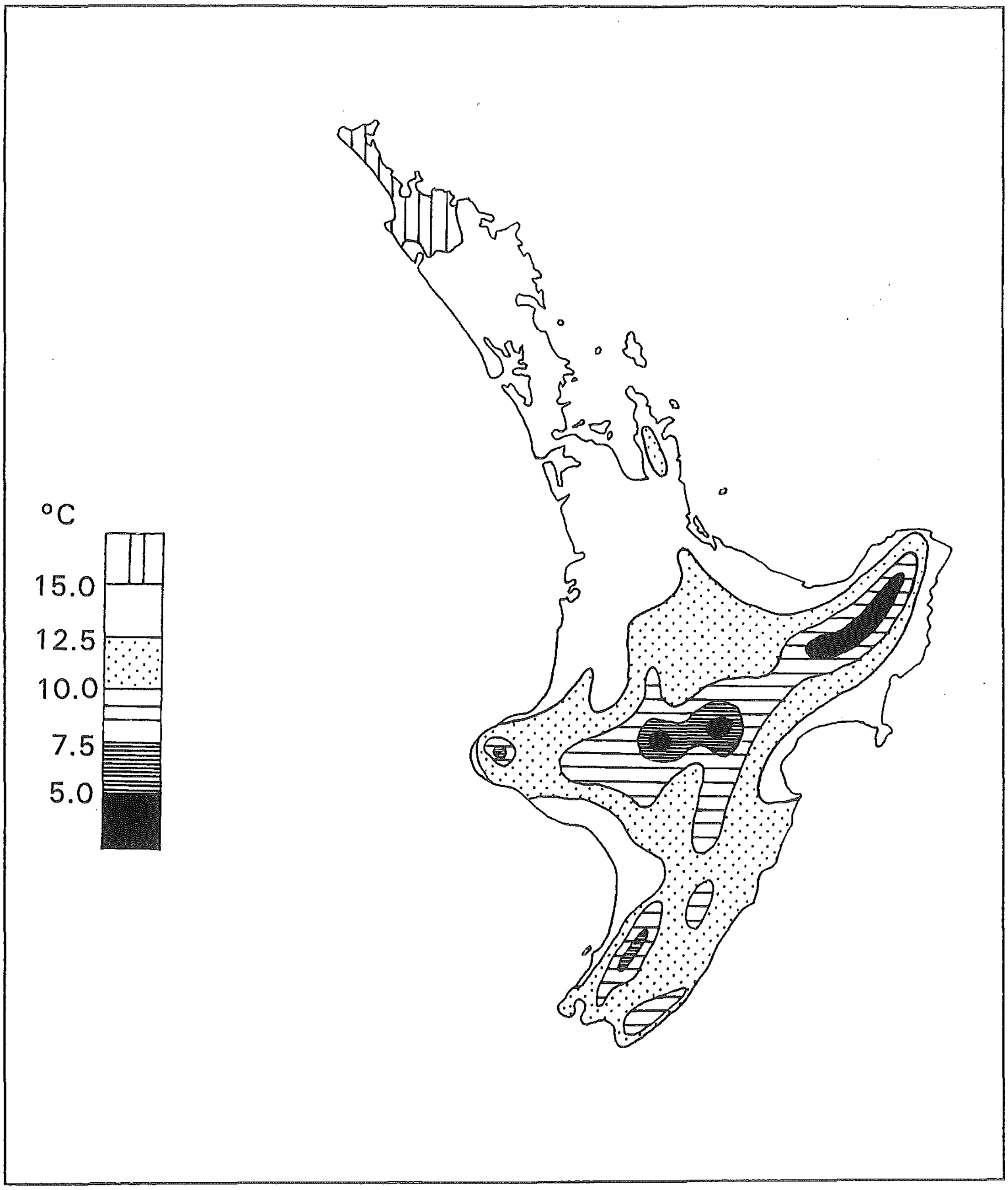


Figure 2.6. North Island mean annual temperatures; from Tomlinson, 1976.

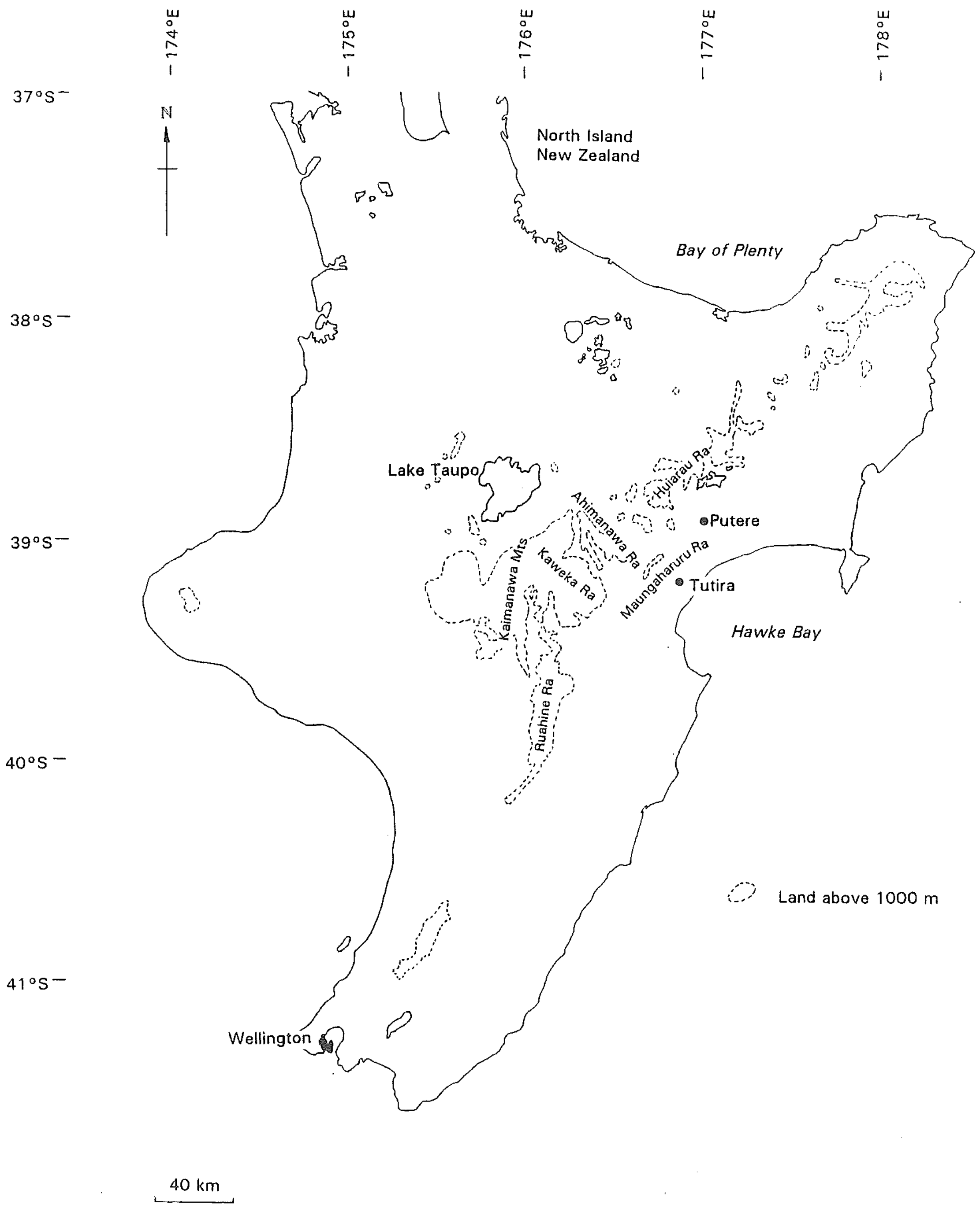


Figure 2.7. North Island mountain ranges mentioned in the text.

Hawke's Bay has some of the highest rainfall variabilities (defined by the coefficient of variation) in New Zealand with an annual variability in excess of 25% at Tutira and about 25% at Putere (Figure 2.8). Rainfall variability is greatest during the summer, and rainfall frequency greatest during winter.

Natural disturbance in Hawke's Bay

Droughts

Dry periods are more common in lowland Hawke's Bay than in the ranges, and usually occur when rainfall variability is at a maximum. Dry periods are defined as "droughts" when there is no measurable rain over a period of 15 days, and as "dry spells" when less than 1 mm of rain is recorded per day over the same period. Approximately three dry spells and one drought occur each year in lowland Hawke's Bay, but less frequently in the mountain ranges. Droughts can be detrimental to forests and have been shown to initiate widespread mortality of a variety of forest species in New Zealand, for example in the Kaimai Ranges, west of Tauranga Harbour, Bay of Plenty (Jane & Green, 1983a, 1983b); in lowland podocarp-hardwood forests in the Manawatu District (Atkinson & Greenwood, 1972); and mountain beech forests in the Kaimanawa Range (Grant, 1984).

Storms

Short duration and high intensity rainstorms can occur throughout the year but are more common in autumn. Severe storms of extratropical origin affect Hawke's Bay and many of these storms cause extensive damage to the indigenous vegetation (Shaw, 1983). Tropical cyclones reaching northern New Zealand that still retain their true cyclonic characteristics are rare (Revell, 1981). During 1960 to 1985 two cyclones passed directly over Hawke's Bay, and since this time, others have passed close to the region (Figure 2.9). All storms were accompanied by heavy rain and strong gusty winds which caused erratic but widespread damage to indigenous forests (Thompson, 1987; Shaw, 1983) (Figure 2.10). The most recent high-intensity rainstorm to affect Hawke's Bay was Cyclone Bola, which passed over the East Coast of the North Island in 1988 bringing heavy rain and strong easterly winds (New Zealand Meteorological Society, 1988). Cyclone Bola caused extensive and widespread landslide erosion, flooding and silting in the Tutira and Putere

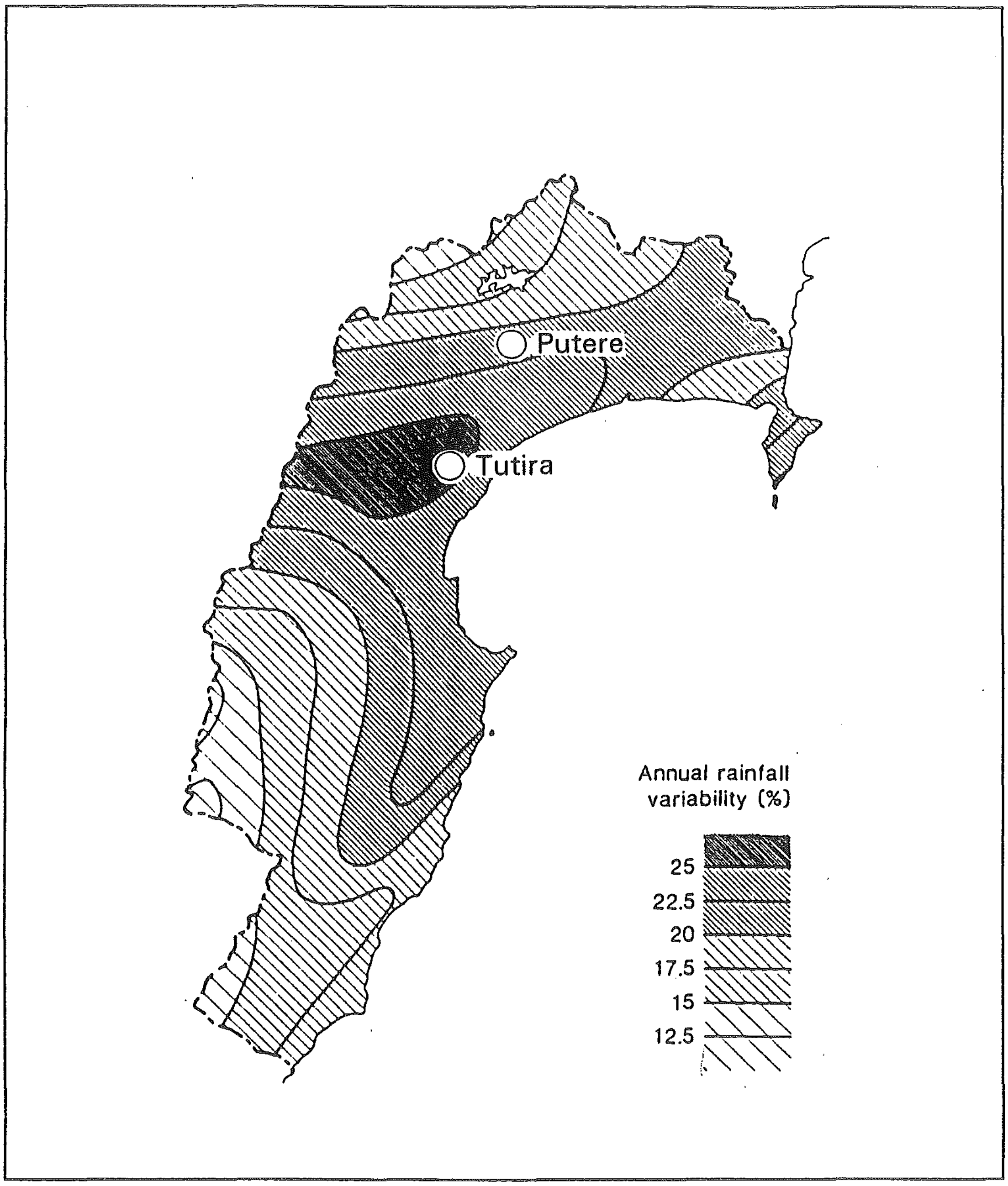


Figure 2.8. Annual rainfall variability in Hawke's Bay, based on the normal period 1951-1980; from Thompson, 1987.

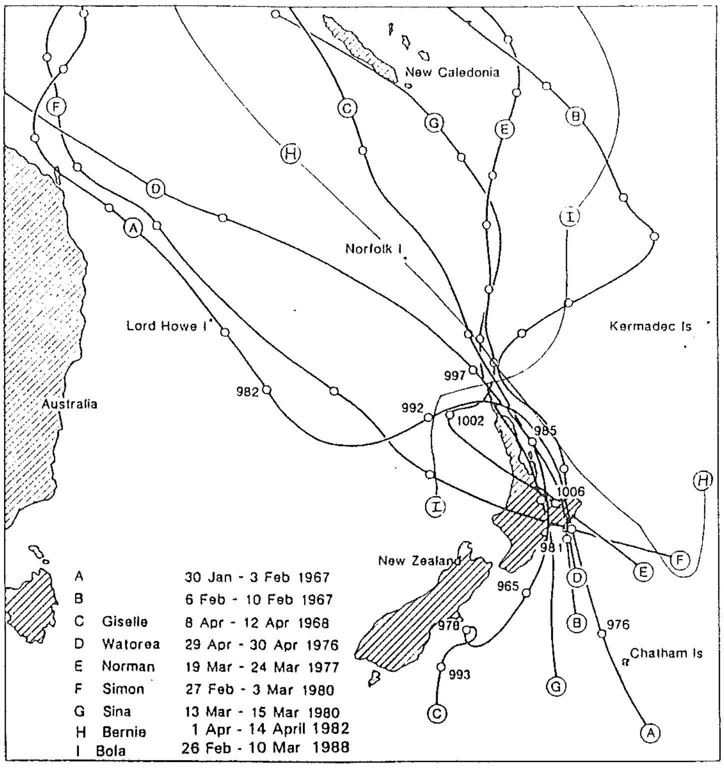


Figure 2.9. Tracks of tropical cyclones that passed over or near Hawke's Bay between January to March during the period 1960 to 1988: from Thomspon (1987:13) and Hessel (1988:15).

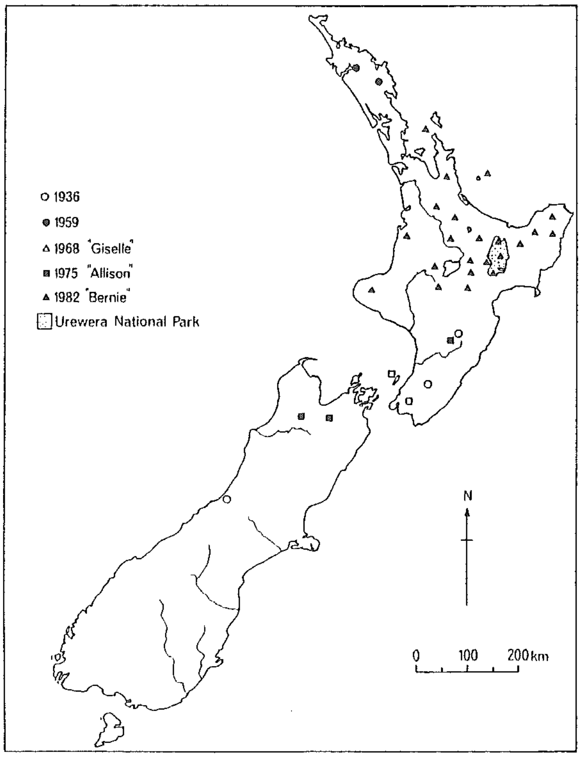


Figure 2.10. Currently known locations of indigenous forest damage caused by tropical cyclones, for the period 1936-1982 (from Shaw, 1983:407).

catchments, particularly on the steeper hillslopes (Phillips *et al.* 1990; Page *et al.* 1994b). Evidence of these landslides is visible in Plate 2.3. The Tutira catchment was particularly affected, shown by the many landslide scars and the silty water colour of the lake in the oblique aerial photograph on Plate 2.1, which was taken shortly after the storm.

During intense storms, vast amounts of soil and riverbank sediment can be rapidly transported into the lake and preserved in the sediments as a discrete erosion pulse. Plate 2.4 shows the surface 50 cm of sediment taken from Lake Tutira with a freeze-box corer. The plate shows the thick deposit of inwashed catchment soil that reached the lake during Cyclone Bola, and pulses from other large storms (see Chapter 3). During this century, the steeper hillsides in Hawke's Bay have been susceptible to landslide erosion after high intensity rainstorms (Page *et al.* 1994a; Page *et al.* 1994b). Between AD 1895 and 1988 in the Tutira catchment there have been at least 105 high intensity rainstorms, 20 of which caused major soil erosion (Page *et al.* 1994a).

Fires

The frequency of lightning discharges over the surface of the Earth has been estimated at 100 per second (Komarek, 1964 quoted in Patterson *et al.* 1987). Lightning strike is the most common cause of natural fire, and the high rainfall variability and frequency of dry periods in Hawke's Bay, make this region one of the more fire prone in the North Island. During the early phases of European settlement and forest and shrub clearance in Hawke's Bay, severe outbreaks of fire coincided with prolonged drought (Arnold, 1994). Undoubtedly, droughts would have predisposed forests to similar risks from lightning strike ignitions in the past. Charcoal fragments produced during forest fires are transported into lake basins *via* runoff or aerial deposition, and their high resistance to decay ensures the fragments remain archived in the sediments.

Volcanism

Volcanic eruptions are another source of environmental disturbance in Hawke's Bay. The Central Volcanic Zone of New Zealand (Froggatt & Lowe, 1990) lies *c.* 90 km west of Tutira and Putere (Figure 2.1). Airfall tephra can damage the vegetation in several ways, including mechanical overload, physical smothering and chemical toxicity, and can modify

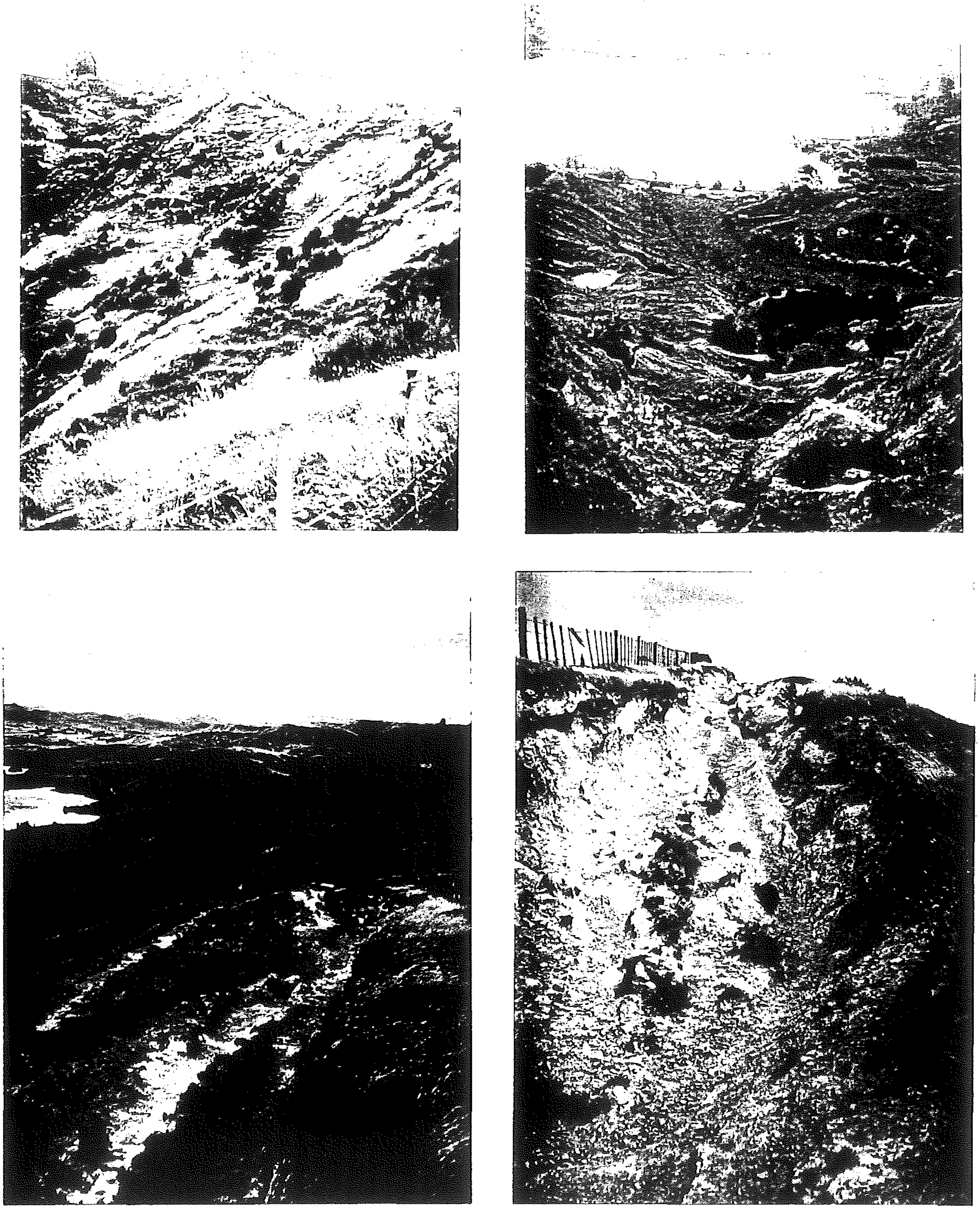


Plate 2.3. Landslide erosion in the Tutira and Putere catchments

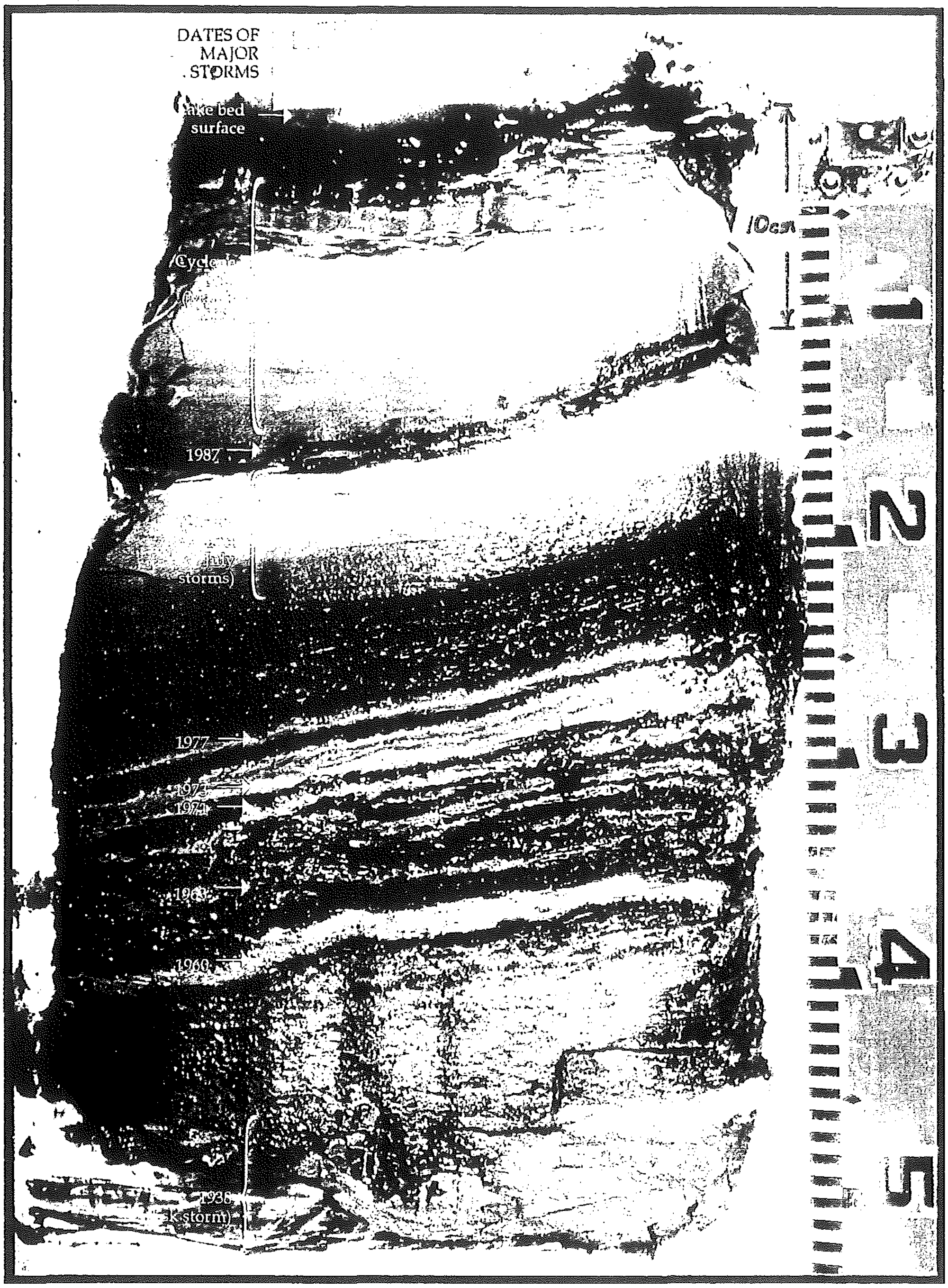


Plate 2.4. Freezer core showing the surface 50 cm of sediment collected from Lake Tutira. The pale layers represent rapidly deposited erosion pulse sediment (allogenic sediment) derived from eroded catchment soils, and the darker layers, organic-rich deposits (authigenic sediment) generated within the lake from the breakdown of algal matter. Pulses from individual storm events are also shown. The dates for these events were obtained by matching the pulses with a 93-year daily rainfall record from Tutira Station (Page *et al.* 1994a).

drainage patterns and soil structure. Tephras from at least three volcanoes in the Central Volcanic Zone, fell over the lake catchments during the past 2000 BP: Taupo Tephra from Lake Taupo (1850 ± 10 BP: Froggatt & Lowe, 1990); Kaharoa Tephra (*c.* 700 BP: Lowe & Hogg, 1992) from the Mount Tarawera complex in the southern part of the Okataina Volcanic Centre; and tephra from various members of the Tufa Trig Formation (Tf) from Mount Ruapehu (Donoghue, 1991).

The violent 1850 BP eruption of the Taupo volcano ejected ash and pumice possibly as high as 30 km into the stratosphere (Wilson *et al.* 1978). Airfall deposits more than 10 cm thick covered approximately 33 000 km^2 of land east of the vent (Wilson & Walker, 1985). The Tufa Trig Formation comprises a sequence of 18 tephras that erupted in an eastern direction from Mt Ruapehu between *c.* 1850 BP and the present (Donoghue, 1991). Tephras from the Tufa Trig Formation that reached the study sites in Hawke's Bay (Eden & Froggatt, in prep.) are the more widespread members Tf2, Tf5, Tf6 and Tf8. The *c.* 700 BP eruption of the Kaharoa Tephra (Lowe & Hogg, 1992) mainly dispersed in a north, north-west direction from the Okataina Volcanic Centre (Pullar, 1973). Because of the direction of this eruption plume, only traces of Kaharoa Tephra are found south of the eruptive centre.

Earthquakes

Seismic activity is an important geomorphic factor in Hawke's Bay. Earthquakes can cause localised landslide erosion and burial of vegetation. The severity of ground motion during an earthquake can vary enormously over short distances, caused by topographic focusing of seismic waves and the varied effects of different geological structures (Grant-Taylor *et al.* 1974 quoted in Smith, 1978). Landslide debris caused by seismic disturbance may be transported directly from steep catchment slopes into a lake. However, if sufficiently high rainfall is needed to transport the debris off the slopes, eroded material will reach the lake some time after the event. Earthquake-induced landslides may have caused enhanced erosion during subsequent large storms. Although seismic activity must have been a potential source of vegetation disturbance in the Tutira and Putere catchments in the past, earthquakes do not always leave discernable lithostratigraphic signatures, such as deformation structures, in lake sediments (e.g., Mathewes & Clague, 1994). The effects

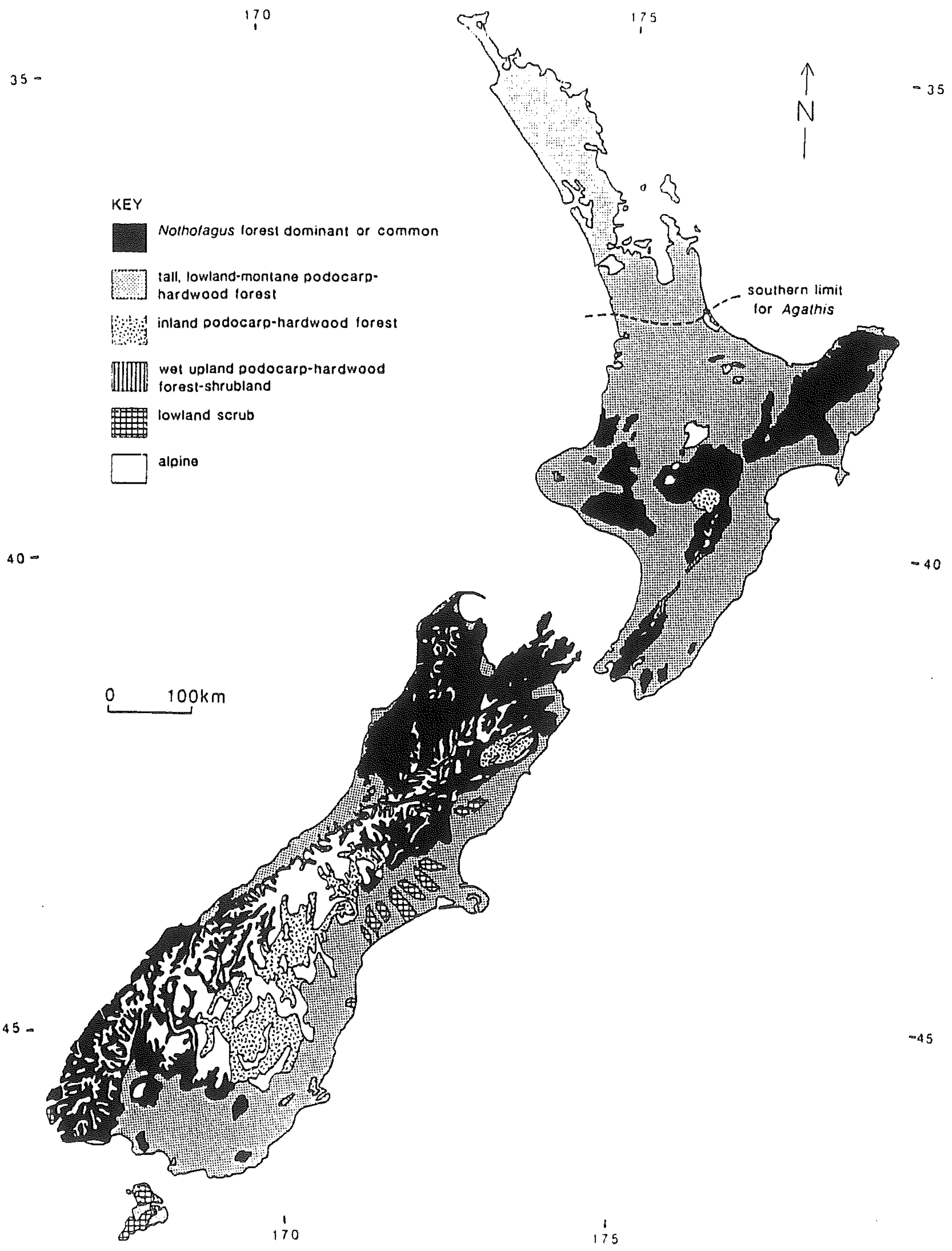


Figure 2.11. Vegetation cover in New Zealand before widespread Polynesian deforestation; from McGlone *et al.* 1993.

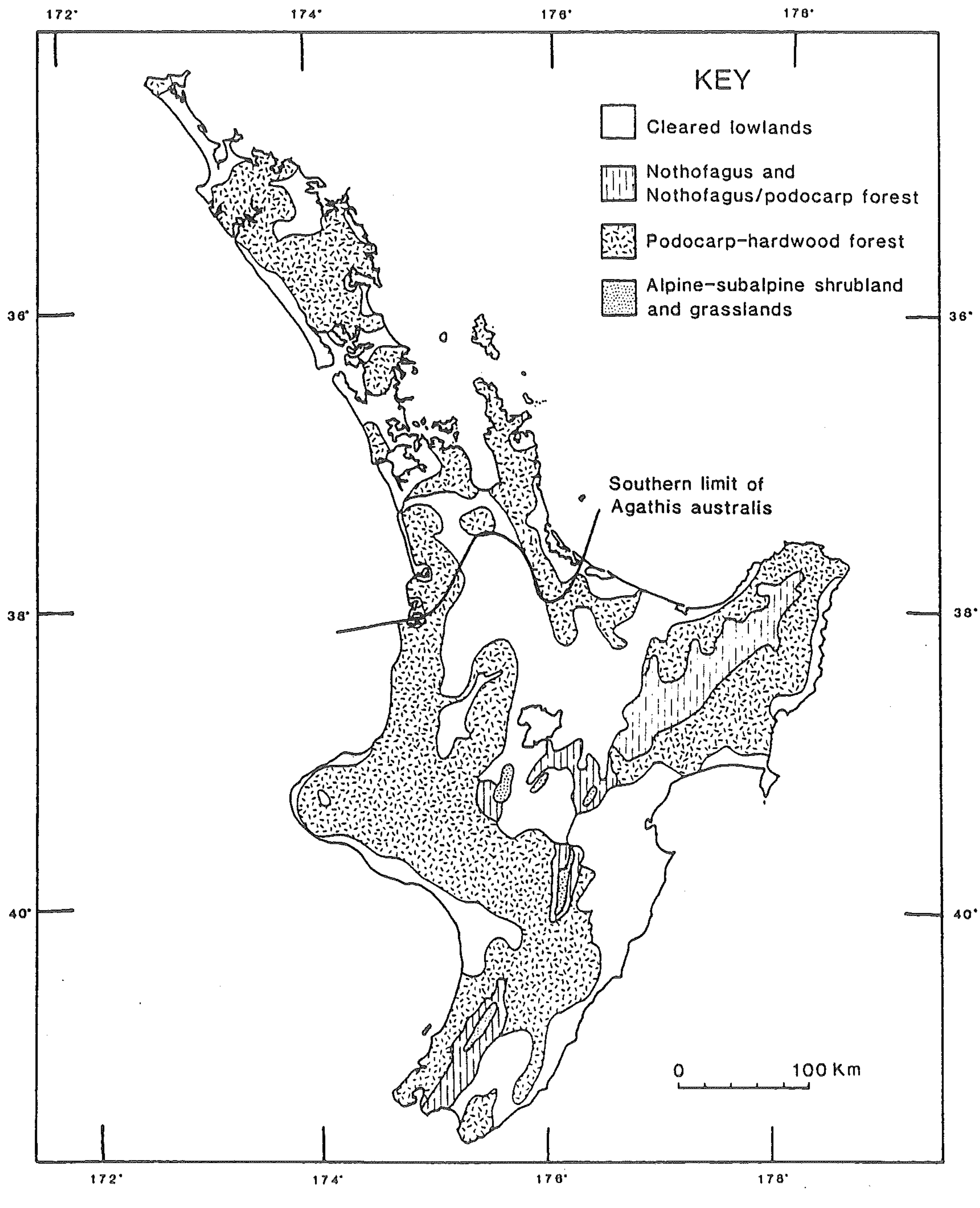


Figure 2.12. Approximate extent of North Island vegetation types in AD 1840, after early European clearance; from McGlone (1988) and Masters *et al.* (1957).

of past earthquakes on the catchment vegetation and soil stability cannot be recognised in the lake sediment cores from Tutira and Putere.

Pre-settlement, post-European and present day vegetation of Hawke's Bay

Before widespread deforestation that followed Polynesian (Maori) settlement, lowland and montane Hawke's Bay was mostly covered with a podocarp-hardwood forest (McGlone *et al.* 1993). The distribution of these vegetation types are shown in Figure 2.11. Polynesian settlement of New Zealand caused the loss of about half the native forest cover (Masters *et al.* 1957). By the 1840s, European settlement and clearance reduced the lowland podocarp-hardwood forest to about 42% of the total land area (Masters *et al.* 1957). The approximate extent of the remaining forest in the North Island at this time is shown in Figure 2.12.

Historical accounts indicate that in the 1870s, both Tutira and Putere were predominantly covered with bracken (*Pteridium esculentum*), tutu (*Coriaria arborea*) and *Hebe salicifolia*, particularly on the eastern and southern slopes, with only small confined pockets of lowland podocarp-hardwood forest (Guthrie-Smith, 1969; King, 1975). Swampland was abundant, dominated by *Phormium tenax*, *Typha orientalis*, *Cortaderia toetoe* and *Carex secta* and by other sedges and rushes on the drier swamp margins. Intensive European clearance converted most of the remaining forest, fern/shrubland and swampland in the study catchments to permanent pasture, and current landuse is dominated by stock production (Guthrie-Smith, 1969; King, 1975). At Tutira, permanent pasture covers about 90% of the catchment, and 1% is used for grain cultivation (NWSCA, 1986). The remaining land supports swamp, and small pockets of manuka shrubland and regenerating native forest. In 1992, 25 hectares of land on the Tutira catchment were planted with native and commercial trees in an attempt to prevent erosion, and there are plans for 250 hectares to be planted over the next 20-40 years (Magill, 1992). By comparison, in the Putere catchments, more land is currently under bracken and regenerating forest (approximately 15%), although permanent pasture still dominates current landuse. Approximately a quarter of the vegetation in the Lake Rotonuiaha catchment consists of a bracken and kanuka/manuka cover.

The limited area (see Newsome's (1987) map of North Island vegetation cover, in back pocket) of remaining lowland podocarp-hardwood forest in Hawke's Bay consists of a multi-storied complex of species. The podocarp group consists of tall, often emergent trees that may dominate the forest canopy, or less often forming nearly pure stands. The hardwoods include a diversity of angiosperm trees and shrubs excluding *Nothofagus*. The composition of each tier of the forest can vary according to altitude, coastal or inland situation, soil type and fertility. The following description of a typical mixed forest on warm, fertile lowland sites in Hawke's Bay is based on descriptions by Wardle (1991) and is presumed to be representative of the forest that existed in the Tutira and Putere catchments before Polynesian deforestation.

The emergent tier consists of tall trees from the Podocarpaceae including *Dacrydium cupressinum*, *Prumnopitys taxifolia*, *Prumnopitys ferruginea*, *Podocarpus totara*, *Dacrycarpus dacrydioides*. Of these, *Podocarpus totara* and *Prumnopitys taxifolia* are usually confined to semi-fertile soils, and are tolerant of sites with low rainfall and droughts. *Dacrycarpus dacrydioides* is also tolerant of lower soil fertility, but is characteristic of wet ground. *Dacrydium cupressinum* and *Prumnopitys ferruginea* are almost ubiquitous on infertile soils, but extend to more fertile sits where moisture is adequate.

The tall hardwood species *Laurelia novea-zelandiae* and *Metrosideros robusta* can also form part of the emergent canopy with the podocarp species. The more continuous canopy below the emergents comprises mostly angiosperms, dominated by *Beilschmedia tawa*, *Weinmannia racemosa*, *Nestegis* spp., *Knightia excelsa*, *Plagianthus* spp., *Elaeocarpus dentatus*, *Quintinia serrata* and *Dodonea viscosa.*

The sub-canopy consists of smaller individuals of canopy trees, together with a diversity of small trees and shrubs including *Streblus* spp., *Griselinia littoralis*, *Hedycarya arborea*, *Alectryon excelsus*, *Carpodetus serratus*, *Kunzea ericoides* and *Pseudowintera* spp. Tree ferns including *Cyathea smithii*, *Cyathea dealbata*, *Cyathea medullaris*, *Dicksonia squarrosa* and *Dicksonia fibrosa* are also present in the sub-canopy and canopy clearings. Occurring below the sub-canopy is a multitude of small shrubs including *Coprosma* spp., *Melicytus* spp., *Melicope* spp., *Neomyrtus pedunculata*, *Pittosporum* spp., *Myrsine* spp. and *Schefflera digitata.*

Climbers are common throughout all tiers of the forest, and they include *Passiflora tetranda, Freycinetia banksii, Clematis* spp., *Ripogonum scandens, Rubus* spp. and *Metrosideros* spp. Epiphytes also form an important component, particularly in the moister forests, and include the herbaceaous *Astelia solandri, Collospermum hastatum*; *Lycopodium varium*; orchids such as *Dendrobium cunninghamii* and *Earina mucronata*; shrubs such as *Coprosma lucida* and *Pittosporum cornifolium*; numerous ferns including *Pyrrosia eleagnifolia*; and bryophytes. A tall herb tier consists mostly of large ferns and some monocotyledonous genera, and at the lowest level of the forest (<10 cm), filmy ferns, mosses, liverworts and small angiosperms are important. Tree ferns, *Aristotelia* spp., *Melicytus* spp., *Pseudopanax* spp., *Fuchsia excorticata, Myrsine* spp., *Rubus* spp., *Brachyglottis repanda, Coriaria arborea* and *Pteridium esculentum* are common along forest margins and in clearings.

The importance of bracken after disturbance

Bracken is ubiquitous, and a relatively predictable pioneer plant in the way it colonizes newly created sites. Thus, the presence or rapid increase of its spores in the fossil pollen record provide an excellent indicator of past disturbance. Bracken is common in open places, disturbed habitats, forest margins and clearings in both the North and South Islands of New Zealand from lowland to sub-alpine regions (Brownsey & Smith-Dodsworth, 1989). It thrives on deep well drained soils, but is intolerant of shade. It is a particularly aggressive colonizer after forest disturbance and can form dense, pure stands which reach heights of 3-4 m in warm lowland areas (Brownsey & Smith-Dodsworth, 1989). Colonies can show enormous variation in fertility depending partly on habitat and situation (Page, 1976), and can spread by spore germination and local rhizome growth (Watt, 1940). Bracken rhizomes are buried to a depth of half a metre or more (Wardle, 1991), allowing the fern to rejuvenate vegetatively after fire and surface disturbances, when many other species perish. Where initial biotic conditions are limiting and competition pressure is low, colonization by bracken is both rapid and profuse. Bracken is often recorded as the first vascular species to colonise newly created, sterile volcanic surfaces in many parts of the world, particularly areas with a tropical or sub-tropical climate (e.g., Hawaii, West Indies, the Canary Islands, Western Samoa, Krakatau and Rangitoto Islands (NZ); see Page, 1976).

The time taken for bracken to be shaded out by regenerating angiosperm broadleaf trees and shrubs varies according to climate, edaphic conditions, density of the stand and the vigour of the regeneration (e.g., see Watt, 1940; Druce, 1957; Page, 1976). There may be no succession from bracken in dry areas where forest seedlings are prohibited from establishing under its canopy because of intense root competition, shade and dry soils - in which case the fern can persist indefinitely, even without fire (Partridge, 1990). Druce (1957) showed in a southern North Island catchment, that bracken (often with *Leptospermum scoparium* and *Kunzea ericoides*) establishes rapidly after fire and is replaced 5-20 years later by broadleaved species such as *Weinmannia racemosa*, *Griselinia littoralis* and *Pseudopanax arboreus*. A study of secondary succession in "The Hanger", a 10 hectare area of regenerating forest in the Tutira catchment (Guthrie-Smith, 1969) revealed that within 60 years a dense cover of bracken was replaced with a stand of *Leptospermum scoparium*, and this shrubland was later replaced with mixed broadleaved species. When conditions are most favourable for bracken it is more difficult for regenerating seedlings to establish under the dense canopy, and takes them longer to suppress the fern by shade, often up to several decades (Baylis, 1958). Generally, bracken cannot persist for much longer than about 60 years unless there are repeated disturbances, such as fire, that keep creating openings necessary for its rejuvenation (Druce, 1957).

Successional pathways after disturbance

Successional pathways after disturbance in a lowland podocarp-hardwood forest vary according to the type of disturbance (fire, storm damage, drought, windthrow, volcanism, pathogen attack), vegetation (composition, age, resistance, vigour), climate, location and the return time of further disturbance. Despite the potential for variation in lowland forest regeneration sequences, some common trends are recognisable. The generalised pattern of regeneration after fire clearance in a 10 hectare area of the Tutira catchment is shown in Figure 2.13, based on long-term observations (Guthrie-Smith, 1969; Wassilieff, 1986).

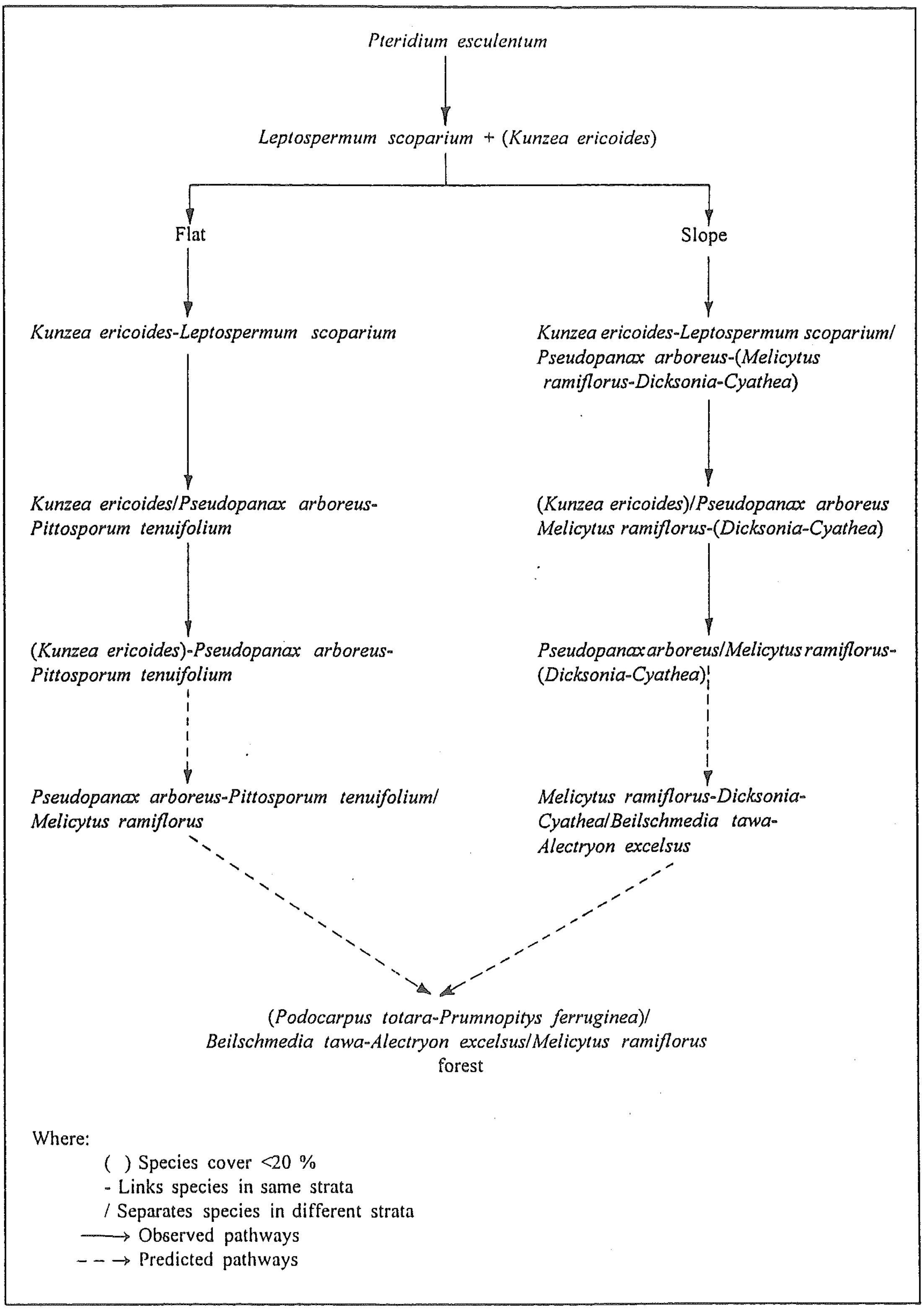


Figure 2.13. Typical successional pathways from burnt clearings to forest cover at Tutira, Hawke's Bay (from Wassilieff, 1986).

CHAPTER 3

METHODS

Core collection

Sediment cores 6 m long, were taken from the deepest part of each lake basin in this study using an air-assisted Mackereth piston corer (Mackereth, 1958) (Table 3.1). The coring sites were located away from inflowing rivers or streams to avoid direct fluvial inwash (Figures 2.2 and 2.3). Sediment cores were systematically sub-sampled (0.5 cm^3) at 10 cm or 15 cm intervals, and at closer intervals of 0.5 to 1 cm above tephra deposits, for subsequent analyses. Sub-sampling of sediment began at the top depth of sediment in the core tubes (Table 3.1).

Table 3.1 Details of lake sediment cores.

	Study site			
	Tutira		*Putere*	
Lake	Tutira	Waikopiro	Rotonuiaha	Rotongaio
Core label	LT16	LW8	RNUI3	RNGA3
Total depth of sediment in core tube (m)	5.9	4.23	5.65	2.9
Depths of surface sediment inside core tube (m).	0.10-5.9	1.62-5.85	0-5.65	0-2.9
Water depth of core site (m)	38	14	29	5

Lake sediment core stratigraphy and chronology

Erosion pulses

An erosion pulse identified in a sediment core, consists of rapidly inwashed, mostly allogenic (produced outside of the lake) catchment material. An erosion pulse visibly grades from coarse sand to silt, then fine clay and indicates a discrete episode of soil erosion in the catchment after a high intensity rainstorm (Dearing, 1991; Page *et al.* 1994a). The presence of graded mineral sediments and a change in the grittiness of sediment were used to identify these pulses in the cores. An erosion pulse was distinct from the smooth, soft, and often textureless authigenic (produced within the lake) lake sediments. Plate 2.4 illustrates the visual difference between the allogenic pulses and authigenic sediments in surface sediments from Lake Tutira.

Dating

Tephras that have been well dated from many sites around the North Island of New Zealand, provided reliable time horizons when they were identified in the lake sediment cores of this study. Tephras in the cores from Lakes Tutira and Rotonuiaha were identified by mineralogy and microprobe analysis (by Denis Eden, Landcare Research: Eden *et al.* 1993; Eden & Froggatt, in prep). The depth of first European influence was pinpointed in the sediment cores by the first appearance of pollen from introduced taxa in the fossil pollen profiles.

Two 0.5 g organic/clay samples were taken from the Lake Rotonuiaha core (RNUI3), and one sample from the Lake Rotongaio core (RNGA3). These samples were submitted to the Rafter Radiocarbon Laboratory, Institute of Geological and Nuclear Sciences, Wellington for accelerator mass spectrometry dating. The dates are presented in this thesis as conventional radiocarbon years uncorrected for secular variation. Calculated ages were based on sedimentation rates, and the relative position of the dated sample to the depth of widely dated tephra deposits (e.g. 1850 BP Taupo Tephra).

Pollen analysis

Past vegetation assemblages were reconstructed using pollen analysis of lake sediment sub-samples. Pollen samples were prepared following the standard techniques of Moore & Webb (1978):

1) Potassium hydroxide digestion to remove humic acids and disperse sediment.
2) Hydrochloric acid treatment to remove any traces of carbonate before hydrofluoric acid treatment.
3) Hydrofluoric acid treatment to remove inorganic material and diatom frustules, followed by rinses with warm hydrochloric acid to bring fluorosilicates into solution, removal of which prevents cloudy slides.
4) Oxidation with bleach solution, to remove lignin and other organic substances unaffected by acetolysis. The oxidation stage tends to cause pollen grains and spores (collectively referred to as palynomorphs) to swell, therefore this stage is followed by acetolysis which partially reverses the swelling.
5) Acetolysis, to destroy cellulose and some organic compounds.
6) Residues containing the concentrated pollen were stained with basic fuchsin and mounted in glycerine jelly on glass slides.

Pollen and spores were identified using a Leitz Ortholux II microscope, at 400 x magnification. When needed, grains were rolled over in the jelly using a heated needle to display the palynomorph in different positions. Difficult grains were identified under a high powered (x 1000) oil immersion objective. Traverses were spaced across the whole area of the coverslip to minimise the effects of differential settling of pollen and spores on the slide. A pollen sum consisting of 250-300 terrestrial pollen and *Pteridium* spores were counted at each depth. After each count, the slide was scanned for "traces" of taxa not encountered in the count.

The reference collection of New Zealand pollen and spores at Landcare Research (Lincoln, NZ) and the *Spore Atlas of New Zealand Ferns and Fern Allies* (Large & Braggins, 1991) were used to check and assist with identifications. The taxonomic nomenclature adopted here follows that of Allan (1961), Moore & Edgar (1976), with the subsequent taxonomic revisions made by Brownsey *et al.* (1985), Connor & Edgar (1987) and Webb *et al.* (1988).

Nothofagus classifications follow Hill & Read (1991) and Hill & Jordan (1993). Pollen and spores were identified to the lowest possible taxonomic level. Often it was necessary to group several taxa from the same family because the pollen and spores were too similar to differentiate between species. In this case "type" was suffixed to one of the species names within the group, e.g.:

Fuscospora: all *Nothofagus* spp. except *Nothofagus menziesii.*
Podocarpus totara type: includes *P.totara* and *P.hallii.*
Leptospermum type: *Leptospermum scoparium* (manuka) and *Kunzea ericoides* (kanuka).
Cyathea dealbata type: *Cyathea dealbata* and *Cyathea medullaris.*
Taraxacum type: all species in the family group Tubuliflorae, native and exotic.
Unknowns: all pollen grains that could not be identified.
Unidentifiables: all pollen so poorly preserved they could only be recognized as pollen.
Undifferentiated (Undiff.): pollen or spores undifferentiated within a group, although there is variation.

Pollen counts are usually expressed as percentages of a sum or as absolute concentrations. The successful application of absolute pollen counts relies on a constant sedimentation rate, or many closely spaced radiocarbon dates along the core to determine any fluctuations in sedimentation (Moore & Webb, 1978). Lake sediments from Tutira and Putere were contaminated by old carbon and therefore returned inaccurate radiocarbon dates, which meant it was not possible to obtain the close chronological control necessary for absolute counting. For this reason, and because of the frequently variable rates of sedimentation found in three of the four lake cores collected for this thesis, the technique of absolute pollen counting was considered inappropriate and not used here.

Instead, the pollen counts were expressed as relative percentages of a dryland pollen sum including all terrestrial pollen grains and *Pteridium* spores. This sum was chosen to provide the clearest information on the surrounding vegetation and to exclude the influence of locally produced pollen (Jacobson & Bradshaw, 1981). Fern spores other than *Pteridium,* were excluded from the sum because of their tendency to be abundantly produced, but poorly dispersed which results in their erratic representation (Pocknall, 1980). Thick walled tree fern spores are highly resistant to degradation and this may lead to their over-representation in the pollen record through differential preservation (Havinga, 1967; and this study). Poorly dispersed wetland pollen types such as Cyperaceae and Typhaceae were also excluded from the sum to avoid the over-representation of local taxa. All pollen diagrams were plotted using the computer program *Tilia Graph* and the taxa arranged into groups including "tall trees", "smaller trees, shrubs and climbers", "wetland", "exotic" and "ferns and fern allies" to improve the readability of the diagrams. Taxa recorded at trace levels are represented on the diagrams as small crosses "+". The main pollen diagrams in Chapter 5 are presented in two parts (a) which includes the main taxa discussed in the text, and (b) the remaining taxa.

Vegetation changes are inferred from the increase or decrease of certain key indicator taxa in the pollen diagrams. For example, the sudden abundance or increased frequency of *Pteridium esculentum* spores or *Coriaria* and *Aristotelia* pollen in a pollen spectra otherwise dominated by forest taxa provides a reliable indication of forest disturbance, based upon the present day ecological behaviours of these taxa.

Multivariate analyses of pollen data from cores LT16 and RNUI3

In addition to standard pollen analyses, multivariate techniques of classification and ordination were used to assist with fossil pollen interpretations from cores LT16 and RNUI3, to assess temporal changes in total species composition. They were also used to confirm links between the compositional vegetation changes and environmental disturbance indicators (tephra, charcoal and erosion pulses). Multivariate analyses allow compositional changes occurring across such disturbance boundaries to be assessed in relation to variation within the whole profile. Cumulative changes in the total composition of the profiles indicate compositional shifts that are often difficult to detect when a subjective approach is used alone.

Multivariate analyses of pollen and spore percentages, by taxa, among sub-samples, were used for the LT16 and RNUI3 pollen profiles to examine patterns of pollen composition within the cores. Of the four cores used in this thesis, only LT16 and RNUI3 were selected for multivariate analyses because they contained the oldest material (Taupo Tephra was present at the base of both cores) and the longest record of vegetation history. Cluster Analysis was used to group samples by composition. Detrended Correspondence Analysis was used to examine gradients of variation. Only samples below the depth of European influence were included in this analysis because of the completely different floral composition in the European era, demarcated by the first presence of European pollen types (see Table 5.5). For Cluster Analysis the similarity measure was Canberra Metric, and the sorting strategy was flexible (UPGMA) with beta set at -0.10. All analyses were performed using the PATN analysis package (see Belbin, 1989, and references therein).

Differential pollen and spore preservation

Sub-samples of lake sediment cores prepared for pollen analysis from the Tutira and Putere lakes, were analysed for the preservation condition of identifiable pollen grains, bracken spores and tree fern spores. Differential preservation analyses are usually based on selected taxa (e.g. Birks, 1970; Tolonen, 1980; Lowe, 1982). In this thesis, three groups have been chosen: (1) pollen, (2) bracken spores and (3) tree fern spores. Pollen and tree fern spores were selected because they represent two groups of palynomorphs with distinctly different susceptibilities to deterioration. The tree fern spores have thicker outer walls and are more resistant to decay than most types of pollen. Bracken spores were selected because this fern is an important indicator of disturbance in the fossil pollen record. It is critical that bracken representation is fully understood so that accurate palaeoecological interpretations can be made from the fossil bracken spore record.

The prepared pollen slides were analysed after the completion of pollen analysis as it was more time-efficient, and allowed greater consistency and objectivity in the analysis. Unidentifiable pollen grains were recorded during routine pollen analysis and presented as a percentage of the total pollen counted in each sub-sample. These palynomorphs were so deteriorated, they were recognisable only as pollen grains.

Three preservation categories were sufficient to describe the different types of palynomorph preservation seen in the Tutira and Putere cores. The categories are based upon those of Cushing (1967):

(1) *Whole:* The exine (resistant outer layer of a pollen/spore wall, depending on structure is sub-divided into endexine and ektexine) shows no sign of deterioration. Grain or spore complete and well preserved.

(2) *Corroded:* The ektexine (outermost layer of exine) is etched or pitted. Corrosion may affect only part of the exine. Severe corrosion may result in most of the ektexine being eaten away, leaving only remnants of ektexine upon the surface of the intact endexine (inner layer of exine). This creates the impression of a "ghost" grain or spore, most commonly seen in the more resistant fern spores.

(3) *Broken:* The endexine is ruptured, leaving the pollen grain or spore incomplete, or torn in half.

These preservation categories are illustrated by micro-photographs (Plate 3.1). Two other categories of deterioration "degraded" and "crumpled" were rarely seen in the Tutira and Putere cores, but are commonly recorded in other works (e.g. Cushing, 1967; Tolonen, 1980; Hall, 1981; Havinga, 1984).

Initial experimental analyses were undertaken during pollen counting, using five preservation categories based on percentage cover of corrosion on the grain or spore surface, but these proved to be too subjective and made reproduction of results difficult. The selection of only three categories allowed for greater consistency and a more objective analysis. Corroded and broken pollen grains or spores were assigned to the corrosion category.

The most subjective category was "broken", and in an attempt to maintain some recording consistency, several conditions were set up before counting proceeded. These were: (1) naturally splitting pollen grains such as Cupressaceae type were only recorded as broken if they appeared to be split more than usually observed on a reference slide; and (2) as bracken spores tend to split easily at the trilete scar (possibly caused by processing techniques) they were only recorded as broken if the endexine was ruptured.

For each sub-sample in the cores, 100 pollen grains (all taxa included), 100 bracken spores and 100 tree fern spores were counted and placed into one of the three preservation groups. If there were insufficient palynomorphs present on a slide to make a representative count, then no count was made.

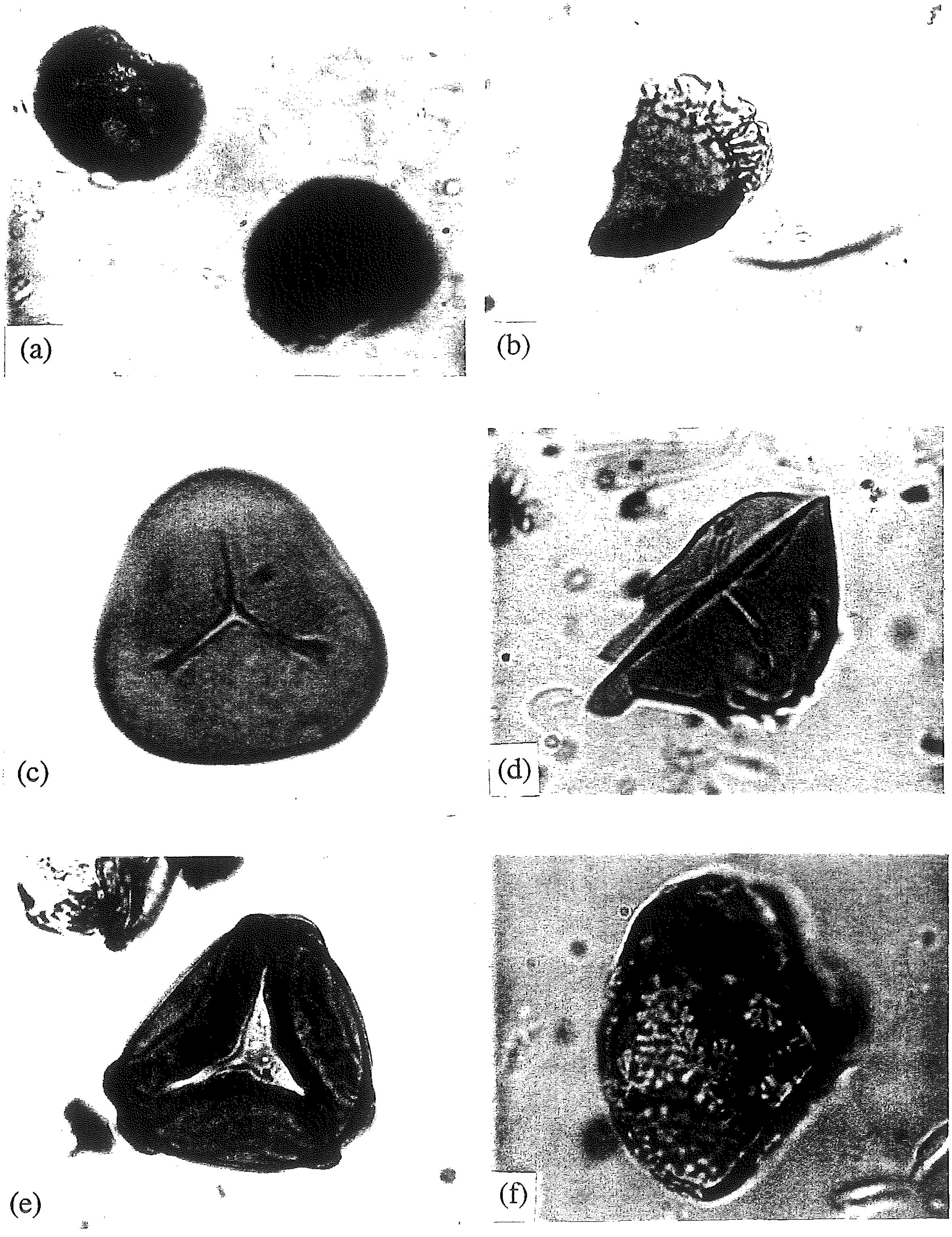


Plate 3.1. Examples of pollen, bracken and tree fern spore preservation categories: (a) *Dacrydium cupressinum*, corroded (left) and whole (right); (b) *Dacrydium cupressinum*, broken; (c) *Pteridium esculentum*, whole; (d) *Pteridium esculentum*, broken; (e) *Dicksonia fibrosa*, whole; (f) *Cyathea dealbata* type, corroded. (All x 1000, except (b) x 400).

Surface pollen sample collection and treatment

A total of 47 surface samples were collected from the Tutira and Putere catchments, 12 catchment soils, 25 moss cushions, and 10 surface sediments from Lake Tutira. At Tutira, the soil samples were collected from topsoils under permanent pasture and next to roadside hedgerows (mostly exotic species). At Putere, they were collected from the fern litter beneath *Pteridium esculentum* and *Paesia scaberula* canopies, and from mineral litter on the edge of an area of regenerating *Leptospermum scoparium/Kunzea ericoides* shrubland. Each soil sample was a composite of separate sub-samples collected from a 3 m^2 area, from the surface 1-2 cm of soil.

At all moss sample sites, at least 4-5 sub-samples of moss cushions were collected from within an area of 3 m^2 and combined into a single sample. Whole moss cushions (excluding soil from the rhizoids) were sampled, to avoid the effects of differential retention of pollen and spores within the cushions (Crowder & Cuddy, 1973). It is not known exactly how many years of pollen entrapment the moss cushions represent, but sampling from mixed, intact moss cushions ensures that an average of at least several years of pollen deposition is analyzed. Composite samples also reduce the effects of seasonal or annual fluctuations in pollen output. Most samples were collected from open pasture or from the edge of patches of regenerating native trees and shrubs to avoid over-representation of local types. At Tutira, moss samples were taken from both the northern and southern ends of the catchment and are organised into "south" and "north" moss samples in the Tutira surface pollen diagram.

Surface lake sediments were collected from the top 1-2 cms of freeze-box cores collected from Lakes Tutira and Waikopiro. The frozen cores were extracted from the lakes using a freeze box corer (design and technique described in: Huttunen & Merilainen, 1978) and were effective at retrieving the sloppy surface sediments and the sediment/water interface.

Pollen analysis followed the same procedures and conventions for fossil pollen analysis (Moore & Webb, 1978), except moss samples did not require hydrofluoric acid treatment. Pollen, bracken spores and tree fern spores in the surface samples were also analysed for differential preservation.

Organic carbon content of sediments

Sub-samples of core LT16, and ten soil samples from the Tutira catchment were placed in a muffle furnace at 1000°C for 20 minutes. Weight loss after combustion (i.e. loss on ignition) was measured to provide an estimate of the organic carbon content of the sediments (Bengtsson & Enell, 1986).

The loss-on-ignition values provide an index of biological productivity in the lake basin, as the correlation between organic carbon content and loss on ignition is generally accepted to be very good (Hakanson & Jansson, 1983). Organic matter may be of authigenic or allogenic origin and be transported to the lake in both dissolved and particulate form. The relative proportion of organic matter derived from the different sources is a function of the catchment characteristics in relation to the lake productivity (Hakanson & Jansson, 1983). In principle, the proportion of organic carbon that originates from outside the lake increases with decreasing lake productivity.

Charcoal analysis

Fossil charcoal analyses are used to reconstruct fire histories (Patterson *et al.* 1987; MacDonald *et al.* 1991; Horn, 1993). Charcoal is formed by the incomplete combustion of plant material and its resistance to decay ensures its preservation in lake sediments and similar deposits. Microscopic charcoal fragments were recorded on the slides made up for pollen analysis at the same time as pollen counting using the point-count technique of Clark (1982). The results are presented in the pollen diagrams as a percentage of the total pollen and spores counted, and as the area of charcoal (mm^2) present on each slide (484 mm^2). The area of charcoal was also used, as displaying charcoal counts as a percentage of the total pollen count, often lead to misleading peaks of charcoal in samples containing low concentrations of pollen. This occurred because relatively more traverses needed to be made on such slides to reach the desired pollen sum, and therefore the probability of "striking" more charcoal fragments was higher.

The point count charcoal method (Clark, 1982) was used in preference to nitric acid digestion (Winkler, 1985) after a preliminary experiment using the latter technique gave unreliable results and was not sensitive enough to pick up low concentrations of charcoal.

In addition it was not possible to make reliable correlations between the results from microscopic counts and nitric acid digestion techniques. These conclusions were also made by MacDonald *et al.* (1991) and Patterson *et al.* (1987). Naturally produced charcoal contains highly variable amounts of elemental carbon (Winkler, 1985). A proportion of material microscopically identified as charcoal is often removed by digestion and leads to underestimations (Patterson *et al.* 1987). The chemical digestion technique also tends to underestimate the charcoal content relative to microscopic counts when the inorganic component of sediments is high (Patterson *et al.* 1987), as occurred with the Tutira samples.

Sediment chemistry

X-ray fluorescence spectrometry (XRF) was used to analyse 59 lake sediment sub-samples from core LT16 for ten major chemical components. Samples were collected from the same depth as the pollen samples. Ten soil samples including topsoil and exposed regolith from the Lake Tutira catchment were also analysed for comparison. The XRF techniques followed the general methods of Norrish & Hutton (1969) with modifications after Harvey *et al.* 1973 and Schroeder *et al.* (1980), using a Philips PW 1400 spectrometer at the Geology Department, University of Canterbury. Calibrations were based on recommended values for 30 international standard rocks. Details of the estimates of accuracy and general precision are given in Weaver *et al.* 1990.

The XRF technique was used to assess the sediment composition of Lake Tutira to show past changes in soil erosion and catchment stability. However, the results showed that bulk sediment chemistry on these highly minerogenic sediments was too crude a technique to reflect such detail. As the results could not be applied as proxies of past catchment erosion, they are discussed in Appendix 5.

CHAPTER 4

POLLEN ACCUMULATION IN MOSS CUSHIONS, SOILS AND SURFACE LAKE SEDIMENTS FROM THE TUTIRA AND PUTERE CATCHMENTS

INTRODUCTION

The data from most modern pollen rain studies in New Zealand are used to help interpret Quaternary fossil pollen records (e.g., Moar, 1970; Pocknall, 1978; McGlone, 1982; Bussell, 1988a; Randall, 1990). Some have been concerned with a variety of objectives including: identification of atmospheric pollen for a guide to hay-fever diagnoses (Clark, 1951; Licitis, 1953); dispersal abilities and representation of certain pollen types (Moar, 1969; Myers, 1973; McKellar, 1973; Dodson, 1976; Moar & Myers, 1978; Macphail & Mildenhall, 1980; Pocknall, 1982a; Salas, 1983); and the use of multiple regression analysis to calibrate transfer functions, that link modern pollen data with climatic variables (Norton *et al.* 1986). Most importantly, the data from these modern pollen rain studies have helped clarify relationships between species abundance and the relative frequency of pollen recorded at a sampling site. A better understanding of modern pollen representation at a site allows a more informed and accurate interpretation of the fossil pollen record.

Most New Zealand surface pollen rain studies have analysed only moss cushions in which pollen and spores are predominantly aerially derived from contemporaneous sources. These results are usually used to help interpret Quaternary pollen records from peat cores. This is a valid comparative approach given that bogs derive most of their pollen from aerial fallout, and little from soils and waterborne sources. However, lake basins derive their pollen and spores from a mixture of aerial and inwashed sources, which may change over time according to environmental conditions in the catchment. Therefore, surface pollen analyses based solely on moss cushions may be of limited use in helping to interpret fossil pollen records from lake sediments. Analyses of surface lake sediments provide additional information about pollen representation and derivation allowing more direct comparisons to be made with pollen records from ancient lake sediments. Several overseas pollen rain studies have focused on identifying sources of pollen and spores in recent lake sediments (e.g., Birks, 1970; Dodson, 1977; Bonny, 1980; Fall, 1992) but only one similar investigation has been completed in New Zealand. Pocknall (1980) analyzed and compared pollen spectra in moss cushions and surface lake sediments from Lady Lake, North Westland. However, these results were applied to the interpretation of a fossil pollen record from a peat core taken from a swampy lake margin, where pollen transport, deposition and preservation processes would be different to those operating in a lake basin.

The problems associated with inwashed soil-derived pollen in lake sediment cores have not been quantitatively addressed in New Zealand palaeolimnological investigations. However, the lake sediment cores collected from Tutira and Putere contain a high proportion of inwashed catchment material (see Chapter 5), and the potential exists for secondary inwashed pollen and spores to contribute substantially to the sediments. Secondary contamination may reduce the ability of the fossil pollen record to accurately represent the past catchment vegetation. Therefore, this surface pollen rain study aims to define the sources of pollen, *Pteridium esculentum* (bracken) and tree fern spores in lake sediments, by comparing the pollen spectra from moss cushions and catchment soils with surface lake sediments. In addition, differential preservation analyses of the pollen and spores in each of the three sample types are used to differentiate between secondary/inwashed and contemporaneous/aerial pollen and spores. The results can then be extrapolated to the fossil pollen record (Chapter 5) to help identify changing sources of pollen and spores over time and to assist with more accurate interpretations.

BACKGROUND INFORMATION

The following sections on pollen dispersal, representation, deposition, transport and source areas provide background information that help with the interpretation of both fossil and surface pollen data. A section on differential pollen and spore preservation outlines the current applications of this technique to palaeoecological studies.

Pollen representation and dispersal

Pollen representation expresses the relationships that exist between species abundance and the amount of pollen recorded at a sampling site. Pollen and spores may be represented in the pollen record at greater percentages than the percentage cover of the source plants within the sampled vegetation (over-represented); at approximately the same percentage (well-represented); or at lower percentages (under-represented). Flowering periodicity, differential pollen production and dispersal between species, plant structure, mode of pollination, shape and weight of pollen, mode of transport and deposition, differential preservation, local environmental factors and source plant abundance in the vegetation may all affect the representation of pollen at a site.

Wind-pollination is uncommon in New Zealand trees and shrubs. Of the major canopy species it only occurs in the podocarps, *Nothofagus* and *Laurelia novae-zelandiae*; among the shrubs and small trees, in a few genera such as *Ascarina*, *Coprosma* and *Dodonaea*; while among the herbs, it is rare except for *Acaena*, *Gunnera* and species in Cyperaceae, Poaceae and Restionaceae (McGlone, 1988c). Animal pollination is found in several genera, e.g., *Metrosideros*, *Fuchsia, Phormium, Dactylanthus taylorii*, but insect-pollination predominates throughout the flora. Some of the insect-pollinated (e.g., *Quintinia* and *Weinmannia*) and bird-pollinated (e.g., *Metrosideros*) canopy trees can produce large amounts of pollen which is dispersed extremely locally. Unless insect-pollinated taxa occur close to the sampling site or their pollen is transported by water, the pollen from these taxa are often severely under-representative of the non-local vegetation cover (e.g., *Leptospermum* type). Although wind-pollinated taxa tend to be over- or well- represented compared to the insect pollinated taxa, exceptions do occur, e.g., *Dacrycarpus dacrydioides* and Cyperaceae (Macphail & McQueen, 1983). However, because of their limited powers of dispersal, if these taxa occur locally they may overwhelm other extra local and regional sources.

While there are many monospecific genera which have prominent pollen types in the modern New Zealand flora (e.g., *Knightia, Dacrydium, Dacrycarpus, Dodonaea, Schefflera*), other pollen taxa have several source species with different ecological ranges and habits (Macphail & McQueen, 1983). The different source plants may change in the course of the pollen profile but will be indistinguishable in the pollen record. *Coprosma* is a good example with *c.* 45 different species (Allan, 1961) represented in the one pollen taxon. *Metrosideros* may be represented in the pollen record by trees (e.g., *Metrosideros robusta*), shrubs (e.g., *M. colensoi*) and climbers (e.g., *M. fulgens*). Knowledge of present day ecological preferences and plant associations can minimise the potential complications this can create when interpreting fossil pollen records (see Chapter 2). Interpretations of pollen records from species-rich forests can be difficult, partly because broad pollen taxa can be of limited diagnostic value, and some insect- or bird-pollinated taxa are severely under-represented. Despite the limitations, accurate indications of vegetation associations can be derived from New Zealand pollen records, particularly when constrained and guided by studies of modern pollen assemblages from surface materials.

Pollen deposition, transport and source area

An estimate of pollen source area (i.e., the area from which most of the pollen sampled at a site is derived) is essential for interpreting fossil pollen records (Oldfield, 1970; Sugita, 1993). This is because ecological patterns and processes are scale dependant, that is the size of the lake or bog chosen for study affects the pollen representation of vegetation (Sugita, 1994). Pollen grains that are not dispersed by animals, are dispersed on wind currents through the atmosphere like other small particles. The rate of dispersal depends on factors such as air turbulence, wind speed and direction, the shape and weight of the pollen grain, and height and strength of the pollen source area (Janssen, 1973). Tauber's (1965, 1977) model of pollen dispersal within a forest proposed that pollen is transported to most sites mainly through trunk space (C_t), above the canopy (C_c), through rain out (C_r) and stream runoff (C_w) (Figure 4.0). Tauber's model predicted these components would be represented in different proportions depending on the size of the site, although it underestimated the importance of stream runoff. Janssen's (1966) model of pollen dispersal described the relationship between the magnitude of pollen deposition at a site and the areas from which they came i.e., local, extra local and regional.

Jacobson & Bradshaw (1981) introduced a gravity component into their model of pollen deposition (C_g) that describes the vertical deposition of dry pollen and inflorescences from plants present on the lake basin edge or overhanging the sampling site. Jacobson & Bradshaw's (1981) model depicts the relationship between basin size and pollen source area, and predicts the proportions of local, extra local and regional pollen received by lake basins of different sizes (Figure 4.0). They define local as pollen originating from plants growing within 20 m of the edge of the sampling basin, extra local as pollen from plants occurring twenty to several hundred metres from the sampling basin, and regional pollen from plants at greater distances. Although this model allows estimates to be made for the pollen source areas of basins without inflowing streams, Jacobson & Bradshaw (1981)

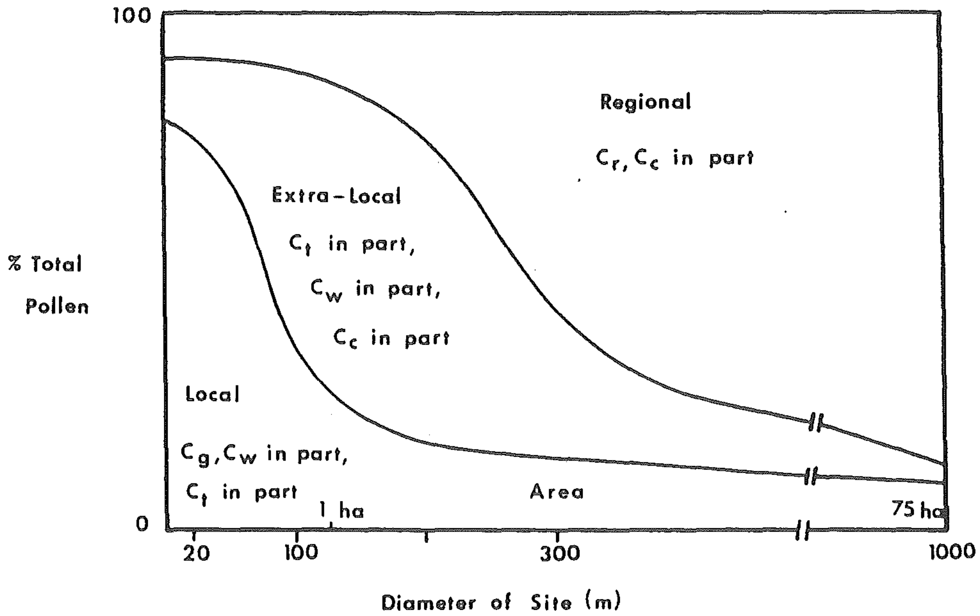


Figure 4.0. Relationship between the size of a site that has no inflowing stream and the relative proportions of pollen originating from different areas around the site; from Jacobson & Bradshaw (1981:82).

recognised that the predictions would be modified by local hydrological and topographical anomalies. They also noted the problem of distinguishing between a few individuals close to the sampling site and many individuals at a greater distance. Prentice (1985, 1988) developed a model that suggested pollen source area and relative pollen representation depend on basin size, according to functions that describe the amount of pollen remaining airborne at increasing distances from single pollen sources. The model simulations showed source areas increased with basin size, and differed substantially for pollen grains with different deposition velocities, predicting lighter pollen grains would be better represented in larger basins.

The above models estimate pollen deposition for a point at the centre of a sampling basin, or for a series of points along a radius, which provide more useful comparisons for pollen records from bogs rather than lake basins. Whereas pollen tends to remain where it is initially deposited on a bog surface, in lake basins pollen becomes mixed and resuspended in the water column and is redeposited over the entire lake basin. For these reasons, Sugita (1993) modified Prentice's (1985, 1988) work to create a model for pollen deposition on the surface of an entire lake basin, although pollen from the trunk space, rainfall and surface runoff components were not considered. Sugita (1993) found that in general, the pollen source radius for an entire basin surface is 10-30% smaller than for a point at the centre, with more substantial differences in the source radius for heavier pollen grains. The model predicts local pollen sources will influence the average pollen input to the entire lake surface more strongly than pollen deposition at the centre, partly because pollen loading to the entire surface includes the effect of heavy accumulation near the edge.

Sugita (1994) emphasises that the above models all assume even spatial distribution of plant abundance for any taxa surrounding the sedimentary basin, despite the fact this is rarely the case in reality. Sugita (1994) developed a model for pollen representation and prediction of relevant pollen source areas using simulated landscapes of patchy vegetation. Sugita's (1994) model identified differences in the sizes of the vegetation patches and the lake basins as the main factors affecting the ability of the pollen to reflect vegetation patchiness.

The earlier models of Prentice (1985, 1988) and Sugita (1993) predict relevant pollen source areas of 30-50 km radius for small to medium sized sampling basins (Figure 4.0).

Simulations from Sugita's (1994) model suggest much shorter distances (or radii) are needed to provide the best correlation between pollen and plant abundances if pollen and vegetation are sampled from areas of similar vegetation type and spatial pattern. For example, the relevant pollen source area would be about 600-800 m from the lake edge for a medium sized lake (radius 250 m) such as Tutira (radius = 75-100 m), and about 300-400 m for a small lake (radius 50 m) such as Rotonuiaha (radius = 30-50 m); and this area would provide a sufficient proportion of the total pollen loading (30-45%) to adequately reflect the local vegetation composition.

The common result produced by these theoretical models of pollen deposition and representation is that pollen representation of the vegetation is affected by the size of the lake or bog sampled, i.e., the larger the diameter of the sampling basin, the more the pollen spectra are influenced by extra local and regional sources. In addition, the spatial resolution provided by pollen records from a lake and a bog of similar diameter will differ. Davis (1994) emphasises the usefulness of this in palaeoecological investigations, i.e., by selecting a lake or bog of an appropriate size, the scale of a study can be regulated to fit the research question.

Differential preservation of pollen and spores

The walls of pollen and spores are made up of an extremely resistant, inert organic compound known as sporopollenin, which is thought to be formed by polymerization of precursors of carotenoids and carotenoid esters (Prahl *et al.* 1985). Generally, sporopollenin is concentrated in the exine. In addition to the exine, it can be found in the perine (the outermost layer outside the exine of certain spores) of most fern spore walls. The amounts of sporopollenin found in the exine vary considerably between plant taxa, but usually pollen and spores with thicker exines are more resistant to decay (Havinga, 1964, 1984; Sangster & Dale, 1964). Although sporopollenin is highly resistant to enzymatic and chemical attack, it can be broken down when exposed to chemical oxidation and highly alkaline environments. The compound has a great propensity to take up oxygen and in an oxidizing situation exines eventually swell and deteriorate.

Experimental work by Havinga (1964, 1984) and Sangster & Dale (1961, 1964) attempted to define the effects of chemical oxidation on pollen exines. It is now generally accepted that exine corrosion is caused by chemical oxidation, although it is difficult to know how quickly decay proceeds. Microbial attack is also thought to cause corrosion of pollen and spore exines. Havinga (1964) showed that chemical or biochemical attack of pollen in soil always began with oxidation, and the more readily pollen was oxidized, the faster the subsequent attack by microorganisms. Although there has been little work on the effects of soil, stream and lake microfauna on the exine of pollen and spores, they may be responsible for some damage (e.g., Conway, 1953; Davis, 1967; Van Toornen & During, 1988). Because of the paucity of information on the effects of micro- and macro-faunal damage to pollen and spores (Lowe, 1982), it is difficult to determine how much and what kind of damage animals can cause in different depositional environments, and ultimately how they affect the representation of different pollen and spore types in fossil pollen spectra.

Little is known about other causes of palynomorph degradation, breakage and crumpling, but some studies have shown correlations between deterioration type and the kind of material in which pollen and spores have been preserved (Cushing, 1967; Birks, 1970; Lowe, 1982). Cushing (1964, 1967) categorised the different types of pollen deterioration seen in a variety of sediment deposits. Birks (1970) and Lowe (1982) modified Cushing's earlier classification of deterioration types, and produced four categories:

(1) *corroded*: exines are pitted or etched, often at random or in a scalloped pattern,
(2) *amorphous or degraded*: exines have a waxy appearance, suggesting structural rearrangement of the exine has occurred,
(3) *broken*: grains are ruptured, parts (such as a pore or bladder) may be missing,
(4) *crumpled*: grains are folded, wrinkled or collapsed.

The preservation categories used in this thesis are based on the above categories (see Chapter 3). The main sources of deteriorated pollen and spores in lake sediments have been summarised by Lowe (1982) and are listed below:

Contemporaneous

(1) pollen and spores that were deposited on catchment surfaces after initial release, and remained there for some time before being washed into the lake by rain and surface runoff. This component is referred to in this thesis as the inwashed contemporaneous component.

The period of settlement provides the necessary time and conditions for exine decay to occur.

Secondary

(2) secondary stored pollen and spores that are inwashed with catchment soils into the lake basin.

(3) redeposition of secondary pollen and spores from eroded basin edge (littoral) sediments caused by lowered local water tables.

(4) redeposition of secondary pollen and spores from eroded riverbank sediments, particularly during periods of rapid discharge.

(5) post-depositional *in situ* deterioration of pollen and spores resulting from lowered lake levels and exposure of sediments to oxidation or biological attack.

(6) physical deterioration caused by diagenetic processes within the lake sediments.

METHODS

Methods for surface sample collection, pollen analysis and differential pollen and spore preservation analysis are outlined in Chapter 3.

RESULTS

Twenty seven surface samples were collected from the Tutira catchment, including 10 surface lake sediment samples (collected January 1992), 7 soil and 10 moss (including one lichen) samples (collected January 1993). Twenty surface samples were collected from the Putere catchments, including 15 moss and 5 soil samples (collected January 1993). The surface samples were selected to represent the major supply areas of pollen and spores to the lake sediments. The locations of the sampling sites in the catchments are presented in the lake catchment maps (Figures 4.1 and 4.2). Further details of each site including sample names, grid reference, local topography and local site vegetation are presented in Appendix 1. Pollen data are presented as a percentage of the dryland pollen sum (see Chapter 3) for all the Tutira surface samples in Figure 4.3, and for the Putere surface samples in Figure 4.4.

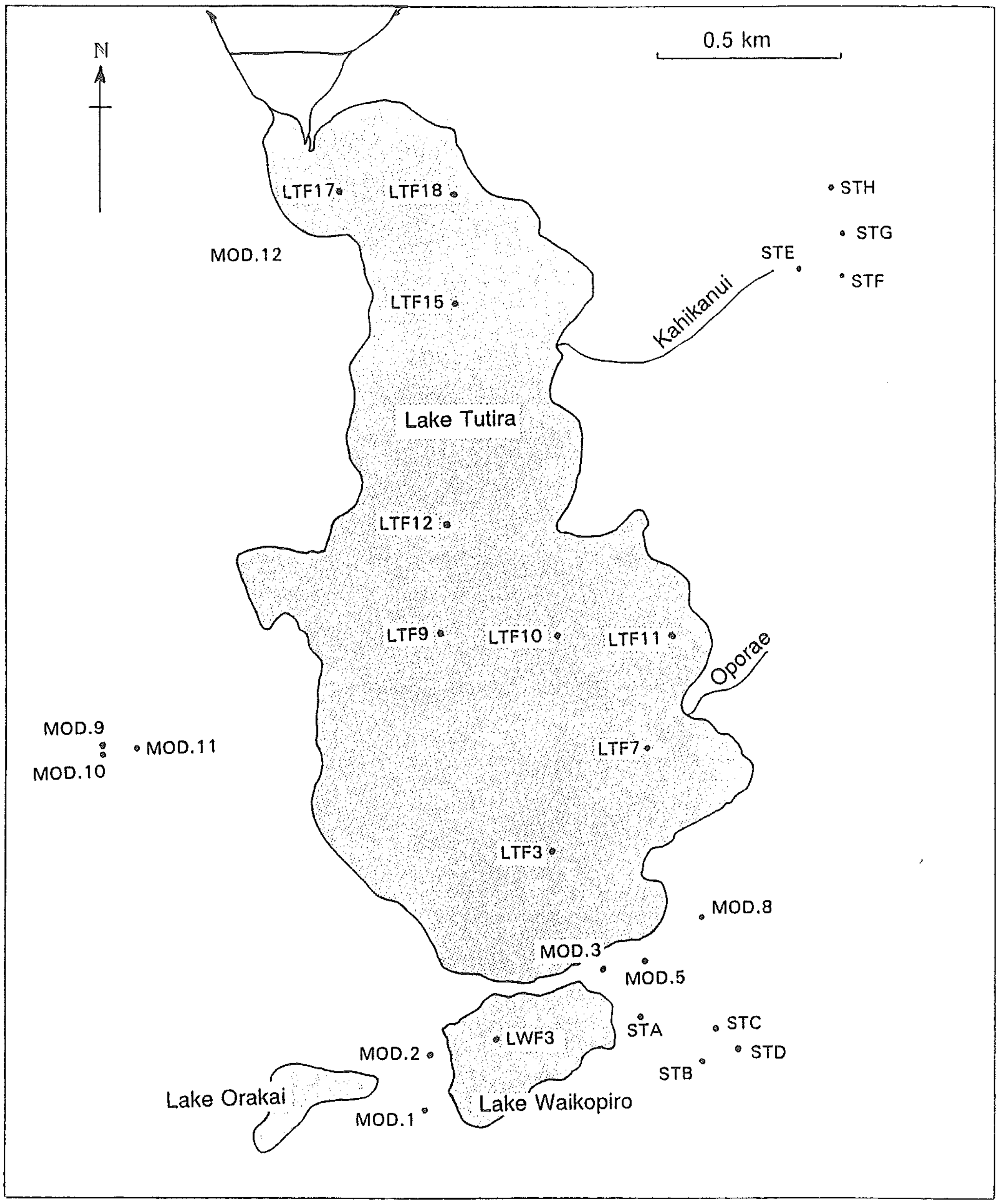


Figure 4.1. Location of surface sample sites in the Tutira and Waikopiro lake catchments.

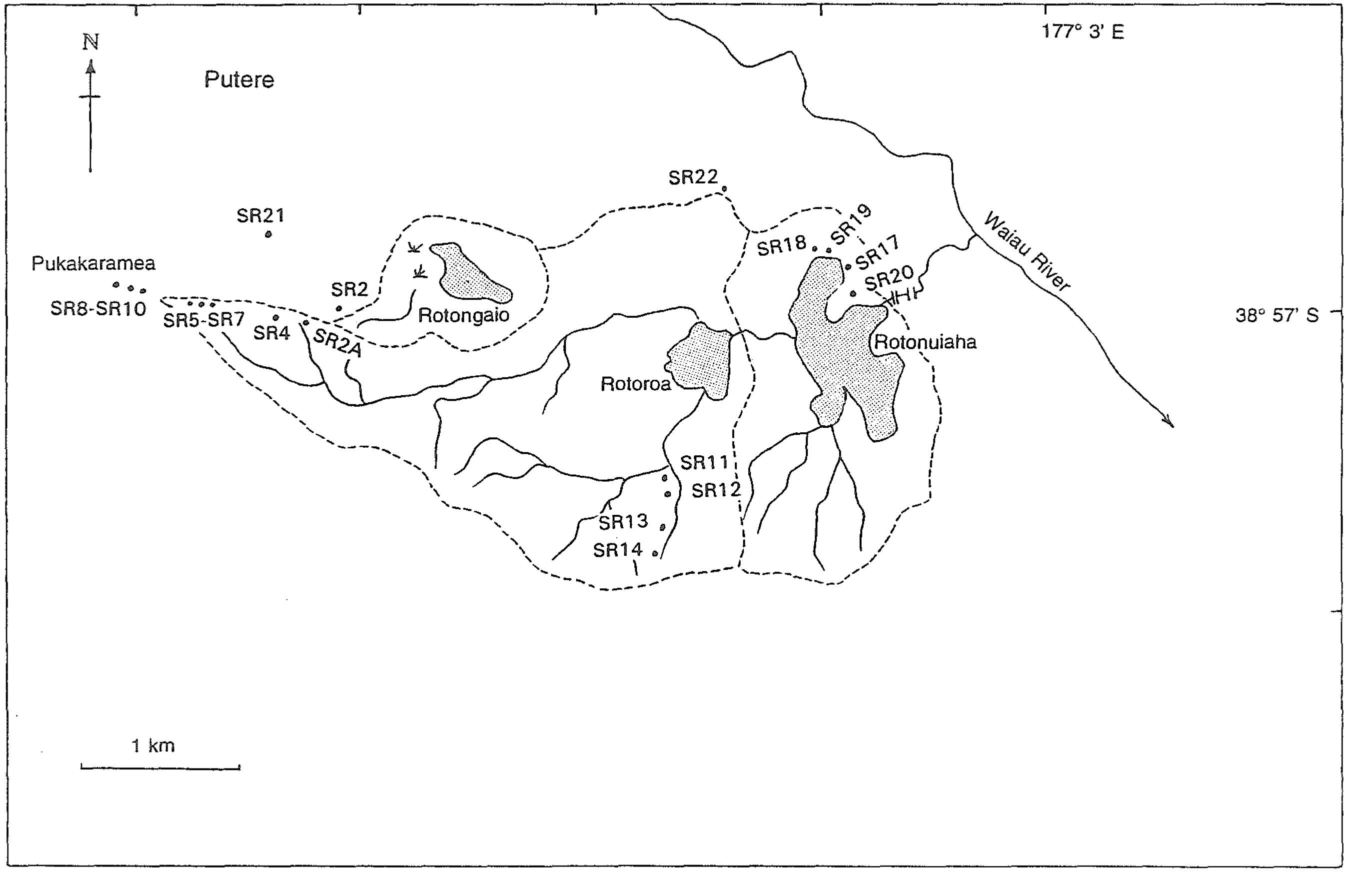


Figure 4.2. Location of surface sample sites in the Putere lake catchments.

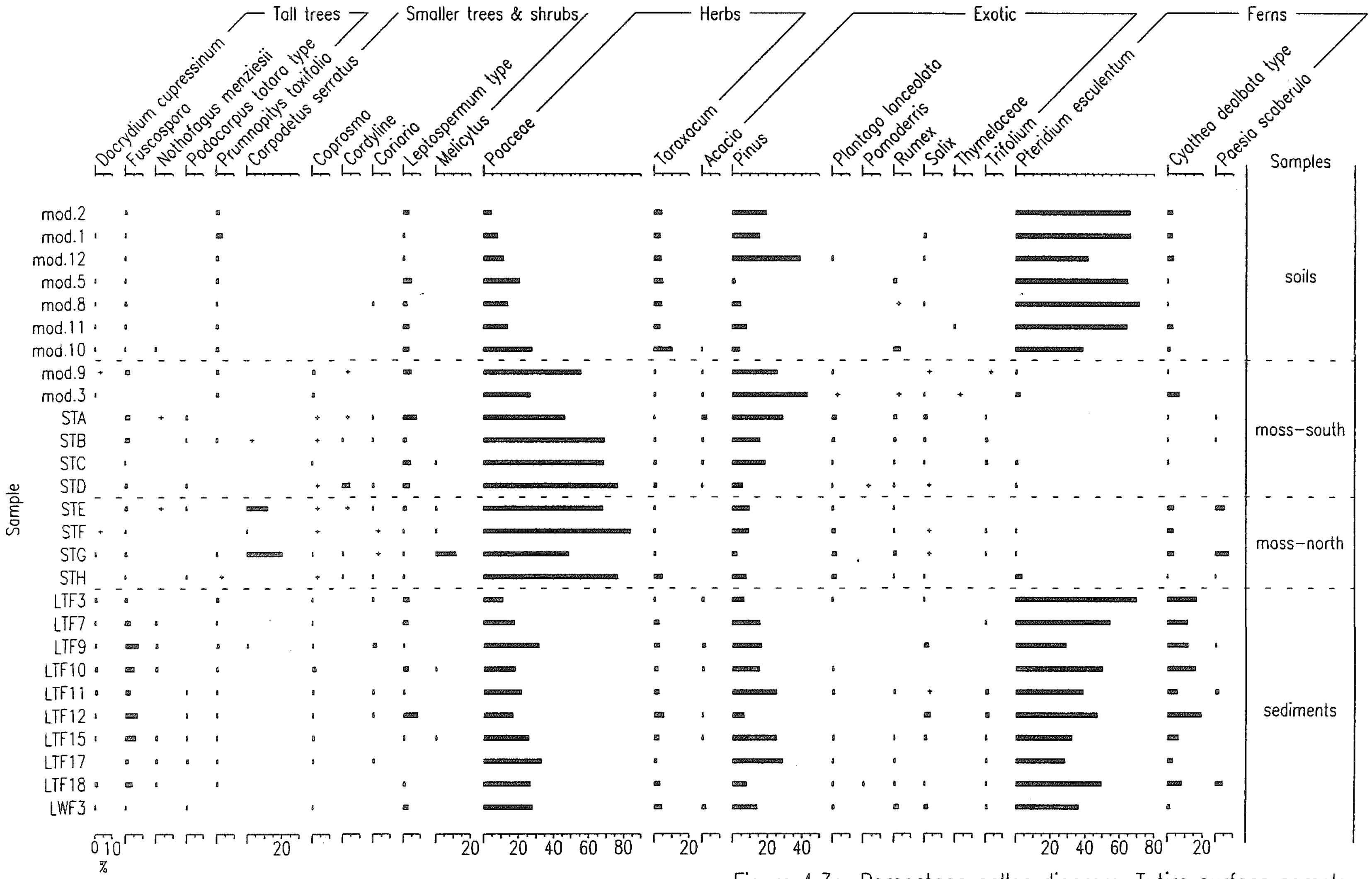


Figure 4.3a. Percentage pollen diagram: Tutira surface samples

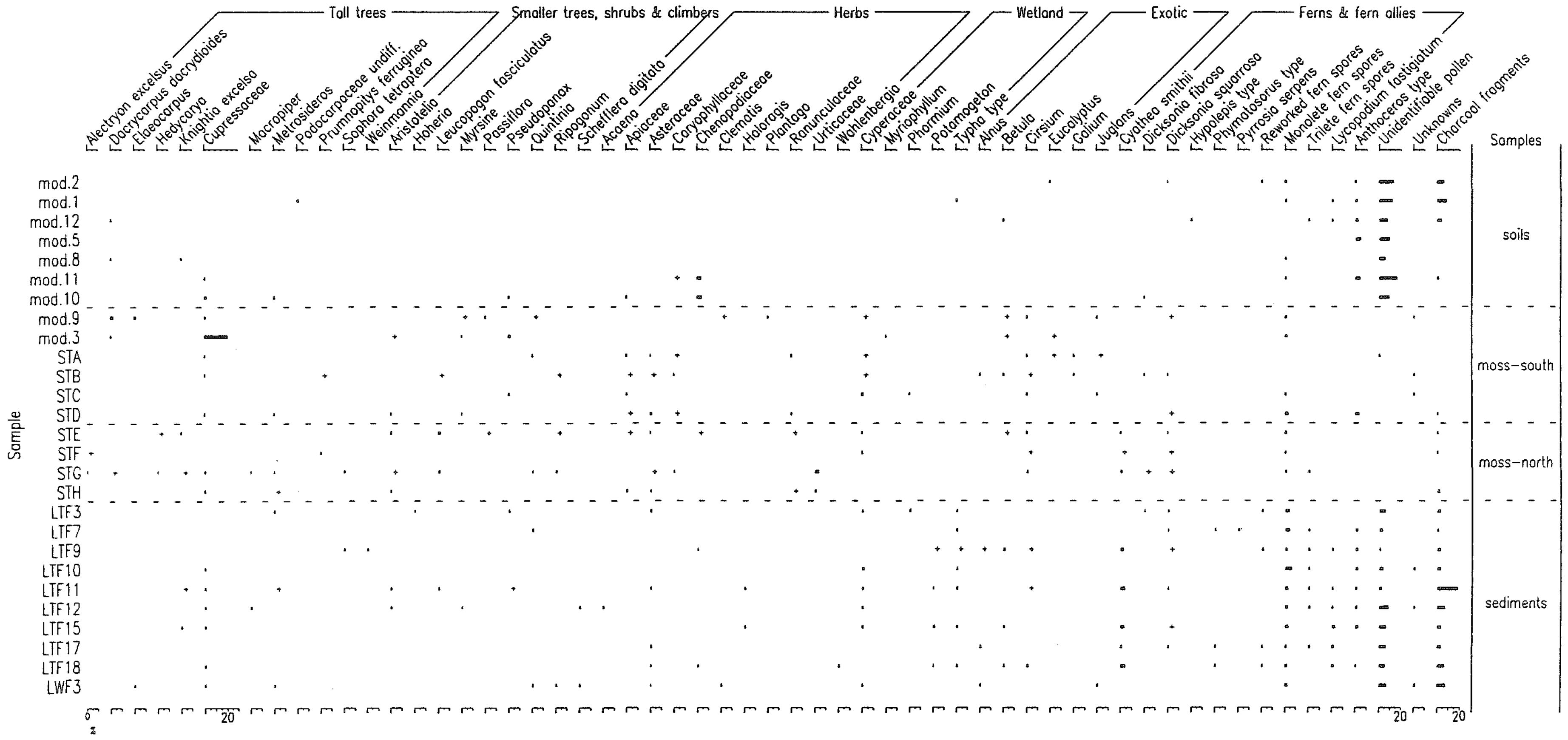


Figure 4.3b. Percentage pollen diagram: Tutira surface samples, cont.

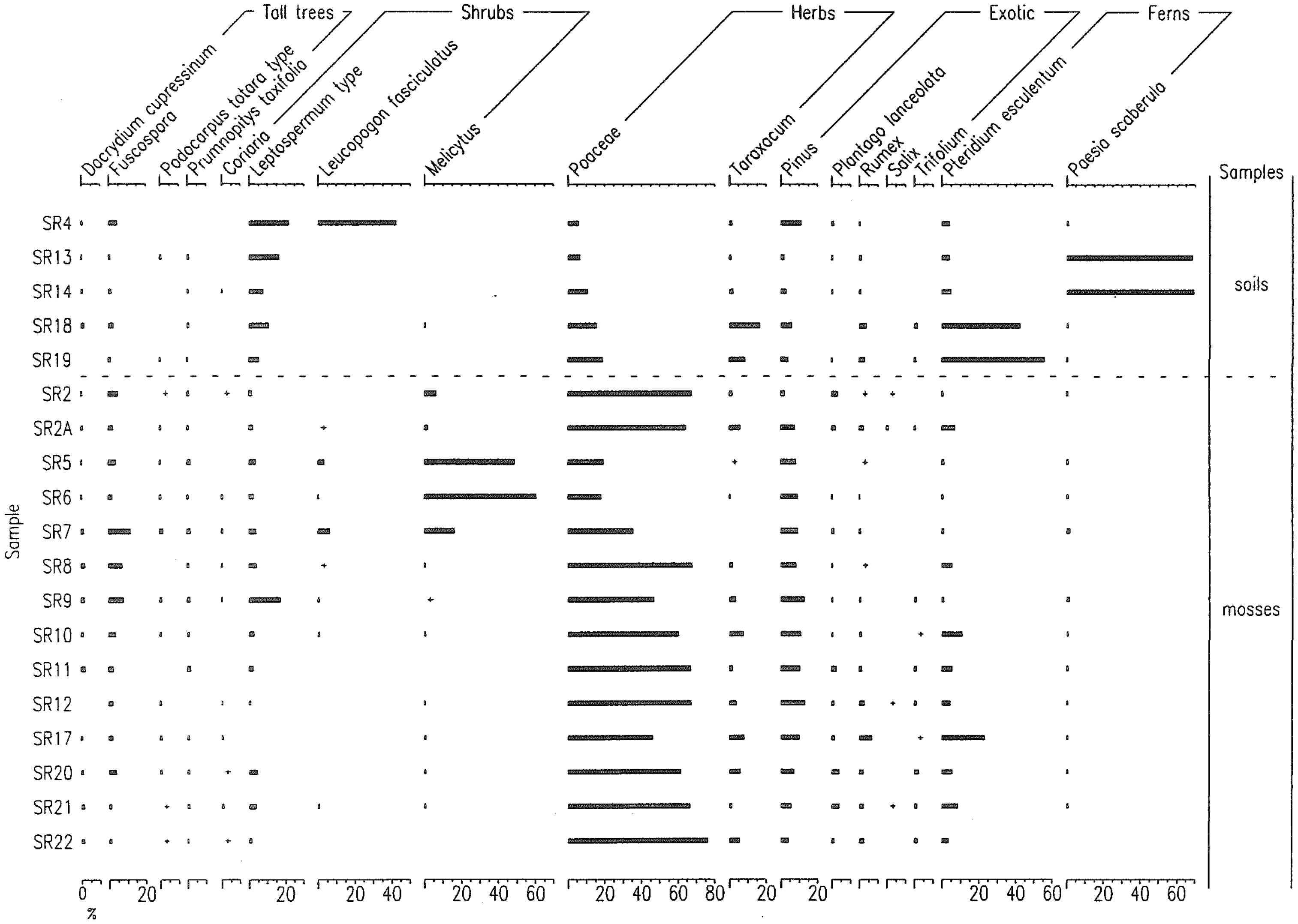


Figure 4.4a. Percentage pollen diagram: Putere surface samples

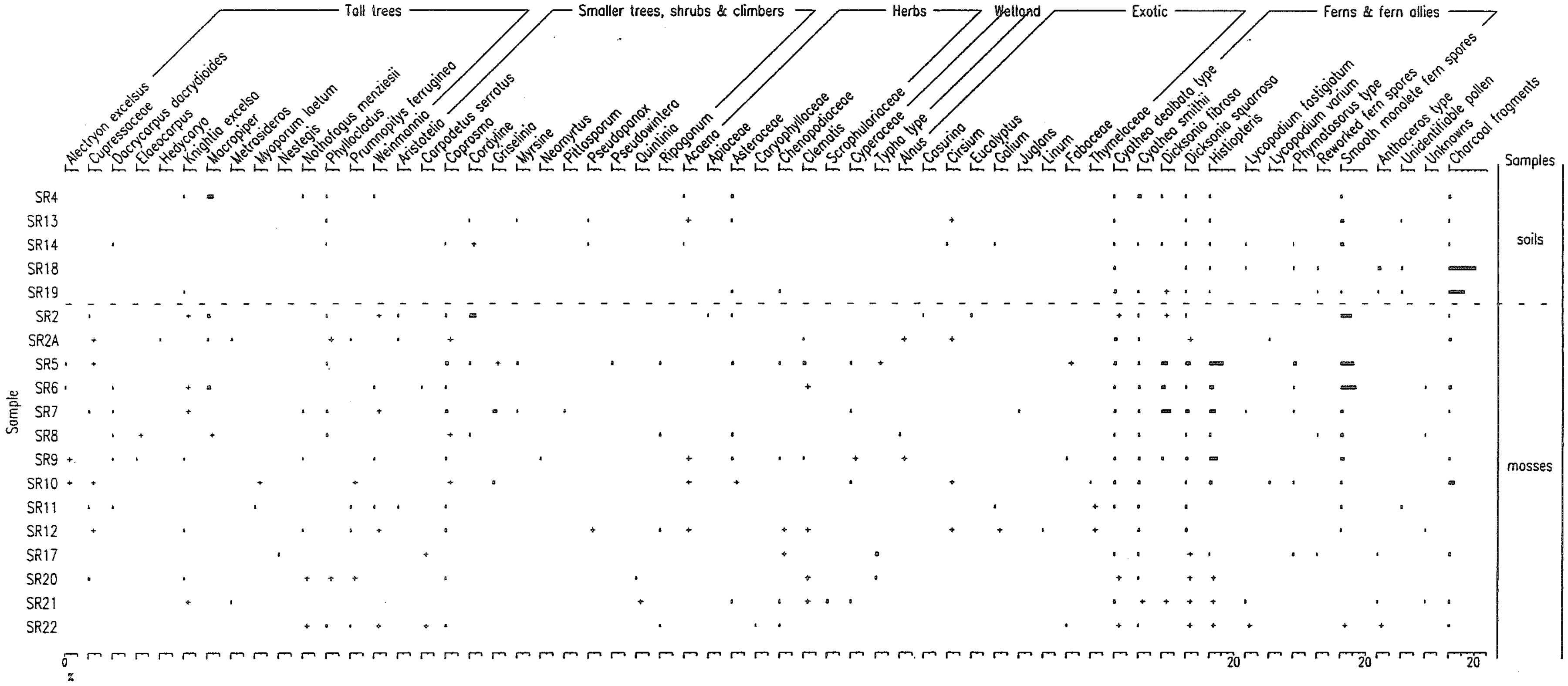


Figure 4.4b. Percentage pollen diagram: Putere surface samples, cont.

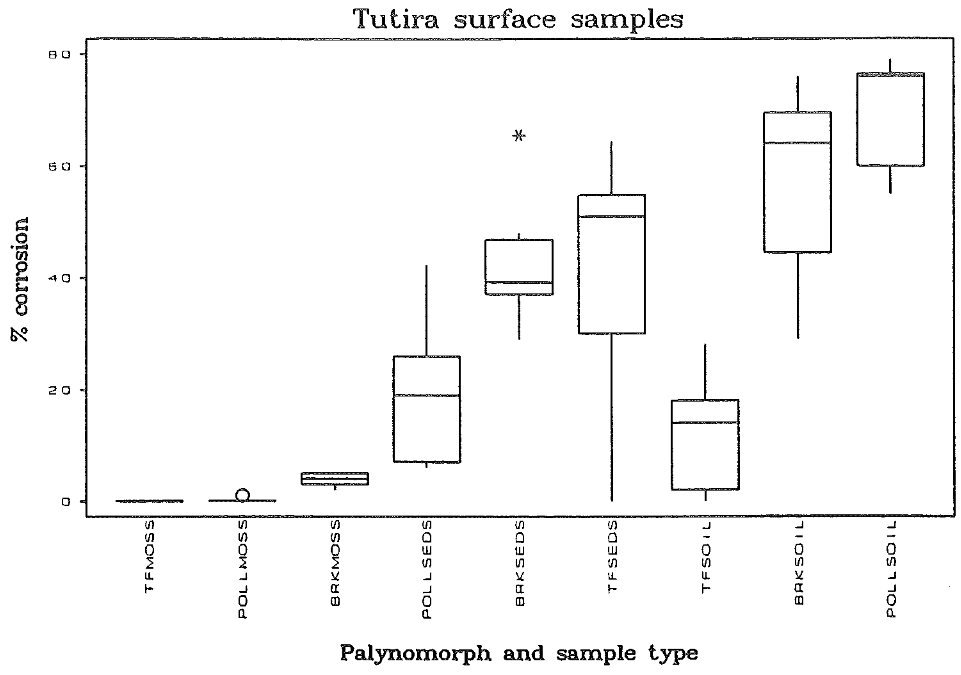


Figure 4.5. Box and whisker plots of corrosion data for pollen (POLL), bracken spores (BRK) and tree fern spores (TF) in surface moss (MOSS), soil (SOIL) and lake sediment (SEDS) samples collected from the Lake Tutira catchment.

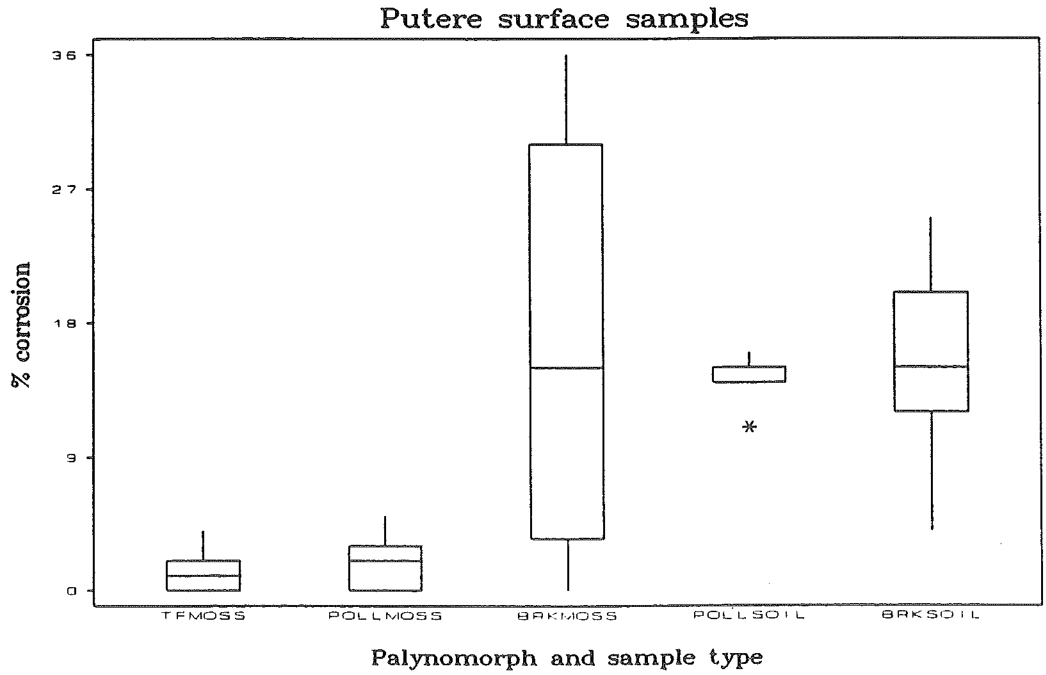


Figure 4.6. Box and whisker plots of corrosion data for pollen (POLL), bracken spores (BRK) and tree fern spores (TF) in surface moss (MOSS) and soil (SOIL) samples collected from the Putere catchments.

The corrosion data for the surface moss, soil and lake sediment samples are presented as relative percentages of the total whole, corroded and broken counts for pollen, bracken and tree fern spores; box and whisker plots are used to illustrate this data (Figures 4.5 and 4.6). Each encloses half of the data between the first and third quartiles, and the box is bisected by a line which represents the median value. The vertical lines at the top and bottom of the box (whiskers) indicate the range of "typical" data values, extreme values are displayed as "*" for possible outliers, and "O" for probable outliers (Statistix, 1992).

Tutira catchment

Soil samples

The soil samples from the Tutira catchment have a relatively low diversity of species represented in the pollen and spore spectra compared with the moss and surface lake sediment samples (see Figure 4.3a and 4.3b).

Bracken spores dominate the dryland pollen sum in all the soil samples but percentages vary considerably (40-70%). *Pinus,* Poaceae and *Taraxacum* pollen make up most of the remaining pollen sum. *Taraxacum* pollen is consistently represented in all soil samples (at 5-10%). All soil samples have low, but consistent percentages (<5%) of pollen from *Fuscospora, Prumnopitys taxifolia*, *Leptospermum* type; and spores from *Cyathea.* Other taxa that contribute small amounts of pollen include *Dacrycarpus dacrydioides*, *Dacrydium cupressinum*, Cupressaceae, *Myrsine*, Chenopodiaceae and *Salix.* Bryophyte spores and unidentifiable pollen grains are more abundant in the soil samples than in the moss and surface lake sediment samples.

Preservation: Bracken spores and pollen grains in the soil samples are poorly preserved in contrast to tree fern spores which are well-preserved (see Figure 4.5 and 4.6). The Tutira soil samples contain more corroded pollen and bracken spores than the surface lake sediments or moss samples (Figure 4.5).

Moss cushions

Poaceae and *Pinus* pollen dominate the pollen spectra in the moss samples (Figure 4.3). Poaceae pollen occurs at higher percentages in the moss samples than in the soils or lake sediments. Poaceae pollen is less abundant in samples MOD.3, STA, and STG compared with the other moss samples. Cupressaceae pollen is abundant in sample MOD.3, *Leptospermum* type in STA, and *Melicytus* and *Carpodetus serratus* in STG. Source plants for these pollen types were locally present at the respective sample sites. Considerable variation occurs in the representation of *Pinus* pollen (*c*.5-45%), the higher percentages occur in samples collected from the southern end of the catchment (MOD.3, MOD.9, STA, STB, STC and STD - Figure 4.3). These southern moss sample sites also have higher percentages of *Acacia* and *Leptospermum* type pollen compared with the northern moss sample sites; the source plants for these pollen types are more abundant in the southern end of the catchment. There are consistent, but low (<5%) contributions of pollen from *Fuscospora*, *Coprosma*, *Taraxacum*, *Plantago lanceolata*, *Rumex*, *Salix*, and *Trifolium*, and smaller contributions from many other taxa. Fern spores are less abundant and diverse in the moss samples compared with the soil and surface lake sediment samples.

The one lichen sample (STG) collected near regenerating forest at the top of the Kahikanui Gully (Figure 4.1) contains a diverse range of well-preserved pollen, and some spores. The two dominant trees in the patch of forest, *Melicytus ramiflorus* and *Carpodetus serratus*, are well represented in the pollen count from this sample. Although *Knightia excelsa* was also prominent in the forest, this tree is only represented by a trace of pollen in the count.

Preservation: All palynomorphs in the moss cushions are well-preserved, showing a maximum of 5% corrosion. Mosses contain less corroded palynomorphs than surface lake sediments or soils (Figure 4.5). Moss samples are typified by low frequencies of unidentifiable pollen grains (Figure 4.3b).

Lake Tutira surface sediments

Bracken spores dominate the pollen sum in all of the surface lake sediment samples, although they occur in variable percentages (30-70% of the pollen sum). Poaceae is the next most abundant pollen type (*c.*12-38%), followed by pollen from *Pinus* (*c.*7-28%). There are consistent contributions of pollen (<10%) from *Dacrydium cupressinum*, Cupressaceae, *Fuscospora* and *Nothofagus menziesii* (more than recorded in soils and mosses), *Prumnopitys taxifolia*, *Coprosma*, *Leptospermum* type, *Taraxacum* (comparable to soils), *Plantago lanceolata* and *Trifolium*. Wetland taxa (such as Typhaceae, *Phormium* and *Potamogeton*) are more abundant in surface lake sediments than soils or mosses. Outside the pollen sum, *Cyathea dealbata* type spores are the most abundant fern spore (*c.*20%) in the surface lake sediments. *Cyathea smithii*, *Dicksonia squarrosa*, monolete and trilete fern spore types, *Lycopodium fastigiatum* and bryophyte spores are consistently represented at low percentages (Figure 4.3b).

Preservation: Pollen and bracken spores are better preserved in the surface lake sediments than they are in the soil samples (Figure 4.5). In contrast, tree fern spores are more corroded in the surface lake sediments than they are in the soils. On average, bracken spores show a similar degree of corrosion to tree fern spores, although the tree fern spore data have a greater range (Figure 4.5).

Putere catchments

Soil samples

Samples SR18 and SR19 taken from soils under a bracken canopy contain between 40-60% bracken spores, with lower percentages from *Leptospermum* type, Poaceae and the exotic taxa *Taraxacum*, *Pinus*, *Plantago, Rumex* and *Trifolium* (Figure 4.4). Samples SR13 and SR14 collected under a *Paesia scaberula* canopy are dominated by spores from this fern (*c.* 70%), with lower percentages of *Leptospermum* type, Poaceae, *Pinus* and *Taraxacum* pollen, and bracken spores. Soil sample SR4 from the understory of a *Leptospermum scoparium/Kunzea ericoides* shrubland contains the highest percentage (24%) of *Leptospermum* type pollen compared with the other surface samples from the Putere catchments.

Preservation: All palynomorphs are well-preserved in the soil samples. Bracken spores are more corroded than the pollen and tree fern spores (Figure 4.6; n.b. tree fern spore data not shown as median value = 0, and maximum corrosion value = 8%). Pollen grains and bracken spores in the Putere soils are less corroded than the respective palynomorphs in the Tutira soil samples (Figures 4.5 and 4.6).

Moss cushions

The pollen spectra of samples SR5, SR6 and SR7 collected from moss growing on tree trunks in a small patch of regenerating forest are dominated by pollen from *Melicytus ramiflorus*, with lesser contributions from Poaceae, *Pinus*, *Leptospermum* type and *Leucopogon fasciculatus* and traces from native trees and shrubs. The other moss samples are dominated by Poaceae pollen, with lesser contributions from *Leptospermum* type and *Pinus.* bracken spores are present in all moss samples between <5-10%. Spores from *Cyathea* and *Dicksonia. Histiopteris* and *Paesia scaberula* are also common in the moss samples in low percentages.

Preservation: Tree fern spores and pollen grains preserved in the Putere moss samples are well preserved (Figure 4.6). Bracken spores are more corroded than the tree fern spores and pollen grains. The median values for corroded bracken spores are similar in the moss samples and soil samples, although the data from the moss samples show a wide range of values (0-36%).

DISCUSSION

Moss cushions

A greater diversity of pollen types is represented in the moss sample pollen spectra compared with the soil or surface lake sediment samples. Pollen and spores preserved in moss cushions usually provide accurate analogues of the contemporaneous local and extra local vegetation. Because of their generally smaller pollen source area, moss cushion pollen spectra represent the local and extra local vegetation more clearly than they do the regional vegetation. The pollen spectra of the Tutira moss samples collected from open sites in pasture were dominated by Poaceae pollen (80%). In contrast, the two samples collected on the margins of some regenerating native forest in this catchment (STE, STG) showed higher percentages of pollen from some of the dominant species present within the forest patch i.e., *Carpodetus serratus*, *Melicytus ramiflorus* and *Paesia scaberula* in samples STE and STG. *Knightia excelsa* was notably under-represented. Pollen from these species only occurred at <5% of the pollen sum in samples STF and STH which were situated only 20 m away in adjacent pasture, indicating their limited dispersal. A similar pattern was found in the other moss samples collected from open sites in the Tutira catchment. Similarly, the moss samples collected from tree trunks in regenerating native forest in the Putere catchments (SR2, SR5, SR6 and SR7) showed higher percentages of pollen from *Melicytus ramiflorus*, *Carpodetus serratus*, *Leucopogon fasciculatus* compared with open sites, and these species are usually under-represented in the pollen record (Macphail & McQueen, 1983).

Sample SR2 was collected from moss on the trunk of *Cordyline australis* and although this sample had the highest recorded percentage of *Cordyline* pollen of all the sampled moss cushions in this study, it was only present at 5%. Similarly, sample SR5 was collected from the trunk of a *Brachyglottis repanda* tree, but only 5% Asteraceae pollen was present in this sample. These results indicate these pollen types are poorly dispersed through the trunk space. Their under-representation agrees with previously collected data from other New Zealand modern pollen studies (e.g Macphail & McQueen, 1983; Newnham, 1990). Many tree taxa including *Sophora*, *Leptospermum* type, *Knightia*, *Pittosporum* and *Hoheria* were also severely under-represented relative to the abundance of these source plants near the sampling sites.

The highest percentages of *Typha* pollen in the Putere moss samples occur in SR17 and SR20. Both samples were located near to the shores of Lake Rotonuiaha where *Typha orientalis* forms a dense fringe along the lake margins. The moss samples from Tutira were all collected further from the lake edge, and consequently contained no *Typha* pollen.

Long-distance components in the moss sample pollen spectra are represented by *Pinus* and *Fuscospora* pollen. Both pine (e.g., McGlone, 1982; Bradshaw & Webb, 1985; Jarvis & Clay-Poole, 1992) and *Fuscospora* pollen (e.g., Moar, 1970; McKellar, 1973; Newnham, 1990) are renowned for their abilities to be dispersed long-distances by wind. At Tutira, pine pollen probably blows into the catchment from pine plantations in the Tangoio catchment, situated *c.* 3-5 km to the south, with a smaller local source from the Taupunga Peninsula on the shores of Lake Tutira (Figure 4.1, to the east of sample LTF12). The proximity of the Tangoio catchment pine plantations to the southern end of the Lake Tutira catchment may explain why there is more *Pinus* pollen in the "south" moss samples compared with the "north" moss samples (Figure 4.3).

In the Putere catchments, *Pinus* pollen probably originates from the forestry plantations located directly south of the Putere catchments in the Tukitukipapa river valley, and *c.* 8 km south on the hillslopes south of the Mohaka River. A small local pine plantation also exists on the crest of the saddle north of the Pukakaramea Bluffs (Figure 4.2). The percentages of *Pinus* pollen in the Putere moss samples (*c.*5-10%) are lower than those recorded in the Tutira moss samples (up to 50%). As the distances of pine plantations from the Tutira and Putere catchments are similar, collecting dates and flowering times, topography and wind direction may affect pine pollen dispersal causing the variability in its percentage representation.

The percentages of *Fuscospora* pollen (<5%) in the Tutira moss samples reflect pollen transported long distances from the beech forests on the inland ranges including the closest Maungaharuru and Te Waka ranges and the Ahimanawa, Kaweka, Kaimanawa and northern Ruahine ranges (see Figure 2.7 and Newsome's (1987) map of North Island vegetative cover, back pocket). At Putere, the Huirarua Ranges may also be an important source. The highest percentages of *Fuscospora* pollen recorded in the Putere samples (*c.* 10%) are from sites with higher altitudes and a more exposed south-facing aspect, such as those samples from the top of the Pukakaramea bluffs (SR8-SR10). Scattered individuals of *Nothofagus* spp. also occur at these altitudes amongst the patches of regenerating native forest, and undoubtedly contributed to the local pollen rain.

Tree fern spores and spores from many ground ferns such as *Paesia* and *Histiopteris* are present in most of the moss samples at low percentages, but generally are more abundant in the Putere samples, reflecting the greater abundance of ferns in the cooler, damper Putere sites. There is also a larger area of land area under regenerating mixed-forest in the Putere catchments compared with Tutira. This is reflected in the Putere moss pollen spectra by the better and more consistent representation of forest taxa and fern spores.

Bracken spores are recorded between 5-10% of the pollen sum in all moss samples (except SR17) and are derived from the limited sources of this fern in the catchments. These results are similar to the background percentages recorded in other surface pollen studies in sites where bracken was not present locally (e.g., McGlone, 1982). These percentages suggest bracken spores are over-represented on a local scale, but adequately represented on an extra local to regional basis. The Putere moss sample SR17 collected from pasture only 250 m from the bracken colony at the northern end of the Lake Rotonuiaha catchment (see Plate 2.2) contained more bracken spores (23%) than the other moss samples in this study. The bracken spores in SR17 are probably aerially derived from this colony. Sample SR20, collected from an almost identical sampling site to SR17, but 100 m further south, contained only *c.* 8% bracken spores, suggesting that aerial deposition from the colony dropped off rapidly with distance from the source plants.

Like most ferns, bracken produces vast numbers of spores, most of which fall to the ground close to the sporophytes, with reduced dispersal further away from the source plant. This limited spore dispersal is partly caused by the sori being positioned on the under-surface of the fern fronds, the dense canopy and relatively low habit. Where bracken occurs in forest clearings and along forest margins, its spores may only be dispersed a short distance from the source plants (e.g., Dodson, 1977), and spore production in bracken gradually decreases with increased degrees of shade (Dring, 1965). Bracken spore production varies enormously according to locality and depends partly on the year, age and habitat of the colony. In addition, many colonies are often infertile (Page, 1976). This may explain the contradictory reports of bracken spore representation in the literature, e.g., under-represented (in Dodson, 1976; 1977; Macphail & McQueen, 1983) and over-represented (in Bussell, 1988a; McGlone, 1982). The age of the moss sample and the number of years of pollen rain it contains may also affect pollen and spore representation. Wind dispersal of bracken spores may be important when a colony is exposed on an open landscape, carrying spores long distances away from the source plants. Wind dispersal may cause bracken to be over-represented in some modern pollen spectra if the sampling site is exposed to the prevailing winds (e.g., McGlone, 1982; Bussell, 1988a) or in spore banks (Milberg, 1991). Thus, bracken spores may be present in the modern pollen spectra at low percentages even when there are no plants locally present, and this is highlighted in the moss sample pollen spectra in this study (except for SR17 and SR20 discussed above).

Palynomorph preservation in moss cushions

Palynomorph preservation was generally excellent in the moss samples from Tutira and Putere, with consistently low percentages of corrosion recorded (Figures 4.5 and 4.6). This suggests these palynomorphs are contemporaneously derived and aerially deposited as the pollen and spores have had neither the time nor the conditions necessary for exine decay to occur. The pollen and spores found in moss cushions presumably only represent several years of accumulation, and will only have been exposed to the processes of decay for a limited time. Moss cushions also provide an acidic and often water-logged environment which is ideal for preservation.

Königsson (1969 quoted in Lowe, 1982) suggests aerial transport would expose regionally derived pollen grains to oxidation and microbial attack, causing exine corrosion. However, the excellent preservation of the pollen and spores in the moss cushions of this study, which include both locally and regionally derived pollen, strongly suggests otherwise. These results indicate there has been little exposure to decay, both during aerial transport, and storage in the cushions.

Soil samples

In the Tutira topsoil pollen spectra (Figure 4.3) bracken spores are the dominant taxa, with smaller and more variable contributions from *Pinus*, Poaceae, *Taraxacum* and *Leptospermum* type pollen. At Putere, samples SR13 and SR14 from beneath a *Paesia* canopy are dominated by *Paesia* spores; samples SR18 and SR19 from beneath a bracken canopy are dominated by bracken spores; and sample SR4 taken from the edge of a patch of regenerating manuka/kanuka shrubland is dominated by *Leucopogon fasciculatus* and *Leptospermum* type pollen.

Bracken

Tutira soil samples

Bracken only occurs sporadically along roadside hedgerows and in small areas of the Tutira catchment, yet bracken spores dominate the pollen sum in the Tutira soil samples

(40-70%), with four pollen types making up most of the remaining sum. Bracken is severely over-represented in these samples, on both a local and regional scale. The bracken spores in the soil samples are not aerially derived from existing local, regional or long-distance sources in the catchment. If they were, similar percentages would be recorded in the exposed moss cushions collected from the catchments, as mosses derive almost all their pollen and spores from contemporaneous aerial fall-out. The difference between bracken spores in soils and mosses is shown in two samples taken within 5 m of each other; one from soil (MOD.10), the other from moss (MOD.9). The soil sample contains 40% bracken spores, compared with <5% in the moss sample (Figure 4.3).

Bracken spores in the soil samples are significantly more corroded than the contemporaneous bracken spores preserved in the moss cushions ($p<0.0001$) (Figure 4.5). Evidently, there has been considerable exposure to yeast, fungal and bacterial action during pollen and spore accumulation in the soils. The results suggest bracken spores in the soils are "stored" spores that have accumulated over several decades, from a time when bracken dominated the catchment vegetation (see Chapter 5). As the stored bracken spores are significantly more corroded than the contemporaneous bracken spores they may be readily differentiated using preservation analysis when they occur in ancient or recent lake sediment samples (see Chapter 6).

Putere soil samples

Compared with the Tutira soil samples, the percentage of bracken spores is much lower in the Putere soil samples i.e., <10% of the pollen sum in those samples not taken from under a bracken canopy (Figure 4.4). There are significantly less corroded bracken spores in the Putere soils than recorded in the Tutira soil samples ($P=0.0006$), primarily because of the soil type and the age of the depositional environment. Whereas the soil samples at Tutira were minerogenic topsoils, the Putere soils samples contained mostly dry organic litter collected beneath fern canopies and from the edge of some regenerating manuka/kanuka shrubland. Because litter builds up faster than topsoils, the minerogenic soil samples from Tutira will be older, and therefore contain bracken spores that have been deposited over a longer time than the Putere litter samples. The bracken spores in the Tutira samples are more corroded than the bracken spores in the Putere soils because they have been exposed to the processes of decay for a longer time (Figure 4.5 and 4.6). In contrast, the younger litter samples contain more recently deposited and better preserved bracken spores, a proportion of which are from contemporaneous source plants which are more abundant at Putere than Tutira.

Leptospermum type

Entomophily in manuka *(Leptospermum scoparium)* and kanuka *(Kunzea ericoides)* ensures that dispersal of their pollen by wind is usually limited to short distances from the source plants e.g., Moar & Myers (1978); Pocknall (1979); Macphail & McQueen (1983); Newnham (1990). As a result, *Leptospermum* type pollen is usually under-represented in the pollen spectra unless it is present within the sampling area, in which case it can dominate the pollen spectra (McGlone, 1988c). As none of the soil samples in the Tutira catchment were collected close to manuka or kanuka trees, no *Leptospermum* type pollen was expected. However, *Leptospermum* type pollen is consistently recorded at *c.* 5% in the soil samples, suggesting this pollen type is stored from a time when these species were more abundant in the catchment (Guthrie-Smith, 1969), rather than from contemporary source plants. This implies *Leptospermum* type pollen is also fairly robust and resistant to decay which is feasible considering their small size and relatively thick exine, and explains its preferential representation in the soil samples.

Pinus and Taraxacum

Studies by Havinga (1964; 1984) clearly show that both *Pinus* and *Taraxacum* pollen grains are highly resistant to oxidation and microbial attack, owing to the high sporopollenin content of their exines. The relatively high percentages of *Pinus* and *Taraxacum* pollen in the Tutira soil samples may reflect their preferential representation in the pollen spectra because of the ability to resist decay. Havinga (1964; 1984) demonstrates these two pollen types have a high degree of resistance to decay.

Poaceae

In contrast to Pinus, *Taraxacum* and *Leptospermum* pollen types, more of the Poaceae pollen in the soil samples is contemporaneous. Poaceae pollen is thin walled, low in sporopollenin content and highly susceptible to the effects of oxidation and microbial attack

(Cushing, 1967). A high susceptibility to decay means that deterioration would occur relatively rapidly after initial deposition, and the pollen is unlikely to be as old as the more resistant types discussed above. Thus, percentages of Poaceae pollen are maintained at 5-30% of the pollen sum because of the continual supply from contemporaneous sources.

Preservation in soil samples

Compared with the moss and surface lake sediment samples, the diversity of pollen and spores preserved in the soil samples is relatively low (Figure 4.3). This occurs as a result of differential preservation and preferential representation of the more resistant pollen types in the soils. The soils provide an environment where the pollen and spores are exposed to oxidation, microbial attack and faunal ingestion, which causes the etched and corroded exines (Havinga, 1964, 1984; Lowe, 1982). Although all palynomorphs preserved in the soils will be exposed to the same stochastic processes of decay, they display differential susceptibilities to these according to their exine structure and sporopollenin content. Preferential representation and the mixed age of the pollen and spores contained within the soil samples means the soil pollen spectra in this study are not reliable proxies for the current vegetation in the catchments.

Although not evident in this study, it is possible that some moss species provide more suitable environments for entrapment and preservation than others (Crowder & Cuddy, 1973; Boyd, 1986). This may account for differential filtering, preservation and representation of pollen and spores reported in other studies.

Surface lake sediments from Lake Tutira

The pollen spectra of the surface lake sediments contain a diversity of pollen types similar to the Tutira moss pollen spectra, but the dominant components, i.e., bracken spores and pollen from Poaceae, *Pinus* and *Taraxacum* closely resemble the percentages found in the soil pollen spectra. As these pollen taxa are preferentially represented in the soils because of their greater resistance to decay, I suggest most of these pollen types and the bracken spores incorporated in the lake sediments are secondary and derived from inwashed catchment soils. In addition, there is only a small significant difference (P=0.402) between the amount of corroded bracken spores in the surface lake sediments and in the Tutira soil samples (see Figure 4.5).

A large component of waterborne pollen and spores derived from eroded catchment material is common in lake basins, like Tutira, that have a large number of inflows and a catchment with steep sided slopes and erosion prone soils. Studies by Davis (1968), Crowder & Cuddy (1973), Peck (1973), Bonny (1976, 1978), Pennington (1979) demonstrate the importance of water-transported pollen in lakes that have inflowing streams (some contributing as much as 97% of the pollen influx). This is accentuated in steep catchments covered in pasture, where runoff rates are usually much higher than catchments under dense shrub cover or forest (e.g., Heathwaite, 1994 and see Chapter 6). Although there is a substantial contribution of secondary pollen in the Lake Tutira surface sediments, a significant component of pollen in the sediments is also aerially derived from contemporaneous vegetation in the catchment. This is shown by the greater diversity, although at low percentages, of pollen types in the lake sediments compared with the soils. However, the inclusion of a high percentage of inwashed bracken spores in the pollen sum has resulted in the apparent under-representation of Poaceae pollen in the surface lake sediment pollen spectra (Figures 4.3 and 4.5).

Salix is present around the margins of Lake Tutira and in the Waikopiro flats, yet *Salix* pollen is often absent or only present at <5% of the pollen sum in the surface lake sediments. This implies the taxa is under-represented in the lake sediment pollen spectra. Although wind-dispersed pollen types are usually well dispersed from the source plants, the low percentages of *Salix* pollen from samples across the entire lake basin indicates otherwise. Locally produced *Salix* pollen tends to fall in higher amounts closer to the source plants in shallow lake waters (e.g., Davis *et al.* 1971) and the grains are highly susceptible to corrosion (Havinga, 1964, 1984). These factors may contribute to the limited dispersal and low percentages of *Salix* pollen in the surface sediments from Lake Tutira, which were collected away from the lake shores, in deep water (10-38 m) (Figure 4.1 and Appendix 1).

Representation of long-distance pollen in surface lake sediments

The long-distance wind-transported pollen of *Fuscospora* occur in the surface lake sediments at *c.* 5-10% of the pollen sum, which is higher than recorded for this taxa in the moss pollen spectra (<5%) (Figure 4.3). The pollen source area differs according to the diameter of the sampling site (Jacobson & Bradshaw, 1981; Sugita, 1993) and determines the relative proportions of pollen derived from local, extra local and regional sources in the pollen spectra of a sample (Figure 4.0). In sites with small source areas such as the moss samples, most of the pollen is from local source plants, with a lower proportion of pollen from extra local and regional source plants. The pollen spectra in the moss samples illustrate this, as they are dominated by Poaceae pollen, presumably derived from the grasses locally surrounding the sampling sites, and have relatively low percentages of pollen derived from long-distance sources such as *Fuscospora*, *Dacrydium cupressinum* and *Prumnopitys taxifolia*. However, sites with much larger source areas will have an increased representation of extra local and regional pollen relative to locally derived types. The surface lake sediment pollen spectra illustrate this with their consistently higher percentages of the tree pollen types just mentioned.

Pollen and spore percentage variability in surface lake sediments

Studies of pollen spectra in surface lake sediment samples have reported both small and large scale variations in percentages for a range of basin sizes (e.g., Davis, 1968; Dodson, 1977; Bonny, 1978; Pocknall, 1980; Davis *et al.* 1984; Beaudoin & Reasoner, 1992). In this study, the percentage pollen data for some of the taxa in the surface lake sediments display considerable variation, for example a 40% range in the case of bracken spores. Although percentages of the major pollen types vary spatially across the lake basin the differences are not associated with aspect, situation, depth or proximity of core location to the shore. This suggests that pollen focusing, i.e., the accumulation of pollen in certain areas of the lake basin, caused by transport and deposition mechanisms (Beaudoin & Reasoner, 1992), is not an important process in the Lake Tutira basin.

In contrast to this study, Pocknall (1980) recorded consistent percentages for most pollen taxa in surface sediments across the basin of Lady Lake, Westland, attributable to redeposition following seasonal recirculation of lake waters. Redeposition may be a more important process in Lady Lake than in Lake Tutira because of Lady Lake's smaller and shallower basin and relatively simple and gently sloping bathymetry. Thus, resuspension and redeposition of sediments and palynomorphs in the shallower regions of Lake Tutira, caused by wave-generated turbulence may contribute to some of the pollen percentage variability in the surface lake sediment samples. The proximity of local source plants (Davis & Brubaker, 1973) and differential settling of pollen and spores (Holmes, 1990) may also partially explain this variability.

If sediment focusing (Davis *et al.* 1984) is responsible for the variation in the pollen percentages, sedimentation rates would be greater in the deepest regions of the lake. However, evidence from a suite of stratigraphically correlated cores collected from Lake Tutira (Page *et al.* 1994a) does not suggest this to be the case; rather sediment accumulation is faster in the shallower regions of the lake closer to inflowing streams, and is more influenced by the complex basin morphology (see Irwin, 1978).

Preservation in surface lake sediments

There are significantly more corroded tree fern spores and bracken spores in the surface lake sediments than there are corroded pollen grains ($p<0.0001$) (Figure 4.5). Assuming well-preserved whole pollen grains are indicative of aerial deposition, then a higher proportion of the pollen grains incorporated in the surface lake sediments are aerially derived compared with either bracken or fern spores. This means the pollen curves in the surface lake sediments are more accurate reflections of the contemporaneous catchment vegetation than the bracken or tree fern spore curves are of their respective source plants. This is because the pollen curves are less contaminated by secondary inwashed pollen of mixed age, as the soils only contain a limited diversity of the more resistant pollen types.

Tree fern spores are more abundant and significantly more corroded ($P=0.0061$) in the surface lake sediments than they are in the Tutira soil samples (Figures 4.3 and 4.5). As there is no post-depositional exine deterioration in the lake sediments (see Chapter 6), this suggests the corroded tree fern spores in the sediments are not derived from soils. The tree fern spores were probably stored in an environment more conducive to decay than the catchment soils. Biologically active riverbank sediments are probably the primary source of corroded tree fern spores. *Cyathea medullaris*, *Cyathea smithii* and *Dicksonia squarrosa* thrive in cool, damp, shady sites (Brownsey & Smith-Dodsworth, 1989), and formed dense stands in river gullies and on river flats in the past (see Chapter 5). These stands would provide a direct source of spores to river beds and proximal fluvial sediments. During high intensity rain storms and rapid runoff, these sediments and stored spores are transported downstream into Lake Tutira, where they are redeposited in the lake sediments in an erosion pulse.

CONCLUSION

The comparative approach using modern analogues is the most useful method currently available for reconstructing past vegetation from pollen diagrams (Birks & Birks, 1980; Gaillard *et al.* 1992; Davis, 1994), particularly when the fossil spectra match up with distinctive modern spectra. However, limitations to the method do exist, in particular when modern pollen spectra are derived from moss cushions and then compared with fossil pollen spectra derived from lake sediments. Moss cushions derive their pollen from aerial deposition and rain-out giving the modern spectra a high local representation. In contrast, lake sediments derive their mixed aged pollen and spores from many sources, depending on the catchment conditions, and contain more extra local and regional pollen. Lake sediment sources can include inwash of secondary pollen and spores of mixed ages from eroded soils, river bank sediments, and littoral sediments, as well as contemporaneous pollen and spores from aerial deposition, rainout, surface runoff and inwash of debris from the catchment. Thus, it can be misleading to compare pollen spectra from mosses with those from lake sediments when each derives its pollen from different sources and source areas. The results from this study highlight this problem. The three sample types analysed reveal distinctly different pollen spectra. Moss pollen spectra provide the most accurate representation of the contemporaneous vegetation; soils provide a pollen spectra comprising mostly corroded stored pollen and spores of the most resistant types; and the surface lake sediments contain an amalgamation of the pollen and spore types represented in both the moss and soil sample pollen spectra.

The results also highlight the risks of using pollen analysis of soil profiles to reconstruct vegetation histories, bearing in mind distortion of the pollen record through differential preservation and representation will vary according to the soil type and environment. Contemporary vegetation reconstructions based on the soil pollen spectra from this study would be misleading both on a local and regional scale. The pollen spectra from the Tutira catchment soils reflect a completely different and mixed vegetation type compared with the existing vegetation, because of the preferential representation of stored bracken spores and more resistant pollen types such as *Pinus*, *Taraxacum* and *Leptospermum*. This information can now usefully be extrapolated to the interpretation of the fossil pollen records from the Tutira and Putere lake sediment cores, which contain many inwashed erosion pulses and corroded palynomorphs.

CHAPTER 5

A 2000 YEAR HISTORY OF VEGETATION AND LANDSCAPE DISTURBANCE IN THE TUTIRA AND PUTERE DISTRICTS, HAWKE'S BAY

INTRODUCTION

Sediment cores from four lakes in the Tutira and Putere districts of Hawke's Bay are analysed in this study, for the remains of pollen, charcoal, tephra and erosion pulses to achieve the following aims:

- To reconstruct the vegetation history of Hawke's Bay before human settlement.

- To establish the relative importance and frequency of different types of pre-settlement environmental disturbance, and how they affected the vegetation and soil stability. Have the disturbances that were important in the past remained important through to the present, and do they affect the vegetation in a similar way and to a similar extent?

- To determine how the explosive Taupo eruption of 1850 BP affected Hawke's Bay forests, and to document subsequent forest recovery.

- To determine the relative importance of high intensity storms before and after human settlement, and whether or not they caused vegetation changes or erosion in the past. Were some vegetation types more protective against storm induced erosion than others? Soil stability is a current concern in the Hawke's Bay region, particularly as a result of damage inflicted by cyclonic storms (see Page *et al.* 1994a; Page *et al.* 1994b). Information about the effects of storms on different types of vegetation in the past, may help to put contemporary storm damage in Hawke's Bay into a longer term perspective.

- To determine the timing, rate, sequence and extent of forest clearance by the first Polynesian settlers in Hawke's Bay, and to establish the effect of deforestation on soil stability.

- To determine the sequence of vegetation and landscape changes that occurred with European settlement in the AD 1800s through to the present.

METHODS

Methods used for the collection, preparation and analysis of lake sediment cores and sub-samples are outlined in Chapter 3.

RESULTS

Multivariate analyses of cores LT16 and RNUI3

For ease of discussion, cores LT16 and RNUI3 are also referred to as Tutira and Rotonuiaha respectively. Ten sample clusters were chosen as the level of interpretation for each core. Frequency of taxa represented within the groups and range of abundances are presented as appendices (Lake Tutira: Appendix 2 and Lake Rotonuiaha: Appendix 3). Single sample clusters were excluded (sample group 10, Rotonuiaha) except for three from Tutira (groups 3 to 5 differing in amounts of *Cyathea*) and two from Rotonuiaha (groups 3 to 4) that were characterised by high levels of *Cyathea dealbata/medullaris* and *Cyathea smithii* types and grouped together as a composite cluster. At Tutira one large group of 28 sub-samples was considered diverse, and was subdivided into 2 sub-groups, labelled 6 and 6A (Appendix 2).

To aid in presentation and interpretation, the clusters were re-ordered from the original output, according to the median DCA ordination value of the constituent samples of each cluster. In both cases, the integrity of the dendrogram structure was maintained. Taxa were similarly ordered (Appendices 2 and 3), but are divided into four groups (1) those that distinguish sample clusters by differences in abundance, (2) those that distinguish sample clusters by differences in frequency only, (3) those that are uninformative in defining clusters, and (4) rare taxa (not shown). Criteria for the usefulness of pollen taxa as indicators of differences between clusters were the absence of overlap in the range of abundance for at least two sample clusters for the first group, and 80% presence and absence contrasts for the second (i.e., must be both >80% present and <80% absent in at least two clusters). Thus, the first two taxa groups show the trend in abundance and frequencies from left to right, and from the top of each list of taxa to the bottom.

Both of the Detrended Correspondence Ordinations produced one interpretable axis (eigenvalues: Tutira 0.440, 0.113, Rotonuiaha 0.449, 0.084 for axes 1 and 2 respectively), although the second axes provided some additional information. Examination of the primary axes revealed that those taxa with the largest ordination values were the most indicative of disturbance, e.g., *Pteridium esculentum* (bracken), *Coriaria* and *Aristotelia* (Appendices 2 and 3). The values from the primary ordination axes were plotted against core depth, and sample groups were superimposed upon these to create a "disturbance index" (Figures 5.1 and 5.2). This index provided an interpretative aid to forest disturbance experienced over time at each site. Ordination and classification features were matched to the presence of tephras, erosion pulses (also referred to as allogenic sediment, in contrast to authigenic sediment) and charcoal fragments, and the distribution of the latter two are presented in Table 5.1. The axis 1 ordination position was tested to see if there was a difference between sub-samples with and without charcoal; and between sub-samples taken from allogenic (erosion pulse) and authigenic sediment.

The disturbance index (Figures 5.1 and 5.2) provides an indication of disturbance and relative stability experienced over time at each site. When considered with charcoal, tephra and erosion pulse data from the cores, the index can provide a supporting measure of the relative impact of different disturbances on the vegetation. Cluster Analysis of the pollen data from the Tutira and Rotonuiaha profiles show that sample groups with high values on the disturbance index have a greater abundance of taxa associated with disturbed and open land, compared with sample groups with low values on the disturbance index which have a greater abundance of forest taxa (Appendices 2 and 3).

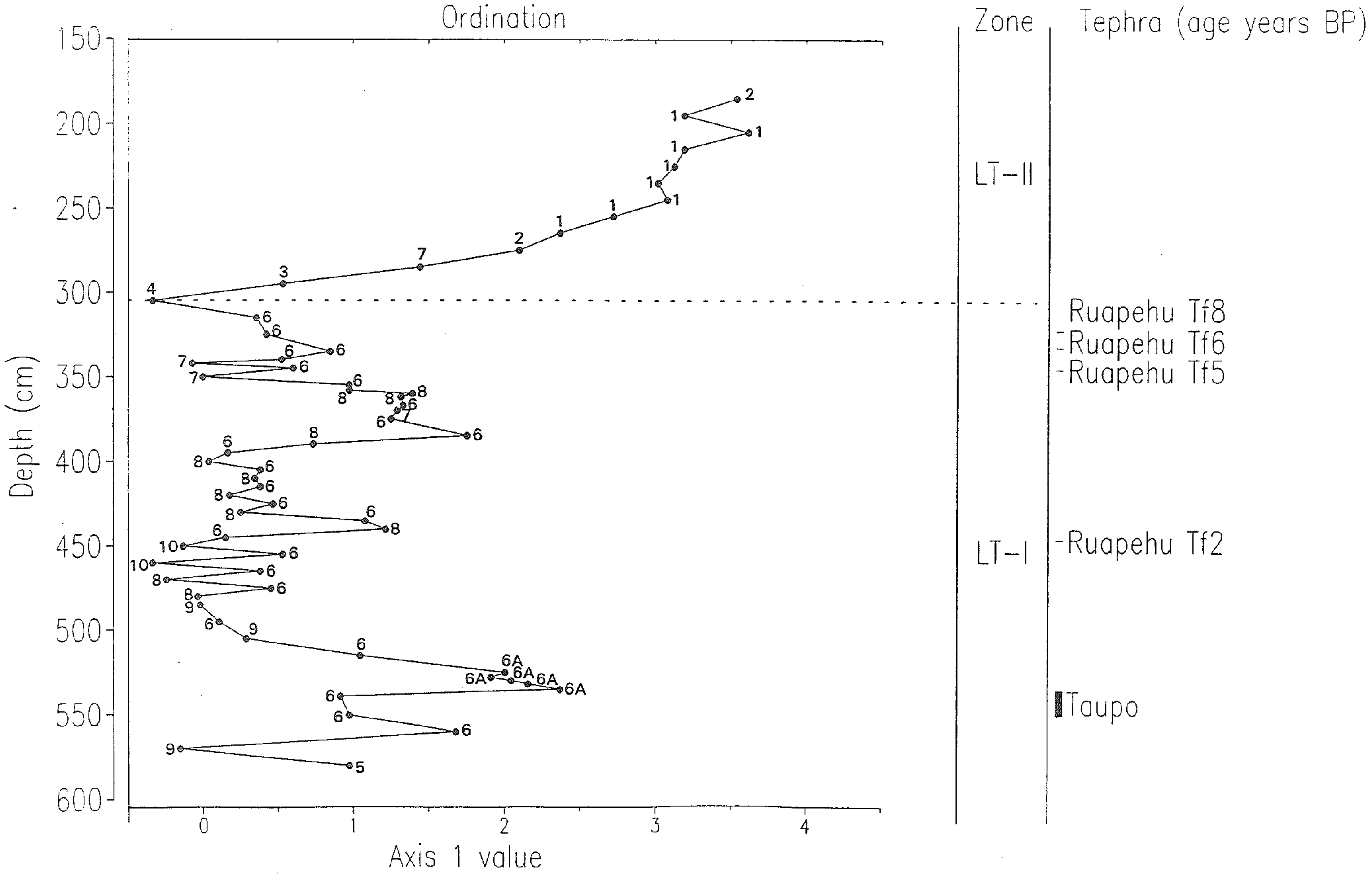


Figure 5.1. Disturbance index for pollen data from zones I (Forest) and II (Polynesian) in core LT16. The index is made by plotting the ordination value for the first DCA axis against core depth, and superimposing the sample group numbers created by the Cluster Analysis (Appendix 2) on each point representing a sub-sample in the core. Positions of tephra deposits are also marked on the diagram.

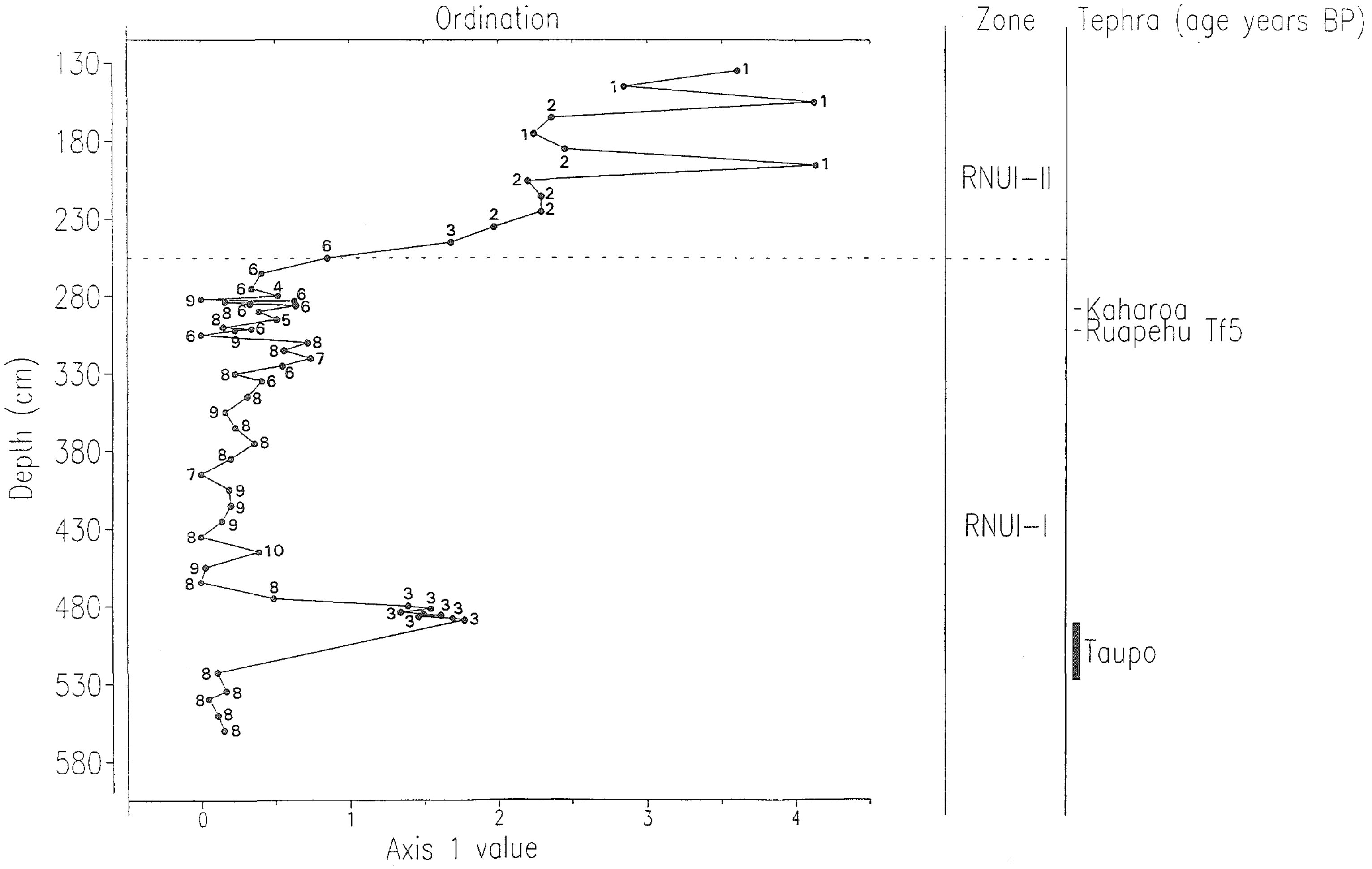


Figure 5.2. Disturbance index for pollen data from zones I (Forest) and II (Polynesian) in core RNUI3. The index is made by plotting the ordination value for the first DCA axis against core depth, and superimposing the sample group numbers created by the Cluster Analysis (Appendix 3) on each point representing a sub-sample in the core. Positions of tephra deposits are also marked on the diagram.

Table 5.1 Correlations of sample groups with sub-sample type (allogenic (erosion pulse) and authigenic) and charcoal (presence/absence) in the Tutira and Putere cores.

Sample group	Allogenic sub-samples	Authigenic sub-samples	Sub-samples with charcoal present	Sub-samples without charcoal	Total sub-samples in sample group
Lake Tutira					
1	2	6	8	0	8
2	1	1	2	0	2
3–5	3	0	3	0	3
6	4	24	22	6	28
7	1	3	3	1	4
8	2	9	2	9	11
9	0	3	2	1	3
10	0	2	0	2	2
Lake Rotonuiaha					
1	1	4	5	0	5
2	1	5	6	0	6
3	0	9	9	0	9
4–5	2	0	2	0	2
6	2	9	3	8	11
7	0	2	2	0	2
8	2	15	1	16	17
9	0	7	1	6	7

Lake sediment core stratigraphy

The lake sediments in cores LT16, LW8 and RNUI3 consisted of a matrix of biogenic silts and clays, interspersed with two types of authigenic sediments, (1) layers of pale yellow pulpy deposits, which microscopic examination revealed to be almost entirely composed of siliceous diatom frustules, and (2) layers of black, organic homogenous mud with little structure, composed of small parts of plant and animal remains, microorganisms and their breakdown products. Erosion pulses of varying thicknesses (cm+ to m+ thick) were present throughout the cores (except RNGA3), although they were more abundant and thicker in the recent (European sections) surface sediments (see Appendix 4 for a list of the recorded depths of erosion pulses in the cores).

The lake sediment in core RNGA3 consisted of a distinctly different material to the other three cores, comprising a homogeneous matrix of light brown biogenic organic lake mud with a mousse-like texture. Coarse erosion pulses were absent, but there were several thin, discrete clay layers (2–4 mm thick) which may have been deposited during floods in the catchment. The low mineral content and predominant authigenic nature of the lake sediments in core RNGA3 occurs because there are no inflowing streams to transport large volumes of sediment to Lake Rotongaio during storms. In addition, the mudstone-sandstone hills on the north-eastern shores of the lake are relatively stable, the remaining area of the catchment is relatively flat and the lake is surrounded by dense swamp vegetation which acts as a filter.

The positions of the erosion pulses in the cores are presented in the stratigraphy columns (Figure 5.3). The total amount of erosion pulse sediment present in specified vegetation zones, i.e., forest, bracken and grass, are given in Figure 5.4 (measured in centimetres and given as a percentage of the total sediment depth in each zone). See also Table 5.5 for zone depths.

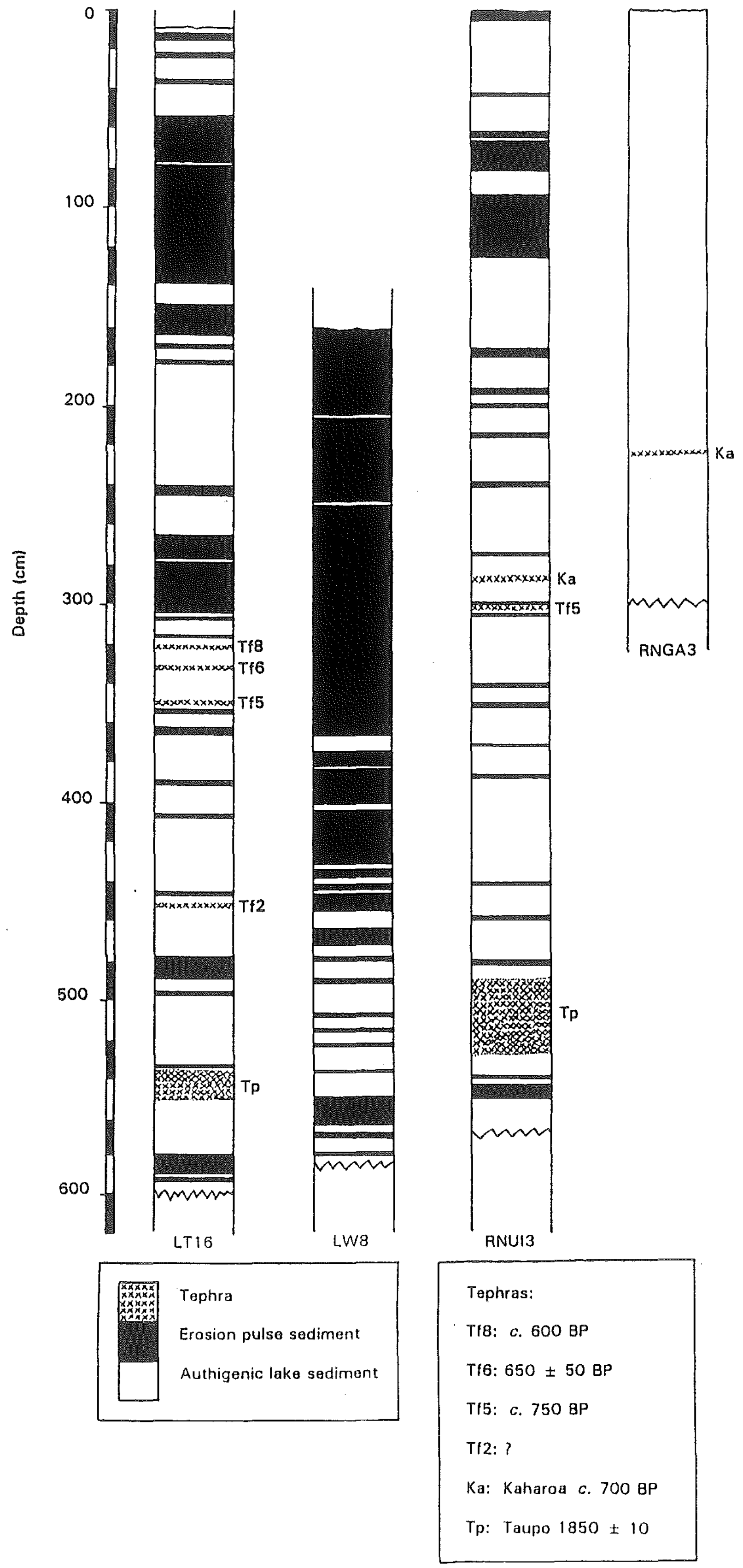


Figure 5.3. Stratigraphy and tephrochronology for cores from Tutira (LT16 and LW8) and Putere (RNUI3 and RNGA3).

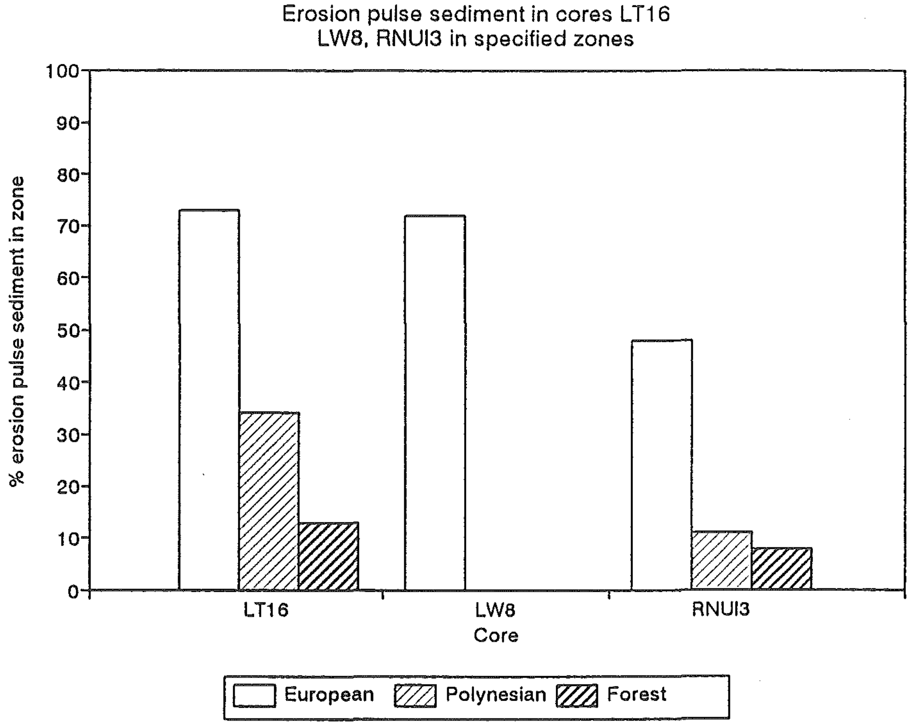


Figure 5.4. Erosion pulse sediment as a percentage of total sediment depth in the European, Polynesian and Forest zones of cores LT16 and RNUI3. Only the European zone is represented in core LW8, and erosion pulses do not occur in core RNGA3.

Core chronology

Radiocarbon dating and tephrochronology

Eden *et al.* (1993) identified 14 known tephra layers in cores from the swamp at the northern end of Lake Tutira. They reported radiocarbon ages for organic-rich clays adjacent to tephra deposits of known age in core LT4, were about 500–800 years older than expected. They attributed this discrepancy to probable sample contamination with reworked or older carbon. The presence of older carbon in a sample, results in the "hard-water error" described by Deevey *et al.* (1954). This error occurs when the amount of inert carbon incorporated in the sediment is increased, for example, when water rich in dissolved carbonate flows into the lake. The inert carbon dilutes the ^{14}C:^{13}C ratio, and makes the determined age of the sample appear greater than it is. Because of this source of error in core LT4, it was not considered a profitable option to try and obtain radiocarbon dates from core LT16. Instead, three samples were collected from the Putere lake sediment cores to determine whether these sediments were also susceptible to contamination, or whether they could return accurate dates.

Radiocarbon ages and calculated ages (based on sediment accumulation between known tephra dates) for samples from Lakes Rotonuiaha and Rotongaio are given in Table 5.2. The radiocarbon ages from the Putere lakes are also much older (600–900 years) than the calculated ages. This may be explained by contamination of the samples with either or both reworked older carbon from inwashed soils and old carbon from the Tertiary limestone beds at Putere. The difference between the calculated age and the radiocarbon age is smaller for sample NZA 3696 (*c.* 620 radiocarbon years) than it is for sample NZA 3695 (*c.* 900 radiocarbon years) (Table 5.2). This suggests sample NZA 3696 is less contaminated with older carbon, which may imply soil erosion was less important in the Lake Rotonuiaha catchment at that point in the core.

In contrast with the Lake Rotonuiaha sediments, the homogenous, biogenic lake sediments lack erosion pulses in the Lake Rotongaio core (RNGA3) suggesting intense soil erosion has never been common over the last 1000 years in the small, gently-sloping Rotongaio catchment. Moreover, the catchment does not have inflowing streams; it is fed only by seepage and surface runoff. This indicates the *c.* 600 year over-estimation for the age of sample NZA 3697 is probably entirely due to hard-water error, and that old reworked carbon from eroded soils is not an important source of contamination in this lake.

Because radiocarbon dating from the Putere and Tutira cores was not successful, tephra deposits recorded in the cores were used to control core chronology and provide inter-lake correlation of cores (Eden *et al.* 1993; Eden & Froggatt, in prep). Many of the tephra deposits (e.g., Taupo Tephra) were clearly visible, whereas others required microscopic verification (Table 5.3 and Figure 5.3).

Table 5.2 Radiocarbon dates (presented as conventional radiocarbon years uncorrected for secular variation) and calculated ages for samples from the Putere cores.

Lake	Rotonuiaha		Rotongaio
Core	RNUI3	RNUI3	RNGA3
Core depth (cm)	465	265	200
Lab number	NZA 3696	NZA 3695	NZA 3697
^{14}C age BP	2326 ± 69	1473 ± 64	1192 ± 68
Calculated age BP from sedimentation rates or tephra	*c.* 1705	*c.* 600	*c.* 585
Difference between calculated age and ^{14}C age: in radiocarbon years	*c.* 620	*c.* 900	*c.* 600
Error factor: ^{14}C age older than calculated age	x 1.36	x 2.5	x 2.04
Sedimentation rate mm/year	1.72	2.6	2.08

Table 5.3 Age and depths of selected tephra formation deposits identified in cores from Tutira and Putere sites (* = no data). Tf=Tufa Trig formation (after Donoghue, 1991).

Tephra formation	Depth of tephras in Tutira site cores (m)		Depth of tephras in Putere site cores (m)		Age of Tephras Years BP	Reference for age
	LT16	LW8	RNUI3	RNGA3		
Kaharoa Tephra	*	*	2.87	2.24	*c.* 700	Lowe & Hogg, 1992
Ruapehu Tf 8	3.225	*	*	*	*c.* 600	Donoghue, 1991
Ruapehu Tf 6	3.325	*	*	*	650 ± 50 maximum	Donoghue, 1991
Ruapehu Tf 5	3.455	*	3.01	*	*c.* 750 (830 ± 60 maximum)	Donoghue, 1991
Ruapehu Tf 2	4.465	*	*	*	?	Donoghue, 1991
Taupo Tephra	5.35-5.5	*	4.9-5.27	*	1850 ± 10	Froggatt & Lowe, 1990

Exotic Pollen as a dating tool

Exotic pollen grains in the pollen record provided a marker horizon for the first signs of European settlement. Dates were recorded when introduced or naturalized plants first appeared on Tutira station by H.G. Guthrie-Smith who was a pioneer farmer at Tutira Station from 1882 (Guthrie-Smith, 1969). These records provide a unique dating reference for the Lake Tutira fossil pollen record; Europeans settled permanently at Tutira in AD 1873 (Guthrie-Smith, 1969). The first Europeans began farming the Putere area in

AD 1875 (King, 1975) and this age is given to the depth where the introduced pollen grains are first recorded in the cores from this site.

Dates from erosion pulses

An erosion pulse (1.16 m thick) in the sediment column of core LW8 between 2.50-3.66 m, and one in core LT16 (24 cm thick) between 0.53–0.77 m are correlated with the 1938 Esk Valley storm (Page *et al.* 1994a). Pinaceae and Poaceae pollen increase rapidly above the 1938 erosion pulse in cores LT16 and LW8. Although the 1938 erosion pulse could not be identified with such certainty in the Putere cores (because of the lack of detailed rainfall records), the 1938 date horizon was extrapolated to a depth in these cores where there was a similar rapid increase of Pinaceae and Poaceae pollen. In the case of RNUI3, these pollen changes occur just above a thick erosion pulse, and this pulse is assumed to have been washed in during the 1938 storm.

Sedimentation results

Lake sedimentation rates for several sections of sediment in the cores are presented in Table 5.4. A calculated age for a given depth in a core, based on a sedimentation rate, will be more reliable from a section where sediment has been deposited at a constant rate, than it will from a section containing numerous, rapidly deposited erosion pulses of different thicknesses where deposition rates are variable. This latter effect is particularly noticeable in the sections of core representing the last 150 years in cores LT16, LW8 and RNUI3 where there is a high incidence of thick erosion pulses.

Table 5.4 Sedimentation rates (mm/year) for Tutira and Putere cores (* = no data).

Upper and lower ages of section boundaries	Names of dated events that form the section boundaries (working down the core)	Sedimentation rate (mm/year)			
		Core LT16	Core LW8	Core RNUI3	Core RNGA3
AD 1988 to 1938 (Tutira) and 1993 to 1938 (Putere)	Top of core to the erosion pulse caused by the "1938 Flood"	12.4	39.8	8.0	5.45
AD 1938 to AD 1870	"1938 Flood" erosion pulse to the first record of introduced European pollen taxa	12.94	22.65	11.76	8.82
AD 1870 to 750 BP	First record of European pollen taxa to the Ruapehu Tf5 Tephra	2.65	*	*	*
AD 1870 to 700 BP	First record of European pollen taxa to the Kaharoa Tephra	*	*	2.57	2.08
750 to 1850 BP	Ruapehu Tf5 Tephra to the Taupo Tephra	1.73	*	1.72	*

Palynological results

Pollen profiles of the four cores are presented in Figures 5.5 to 5.8. Four pollen assemblage zones (zones I to IV) have been assigned subjectively to the diagrams to assist with their discussion. The zones are based on major changes in the composition and abundance of certain pollen and spore types (Table 5.5). Zones IV, III and II are recognisable in all four cores, whereas zone I is only found in the cores from Lakes Tutira and Rotonuiaha. Core initials are prefixed to the zone label to assist with the discussion of specific cores (e.g., LT–IV = Lake Tutira, Zone IV).

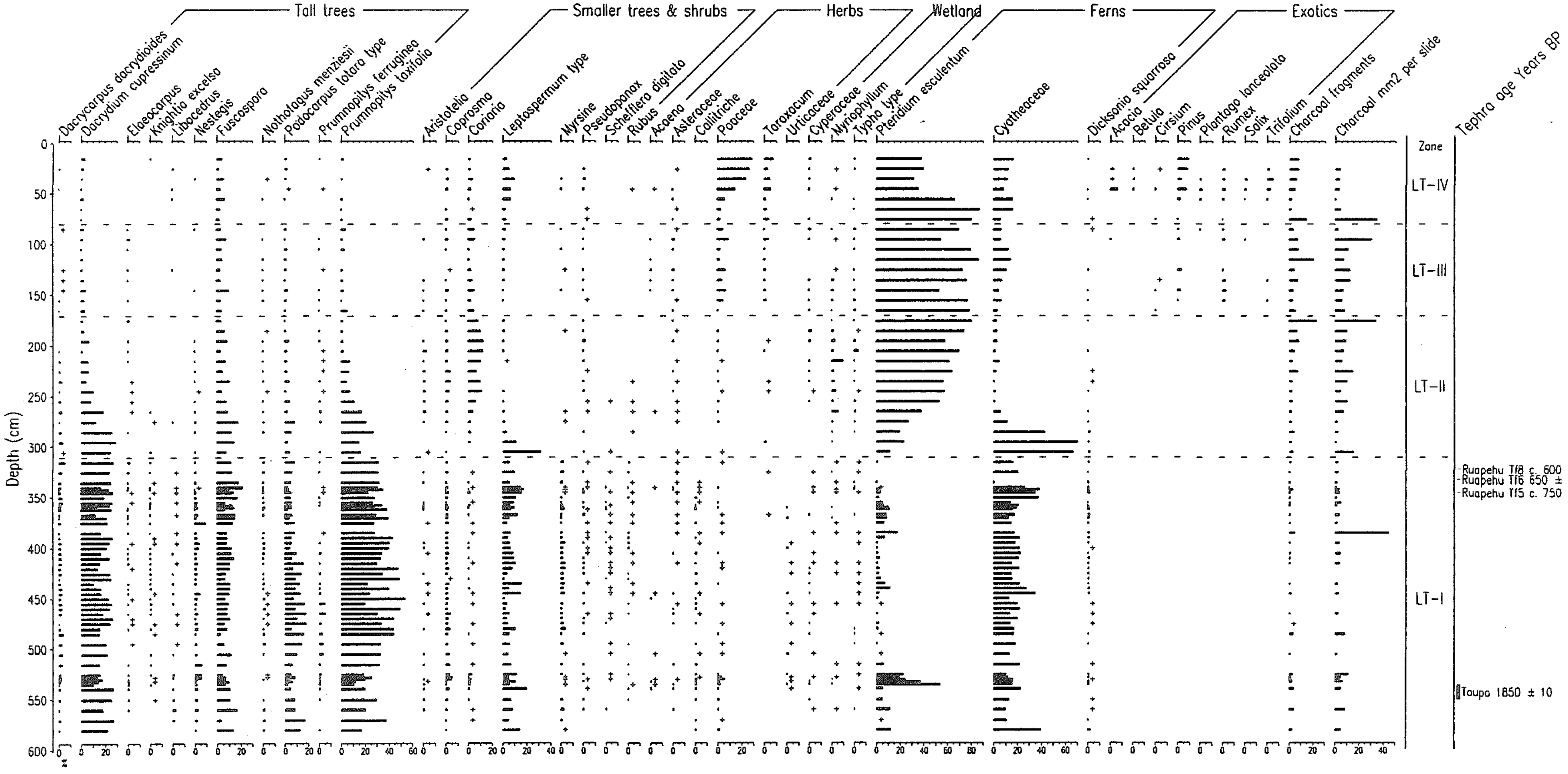


Figure 5.5a. LT16 percentage pollen diagram: main taxa

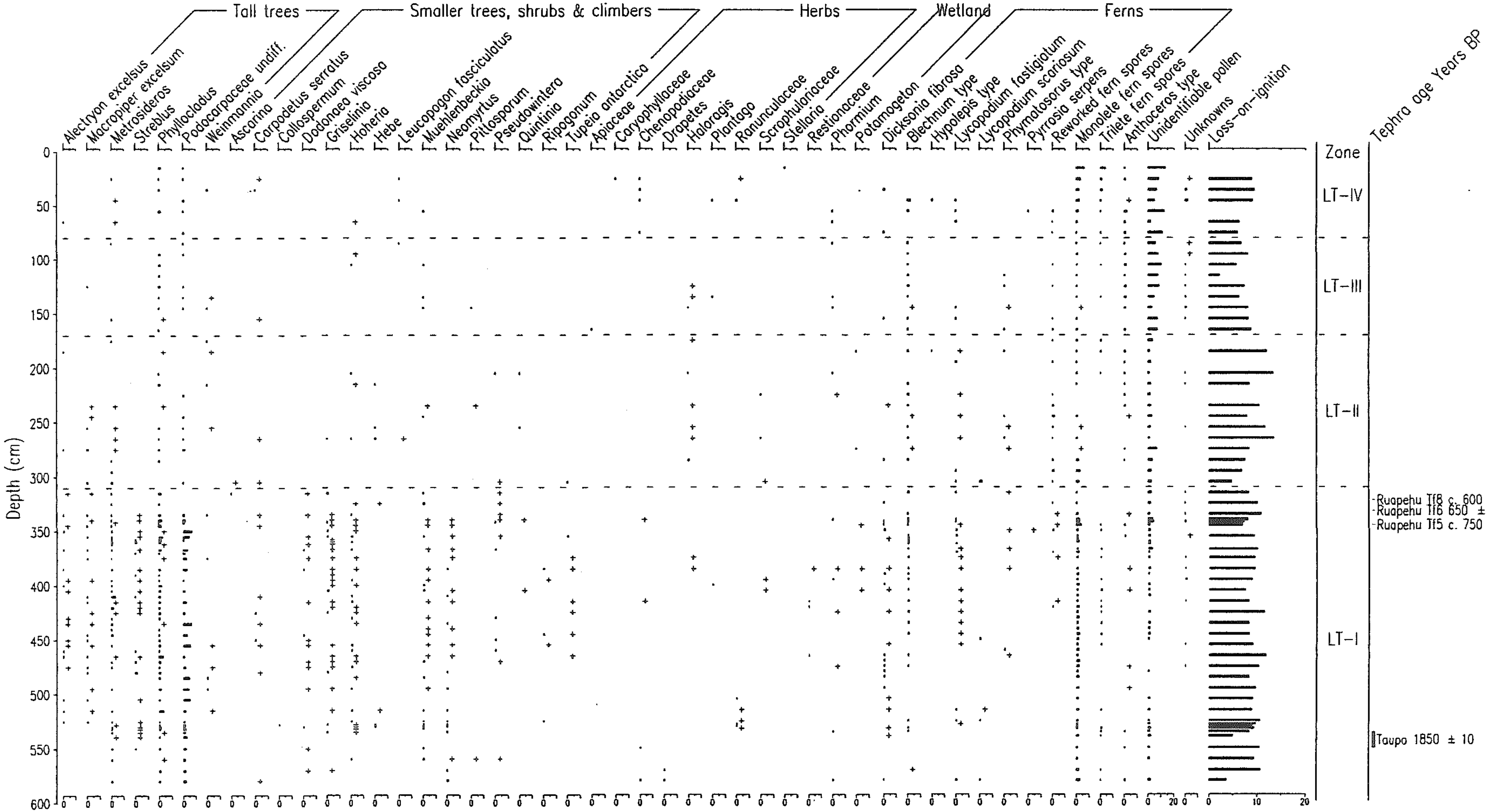


Figure 5.5b. LT16 % pollen diagram continued, with loss-on-ignition

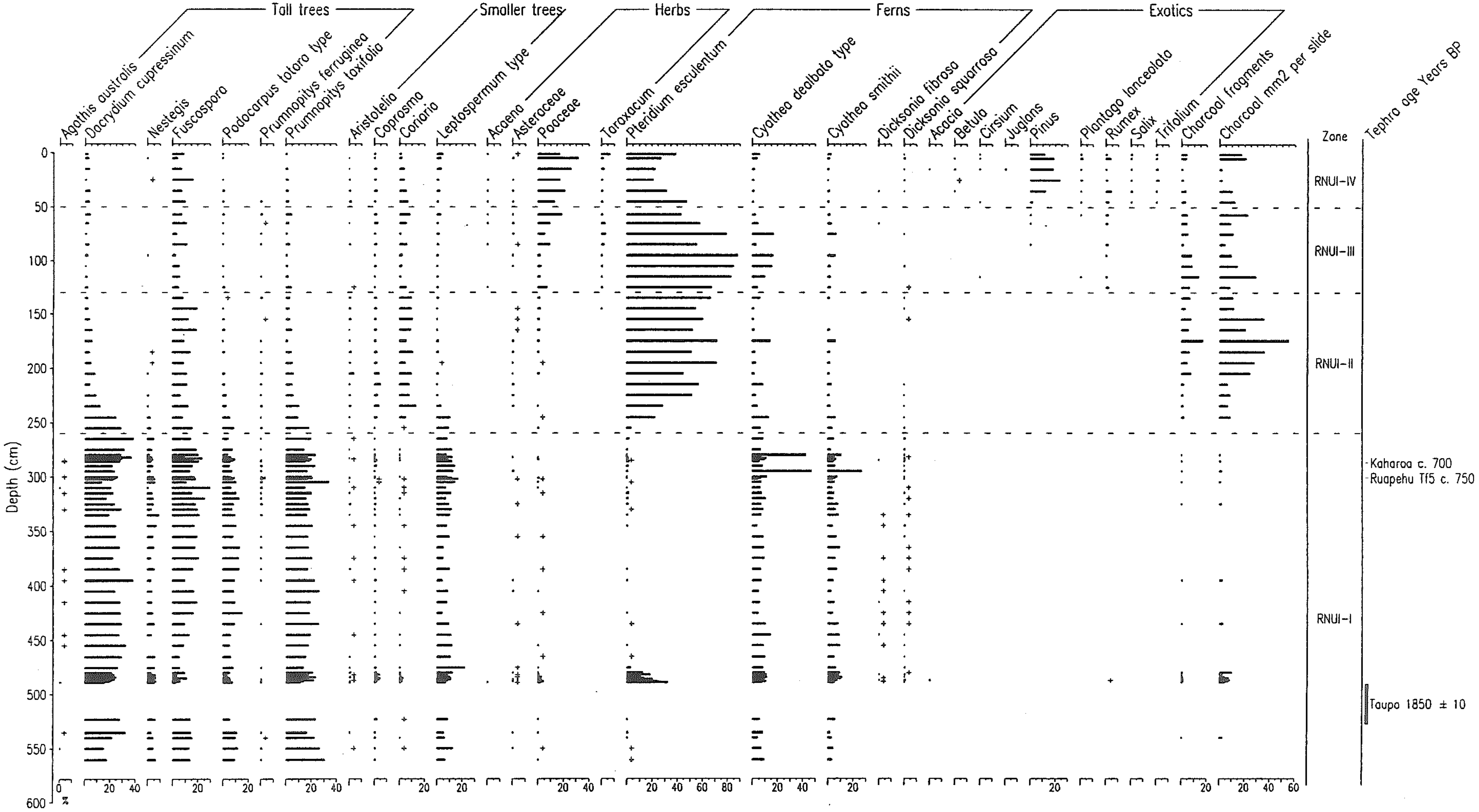


Figure 5.6a. RNUI3 percentage pollen diagram: main taxa

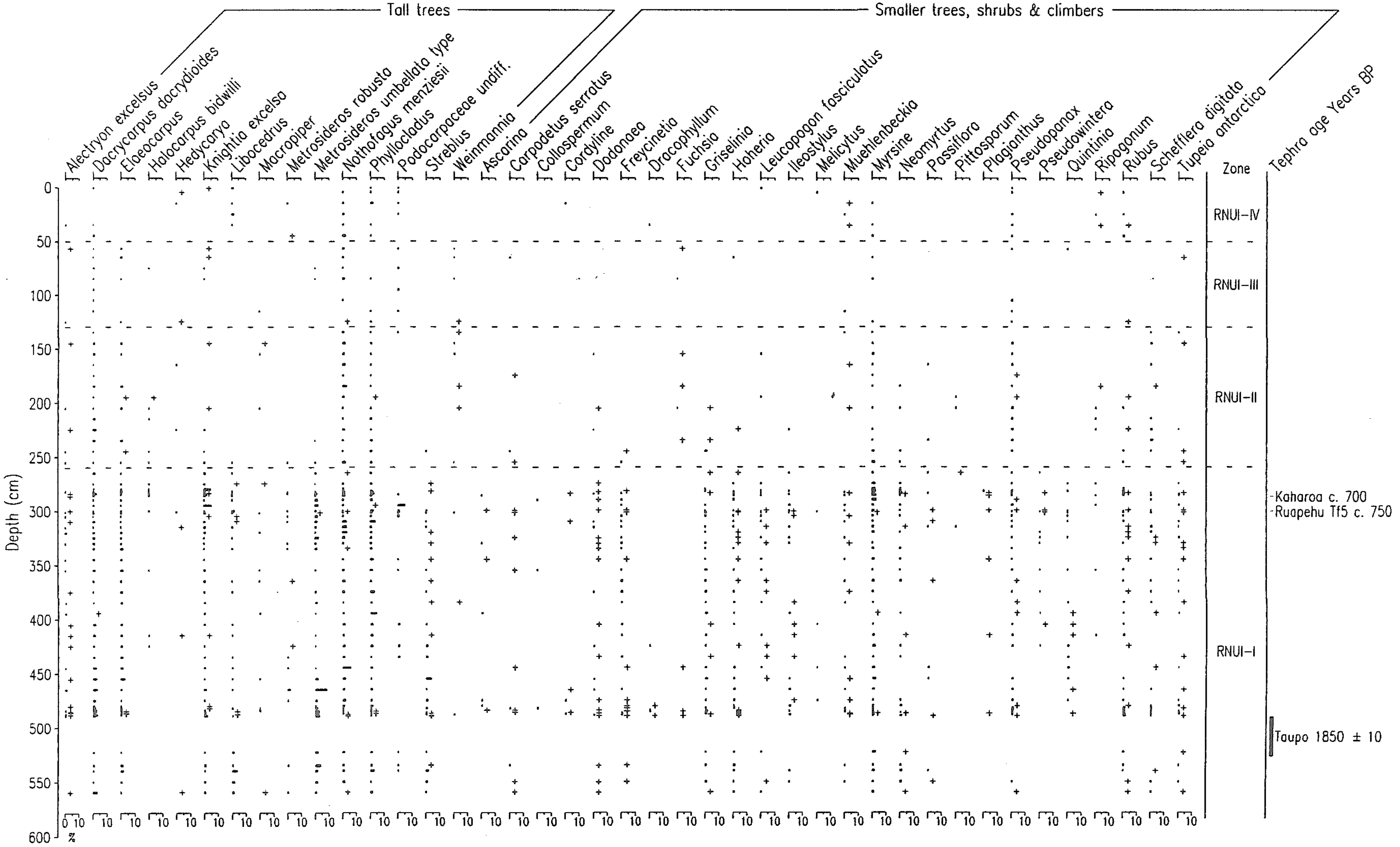


Figure 5.6b. RNUI3 percentage pollen diagram, continued

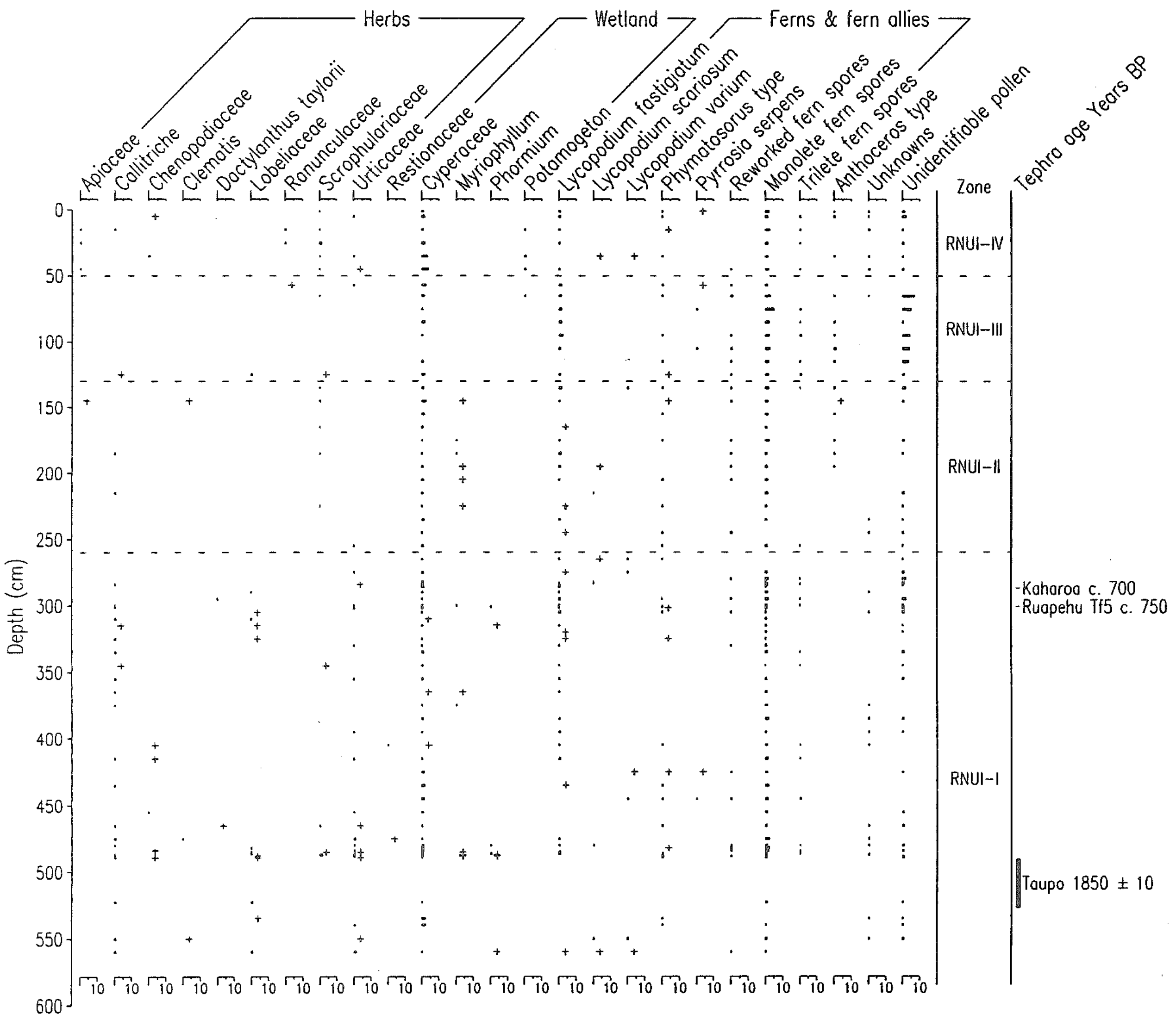


Figure 5.6c. RNUI3 percentage pollen diagram, continued

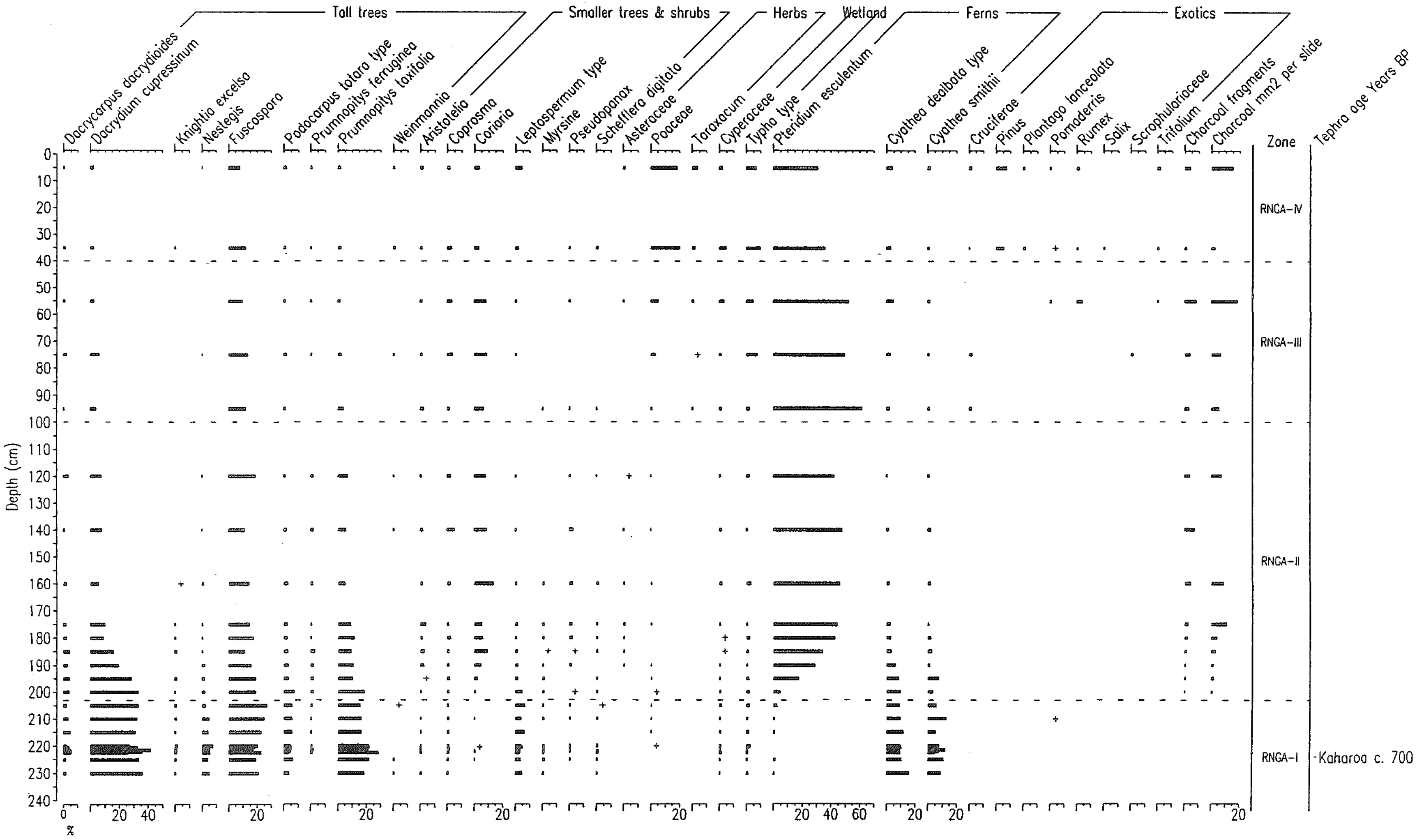


Figure 5.7a. RNGA3 percentage pollen diagram: main taxa

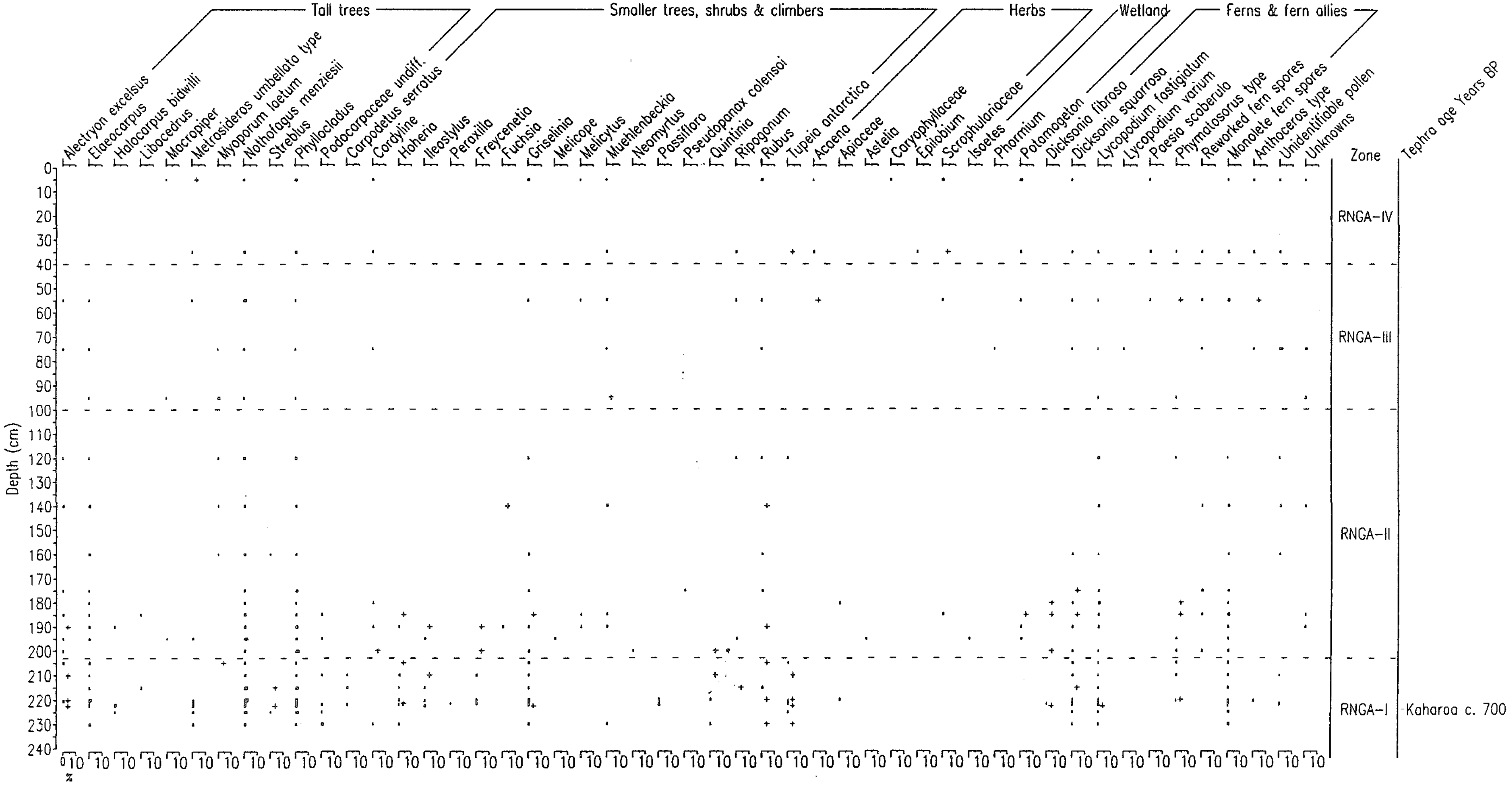


Figure 5.7b. RNGA3 percentage pollen diagram, continued

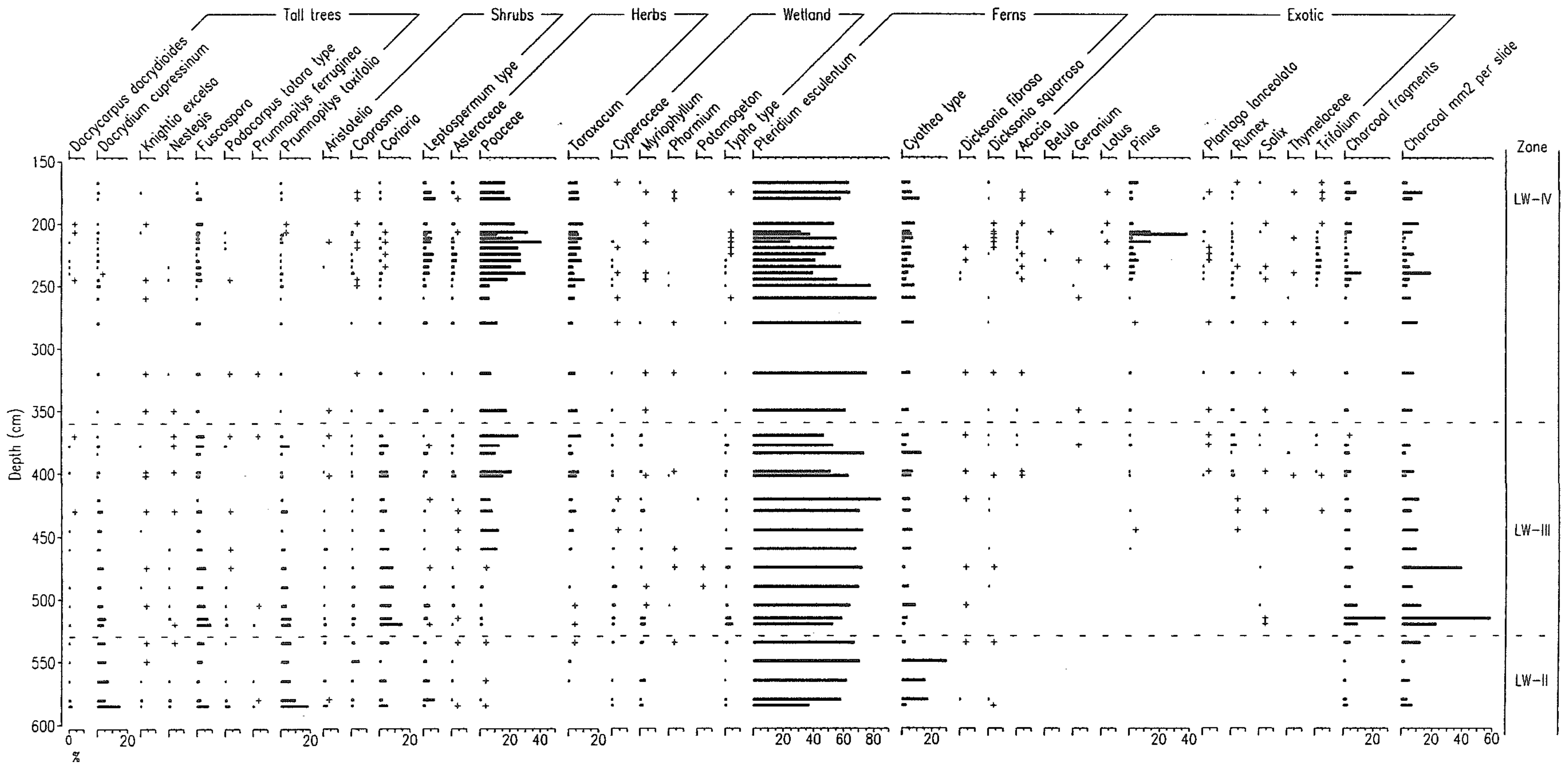


Figure 5.8a. LW8 percentage pollen diagram: main taxa

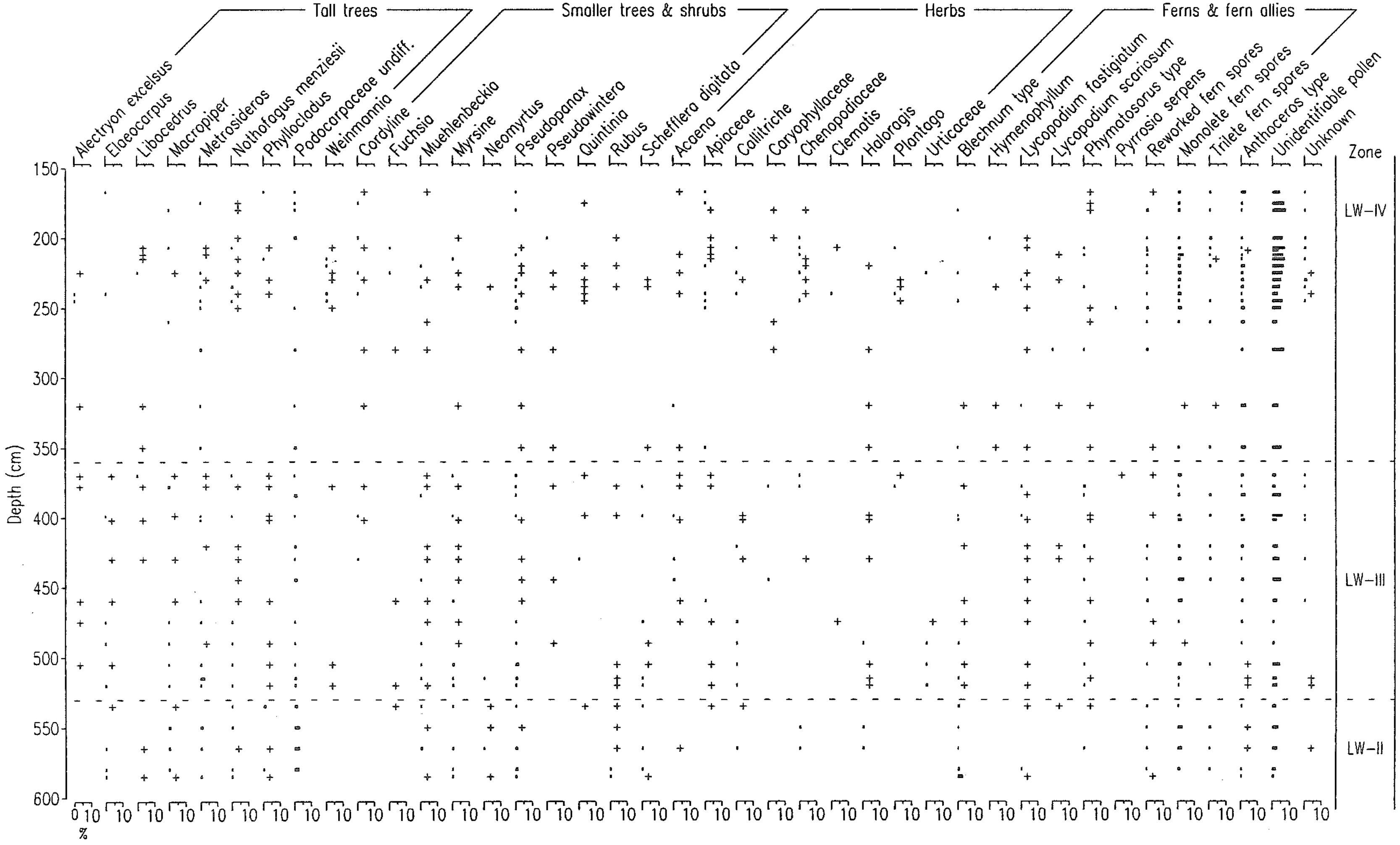


Figure 5.8b. LW8 percentage pollen diagram, continued.

Table 5.5 Pollen zone categories and their depths in Tutira and Putere site cores (* = no sediment in zone).

General zone label	Pollen types characteristic of zone	Pollen zone boundaries in core (m)			
		LT16	LW8	RNUI3	RNGA3
IV	Pinaceae and Poaceae	0.15–0.75	1.67–3.66	0.01–0.45	0.05–0.35
III	Poaceae, *Pteridium* and introduced taxa	0.75–1.65	3.66–5.20	0.45–1.25	0.35–0.95
II	*Pteridium*, *Coriaria* and woody shrub taxa	1.65–3.05	5.20–5.85	1.25–2.55	0.95–2.00
I	*Prumnopitys taxifolia* and *Dacrydium cupressinum*	3.05–5.80	*	2.55–5.60	2.00–2.30

Zone I: *Prumnopitys taxifolia* and *Dacrydium cupressinum* and other tall podocarps

This zone is dominated by pollen from podocarp and hardwood trees and shrubs. *Prumnopitys taxifolia* pollen dominates the pollen spectra in LT-I, in contrast with *Dacrydium cupressinum* pollen in RNUI-I (Figures 5.5 and 5.6). *Leptospermum*-type pollen is the most abundant shrubland taxa represented in both LT-I and RNUI-I. There is an abundance of pollen from *Podocarpus totara* type and *Fuscospora* at both sites, and less but consistent contributions from a number of angiosperm tree and shrub taxa.

Within zones LT-I and RNUI-I there are numerous short-term changes in pollen composition that coincide with either the presence of tephra deposits or charcoal, or a combination of these deposits. One of the most notable peaks on the axis 1 value of both ordination curves (Figures 5.1 and 5.2) occurs above the Taupo Tephra. The Tutira disturbance curve exhibits many smaller peaks, compared with the disturbance index for Rotonuiaha which is otherwise relatively stable. These peaks, and shifts in composition detected by cluster analysis (Appendices 2 and 3), are discussed later.

Zone II: *Pteridium*, *Coriaria* and woody shrub taxa

There is a rapid and sustained increase of *Pteridium* spores in this zone, together with a decline in *Leptospermum*-type, podocarp and many of the hardwood tree and shrub pollen types. For example, there is a permanent reduction of *Prumnopitys taxifolia*, *Dacrydium cupressinum*, *Podocarpus totara* type, *Nestegis*, *Streblus*, *Knightia, Metrosideros* types, *Hoheria*, *Griselinia* and *Freycinetia*, indicating deforestation. There is an increase of pollen from *Coriaria*, *Coprosma* and *Aristotelia.* Poaceae pollen is present at low levels at most depths. Apart from some large peaks of *Cyathea* and *Dicksonia* spores that are associated with a thick erosion pulse in LT-II, these fern spores are generally less abundant and less consistently recorded in zone II compared with zone I. Pollen from plants of wetland and lake margin habitats such as *Myriophyllum*, Cyperaceae and *Typha* increase in LT-II. Charcoal fragments are found at almost every depth in this zone, and in greater quantities than in zone I. At the bottom of zone LW-II, *Pteridium* (35%), *Coriaria* (5%), *Dacrydium cupressinum* (15%) and *Prumnopitys taxifolia* (20%) constitute most of the pollen sum. These percentages equate to those recorded for the same taxa at about two thirds of the way up zone LT-II in Lake Tutira.

The base of pollen assemblage zone II coincides with the most distinct compositional changes and largest peaks in ordination values on the disturbance indices (Figures 5.1 and 5.2). There is a rapid change in pollen composition to the most disturbed sample groups 1 and 2; groups that were not recorded before deforestation. There are also rapid, large scale increases in ordination values, which are unmatched elsewhere in the profiles. Sample groups 1–2 dominate after deforestation in both the Tutira and Rotonuiaha profiles and contain the highest percentages of *Pteridium* and *Coriaria* in the core (Appendices 2 and 3). These most disturbed sample groups are also strongly correlated with the presence of charcoal. Charcoal occurs in all sub-samples with groups 1–5 (Table 5.1).

Zone III: Poaceae and introduced taxa

Exotic pollen types first appear in this zone, including taxa such as *Cirsium* type, *Pinaceae*, *Plantago lanceolata*, *Rumex*, *Salix*, *Trifolium* and *Juglans*. Poaceae, *Acaena* and *Taraxacum* pollen increases. *Pteridium* spores remain at high percentages and continue to dominate the pollen sum. *Coriaria*, *Coprosma* and *Aristotelia* cease to be as prominent as they were in zone II, whereas *Cyathea* spores become more abundant. Charcoal fragments remain abundant.

Zone IV: Pinaceae and Poaceae

A steady increase of Poaceae and Pinaceae pollen coincides with a decline of *Pteridium* spores and *Coriaria* pollen. *Leptospermum*-type increases. Pollen from native forest taxa are recorded at their lowest percentages in the profile, except for *Fuscospora* which remains at *c*. 5-10% throughout zones IV and III. Cupressaceae pollen suddenly becomes more abundant in LT-IV and RNUI-IV, after being almost absent since the top of zone I. In the Putere cores, *Typha* and Cyperaceae pollen increase in this zone, whereas *Myriophyllum* pollen decreases in all profiles (except RNGA3 where it was not present). Charcoal fragments are recorded throughout the zone.

Core LW8 from Lake Waikopiro has many thick erosion pulses (up to 1.16 m thick) in the sediment column (Figure 5.3) which distort the shape of the pollen curves relative to the other cores. This effect occurs mainly in zones LW-IV and LW-III where the erosion pulses are thickest, for example, the 1.16 m erosion pulse that lies between 2.50-3.66 m in zone LW-IV. Although erosion pulses are present in zone LW-II they are only 1–7 cm thick. Only a small degree of variation in the relative pollen percentages occurs in samples taken from within the same erosion pulse, reflecting the rapid nature of sediment deposition during a storm (Figure 5.8). However, compared with the pollen spectra immediately below the 1.16 m pulse, the pollen spectra in the erosion pulse shows a decline of Poaceae pollen and an increase of *Pteridium* spores. Between 2.05-1.62 m in LW8 another thick erosion pulse (43 cm) represents a pulse of inorganic material washed in during the 1988 Cyclone Bola storm. The pollen spectra in the samples taken from within this pulse also show a decrease of Poaceae pollen (in addition to Pinaceae and *Trifolium* pollen) and an increase of *Pteridium* spores.

Correlations with charcoal, tephra and erosion pulses

There is no pattern of change in the pollen taxa within erosion pulses in the Tutira and Rotonuiaha profiles; erosion pulses occur in all sample compositions, with the exception of the five samples that represent peaks of *Cyathea* which always occur in erosion pulses (statistically significant, $p<0.01$). These *Cyathea*-dominated compositions constitute the main peaks on the second axes of the ordinations. In the Tutira profile, three out of the four highest ordination values are from *Cyathea* dominated sample groups 3 to 5, while in the Rotonuiaha profile, the similar sample groups 4 and 5 have the highest ordination values. In both profiles, those sub-samples with charcoal fragments present have significantly higher mean ordination values than those without charcoal ($p<0.01$). There was no correlation between charcoal presence and erosion pulses ($p<0.01$). There were insufficient tephras present in the cores to test in such detail.

Loss-on-ignition: Lake Tutira

Loss-on-ignition results for core LT16 are presented in Figure 5.5b. Values range from 2% to 17% of the sediment's dry weight. There is a marked decline from 10.49% to 4.89% immediately above the Taupo Tephra, after which there is a steady recovery to *c.* 10%. There are three distinctly low values in the core that coincide with sandy sediments at the base of thick graded erosion pulses. Soil samples also gave a wide range of values: samples collected from organic rich top soils contained between 8.41-19.43% organic matter, whereas regolith from exposed slip scars contained lower amounts, between 2.94-6.33%.

DISCUSSION

Palaeoecological analysis of lake basins with different sizes, pollen source areas: data replication

Recent theoretical models of pollen source areas (Prentice, 1985; Sugita, 1993, 1994) provide algorithms that predict the pollen source areas for lake basins of different sizes, so that the area and scale of vegetation reconstruction can be defined in a study (see Chapter 4). By selecting combinations of sites in a study area which have different sizes and source areas, past vegetation can be reconstructed at different scales to suit the research question (Jacobson & Bradshaw, 1981; Davis, 1994). However, in this thesis, the fossil pollen records from different sized lakes do not show large differences in the representation of local and regional pollen types. Sugita (1994) suggests that when the vegetation in the pollen source area is patchy, and the size of the patches of a given taxa are much smaller than the lake basin, then pollen loading may record vegetation as homogeneous rather than patchy. This may explain some of the homogeneity seen in the pollen profiles from this study, if the vegetation on the Tutira and Putere landscapes was patchy. Given the varied topography and drainage at both catchments, the diverse type of habitat available, and the frequent and varied types of disturbance each site has experienced over time (volcanic ashfall, fires, storms, deforestation, modifications by human settlement) then it is feasible the vegetation cover was in fact patchy in the past. Based on Sugita's (1994) theoretical model of pollen dispersal and representation, about 30–45% of the total pollen loading to Lakes Tutira and Rotonuiaha would respectively be derived 600–800 m and 300–400 m from the lake edges. According to the model, this proportion of pollen is adequate to reflect the local vegetation, provided the background pollen is consistent.

The complete pollen records from Lakes Tutira and Rotonuiaha, sites that are 35 km apart, show remarkable similarities between vegetation trends over a period of *c.* 2000 years, in addition to subtle differences caused by the physiographical characteristics of the catchments. Such detailed replication of pollen data, and the excellent independent cross-correlation of cores by tephrochronology provides reassuring evidence that the changes interpreted from the different sediment profiles are representative of changes that occurred at the local and extra-local scale (lake catchments) in addition to the regional scale (Hawke's Bay). Replication of pollen records from separate sites has been more profitable in this thesis for reconstructing regional vegetation and landscape change, than pollen analyses of several cores would have been, from one medium sized lake basin.

The following discussion of changes in vegetation and soil stability based on the pollen, charcoal and sediment data is presented below in three sections:

A: Pre-deforestation vegetation 1850 to 600 BP
B: Polynesian deforestation 600 BP
C: European settlement: AD 1870

The discussions of parts A, B and C are based on multivariate analyses with the pollen, charcoal, tephra and erosion pulse data. The multivariate analyses do not extend to the European period (D) (see Chapter 3).

A: PRE-DEFORESTATION VEGETATION 1850 TO 600 BP

The pollen assemblages from zones LT-I and RNUI-I (Figures 5.5 and 5.6) indicate that between 1850 and 600 BP the Tutira and Putere catchments were covered with a lowland podocarp-hardwood forest similar in composition to extant remnants of this forest type in the Hawke's Bay region.

There are small differences in pollen composition between the two sites. At Tutira, which is situated in one of the drier areas of Hawke's Bay, *Prumnopitys taxifolia* was the dominant tall podocarp compared with *Dacrydium cupressinum* in the higher rainfall area of Putere. Smaller amounts of other podocarp taxa at both sites included *Podocarpus totara* type *Prumnopitys ferruginea* and *Dacrycarpus dacrydioides*.

The insect- and bird-pollinated tall hardwood trees are relatively poorly represented in the pollen record, compared with the wind-pollinated podocarps. They tend to be under-represented in the pollen record (Macphail & McQueen, 1983; Bussell, 1988a; McGlone, 1988c) because of their relatively lower pollen production (e.g., *Knightia, Nestegis*) and often local dispersal (e.g., *Metrosideros, Elaeocarpus, Alectryon, Quintinia* and *Weinmannia*). Despite this, these taxa and smaller trees including *Schefflera digitata, Pseudopanax, Hoheria* and *Myrsine* are consistently represented, although only at relatively low percentages. During the 1880s, *Beilschmiedia tawa* was described as a dominant canopy species in the remnant mixed lowland forest of the Tutira district (Guthrie-Smith, 1969). This tree presumably formed an important component of the forest canopy in the past, even though its fossil pollen was not recorded in the cores. *Beilschmiedia* pollen is severely under-represented in New Zealand pollen spectra, even from areas surrounded by *Beilschmiedia*-dominated mixed forest (Bussell, 1988a, 1988b; Newnham & Lusk, 1990). Macphail (1980) attributes this phenomenon to extremely low pollen production by the species, rather than to its poor dispersal or preservation. This is supported by the fact that it is difficult to extract even small amounts of pollen from their flowers (McGlone, pers. comm.). Other taxa sure to be present in the forests, although missing or severely under-represented in the pollen record, include *Sophora, Melicytus, Hedycarya* and *Pennantia.*

Fuscospora pollen is recorded at relatively high percentages (*c.* 10–20%) in zone I of the Tutira pollen profile. Most pollen of this type probably originated from beech forests on the inland ranges such as the Kaimanawa, Kaweka, Ahimanawa, Maungaharuru, Huiarau and the northern Ruahine Ranges (see Elder, 1959, 1965; Nicholls, 1966; Rogers & McGlone, 1989). The distribution and extent of these forests were similar to the extant beech forests on these ranges (See Figure 2.7, 2.11 and Newsome's (1987) map of North Island vegetation cover, in back pocket). *Fuscospora* pollen is transported long-distances by wind (Moar, 1970; Macphail & McQueen, 1983) and is the most widely dispersed pollen type throughout New Zealand (McGlone & Topping, 1983). In contrast with the Tutira profile, greater percentages of *Fuscospora* pollen (*c.* 10–30%) are recorded in zone I of the Rotonuiaha and Rotongaio profiles. Putere is closer to the axial ranges such as the Huiarau Range, where large forest tracts are dominated by *Nothofagus fusca* and *Nothofagus menziesii.* The beech forests presently surrounding Lake Waikaremoana, *c.* 20 km north of Putere, probably provided the regional source area for *Nothofagus* pollen at the Putere lakes. *Nothofagus fusca* grows in some of the higher altitude areas (*c.* 700 m) of the Putere district and probably had a more widespread distribution in the past, providing a larger local source of this pollen type to the Putere lakes than the Tutira site lakes.

Agathis australis does not occur south of 38° in New Zealand (Allan, 1961; and Figure 2.12) and did not grow locally in either the Tutira or Putere catchments during the Holocene (Ogden *et al.* 1993). Therefore, its presence in the Putere pollen record implies the pollen has been carried long-distances from northern sources (see Newsome's (1987) map of North Island vegetation cover, in back pocket). The presence of *Agathis* pollen at Putere (38° 57') represents the most southern record for this pollen type in post-glacial deposits from the east coast of New Zealand. The only site where *Agathis* pollen is recorded further south of Putere is Taranaki, where McGlone *et al.* (1988) found traces in late Quaternary deposits from Ahukawakawa Swamp, north of Mt Egmont at 39° 15' S. *Agathis* pollen is not present in the Tutira core (39° 12' S), nor in cores taken from Lake Poukawa, which lies 75 km to the south of Tutira (39° 50' S) (McGlone, 1978 and pers. comm.).

Smaller trees, shrubs, herbs and ferns were important in the sub-canopy and shrub layers or in openings and lake and stream margins. They are represented in the pollen record by low percentages of diverse taxa (Appendices 2 and 3). *Leptospermum* type pollen is abundant in zone I of the Tutira and Rotonuiaha pollen profiles until deforestation in zone II. As wind dispersal of *Leptospermum* type pollen is usually restricted to short distances from the source plants (Pocknall, 1979; Macphail & McQueen, 1983) its abundance in the forested zone I reflects the local presence of *Leptospermum scoparium* and *Kunzea ericoides*. *Leptospermum* type pollen was probably derived mainly from a narrow fringe of *Leptospermum scoparium* dominated shrubland around the lake margins at both sites. Lesser amounts would have come from shrubs on wetland areas and small alluvial flats where streams entered the lakes. Percentages of *Leptospermum* type pollen fluctuate in zone I, possibly reflecting episodic changes in lake levels which could cause the disturbance or loss of lake margin habitats. Cyperaceae pollen also occurs throughout zone I, indicating sedges were common around the lake margins and in swampy parts of the Tutira and Rotonuiaha catchments.

The current distribution and ecological requirements of *Leptospermum scoparium* and *Kunzea ericoides* in lake margin habitats supports the pollen evidence for the presence of these species around the margins of the study lakes. Small fragmented patches of *L. scoparium* and *L. scoparium/K. ericoides* shrubland currently occur in Lake Rotonuiaha margin habitats at Putere. *Leptospermum scoparium* forms a narrow fringe right up to the water's edge on the south-east and northern margins of the lake (pers. obs.). This pattern is also recorded at other lake margin sites, for example, McKelvey (1963) described *L. scoparium* and *K. ericoides* growing in narrow fringes around swampy clearings in the

West Taupo region. Similarly, *Leptospermum*-dominated shrub vegetation forms an important, narrow fringe between the forest and lake edges on the shoreline of Lakes Manapouri and Te Anau (Johnson, 1972a, 1972b; Mark *et al.* 1972) and the surrounding mires in the Manapouri-Te Anau lowlands (Burrows & Dobson, 1972).

The pollen records show *Cyathea* species dominated the tree fern flora, whereas *Dicksonia fibrosa* and *D. squarrosa* were less common. Also present were a variety of ground ferns (represented by the monolete fern spores) and fern allies including *Lycopodium*. Climbing shrubs including *Passiflora*, *Muehlenbeckia*, *Rubus* and *Freycinetia* and the perching plant *Collospermum* were present. Traces of pollen from the root parasite *Dactylanthus taylorii* occur in the Rotonuiaha profile. This plant is a ground dweller and localised dispersal of its pollen usually means only small percentages are ever recorded in the pollen record (Macphail & McQueen, 1983; Macphail & Mildenhall, 1980). Thus, the presence of *D. taylorii* pollen in the Lake Rotonuiaha sediments suggests the plants were present locally. This raises an interesting question about the mechanism of its pollen dispersal from the parent plant or forest floor to the lake. The short-tailed bat (*Mystacina tuberculata*) that pollinates *D. taylorii* (Ecroyd, 1993) was probably also an effective pollen disperser for the plant, together with slope wash near the lake edges. *Dactylanthus taylorii* pollen may have reached the lake *via* bat droppings and from the fur of these omnivorous bats while they searched for insects hovering above the lake surface.

Forest disturbance from the Taupo eruption (1850 BP)

The most recent 1850 BP Taupo eruption was also the most violent and the largest of all known eruptions in the world in the past 5000 years (Wilson & Houghton, 1993; Wilson & Walker, 1985). The eruption from the Taupo caldera (Figure 2.1) generated a variety of pyroclastic deposits, with airfall deposits more than 10 cm covering an area of *c.* 30 000 km^2 east of the vent and ignimbrite deposits covering a near-circular area around the lake of *c.* 20 000 km^2 (Wilson & Walker, 1985) (Figures 5.9a and 5.9b). This eruption caused changes to the forest and landscape of the central North Island. Remains of Taupo Tephra are recorded in cores LT16 and RNUI3 (Table 5.3) and discussions about the effects of this eruption on the vegetation of Hawke's Bay are based on pollen evidence immediately above these tephra deposits.

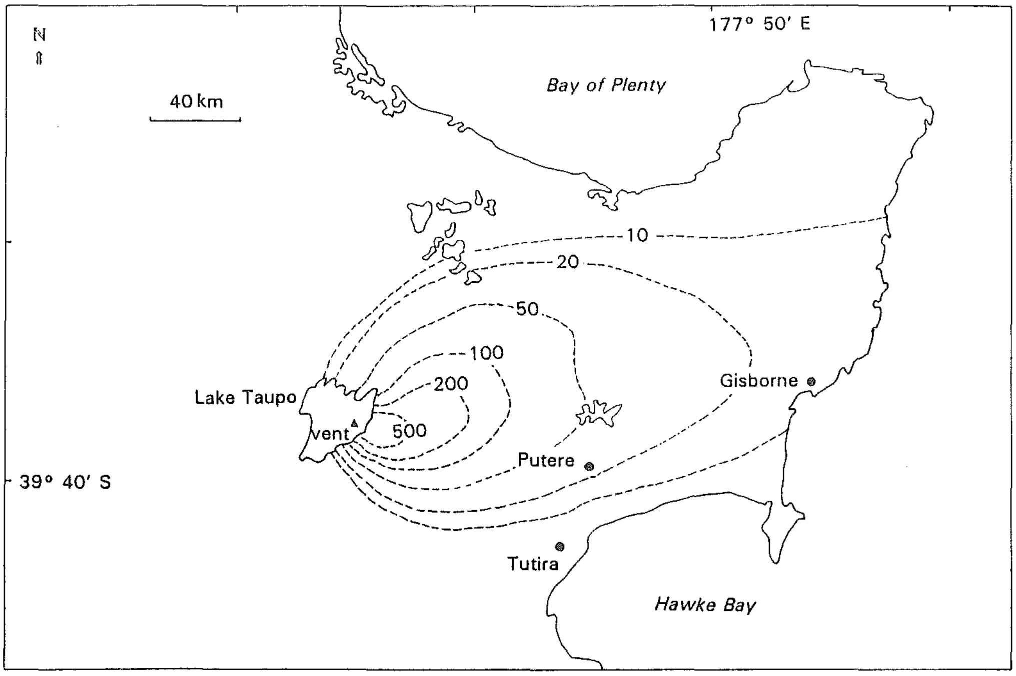


Figure 5.9a. Isopachs (cm) of the total thickness of airfall deposits from the Taupo eruption (including layers 1 and 2 of the ignimbrite phase) over the eastern central North Island (from Wilson & Walker, 1985: 222).

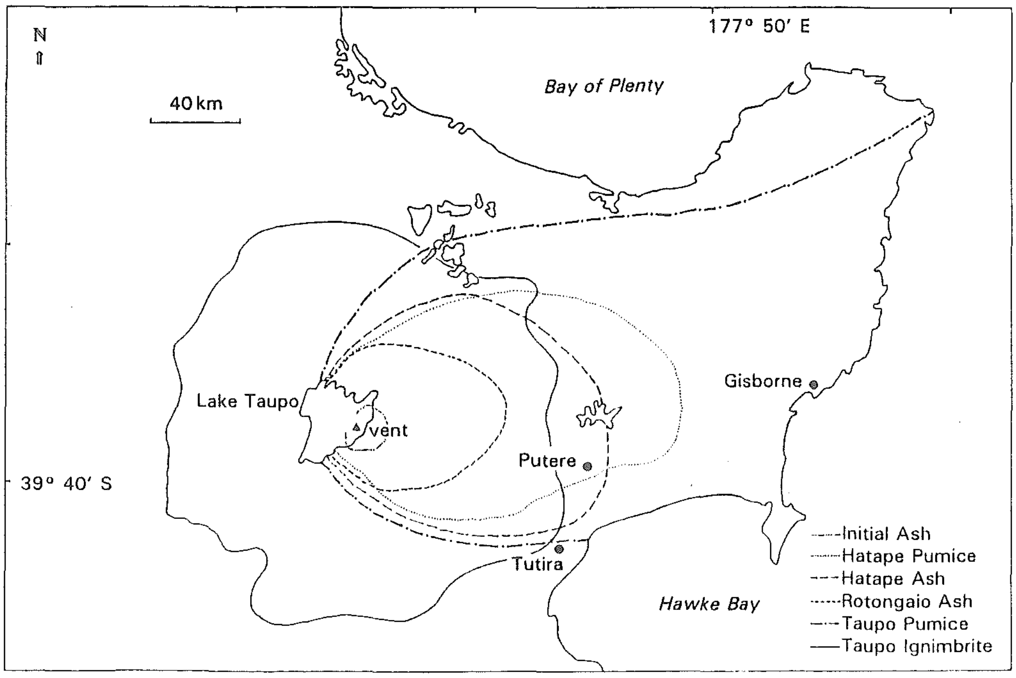


Figure 5.9b. Dispersal patterns of airfall deposits from the Taupo eruption over the eastern central North Island (from: Wilson & Walker, 1985: 214). The margin of each deposit is represented by the 3 cm isopach. The approximate outer limit of the Taupo Ignimbrite is also shown.

The timing of the Taupo eruption

The age of the Taupo eruption is well constrained by multiple radiocarbon ages. Froggatt & Lowe (1990) selected a number of the most reliable (in their opinion) radiocarbon ages for Taupo Tephra deposits and combined them to calculate an error-weighted mean age of 1850 ± 10 BP. This age is adopted here. However, Wilson (1993) suggests the figures derived from each radiocarbon age by Froggatt & Lowe (1990) are subject to much larger errors, firstly, because of the assumption the ages represent measurements of the same event. Wilson (1993) suggests this assumption may be questionable if the sample to be dated has come from different chronological positions around a tephra deposit (e.g., from material above or below the tephra, or from associated charcoal in or above the tephra). Secondly, Wilson warns that the errors given by Froggatt & Lowe (1990) are only the 1 s.d. errors based on laboratory counting statistics and therefore they take no account, for example, of errors due to sample spread or differences between laboratories. Wilson (1993) re-evaluated the available data on the ages of Taupo eruptive units and suggests a 1 s.d. error of ± 2–3% is a realistic estimate of total error derived from field and laboratory related uncertainties for any single ^{14}C age.

Airfall Taupo Tephra on the Tutira and Putere landscapes

Airfall tephra from the Taupo eruption coated the central North Island landscape in varying thicknesses according to distance away from the eruptive centre and from the ash plume (Figure 5.9a). The Tutira and Putere sites lie to the east of the Taupo volcanic vent in line with the path of the ash plume which travelled predominantly east of the vent (Figure 5.9a). The position of the catchments in relation to the Taupo vent and to the different depths of Taupo Tephra on the landscape is shown in Figure 5.9a and 5.9b (from Wilson & Walker, 1985). Although similar distances from the vent (Table 5.6), the Putere landscape was covered with thicker layers of airfall tephra than Tutira.

Table 5.6 Summary of Taupo Tephra deposits at Tutira and Putere.

	Tutira	Putere
Distance of site from Taupo volcanic vent	*c.* 90 km	*c.* 93 km
Thickness of tephra deposits in lake sediment core	18 cm	37 cm
Thickness of Taupo Tephra on present landscape	10–15	20–30
Position of site relative to isopach zones (Wilson & Walker, 1985)	0–10 cm	20–50 cm

The difference in thickness of Taupo Tephra at the two sites is obvious on the present landscape, and is also reflected in the lake sediment records. The tephra is visible in cuttings, erosion scars and soil profiles from both catchments. On gentle slopes in the Tutira catchment, Taupo Tephra forms a 10–15 cm thick layer mixed in the A and AB soil horizon. In the Putere catchment, the layer is much thicker, and forms a distinct 20–30 cm deposit in the soil. In the sediment record, Taupo Tephra is 19 cm greater in core RNUI3 than it is in core LT16 (Table 5.6). The thicker deposits occur at Putere because this site is closer to the fallout zone of the smaller eruptive episodes that occurred before the penultimate and most widespread eruption of the Taupo Pumice (see chronological order and isopach limits of the eruptive episodes in Figure 5.9b). Putere is situated nearer to the 3 cm isopach limits of the Hatape Pumice and Hatape Ash deposits (as demarcated by Wilson & Walker, 1985; Figure 5.9b.) and as a result received more airfall tephra from these episodes than Tutira.

Possible types of vegetation damage from airfall Taupo Tephra

Airfall tephra would have caused varying degrees of damage to the vegetation on the Tutira and Putere landscapes, depending on many factors including the thickness of the ash and its chemical composition, plant morphology and local topography (e.g., Mack, 1981). The Taupo eruption would have damaged the forests at Tutira and Putere in many different ways, creating mosaics of disturbed vegetation. The most likely causes of damage are listed below:

1) physical damage to the crowns of the more exposed trees from mechanical overload and collapse of smaller branches, and defoliation from the weight of ash. Exposed and small plants would be buried under 10–30 cm of tephra.

2) leaf death, brought about by toxic compounds leaching from the ash, such as sulphur.

3) physical smothering of leaves with ash, interfering with gas exchange and photosynthesis and causing premature leaf abscission.

4) fires associated with the eruption.

Hot ash and water fell out relatively close to the vent, whereas further away from the eruptive centre, cold airfall tephra and ash were washed out of the plume by rain. Thus, at Tutira and Putere it is unlikely that heat or hot ash contributed to vegetation damage. It is unlikely that the blast effects from the eruption damaged forests as far away as Tutira and Putere; I have not seen any evidence in the catchments that implies forests were flattened or buried under Taupo Tephra.

Ashfall- and fire-related disturbance would have created a mosaic of damaged and regenerating forest patches in the Tutira and Putere catchments. Disturbance would have ranged from gaps in the canopy to more extensive cleared areas. Clarkson (1990) assessed vegetation changes following recent (<450 years) eruptions from volcanoes in the North Island. He found that where forest canopies were partly killed, mosaic vegetation patterns developed. Other contemporary observations of vegetation decline after volcanic eruptions in New Zealand also show that damage can be very variable, even over short distances. Clarkson & Clarkson (1994) observed after recent eruptions on White Island, Bay of Plenty (1976–1990) that vegetation disturbance ranged from complete destruction to full survival, including sites close to the source. Similar variation in the extent and type of forest damage and recovery has been recorded on Mt Tarawera after the AD 1886 eruption

(Aston, 1916; Burke, 1974; Clarkson & Clarkson, 1983) and on Mt Taranaki after the AD 1655 Burrell eruption (Druce, 1966).

The absence of thick erosion pulses above the Taupo Tephra in both the Tutira and Rotonuiaha profiles indicates there was no major erosive period after the eruption. After initial deposition of ash on the catchments, airfall deposits may have re-mobilised, particularly off steep slopes, causing accumulation and thickening on gentle slopes and valley floors. However, there is no visible evidence in the Tutira or Rotonuiaha sediment records, that suggests major redeposition of tephra occurred in these catchments after the eruption. The Taupo Tephra forms a distinct layer in both sediment cores. The fact that there was no slumping of tephra or woody debris from the catchment into the lakes after the initial ashfall, indicates that forests were not completely destroyed and the initial ash cover remained on the landscape. A substantial cover of vegetation (even if it was damaged) must have remained on the catchments after the eruption to prevent the slumping of tephra and vegetative debris into the lake.

Pollen evidence of forest disturbance above the Taupo Tephra

The Taupo eruption was the largest disturbance event to have affected the forests of Hawke's Bay during the 1200 radiocarbon years before widespread deforestation. This is shown by distinct changes in the pollen spectra from cores LT16 and RNUI3 (Figures 5.10 and 5.11), and as a large and distinct peak above the Taupo Tephra on the disturbance indices in Figures 5.1 and 5.2. The Cluster Analyses identify this change as a shift from sample group 6 to 6A at Tutira, and from group 8 to 3 at Rotonuiaha, both of which indicate a transition to a more disturbed vegetation composition.

The summary pollen profiles (Figures 5.10 and 5.11) show a rapid decline of pollen from the tall forest taxa immediately above the tephra. Pollen from *Dacrydium cupressinum* and *Prumnopitys taxifolia* both decline by *c.* 10-15% of the pollen sum, and *Podocarpus totara* type by *c.* 8%. There is a decrease of *Fuscospora* pollen above the Taupo Tephra at both sites; from *c.* 14% to 3% in the Rotonuiaha pollen profile, and from *c.* 10% to 5% in the Tutira profile. This pollen evidence suggest forests in the Tutira and Putere catchments suffered considerable damage during the Taupo eruption, but much of the forest still remained standing on the landscape after the event. Most of the *Fuscospora* pollen in the

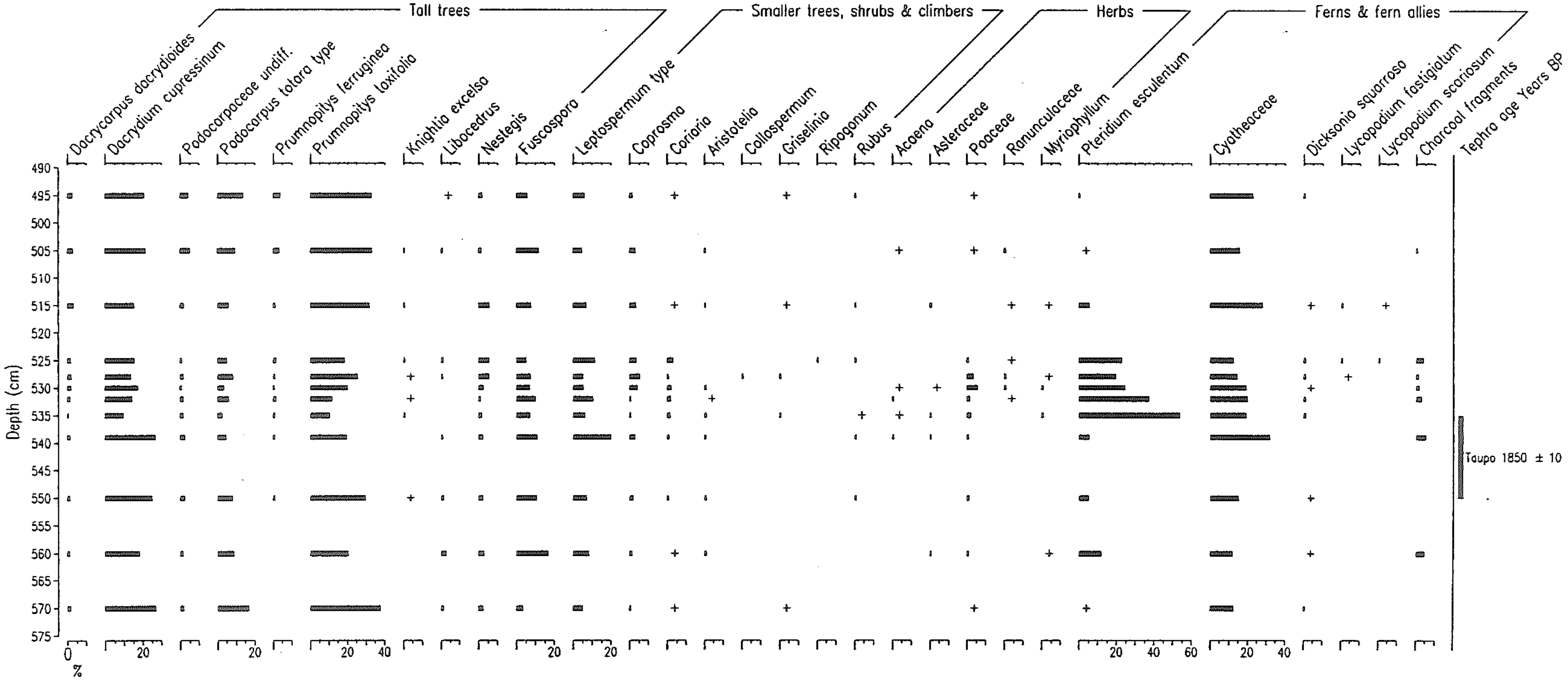


Figure 5.10. LT16 summary % pollen sequence: post–Taupo eruption

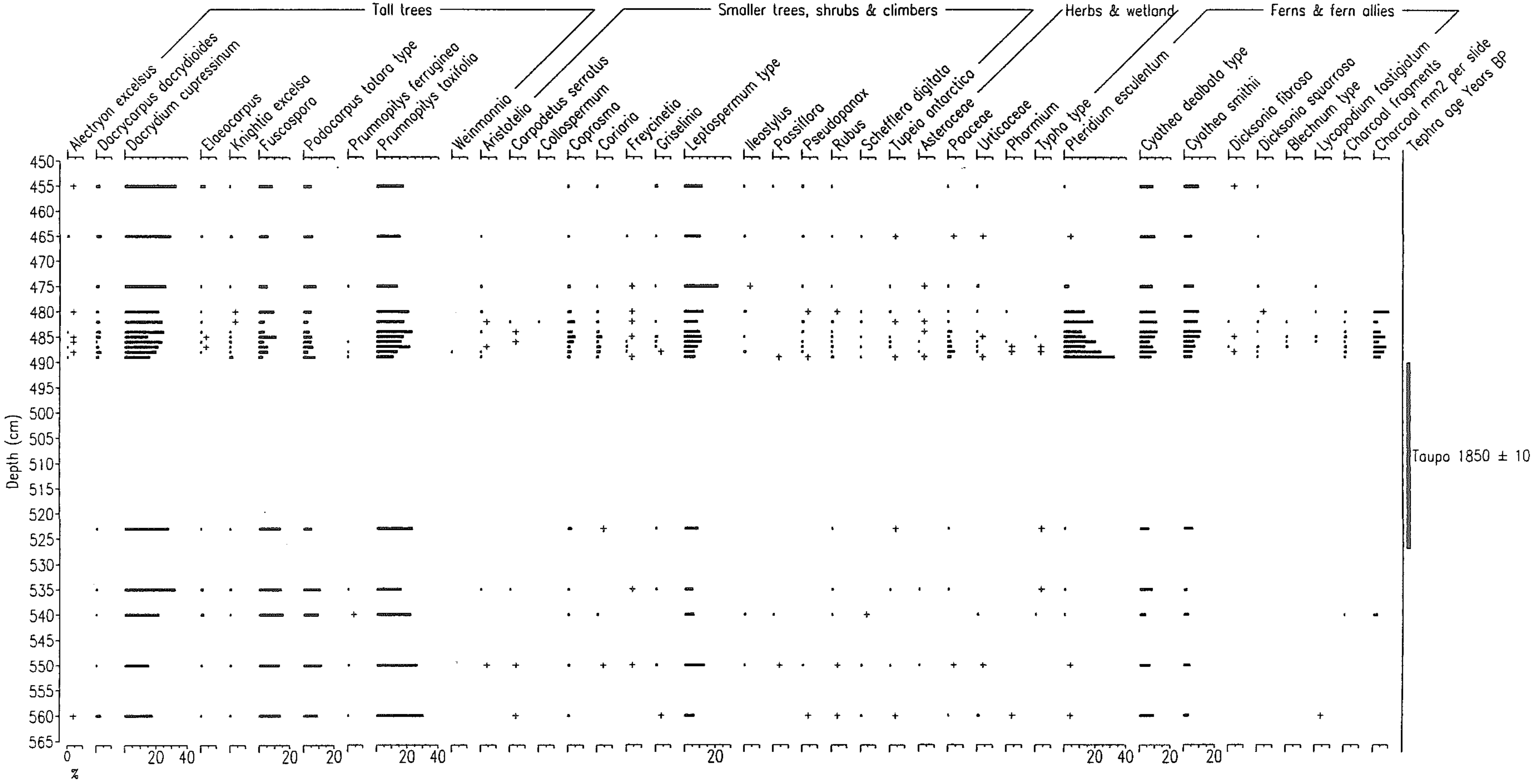


Figure 5.11: RNUI3 summary % pollen sequence: post–Taupo eruption

profiles will have come from beech forests on the adjacent inland ranges (see Chapter 4), and its decline above the Taupo Tephra probably represents a long-distance signal of beech forests that were buried by thick airfall and flow deposits closer to the vent. Pollen evidence from the Three Kings Range south of Lake Taupo (shallow site: Rogers & McGlone, 1989) (see Figure 5.12) suggests beech forests were inundated and devastated by Taupo Ignimbrite.

The decline of *Fuscospora* pollen at Putere was greater than at Tutira, as Putere had a much closer source of beech forest in the Huiarau Range (Figure 2.7). The Huiarau Range is situated about 60 km from the Taupo volcano's eruptive centre and its vegetation endured more damage because it was directly situated in the pathway of the ash plume (compared with the beech forests on the Ahimanawa and Kaweka Ranges nearer Tutira: see Figures 2.7 and 5.12). The Taupo Ignimbrite also reached the western sides of these ranges; the decline of *Fuscospora* pollen at Tutira (Figure 5.10) may also reflect forest destruction from flow deposits.

Above the Taupo Tephra in the LT16 and RNUI3 profiles there is an increase of pollen from taxa that are characteristic of disturbed forests. For example, pollen from *Knightia, Carpodetus serratus, Aristotelia, Coriaria, Coprosma, Schefflera digitata* and spores from *Pteridium* and *Dicksonia squarrosa* increase or become more abundant. These are the canopy and sub-canopy taxa that regenerated rapidly and exploited the considerable number of newly formed open-sites in the forest. *Alectryon excelsus* pollen also occurs above the Taupo Tephra. Bray (1989) suggests this pollen type is indicative of disturbance when it shows a gradual increase from low counts or nil to a fluctuating average percentage in the pollen record.

Of the tree fern spores recorded in the profiles, only *Dicksonia squarrosa* increases above the Taupo Tephra. This reflects its ability to colonise rapidly in newly created clear areas after the eruption. Unlike other tree ferns, *D. squarrosa* has spreading rhizomes that can reach more than 1 m from the main stock and produce subsidiary erect trunks which can form groves (Allan, 1961). This habit allows for rapid regeneration after disturbance and may have contributed to the successful establishment of *D. squarrosa* after the eruption compared with other tree ferns (Figures 5.10 and 5.11). Climbers and epiphytic perching plants were also quick to exploit light-gaps created by ash-laden branches falling through the sub-canopy. This is shown in the pollen record by small increases of pollen from the shrub and small-tree parasites *Ileostylus micranthus* and *Tupeia antarctica*, the perching lily *Collospermum;* climbers that scramble over extensive cleared areas such as *Freycinetia* and *Ripogonum*; and climbing shrubs such as *Passiflora, Griselinia (G. lucida)* and *Rubus* (Figures 5.10 and 5.11). Increased abundances of pollen from lianes and epiphytes were also recorded in pollen profiles from the flanks of Mt Taranaki (Lees & Neall, 1993) where forests were damaged by lapilli from Mt Taranaki eruptions.

Fires associated with the Taupo eruption

Large volumes of ash particles in the atmosphere after the Taupo eruption may have caused short-term changes in climate. Ash particles can cause solar radiation to be scattered back to space, which can trigger surface cooling and increased storminess (*c.f.* Mount St Helens: Christiansen, 1980; Sear & Kelly, 1980). During an eruption, electrical discharges from ash laden clouds can cause outbreaks of fire as the plume moves along. These fires would be fuelled by accumulated plant debris in the damaged forests, and be exacerbated by drought conditions if they existed at the time. After the AD 1886 Mt Tarawera eruption, central North Island, lightning episodes accompanying this eruption occurred on a large scale. Electric flashes frequently ended in fire-balls that caused forest fires in the Tarawera district (Pond & Smith, 1886). During 1886 AD there was a severe drought throughout New Zealand (Arnold, 1994) which predisposed the forests to a greater risk of fire. Ash particles in the atmosphere after the 1980 Mount St Helens eruption also promoted lightning which caused hundreds of small forest fires (Christiansen, 1980).

The presence of charcoal fragments immediately above the Taupo Tephra in both the Tutira and Rotonuiaha profiles (Figure 5.10 and 5.11) suggest a number of fire episodes occurred after the Taupo eruption. These fires may have created and maintained extensive forest clearings, allowing colonisers such as *Pteridium*, *Coriaria*, *Aristotelia*, *Poaceae* (*Cortaderia fulvida*), Asteraceae, *Acaena* and *Urtica* (the pollen of which increases above the Taupo Tephra) to persist for longer than they could if regeneration sequences were uninterrupted. The greater amount of charcoal recorded in the Tutira profile compared with Rotonuiaha, suggests that this drier site (see Chapter 2) was more susceptible to fire. This may explain why the percentage of *Pteridium* spores is greater and more sustained above the Taupo Tephra in the Tutira profile compared with Putere. McGlone (1981) suggests that in areas situated at remote distances from large eruption centres (as Tutira and Putere are relative to the Taupo vent), a succession of dry summers after the eruption would be needed if fire was to destroy large areas of forest.

Post-disturbance forest redevelopment: pioneer invaders and survivors

After the Taupo eruption, the vegetative expansion of damaged but surviving trees would have made an important contribution to forest redevelopment at Tutira and Putere. This is reflected in the pollen record by the steady increase of pollen from tall tree taxa after the initial decline above the tephra. In the clearings, pioneer species would have been quick to invade and colonise the new sites, shown by the increase of spores and pollen in both profiles (Figures 5.5 and 5.6) from *Pteridium esculentum, Coriaria* (source plant probably the woody shrub, *C. arborea*) and *Aristotelia* (source plants most probably the small tree, *A. serrata*). The pollen diagrams also show increases of pollen from Asteraceae, Poaceae (particularly *Cortaderia fulvida*), *Acaena* and *Urtica* which would also have rapidly colonised open areas.

It has been reported elsewhere, that after the fallout of volcanic ash, most of the regeneration following burial is from the vegetative expansion of plants that survived the eruption, rather than by the invasion of pioneer species (Burke, 1974; Antos & Zobel, 1985; Tsuyuzaki, 1987; Zobel & Antos, 1992). After most types of disturbance, revegetation from seed and spore banks usually takes place during the next growing season. However, after burial with tephra, these types of regeneration mechanisms are often inhibited for long periods of time making recovery much slower (Zobel & Antos, 1992). The invasion of pioneer species may have been as important as recovery of survivors at Tutira and Putere after the Taupo eruption because tephra deposits were not deep enough to cause complete forest destruction, leaving adequate seed sources behind on the patchy landscape.

The successful establishment of opportunist invaders such as *Pteridium, Coriaria* and *Aristotelia* after volcanic disturbance may be attributed to (a) the period of time pre-existing plants can survive burial, (b) effective shoot penetration of the tephra and (c) effective bird, water or wind dispersal of seeds and spores from other vegetated areas. *Pteridium* spores, for example, can be transported long-distances by wind, can tolerate a wide range of conditions for germination, and successfully establish colonies in new sites (Page, 1976). *Pteridium* is also highly proficient at spreading vegetatively by rhizome expansion from established plants. For example, *Pteridium* emerged through Rotomahana mud that was half a metre thick, one year after the AD 1886 Mt Tarawera eruption (Nicholls, 1963). The *Pteridium* curves in both the LT16 and RNUI3 profiles clearly show this fern to be the quickest of all invading species to establish after the eruption. *Coriaria arborea* has stout basal shoots (Wardle, 1991) which would have helped pre-existing plants of this species to tolerate burial, as new shoots could push through the tephra layer. Seeds of *Coriaria* and *Aristotelia* would have been dispersed rapidly after the eruption, by birds that fed on the fleshy fruits of these shrubs. After the AD 1886 Mt Tarawera eruption, *Coriaria* was the first shrub to colonise some of the northern scoria covered slopes, and its rapid establishment was reportedly assisted by bird-dispersal of seeds (Aston, 1915).

The establishment of these pioneer species on sites that were initially unfavourable for most other plants, may have lead to the modification of the substratum, for example, by recycling nutrients from the buried soils, adding nutrients from decaying plant matter, increasing soil depth with litter and altering the drainage. Eventually more suitable conditions would be available for less tolerant species to invade, establish or grow to maturity. For example, a deep litter can accumulate relatively quickly under a dense *Pteridium* canopy. The litter builds soil depth and increases the nutrient content under the fern canopy, and produces a suitable environment for forest seedlings to establish, providing soil type and soil moisture is adequate (Partridge, 1990). *Coriaria* can also alter the nutrient status of its substrate by fixing nitrogen through a symbiotic relationship with an actinomycete endophyte (Silvester, 1978).

Forest redevelopment after the Taupo eruption

The disturbance indices in Figure 5.1 and 5.2 show that once the ordination peaks decline above the Taupo Tephra, the sample groups return to the same compositional groups that were present below the tephra (group 6 at Tutira and group 8 at Rotonuiaha). This implies that after the eruption disturbance, the Tutira and Putere forests made a full recovery to pre-eruption forest compositions.

The speed of forest redevelopment after disturbance from the Taupo eruption has been derived using sedimentation rates (Table 5.4) and the point where the *Pteridium* curves drop to trace levels above the Taupo Tephra. Using this approach, complete forest redevelopment was achieved at Tutira within approximately 175 years, compared with 145 years at Putere. These estimates are assumed to indicate the time taken for cleared areas in the forest to close over, the forest taxa to regenerate, and *Pteridium* to be completely shaded out.

The pollen evidence suggests the forests at Tutira took slightly longer to recover than they did at Putere, despite the thinner deposits of tephra on the Tutira landscape. I suggest this was because Tutira is in a lower rainfall region than Putere, and to some extent this may have governed recovery rates. Forest regeneration is usually faster in areas of high rainfall or in damper sites, and in such cases *Pteridium* is suppressed more readily by re-establishing forest saplings growing under its canopy. Levy (1923) found that if *Pteridium* was left undisturbed in damp gullies and on better soils in the Taranaki hill country, it was replaced rapidly after about five years by *Aristotelia*, *Fuchsia*, *Hoheria* and *Coriaria*. However, on drier sites, replacement took over several decades before shrubs (in particular *Coriaria*) began to re-establish amongst the fern. The faster shading out of *Pteridium* by rapidly re-establishing broadleaf taxa at the wetter Putere site may also explain why *Pteridium* spores reached a lower maximum percentage above the Taupo Tephra in the Rotonuiaha profile (32%) compared with the Tutira profile (53%) (Figures 5.10 and 5.11). This difference is evident even though the potential number of colonizable sites for this fern after the eruption was probably greater at Putere, because of the thicker deposits of tephra on the Putere landscape.

The timespan suggested for forest recovery at Tutira and Putere after the Taupo eruption accords well with estimates made by Clarkson *et al.* (1986) for new forest development after complete burial of west Taupo forests with Taupo Ignimbrite (*c.* 450 years). The timespans also agree well with estimates of forest regeneration after volcanic disturbance in the North Island (Table 5.7).

Table 5.7 Timespans for revegetation after volcanic disturbance in some North Island sites (from Clarkson, 1990:62).

Location	Bioclimatic zone	Main present day vegetation type	Estimated timespan for recovery (years)
White Is.	Coastal	*Metrosideros excelsa* forest and scrub	10–20
Rangitoto Is.	Coastal	(a) *Metrosideros excelsa* forest	> 200
		(b) *Leptospermum scoparium-Olearia furfuraceae* scrub	> 200
Mt Tarawera	Lowland	(a) *Beilschmiedia tawa* forest	103
		(b) *Weinmannia racemosa* forest	103
		(c) *Melicytus ramiflorus* forest	103
Mt Tarawera	Montane	*Coriaria arborea* scrub, grass-herb-lichen patches	103
Mt Tongariro	Montane	*Phyllocladus alpinus/Leptospermum scoparium* scrub	*c.* 450
Mt Taranaki	Lowland	(a) *Metrosideros robusta-Weinmannia racemosa* forest	*c.* 450
		(b) *Dacrydium cupressinum-Metrosideros robusta/Melicytus ramiflorus-Weinmannia racemosa* forest	*c.* 330
		(c) *Leptospermum scoparium/Baumea rubiginosa* sedgeland	*c.* 450
Mt Taranaki	Montane	(a) *Weinmannia racemosa* forest	*c.* 330
		(b) *Brachyglottis elaeagnifolia* scrub	*c.* 450

Other records of North Island forest-disturbance caused by the Taupo eruption

In Table 5.8 the key indicator of disturbance, i.e., peaks of *Pteridium* spores, from material pollen analysed immediately above Taupo Tephra in several central North Island pollen sites are compared. Several trends regarding forest disturbance are apparent:

(1) The effects of the Taupo eruption on the vegetation of the central North Island were widespread but highly variable. Peaks of *Pteridium* spores above Taupo Tephra ranged from *c.* 1–60% of the pollen sum. The variability is probably a reflection of numerous biological and physical factors operating locally at each site. For example, different vegetation types may have had different susceptibilities to the physical and chemical effects of airfall tephra. The leaves of some taxa may be more resistant to toxic chemicals than others. Senescent forests may have been worse affected by the eruption than more robust and youthful forests. Large leaves may be more vulnerable than small and narrow leaves because of the larger surface area available for the adhesion of ash particles. Some taxa with dormant buds may have been less affected because the eruption occurred in late summer or early autumn (Palmer, 1986; Clarkson *et al.* 1988; Palmer *et al.* 1988; Clarkson *et al.* 1992). Tephra depth would also have varied extensively on a local scale according to topography, slope, aspect and vegetation type. Topography and local tephra thickness would have governed changes in drainage, which in turn determined the types of vegetation that could tolerate, or establish on, the newly created habitats.

A combination of local physical and biological factors was probably responsible for the apparently large scale changes occurring at more distant sites from the Taupo vent, where tephra depth was not particularly thick. For example, at Tunapahore, Bay of Plenty, which lies 160 km north-north-east of the Taupo vent (Figure 5.12), a 60% peak of *Pteridium* and some forest decline was recorded above Taupo Tephra deposits of only *c.* 7–10 cm thickness (McGlone, unpubl.).

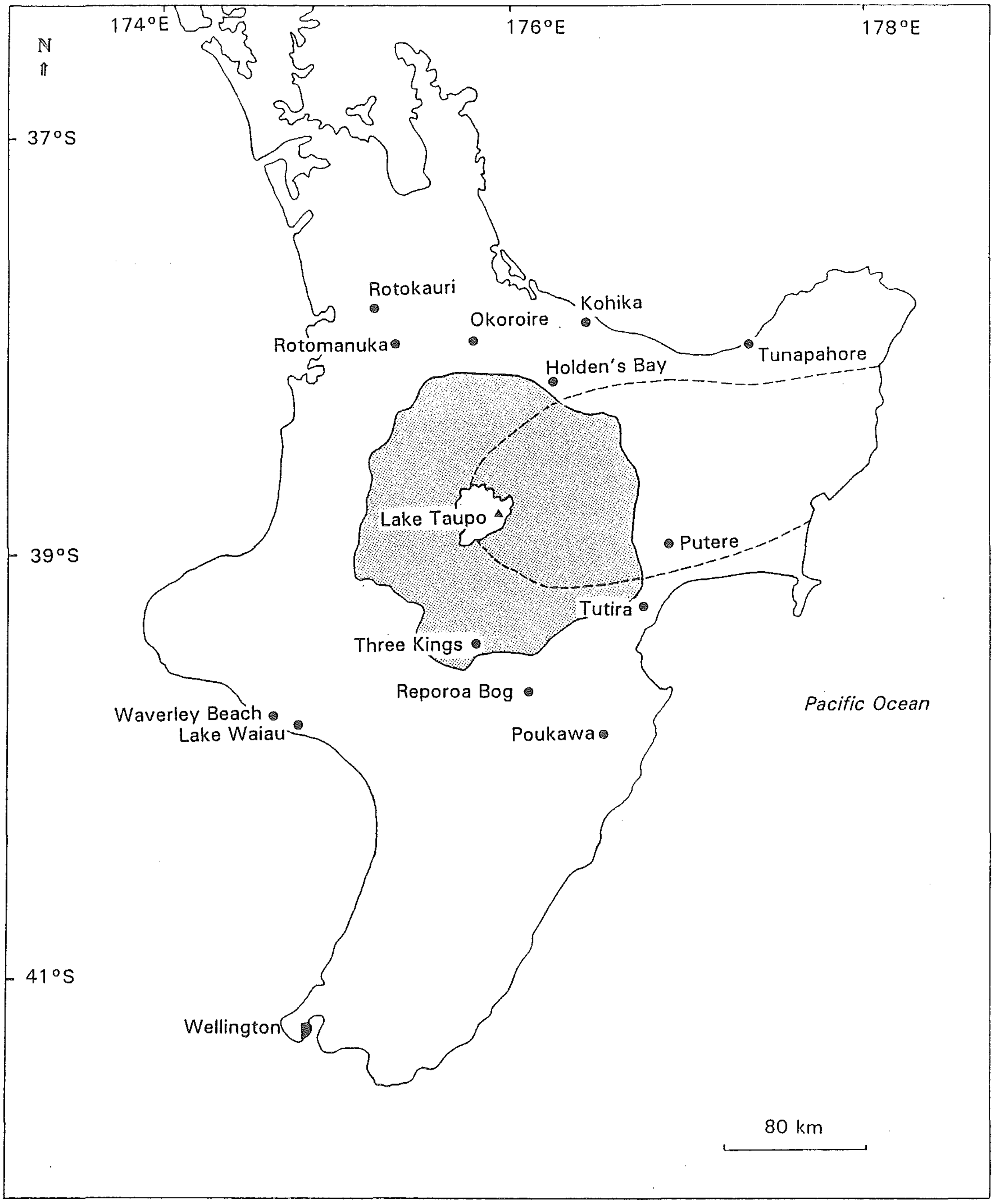


Figure 5.12. Pollen sites in the central North Island mentioned in the text, regarding vegetation change immediately above Taupo Tephra deposits (see also: Table 5.7). The dotted line represents the margin of the 10 cm isopach for the total thickness of airfall Taupo Tephra, and the shaded area represents the approximate outer limit of the Taupo Ignimbrite.

Table 5.8 Central North Island palynological sites that record peaks of *Pteridium* spores above Taupo Tephra. See also Figure 5.12 for location of these sites.

Site name	Direction of site from Taupo vent	Distance from Taupo vent (approx. km)	Tephra thickness in core (cm)	*Pteridium* % dryland pollen sum below/above tephra	Reference of source
Lake Tutira, Hawke's Bay	E	90	18	5 / 53	This study
Lake Rotonuiaha, Hawke's Bay	E	93	37	<1 / 32	This study
Tunapahore, Bay of Plenty (site B)	NE	160	7	0 / 60	McGlone, (unpubl.)
Lake Poukawa, Hawke's Bay (site 2)	SE	128	4	1 / 13	McGlone, 1978
Kohika Swamp, Bay of Plenty	NNE	121	5	<1 / 6	McGlone, 1981
Holdens Bay, Lake Rotorua	NNE	80	5	0 / 2	McGlone, 1983a
Reporoa Bog, northern Ruahine Range	S	93	5	0 / 13	Rogers & McGlone, 1989
Waikato lowlands:					Newnham *et al.* 1989
1. Lake Rotomanuka	NNW	112	<5	0 / 2	
2. Lake Rotokauri	NNW	134	<5	0 / 1	
3. Lake Okoroire	N	100	<5	<1 / 5	

(2) In some areas, the total depth of Taupo Tephra deposited at a site controlled the amount of forest disturbance. The thickest deposits of Taupo Tephra recorded in the cores listed in Table 5.8 were from Lake Rotonuiaha (37 cm) and Lake Tutira (18 cm), and at both of these sites, a substantial increase of *Pteridium* spores, and a clear indication of forest decline occur above the tephra.

(3) The distance of a site from the eruptive centre and the relative position of the site in relation to the pathway of the ash plume, which travelled predominantly in an easterly direction from the vent (Wilson & Walker, 1985), were both important factors controlling disturbance. Sites that were both closest to the vent or directly in line of the ash plume received more airfall tephra deposits than those further away from the vent or out of the path of the ash plume. The direction and extent of the travelling ash plume were dependent on the weather conditions at the time and distinctly controlled the extent of tephra-related vegetation disturbance after the Taupo eruption.

For example, Lake Rotonuiaha lies *c.* 90 km east of the Taupo vent, which was directly in line of the ash plume, and recorded a 32% peak of *Pteridium* above the tephra. In contrast, Holdens Bay, Lake Rotorua (McGlone, 1983a) lies *c.* 80 km north-north-east of the vent (Figure 5.12), but only a 2% increase of *Pteridium* spores was recorded above the tephra. This small increase suggests forest disturbance was less extensive at Lake Rotorua, and occurred because the site was situated out of the major fallout zone of airfall tephra (Figure 5.12). Similarly, Reporoa Bog, Northern Ruahine Ranges (Rogers & McGlone, 1989) lies *c.* 93 km south of the vent and showed greater disturbance than Lake Okoroire (Newnham *et al.* 1989) which is *c.* 100 km, but directly north, of the vent (Figure 5.12). In this case, Reporoa Bog was closer to the fallout zones of airfall tephra and as a consequence suffered more disturbance. Sites located far enough away from the fallout zone of ash were evidently completely unaffected by the Taupo eruption. For example, Bussell (1988b) records no trace of Taupo Tephra or vegetation disturbance in pollen sites at Lake Waiau and Waverley Beach, Taranaki which were in the opposite direction (south west) to that of the travelling ash plume (Figures 5.9b and 5.12).

The sampling strategy within each core determines the amount of detail obtainable in an analysis. If sampling intervals above the tephra are coarse, the disturbance may be missed altogether, or only partially recorded. Coarse sampling introduces uncertainty about whether the peak or the tail-end of the disturbance response has been analysed. Close sample intervals above a tephra will provide the most complete picture of vegetation change and this has been shown in the diagrams from Tutira and Rotonuiaha (Figures 5.10 and 5.11). These pollen diagrams record more detail than the other studies (Table 5.8) because contiguous sampling at 5–10 mm intervals was used immediately above the tephra deposits. The rapid rate of lake sediment and pollen deposition in both lakes made it easier to analyse short intervals of time above the tephra.

Smaller volcanic disturbances that occurred after the Taupo eruption

The only other records in the Tutira and Putere profiles of forest disturbance occurring after airfall tephras are above the Ruapehu Tf5 Tephra at both sites, and the Ruapehu Tf2 Tephra at Tutira. In all cases the presence of these tephras coincides with changes in pollen composition to group 6 (Appendices 2 and 3) and an increase in ordination value (Figures 5.1 and 5.2), both of which indicate increased disturbance. At Tutira, there was an increased abundance of *Pteridium*, and an increased frequency of taxa that readily colonise open sites after disturbance including *Coriaria* and *Hoheria*. There is also a decline in the abundance of *Fuscospora* pollen. *Coriaria* was also recorded as an important coloniser after disturbance caused by eruptions from the Mt Taranaki volcano (Lees & Neall, 1993). After the fallout of Ruapehu Tf5 Tephra at Tutira, most of the tall tree taxa were unaffected, except for *Fuscospora*. As the long-distance transported beech pollen mostly originated from the inland ranges, its decline probably reflects ashfall damage to beech forests closer to the eruptive source of the Mt Ruapehu volcano. The same phenomenon occurred at Tutira after the fallout of Ruapehu Tf2 and Taupo Tephra.

The Rotonuiaha profile also shows an increased abundance of *Pteridium* spores above Ruapehu Tf5 Tephra. However, the frequency of *Fuscospora* pollen at this site does not change, and may reflect the fact that Lake Rotonuiaha derived more *Fuscospora* pollen from beech forests closer to Putere, which were not damaged by ash. Although these Ruapehu tephra formations reached some parts of Hawke's Bay, the absence of a decline in pollen from tall forest taxa indicates these ashfalls did not cause major forest disturbance. Chemical toxicity from the ashfall may have caused minor damage, but as charcoal fragments occur with each tephra deposit, I suggest that fires associated with these eruption plumes were a greater cause of disturbance. Small amounts of charcoal were also recorded above the Kaharoa Tephra in core RNUI3, although there is no record of accompanying changes in pollen composition. These charcoal fragments may have been blown in from fires in forests situated further north of Putere that were closer to the Kaharoa eruption centre (Figure 2.1).

There is no correlation between charcoal and erosion pulses in the sub-samples from cores LT16 and RNUI3 ($p<0.01$). Charcoal is found in sub-samples from erosion pulses as well as in non-erosion sediments. This suggests that charcoal was not only transported to the lake by soil erosion. In many cases charcoal was deposited aerially or fluvially after contemporaneous fire episodes, of either local or regional origin. In both cores, all sub-samples with charcoal fragments present have significantly higher mean ordination values than those sub-samples without charcoal ($p<0.01$). This suggests when charcoal is present in a sub-sample, it is highly likely that a corresponding change in vegetation composition will occur. These changes are assumed to be associated with fire disturbance.

The presence of tephra and charcoal deposits without vegetation change

In both the Tutira and Rotonuiaha sediment records, there are cases where charcoal fragments or tephras (other than Taupo Tephra) occur, but without an accompanied change in pollen composition or ordination value. For example, the presence of Ruapehu Tf8 and Tf6 Tephras in the Tutira profile, and Kaharoa Tephra in the Rotonuiaha profile (see Figure 5.3) are not correlated with changes in pollen composition or ordination value. In the case of these tephras, the forests in Hawke's Bay were probably too far away from the eruptive centre to be adversely disturbed by airfall tephra, or the chemical toxicity of a particular ashfall may have been lower. In the case of charcoal, fragments were probably blown in from fires that destroyed forests situated beyond the range of the pollen source area for the two lake sites.

Fires and droughts

Between the depths of 4.80 m and 3.85 m in the Tutira profile (Figure 5.5) there is a marked alternation in the dominance of *Podocarpus totara* type and *Prumnopitys taxifolia* pollen over *c.* 500 years (between *c.* 1500 and 1000 BP calculated from sedimentation rates Table 5.4). The classification analyses show these as fluctuations between sample group 6 (where *P. totara* dominates) and sample group 8 (where *P. taxifolia* dominates). Ordination values for sub-samples with the more disturbed group 6 are greater than for those with group 8, and this is clearly shown by a series of peaks and troughs on the disturbance index (Figure 5.1). Significantly more sub-samples with group 6 contain charcoal fragments compared with group 8 ($p<0.001$). There is no correlation between the presence of charcoal fragments and erosion pulses in sub-samples with group 6 ($p<0.01$) (Table 5.1). This indicates the charcoal fragments recorded in these sub-samples were deposited contemporaneously by aerial fallout, rather than from reworked material transported to the lake with eroded soils.

The main differences in composition between sample groups 6 and 8 (see Appendix 2) includes the relatively greater abundance in group 6 of *Pteridium*, *Podocarpus totara* type, *Dacrydium cupressinum*, *Prumnopitys ferruginea*, *Rubus*, and a small increase in frequency of *Coriaria*, *Aristotelia*, Poaceae, Asteraceae, *Hoheria, Schefflera*, *Macropiper*, *Nestegis*, *Libocedrus*, *Meuhlenbeckia*, *Weinmannia*, *Tupeia antarctica, Dodonea, Alectryon* and *Griselinia*. Both sample groups 6 and 8 contain *c.* 20% *Leptospermum* type pollen. Group 8 contains higher relative percentages of *Prumnopitys taxifolia* pollen and *Cyathea* spores than group 6. The composition of pollen types in group 6 is also more diverse than in group 8; perhaps a more disturbed, patchy landscape offered a greater number and variety of habitats.

The pollen and charcoal records for sub-samples with group 6 may indicate periods of forest disturbance in Hawke's Bay, caused by lightning-strike fire episodes associated with cyclical drought periods. It is difficult to interpret from the pollen records whether the responses in the pollen diagram specifically reflect changes caused by drought or fire, because the two types of disturbance would be closely linked in time. However, drought-damaged forests would certainly be more susceptible to damage by lightning-strike fires. One of the consequences of drought on emergent podocarps and canopy trees, is to leave tall upright, but dead, crowns and branches in the forest. Atkinson & Greenwood (1972) suggest that damaged trees of this nature persisting in a podocarp/hardwood forest after a major drought, would increase the vulnerability of forests to lightning-induced fires.

Although lightning-strike is the most significant natural source of fire, only 0.03% of lightning discharges that strike vegetated areas of the world result in a fire (Taylor, 1974 quoted in Sousa, 1984:360). Sousa (1984) emphasises that ignition, intensity and areal extent of fire outbreaks are controlled by complex interactions among the following list of factors:

(a) frequency and seasonality of ignition sources
(b) moisture content of fuel
(c) rate of fuel accumulation
(d) combustibility of fuel type
(e) mosaic nature of landscape
(f) local weather conditions at the time of fire.

Evidence from contemporary forest studies in the North Island supports the suggestion that droughts may have caused widespread and severe forest mortality in Hawke's Bay. For example, in the upland forests of the Kaimai Ranges (northern Bay of Plenty) widespread forest mortality associated with severe droughts affected a wide range of forest species and forest types (Jane & Green, 1983a). In these forests, Jane & Green (1983a:23) found that the intensity of damage ranged from complete forest destruction that gave rise to grassland or young seral forests, to largely intact forest in which the trees showed partial mortality and extensive leader die-back. Similarly, Grant (1984) presents evidence of damage to canopy trees in the upland forests of the Ruahine Ranges, which occurred after a severe drought in 1914-1915. Between droughts, substantial amounts of fuel from decaying plant matter can accumulate, providing a source of fuel for the next fire. In addition, the accumulation of plant debris in a forest may also make the forest more vulnerable to ignitions.

The clearings in the forest initiated by drought and fire related mortality would have been readily exploited by the taxa in group 6 (Appendix 2). Many of these taxa are known from contemporary ecological studies to establish or recover quickly and effectively after disturbance because of certain attributes they possess. For example, *Weinmannia* can expand vegetatively from epicormic buds (Wardle, 1991); *Griselinia*, *Coriaria arborea, Carpodetus serratus* and *Melicytus ramiflorus* can regenerate rapidly from seed (*c.f.* Burrows, 1994a); climbers such as *Rubus* and *Ripogonum* can grow rapidly (Brockie, 1992); seeds of *Coriaria arborea* and *Aristotelia serrata* are dispersed rapidly by birds (Burrows, 1994a, 1994b); and *Pteridium* spores are effectively dispersed by wind (Page, 1976). Regeneration from basal stem sprouts may also have permitted many angiosperm trees to recover rapidly after fire, such as *Alectryon excelsus*, *Aristotelia serrata*, *Griselinia littoralis* and *Hoheria* (Burrows, 1994c). In addition to the pollen types represented in group 6, *Beilschmiedia tawa*, an important canopy tree in lowland podocarp/hardwood forests (but not represented in the pollen record) can also recover after crown damage or from fire, from basal sprouts and by coppicing (Aston, 1915; Wardle, 1991; Burrows, 1994c).

During the suggested period of cyclical drought and fire disturbance (*c.* 1500 to 1000 BP) global events may have triggered changes in the climate of New Zealand that initiated more extreme periods of alternating warm (El Niño) and cold (La Niña) phases characteristic of the Southern Oscillation. This phenomenon may have initiated the cyclical periods of drought and fire identified in the Tutira pollen record (Figure 5.5). The dominant influence of El Niño/Southern Oscillation on South Pacific climates is to increase the variability of precipitation (McGlone *et al.* 1992). During El Niño events in the east coast of the North Island, rainfall decreases causing severe drought conditions. El Niño events recorded in New Zealand have usually been accompanied by severe or widespread droughts (Burrows & Greenland, 1979; Quinn & Neal, 1992). The characteristic alternation of very wet years with very dry years associated with the El Niño/Southern Oscillation increases the likelihood of severe fires (McGlone *et al.* 1992). During the drought periods, plant debris from normal senescence, and drought-related mortalities would have accumulated, providing a potential fuel supply, thereby making the forests more vulnerable to lightning-strike fire. During the wetter La Niña periods, in regions that were usually dry, vegetation would flourish and provide the fuel supply for fires in the following dry El Niño periods, contributing to the drought-fire cycle (McGlone *et al.* 1992).

The cyclical disturbances recorded in the Tutira profile are not evident in the Rotonuiaha profile over the same time period. It is suspected the evidence for disturbance may be accentuated in the Lake Tutira profile for two reasons. Firstly, because Tutira is in a lower rainfall district with a higher rainfall variability (Thompson, 1987), drought periods may have been more prolonged than at Putere, making the forests more prone to drought mortality. Secondly, if large expanses of forest in Hawke's Bay were affected by the droughts, and larger lakes record higher proportions of long-distance pollen compared with smaller basins (Prentice, 1988), then the Lake Tutira sediments may provide better regional pollen and charcoal evidence of drought than Rotonuiaha, because of the much larger area of the Tutira catchment.

At a depth of 3.85 m in the Tutira profile, there is a large increase in ordination value (almost as large as the post-Taupo ordination values) and a shift from a sample group indicating less disturbance to one indicating more disturbance (group 8 to 6) (Figure 5.1). In the Tutira pollen diagram (Figure 5.5), these changes are illustrated clearly by the decline of *Prumnopitys taxifolia* and *Dacrydium cupressinum*, and an increased abundance of *Pteridium* and charcoal fragments. Although this compositional change involves the same sample groups that were involved in the previously described cycles of forest disturbance, at this particular depth this change is accompanied by a much larger and sustained increase in ordination value (Figure 5.1). It is proposed that drought and fires were also the cause of the changes at 3.85 m, but in this event, a more intense and prolonged period of drought may have occurred that resulted in greater forest disturbance. In addition, long drought periods allow large amounts of plant debris to accumulate, providing fuel for fiercer fires which in turn cause more intense damage.

Storms and erosion

The Hawke's Bay region is frequently exposed to high intensity rain storms, some of cyclonic origin (Thompson 1987; see Chapter 2). Within the last 150 years they have caused accelerated soil erosion, landslides and general soil instability in Hawke's Bay (Page *et al.* 1994b). Current concerns regarding land stability in Hawke's Bay (Magill, 1992; Trustrum & Page, 1992; Page *et al.* 1994a; Page *et al.* 1994b) invoke questions about storm frequency and soil erosion processes in the past; for example, did storms also cause soil erosion before human settlement, and if so, were the events severe enough to cause forest disturbance? Evidence of past erosion is present in the sediment cores from Tutira and Putere as discrete erosion pulses (Figure 5.3). Erosion pulses in lake sediments are routinely used in palaeolimnological investigations to indicate periods of soil erosion in the catchment, and the transport of eroded material into the lake basin (Dearing *et al.* 1987; Dearing, 1991). Interpretation of the erosion pulses in the Tutira and Putere sediment profiles, in conjunction with the pollen records (Figures 5.5–5.6) can help to answer the question above.

The presence of erosion pulses throughout the Tutira and Rotonuiaha cores (Figure 5.3) indicates soil erosion occurred episodically in these forested catchments. However, there is no evidence to suggest storm-induced erosion was associated with extensive forest damage. This is supported by the fact there is no correlation between changes in vegetation composition and erosion pulses in the cores (Table 5.1). Instead, in the forested zone I, the main effect of storms in the forested catchments was to generate a sudden increase in the rate of surface runoff and fluvial transport, causing riverbank sediments to be scoured and transported into the lake, creating the erosion pulses in the lake sediments.

In both the Tutira and Rotonuiaha profiles, in several cases these erosion pulses coincide with a shift in vegetation composition to sample groups 3-5 (Tutira) and 4-5 (Rotonuiaha), but without a corresponding increase in ordination value (Figures 5.1 and 5.2). Moreover, sample groups 3–5 always occur in erosion pulses (statistically significant, $p<0.0001$). The only taxa to change in these groups is *Cyathea* spores, and these were significantly more corroded in sub-samples from erosion pulses than they were in authigenic lake sediments ($p<0.05$) (see Figure 6.3). *Cyathea* favour damp, shady river gully and river-flat habitats (Brownsey & Smith-Dodsworth, 1989) and no doubt formed dense stands in such places in the Tutira and Rotonuiaha catchments before deforestation. The tree ferns in these habitats would have contributed a direct source of spores to the river beds and proximal riverbank sediments. As alluvium was washed into the lake during periods of rapid runoff, the corroded spores stored within them were also transported, and deposited as part of the erosion pulse.

Both Grant (1985, 1989, 1994) and McFadgen (1985, 1989, 1994) propose that distinct periods of increased erosion and alluvial sedimentation alternated with relatively longer soil building intervals (at inland and coastal sites respectively) and these occurred simultaneously throughout New Zealand over the past 2000 years. They suggest these erosive episodes occurred during warmer, windier and drier climatic periods related to an increased frequency of tropical and extratropical cyclonic storms, and that they were independent of anthropogenic activities.

Lake sediments in basins which have a large, soft-rock catchment and numerous inflows (such as Lake Tutira) usually contain particularly detailed records of past catchment stability. Therefore, if the erosion episodes suggested by Grant (1985) and McFadgen (1985) were as universal and distinctive as they imply, and initiated simultaneous widespread erosion, then these episodes should also be clearly defined in the lake sediments from Tutira, and similar lakes. The longer quiescent episodes of soil formation and stability should be distinct from the erosive episodes. However, the specific erosive episodes cannot be discriminated in the Lake Tutira sediment record; nor from the Rotonuiaha sediment record. When the erosion pulses from the Tutira and Rotonuiaha cores are compared with the erosion episodes of Grant (1985) and McFadgen (1985), there is no correlation between any of the data sets (Figure 5.13). Of particular interest, is Grant's (1985) suggestion that his "Taupo Period" of erosion, "may have resulted from heavy rainfalls induced by the Taupo Pumice eruption". There is no evidence in the Tutira or Rotonuiaha cores to support this suggestion; there are no major erosion pulses above the Taupo Tephra, nor any indication that the tephra was eroded off the landscape into the lakes (Figure 5.13).

Sedimentation rates in Lakes Tutira and Rotonuiaha have not been uniform over the past 2000 years, indicated by the numerous erosion pulses of varying thickness and frequency throughout the depth of the cores. Cyclonic storms associated with warmer, windier and drier climatic periods suggested by Grant (1985) and McFadgen (1985) were probably responsible for triggering many of these erosion episodes in the catchments. Cyclonic storms frequently pass over or near Hawke's Bay (see Figure 2.9).

McGlone (1989a:121) emphasises that accepting the climatic cycle hypothesis means also having to accept that soil forming periods occurred simultaneously throughout New Zealand, and as Figure 5.13 illustrates, there is currently little support for this claim. The erosion hypotheses of Grant (1985) and McFadgen (1985) rely on precise dating of the recognized erosion episodes. The radiocarbon ages determined for the more recent

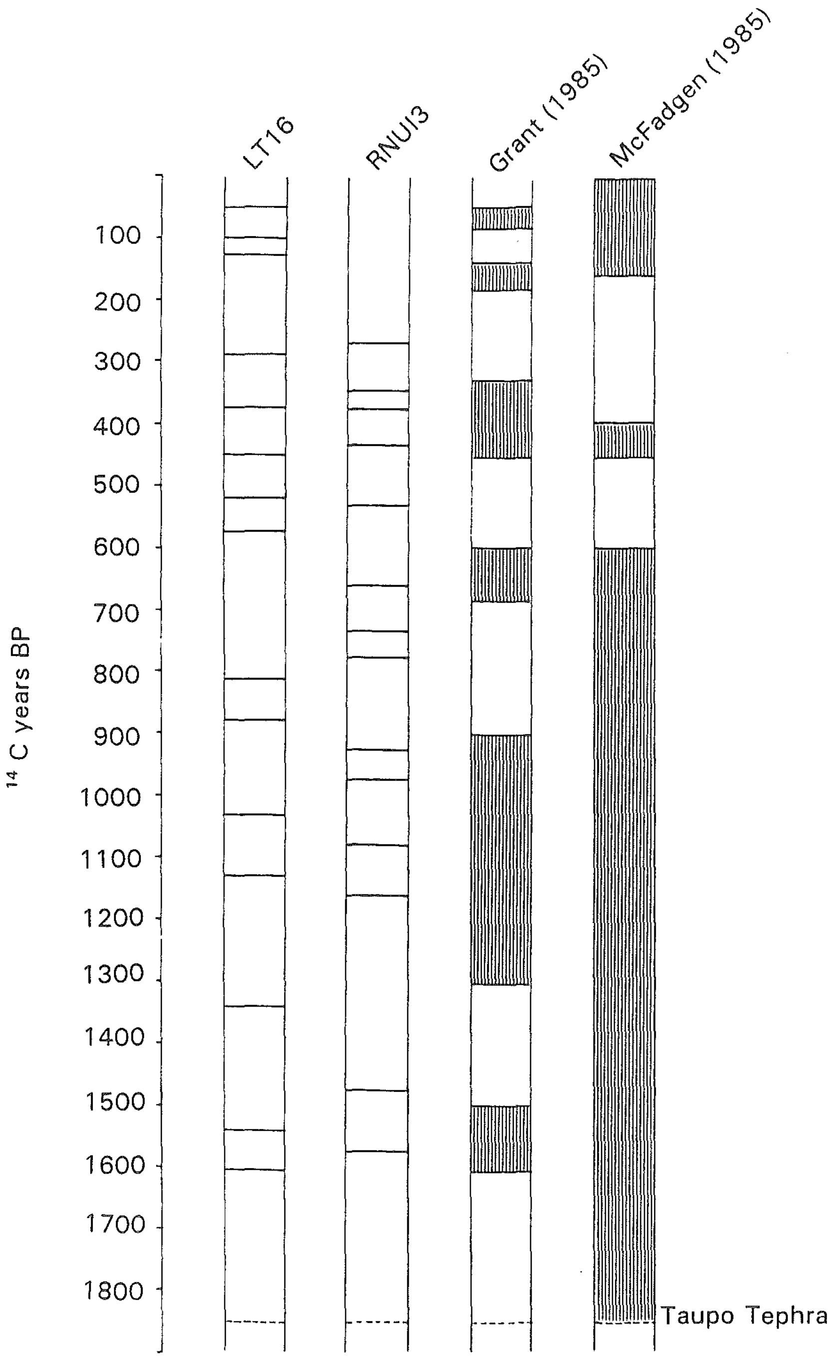


Figure 5.13. Dates of major erosion pulses (horizontal lines) in the core profiles from Lake Tutira (LT16) and Rotonuiaha (RNUI3) compared with the erosion periods (shaded blocks) suggested by Grant (1985) and McFadgen (1985).

episodes (over the last 450 BP) are subject to large errors; and a high degree of uncertainty must be involved with the dating of such short periods of time (many as brief as 30 years) proposed for the duration of the erosion and soil building episodes. Statistical counting errors alone mean that events less than 140 radiocarbon years apart are indistinguishable by any 2 radiocarbon dates (McFadgen, 1982). For these reasons, McGlone (1989a) suggests it is not possible to establish whether erosion episodes occurred at the same time from site to site using their dating methods, and that the episodes can only be dated this way if they are presumed to have occurred simultaneously.

The short duration suggested for erosion phases also introduces uncertainties. For example, do dated tree-remains in alluvium represent their rapid establishment upon the newly deposited material, or their later establishment if the deposit is not eroded away? Furthermore, other dated material such as buried trees that are not in their *in situ* growth position may have considerable inbuilt ages (i.e., the growth age of the tree, plus the time it has been stored on the landscape after death). McFadgen (1982) states that the maximum inbuilt age for wood on the ground surface would be about 3000 years, or older where the wood is found under water.

Regardless, the distinct phases recognised by Grant (1985) and McFadgen (1985) cannot be detected in the Tutira and Rotonuiaha sediment records. I can only conclude from this evidence, in agreement with McGlone (1989a), that erosion has varied episodically since at least the Taupo eruption *c.* 1850 BP. Nationwide simultaneity of past erosive phases initiated by cyclonic storm damage is difficult to prove, particularly because forest damage associated with such storms is usually random and localized (Jane & Green, 1983a, 1983c; Shaw, 1983).

Although even more difficult to determine, it is possible that earthquakes may have been responsible for some of the erosion episodes suggested by Grant (1985) and McFadgen (1985), and in the Tutira and Putere cores. Earthquake-induced landslides are common in Hawke's Bay, and although some studies have interpreted sediment pulses in lake sediments as a result of earthquakes (*c.f.* Doig, 1986; Mathewes & Clague, 1994), it is impossible to distinguish these from erosion events caused by storms. As there are no indications from the pollen and erosion pulse data for vegetation changes coinciding with erosion pulses, it is not of paramount importance that the cause of each erosion pulse is determined. However, given that storms occur more frequently than earthquakes in Hawke's Bay, most of the erosion pulses in the Tutira and Putere cores are presumed to have been caused by storm events.

B: POLYNESIAN DEFORESTATION 600 BP

Deforestation and associated changes in the vegetation

Changes in vegetation composition and charcoal frequency in zone II indicate major deforestation by fire. Forest taxa decline rapidly and are superseded by bracken, and shrub taxa *Coriaria*, *Aristotelia* and *Coprosma*. The disturbance indices in Figures 5.1 and 5.2 show a major shift to the most disturbed sample groups 1 and 2. These shifts in composition coincide with the largest recorded ordination peaks in the disturbance indices (Figures 5.1 and 5.2). Bracken dominates the pollen sum until European settlement *c. 500* years later. Charcoal fragments are recorded more frequently and in greater abundance in zone II than zone I, indicating fires were common even after major deforestation. At Tutira, *Dacrydium cupressinum* and *Prumnopitys taxifolia* decline at approximately the same rate, even though *D. cupressinum* is usually more fire resistant than *P. taxifolia* (Bray, 1989). Compared with Putere, forests in the Tutira district may have been more susceptible to fierce fires because of the drier climate, and presence of a dry, readily combustible fuel supply. At Putere the *P. taxifolia* curves decline faster than *D. cupressinum* curves. The less fire resistant *P. taxifolia* is common on drier sites (Wardle, 1991) and probably burnt faster and more readily than *D. cupressinum*. In addition, *D. cupressinum* is common on infertile soils in moister sites (Wardle, 1991) which would be more difficult to burn. Small areas of forest in the catchments survived the fires, protected in damp sites such as along steep river banks and gullies, and these remnants provided the continuous, low representation of some of the forest pollen types well after deforestation.

Manuka (*Leptospermum scoparium*) and kanuka (*Kunzea ericoides*) formed an important part of the local vegetation at Tutira and Putere before Polynesian deforestation, in lake margin, forest fringe and mire habitats. However, after forest clearance, *Leptospermum* type pollen declines abruptly, implying these localised habitats were also burnt and destroyed. The burning of forest and shrubland vegetation right to the lake edges would have been inevitable with the uncontrollable nature of large fires. The reduction of manuka and kanuka from lake margin and wetland habitats after Polynesian deforestation, appears to have a been widespread event, and is shown in other palynological sites in the central North Island e.g., Tunapahore (site B), Bay of Plenty (McGlone, unpubl.); Waipehi, Bay of Plenty (McGlone, unpubl.); Kohika, Bay of Plenty (McGlone, 1988a); Potaema Bog, Taranaki (McGlone *et al.* 1988); Lake Waiau Swamp, Wanganui (Bussell, 1988b); Mahuia Forest and Mahuia Bog, Ruapehu (Steel, 1989) (see Figure 5.14 for locations and dates).

The increase of *Typha* pollen after deforestation suggests that fertile lake margins allowed large *Typha* communities to establish, which would have usurped the place of manuka and kanuka. The increased abundance of *Myriophyllum* pollen in zone LT-II and RNUI-II may also indicate the presence of shallow, organic lake margin habitats. Once the catchments were dominated by dense colonies of bracken, fern litter would have accumulated, creating deep, organic-rich soils. Repeated fires and rainstorms would have promoted the leaching of nutrients from the deep bracken soils, adding to the nutrient flux at the lake margins. When bracken dominated the catchment vegetation the organic content of the sediments was the highest recorded in the core (Figure 5.5b).

Pre-deforestation fires: natural or cultural ignitions?

There is no reliable method of determining the cause of a fire in palaeoecological studies, therefore it remains difficult to discriminate between natural and cultural ignitions (McGlone, 1983b; Sutton, 1987; McGlone, 1989a; Nunn, 1994). The exception to this occurs when sustained and permanent deforestation coincides with a sudden increase of charcoal, and is supported by archaeological evidence. McGlone (1981, 1983b) recorded small scale fire disturbances in some North Island sites (i.e., shown as minor increases of bracken spores and charcoal) that occurred about 300 years before the pollen spectra indicated widespread deforestation. He suggests humans may have caused these small fires. Sutton (1987) argues smaller fires preceding deforestation are highly suggestive of anthropogenic disturbance, and that any fires occurring before deforestation should be considered as possibly anthropogenic. Sutton (1987) suggested that any fire disturbance could indicate human settlement, but this implies that settlement of New Zealand may have been thousands of years ago, because there is ample evidence of smaller fires during the

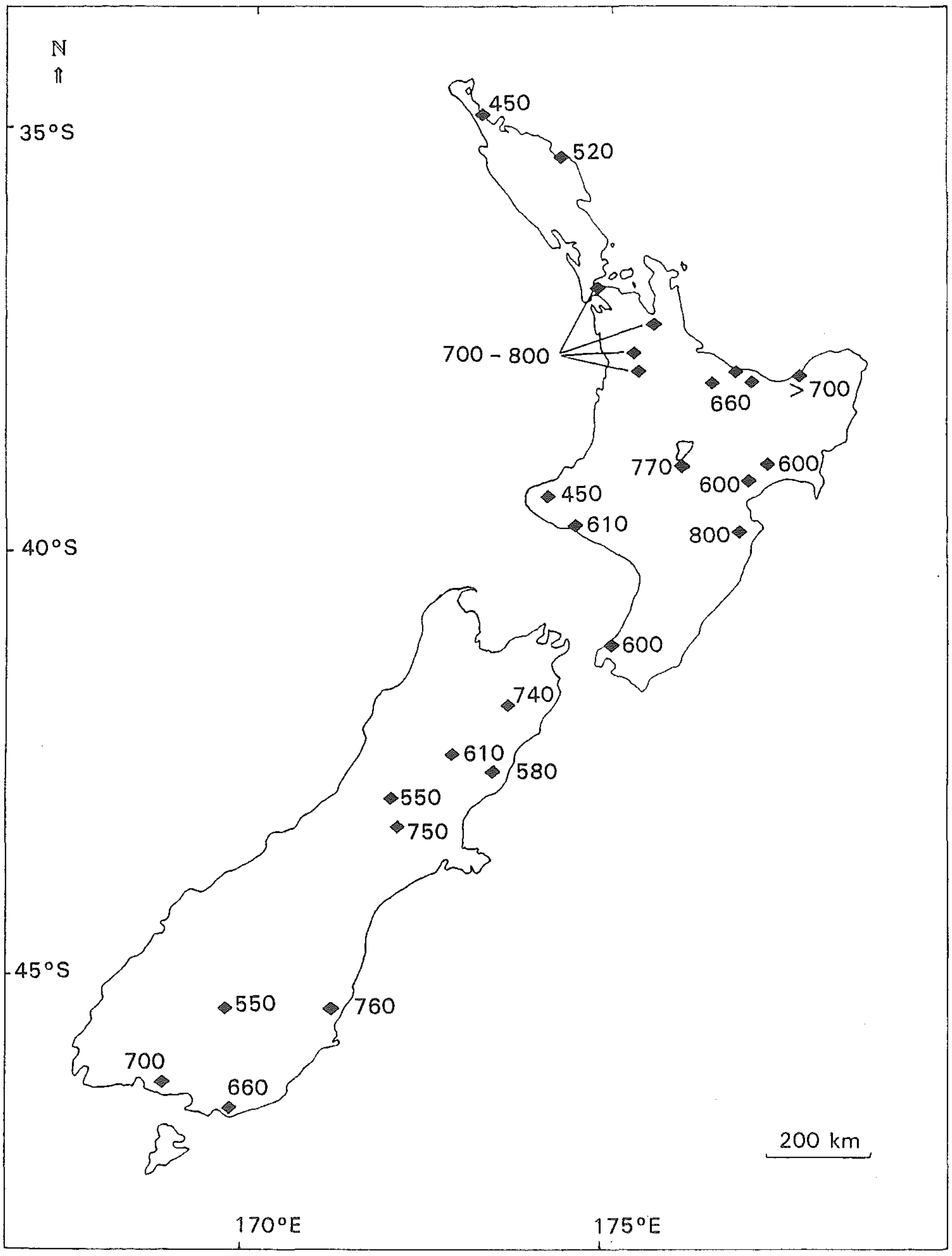


Figure 5.14. Radiocarbon dates (years BP) for the onset of pollen-based deforestation in New Zealand (from McGlone *et al.* (1994); McGlone & Basher (in press); McGlone (unpubl.) and Newnham (1990).

Holocene in many New Zealand palynological records (e.g., this study; McGlone, 1989a; Rogers & McGlone, 1989; Newnham *et al.* 1989; Burrows *et al.* 1993; McGlone & Basher, in press).

It seems unlikely that people could have remained in New Zealand for thousands of years without causing any measurable changes to the vegetation and fauna, and without leaving behind any cultural remains. Most of the dates from the archaeological remains of early Maori settlement in New Zealand lie between 700–600 BP, the same as the majority of dates for widespread deforestation (Figure 5.14), and Anderson (1991) points out there are few and only dubious dates older than this. In addition, no cultural remains have been found *in situ* buried by Taupo Tephra (1850 BP) or Kaharoa Tephra (700 BP) in the east coast of the North Island (Anderson, 1991). Anderson (1991) argues that even small groups of coastal explorers would have left some noticeable traces of their presence. The paucity of archaeological remains from Hawke's Bay that predate deforestation lend no support to the postulate that the earlier occurring fire disturbances at Tutira and Putere were culturally induced.

McGlone *et al.* (1994) suggest eastern Polynesians may have made systematic resource reconnaissance visits to New Zealand before large-scale permanent settlement occurred. McGlone (1983b) and McGlone *et al.* (1994) propose that when permanent settlement began, a large number of Polynesian settlers arrived in New Zealand within a short time span and this was followed by a rapid population expansion and widespread dispersal. The extensive deforestation recorded in the pollen records from Tutira and Putere, and from palynological sites around New Zealand (Figure 5.14), most probably reflects this phase of population expansion and the associated environmental changes that would have followed.

If this scenario of settlement is accepted, we can assume that the initial explorers discovered a relatively large, habitable country rich in food and material resources. The explorers would have returned home, and news of their discoveries would have spread rapidly around their island group and to other islands (McGlone *et al.* 1994). If the push factors of migration were strong enough to encourage the exploration of resources in the first place (McGlone *et al.* 1994), I suggest New Zealand would have been colonised relatively soon after the reconnaissance visits, at least within a few generations of their discovery. It is difficult to believe that a known, relatively large, resource-rich country would be left alone for hundreds of years before being permanently settled. Based on the assumptions of this scenario, and the currently available palaeoecological and archaeological evidence, the smaller fire disturbances occurring several hundred years before deforestation in this study, and in other sites (e.g., McGlone, 1981, 1983b, 1989a), were most likely caused by lightning-strike.

Supporting evidence for Polynesian (Maori) deforestation by fire

The broad patterns of deforestation recorded in the Tutira and Putere profiles (Figure 5.5–5.8) are typical of forest clearance in other North Island pollen records (e.g., McGlone, 1978, 1981, 1983a; Bussell, 1988b; McGlone *et al.* 1988; Newnham *et al.* 1989). Widespread deforestation is currently accepted as one of the most important indications of early Polynesian settlement, although whether or not it was caused by natural or human fires remains a contentious issue in New Zealand (see McGlone, 1983b; McGlone, 1989a; McGlone *et al.* 1994). The following points based on pollen and charcoal data from this study are considered with the current archaeological evidence (McGlone *et al.* 1994). The following findings from this thesis strongly support the argument that widespread deforestation was caused by human fires.

- Compared with the fire-related vegetation disturbances identified in the pollen and sediment records from Tutira and Putere during the previous 1200 radiocarbon years, the scale of disturbance caused by deforestation is unmatched elsewhere in the profiles. In addition, there is no equivalent palynological evidence from other sites in New Zealand for such large scale, widespread and synchronous deforestation in New Zealand since the end of the last glaciation.

- Deforestation at Tutira and Putere produced the largest recorded peak on the disturbance indices (Figures 5.1 and 5.2), even larger than the disturbance recorded above the Taupo Tephra which was the biggest natural disturbance event recorded before deforestation.

- Observations of contemporary cultural fires and ethnographic records indicate anthropogenic fires usually occur at an order of magnitude more frequently than natural outbreaks (Anderson & McGlone, 1992) and usually on a larger scale. This is apparent from the charcoal records in the Tutira and Putere profiles; there is a sudden and sustained increased frequency and abundance of charcoal fragments at the same time as, and above deforestation.

- Compared with the changes in forest composition that occur after natural fire and tephra related disturbances, the compositional changes associated with deforestation are unique to the cores. In particular, the extremely high and sustained percentages of bracken spores recorded after deforestation are not found elsewhere in the core.

- After deforestation, in zone II the only fluctuations in composition occur between sample groups 1 and 2, presumably caused by the high frequency of fires that burnt back the bracken. The major difference between these two groups is the greater abundance of bracken in group 1.

- After pre-deforestation disturbances, there was always a relatively rapid and complete redevelopment of forest, but this did not occur after deforestation. Instead, post-disturbance taxa such as bracken, *Aristotelia* and *Coriaria* persist after deforestation, where as previously they were quickly replaced by regenerating forest taxa. Many forest taxa are either infrequently recorded in trace amounts or are not recorded again in the core, e.g., *Elaeocarpus*, *Knightia*, *Nestegis*, *Dodonea*, *Schefflera*, *Griselinia*, *Hoheria*, *Myrsine*, *Rubus*, *Streblus*, *Neomyrtus*, *Tupeia*, *Pseudowintera*, *Quintinia*, *Callitriche* and *Urtica*. Their decline or disappearance suggests that once the bracken and shrubs established after deforestation, the high frequency burning and competition prevented their regeneration.

Timing of deforestation

In the Tutira core, the dated Ruapehu Tf5, Tf6 and Tf8 tephras all lie below the depth where deforestation occurs, and provide good reference points for dating deforestation (Table 5.3). Based on the relative position and ages of these tephras, deforestation in the Tutira region certainly occurred after *c.* 750 BP (Tf5), but probably before *c.* 540 BP, estimated from sedimentation rates and the relative position of the radiocarbon dated Ruapehu Tf5 Tephra (Tables 5.3 and 5.4). In both Putere cores, the Kaharoa Tephra lies just below the depth of deforestation which means forest clearance began shortly after

700 BP. Dates estimated from the sedimentation rates (Table 5.4) suggest deforestation began *c.* 580 BP at Rotonuiaha, and *c.* 585 BP at Rotongaio.

The dates for deforestation at Tutira and Putere are consistent with dates for major deforestation recorded from other palynological sites in New Zealand (McGlone *et al.* 1994; Figure 5.14). The dates support the short prehistory hypothesis (Anderson, 1991; McGlone *et al.* 1994) which postulates that the colonisation of New Zealand occurred *c.* 800–700 BP. McGlone *et al.* (1994) show the substantial agreement between radiocarbon dates for deforestation and other indications of human settlement such as cultural artefacts and faunal extinctions.

McGlone *et al.* (1994) suggest there was a relatively intense phase of moa hunting between 800–500 BP, based on radiocarbon dates of moa bones in Maori middens (Anderson, 1989, 1991), but by 400 BP it had declined in frequency as the moa became increasingly rare and in the case of some species, extinct (Anderson, 1984; McGlone *et al.* 1994). Other animals hunted by Maori such as seals (Smith, 1989), small birds and reptiles (Cassels, 1984) show a similar pattern of decline. McGlone *et al.* (1994) speculate the population of New Zealand expanded rapidly in the first few centuries of settlement owing to the abundance and diversity of food resources available, particularly of large game animals. However, by 600 BP, these abundant resources became over-exploited and the forests began to lose their value as resource bases, particularly for large birds that became over-exploited and/or declined through loss of habitat, disease and predation from the introduced Polynesian rat *(Rattus exulans)* and dog *(Canis familiaris)* (McGlone *et al.* (1994). By 600 BP, widespread and sustained burning of the remaining forest and fern/shrubland was well advanced in New Zealand (Figure 5.14). McGlone (1989a) and McGlone *et al.* (1994) suggest forest clearance may have been a deliberate strategy by the Maori to increase the productivity of the land in other ways.

The dates for Polynesian deforestation at Tutira and Putere are consistent with dates recorded for this event at other sites in the central North Island (Figure 5.14). These dates range from 800-450 BP, but mostly lie between 700–600 BP. The earliest date recovered for the onset of deforestation in the Hawke's Bay region is presently *c.* 800 BP, based on radiocarbon dates from Lake Poukawa (McGlone, 1978). However, the dates reported for deforestation at Tutira and Putere indicate forest clearance in the Hawke's Bay region began about 200 years later than at Poukawa. Tutira and Putere lie only 75 and 120 km north of Lake Poukawa. Given the speed of deforestation (see next heading) it is most unlikely that 200 years elapsed before deforestation began in closely neighbouring sites. The age of *c.* 800 BP for deforestation at Lake Poukawa, (McGlone, 1978) is also several hundred years older than the ages attributed to deforestation in many of the other central North Island sites (e.g., at Rotorua (McGlone, 1983a); Kohika (McGlone, 1983a); and Tunapahore (McGlone, unpubl.). Lake Poukawa is located in a depression bordered by two limestone ranges, and is in a situation where water rich in dissolved carbonate can flow into the lake. The radiocarbon ages from the Poukawa site (McGlone, 1978) were not corrected for the hard-water error (Deevey *et al.* 1954) and this may explain why the date for deforestation is much older than those recorded elsewhere in Hawke's Bay and other central North Island sites. The problems of radiocarbon dating potentially contaminated material have been highlighted by the much older dates returned from sediment in Lake Tutira (Eden *et al.* 1993) and the Putere lakes (Table 5.2). Kaharoa Tephra has been found subsequently in other cores from Lake Poukawa (Howorth *et al.* 1980), and if its position could be established in relation to pollen-based deforestation at Poukawa, this would clarify the debate.

Patterns and processes of deforestation

An estimate of the time it took for the forests to be cleared from the Tutira and Putere landscapes can be calculated using changes in the pollen profile, and the sedimentation rates in Table 5.4. The transition point in the pollen records is taken to be where the downward trend of pollen from the dominant podocarp taxa stops, and when bracken spores and *Coriaria* pollen become dominant: at Tutira this took *c.* 64 years, and at Putere between *c.* 153 years (Rotonuiaha) and *c.* 168 years (Rotongaio). These findings agree with McGlone (1983b) who suggests that at most sites, once forest clearance began, widespread deforestation proceeded rapidly. He notes that it was accomplished rapidly at some sites (e.g., Kohika, Bay of Plenty) compared with others (e.g., Lake Taupo), but the process was well advanced throughout New Zealand within about 200 years.

Although the dates are only approximate, I believe the relatively shorter time taken for deforestation at Tutira is significant. It indicates, in agreement with McGlone (1989a) and McGlone *et al.* (1994), forests in drier regions were more vulnerable to fire and would have burnt faster and more extensively than forests in wetter regions. Early European observations in the Tutira district describe the presence of old, weathered tree hummocks with rotted roots at the coast, and more recently charred tree trunks, many of which were still standing, nearer to the inland ranges (Guthrie-Smith, 1969). The presence of a topographical rainfall gradient may explain these observations. Accounts of European fires in the North Island during the drought year of 1886, describe forests in the lower rainfall areas being more susceptible to fires and burning more extensively than in wetter areas (Arnold, 1994). The dates for deforestation throughout New Zealand indicate there was little difference between the timing of clearance at northern or southern sites (McGlone *et al.* 1994; Figure 5.14).

McGlone *et al.* (1994) propose there is no difference in timing for the start of deforestation at coastal or inland sites. Instead of locality, they suggest that rainfall and topography were the main factors controlling the timing and extent of deforestation at different sites around the country. The greater vulnerability to fire at Tutira has already been observed in the pre-deforestation section (zone I) of the pollen profiles (Figures 5.5 and 5.6) where the frequency and abundance of charcoal fragments coinciding with forest disturbance is greater at Tutira than at Putere. A similar pattern is also seen after the Taupo eruption at Tutira and Putere. Forests at the drier Tutira site suffered more extensive damage after the eruption, and took longer to recover than forests at Putere.

The *Fuscospora* pollen curves from the Tutira and Rotonuiaha profiles provide further evidence for the earlier burning of lowland forests compared with the upland forests. When the more regional podocarp and hardwood forest taxa rapidly decline with deforestation, the *Fuscospora* curves show little change. The curves fluctuate slightly throughout the pollen profiles, and only gradually decline towards the top of the profile. This long-distance transported pollen type is mainly from the beech forests on the axial ranges (see Section A: pre-deforestation vegetation) and the behaviour of the curves suggest these forests were not being burnt at the same time the lowland podocarp/hardwood forests were at Tutira.

During the 1880s some of the oldest Maori in the Tutira district were asked about their knowledge of forest fires in the area; they had no recollection of extensive forest fires, nor had such accounts been passed on in tribal history (Guthrie-Smith, 1969). This indicates most of the large forest fires in the area occurred during the earlier phase of Maori settlement.

Pollen evidence for contemporaneous deforestation in Waikato and Hawke's Bay

Trace amounts of pollen from *Agathis australis* are recorded consistently in zone RNUI-I, but the pollen is not recorded again after deforestation. As *Agathis* does not presently grow in Hawke's Bay, and has never been present there during the Holocene (Allan, 1961; Ogden *et al.* 1993), its pollen in the Rotonuiaha profile indicates a long-distance source, most likely from the Waikato region (see Newsome's (1987) map of North Island vegetation cover, in back pocket). McGlone *et al.* (1988) also record long-distance *Agathis* pollen in a core from Ahukawakawa Swamp (Taranaki) which became abruptly less common after Polynesian deforestation. *Agathis* pollen also declines rapidly with the onset of deforestation in pollen profiles from mid-Northland (Newnham, 1992) and Waikato (McGlone & McCabe, unpubl.). Newnham (1992) notes *Agathis* was particularly susceptible to burning and was more rapidly and severely damaged after Polynesian deforestation than other tree species. I suggest the disappearance of *Agathis* pollen from the RNUI profile, at the same time *Agathis* disappears from more northern pollen sites, reflects the contemporaneous destruction by Maori fires of northern kauri forests. Regardless of the actual date of deforestation, this suggests Hawke's Bay forests were burnt at approximately the same time as the Waikato forests. Most radiocarbon dates for the start of deforestation in the North Island fall between 700–600 BP and their close agreement indicates clearance was virtually simultaneous. The *Agathis* pollen curve in the Rotonuiaha core provides important independent evidence for simultaneous deforestation in different regions of the North Island.

Effects of deforestation on soil stability

Soil erosion occurs at different rates according to slope angle, bedrock type, soil structure, vegetation cover and climate. Cyclonic storms, earthquakes, windthrow, lightning, snow avalanches, as well as human activities can initiate or accelerate soil movement. When vegetation is removed from steep slopes the soil structure becomes weakened as the contribution from binding roots is lost (McSaveney & Whitehouse, 1989), thereby reducing stability and increasing the likelihood of soil movement. McGlone (1983b: 14) suggested

Polynesian deforestation by burning may have caused subsequent episodes of soil erosion in New Zealand. He states, that although deforestation is not the only cause of erosion and soil movement and other events may trigger the episodes, burning the forest was a primary cause of soil movement. This hypothesis was rejected by Grant (1985:109) who argued burning the vegetation "may increase the supply of available material for transport, but it cannot contribute directly to sediment transport", and "there is no unquestionable evidence in New Zealand that damage to vegetation by fires has been, and is at present, a primary cause of increased erosion and sedimentation on a major scale". There is however, abundant geomorphological evidence from New Zealand (e.g., McSaveney & Whitehouse, 1989; O'Loughlin & Pearce, 1992; DeRose *et al.* 1993), and palaeoecological data, from this study and others (e.g., Hume & McGlone, 1986) to dispute Grant's (1985) claims.

Several thick erosion pulses are present in the Tutira core at the same depth the pollen and charcoal records indicate the onset of Polynesian deforestation (Figure 5.3). This suggests forest clearance by fire temporarily accelerated soil erosion in the Tutira catchment, which supports McGlone's (1983b) hypothesis discussed above. However, in contrast to the Tutira profile, erosion pulses do not coincide with deforestation in the Rotonuiaha and Rotongaio cores, indicating forest clearance did not cause soil instability in the Putere catchments (Figure 5.3). McGlone (1989a:121) points out that although Maori fires initiated erosion at all scales, areas with soft, unstable and weak bedrock were more vulnerable to widespread mass-movement than stable, hard rock areas. Although this may be true in a general sense, the geology and soil type in the Tutira and Putere catchments are similar, but the effects of Polynesian deforestation on soil stability were different.

I suggest the combination of local physical and biological factors operating at each site determined the type of impact deforestation had on soil stability. During the rapid period of deforestation at Tutira (*c.* 64 years), the relatively large catchment area, steep hillslopes, and large number and size of inflowing streams (that allowed faster and greater fluvial deposition) all contributed to increased rates of soil erosion and lake sedimentation. Compared with Tutira, the rate of forest clearance was slower at Putere (*c.* 145–170 years), the catchments smaller and shallower with fewer inflows. Collectively, these factors may explain why deforestation caused less of an impact on soil stability in the Putere catchments.

Palaeoecological studies from other central North Island sites also reveal Polynesian deforestation did not affect soil erosion processes equally. Some sites indicate accelerated soil erosion after deforestation (e.g., Kohika, Bay of Plenty (McGlone, 1981) and Hakanoa, Waikato (McGlone & McCabe, unpubl.)), whereas other sites show no signs of alluvial inwash (e.g., Holden's Bay, Lake Rotorua (McGlone, 1983a) and Lake Poukawa, Hawke's Bay (McGlone, 1978)).

The role of bracken as a soil stabiliser after deforestation

After deforestation in both the Tutira and Putere catchments, when bracken and shrub vegetation types had become established, soil stability, perhaps paradoxically, was maintained. This is inferred from the reduced frequency of erosion pulses in the cores coinciding with the period of bracken domination in zone II (Figures 5.3 and 5.4). Increased sediment yields usually occur within the first years of vegetation removal, and as the vegetation recovers, soils become strengthened and re-stabilise (McSaveney & Whitehouse, 1989). I suggest that bracken was a rapid and effective agent for stabilising soils after deforestation and was as effective at minimising soil erosion as forest. This is reflected in Figure 5.4 and in the sediment stratigraphies (Figure 5.3); there is little difference between the proportion of erosion pulse sediment in the Forest and Polynesian zones (I and II) in the cores.

Bracken rhizomes can penetrate the soil to half a metre or more in depth (Wardle, 1991) and the total length of a whole plant's excavated rhizome, excluding short laterals but including long laterals, has been measured to 61 m (Watt, 1940). The tangle of numerous rhizomes in the soil would have intermeshed the catchment soils after deforestation. This would improve the strength and cohesion of the soils and greatly help to reduce soil movement. Soil stability was maintained even after the frequent fires that burnt the bracken throughout this period, because the underground soil-binding rhizomes were not destroyed by fire. The tall dense canopy created by extensive bracken colonies would also have protected soils from slope wash, by shielding the ground from rain-drop impact, particularly during high intensity rain storms that are common in Hawke's Bay (Thompson, 1987).

Low rates of sedimentation after Polynesian deforestation are also recorded in other North Island sites where bracken was the dominant vegetation, e.g., Firth of Thames (McGlone, 1989b); Whangapoua and Whitianga Harbours in the Coromandel Peninsula (McGlone, 1988b); Lake Poukawa, Hawke's Bay (McGlone, 1978); Holden's Bay, Lake Rotorua (McGlone, 1983a) and Kohika, Bay of Plenty (McGlone, 1981). Grant (1985) suggests there was a decreasing magnitude of erosion in New Zealand after 600 BP, compared with a preceding period of 1200 years. Grant (1985) states that erosion periods and soil building intervals since 1600 BP were climatically controlled and occurred regardless of the presence or absence of people in the environment (see earlier section "storms and erosion"). However, Grant (1985) questions how "soil building intervals" could have been sustained in the presence of an increasing Polynesian population between periods of erosion and sedimentation. While the timing and frequency of erosion pulses in the Polynesian zones of the cores do not correlate with Grant's erosion periods during this period (See Figure 5.13), I do suggest that where extensive colonies of soil-stabilising bracken were maintained on the landscape by Maori fires for several centuries after deforestation, soil structure would be reinforced and allow for "soil building" intervals.

Post-deforestation maintenance of seral vegetation

After deforestation in Hawke's Bay, bracken dominated the landscape for about 500 years, until the time of European settlement in the mid-1800s. In contrast, before deforestation, bracken was only ever present for relatively short periods that coincided with fire or tephra-related disturbances. The time it takes for regenerating forest seedlings to shade out bracken is variable and usually dependent on climate, edaphic conditions, density of the stand and the vigour of the regenerating seedlings (e.g., Watt, 1940; Druce, 1957; Page, 1976), but usually it does not persist for longer than about 60 years (Druce, 1957). Therefore, its prolonged presence on the landscape after deforestation indicates repeated disturbances must have occurred, as these would create the clearings necessary for its rejuvenation and continual re-establishment.

The constant presence of charcoal fragments above the level of deforestation indicates outbreaks of fire became more frequent after *c.* 600 BP. The increased abundance of charcoal also suggest the scale of fires was much larger than those occurring before deforestation. As Hawke's Bay became increasingly depleted of forest as a result of frequent fires, seed sources became increasingly diminished and remote. Together with intense root competition and shade from a dense bracken canopy, this would have made successful forest regeneration slower and more difficult. Repeated fires would have favoured the spread of bracken, because the buried rhizomes are not damaged by fire. This permitted rapid growth and reestablishment of bracken after the fires. With little competition from regenerating forest seedlings, and repeated disturbance, bracken colonies could persist for extended periods. Low soil moisture, related to topography and rainfall, may have been another important factor favouring the persistence of bracken after deforestation. Even without repeated burning, bracken colonies can be maintained indefinitely if soils are dry, as forest seedlings cannot establish under its canopy (Partridge, 1990).

Maori landuse and forest clearance

Many of the crops that were brought from Polynesia during early settlement were either lost or difficult to cultivate owing to cooler climates and different soils in New Zealand (Best, 1976). Although kumara (*Ipomoea batatas*) formed an important part of the Maori diet in some areas, its successful cultivation relied on friable, well-drained soils of moderate fertility in relatively frost-free areas (Taylor, 1958; Best, 1976). In some parts of Hawke's Bay, where topsoils were sandy and potentially suitable for kumara growth, the pronounced seasonal dryness made the cultivation of this tropical crop unreliable (Taylor, 1958). Maori may have grown kumara at Tutira and Putere but probably only on a small-scale. Abandoned kumara gardens have been found east of Tutira nearer the coast, where conditions were more suitable for kumara growth (Guthrie-Smith, 1969). Even in the most favourable sites, cultivated kumara is thought to have provided a low yield of small tubers, and thus only enough to supply a small component of the total calorific intake of the Maori diet (Shawcross, 1967; Parsonson, 1980; Jones, 1989).

With the problems inherently associated with procuring enough carbohydrate-rich food, Maori had to rely upon wild products for this important component of their diet. Bracken root was particularly important and especially so in areas where it was not possible to cultivate crops (Best, 1976). Colenso (1868) noted that compared with the labour required for crop cultivation, fern root was relatively easily procured, and were often sorted, dried and stored for later use. Although bracken was abundant and widespread after deforestation, sites where it grew exceptionally well were more limited; and these were prized and dug regularly (Colenso, 1868). Maori regularly burnt these sites at regular intervals to keep rejuvenating the bracken, and to prevent regenerating forest seedlings from establishing. Even if only the most productive sites were burnt for these reasons, the fires would have destroyed much larger areas of vegetation than intended (McGlone, 1983b). Therefore, in this way crop cultivation and the reliance on bracken as the essential food item contributed to forest clearance in New Zealand. Other reasons for repeated forest clearance are given by McGlone (1983b). These include, to make travel much faster and easier; improve access to sites with natural resources; to increase the productivity of the land after important forest based bird-resources were depleted; to clear forest around settlements and fortifications increasing visibility; and to reduce deliberate fire attacks and enemy ambushes.

Given the relatively dispersed and low density Maori population (McGlone *et al.* 1994) and the abundance of bracken in pre-European contact New Zealand, it is unlikely these Maori activities were solely responsible for almost half (Masters *et al.* 1957) of the New Zealand forest being cleared (see Newsome's (1987) map of North Island vegetation cover, in back pocket). Periodic droughts may have made the fire-susceptible forests of New Zealand even more vulnerable to the effects of the high frequency Maori fires. Intentional or not, this would have expedited the rapid and extensive removal of native forest. The replacement of forest with the highly flammable bracken and shrubs would only have exacerbated the process of clearance by providing ready fuel supplies.

During the post-Taupo to pre-deforestation period in Hawke's Bay, the results from Tutira and Rotonuiaha show fires have been the most frequent kind of forest disturbance. I have argued that during this period, the forests may have been susceptible to disturbance from fires because of periodic droughts. The same frequency of drought episodes may have continued during the period of Polynesian discovery and occupation of New Zealand. Perhaps the initial Polynesian fires coincided with, or followed, a prolonged and severe drought in New Zealand? Recent evidence from sites around the world have shown that for several hundred years before about 600 BP anomalous climatic conditions persisted, where temperatures were warmer and severe droughts common (Stine, 1994). Stine (1994) suggests this climatic anomaly was a global phenomenon. If this extended to New Zealand, then the increased frequency and scale of deliberate and accidental cultural ignitions may have been enough to initiate and accelerate widespread forest clearance, particularly at a time when conditions were drier and forests were drought stressed. This would support the suggestion of McGlone (1983b) and McGlone *et al.* (1994) that the timing, extent and speed of deforestation in New Zealand were related to rainfall and topography rather than location, i.e., forests in drier flat to rolling areas burnt faster and more extensively than those in wetter, hilly areas. Deforestation, and the increased frequency and scale of fires that followed, reduced the resilience of fire-sensitive forests to disturbance.

C: EUROPEAN SETTLEMENT

Early European settlement and forest clearance

The potato (*Solanum tuberosum*) was introduced to the Maori by European voyagers between 1769 and 1790 (Cameron, 1964). Its subsequent cultivation contributed to some considerable changes to the existing vegetation. The Maori welcomed this new vegetable plant and rapidly spread the potato to tribes in other areas where it was successfully cultivated, to such an extent that it replaced bracken roots as the staple carbohydrate in their diet (Best, 1976). Potatoes were tolerant of different soils and climate, grew faster and were easier to cultivate than kumara. They were also more palatable than bracken roots. Potatoes began to be cultivated on a large scale to exchange goods with European trading ships. This period of rapid Maori agricultural expansion and the pursuit of fertile soils led to a considerable resurgence of forest and fern clearance (Cameron, 1964; Best, 1976). However, by the 1860s, the potato ceased to be a valuable trade commodity when the market collapsed owing to the increased proficiency of European food and vegetable production and the decline of the Maori tribal system (Cameron, 1964). This resurgence of forest clearance is reflected in the pollen records from Tutira and Putere where the continued decline of forest taxa occurs with a steady influx of charcoal toward the top of zone II (Figures 5.5 to 5.7). Potato tubers were discovered growing in deserted Maori gardens on Tutira Station in 1882 (Guthrie-Smith, 1969). Pollen from *Solanum tuberosum*, or from crop plants introduced by Maori have not been found in New Zealand pollen records and therefore cannot provide an independent record of Maori cultivation.

It is estimated that over half of the native forest had been burnt by the Maori before Europeans settled in New Zealand, and by 1847 only about 42% of the total land area of the country remained forested (Masters *et al.* 1957) (see Figures 2.11 and 2.12). With the advent of permanent European settlement after *c.* 1840, the vegetation of New Zealand experienced another period of major change as the remaining forest and fern/shrubland was steadily cleared away. Reasons for the earliest European forest clearance revolved around four major issues: security, logging, settlement, and farming. Because of the disputes and battles that occurred between Maori and Europeans over land rights during the 1860s, the scattered European bush settlements felt vulnerable against the threat of Maori ambush. Thus, a political move was made in the late 1860s to demilitarise the existing North Island frontier and encourage rapid expansion of colonial settlement (Arnold, 1994; Sorrenson, 1981). Part of this scheme required clearance and occupation of large expanses of forest in order to strengthen the already established but isolated European settlements. The plan was under way by the mid 1870s as a rapid influx of migrants arrived to establish new settlements, and large areas of the remaining lowland forest were cleared (Arnold, 1994). The forests were felled for timber, firewood and building materials, and created the foundations for one of the most successful industries in New Zealand at the time. Farmland also began to be cleared intensively and developed into pasture. This change is registered in the pollen profiles as an increase of grass pollen and the appearance of exotic pollen types (Figures 5.5-5.8).

First pollen evidence of European settlement at Tutira and Putere

Europeans began sheep farming in the Tutira and Putere districts of Hawke's Bay in the 1870s (Guthrie-Smith, 1969; King, 1975). The first indication of European presence in these catchments is registered in zone III of the pollen diagrams (Figures 5.5–5.8) by the first appearance of introduced pollen, including *Rumex, Trifolium*, *Cirsium* type, *Pinus*, *Plantago lanceolata* and *Salix*. These records provide a date horizon of *c.* 1870 where they first appear in the pollen profile. The dates that some species were planted or introduced on Tutira Station were recorded in personal journals (Guthrie-Smith, 1969). These have provided a unique method of dating certain horizons in the Tutira cores. For example, *Pinus radiata* and *P. nigra* were planted in 1880 at the Taupunga Peninsula on the north-east shore of Lake Tutira, and trace quantities of *Pinus* pollen first appear in the pollen profiles at 1.55 m in core LT16, and 5.20 m in core LW8. Thus, a date of *c.* 1880 + 15 years can be assigned to these depths, allowing time for pollen production and pollen deposition in the lake sediments. The first record of European diatoms (in particular, *Asterionella formosa)* at a depth of 1.55 m in core LT16 provides an additional time horizon for European settlement (Harper, 1993).

European land development at Tutira and Putere

Guthrie-Smith (1969) documented the intensive "fern-crushing" methods of clearance on Tutira Station during the 1870s. The task was a difficult one, partly because of the resilient nature of bracken and manuka (*Leptospermum scoparium*) after fire. Spring fires were the main tool used to clear the land in preparation for permanent pasture (Guthrie-Smith, 1969; King, 1975; Arnold, 1994). Fires were lit at 5–7 year intervals until the dense thickets of bracken and tutu (*Coriaria arborea*) were destroyed. Manuka dominated shrubland invaded in profusion after the fern and tutu were cleared, but this was eventually cleared using manual axe work. Numerous bags of European grass seed were sown, but these usually failed to establish. Native grasses eventually succeeded after the soils became compacted with the trampling effect of sheep (Guthrie-Smith, 1969). Once pastures were established that were capable of supporting stock, frequent fires were lit to scorch back the stunted regrowth of bracken and manuka to help maintain the grassland.

After the first record of introduced pollen types, significant changes occur in zone III of the pollen profiles. These changes correspond closely with the historical accounts of early European clearance. These include an increase of grass pollen, a continued decline of podocarp taxa, and a stabilisation of the bracken curve. Tutu becomes less important, and there is a steady influx of charcoal. The changes reflect the progressive yet intensive attempts made by the early European settlers to clear the remaining forest and fern/shrubland in Hawke's Bay. As a result of this land development an estimated 60% of the remaining forest in New Zealand had been destroyed by AD 1909.

Post 1938 vegetation changes

Zone IV is characterised by a rapid increase of Poaceae and *Pinus* pollen, an increased abundance of exotic taxa associated with pasturage (such as *Plantago lanceolata, Rumex, Taraxacum* and *Trifolium*), a decline in the percentage of bracken spores and the lowest recorded levels of podocarp pollen in the cores. These changes represent the last phase of the conversion by European farmers, of remnant forest, shrubland and fernland to pasture. When aerial topdressing became standard practise after the 1950s, agricultural productivity increased and the rate of land development accelerated (Brooking, 1981). By 1955, only *c.* 25% of the North Island was covered with native forests (Masters *et al.* 1957).

Pine (*Pinus*) pollen rapidly increases in zone IV of all cores. In the Lake Tutira and Lake Waikopiro profiles, this may be attributed to the planting of pine trees in the Tangoio Catchment situated south east of Lake Tutira following extensive landslides caused by the 1938 Esk Valley flood (Guthrie-Smith, 1969). In 1946, a tree planting programme was established in an attempt to stabilise the slip-eroded slopes, and approximately one million pine trees were planted over 500 acres (Campbell & Anaru, 1964). Of the 500 acres, 240 acres were planted with *Pinus radiata* and 130 acres with *Pinus laricio*. The plantations probably provided a substantial input of pine pollen to the Tutira and Waikopiro pollen spectra, together with the smaller local source from the Taupunga Peninsula on the shores of Lake Tutira. Sources of pine pollen in the Putere catchments also came from forestry plantations located directly south of Putere, in the Tukitukipapa river valley and on hillslopes south of the Mohaka River (see Chapter 4).

Centuries of drainage, burning and modification of swampland by Maori and Europeans have led to increased disturbance and nutrification of lake margins and swamp habitats. In the more sheltered Putere lakes, *Typha* pollen increases in zone IV, and presently forms a dense fringe around much of the lake margins of Rotonuiaha and Rotongaio. Characteristically, *Typha* pollen is not dispersed far from source and therefore tends to be under-represented in sediments collected from the deepest parts of large lakes. This effect is highlighted in the pollen profile from Lake Tutira, which is the largest and deepest of the lakes in this study. Percentages of *Typha* pollen are relatively low in zone IV given the abundance of *Typha* around some parts of Tutira's lake margins. In contrast, the small and shallow Lake Rotongaio has the highest percentages of *Typha* pollen, because the lake has a smaller source area and receives more locally derived pollen.

Other vegetation changes noted in zone IV include a decrease of *Myriophyllum* pollen and an increase of *salix* pollen. In core LT16, this coincides with a thick erosion pulse, visible in the sediment record at a depth of 0.75–0.55 m. Severe flooding after the 1938 Esk

Valley flood caused this pulse of inwashed material into Lake Tutira (Page *et al.* 1994a). According to historical records, swampland surrounding the lake was buried by "thousands of tons" of soil and silt during the storm (Guthrie-Smith, 1969). In addition, grasses and sedges growing in the river valleys draining into Lake Tutira were frequently buried in silt deposited by surface slips and flood waters. An increase of algae in the shallower regions of Lake Tutira, encouraged by high nutrient loads in the lake, may also have retarded *Myriophyllum*. Habitat loss through competition from introduced semi-aquatic plants and from grazing birdlife may also have contributed to the decline of *Myriophyllum*.

Evidence of increasingly eutrophic conditions in the lake sediments appear in the Tutira profile as highly organic, black authigenic sediments sandwiched between the numerous erosion pulses in the surface 50 cm of sediment (Plate 2.4). This recent nutrification of Lake Tutira resulted from aerial topdressing of phosphate fertilizers in the early 1950s, which reached the lake *via* runoff and soil erosion (see next section) in the catchment. Algal blooms and dense weed beds were noted in Lake Tutira from the late 1950s; they were responding favourably to the increase of nutrients in the lake water (Teirney, 1980). The increasingly organic nature of the sediments is not reflected in the loss on ignition profile (Figure 5.5b) because of the relatively coarse sub-sampling and the large proportion of inwashed minerogenic material in the cores that has effectively 'diluted' the organic component.

The long distance dispersed pollen types that are usually well or over represented in the pollen record (including the emergent podocarps and *Nothofagus* spp; McGlone, 1988c) continue to be recorded in the European sections of the pollen profiles even though the study catchments were almost totally cleared of forest by the beginning of this century. These pollen curves reflect the long-distance transport of regional forest taxa from the inland axial ranges. Pollen dispersal theories (Jacobson & Bradshaw, 1981) predict that as the tree canopy opens out, for example, after local deforestation, extra local and regional pollen are increasingly represented relative to local pollen in larger lake basins. This effect is most clearly illustrated by the *Fuscospora* pollen curves which remain at *c.* 5-10% of the pollen sum after Polynesian deforestation and European clearance.

Effects of European settlement on soil stability

The effects of recent intense rainstorms on the landscape of the Tutira catchment this century have been documented through the analysis of erosion pulses in the surface lake sediments of Lake Tutira (Page *et al.* 1994a). Individual storm events were matched to erosion pulses in the cores. These were correlated with a 93 year daily rainfall record. Page *et al.* (1994a) found that erosion-producing storms occurred almost annually, and the more intense storms caused thicker erosion pulses. They concluded the geomorphology of the Tutira catchment had been shaped significantly by the high frequency of erosion-inducing storms.

The frequency and extent of catchment erosion in the European period is reflected in zones III and IV of the sediment cores from Lakes Tutira, Waikopiro and Rotonuiaha. When over half of the total sediment depth in these zones includes material that has been washed in from the catchment during storms (Figure 5.4), this can affect the ability of the pollen spectra to accurately represent the catchment vegetation (see Chapter 6). During a storm, sediment is deposited rapidly. The pollen transported within this inwashed sediment pulse will contain a proportion of decay-resistant palynomorphs that were stored in the catchment soils. While there may be a constant input of pollen and spores from inwashed soils to the lake sediments of a lake which has inflowing streams and unstable catchment soils, at times of rapid inwash, the proportion of these transported soil palynomorphs will increase. Conversely, when this occurs, the pollen spectra contain fewer contemporary pollen and spores and they become a less accurate analogue of the contemporaneous vegetation. Of particular concern is the over-representation of bracken in the surface sediments of all cores (zone IV), especially because of this species' importance as a disturbance indicator in the fossil record. The Lake Rotonuiaha catchment is the only site in this study where bracken currently covers a substantial area of its drainage basin (approximately 15–20%), yet the percentage of bracken spores in the surface sediments is *c.* 40% in RNUI3. Similarly, bracken spores are over represented in cores RNGA3 (30%), LT16 (40%) and LW8 (65%). The relationships between pollen and spore representation, preservation and erosion pulse sediment are addressed in detail in Chapter 6.

Links between erosion and vegetation: past and present

Erosion pulses make up *c.* 70% of the total sediment depth in the European zones III and IV of LT16 and LW8, 48% in RNUI3 (Figure 5.4) and were absent in RNGA3. The increased proportion of inwashed sediment in the European zones of the cores suggests that either there was an increased frequency of high intensity storms that coincided with European settlement, or the vegetation type that dominated in the catchments in the European zone was influencing soil stability. As there is currently no evidence for the former occurring in New Zealand (Burrows & Greenland, 1979) I suggest over the last 2000 years, vegetation cover has been an important determinant of erosion in Hawke's Bay.

When the catchments were fully forested (zone I), storms did occur and cause erosion, but there was less movement of catchment material into the lake compared with the present (Figures 5.3 and 5.4). In zone II, when the landscape was dominated by bracken and shrubland, there is a small increase, compared with the Forest zone, in the proportion of inwashed sediment, i.e., by 20% in LT16 (although most of this occurred immediately after deforestation); and by 3% in RNUI3 (Figure 5.4). However, with intense European clearance and the conversion of fern/shrubland to pasture, there was a marked increase in the amount of eroded material being washed into Lakes Tutira and Rotonuiaha: about 40% more in zones III and IV than in zone II.

Although changes in soil structure would have occurred after deforestation, soil strength was probably not reduced because the rhizomes and roots of bracken and dense shrub contributed to soil strength as much as the forest. Although the soil binding properties and drainage would have been different under forest and fern/shrubland, evidently both were capable of offering a greater degree of soil stability at Tutira and Putere than when the catchments were covered in pasture. Pasture lacks the canopy protection, better drainage and root binding properties provided by forest and dense fern/shrubland. If the grass has a thick root mat and is also trampled on by grazing ungulates, the soil's A horizon tends to become compacted (Pain, 1971). During dry periods cracks develop in the soils and this allows water to reach the underlying horizons during intense rainstorms. Because water cannot infiltrate the compacted A horizon, it moves down the cracks and saturates the uncompacted soil horizons below, making the slope vulnerable to landslide erosion (Pain, 1971).

Landslide erosion is the most important type of erosion to occur on the steep hilly landscapes of New Zealand (Page *et al.* 1994b). It is currently of great concern to the identification of appropriate and sustainable land use and management in such erosion prone regions. Results from this thesis show that fern/shrubland or forest were effective at reducing soil erosion compared with grassland, and this supports the results from contemporary studies of landslide damage in North Island hill country.

Plate 5.1 clearly illustrates the greater frequency of landslide scars on slopes covered with pasture compared with slopes under pine plantation or dense bracken/shrubland in the Tutira catchment after Cyclone Bola, 1988. Observations from flights over the East Coast of the North Island after the 1988 Cyclone Bola also revealed differing susceptibilities to landslide erosion, with a strong relationship between vegetation cover and degree of landslide initiation (Bergin *et al.* 1993). Surveys revealed that closed canopy forest (both native and exotic pine plantations >8 years old) were 16 times more effective at preventing initiation of new landslides during high intensity rainstorms than pasture or young pine plantations, and four times more effective than regenerating manuka/kanuka shrubland (Marden & Rowan, 1993). The full impact of intense rainfall on the landscape is lessened by canopy interception and root reinforcement of the soil. This effect is best where a dense network of roots and a closed canopy are provided by mature forest and dense shrubland. Similarly, DeRose *et al.* (1993) observed in the Taranaki region after Cyclone Hilda in 1990, that erosion had occurred in areas under forest, shrubland, pine plantation and pasture, but to a greater extent on the pasture land. Hicks (1990) showed that landslide damage to hill country in Taranaki after Cyclone Hilda was significantly less under forest and dense shrub-cover than under pasture. Pain (1969, 1971) also found that vegetation had a distinct influence on the type and frequency of erosion in the Hunua Ranges, south east of Auckland, by controlling the extent of water movement through the regolith. Landslides occurred in both forested and grass covered catchments on the Hunua Ranges, but more frequently under grassland.

High stocking rates on steep erosion prone pasture land in the catchments may also increase the risk and rates of soil erosion, as compacted, trampled grassland will experience

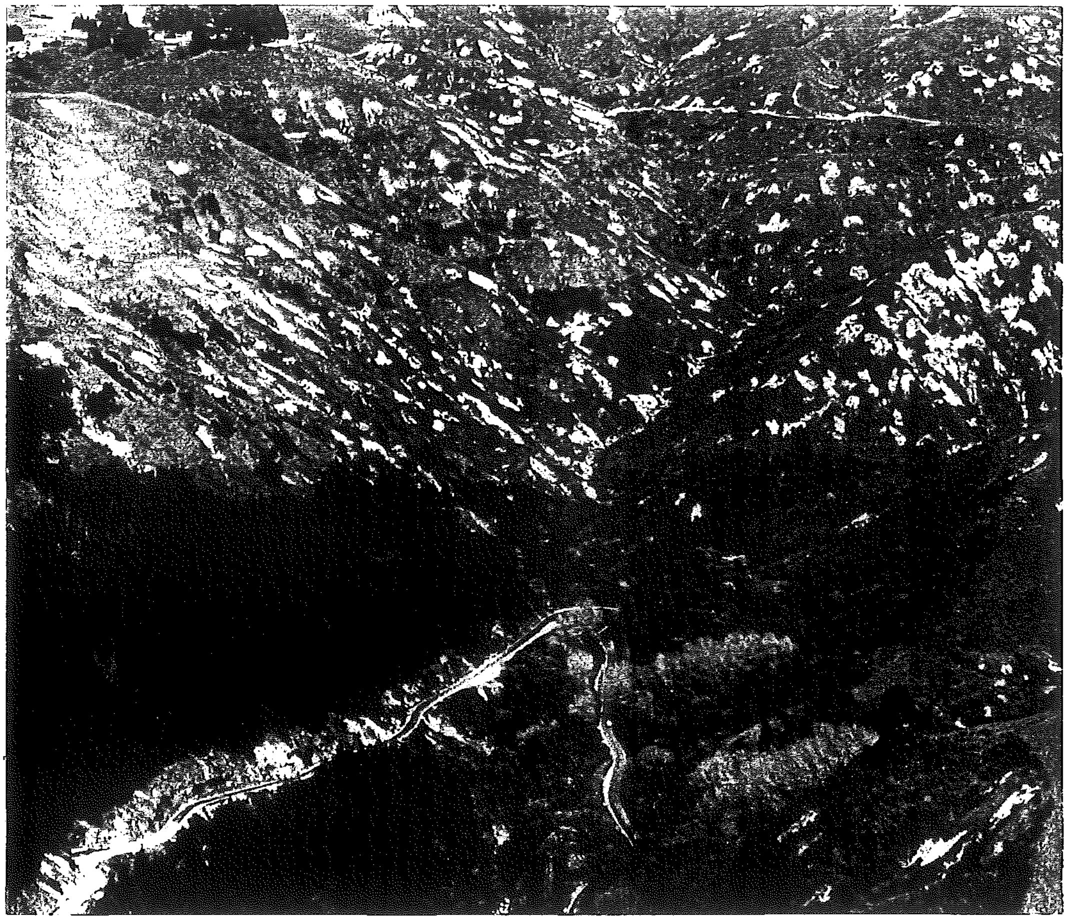


Plate 5.1. Landslide erosion in the Tutira catchment after Cyclone Bola, showing the high frequency of landslide scars on the hills under permanent pasture compared with dense scrub (right) and pine forest (left).

poorer drainage and rapid surface runoff. Heathwaite (1994) found that on heavily grazed pasture, runoff was 12 times greater and sediment production 30 times greater than on ungrazed pasture. Heathwaite (1994) suggests that livestock density grazing on permanent pasture is capable of strongly influencing the concentration of sediment and solutes in the drainage network of catchments.

The response and recovery of the landscape after disturbance is not only influenced by the type of vegetation, but also by the frequency and extent of previous and subsequent events (Pearce, 1986). Before European settlement in the Tutira and Putere catchments, redevelopment of the vegetation after any type of disturbance was relatively rapid when the landscape was covered with either forest or fern/shrubland. Regeneration was also relatively complete before the next large disturbance occurred. However, during the European period, when the protective types of vegetation were cleared from the Tutira and Putere catchments and replaced with more erosion-prone pasture, subsequent disturbances caused relatively more damage, and more time was needed for recovery.

CHAPTER 6

DIFFERENTIAL PRESERVATION OF POLLEN AND SPORES IN LAKE SEDIMENT DEPOSITS

INTRODUCTION

Lake basins with inflowing streams and steep slopes can receive a large proportion of their sediments from allochthonous sources, including rapidly inwashed soils and riverbank sediments mobilised during intense rainstorms. Palynomorphs stored in soils are exposed to prolonged periods of chemical oxidation and biological degradation before being transported into the lake basin by erosion. These biochemical and physical processes cause corroded and pitted exines (Cushing, 1967; Lowe, 1982; Havinga, 1984). In contrast, contemporaneous pollen deposited aerially on the lake surface undergoes little or no degradation leaving the exines intact. Because of the poor preservation environment in the soils, the more resistant pollen and spore types become preferential represented in the soil pollen spectra. Soil palynomorphs may be of considerable and mixed age, and be derived from a different type of vegetation to that on the contemporary landscape. When a substantial proportion of the pollen and spores in the lake sediments are of mixed age, this causes the representation of the contemporary vegetation in the lake sediment pollen spectra to be less accurate.

Research rationale

An initial qualitative assessment of the pollen and spores contained in the four lake sediment cores from Tutira and Putere, indicated differential preservation was related to the type of sediment deposit from which the palynomorphs were collected. Preservation appeared to be better in the authigenic (produced within the lake) sediments compared with the allogenic (derived from the catchment) erosion pulse sediments. The four cores contain many erosion pulses, with increasing amounts of these inwashed sediment pulses in the most recent sections of the cores (i.e within the European period) (see Figure 5.3 for core stratigraphies). Palynomorphs in the cores were analysed quantitatively for differential preservation in an attempt to establish the following:

1) whether a relationship exists between the type of palynomorph preservation and the type of sediment deposit in the cores, i.e., allogenic and authigenic sediment.

2) whether pollen and spore preservation has changed over time, under different catchment conditions. This is examined by analysing the differential preservation of pollen and spores from sub-samples within the three major pollen assemblage zones of the cores (Table 6.1).

3) whether contemporaneous and secondary sources of pollen and spores to lake sediments can be identified using differential preservation analyses.

Ultimately, the aim of this experiment is to separate the contemporary palynomorphs in the lake sediments from those that are inwashed and of mixed age. This is important to define in lake sediment cores that contain a high proportion of inwashed sediment, because it allows real disturbance-induced vegetation changes to be recognised and separated from spurious signals of disturbance caused by contamination of the pollen record with inwashed palynomorphs. The application of results gained from this study enhances the interpretation of the fossil pollen records from the Tutira and Putere lake cores in Chapter 5.

Table 6.1 Three major pollen assemblage zones in the fossil pollen spectra with the dominant vegetation type characteristic of the zone. Italicized words used in text to identify zone.

Zone	Period	Dominant vegetation
IV and III	*European* settlement	Grass
II	*Polynesian* settlement	Bracken
I	Pre-human settlement	*Forest*

METHODS

The methods used for the analysis of differential pollen and spore preservation are presented in Chapter 3. After counting, the data from sub-samples collected from allogenic sediment were separated from those collected from authigenic sediment, and are presented in Table 6.2.

RESULTS

Erosion pulses

The percentage of erosion pulse sediment in each of the three designated zones, i.e., European, Polynesian and Forest, is given for each core (Figure 5.4). Preservation data for the Forest zone of core LW8 are excluded from the results because of the low number of sub-samples in the zone (n=5). Erosion pulses were not present in core RNGA3. The core stratigraphies indicate the thickness and position of erosion pulses in the cores (Figure 5.3) the precise depths of which are given in Appendix 4.

The European zones of LT16 and RNUI3 contained more allogenic sediments than authigenic sediments, with *c.* 70% allogenic sediment in LT16 and LW8, and 48% in RNUI3. The European zones of LT16 and RNUI3 contained more allogenic sediments than the Polynesian and Forest zones (Figure 5.4), reflecting the increase of erosion and soil inwash in these lake catchments since European settlement. LT16 had a higher percentage of allogenic sediment in all zones compared with RNUI3 (11). The amount of erosion pulse sediment in the Polynesian zones is greater than in the forest zones, but only by 3% in RNUI3, and 20% in LT16.

Whole and corroded pollen and spores dominate the counts. For all taxa the broken category contributes a relatively small proportion of the total grains or spores counted. The only trend to emerge within the broken category involves bracken spores, which, in core LT16, were significantly more broken than the pollen grains and tree fern spores ($p<0.001$). This may be attributed to the relatively thin exine and trilete nature of the bracken spores which makes them more susceptible to rupture than the more robust tree fern spores and the more compact and solid types of pollen grain. Tolonen (1980) suggested that exine rupture may result from mechanical damage occurring during transport in minerogenic sediments. However, there has been little experimental work to find the cause of pollen and spore exine rupture.

Table 6.2 Total number of pollen and spores counted in authigenic and allogenic lake sediments of cores LT16, LW8, RNUI3 and RNGA3. RNGA3 has no allogenic sediments.

	Pollen grains		Bracken spores		Tree fern spores	
Core	Authigenic	Allogenic	Authigenic	Allogenic	Authigenic	Allogenic
LT16						
Whole	4413	1246	1811	1057	2388	856
Corroded	1239	929	149	503	1323	660
Broken	280	85	275	228	215	96
LW8						
Whole	1196	1047	952	1392	207	401
Corroded	601	1256	394	913	282	538
Broken	35	25	316	566	43	72
RNUI3						
Whole	4935	1017	2471	505	4099	817
Corroded	761	437	103	263	1049	641
Broken	204	46	126	32	152	42
RNGA3						
Whole	2026		1153		1346	
Corroded	195		36		418	
Broken	179		111		76	

The corrosion data for each sub-sample in the cores, are presented as relative percentages of the total of whole, corroded and broken counts for pollen, bracken spores and tree fern spores. Box and whisker plots are used to illustrate the corrosion data (Figures 6.1–6.7). Each box encloses half of the data between the first and third quartiles, and the box is bisected by a line which represents the median value. The vertical lines at the top and

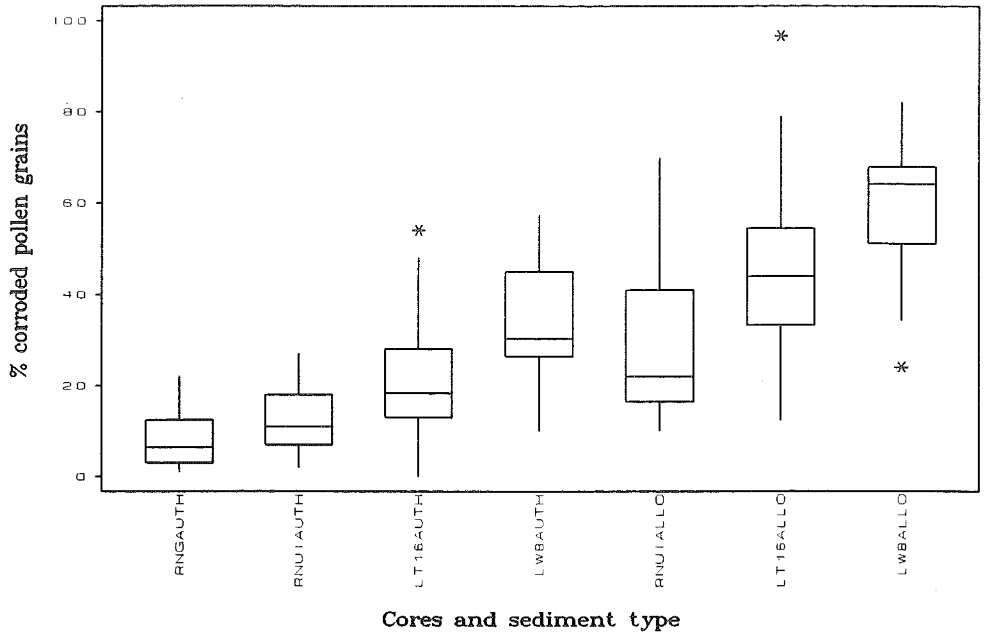


Figure 6.1. Box and whisker plots of corrosion data for pollen grains in the authigenic (AUTH) and allogenic (ALLO) lake sediments of cores LT16, LW8, RNUI3 and RNGA3.

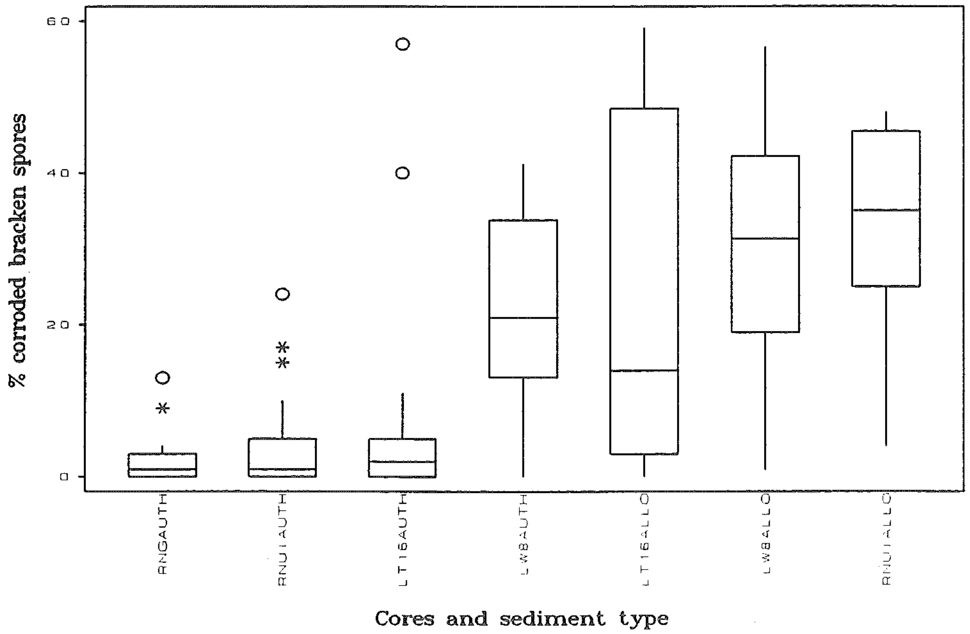


Figure 6.2. Box and whisker plots of corrosion data for bracken spores in the authigenic (AUTH) and allogenic (ALLO) sediments of cores LT16, LW8, RNUI3 and RNGA3.

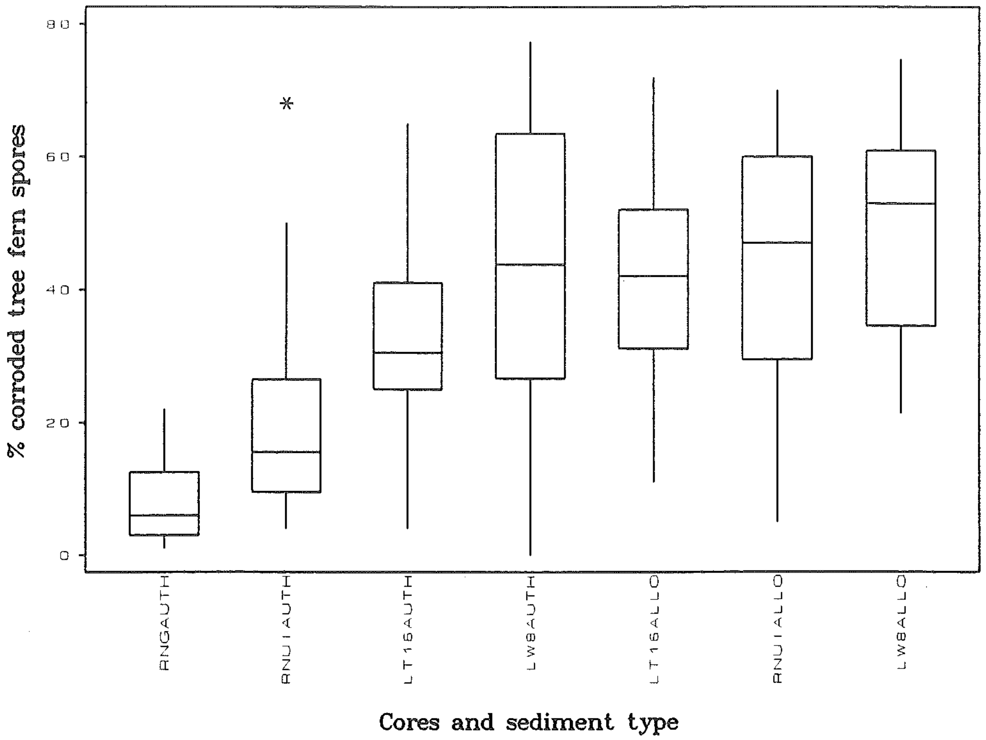


Figure 6.3. Box and whisker plots of corrosion data for tree fern spores in authigenic (AUTH) and allogenic (ALLO) lake sediments of cores LT16, LW8, RNUI3 and RNGA3.

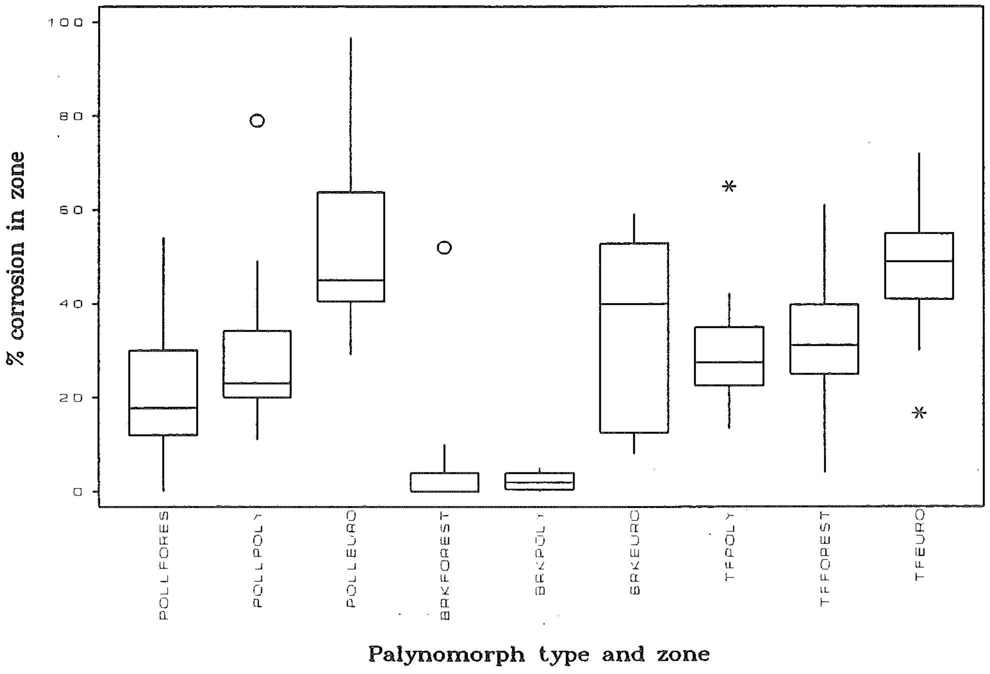


Figure 6.4. Box and whisker plots of corrosion data for pollen (POLL), bracken spores (BRK) and tree fern spores (TF) in the European (EURO), Polynesian (POLY) and Forest (FOREST) zones of core LT16.

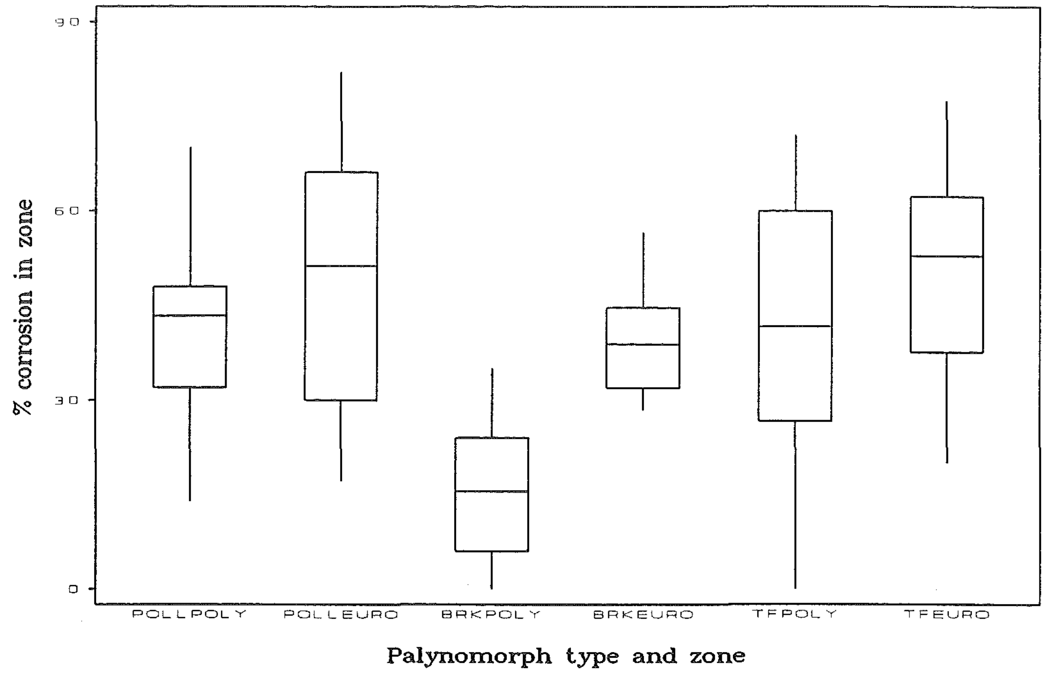


Figure 6.5. Box and whisker plots of corrosion data for pollen (POLL), bracken spores (BRK) and tree fern spores (TF) in the European (EURO) and Polynesian (POLY) zones of core LW8.

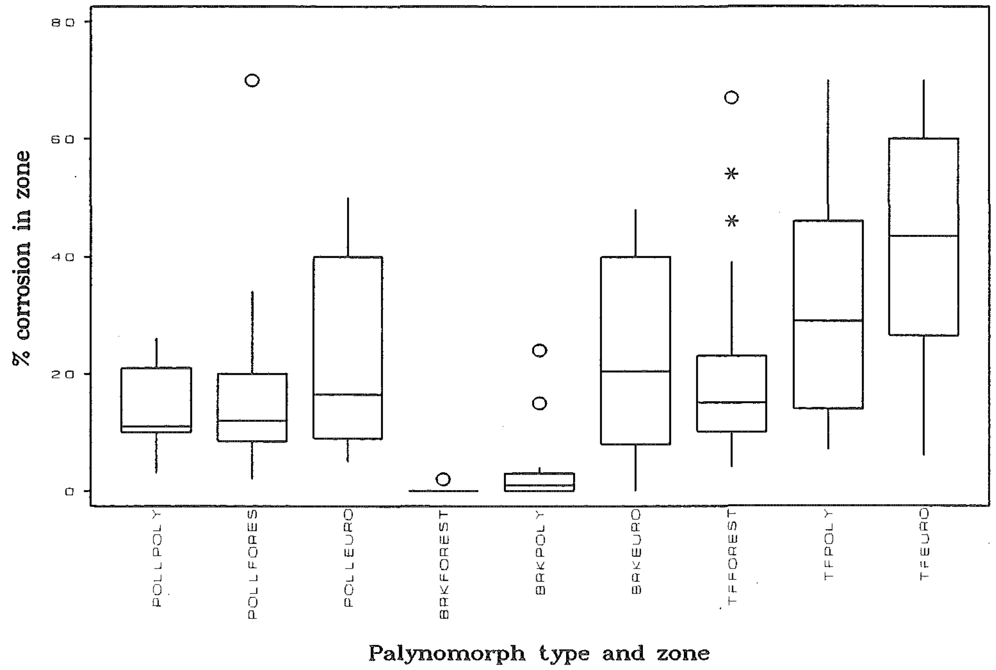


Figure 6.6. Box and whisker plots of corrosion data for pollen (POLL), bracken spores (BRK) and tree fern spores (TF) in the European (EURO), Polynesian (POLY) and Forest (FOREST) zones of core RNUI3.

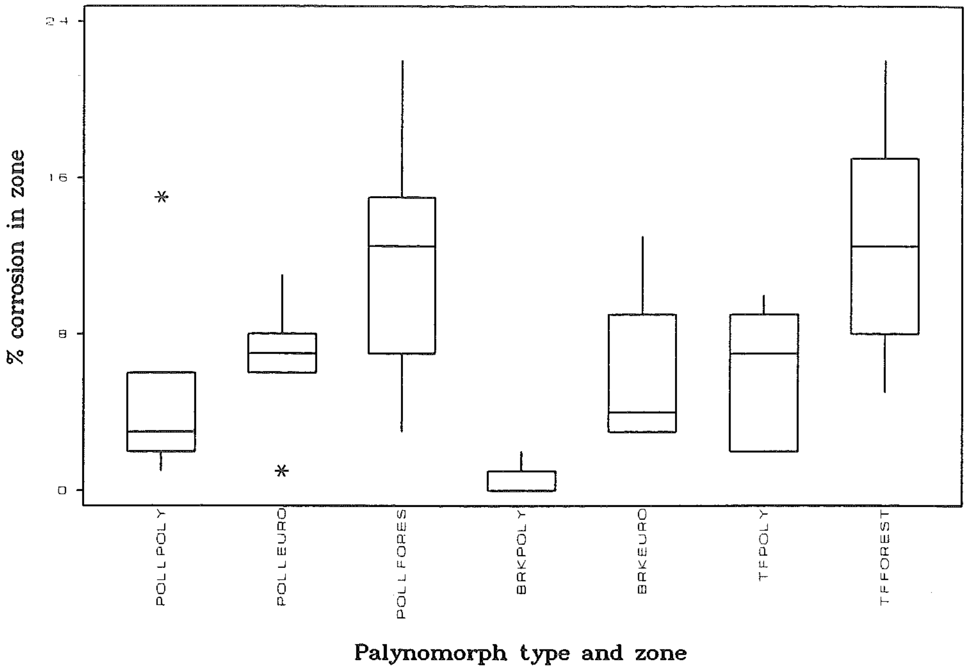


Figure 6.7. Box and whisker plots of corrosion data for pollen (POLL), bracken spores (BRK) and tree fern spores (TF) in the European (EURO), Polynesian (POLY) and Forest (FOREST) zones of core RNGA3.

bottom of the box (whiskers) indicate the range of "typical" data values, extreme values are displayed as "*" for possible outliers, and "O" for probable outliers (Statistix, 1992).

Differential preservation of pollen, bracken and tree fern spores in authigenic and allogenic sediments.

Relative frequency data for the corroded pollen, bracken spores and tree fern spores in authigenic and allogenic sediments are plotted with the median values arranged in ascending order to emphasise the differences between the two sediment types and between the cores (Figures 6.1–6.3). The boxplots illustrate, that for each of the three palynomorph types, there is more corrosion in the allogenic sediments than in the authigenic sediments. Of the three palynomorph groups in the authigenic sediments, bracken spores are significantly less corroded. Bracken spores also show the greatest difference between corrosion in the authigenic and the allogenic sediments ($p<0.0001$) (Figure 6.2). Tree fern spores are the most corroded palynomorph in the authigenic sediments. In all cores, there is no significant difference in the amount of corroded tree fern spores in allogenic or authigenic sediments ($p<0.0001$) (Figure 6.3). The increasing order of corrosion for all palynomorphs in the authigenic sediments of the cores is, RNGA3→RNUI3→LT16→LW8. This order positively correlates with increasing amounts of allogenic sediment in these cores (Figure 5.4).

Differential preservation of pollen, bracken and tree fern spores by zone

Relative frequency data for the corroded palynomorphs within the pollen zones of each core (Table 6.1) are presented in Figures 6.4-6.7. For each core, the box plots are grouped into palynomorph type and arranged with the meridian values in ascending order to emphasise differences between palynomorph type and between zones. There is a general trend for the pollen and spores to be more corroded in the European zones, although the differences between the amount of corrosion in this zone compared with the Forest and Polynesian zones vary between cores and between palynomorph type. In all cores, bracken spores show the greatest difference between corrosion in the European zones compared with the Forest and Polynesian zones. Bracken spores are the least corroded palynomorph in the Polynesian and Forest zones compared with tree fern spores and pollen grains, but in the European zones bracken spores are as corroded as the other palynomorphs.

Unidentifiable pollen grains recorded during routine pollen analysis

The record of deteriorated, unrecognizable pollen grains in the four cores are presented in Figure 6.8. The unidentifiable pollen curves tend to reflect the trends in differential preservation of identifiable pollen grains, i.e., preservation is poorest in sub-samples collected from erosion pulses. Unidentifiable pollen grains are generally more abundant towards the surface of the cores in the European zones. There are more unidentifiable pollen grains in cores LT16 and LW8 than there are in cores RNUI3 and RNGA3, and this correlates well with the greater amount of allogenic sediments in LT16 and LW8 (see Figure 5.4). These pollen grains may have become extremely deteriorated to the point of being unidentifiable during transport to the lake by rivers or surface runoff (Cushing, 1964). The number of unidentifiable pollen grains in a count provides a good general indication of pollen preservation in a sample.

DISCUSSION

There is no correlation between corroded palynomorphs and depth of burial in the cores. This indicates that compression, duration of burial, or post-depositional *in situ* diagenesis of palynomorphs in the lake sediments have not influenced pollen and spore preservation. There is a significant relationship between pollen and spore corrosion and the type of lake sediment from which the palynomorphs were collected. Pollen and spores in the allogenic erosion pulse sediments of the cores are significantly more corroded than those in authigenic sediments ($p<0.001$) (Figures 6.1–6.3). Aerially deposited pollen and spores are usually well-preserved (aerially derived pollen in moss cushions from the catchments showed limited signs of corrosion - see Chapter 4) therefore, the corroded palynomorphs in the lake sediments were derived from other sources, which vary according to palynomorph type.

Sources and transport of tree fern spores

Tree ferns produce vast numbers of relatively heavy spores but they tend to be poorly dispersed. As a result, most of these spores fall close to the source plants, are not transported far by wind and are under-represented in the pollen spectra (Macphail & McQueen, 1983). Tree fern spores are extremely resistant to degradation because of their

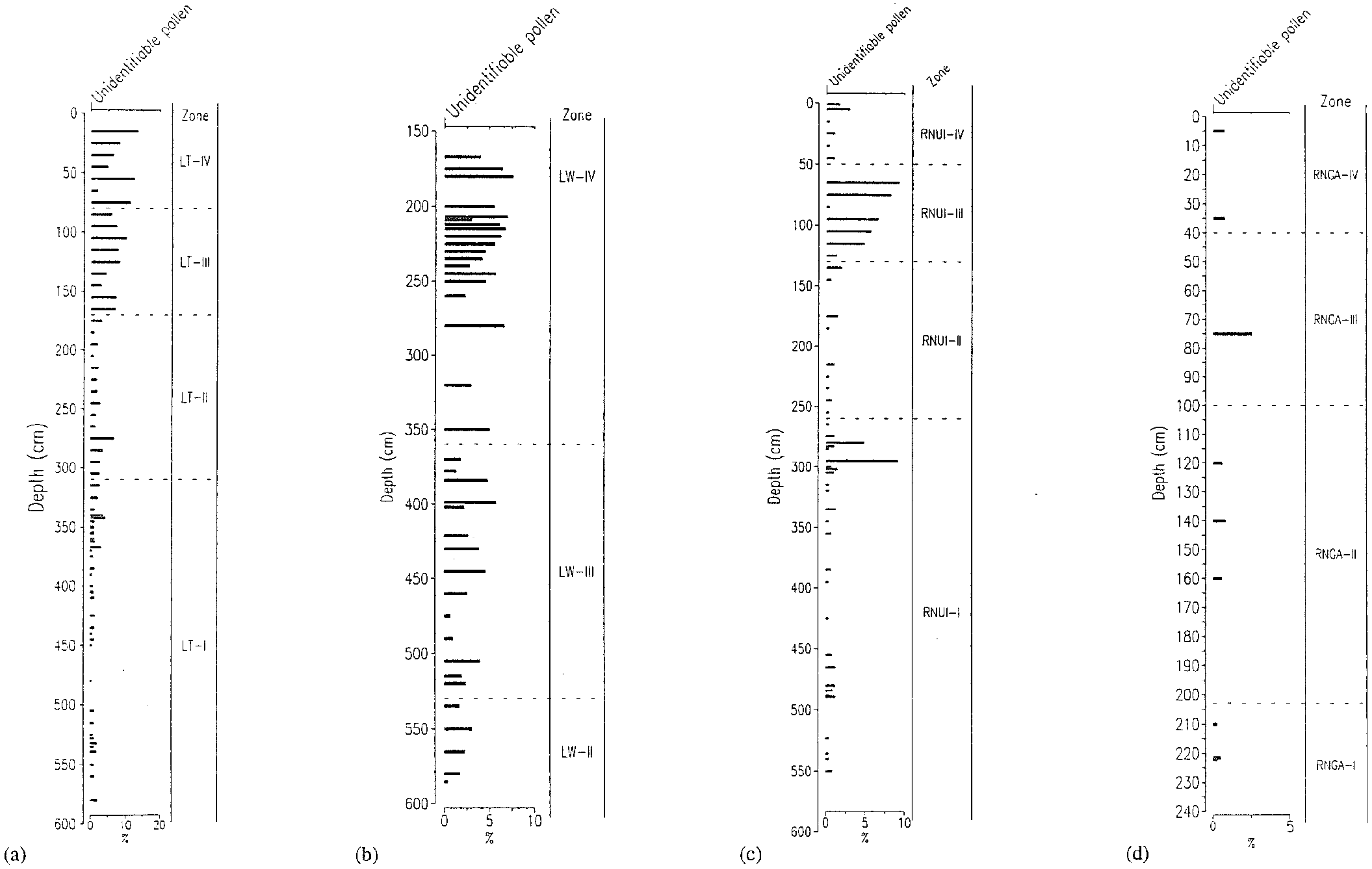


Figure 6.8. Unidentifiable pollen grains as a percentage of the total pollen count in cores LT16 (a), LW8 (b), RNUI3 (c) and RNGA3 (d).

high sporopollenin content. The resistance allows for long-term storage, even when exposed to chemical oxidation or high biological activity typical of soils or river bank sediments. Despite this resistance, tree fern spores still show signs of corrosion. However, experimental evidence suggests that while the exines of thick-walled spores may corrode, unlike many thin-exined palynomorphs, they are not completely destroyed (Havinga, 1984),

In all zones of the cores, tree fern spores in allogenic and authigenic sediments show more corrosion than pollen and bracken spores. In addition, the proportion of corroded tree fern spores increases in the European zones, where there are more erosion pulses. Because tree fern spores are highly resistant to degradation, they survive where other less resistant palynomorphs are totally destroyed, For this reason, the corroded tree fern spores are preferentially represented and over-represented in the pollen spectra from erosion pulses. This has also been recorded in lake sediments from Lady Lake, Westland, by Pocknall (1980), who suggested these corroded spores were derived from inwashed catchment soils or riverbank sediments. McGlone (1983a) also found corroded tree fern and monolete fern spores in cores from sites near Lake Rotorua, which he suggested were water transported to the site from eroded catchment soils.

While inwashed catchment soils may have provided some corroded tree fern spores to the lake sediments of this study, they can be excluded as the primary source of corroded tree fern spores, at least from the European zones, based on pollen analysis results from catchment soils and surface lake sediments in the Tutira and Putere catchments (see Chapter 4). These analyses revealed low levels (10%) of tree fern spore corrosion in catchment soils compared with up to 50% corrosion in the surface lake sediments. Moreover, tree fern spores were not particularly abundant in the soils, i.e., only 5% of the total pollen count in soils, compared with up to 20% in surface lake sediments. Before deforestation, when tree ferns were more abundant in the catchments, more tree fern spores would have accumulated in the soils. Therefore, soils may have been a more important source of corroded tree fern spores in the Forest zones than in the European zones.

I suggest eroded riverbank sediments have provided the most important source of corroded tree fern spores to the allogenic sediments of Lakes Tutira and Rotonuiaha. During intense rainstorms in these catchments, river levels rise, water flow increases and riverbank sediments are sloughed into the lake where they are preserved in the lake sediments as erosion pulses. During such events, the secondary tree fern spores stored within these riverbank sediments are also washed into the lake and redeposited with the erosion pulse.

As biological activity is generally higher in riverbank sediments than in topsoils (Havinga, 1984) spores stored within the riverbank sediments are more exposed to the processes of decay than the pollen spectra in the soils. Experimental studies of palynomorph preservation in river clay soils (Havinga, 1984) have shown pollen degradation was so rapid that more than half the pollen grains were lost to corrosion within the first two years, after which decay occurred at a slower rate and reduced some pollen types to trace amounts. In contrast, Havinga (1984) found *Lycopodium* spores remained well-preserved throughout the duration of the experiment, demonstrating the robust nature of thick walled spores compared with most types of pollen grains. Thus, only the most resistant palynomorphs such as the tree fern spores survive in any great numbers in the riverbank sediments, and even these suffer from exine attack. When the riverbank sediments are eroded and transported into the lake during intense rainstorms, they contain pollen spectra that are characteristically dominated by corroded tree fern spores, and show a marked reduction in pollen concentration and diversity (See Chapter 5).

There is no mention in the historical records (e.g., Guthrie-Smith, 1969) that tree ferns expanded in the study catchments after the onset of European settlement. This provides independent support for the suggestion that the increase of corroded tree fern spores in the European zones of the pollen profiles (Figures 5.5-5.7) is related to the increase of erosion and reworked sources.

In addition to soils and riverbank sediments, reworked littoral sediments may also have provided a source of corroded tree fern spores to the lake sediments. Tree fern spores are larger and heavier than many of the pollen grains and may only be transported a short distance from river flat and river gully habitats, causing them to concentrate in the coarse littoral sediments. This may be illustrated by the high percentages of corroded tree fern spores recorded in erosion pulse sediments of cores LT16 and RNUI3 (see Chapter 5). Experimental work on the differential transport of pollen and spores (Holmes, 1990) has shown that palynomorph size, and possibly specific gravity, control the rate of settling, with the larger types settling first. Coarse sandy bed materials over which the water current flows, were also found to increase the deposition rates of palynomorphs. The tree fern spore's robust nature and resistance to degradation in such environments may also encourage their concentration relative to the pollen grains in littoral sediments.

Bracken spore preservation and representation

There are significantly less corroded bracken spores in the authigenic lake sediments than there are corroded pollen grains and tree fern spores ($p<0.0001$) (Figures 6.1–6.3). The pollen spectra of the Forest and Polynesian zones (zones I and II) contain relatively low proportions of corroded bracken spores, but, in the European zones (III and IV) the proportion of corroded spores increases abruptly (Figure 6.4–6.7). Although the same pattern occurs with the corroded pollen and tree fern spore data, the difference in the amount of corrosion between these zones is much more distinctive for bracken spores than it is for the other palynomorphs. This abrupt increase of corroded bracken spores in the European zones suggests the bracken spores were derived from different sources during this period compared with the Forest and Polynesian zones.

In the Forest and Polynesian zones, the predominantly well-preserved bracken spores of the fossil pollen profiles were probably derived from the contemporaneous bracken in the catchments. These spores reached the lakes mostly *via* surface runoff and stream transport, and to a lesser extent by aerial dispersal shortly after their release. If the bracken spores had been stored for long periods on catchment surfaces or in soils before reaching the lake, they would be corroded (see results from Chapter 4). Peck (1973) showed that contemporary bracken spores can be almost entirely water transported to a lake basin. Cushing (1964) suggested that when contemporaneous pollen grains reach the lake sediments by water transport, they are characteristically highly corroded. However, this does not seem to apply to the bracken spores because of their greater resistance to degradation compared with most types of pollen. The outer perine of the bracken spore probably offers some protection during transport and against decay, and explains why these otherwise thin-exined spores are more resistant than many pollen types.

In the European zones of the pollen profiles, the increased abundance of corroded bracken spores correlates with the increased proportion of inwashed sediment in these zones (Figure 5.4; and Figures 6.4–6.7). I suggest that corroded bracken spores in the European zones are predominantly secondary and derived from inwashed catchment soils. This postulate requires that the catchment soils contain a reservoir of corroded bracken spores. It is feasible that such a store of bracken spores has accumulated in the Tutira and Putere catchment soils over a long period of time. This is supported by results from the surface and fossil pollen analyses in Chapters 4 and 5. For example, topsoils from the Tutira catchment contained 40-70% bracken spores, and up to 76% of these spores were corroded. In contrast, moss cushions contained <5% bracken and these were excellently preserved. In addition, the fossil pollen spectra (Figure 5.5-5.8) show that bracken has dominated the vegetation of the Tutira and Putere catchments for the last 500 years, since the time of Polynesian deforestation. Thus, I conclude, that with the onset of European clearance and conversion to permanent pasture, the increased occurrence of erosion and soil inwash has caused a substantial supply of these stored corroded bracken spores to be transported to the lakes.

One of the most important implications of this result is the effect it has upon the accuracy of bracken representation in the pollen records. Bracken is generally over-represented in the European zones of the pollen profiles (see Chapter 5: Figures 5.5 to 5.8). Bracken was cleared from the catchments by European settlers before the 1900's (Guthrie-Smith, 1969; King, 1975), yet the frequency of bracken spores in zones III and IV of the fossil pollen profiles remain high. The degree of distortion recorded for the bracken spore curves in the pollen profiles is directly related to the presence of inwashed sediments. To illustrate this effect, for each sub-sample in the cores where bracken spores were recorded, the percentage of spores that were corroded were subtracted from the original bracken spore count. The "corrected" count was then recalculated as a percentage of the dryland pollen sum (Figure 6.9). Therefore, the corrected counts for bracken only include the well-preserved and broken fractions.

The graphs clearly illustrate the small differences between the original and corrected counts of bracken spores in the Forest and Polynesian zones. This reflects the low amount of corrosion, and the contemporaneous origin of the spores. However, in the European zones, a substantial difference exists between the corrected and original curves. Once the inwashed corroded spores are removed from the count, the corrected values (15-25%, compared with the original 30-65%) provide a more accurate representation of regional bracken sources in the catchments. However, despite the correction factor, the percentage of well preserved bracken spores in the surface lake sediments still remains higher than

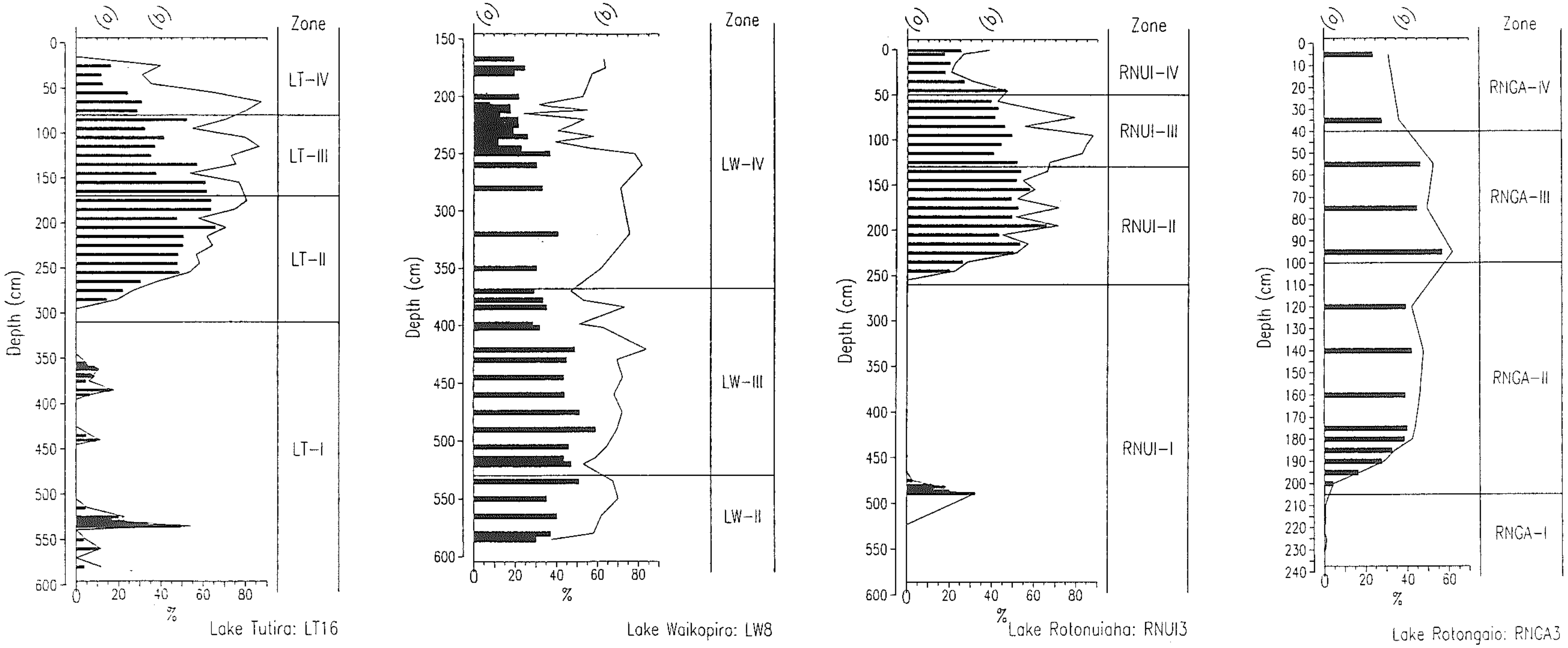


Figure 6.9. Bracken spore curves for cores LT16, LW8, RNUI3 and RNGA3: (a) the corroded proportion has been removed from the original count and the new count recalculated and plotted as a percentage of the dryland pollen sum, and (b) the original count plotted as a percentage of the dryland pollen sum.

those recorded in the surface moss samples from the catchments (see Chapter 4). This is probably because the lake basins have larger source areas than the moss cushions, which means they contain more regionally derived pollen and spores. Therefore, some of the well preserved bracken spores in the lake sediments may have been wind dispersed from bracken plants outside the catchments.

Of all the cores in this study, LT16 and LW8 have the greatest amount of inwashed sediment in the European zones (70%), and correspondingly reveal the greatest difference between the original and corrected counts in zones III and IV (Figure 6.9). In RNUI3, the greatest difference between the original and corrected curves lies in zone III (Figure 6.9) which positively correlates with an increase of inwashed sediment in this zone. However, in zone IV of this core, where original and corrected curves are similar, there is a marked reduction of inwashed sediment (Figure 5.4) and the original count of bracken spores decreases to more accurate representations of the bracken present in the catchment and surrounds. In the surface sediments of core RNUI3, the original bracken count increases again up to 40% and this coincides with the presence of an erosion pulse at this depth. However, the corrected count reduces this to *c.* 25%, which is a more accurate representation of the bracken in the Lake Rotonuiaha catchment today (see Chapter 4).

Pollen grain preservation and derivation

Surface pollen analyses of soils from the Tutira and Putere catchments (Chapter 4) showed pollen grains were highly corroded, pollen diversity was low, and only the more resistant pollen types were represented in the soil samples. In contrast, moss cushions contained a more diverse range of well-preserved, aerially derived pollen types. Surface lake sediments contained an amalgamation of soil and aerially-derived pollen grains. Differential preservation analyses of the fossil pollen in the lake sediment cores indicates the fossil pollen was also derived from mixed sources.

There are significantly more corroded pollen grains than corroded bracken spores in both the allogenic and authigenic sediments of the cores ($p<0.001$) (Figures 6.1 and 6.2), and more corroded pollen in the Forest and Polynesian zones of the cores than corroded bracken spores (Figures 6.4–6.7). This indicates the main sources of corroded pollen grains may be different from the corroded bracken spores. Corroded bracken spores in the sediment cores have been identified as being predominantly derived from catchment soils, based on the similarity of the bracken spore content in catchment soils and surface sediments (see Chapter 4; Figures 6.1 and 6.3). However, as the pollen content of the catchment soils does not resemble the pollen content of surface lake sediments to the same extent, the catchment soils are not considered to be the primary source of the corroded pollen grains. Moreover, if corroded pollen was derived from inwashed catchment soils, then this would not account for the relatively high proportion of corroded pollen grains also recorded in the authigenic sediments of the cores (Figure 6.1).

Although some of the corroded pollen grains in the allogenic sediments may be derived from inwashed soils, differential preservation results from the Tutira and Putere lakes indicate a large proportion of these corroded grains, in both types of sediment, are derived from the contemporary vegetation. However, instead of their deposition in the lake soon after their release from the parent plant, these "inwashed contemporary" pollen grains settle on catchment surfaces until they are transported to the lake basins by surface runoff. It is during this settling period that corrosion of the least resistant pollen grains occurs. The settling period may vary from several weeks to months (Havinga, 1964) depending on rainfall and slope angle. Experimental work on differential pollen preservation has shown how exine corrosion can proceed rapidly after initial deposition in the catchment, with many pollen types displaying signs of corrosion within the first few years after exposure to attack (Havinga, 1984). Similarly, Königsson (1969 quoted in Lowe, 1982) found that pollen corrosion in Swedish lake sediments occurred as soon as one or several summer seasons after initial deposition. Cushing (1964) also identified this inwashed contemporary pollen in lake sediments from east-central Minnesota and found the grains deposited in this way were characteristically highly corroded.

Because inwashed contemporary pollen contributes a significant proportion of the total pollen content in both the allogenic and authigenic lake sediments, the fossil pollen profiles from the Tutira and Putere lake sediment cores are not "distorted" (i.e., contaminated with secondary pollen). This is true even in the European zones of LT16, LW8 and RNUI3 which contain a high proportion of inwashed erosion pulse sediment (see Figure 5.4). These results suggest that contemporary inwashed pollen is also incorporated in the erosion pulses with smaller proportions of soil-derived pollen. If the erosion pulses contained only soil-derived pollen, then the pollen diagrams would be obviously distorted and 'noisy', and surface lake sediments would closely resemble the pollen spectra of the catchment soils, and they do not (see Chapter 4; Figure 4.3).

Increase of corroded pollen in the European zones of the cores

The proportion of corroded pollen grains is greater in the European zones compared with the Forest and Polynesian zones, and this coincides with an increase of allogenic sediment in these zones. However, as the majority of the corroded pollen grains are not derived from the inwashed catchment soils, the increased corrosion may be explained by a shift in the most abundant type of pollen from zone to zone and their resistance to degradation. Podocarps were the dominant pollen type in the Forest zone, *Coriaria* pollen in the Polynesian zone, and Poaceae pollen in the European zones. The podocarps and *Coriaria* are relatively robust pollen grains owing to their thicker exines, whereas the thin exined Poaceae pollen are easily corroded. Therefore, the higher incidence of corrosion in the European zones reflects the lower resistance of the dominant pollen type in the zone rather than an increase of inwashed and corroded soil pollen. These conclusions indicate more detailed pollen preservation analyses, that target pollen taxa of particular interest, may further enhance fossil pollen interpretations.

Other sources of pollen recruitment to the lake sediments

A substantial contribution of pollen in the sediments was derived from the contemporaneous aerial pollen rain, and these probably make up the bulk of the well-preserved pollen grains in the cores. Sediments from those lake basins with inflowing rivers may also have derived a small proportion of the corroded pollen from eroded riverbank sediments in the same way described earlier for the corroded tree fern spores. The pollen in riverbank sediments will be mainly restricted to those taxa occurring close to the rivers, and to the more resistant pollen types because of the high biological activity in this environment (Havinga, 1984). Therefore, corroded pollen from river bank sediments may only contribute a small amount of the total pollen influx to lake sediments. This proportion will depend on the number of inflowing rivers, density of the vegetation present in, or close to, the river bank habitats and pollen resistance to degradation. Crowder & Cuddy (1973) pollen analysed river samples in Canada and inferred that slope wash with stream bank erosion can contribute pollen to lake sediments throughout the year.

Water turbulence in shallow waters caused by wind-induced waves may resuspend littoral surface sediments and cause them to be redeposited across the lake basin. If these sediments had been previously exposed to the air as a result of lowered lake levels, the pollen and spores contained within them may have become corroded through oxidation and biological attack. Davis (1968) found that after disruption, these sediments and their pollen load are resuspended more or less evenly in the water and redeposited over the entire lake basin. This process may account for some of the corroded palynomorphs found in both the allogenic and authigenic lake sediments of this study. Mixing and redeposition of surface sediments may have affected the entire Lake Rotongaio basin because of the lake's saucer-shaped basin and shallow water depth (maximum 5 m). Although mixing of surface sediments in the larger and deeper lakes (Tutira, Waikopiro and Rotonuiaha) would be confined to the littoral sediments in the shallower water depths, it may still have been important because the littoral region in large lakes constitutes a relatively large surface area.

Pollen and spores in Lake Rotongaio sediments

In core RNGA3 there are no erosion pulses in the sediment record, and only low frequencies of corroded pollen and spores occur throughout the core (Figures 6.4–6.7). This indicates inwash of catchment soils has been relatively insignificant in the Rotongaio lake basin compared with the other lakes in this study. Lake Rotongaio has no inflowing streams, a shallow catchment with relatively stable slopes, and a dense surround of swampland which effectively acts as a sediment filter for the lake basin. Because of these lake catchment characteristics, catchment soils and riverbank sediments can be excluded as possible sources of corroded pollen and spores in this core.

The low proportions of corroded pollen and spores in the RNGA3 sediments are most likely of contemporaneous origin, derived from inwashed surface catchment materials. Corroded palynomorphs may also have been derived from eroded littoral and surrounding swamp sediments at times when lake levels were lower and pollen and spores were exposed to aerobic conditions and subsequent exine decay. When the water levels increase again these basin edge sediments and their stored pollen and spores are resuspended and redeposited in the lake where they become re-incorporated into the lake sediments. The littoral sediments may contribute relatively larger amounts of corroded pollen and spores to the Lake Rotonuiaha basin than the other basins in this study, because its basin characteristics make it more susceptible to wind turbulence, lowered water tables and drying of littoral sediments.

CONCLUSIONS

Effect of inwashed corroded pollen and spores on the fossil pollen spectra

Because erosion pulses comprise rapidly deposited material transported from the catchment during periods of high rainfall, they tend to contain pollen and spores derived from several different sources. These include eroded catchment soils, riverbank sediments and contemporaneous inwash. The greater the proportion of inwashed secondary pollen and spores in the pollen spectra, the more the fossil pollen spectra becomes distorted. When this occurs, the pollen spectra are less accurate at representing the contemporaneous catchment vegetation, because the inwashed pollen and spores are derived from non-contemporaneous source plants.

The pollen spectra of erosion pulse sediments show that when soils are inwashed, not all of the pollen and spore curves are automatically distorted, because of the differential palynomorph preservation and representation in the soils. Surface pollen analyses of catchment soils have shown that only the more resistant palynomorphs are preserved in the soils. These include bracken spores and a limited number and diversity of pollen grains. Thus, the extent of distortion in an erosion pulse will be related to the pollen and spore content of the soils, and the amount of eroded material that is transported from the catchment to the lake.

Changing vegetation cover and pollen and spore sources

The Tutira and Putere lake sediments receive pollen and spores from a number of different sources, which vary according to lake catchment characteristics. Because the catchment vegetation and landscape features have been modified in the study sites since human settlement the relative importance of the different sources of pollen and spores recruited to the lake sediments has changed. These changes are summarised in Table 6.3. Catchment and lake basin size and morphology, water and sediment chemistry, catchment drainage, soil types, erosion susceptibilities, vegetation cover and rainfall may all affect the proportion, age and preservation condition of the inwashed pollen and spores reaching the lake sediments.

As the catchment vegetation changed to permanent pasture, aerially deposited contemporaneous pollen and spores contributed less to the pollen spectra in the European zones, relative to inwashed contemporaneous and secondary pollen and spores. Tolonen (1980) also found the proportion of inwashed soils and corroded pollen reaching the lake sediments increased after forest clearance in Finland during the early Iron Age. Similarly, Bonny (1978), Pennington (1979) and Davis *et al.* (1984) also found more degraded pollen and spores in sediment cores from lakes that received a high percentage of pollen through stream inflow and soil wash-off relative to direct aerial deposition.

Table 6.3 Summary of pollen and spore sources and preservation during Forest/Polynesian and European zones of the lake sediment cores.

	Forest/Polynesian	European
Vegetation cover	Closed →	Open
Pollen and spore preservation	Good →	Corroded
Surface runoff	Relatively low →	Relatively high and more frequent
Main sources of tree fern spores	Contemporaneous aerial and inwash (whole spores) → Eroded riverbank (corroded) → Reworked littoral sediments (corroded)	More from eroded river bank sediments (corroded)
Main sources of bracken spores	Contemporaneous aerial and inwashed (whole) →	Plus inwashed secondary spores from eroded catchment soils (corroded)
Main sources of pollen grains	Contemporaneous aerial and inwashed (whole and corroded) →	

Studies of differential pollen and spore preservation in the northern hemisphere have reported a variety of correlations between exine conditions and sediment type. For example, differential pollen preservation analyses of sediment cores from the Isle of Skye that contained moss bands inter-stratified in limnic silts, showed pollen from the moss bands was mostly corroded, whereas pollen from the silts tended to be broken and amorphous (Birks, 1970). Birks attributed the corrosion to chemical oxidation and microbial attack, and the broken and amorphous pollen to mechanical damage. Cushing (1964) found pollen grains were degraded in silt, crumpled in algal copropel, and corroded in moss peat. Lowe (1982) questioned the assumption made by Cushing (1964) and Birks (1970) that degraded or amorphous exines indicate physical alteration of the grain, because insufficient experimental work on the causes of deterioration has been undertaken to confirm this idea. In contrast, this study finds corroded bracken spores are associated with inwashed soils; corroded tree fern spores are probably associated with eroded river bank sediments and reworked littoral sediments; inwashed contemporaneous pollen grains can be corroded; and broken or ruptured exines are apparently unrelated to time, changing catchment vegetation and sediment type. Differential preservation analysis has shown differences between sediment types within each core, between the cores from different lake basins, and between the different types of palynomorph.

Although some generalisations have been made about preservation and sediment type in this study, the relationships existing between pollen and spore preservation and sediment type at one site may be of limited use when extrapolated to other sites with different sets of conditions. However, if differential pollen and spore preservation is evident during routine pollen analyses, interpretations of the palaeoecological record can only be enhanced through differential preservation analysis of selected taxa at each site.

CHAPTER 7

SUMMARY OF CONCLUSIONS

The results and conclusions drawn from Chapters 4, 5 and 6 are summarised below. The first three headings outline the main disturbances experienced by the vegetation and landscape at Tutira and Putere since *c.* 1850 BP. These details are followed by a summary of conclusions derived from the surface pollen and preservation analyses (Chapter 3) and the preservation analyses of fossil pollen and spores (Chapter 6).

Pre-deforestation vegetation: 1850-600 BP

- Pollen evidence from the Tutira and Putere catchments indicates podocarp-hardwood forests covered the lowland regions of Hawke's Bay, up until the time of widespread deforestation.

- At Tutira, the disturbance index shows frequent disturbance kept the forests in an ongoing state of change. Most of the sub-samples in the forest zone have a relatively disturbed composition (group 6). Fewer sub-samples have compositions that are suggestive of relatively extreme disturbance (groups 1-5) or relatively extreme stability (groups 7-9).

- Fires and volcanic eruptions were the most significant disturbances in the Tutira and Putere catchments before deforestation. Natural fires have not previously been considered a primary cause of forest disturbance in the North Island during the late Holocene. However, results show that forests in Hawke's Bay were frequently disturbed by lightning-strike fires associated with cyclic and episodic droughts, and volcanic eruptions. Regardless of the frequency of these disturbances, full forest redevelopment occurred after each event.

- At the higher rainfall site of Putere, although the area was also exposed to frequent disturbance, the vegetation was evidently not as sensitive to disturbance. A greater proportion of the sub-samples in the Rotonuiaha profile had pollen compositions typical of groups 6 to 9, which represent greater relative stability.

- The disturbance index for Rotonuiaha is less extreme than for the Tutira profile. The drier climate at Tutira probably made the area more vulnerable to the effects of disturbance, and made forest redevelopment at this site much slower than it would have been at Putere.

- When the Tutira and Rotonuiaha catchments were fully forested, storms and erosion-related disturbance caused no measurable changes in pollen composition.

- The 1850 BP Taupo eruption was largest single natural disturbance in Hawke's Bay before Polynesian deforestation. Although the forests were considerably damaged at Putere and Tutira, full forest recovery occurred at these sites within the following *c.* 145-175 years.

Polynesian deforestation: bracken and shrubland, 600 BP to AD 1870

- Widespread deforestation by fire occurred in the Hawke's Bay region *c.* 600 BP. Bracken became the dominant vegetation type, and remained so until the time of European settlement. The increase of charcoal fragments, the decline of pollen from tall forest taxa and the rapid and sustained increase of bracken spores in the pollen profiles are interpreted as the first indication of large-scale permanent settlement in the area. The timing and sequence of change agrees with other pollen based studies and current archaeological evidence from Hawke's Bay.

- Deforestation at 600 BP was the largest and most sustained disturbance to have occurred in Hawke's Bay, probably since the end of the last glaciation.

- Long-distance dispersed *Agathis australis* pollen declines in the Rotonuiaha pollen profile after deforestation, suggesting contemporaneous deforestation in the Waikato region.

- Polynesian deforestation may have coincided with or followed a severe, prolonged drought which, together with the increased frequency and scale of both deliberately and accidentally lit fires, may have facilitated widespread and rapid forest clearance.

- Deforestation occurred at Tutira and Putere at approximately the same time, but was completed faster at the drier site of Tutira (*c.* 64 years) compared with Putere (*c.* 160 years).

- The normally seral bracken, maintained dominance on the landscape until European settlement because it was repeatedly burnt.

- Deforestation did not initiate erosion at Putere, but at Tutira there was a temporary period of erosion immediately after forest clearance. The rapid establishment of bracken on the landscape after deforestation helped to increase soil strength and structure by way of deeply penetrating rhizomes and a dense fern canopy. I consider both factors helped minimise erosion throughout the Polynesian period.

- Periodic droughts throughout the Polynesian period may have made the forest and fern/shrubland more vulnerable to fire. Drought may also have assisted Maori with the steady removal of more than half the native forests from Hawke's Bay.

- Considering the amount of forest destroyed and the speed of clearance, the soil stability and the bracken/shrubland dominated vegetation remained relatively stable for 500 years.

European settlement: pasture, AD 1870 to present.

- Since European settlement, erosion caused by intense rainstorms has been and is at present the most significant and frequently occurring type of disturbance in the Hawke's Bay region.

- The European zones of cores LT16 and RNUI3 contained more erosion pulse sediment than the Polynesian and Forest zones, reflecting the increased frequency and extent of erosion and soil inwash in these lake catchments since European settlement.

- Erosion occurred more frequently during the European period when the catchments were under grassland, compared with either forest or bracken/shrubland vegetation. These results agree with contemporary studies of landslide erosion under similar vegetation types.

- Since pasture became the dominant vegetation type, the soft-rock hill country of the Tutira and Putere districts has become more vulnerable to erosion and landslides.

- Given the relatively short time and high intensity of European clearance, disturbance to the vegetation and landscape has probably been greatest in the European period compared with previously occurring natural disturbances, or the period of Maori settlement in Hawke's Bay.

- High intensity rainstorms, occurring on an increasingly degraded environment which is also exposed to sustained landuse pressures, have caused long-term changes in vegetation and soil stability.

Surface pollen and preservation analyses

- Pollen analyses of mosses, soils and surface lake sediments show the surface lake sediment pollen spectra represent an amalgamation of both contemporaneous and secondary inwashed pollen and spores of mixed age. Mosses contain almost entirely contemporaneously derived palynomorphs from small source areas; soils contain a lower diversity of mixed aged pollen and spores; and the surface lake sediments contain palynomorphs from a combination of these sources. The pollen spectra from moss samples accurately reflect the local vegetation, but the soils provide a pollen spectra that is very different to the contemporaneous vegetation.

- Because of the mixed sources of pollen and spores in the lake sediments, using pollen data from moss samples alone to calibrate the fossil pollen spectra from lake sediments will lead to misleading interpretations. Results from this study show that palaeoecological interpretations benefit from comparative pollen analyses of surface materials. Interpretations are particularly enhanced when as many as possible of the potential sources of pollen (mosses, soils, riverbank sediments, surface debris etc) are sampled and analysed from the lake catchment.

- Results of palynomorph preservation in mosses, soils and surface lake sediments show there are significant relationships between the amount of exine corrosion, deposit type and taxa. Mosses contained almost entirely well preserved pollen and spores; soils contained highly corroded bracken spores and pollen, but less corroded tree fern spores; and surface lake sediments contained highly corroded bracken and tree fern spores, with better preserved pollen.

- These variations in pollen and spore preservation are attributed to different sources in the catchment, the results of which are summarised: in the surface lake sediments most of the bracken spores were derived from soils, whereas most of the pollen was derived from contemporaneous sources. Corroded tree fern spores in the lake sediments were presumed to have been eroded from river bank sediments. Variations in preservation condition between palynomorph types are also related to the degree of resistance.

- Work that would further enhance the interpretation of the fossil pollen record, would include pollen and pollen preservation analyses of littoral and riverbank sediments to establish their pollen and spore content. The importance of these sources could then be defined in the fossil pollen record.

Preservation analyses of fossil pollen and spores

- Differential preservation analysis of pollen and spores in four cores from four lakes show differences between sediment types within each core, between the cores from different lake basins, and between the different types of palynomorph.

- Corroded bracken spores are strongly associated with inwashed soils. In lake basins that receive inwashed soils, these soils can continue to supply old, corroded bracken spores to the pollen spectra, even though the fern may be absent or uncommon in the catchment. Differential preservation analysis allows the proportion of these corroded bracken spores to be estimated and removed from the pollen sum, permitting a more accurate representation of this fern spore in the fossil pollen record.

- Corroded tree fern spores are probably associated with eroded river bank sediments and reworked littoral sediments. Thus, sudden peaks of corroded tree fern spores that coincide with an erosion pulse indicate rapid scouring, transport and deposition of riverbank sediments complete with their store of corroded tree fern spores, rather than a signal of tree fern proliferation in the catchment.

- Broken or ruptured exines are apparently unrelated to duration of burial, changing catchment vegetation and sediment type. Although unproven, it is suspected breakage may be related to fluvial transport or processing methods.

- The extent of pollen spectra distortion in an erosion pulse will be related to the pollen and spore content of the soils, and the amount of eroded material that is transported from the catchment to the lake. Thus, the greater the proportion of inwashed secondary pollen and spores in the pollen spectra, the more distorted and less accurate the fossil pollen spectra will be at representing the contemporaneous catchment vegetation, because the inwashed pollen and spores were not derived from the contemporaneous vegetation.

Application of surface and preservation pollen analyses to the interpretation of fossil pollen spectra

Fine resolution pollen analyses of sediment cores from lakes in the Tutira and Putere districts have allowed the Hawke's Bay vegetation to be documented in some detail since the time of the Taupo eruption. Interpretations of the fossil pollen and sediment record were greatly enhanced by applying the information gained from two other palynological techniques, i.e., pollen analysis of modern catchment materials, and analyses of differential pollen and spore preservation. The data from these additional studies helped define the changing sources of pollen and spores in the lake sediments over time, separating contemporary palynomorphs from those that were inwashed. This allowed real disturbance-induced vegetation change to be recognised and separated from spurious signals of vegetation disturbance, that were generated by contamination of the pollen record with inwashed palynomorphs.

APPENDIX 1

SURFACE SAMPLE LOCATION/VEGETATION DATA FROM THE TUTIRA AND PUTERE CATCHMENTS

Tutira moss samples

Grid references from map sheet: NZMS 260 V20 ESK.

Sample: MOD.9
Grid reference: 453124
Site description: Eastern edge of "The Hanger", patch of native regenerating bush.
Local vegetation (within 20 m): Pasture. Tall *Pteridium* dominant plant on fringe of forest, with *Clematis* and *Rubus*. Taken from next to MOD.10 (soil).

Sample: MOD.3
Grid reference: 466118
Site description: Grassy bank near edge of track at south end of Lake Tutira.
Local vegetation (within 20 m): Pasture. Scattered *Rubus*, *Leptospermum scoparium*, *Pittosporum*, *Sophora*, *Salix, Pinus*, *Dacrycarpus dacrydioides*, *Clematis*, *Cordyline* and *Cupressus*.

Sample: STA
Grid reference: 466114
Site description: Edge of track above Lake Waikopiro, south end of Lake Tutira.
Local vegetation (within 20 m): Pasture. Adjacent to patch of grazed *Leptospermum scoparium* and *Kunzea ericoides* shrubland, understory dominated by pasture.

Sample: STB
Grid reference: 469111
Site description: Top of track above Lake Waikopiro, south end of Lake Tutira.
Local vegetation (within 20 m): Pasture.

Sample: STC
Grid reference: 469114
Site description: Exposed north-west facing, steep hillside, at summit marking southern end of Lake Tutira catchment.
Local vegetation (within 20 m): Pasture. Scattered *Leptospermum scoparium*, *Kunzea ericoides* and *Cordyline.*

Sample: STD
Grid reference: 469115
Site description: North-west facing gully, 20 m north of sample STC.
Local vegetation (within 20 m): Pasture.

Sample: STE, STG (Lichen)
Grid reference: 484145
Site description: Edge of regenerating forest patch, head of the Kahikanui gully, below Mt Ridgemont road carpark.
Local vegetation (within 20 m): Pasture. Dominant regenerating natives include *Carpodetus serratus*, *Melicytus ramiflorus*, *Knightia excelsa*, Podocarps and *Cyathea* spp.

Sample: STF, STH
Grid reference: 483147, 485146
Site description: 20 m from edge of regenerating forest, head of the Kahikanui gully, below Mt Ridgemont road carpark.
Local vegetation (within 20 m): Pasture. Dominant regenerating natives include *Carpodetus serratus*, *Melicytus ramiflorus*, *Knightia excelsa*, Podocarps and *Cyathea* spp.

Tutira soil samples

Sample: MOD.2
Grid reference: 452087
Site description: From side of road (state Highway 2) along west edge of Lake Tutira.
Local vegetation (within 20 m): Pasture. Hedgerow with *Pteridium*. Scattered pine.

Sample: MOD.1
Grid reference: 452087
Site description: From side of road (state Highway 2), further north than MOD.2.
Local vegetation (within 20 m): Pasture. Hedgerow with *Pteridium*. Scattered pine.

Sample: MOD.12

Grid reference: 456137

Site description: From side of road (state Highway 2), further north than MOD.1

Local vegetation (within 20 m): Pasture. Scattered *Salix, Clematis*, *Populus*, *Pinus.*

Sample: MOD.5

Grid reference: 467119

Site description: Exposed landslide scar, edge of track, south of Lake Tutira.

Local vegetation (within 20 m): Pasture.

Sample: MOD.8

Grid reference: 465117

Site description: Exposed landslide scar, edge of track, south of Lake Tutira.

Local vegetation (within 20 m): Pasture.

Sample: MOD.11

Grid reference: 453124

Site description: Paddock 20 m east of "The Hanger".

Local vegetation (within 20 m): Pasture.

Sample: MOD.10

Grid reference: 453124

Site description: Along "The Hanger" fence line.

Local vegetation (within 20 m): Pasture. Tall *Pteridium* dominant plant on fringe of forest, with *Clematis* and *Rubus* on other side of fence. Taken from next to MOD.9 (moss).

Lake Tutira surface lake sediment freezer box cores/water depths (m)

LTF3 / 38.0

LTF7 / 25.8

LTF9 / 28.5

LTF10 / 36.8

LTF11 / 12.0

LTF12 / 23.5

LTF15 / 23.7

LTF17 / 16.8

LTF18 / 21.2

LWF3 (Lake Waikopiro) / 10

Putere moss samples

Grid references from map sheet: Info map 260 W19, Topomap MOHAKA

Sample: SR2
Grid reference: 568433
Site description: From trunk of *Cordyline* tree.
Local vegetation (within 20 m): Pasture near patch of regenerating forest.

Sample: SR2A
Grid reference: 566432
Site description: Paddock on ridge
Local vegetation (within 20 m): Pasture, near patch of regenerating forest.

Sample: SR5, SR6, SR7
Grid reference: 561433, 561433, 561433
Site description: From tree trunk (chest height) of *Brachyglottis repanda* within pocket of regenerating forest.
Local vegetation (within 20 m): Dominant trees included: *Cordyline*, *Sophora*, *Pittosporum*, *Hoheria*, *Melicytus ramiflorus*, *Griselinia*, *Knightia excelsa*, *Carpodetus serratus*, *Cyathea* spp., *Leptospermum scoparium*, *Kunzea ericoides*.

Sample: SR8, SR9, SR10
Grid reference: 554434, 554434, 554434
Site description: Top of Pukakaramea Bluffs.
Local vegetation (within 20 m): Pasture. Regenerating forest and shrubland near by, with scattered *Nothofagus fusca*.

Sample: SR11
Grid reference: 589422
Site description: Exposed bank overlooking Lake Rotoroa.
Local vegetation (within 20 m): Pasture. Scattered *Leptospermum scoparium*, *Kunzea ericoides*.

Sample: SR12
Grid reference: 589421
Site description: Exposed west facing slope overlooking Lake Rotoroa.
Local vegetation (within 20 m): Pasture. Scattered *Leptospermum scoparium*, *Kunzea ericoides*.

Sample: SR17
Grid reference: 602433
Site description: Paddock near to shores of Lake Rotonuiaha.
Local vegetation (within 20 m): Pasture. Scattered *Pteridium* (young infertile fronds), *Leptospermum scoparium*, *Kunzea ericoides*.

Sample: SR20
Grid reference: 603432
Site description: Paddock near to shores of Lake Rotonuiaha.
Local vegetation (within 20 m): Pasture. Scattered *Pteridium* (young infertile fronds), *Leptospermum scoparium*, *Kunzea ericoides*.

Sample: SR21
Grid reference: 559442
Site description: Roadside cutting, bottom of Pukakaramea bluffs.
Local vegetation (within 20 m): Pasture.

Sample: SR22
Grid reference: 590438
Site description: Paddock above Te Putere School, overlooking Lake Rotoroa from north.
Local vegetation (within 20 m): Pasture.

Putere soil samples

Sample: SR4
Grid reference: 564433
Site description: Edge of shrub patch.
Local vegetation (within 20 m): *Leptospermum scoparium, Kunzea ericoides*, pasture.

Sample: SR13, SR14

Grid reference: 589416, 589417

Site description: Litter from below *Paesia scaberula* canopy.

Local vegetation (within 20 m): *Paesia scaberula.*

Sample: SR18, SR19

Grid reference: 598435, 600435

Site description: Litter from below *Pteridium esculentum* canopy.

Local vegetation (within 20 m): *Pteridium esculentum*.

APPENDIX 2

Frequency and abundance of pollen taxa in the sample groups produced by Cluster Analysis from the Tutira pollen data set (LT16: zones I and II). The main value is frequency (1 = 1-10%, 2 = 11-20% etc), while the superscript value represents the range of abundances (^{1} = trace to 10% of the sample, ^{2} = 11-20% etc). The taxa are split into three groups according to frequency criteria (see Chapter 5). Frequencies of > 80% are highlighted in bold.

LT16 SAMPLE GROUP	1	2	3-5	6A	6	7	8	9	10
NUMBER OF SUB-SAMPLES	8	2	3	5	23	4	11	3	2
1									
Pteridium esculentum	**10^{6-8}**	**10^{3-8}**	**10^{1-6}**	**10^{1-3}**	**10^{1-3}**	**10^{1-2}**	**9^{1-2}**	**10**	5
Fuscospora	**10^{1-2}**	**10^{2-3}**	**10^{1-2}**	**10^{2}**	**10^{1-3}**	**10^{2}**	**10^{2}**	**10^{1}**	**10^{2}**
Dacrydium cupressinum	**10^{1-3}**	**10^{1-2}**	**10^{2}**	**10^{2-3}**	**10^{2-4}**	**10^{2-3}**	**10^{2}**	**10^{2}**	**10^{3}**
Podocarpus totara type	**10**	**10^{1-2}**	**10^{1-2}**	**10^{1-2}**	**10**	**10**	**10^{1}**	**10^{2}**	**10^{2}**
Prumnopitys taxifolia	**10^{1-3}**	**10^{1-2}**	**10^{1-2}**	**10^{2-3}**	**10^{3-4}**	**10^{2-5}**	**10^{3}**	**10^{4}**	**10^{5}**
Cyathea type	**10^{1-2}**	**10^{1-2}**	**10^{5-9}**	**10^{2-4}**	**10^{2-4}**	**10^{2-6}**	**10^{3}**	**10^{2}**	**10^{2}**
2									
Coriaria	**10^{2}**	**10^{1-2}**	3	**10**	**8**	5	6	7	
Myriophyllum	**10^{1-2}**	**10**	3	6	5	7	1		
Typha type	**10**	**10**		2	7	5	1	3	
Aristotelia	**10**	5	3	**8**	6		4	3	
Anthoceros type	7	**10**	3	2	3	2			
Poaceae	**10**	**10**	7	**10**	7		2	**10**	
Potamogeton		**10**			1				
Phymatosorus type	4	**10**			1	2			5
Asteraceae	**9**	**10**	3	6	7	2			5
Blechnum type	7	**10**		4	7	5	4	3	
Pseudopanax	**10**	5	3	6	**9**	5	6	3	
Lycopodium fastigiatum	5	5	**10**	2	6	7	1		
Acaena	1			**8**	1			3	5
Elaeocarpus	**9**			**8**	**9**	7	7		5
Prumnopitys ferruginea	**10**	**10**	7	**10**	**9**	2	2	7	
Dicksonia squarrosa	6	5	**10**	**8**	**10**	7	**8**	7	
Hoheria	4			**8**	**8**	2	5	3	5

LT16 SAMPLE GROUP	1	2	3-5	6A	6	7	8	9	10
NUMBER OF SUB-SAMPLES	8	2	3	5	23	4	11	3	2
Callitriche			3	**10**	**8**	2	4	7	**10**
Metrosideros	4	5	**10**	**10**	**10**	7	**8**		
Rubus	4			4	**9**	5	3		
Schefflera digitata	1		3	2	7		**8**	3	
Podocarpaceae undiff.	5	5	7	**10**	**9**	7	1	**10**	
Alectryon		**10**			6	2	2	3	**10**
Pseudowintera	1		3		3	2	2		**10**
Urtica				**8**	4	2	2	3	
Streblus				**8**	6	5	6	3	5
Knightia excelsa	1	5	3	6	**9**	5	**8**	7	**10**
Myrsine	1	**10**	3	6	**10**	7	**10**	**10**	5
3									
Haloragis	5				1	2			
Taraxacum	5		3		1				
Hebe	4			4	1				
Cyperaceae	7	5		6	6		1	7	
Phormium	2		3	2	2				
Ranunculus				6	1			3	
Weinmannia	2	5			3			3	
Coprosma	**10**	**10**	7	**10**	**10**	**10**	**10**	**10**	**10**
Trilete fern spores	1	5	3	6	5	2	1	3	
Macropiper	4	5	3		7		2	3	5
Nestegis	**10**	5	7	**10**	**10^{1-2}**	**10**	**9**	**10**	**10**
Nothofagus menziesii	**10**	**10**	3	4	**9**	7	**8**	**10**	**10**
Neomyrtus			3	6	6		3	3	
Dacrycarpus dacrydioides	**9**	5	**10**	**10**	**10**	**10**	**9**	**10**	**10**
Ripogonum					3				
Libocedrus		5		4	7			7	
Phyllocladus	6	**10**	3	**10**	**10**	**10**	**10**	**10**	**10**
Muehlenbeckia	2			6	7		4	3	3
Leptospermum type	7	**10**	**10^{1-2}**	**10^{1-3}**	**10^{1-2}**	**10^{1-2}**	**10^{1}**	**10**	**10**

LT16 SAMPLE GROUP	1	2	3-5	6A	6	7	8	9	10
NUMBER OF SUB-SAMPLES	8	2	3	5	23	4	11	3	2
Monolete fern spores	7	**10**	**10**	**10**	**10**	**10**	**9**	**10**	**10**
Dodonaea viscosa				2	6		2	3	5
Tupeia antarctica			3		3				
Carpodetus serratus	2		7		2		2		5
Griselinia	1			4	7	5	7	3	
Dicksonia fibrosa	1		3	4	4	7	4	7	

APPENDIX 3

Frequency and abundance of pollen taxa in the sample groups produced by Cluster Analysis from the Rotonuiaha pollen data set (RNUI3: zones I and II). The main value is frequency (1 = 1-10%, 2 = 11-20% etc), while the superscript value represents the range of abundances (^{1} = trace to 10% of the sample, ^{2} = 11-20% etc). The taxa are split into three groups according to frequency criteria (see Chapter 5). Frequencies of > 80% are highlighted in bold.

RNUI3 SAMPLE GROUP	1	2	3	4-5	6	7	8	9
NUMBER OF SUB-SAMPLES	5	6	9	2	11	2	17	7
1								
Pteridium esculentum	**10^{7-8}**	**10^{4-7}**	**10^{2-4}**	**10**	**10**	**10**	**9**	4
Coriaria	**10^{1-2}**	**10^{2}**	**10^{2-4}**	5	**8**	5	7	6
Fuscospora	**10^{2-3}**	**10^{2-3}**	**10^{1-2}**	**10^{1-2}**	**10^{2-3}**	**10^{2-4}**	**10^{2-4}**	**10^{2-3}**
Cyathea dealbata type	**10^{1-3}**	**10^{1-2}**	**10^{2-3}**	**10^{7}**	**10^{2}**	**10^{2}**	**10^{2}**	**10^{2}**
Cyathea smithii	6^{1-2}	**10**	**10^{2}**	**10^{2-4}**	**10^{1-2}**	**10^{1-2}**	**10^{1-2}**	**10^{1-2}**
Dacrydium cupressinum	**10^{1-2}**	**10^{1-2}**	**10^{3}**	**10^{2-3}**	**10^{3-4}**	**10^{3-5}**	**10^{3-4}**	**10^{3-5}**
Prumnopitys taxifolia	**10^{1-2}**	**10^{1-2}**	**10^{2-3}**	**10^{1-2}**	**10^{3-4}**	**10^{3}**	**10^{3-4}**	**10^{3-4}**
Leptospermum type	**10**	**10**	**10^{2}**	**10**	**10^{2}**	**10^{1-2}**	**10^{1-2}**	**10^{1-3}**
Podocarpus totara type	**8**	**10**	**10^{1-2}**	**10**	**10^{1-2}**	**10^{2}**	**10^{2}**	**10^{2-3}**
2								
Anthoceros type	**10**	2						
Aristotelia	**10**	**10**	**8**		7	5	6	
Poaceae	**10**	7	**10**		4		6	**9**
Asteraceae	**8**	**10**	7	5	1	5	2	6
Typha type	**10**	7	3		2	**10**	4	3
Phymatosorus type	**8**	3	6	5	5		2	4
Schefflera digitata	4	**8**	7		3	**10**	7	1
Macropiper excelsum	4	2	2		1	**10**	1	4
Trilete fern spores	2		3	**10**	2		2	3
Tupeia antarctica	4	2	**8**	5	6	5	**8**	3
Muehlenbeckia	2	3	4	5	4		**8**	1
Dodonaea viscosa	2	3	4		5		**8**	4
Rubus	2	3	**10**	5	6	**10**	**9**	**10**

RNUI3 SAMPLE GROUP	1	2	3	4-5	6	7	8	9
NUMBER OF SUB-SAMPLES	5	6	9	2	11	2	17	7
Alectryon excelsus	2	3	9		4	10	6	9
Knightia excelsa	2	3	10	10	9	10	10	10
Nestegis	2	7	10^{1-2}	10	10^{1-2}	10	10^{1-2}	9^{1-2}
Freycinetia			9	5	4		8	7
Leucopogon fasciculatus	4				6		8	9
Neomyrtus		3	6	10	5	10	7	6
Griselinia		3	7	10	3	10	9	10
Metrosideros umbellata type		2	9	5	9	10	8^{1-2}	9
Hoheria		2	9		8	10	9	7
Streblus			7		1	5	9	10
Libocedrus			4		8		8	7
Pseudowintera					3	10	2	6
Quintinia			1		3	5	4	10
3								
Weinmannia	6	3	1		1		1	1
Fuchsia	2	5	2					
Scrophulariaceae	4	5	2				1	
Myriophyllum	6	5	3				2	
Coprosma	10	10^{1-2}	10	10	10	10	10	10
Ripogonum		7		5	2			3
Dracophyllum			4					1
Blechnum type			4		1	5		
Lycopodium fastigiatum	8	8	4	5	8	10	5	6
Pseudopanax	8	10	9	5	9	5	7	9
Lycopodium scariosum	2	2	1		2		1	1
Monolete fern spores	10	10	8	10	9	10	9	10
Cyperaceae	10	10	9	5	10	10	10	10
Phormium			4		1		1	
Prumnopitys ferruginea	8	8	4	5	9	10	7	3
Hedycarya		3			1		1	1
Dacrycarpus dacrydioides	10	10	10	10	10	10	10	10

RNUI3 SAMPLE GROUP	1	2	3	4-5	6	7	8	9
NUMBER OF SUB-SAMPLES	5	6	9	2	11	2	17	7
Nothofagus menziesii	**10**	**10**	**8**	**10**	**10**	**10**	**10**	**10**
Halocarpus bidwillii	2	3	1	5	5		1	6
Passiflora		2	1		1		4	1
Dicksonia squarrosa	6	5	**8**	**10**	**8**	5	7	**10**
Carpodetus serratus	2		4		2		2	3
Cordyline			2				2	
Lobeliaceae			6		3		3	
Lycopodium varium	2				2		1	1
Elaeocarpus	6	5	**9**	**10**	**9**	5	**10**	**10**
Callitriche		3	4		3		7	3
Phyllocladus	**10**	**10**	**10**	5	**10**	**10**	**10**	**10**
Myrsine	**8**	**8**	**10**	**10**	**9**	**10**	**10**	**10**
Dicksonia fibrosa			4		2	5	2	6
Urtica			7		3	5	5	6
Ascarina			2		1	5	2	
Ileostylus		2	3	5	5	5	5	7
Agathis			1		2		4	3
Plagianthus			1		1		2	3
Podocarpaceae undiff	2			5			6	

APPENDIX 4

DEPTH (CM) OF EROSION PULSES IN SEDIMENT CORES LT16, RNUI3 AND LW8.

LT16		RNUI3		LW8	
Upper	Lower	Upper	Lower	Upper	Lower
11	16	0	5	162	205
21	24	42	43	206	214
35	37	61	64	244	248
53	77	65	81	248	250
78	85	93	94	250	366
85	93	95	124	374	379
93	117	170	175	379	382
117	138	191	194	383	401
148	164	199	201	404	427
169	171	214	216	428	429
177	179	239	241	430	431
240	245	274	275	434	438
265	277	291	300	442	444
278	304	305	306	446	455
305	309	340	342	465	468
315	317	350	352	468	469
353	355	371	372	469	472
362	366	386	388	478	480
389	391	441	442	489	491
406	408	458	460	506	508
445	447	538	539	514	515
478	490	542	545	521	522
495	497			535	536
578	582			548	552
583	584			552	559
				559	562
				567	569
				579	580

APPENDIX 5

ANALYSIS OF LAKE TUTIRA SEDIMENT GEOCHEMISTRY USING X-RAY FLUORESCENCE SPECTROMETRY: AN EXPLORATORY STUDY

INTRODUCTION

The biological and chemical characteristics of lakes are closely related to the biogeochemistry of their catchments. Mackereth (1966) showed that this relationship is also reflected in the chemical composition of the lake sediments. The characteristics of deposited sediments are strongly influenced by the input of materials, and changes to these inputs, from the catchment into the lake. By analysing the constituent parts of lake sediments, details concerning the former drainage basin history can be reconstructed. Previous chemical analyses of lake sediment cores have shown that the relative intensity of soil erosion is generally reflected in the concentration of elements primarily associated with clastic minerals such as Na, K, and Mg (e.g. Mackereth, 1966; Engstrom & Wright, 1984; Heathwaite, 1994). These elements are used to reveal the transport of mostly unaltered and unweathered catchment soils into the lake, as there is no definite evidence for post-depositional, within-lake changes of clay minerals in lake sediments (Jones & Bowser, 1978).

This study explores whether X-ray fluorescence (XRF) spectrometry of the Lake Tutira sediments in core LT16 can provide such information about past erosion in the Tutira catchment. The analyses are used to establish whether any shifts in sediment composition coincide with major pollen-based vegetation changes in the catchment over the last 2000 years (see Chapter 5). In addition, average values of elements in the core are compared with a baseline geochemistry study of other New Zealand lake and nearshore sediments (Stoffers *et al.* 1983).

METHODS

See Chapter 3 for methods of analysis.

RESULTS

Chemical components are presented as a percentage of the sediments dry weight (Figure 1). SiO_2 is the dominant component (x=66.87 ± 3.06% dry weight), followed by Al_2O_3 (x=17.28 ± 1.77%) and Fe_2O_3 (x=6.65 ± 1.11%). Significant shifts in geochemical sediment composition that coincide with the pollen zones (see Chapter 5), include an increase of P_2O_5 in zones I and II ($P<0.0008$), and a decrease in loss-on-ignition values in zone I ($P=0.0093$). Compared with soils, lake sediments contain higher average percentages (dry weight) of TiO_2, Al_2O_3, Fe_2O_3, MgO and K_2O, and lower average percentages of SiO_2, CaO and Na_2O (Table 1). The Tutira sediments are of a similar average chemical composition to North Island lake sediments and nearshore sediments (Table 1) which were measured by XRF spectrometry in a baseline study by Stoffers *et al.* (1983). The matrix of correlation coefficients (Pearsons) for the XRF data from LT16 (Table 2) shows a high degree of correlation between SiO_2 and TiO_2, Al_2O_3, Fe_2O_3, MgO and K_2O; and between TiO_2 and Al_2O_3, Fe_2O_3 and MgO; and between K_2O and Al_2O_3.

Table 1. Comparisons of average chemical composition (% dry weight, with standard deviations) for Lake Tutira sediments and catchment soils, and other North Island lake, harbour and estuarine sediments (*from Stoffers *et al.* 1983:478).

Component % dry weight	Lake Tutira sediments n=59	Tutira catchment soils n=10	*North Island lakes n=12	*North Island harbours and estuaries n=24
SiO_2	66.87 ± 3.06	73.32 ± 1.17	68.21 ± 6.30	58.03 ± 10.77
TiO_2	0.75 ± 0.12	0.51 ± 0.10	0.38 ± 0.16	0.61 ± 0.28
Al_2O_3	17.28 ± 1.77	13.73 ± 0.50	12.32 ± 4.13	13.28 ± 2.58
Fe_2O_3	6.65 ± 1.11	4.06 ± 0.93	4.13 ± 0.99	4.99 ± 2.92
MnO	0.10 ± 0.02	0.11 ± 0.03	0.12 ± 0.05	0.06 ± 0.04
MgO	1.75 ± 0.34	1.04 ± 0.16	1.04 ± 0.30	1.84 ± 0.48
CaO	1.51 ± 0.19	2.03 ± 0.74	1.50 ± 0.49	5.49 ± 7.25
Na_2O	2.20 ± 0.43	3.02 ± 0.29	1.24 ± 0.77	2.71 ± 0.78
K_2O	2.63 ± 0.27	2.0 ± 0.13	1.96 ± 0.76	2.01 ± 0.54
P_2O_5	0.24 ± 0.11	0.21 ± 0.17	0.21 ± 0.09	0.17 ± 0.04

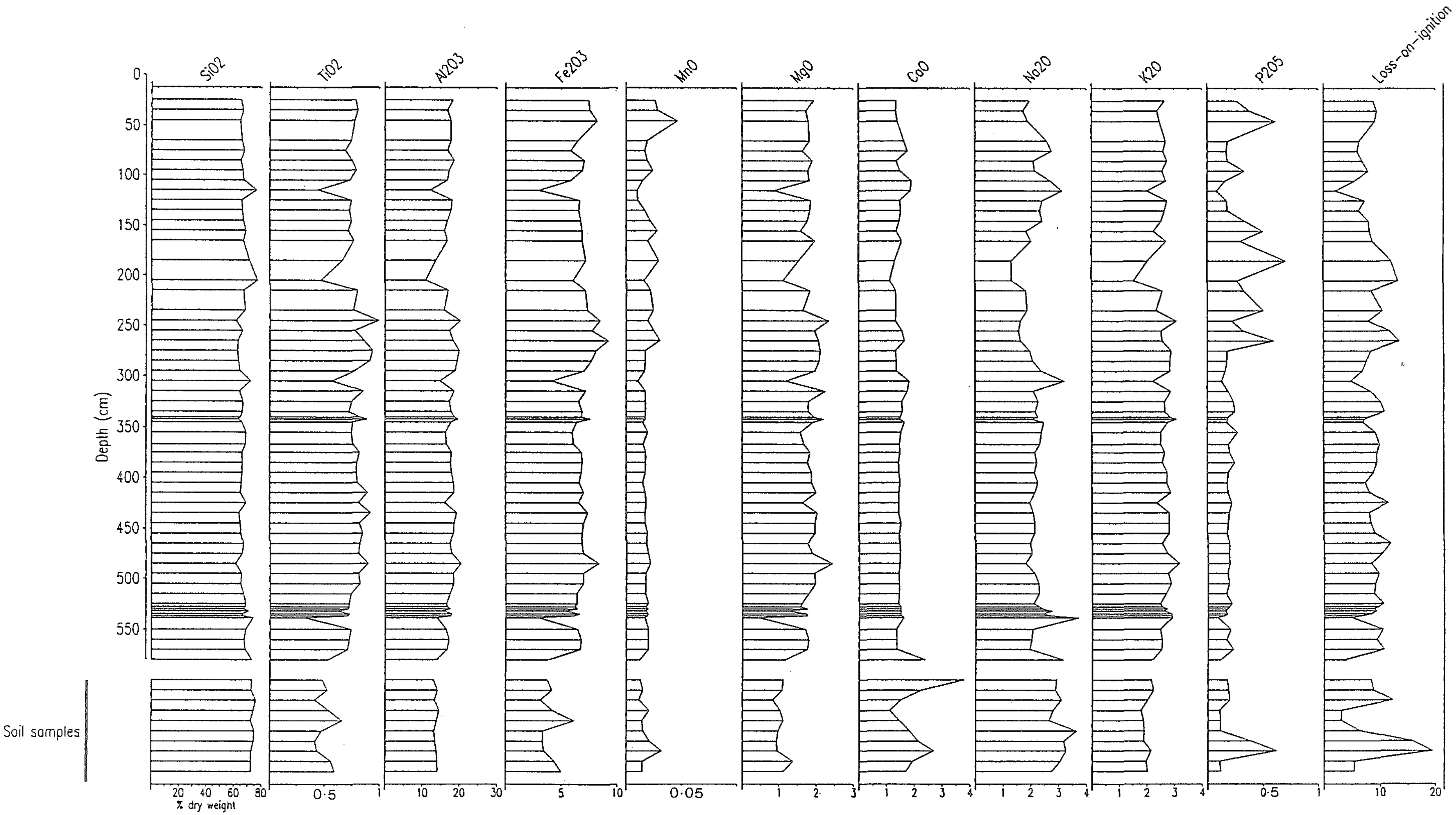


Figure 1. LT16 XRF data: trace elements % dry weight sediment

Table 2. Matrix of correlation coefficients (Pearsons) from XRF data for ten major chemical components in core LT16.

	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O
TiO_2	-0.8710								
Al_2O_3	-0.9821	0.8140							
Fe_2O_3	-0.8020	0.8630	0.7032						
MnO	-0.1833	0.1532	0.0818	0.3471					
MgO	-0.8592	0.8528	0.8268	0.7483	-0.0014				
CaO	0.2185	-0.3265	-0.2059	-0.5252	0.0429	-0.1697			
Na_2O	0.3649	-0.6075	-0.2498	-0.8205	-0.1986	-0.4773	0.6489		
K_2O	-0.8061	0.5392	0.8641	0.3754	-0.0593	0.6180	-0.0346	0.0846	
P_2O_5	-0.0393	0.2107	-0.1184	0.4970	0.5701	-0.0153	-0.3246	-0.6062	-0.3585

DISCUSSION

The absence of a trend between the percentage of major chemical components and depth in the core, suggest progressive burial and diagenesis (post-depositional changes) have had little effect on the bulk lake sediment composition of LT16, that is measurable by XRF spectrometry. In addition, there are few measurable trends in the bulk chemical composition of the sediments that coincide with major pollen based vegetation changes in the catchment in the past 2000 years (Chapter 5).

The general chemical composition of the Lake Tutira sediments is similar to that of other North Island lakes, harbour and estuarine sediments (see Table 1) with some variation, probably caused by differences in catchment lithologies. Silica is the most abundant component in the Lake Tutira sediments, reflecting the importance of both biogenic (from siliceous diatom frustules) and volcanogenic contributions of silica to the sediments. However, it is only possible to establish the relative importance of the different forms by sediment fractionation.

Silica and aluminium are typically the most abundant inorganic components in lacustrine sediments, and are mostly contributed by clastic silicate minerals (Engstrom & Wright, 1984). The matrix of correlation coefficients (Table 2) shows the high degree of correlation between silica and aluminium, iron, magnesium, titanium and potassium, which may reflect the presence of aluminosilicates in the sediment. The primary source of these would be clay minerals transported from the catchment, which are rich in volcanic minerals such as the smectite group.

Chemical components as potential erosion indicators

Aluminium and titanium are usually primarily allogenically derived in lake sediments, therefore, increases of these elements have been used in palaeoecological studies as indicators of erosion intensity and soil leaching (Engstrom & Wright, 1984; Heathwaite, 1994). The average percentages of these oxides determined in LT16 are higher than those recorded in the catchment soil samples and other North Island sediments (Table 1). In addition, percentages of aluminium and titanium oxides do not increase in all the sub-samples collected from erosion pulses in the core, indicating that a significant proportion of these components may be authigenically deposited. It would only be possible to determine this more certainly by isolating the sediment fractions to their biogenic, authigenic and allogenic origins (e.g. Heathwaite, 1994). High levels of aluminium and titanium oxides have also been recorded in South Island lake sediments (Stoffers *et al.* 1983) and in sediments from dystrophic, humic-rich lakes in Finland, resulting from the chelation of these metals in acid soils by humic substances which then become sedimented as organic colloids (Koljonen & Carlson, 1975). Although Lake Tutira is not currently a dystrophic lake, it may have been in the past, and this could explain the high levels of these two chemical components in the core.

Mackereth (1966) first considered that the alkali and alkaline-earth elements (which are closely related to detrital minerals) present in lake sediments, could be used to reflect erosion intensity and soil weathering in the catchment. In principle, during periods of active erosion, unleached soils are transported to the lake basin and increase the amount of K, Na and Mg in the sediments. In contrast, during periods of soil stability in the catchment, the soils are deeply weathered which reduces the base content of the mineral material before it is eroded and transported to the lake.

Therefore, the percentages of Na_2O, K_2O and MgO together with SiO_2, Al_2O_3 and TiO_2 in LT16 could be expected to increase at the same depth that erosion pulses occur in the core (documented in Appendix 4). This does not occur; the XRF data from LT16 show no consistent increases or decreases of any chemical component when erosion pulses occur in the sediment record. Bulk chemical analysis of the lake sediments by XRF spectrometry has not provided enough information to predict past erosion in the Lake Tutira catchment.

In addition, the systematic sub-sampling of the core takes no account of the frequent changes in physical sediment type. Samples vary from predominantly coarse inwashed material to more organic authigenic sediments in the core, and this alone may cause the minor fluctuations revealed in the XRF chemistry results (Figure 1). In retrospect, more information may have been gained by subjecting each sub-sample to grain size analysis, and then separately analysing each grain size fraction for their chemical content, allowing comparisons between similar sediment types. In addition, the analysis would be improved by a subjective sampling strategy, by specifically collecting from both the erosion pulse sediments and authigenic sediments. The systematic sampling strategy used in this study has generated results that are more useful as a measure of the general chemical composition of the sediments, rather than an indicator of past soil erosion and weathering in the catchment.

Figure 1 illustrates six distinct peaks of SiO_2 at the following depths (cm): 539, 355, 305, 115, 425 and 205 cms and these are considered here. The first peak occurs in thin bands of inwashed material immediately above the Taupo Tephra and the following three coincide with thick erosion pulses in the core. With each of these increases of SiO_2 there are decreases in the percentages of TiO_2, Al_2O_3, Fe_2O_3, K_2O and MgO. These oxides are strongly negatively correlated with SiO_2 in the core (Table 2), due largely to the constant sum effect (i.e. sum of all major components equals 100%) and SiO_2 is by far the most abundant component in the sediments. In the samples from erosion pulses, Na_2O and CaO also increase, with a decrease in the loss-on-ignition values. Averages of SiO_2 are higher in catchment soils than in the lake sediments (Table 1) and the averages of TiO_2, Al_2O_3, Fe_2O_3, MgO and K_2O are lower in the soils than in the lake sediments. As the composition of the sediments at the depths of these events closely resemble the catchment soils, it may be assumed these signals indicate the inwash of catchment soils. The two samples with silica peaks that do not coincide with erosion pulse sediments in the core (425 and 205 cm) show corresponding decreases in Na_2O and CaO and an increase in loss-on-ignition values. These samples may reflect increases of biogenic silica, rather than allogenic forms, although this is difficult to prove without analysing the different fractions of silica in the sediment.

Other chemical components

The P_2O_5 content of lake sediments is often used as a measure of past lake productivity because of the close association between primary productivity and phosphorus (Engstrom & Wright, 1984). Mean P_2O_5 levels are significantly higher in zones II, III and IV of the core than they are in zone I below ($P=0.0008$), but are similar to those values in the catchment soil samples (Table 1). This may reflect increasing lake productivity since deforestation and human settlement of the area, particularly during the European period as a result of superphosphate fertilizer application in the Tutira catchment since the 1950s. However, because phosphorus (like iron and manganese) occurs in both the allogenic and authigenic fractions of lake sediments, and the limnological factors that control the extent to which it becomes incorporated into the sediments can change over time, the interpretation of the bulk XRF P_2O_5 results remains limited. The average MnO content in LT16 is relatively low (Table 1), but typical of New Zealand lake sediments and may indicate the post-depositional remobilization of manganese out of the sediment column under reducing conditions (Stoffers *et al.* 1983). On average Na_2O constitutes 2.2 ± 0.43% dry weight of LT16 sediments, which is greater than the average values measured in other North Island lake sediments (Table 1). The average Na_2O measurements in the Tutira sediments more closely resemble measurements made from North Island harbour and estuarine sediments which suggests the Tutira sediments may derive a significant proportion of sodium from seawater sources, which is feasible given that the lake lies only 10 km west of the Pacific Ocean.

CONCLUSION

The XRF technique was used to assess the sediment composition of Lake Tutira and to show past changes in soil erosion and catchment stability. Although XRF spectrometry has provided an accurate assessment of the general chemical composition of the sediments in LT16, the bulk analyses do not provide the information necessary to make inferences about changing sources of mineral elements in the sediments. This is because different environmental information is contained within the biogenic, authigenic and allogenic fractions of the sediment (Mackereth, 1966; Engstrom *et al.* 1991). Reconstructions of catchment erosion and soil weathering can only be achieved through the fractionation and separate analyses of these different components. However, the disadvantages of sediment fractionation is that it is a time consuming technique, and currently there is no reliable and accepted convention for lake sediment partitioning (Engstrom & Wright, 1984). In the Tutira lake basin which has a steep catchment and many inflowing streams, a cheaper and faster method of documenting past catchment erosion has been obtained by recording the frequency and depth of erosion pulses in the sediment core. The record of erosion pulses (see Chapter 5) has contributed more information about past erosion-producing events in the catchments than the results from the XRF bulk sediment analyses. The XRF results have given no clues to the presence of the numerous erosion pulses in the sediment core, or to the variable physical properties of the sediment.

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