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(1)

SOME ASPECTS OF QUATERNARY HISTORY OF
TONGARIRO VOLCANIC CENTRE

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Frontispiece

Ngauruhoe in eruption 26th January, 1974. Large, turbulent, ash-laden eruption column about 2,000 m high. Collapse of the lower, denser part of the column has produced block and ash avalanches down the flanks of the cone. N.Z. Geological Survey photo by D. L. Homer.

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- Fig 1: Location of sample sites

ABSTRACT

The Tongariro Volcanic Centre*, at the southern end of the Taupo Volcanic Zone, North Island, New Zealand, consists of five large andesite volcanoes - Ruapehu, Tongariro, Ngauruhoe, Pihanga and Kakaramea-Tihia - with several associated minor volcanoes and vents all of Quaternary age. In the northern part of the Centre the north-westerly trending Kakaramea-Tihia Massif and Pihanga form a chain of volcanoes which last erupted more than 20,000 years BP, but from which large mudflows have recurred up to as recently as 1910 A.D. By contrast the other two multiple vent volcanoes - Ruapehu and the Tongariro Massif - include several vents (four and possibly five) that have been active during the last 100 years and, in particular, Ngauruhoe and Ruapehu Crater Lake.

In the first part of the thesis the tephrostratigraphy of the Tongariro area is described. Thirteen rhyolitic tephtras erupted from Okataina, Maroa and Taupo Volcanic Centres over the last 20,000 years are interbedded with local andesitic tephtras. The order of succession of the 13 tephtras is established by stratigraphy, and is confirmed by their mineralogical composition and by chemical analysis of their titanomagnetites. Seven of the rhyolitic tephtras have been previously dated by ^{14}C , four more (Rotorua Ash, Karapiti Lapilli, Papanetu Tephra and Peronui Tephra) are dated here, and two others are not yet dated. Six further rhyolitic tephtras are of less use as marker beds. Four of these are tentatively correlated with rhyolite tephtras from the more northerly volcanic centres and all but one are older than 20,000 years BP.

These rhyolitic tephra marker beds have provided valuable time control which, together with 12 further radiocarbon dated events has

* Refer to Fig 1 , page 9 for locality map.

allowed a chronology of the andesitic tephrae erupted from vents within the Tongariro Volcanic Centre. Two previously named tephrae, Ngauruhoe Tephra and Mangatawai Tephra, are given formation status, and a further four formations (Papakai Tephra, Mangamate Tephra, Okupata Tephra and Rotoaira Lapilli) are defined. Ngauruhoe Tephra (0-1819 years BP), Mangatawai Tephra (c. 1819-2,500 years BP), and Papakai Tephra (c. 3,400-9,700 years BP) have all accumulated as a result of intermittent activity from several vents.

Mangamate Tephra, with six named members, was erupted mainly from the Tama Lakes-Ngauruhoe area between c. 9,700-9,780 years BP. Four of the members were deposited eastwards from the Tongariro Massif. The oldest member, Te Rato Lapilli, was erupted c. 9,780 years BP probably from North Crater. It was distributed in a single lobe to the NNE and is the best andesitic tephra marker bed in rhyolite tephra sequences further north. The youngest member, Poutu Lapilli, was erupted as three lobes (NW, NE, SE) from a source probably at Blue Lake about 9,700 years BP. Poutu Lapilli has a volume of 0.9 km^3 and the tephra of the total formation is likely to have destroyed more than $1,000 \text{ km}^2$ of the pre-Mangamate forest.

Ruapehu was very active between c. 10-14,000 years BP. Most of the lapilli and ash beds were deposited east of the volcano and most of the remainder were deposited to the north. The youngest of the units erupted northwards, Okupata Tephra, underlies Te Rato Lapilli and probably has an age between 10-12,000 years BP.

Rotoaira Lapilli is prominent north-east of the Tongariro Massif. It was probably erupted from lower Te Mari Crater c. 13,800 years BP and has been used to define the base of the Tongariro Sub-group. This sub-group is of Aranuiian (post-glacial) age and includes all tephrae accordant with the present day topography and which have been erupted from the Tongariro Volcanic Centre.

Much of the tephra record between 20,000 and 14,000 years BP was lost through contemporaneous erosion and andesitic tephra have been reworked in with Oruanui tephra to form loess beds of late Otiran age. A cool-climate origin for these loesses is consistent with the pollen record of the Tongariro area which shows that between 20,000 and 14,000 years BP there was a change from Nothofagus forest, grassland and shrubland to podocarp-broadleaf forest. This implies a change to a warmer climate during that period. The major erosional unconformities in the Tongariro area are also of this age.

An unconformity at the top of the Mangamate Formation (9,700-9,780 years BP) resulted from erosion during the time taken for vegetation to recolonise the surface of the thick tephra sequence following total devastation of the forest. Periods of widespread erosion followed deposition of the thick Oruanui Breccia and Taupo Pumice tephra flow units. Widespread present day erosion is probably due primarily to extensive pre-European and early European fires.

Late Otiran glacial moraines recognised in five valleys about the Tongariro Massif are older than 14,700 years BP and moraine on eastern Ruapehu is probably older than 20,000 years BP.

The amount of soil development undergone by andesitic tephra is related to the net rate of tephra accumulation. Mangatawai Tephra shows least soil development and had the fastest accumulation rate; Papakai Tephra shows most soil development and had the slowest accumulation rate. The degree of paleosol development also varies according to the distribution of the tephra from the source vents and their related particle sizes: soils around Tongariro were least well developed ESE of the massif where the rate of tephra accumulation was highest, and were best developed in the west to south quadrant where the rate of tephra accumulation was lowest.

Eruptions of Mangamate Tephra were violent and the tephra were generally very well sorted. These eruptions were from magma of a "new" chemical composition and their deposition was associated with the first tephra erupted for about 10,000 years from the Taupo Volcanic Centre. It is likely that the upward movement of this andesite of "new" composition and its initial eruption about 10,000 years ago provided the trigger for eruption of the oldest Taupo Sub-group tephra. Timing of subsequent eruptions of rhyolitic tephra of a "new" magma composition was probably controlled by increase of vapour pressure over confining pressure with subsequent healing of fractures and a new build up of pressure. The concurrent intermittent andesitic volcanism probably had no significant effect on the timing of the youngest rhyolitic eruptions.

Ngauruhoe, a composite cone about 900 m high at the southern end of the Tongariro Massif is considered to have first erupted about 2,500 years ago and to have completed most of its growth during deposition of Mangatawai Tephra. Red Crater which lies within a small scoria cone on the central part of the Tongariro Massif is mainly younger than 3,400 years BP although the oldest flow can only be dated as younger than 9,700 years BP. The six lavas extruded before 1819 years BP are olivine andesites; the five lavas extruded since 1819 years BP are basalts. The Te Mari Craters on northern Tongariro have been active from at least 13,800 years ago to 1896 A.D. Lava was extruded following the eruption of Rotoaira Lapilli (13,800 years BP) and a large flank extrusion occurred between 9,700 and 6,000 years BP. Lava flows from the upper Te Mari Crater were probably extruded in the early 16th century.

North Crater, near the north-western end of the Tongariro Massif probably dates from about 70,000 years ago (Stipp 1968) and most of the cone is older than 10,000 years. A nuée ardente was erupted about 10,000

years BP and Te Rato Lapilli was erupted about 9,780 years BP. The upper part of the cone probably dates from 4,800 years BP and all major eruptions had ceased by 1819 years BP. Blue Lake was the site of the Poutu Lapilli eruption c. 9,700 years BP and has probably been active more recently. The Upper and Lower Tama Lakes now occupy the sites of many of the Mangamate Tephra eruptions of 9,700-9,780 years BP. Some eruptions of Papakai Tephra were probably also from this area.

Pukeenake Scoria Cone, west of the Tongariro Massif, and the two plugs to its north define a fissure from which extensive olivine andesites were extruded more than 20,000 years ago. Pukekaikiore dome west of Ngauruhoe is possibly an old cumuledome of labradorite andesite flows. Small olivine andesite flows and associated tephra were erupted from a vent near the summit of the dome about 14,700 years BP.

While most of the lahars from the Tongariro Massif are older than 20,000 years BP at least five occurred on northern Tongariro during deposition of Papakai Tephra, and tree-ring dating provides an estimated age of 1895 A.D. for a historic mudflow from Ketetahi Springs, also on northern Tongariro.

Eruptions from the Kakaramea-Tihia Massif are all older than 20,000 years BP and the youngest may be represented by a *mucée ardente* deposit from a vent WSW of Tihia. This deposit came to rest above its Curie point and was radiocarbon dated at >40,300 years BP. Eruptions from Rotopounamu Graben and Pihanga are also older than 20,000 years BP. Lahars from these centres may date back to 0.6 m.y. but there have been several Aranuiian lahars and the most recent were in 1846 and 1910 A.D.

Ruapehu erupted numerous tephra beds from 10-14,000 years BP, probably from a northern crater. An extensive aa flow from the north-western summit area has an age between 5-10,000 years BP, similar to the age of lava flows from a parasitic vent lower on the northern side.

Murimotu Lahars on the lower north-western slopes of Ruapehu span the final 3,000 years of the tephra deposition. One of the largest lahars, that formed conical mounds, came to rest above its Curie point and is likely to have been initiated by displacement of a crater lake by lava or a growing lava dome. It is probable that this 'hot' lahar, aged between 9,540 and 12,450 years BP, occurred during the Gothenburg reverse polarity event. The vent presently occupied by the Crater Lake was initiated probably about 2,500 years BP and most lahars since that time have been confined to the Whangaehu River. Since 1859 eruptions through Crater Lake have caused two large lahars in Whangaehu River and there have been four cold lahars. The most recent of the cold lahars, on 24 December, 1953 destroyed the railway bridge at Tangiwai about five minutes before an express reached the bridge and 151 lives were lost.

Lavas of Hauhungatahi cone, 12 km north-west of Ruapehu, are older than 20,000 years BP. The explosion craters at Ohakune, about 19 km south-west of the summit of Ruapehu, are also older than 20,000 years BP.

Tephrochronology provides minimum ages for several rhyolite and dacite domes within or near the northern end of the Tongariro Volcanic Centre: Papanetu Tephra was erupted from the site of Kuharua Dome c. 9,785 years BP towards the end of dome formation; Puketarata Ash was erupted from the site of Puketarata Dome in the Maroa Volcanic Centre towards the end of dome formation approximately 13,500 years BP; Manganamu Dome is younger than 1819 years BP and Koroi Dome is likely to be close to 1819 years BP; Pukeyaikio Dome is older than 9,790 years BP; Horohoro Dome is older than 14,000 years BP; and Motuepuhi Island, Lake Rotoaira, is older than 20,000 years BP.

Ages for several fault movements near the Tongariro Massif are given. At least one fault movement was associated with eruption of

the Mangamate Formation. Fault movements at both ends of Lake Rotoaira occurred after eruption of Taupo Pumice and it is suggested that they were in response to eruption of some of the Taupo Pumice from within that lake.

The reverse polarity of andesite lava in Tongariro River suggests its extrusion during the Matuyama reverse polarity epoch. The age of >0.69 m.y. is the oldest age for lava within Tongariro Volcanic Centre.

INTRODUCTION

Volcanic History of the Taupo Volcanic Zone

The Taupo Volcanic Zone (Healy 1962), an area of Quaternary tectonism and calc-alkaline volcanism, extends north-eastwards from the andesite volcanoes of the Tongariro area for 250 km to White Island in the Bay of Plenty (Fig 1). It is often referred to as the Taupo-White Island Depression and it is both a structural and topographic low. The graben structure and volcanic history of the Taupo Volcanic Zone have been described in some detail by Healy (1962, 1964), Healy et al (1964), Grindley (1960), Thompson (1964), Gregg (1960, 1961), and Modriniak and Studt (1959).

Andesitic lavas, estimated at 820 km^3 by Ewart and Stipp (1968), occur mainly at the extreme ends of the Taupo Volcanic Zone (Clark 1960) although those at the north-eastern end - White Island, Whale Island, Edgecumbe and Manawahe - are transitional to dacites (Duncan 1970). At the south-western end five large volcanoes - Ruapehu, Ngauruhoe, Tongariro, Pihanga and Kakaramea-Tihia - comprise the Tongariro Volcanic Centre (Grindley 1960).

The central part of the Taupo Volcanic Zone, up to 40 km wide, includes the three large rhyolitic volcanic centres of Taupo, Maroa and Okataina (Healy 1962, 1963). From these three centres and the more westerly Rotorua Caldera an estimated $16,400 \text{ km}^3$ (Healy 1962) of lavas, welded ignimbrites and unwelded pumice breccias have been spread over an area of at least $45,000 \text{ km}^2$ (Healy 1971).

The sequence of eruptive vents for Taupo and Okataina Volcanic Centres was considered by Healy (1963) to have been (1) eruption of ignimbrites, accompanied or succeeded by the formation of calderas; (2) extrusion of

Fig 1: General map of the Taupo Volcanic Zone (after Cole 1973) showing locations of the Tongariro, Taupo, Maroa and Okataina Volcanic Centres. Detail of the Tongariro Volcanic Centre is shown in Fig. 2.

Fig 2: Location of volcanoes, domes and vents within Tongariro Volcanic Centre. Andesite outcrop boundaries are mainly after Grindley (1960) and Hay (1967).

viscous rhyolite domes and flows, typically around the margin of the centre or caldera; (3) further subsidence, accompanying the eruption of extensive pumice breccias of nuée ardente origin; (4) extrusion of rhyolite domes and flows, often within the central portions of the volcanic centres; (5) violent tephra-fall eruptions, depositing tephra cover beds over at least 45,000 km² (Healy 1971).

Ignimbrites, covering an area of about 25,600 km² (Marshall 1935), form broad plateaus on either side of the Taupo Volcanic Zone and it is possible that ignimbrite once formed a continuous surface across the zone (Thompson 1964).

Several dacitic domes, of Late Pleistocene or Recent age (Thompson 1964), are distributed along the eastern side of the Taupo Volcanic Zone from Lake Rotoaira to the southern end of the Okataina Volcanic Centre.

High-alumina basalts, with the exception of the scoriaceous tephra eruption from Tarawera in 1886 and the Matahi Basaltic Tephra of > 44,000 years BP (Pullar and Nairn 1972), occur as isolated flows and scoria cones with a total estimated volume of 41 km³ (Ewart and Stipp 1968). Cole (1972) has shown that the basaltic vents are located where the NNE trending regional faults cross caldera structures.

On both sides of the Taupo Volcanic Zone the ignimbrite plateaus abut and in places overlie ranges of greywacke and argillite of upper Paleozoic to Mesozoic age. To the west and north-west of Tongariro Volcanic Centre the Hauhungaroa Range is composed mainly of volcanic-derived greywacke (Reed 1965). To the north-east of Tongariro Volcanic Centre ignimbrites of the Kaingaroa plateau occupy an arcuate, partial "cone of depression" (Healy 1962) abutting against and probably overlying a miogeosynclinal "axial" facies of quartzofelspathic greywacke (Reed 1965).

In the central Taupo Volcanic Zone the basement, probably of greywacke according to Modriniak and Studd (1959), has subsided to more than 3,600 m below sea level to form a linear trench, the Taupo-White Island Depression.

The graben-like nature of this trench is accentuated by many recent faults - Grindley's (1960) "Taupo Fault Belt" - which strikes NNE to NE. At the southern end of the Taupo Volcanic Zone the Tongariro National Park volcanic vents are mainly aligned NNE and may overlie a deep-seated fracture (Gregg 1960). The occurrence of ignimbrite at different altitudes in the Kaimanawa Range outside the graben suggests some partial warping accompanied block faulting.

Tongariro Volcanic Centre occupies the southern 65 km of the Taupo Volcanic Zone and comprises three main volcanic complexes. In the north the large cones of Pihanga (1,304 m), Kakaramaea (1,280 m) and Tihia (1,147 m) and smaller cones - Puketopo (c. 930 m) and Pukemohono (c. 795 m) - within Rotopounamu Graben, are all extinct and are aligned NW-SE for about 10 km, approximately normal to the NNE-SSW trend for the more recently active vents on the Tongariro Massif.

The Tongariro Massif has basal dimensions of 14 km N-S by 8 km E-W and a summit area of 8 km long by 3.2 km wide. Ngauruhoe (2,251 m) at the southern end and Red Crater (c. 1,800 m) in the centre of the massif are cones constructed entirely within post-glacial time and much of the activity from Blue Lake, Te Mari Craters, and North Crater post-dates an extensive glaciation of the massif which has exposed at least nine old vents (Mathews 1967). Pukeonake Scoria Cone and two plugs to the north lie along a north-south fracture west of Tongariro.

Ruapehu (2,753 m) has a summit depression, probably an original large crater (Grange and Williamson 1930), with dimensions of about 2.7 km N-S by 1.8 km E-W, and within which up to five craters can be recognised - West Crater, East Crater, and Girdlestone Crater (Grange and Williamson 1930) and a northern crater first described by Friedländer (1899) which may include two overlapping craters (Gregg 1960).

The currently active vent on Ruapehu, Crater Lake, lies in a volcanic cone near the eastern side of West Crater. There is also a small cone at

1,500 m on northern Ruapehu from which lavas have been extruded.

Hauhungatahi with two small more northerly cones is about 12 km north-west of Ruapehu.

The southern extremity of the Taupo Volcanic Zone, 20 km south-west of Ruapehu, is marked by several basic andesite explosion craters to the north and south of Ohakune.

Andesitic conglomerates and breccias, assumed to be of laharic origin, form ring-plains about the three andesite complexes. Hauhungaroa Lahars are preserved west and north-west of the Kakaramea-Tihia Massif; Rangipo Lahars form the deeply dissected ring-plain of the Tongariro Massif; Waimarino Lahars form the main part of the Ruapehu ring-plain; Hautapu Lahars are distributed to the south-east, and Murimotu Lahars to the south and north-west of Ruapehu. Recent lahars are confined to the Whangaehu River which drains south-eastwards from Crater Lake (lahar formations defined by Grindley 1960).

Purpose and Scope of this Study

The principal aim of this thesis is to add to knowledge of recent volcanism in the southern part of the Taupo Volcanic Zone (Fig 1) through a study of the andesitic tephra units erupted from within the Tongariro Volcanic Centre during the last 20,000 years. A convenient lower limit for detailed work is provided by the Oruanui Formation (Vucetich and Pullar 1969), a rhyolitic tephra erupted from the Maroa Volcanic Centre, which has been dated at c. 20,000 yr BP and is an easily recognised marker within the andesitic tephra deposits.

Other aspects of Quaternary history with a bearing on either the stratigraphic sequence or chronology have also been studied.

Previous geological work in the Tongariro Volcanic Centre has been concerned with regional mapping (Grange and Hurst 1929; Grange and Williamson 1930, 1933; Gregg 1960); mapping of lava flows and lahar

Table 1. K/Ar dates of andesites from the Tongariro Volcanic Centre (from Stipp 1968)

Sample No.	Locality	Grid Reference	Eruptive Source	Age (m.y.)
GA 1969	Lava exposed on Turangi-Taumarunui Road at Waihi Fault scarp	N102/226059	Kakaramaea	0.222 ^{+0.001}
GA 3255	Lava exposed on Turangi-Taumarunui Road 2.4 km west of Tokaanu, southern end of Lake Taupo	N102/240050(?)	?Tihia	0.172 ^{+0.015} 0.192 ^{+0.023}
GA 3256	Boulder from Poutu Stream, SE end of Lake Rotoaira	N112/237914	Pihanga	0.125 ^{+0.004} 0.123 ^{+0.0075}
GA 3254	Hornblende andesite lava from the ridge between Upper and Lower Tana Lakes	N112/103767	Tongariro	0.261 ^{+0.004} 0.259 ^{+0.008}
GA 3257	Lava about 800 m east of Mangatepopo Hut, on northern wall of Mangatepopo Valley	N112/100826	Tongariro	0.104 ^{+0.002} 0.097 ^{+0.003}
GA 3258	Lava exposed on fault scarp at Otukou Quarry	N112/138951	Tongariro (North Crater?)	0.060 ^{+0.005} 0.083 ^{+0.004}
GA 1967	Lava exposed on Bruce Road, 1,100 m below Top-o-the-Bruce	N112/041716(?)	Ruapehu	0.219 ^{+0.012}
GA 3259	Lava cliffs exposed on high southern side of Ruapehu	N112/038626	Ruapehu	0.040 ^{+0.0035} 0.022 ^{+0.003}
GA 3260	Lava from top of Mangawhero Falls, Ohakune Mountain Road	N122/002610	Ruapehu	0.024 ^{+0.002} 0.037 ^{+0.005}

ring plains (Grindley 1960, Grindley and Mathews 1965, and Mathews 1967) and K/Ar dating of nine lava flows (Stipp 1968, Table 1). These will be treated in detail in relevant sections.

Fieldwork for this study was mainly carried out from November 1970 to February 1971 and November 1971 to February 1972 with about 14 further weeks between March 1970 and March 1973. Tephra descriptions and thickness data were recorded from 467 sections from an area of approximately 5,200 km². The large number of sections was required to establish the relationships of tephra units with lava flows, rhyolitic domes, lahars, craters, fault scarps, alluvium, and moraines in order to date them. Moreover, material suitable for radiocarbon dating, and several of the andesitic and rhyolitic tephras themselves, were present in one or two sections only. The majority of the sections are in road cuttings, and almost all sections within the Tongariro National Park are close to streams or slips, 32 pits were excavated by the author.

The main andesitic tephra units are defined as formations or members, isopach maps showing their distribution patterns are presented, and 18 radiocarbon dates have been obtained from associated peat, wood or charcoal. The andesitic tephras are described in the paper: "Tephrostratigraphy and chronology of late Quaternary eruptives from the Tongariro Volcanic Centre, New Zealand" - Topping (1973).

Most tephrochronology in New Zealand has been concerned with rhyolitic tephras. These tephras have several advantages as time markers over andesitic tephras: the eruptions are usually much larger than andesitic eruptions so that the tephras cover much larger areas. The eruptions also tend to be 'paroxysmal' - bursts of activity are separated by long periods of inactivity, so that each tephra can be considered a discrete unit deposited in an instant of time (Taylor 1953). Most andesitic units are however 'intermittent'; accumulating over long periods of time and hence are not equally useful as time planes. Their intermittent accretion does, however, serve to preserve rhyolitic tephras.

Rhyolitic tephtras erupted from volcanic centres to the north of Tongariro Volcanic Centre were found to be useful in correlating andesitic tephtras between sections early in the fieldwork. Thirteen rhyolitic tephtras were recognised and correlated by means of stratigraphic position, grain size, ferromagnesian assemblages, and titanomagnetite analysis with tephtras from Taupo, Maroa, and Okataina Volcanic Centres (Fig. 1). They have been described in the paper: "Rhyolitic tephtra marker beds in the Tongariro area, ^{North Island} New Zealand" - Topping and Kohn (1973).

Titanomagnetite data and ^{14}C ages for rhyolitic and andesitic tephtras were used in a study, with Mr B. P. Kohn, of the relationship between andesitic volcanism in the Tongariro Volcanic Centre and rhyolitic volcanism in the Taupo Volcanic Centre.

Many of the rhyolitic tephtras identified in the Tongariro area have previously been dated in their source areas and these ages, together with the radiocarbon ages for the andesitic tephtras, have provided a chronology for the tephtra sequences from Ruapehu and Tongariro. This chronology has been used to provide minimum ages for rhyolitic and dacitic domes, andesitic lava flows and glacial moraines, and minimum and/or maximum ages (^{14}C) for faulting and laharic debris, alluvium, loess, peat, etc, enclosed by tephtra beds. A comprehensive knowledge of the post-20,000 yr B.P. volcanic history of the Tongariro Massif; a lesser knowledge of the Pihanga-Kakaramaea group of volcanoes and some data on recent events concerning Mt Ruapehu have thus been obtained.

Peat samples collected during the course of the fieldwork have been analysed for pollen by Mr M. S. McGlone, Botany Division, DSIR, Christchurch, and together with chronology from the tephtras, data on the occurrence of loess and erosion breaks, have been used in interpreting the recent paleoclimatic history of the area. Some of the preliminary data have been used in a recent paper: "Late Otiran/early Aranuiian vegetation in the Tongariro area, North Island, New Zealand" - McGlone and Topping (1973).

Reconnaissance petrology and petrochemistry of the Tongariro National Park volcanoes have been done by R. H. Clark (1960) and additional work in these fields is beyond the scope of this thesis. However, ferromagnesian assemblages were determined to aid correlation of rhyolitic tephra. Chemical analyses are also presented for four of the Tongariro tephra and for a rhyolitic tephra described for the first time in Topping and Kohn (1973). Five analyses are presented for olivine andesite flows erupted to the west of Tongariro, and 11 analyses for a sequence of Red Crater lavas to show variation in chemistry with time.

Tephra granulometric analysis was used in a detailed study of the Te Rato Lapilli (Topping 1973) in an effort to better define the eruptive vent for this tephra. Samples of seven other Tongariro-source tephra were analysed for comparative purposes.

Two further projects were carried out to extend the volcanic chronology. Tree-ring dating was used to obtain an accurate age for an historic mudflow from Ketetahi Springs and an estimated age for an aa flow from upper Te Mari Crater. The chronology obtained from radiocarbon dates and nine K/Ar dates (Stipp 1968, Table 1) in Tongariro Volcanic Centre has been extended by determinations of the polarity of NRM (natural remnant magnetism) for six lava flows. Paleomagnetic work was also used to provide data on temperature of emplacement for a nuée ardente deposit from a peak WSW of Tihia and for a lahar deposit on the lower north-western slopes of Ruapehu.

Nomenclature

Pyroclastic Nomenclature

Pyroclastic nomenclature has varied according to whether the subject was concerned with - (a) soil-forming air-fall deposits and the use of marker beds for geomorphic studies (e.g. Healy et al 1964, Vucetich and Pullar 1969); (b) volcanology of eruptives close to source (e.g. Nakamura 1960, 1964; Curtis 1968; Walker and Croasdale 1971, 1972); or (c) petrological and petrochemical aspects of pyroclastic rocks (Ewart 1968, Cole 1970, Kohn 1970). Until uniform conventions are adopted all terms must be defined explicitly (Healy 1972).

Pyroclastic has been defined by Wentworth and Williams (1932) as "an adjective commonly applied to rocks produced by explosive or aerial ejection of material from a volcanic vent." It includes deposits of air-fall eruptions and nuées ardentes.

Tephra was proposed by Thorarinsson (1954) for "all the clastic volcanic material which during an eruption is transported from the crater through the air, corresponding to the term lava to signify all the molten material flowing from the crater." Although previously restricted in New Zealand to pyroclastic rocks of air-fall origin (e.g. Pullar 1972; also in Japan, Kaizuka 1968) it has recently been suggested (Cole and Kohn 1972) that "tephra" should include pyroclastic flow deposits. This is consistent with the original use of the term by Thorarinsson (1954). Tephra is particularly useful as a general term for unconsolidated deposits as it is not restricted to certain grain sizes. When more is known about the deposit, for example, its distribution and relation to topography, the position of charcoal if present, and the degree of sorting of clasts, the deposit can be referred to as either "tephra-fall" or "tephra-flow". These two terms are necessarily genetic but little field work is usually

required to distinguish them. If there is doubt the general term tephra can be used for both although use of this term still requires some genetic knowledge of the deposit, e.g. in distinguishing it from loess and colluvial deposits. The use of "tephra-fall" and "tephra-flow" would thus bring New Zealand usage into line with the similar Japanese distinction between "pumice fall" and "pumice flow" deposits (e.g. Kuno et al 1964).

The grade size limits defining the classes within pyroclastic deposits (Table 2) are those of Fisher, 1961 (modified from Wentworth and Williams 1932). However, it has been found convenient while describing andesitic tephra in the Tongariro area to subdivide the lapilli class (64-2 mm) into coarse-, medium-, and fine-lapilli, with size ranges of 64-20, 20-10, and 10-2 mm respectively, and to divide Fisher's "coarse ash" (2-1/16 mm) into coarse ash (c. 2-1/2 mm) and medium ash (c. 1/2-1/16 mm). These correspond respectively to Folk's (1968) very coarse and coarse sand; and medium, fine, and very fine sand subdivisions (Table 2). These modifications in the ash and lapilli classes have allowed greater differentiation and flexibility in tephra descriptions and were essential for correlation purposes. Some tephra could be recognised on their colour but others required detailed grade size description to distinguish them from enclosing tephra beds.

Breccias within Tongariro Volcanic Centre are named according to the classifications of Fisher (1960) and Wright and Bowes (1963).

Volcanic breccia is used when the brecciation and/or emplacement was the result of volcanic action (after Wright and Bowes 1963).

Flow breccias, formed by fragmentation of an advancing and congealing lava flow, are of two types. Aa breccia is the breccia formed by aa lava flows and block breccia is composed of the generally smooth polyhedral blocks of block lava flows.

Table 2: Terminology and grain size limits for pyroclastic and epiclastic fragments used in this study (modified after Fisher (1961) with sand subdivisions after Folk (1968)).

GRADE SIZE (mm)	EPICLASTIC FRAGMENTS	PYROCLASTIC					
		UNCONSOLIDATED: TEPIRA Fisher (1961)			CONSOLIDATED this work		
		Coarse	Blocks and bombs	Coarse	Blocks and bombs		
256	Boulder						Breccia/ Agglomerate
64	Cobble	Fine		Fine			
20	GRAVEL Pebble	Lapilli		Very Coarse	Lapilli		Lapilli tuff
40				Coarse			
2				Medium			
1				Fine			
1/2	SAND Very coarse sand Coarse sand Medium sand Fine sand Very fine sand	Coarse	Ash	Coarse	Ash	Coarse	Tuff
1/4						Medium	
1/10							
1/16						Fine	
1/256	Silt	Fine					
	Clay						

Laharic breccia describes the deposits of mudflows which contain debris and angular blocks of chiefly volcanic origin. "Conglomerate" is used for deposits formed predominantly of large rounded water-worked volcanic fragments, with a lower size limit of 2 mm (Fisher 1958) and "laharic" is prefixed if such an origin can be shown.

Ignimbrite has frequently been applied by New Zealand geologists to tuffs which are partly or wholly welded (e.g. Cole and Kohn 1972). The two ignimbrites outcropping near Tongariro, Whakamaru Ignimbrite and Te Whaiti Ignimbrite, are formalised units which are partly welded. Two tephra flow deposits, Oruanui Breccia and Taupo Pumice, are unwelded and are regarded here as pumice breccias. However, some overseas writers (e.g. Walker 1971, Table 2, p. 707) would regard these deposits as ignimbrites.

Petrographic and Chemical Nomenclature

There is no fully adequate means of distinguishing calc-alkaline basalts, andesites, dacites and rhyolites by chemical or modal parameters (Irvine and Baragar 1971).

The scheme followed in this thesis is the Taylor et al (1969) chemical classification for calc-alkaline rocks (Fig 3):

Fig 3: Classification of intermediate calc-alkaline volcanic rocks (Taylor, S. R.; Capp, A. C.; Graham, A. L. 1969: Trace element abundances in andesites II. Saipan, Bougainville and Fiji. Contributions to Mineralogy and Petrology 23: 1-26.

where the andesite-dacite boundary is 63 per cent silica and the basalt-andesite boundary is 53 per cent. Clark (1960) and Ewart (1965) regarded all rocks from the Tongariro National Park volcanoes as andesites because none had less than 53 per cent silica. Four recently analysed lava flows from Red Crater contain less than 53 per cent silica; they have previously been referred to as basalts (Healy 1962, 1965); and are here regarded as basalts. The andesite-dacite boundary of 63 per cent silica has allowed recognition of a dacitic lapilli component in at least four Tongariro Sub-group tephrae. Eruptives from Tongariro Volcanic Centre while almost entirely andesitic in composition do therefore include minor amounts of basalt and dacite. Chemical analyses of lavas from Mt Edgecumbe volcano 145 km further NE, and also within the Taupo Volcanic Zone, similarly span the andesite-dacite boundary (Duncan 1970).

A petrographic subdivision of the andesites of Tongariro Volcanic Centre in terms of phenocryst content is given below (after Clark 1960):

- (a) Labradorite andesite - porphyritic plagioclase dominant over pyroxene phenocrysts.
- (b) Labradorite-pyroxene andesite - proportion of pyroxene to plagioclase phenocrysts substantial.
- (c) Pyroxene andesite - porphyritic pyroxene dominant over plagioclase phenocrysts.
- (d) Olivine andesite - olivine an important porphyritic constituent.
- (e) Hornblende andesite - significant numbers of hornblende phenocrysts present.

Clark's (1960) usage of a porphyritic pyroxene ratio to distinguish quantitatively between labradorite andesite and labradorite-pyroxene andesite is adopted. Where the per cent ratio of $\frac{\text{porphyritic pyroxene}}{\text{porphyritic pyroxene} + \text{feldspar}}$ is less than 33.3 then the rock is a labradorite andesite.

PART 1

TEPHROSTRATIGRAPHY AND
TEPHROCHRONOLOGY

Late Pleistocene tephras at Poutu Reference Section. See
Fig 2, p.26 for identification of the tephras.
Photo courtesy of Soil Bureau.

RHYOLITIC TEPHRA MARKER BEDS IN THE TONGARIRO AREA, NORTH ISLAND, NEW ZEALAND

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ABSTRACT

In the Tongariro area 13 rhyolitic tephra erupted from Okataina, Maroa, and Taupo Volcanic Centres over the last 20 000 years are interbedded with local andesitic tephra. The order of succession of the 13 tephra is established by stratigraphy, and is confirmed by their mineralogical composition and by chemical analysis of their titanomagnetites. Seven of the rhyolitic tephra have been previously dated by ^{14}C , four are dated here, and two are not yet dated. The four new ^{14}C dates provide ages of c. 12 500 years B.P. for Rotorua Ash (NZ 1186, NZ 1187); 9785 ± 170 years B.P. for Papanetu Tephra and Karapiti Lapilli (NZ 1372, NZ 1374); and c. 9740 years B.P. for Poronui Tephra.

INTRODUCTION

Andesitic tephra erupted from the Tongariro National Park volcanoes (Fig. 1) have been studied during the course of regional geological mapping (Grange & Hurst 1929; Grange & Williamson 1930; Gregg 1960) and soil mapping (Grange 1931; Grange & Taylor 1931; New Zealand Soil Bureau 1954). Only the youngest tephra have been formally named and mapped in any detail. Ngauruhoe Ash (Grange & Hurst 1929, p. 6) was mapped by Grange (1931) as a soil-forming ash and includes all andesitic ash from the Tongariro Volcanic Centre (Grindley 1960) above the rhyolitic Taupo Pumice (Baumgart 1954; Healy 1964). Gregg (1960) formally named the Mangatawai Ash for "... thinly bedded dark-grey andesite ash containing leaves . . ." (Grange & Hurst 1929, p. 7) immediately underlying Taupo Pumice. Tongariro Ash was a comprehensive name for andesitic tephra older than Mangatawai Ash (Gregg 1960, p. 38).

Individual beds within the Tongariro Ash are "confusingly alike" (Gregg 1960, p. 38). Where stratigraphic sections are close together, the andesitic tephra can be correlated without difficulty, but where sections are more than 0.5 km apart the similarity in appearance and complex distribution pattern of andesitic lapilli units makes correlation difficult.

The only rhyolitic tephra previously identified within the Tongariro tephra sequence have been Taupo Pumice (Baumgart 1954; Healy 1964) and Oruanui Formation (Vucetich & Pullar 1969). Gregg (1960) noted that other rhyolitic tephra occurring within the andesitic sequence may correlate with Taupo Sub-group members.

Twelve rhyolitic tephra of known age have now been identified within the andesitic tephra sequence, and have proved to be very useful marker beds. Most sections within the Tongariro area contain at least one rhyolitic tephra, and up to seven may be present in any one section. Eight rhyolitic

FIG. 1—Locality map of study area. Numbers refer to reference sections (see Appendix): 1—Mangatawai, 2—Access 10, 3—Poutu, 4—Te Ponanga Saddle, and 5—Wairoa

tephras are widespread and useful as markers. The widespread rhyolitic tephras also provide valuable time control in the southern part of the study area, where tephras from Ruapehu are dominant and where tephras from Tongariro are absent. A further five rhyolitic tephras are present in the area, but appear in too few sections to be of much value. However, the stratigraphic position of these less common tephras adds further time control to the otherwise difficult andesitic sequence.

North of Tongariro, identification of rhyolitic tephras can be made from their stratigraphic position in relation to prominent andesite lapilli beds (Table 1). In the laboratory, identification of rhyolitic tephras has been

TABLE 1—Stratigraphic column showing the relationship, in the Tongariro area, of andesitic tephtras of the Tongariro Sub-group with interbedded rhyolitic tephtras from the Okataina, Maroa and Taupo Volcanic Centres.

FORMATION	NAMED MEMBERS	UNNAMED BEDS	SYMBOLS	VOLCANIC CENTRE (SOURCE)	INFERRED STRATIGRAPHIC AGE (NOT 14C-DATED)	14C AGES IN YEARS BEFORE 1950	NZ14C NUMBER
¹ Ngauruhoe Tephra			ng	Tongariro			
² Taupo Pumice	Upper Taupo Pumice		tp 1				
	Taupo Lapilli		tp 3	Taupo		1,819 ± 17	Averaged from many dates (Healy 1964)
	Rotongaio Ash		tp 4				
	'Putty Ash'		tp 5				
³ Mangatawai Tephra			mg	Tongariro		2,500 ± 200 (basal 80 mm)	NZ186
		Andesitic tephra					
⁴ Whakaipo Tephra			wo	Taupo		2,670 ± 50 (above ash) 2,730 ± 60 (below ash)	NZ1070 NZ1071
		Andesitic tephra					
² Waimihia	Waimihia Lapilli		wm	Taupo		3,170 ± 80 (above ash) 3,440 ± 80 (below ash)	NZ504 NZ505
⁵ Papakai Tephra			pp	Tongariro			
⁴ Hinemaiaia Ash			hn	Taupo		6,390 ± 120 (above ash) 6,190 ± 70 (below ash)	NZ1137 NZ1247
⁵ Papakai Tephra			pp	Tongariro			
⁶ Rotona Ash			rm	Okataina		7,330 ± 235	NZ1199
⁵ Papakai Tephra			pp	Tongariro			
⁴ Opepe Tephra			op	Taupo		8,850 ± 1000	NZ185
⁵ Papakai Tephra			pp	Tongariro			
⁵ Mangamate Tephra	Poutu Lapilli		pt	Tongariro	9,700		
		Andesitic tephra		Tongariro			
⁴ Poronui Tephra			po	Taupo	9,740		
⁵ Mangamate Tephra		Andesitic tephra		Tongariro			
	Te Rato Lapilli		tt	Tongariro		9,700 ± 200 (below lapilli) 9,780 ± 170 (" ")	NZ1373 NZ1372
Papanetu Tephra			pa	Taupo	9,785		
⁴ Karapiti Lapilli			kp	Taupo	9,790		
⁵ Okupata Tephra		Unnamed ash Basal lapilli	oa	Tongariro		9,790 ± 160 (above ash)	NZ1374
		Andesitic tephra		Tongariro			
⁶ 7 Rotorua Ash			rr	Okataina	12,500	12,350 ± 220 (above ash) 13,150 ± 300 (below ash)	NZ1187 NZ1186
		Andesitic tephra		Tongariro			
⁷ 7 Puketarata Ash			pk	Maroa	13,500		
		Andesitic tephra		Tongariro			
⁵ Rotoaira Lapilli			rt	Tongariro		13,800 ± 300 (below lapilli)	NZ1559
		Andesitic tephra		Tongariro			
⁶ Rerewhakaaitu Ash			rk	Okataina		14,700 ± 200 (below ash)	NZ716
		Andesitic tephra		Tongariro			
⁸ Oruanui Formation	Oruanui Breccia		ou	? Maroa			
	Oruanui Ash					20,670 ± 300 (within ash) 19,850 ± 310 (below ash)	NZ12 NZ1056

- 1 Named by Grange & Hurst (1929)
 2 " " Baumgart (1954)
 3 " " Gregg (1960)
 4 " " Vucetich & Pullar (1973)

- 5 Named by Topping (1973)
 6 " " Vucetich & Pullar (1964)
 7 " " Lloyd (1972)
 8 " " Vucetich & Pullar (1969)

determined by radiocarbon dating of associated organic matter, heavy mineral determinations, and chemical analysis of titanomagnetites within the tephra (Kohn 1970).

The identification of rhyolitic tephra provides a time-stratigraphic column (summarised in Table 1) for tephra in the Tongariro area. The established chronology therefore allows dating of other important late Quaternary events.

IDENTIFICATION AND CORRELATION OF RHYOLITIC TEPHRAS

Radiocarbon Dating

Seven new radiocarbon dates from sites north-west of Tongariro provide ages for four rhyolitic tephra not previously dated. Papanetu Tephra, bracketed by two radiocarbon dates (NZ 1372, NZ 1374; see Table 2), is assigned an age of 9785 years B.P. Papanetu Tephra was erupted immediately following eruption of Karapiti Lapilli (Vucetich & Pullar 1973) and therefore the age of Karapiti Lapilli is also about 9785 years B.P. An ash considered to be Rotorua Ash (Vucetich & Pullar 1964) is bracketed by two radiocarbon dates (NZ 1187, NZ 1186; see Table 2), and is estimated to be 12 500 yr B.P.

Two wood samples from peat in a swamp cut by the Otamangakau Canal (N112/109984)*, which underlies Taupo Pumice, and the age of the pumice itself, indicate that the peat accumulated uniformly at approximately 0.45 m per thousand years. The rate is used to date two interbedded tephra and one basal tephra not previously dated. The results are shown below:—

Tephra	Ages from rate of peat accumulation	Previous dates
Rotorua Ash (Vucetich & Pullar 1964)	7430 yr B.P.	7330 yr B.P. (Pullar & Heine 1971)
Opepe Tephra (Vucetich & Pullar 1973)	8600 yr B.P.	8850 yr B.P. (Healy 1964)
Poutu Lapilli (Topping 1973)	9700 yr B.P.	—

Poronui Tephra (Vucetich & Pullar 1973) lies between Poutu Lapilli and Papanetu Tephra, so that its age is estimated to be 9740 years B.P.

Ferromagnesian Assemblages and Chemical Analysis of Titanomagnetites

Rhyolitic tephra of the Taupo Sub-group (Healy 1964) contain a ferromagnesian assemblage of dominantly hypersthene with or without ($\pm$) augite, and with very rare hornblende, biotite and olivine (Ewart 1963).

The Rotorua Sub-group tephra (Vucetich & Pullar 1964) include three different ferromagnesian assemblages (Ewart 1966; Cole 1970; Kohn 1973),

*Grid reference based on the national thousand-yard grid of the 1:63 360 topographical map series (NZMS 1).

TABLE 3—Dominant ferromagnesian assemblages for rhyolitic tephtras identified in the Tongariro Volcanic Centre.

Hypersthene ± augite	Hypersthene + calcic hornblende ± cummingtonite	Biotite + hypersthene ± calcic hornblende ± augite
Taupo Pumice	Oruanui Formation (may contain augite)	?Rotorua Ash
Whakaipo Tephra		?Puketarata Ash
Waimihia Lapilli	?Rotoma Ash (contains biotite where sampled in Tongariro region)	Rerewhakaaitu Ash
Hinemaiaia Ash		
Opepe Tephra		
Poronui Tephra		
Papanetu Tephra		
Karapiti Lapilli		

i.e., (a) hypersthene ± augite; (b) hypersthene + calcic hornblende ± cummingtonite; and (c) biotite + hypersthene ± calcic hornblende ± augite.

The Oruanui Formation erupted from north of Lake Taupo (Vucetich & Pullar 1969) contains a ferromagnesian assemblage of hypersthene + calcic hornblende ± sparse augite ± rare biotite.

Taupo Sub-group tephtras (i.e., erupted from Taupo Volcanic Centre), in containing very rare biotite and calcic hornblende, can generally be distinguished from tephtras erupted from the other sources, but the uniformity of the ferromagnesian assemblage does not allow identification of individual formations (Table 3). The chemical analysis of titanomagnetites (Kohn 1970) was used to distinguish younger and older Taupo Sub-group tephtras, and also to confirm correlation of rhyolitic tephtras from other centres.

Rhyolitic tephtras sampled for chemical and mineralogical analysis were taken from the middle of pockets and lenses, and were considered to be least contaminated.

Titanomagnetite analyses are presented in Table 4.

DESCRIPTIONS OF RHYOLITIC TEPHTRAS

Taupo Pumice (tp)

Taupo Pumice has long been recognised as an important and widespread deposit in the study area, and was once believed to have been erupted from the Tongariro volcanoes (Dieffenbach 1843, p. 128; Wakefield 1845, p. 236; Taylor 1855, p. 225). Gregg (1960, p. 39) summarised previous work and showed its distribution by a generalised isopach map. However, within the Tongariro area varying amounts of primary deposits (airfall and nuée ardente origin, almost certainly erupted from more than one source) and water-sorted pumice make the distribution pattern more complex.

In the northern part of the area two further members of the Taupo Pumice Formation are present. Rotongaio Ash (Baumgart, 1954; Healy, 1964), with its distinctive steel-grey colour, is 5–20 mm thick at sections near Kuratau (see Fig. 1), and also about 20 mm thick on Kepa Road, east of Turangi (N102/382012). At the latter locality 20 mm of cream-coloured ash ("Putty Ash", Tsg member 5; Healy 1964) underlies Rotongaio Ash, but has not been seen further south.

According to Gregg (1960) the Taupo Pumice defines the top of the Mangatawai Ash and the base of the Ngauruhoe Ash.

Whakaipo Tephra (wo)

Whakaipo Tephra (Vucetich & Pullar 1973) can be identified in the northern part of the region studied, where it is of lapilli grade. On Kepa Road (N102/382012), 90 mm of pale yellow Whakaipo Tephra occurs within Mangatawai Ash 0.16 m above Waimihia Lapilli. Further south, the Mangatawai Ash separating them becomes indistinct, so that Whakaipo Tephra cannot be distinguished from Waimihia Lapilli. Still further south (N122/223671) Whakaipo Tephra is significantly finer.

Correlation was established by stratigraphy and presence of hypersthene + augite. Titanomagnetite was not analysed.

Waimihia Lapilli (wm)

Waimihia Lapilli (Baumgart 1954; Healy 1964) can be identified up to 9 km south-west of Ruapehu (N121/993595) and in the southern area of the Rangipo Desert (N122/165595, 10 km south-east of Ruapehu). It has not been found to the west of the volcanoes.

In the south (N122/097565) the ash is fine and yellow to pale yellow, and forms a well defined horizon up to 50 mm thick. About 34 km further north-east, where Waimihia Lapilli is of less use as a marker, it consists of 0.3 m of medium pale pumiceous ash scattered throughout fine yellowish brown ash.

The ferromagnesian assemblage (hypersthene + augite) and the relatively high titanium, chromium and zirconium, and low vanadium, cobalt and nickel of the titanomagnetites confirms identification as Waimihia Lapilli (*Table 4, analyses 8–13). It is distinguished from the otherwise mineralogically and chemically similar Taupo Pumice by its relatively high zirconium content (>100 ppm).

Hinemaiaia Ash (hn)

Fine white rhyolitic tephra interbedded with the Papakai Tephra (see Table 1), and occurring at all sections along the Desert Road from Makahikatoa Stream bridge (N112/250787) south to Mangatoetoeui Stream (N112/216709), is correlated with Hinemaiaia Ash (Vucetich & Pullar

*All analysis Nos. refer to analyses given in Table 4.

TABLE 4—Titanomagnetite analyses of rhyolitic tephra from near source and within Tongariro area. Analyses involved apparatus and operating conditions described by Kohn (1970), and are the averaged result of samples generally run in triplicate. The analytical precision, expressed as relative deviation, was $\pm 10\%$. Numbers prefixed by P refer to the petrological collection of the N.Z. Geological Survey.

Analysis Sample No.	Locality	Grid Ref.	Ti				V				ppm			
			Mg	%	Mn	Ca	Cr	Co	Ni	Zr	Cu			
1	Taupo Pumice	Napier-Taupo Highway; basal 30 cm	N94/564354	7.92	1.06	0.69	0.54	649	131	16	27	68	22	
2	Taupo Pumice	Wairakei-Putaruru Highway (Route 1)	N94/516544	7.92	0.69	0.80	0.66	847	117	35	55	83	43	
3	Taupo Pumice	Old Ketatahi Track	N112/133894	7.63	0.89	0.92	0.77	968	162	50	55	78	68	
4	Taupo Pumice	Cutting near Waikato Falls	N112/309830	7.87	0.75	0.66	0.74	1043	143	50	58	82	65	
5	Taupo Pumice	Top of Pukeyake Cone	N112/066824	7.41	0.82	0.59	0.51	896	220	51	85	60	100	
6	Mapara Tephra	Burrows Quarry; basal 15 cm lapilli	N94/647394	7.55	0.90	0.87	0.30	633	106	33	41	71	39	
7	Whakaipo Tephra	Mapara Road; basal 15 cm pumice blocks	N94/466364	8.45	0.50	0.70	0.35	443	73	35	24	454	61	
8	Waimihia Lapilli	Napier-Taupo Highway; basal 20 cm pumice blocks	N94/572354	7.28	1.23	0.79	0.67	699	149	24	27	332	41	
9	Wairakei Lapilli	Wairakei-Putaruru Highway (Route 1)	N94/516544	8.02	0.78	0.89	0.46	1023	135	55	68	380	60	
10	Waimihia Lapilli	Ohakune Mountain Road	N121/996602	9.17	0.72	0.55	0.06	1008	201	43	75	226	99	
11	Waimihia Ash	Rangipo Desert	N122/165595	7.61	0.62	0.63	0.17	709	128	30	36	222	42	
12	Waimihia Ash	West Taupo Road	N102/179194	7.34	0.68	0.69	0.16	714	95	40	38	239	98	
13	Waimihia Ash	Desert Road	N122/219675	10.44	1.29	0.77	0.25	989	136	50	87	225	126	
14	Hinemaia Ash	P28856	N94/587347	8.08	0.55	0.82	0.29	887	85	44	55	663	50	
15	Hinemaia Ash	National Park-Taupo Road	N112/125924	6.55	0.59	0.65	0.08	762	99	34	35	176	80	
16	Opepe Tephra	Napier-Taupo Highway	N94/572354	7.24	0.80	0.59	0.37	3470	117	69	87	226	59	
17	Poronui Tephra	P28866	N94/587347	7.81	0.76	0.61	0.18	3066	114	75	99	280	56	
18	Poronui Tephra	Iwatahi Gully; basal 15 cm lapilli & ash	N103/735200	7.02	0.67	0.47	0.24	3602	131	75	110	136	78	
19	Poronui Tephra	Desert Road	N112/298951	6.25	0.90	0.52	0.23	2804	113	82	99	497	59	
20	Poronui Tephra	Above Taupo-Turangi Road	N102/341070	6.10	0.72	0.53	0.13	2960	102	76	90	584	107	

21	Poronui Tephra	Head of Waipakihī River	N112/431846	8.78	0.75	0.38	0.08	3039	146	66	113	193	74
22	Papanetu Tephra	Top of Kuharua Dome	N102/188082	7.34	1.09	0.37	0.10	3531	710	127	179	114	72
23	Papanetu Tephra	Te Ponanga Road	N112/224983	6.91	0.90	0.50	0.09	3889	285	101	163	284	133
24	Papanetu Tephra	Te Ponanga Road	N102/256015	6.30	1.10	0.43	0.08	4044	462	113	179	217	107
25	Karapiti Lapilli	Iwatahi Gully basal 5 cm lapilli & ash	N103/735200	6.92	0.87	0.54	0.10	3906	179	75	115	192	64
26	Karapiti Lapilli	P28865	N94/587347	7.43	0.67	0.57	0.14	3090	111	76	114	350	50
27	Rotorua Ash	Rotorua-Taupo Highway basal 15 cm lapilli & ash	N76/780908	4.21	0.98	0.59	0.63	2039	124	48	56	524	20
28	Rotorua Ash	Lynmore Hill	N76/774010	4.99	0.93	0.62	0.06	2364	161	75	67	639	22
29	Rotorua Ash	Road west side Lake Rotorua, basal pumice blocks	N76/677135	5.29	0.92	0.64	0.41	2398	143	48	43	453	43
30	? Rotorua Ash	Cutting near Waikato Falls	N112/301844	4.69	1.04	0.51	0.07	3178	492	82	150	394	36
31	? Rotorua Ash	Mangatepopo Track	N112/069798	4.99	1.01	0.59	0.18	2633	532	84	119	270	52
32	? Rotorua Ash	Otamangakau Canal	N112/105979	5.79	0.98	0.63	0.10	2968	454	94	155	337	112
33	Puketarata Ash	Wairakei-Putaruru High- way (Route 1)	N94/516544	6.39	0.43	0.78	0.50	1936	179	82	79	435	56
34	? Puketarata Ash	Desert Road	N112/250806	5.39	0.66	0.71	0.13	1923	141	60	66	409	83
35	Rerewhakaaitu Ash	Democrat Road basal 15 cm ash	N86/934824	4.79	0.61	0.71	0.11	2122	149	58	67	733	41
36	Rerewhakaaitu Ash	Gavin Road	N86/995824	5.34	0.45	0.62	0.24	1920	151	35	33	684	20
37	Rerewhakaaitu Ash	Mangatepopo Valley (on moraine)	N112/089823	5.06	0.54	0.70	0.09	2245	142	53	46	451	34
38	? Rerewhakaaitu Ash (contaminated)	National Park-Taupo Road	N112/239901	6.67	0.73	0.62	0.10	3389	351	80	103	602	76
39	Oruanui Ash	Wairakei-Putaruru High- way (Route 1)	N94/523521	6.17	0.62	0.44	0.16	2714	195	75	69	184	36
40	Oruanui Ash	basal lapilli Braemar Road 12 cm from top	N68/202265	5.30	0.80	0.55	0.11	2963	261	90	115	391	95
41	Oruanui Ash	Rangipo Desert	N122/175575	6.47	1.01	0.51	0.30	3292	250	85	109	223	70
42	Oruanui Breccia	NE side Tongariro River	N102/303015	5.78	0.75	0.63	0.86	3559	239	72	100	418	63

1973). Between these localities the ash typically occurs about 0.15 m above Poutu Lapilli and about 0.5 m below the top of Papakai Tephra (Topping 1973). Near Makahikatoa Stream, Hinemaiaia Ash occurs as "cream cakes" (Healy 1964, p. 10) or in isolated pockets. Further south, and due east of the Tama Lakes, it forms a continuous horizon. It is suggested that the continuous eruption of andesitic tephra from one of the Tongariro vents protected Hinemaiaia Ash from subsequent erosion or disturbance during soil-forming processes.

North of Tongariro, Hinemaiaia Ash occurs in only a few sections. On an old Ketetahi Springs track (N112/135915) it is 50 mm thick and 50 mm above the base of the 0.73 m-thick Papakai Tephra. About 1.3 km WNW (N112/125924), it occurs as an isolated pocket, 60 mm thick, in the lower part of the Papakai Tephra. The occurrence of Hinemaiaia Ash to the north of Tongariro, in pockets only rather than as a continuous horizon, indicates little protection from erosion by subsequent andesitic tephra.

According to the stratigraphic position and ferromagnesian mineral content (hypersthene + augite) the ash could be Hinemaiaia Ash or Opepe Tephra. However, the titanomagnetite analysis (analysis 15) identifies the ash as Hinemaiaia Ash.

? Rotoma Ash (rm)

The rhyolitic ash scattered through 20 mm of peat in the swamp cut by the Otamangakau Canal (N112/109984) has an age, by interpolation, of 7430 years B.P. According to Pullar & Heine (1971), Rotoma Ash has an age of 7330 ± 235 years B.P. (NZ 1199). The ferromagnesian assemblage of a sample from the peat comprises hypersthene + biotite + calcic-hornblende + augite. That for the Rotoma Ash (Vucetich & Pullar 1964) comprises calcic hornblende + hypersthene + rare augite. The amount of biotite in the sample from the swamp is anomalously high. Most of the augite in the sample from the peat is larger in size than the other ferromagnesian minerals, and is probably contamination from andesitic tephra. The age, and presence of calcic hornblende, suggests correlation with Rotoma Ash.

Opepe Tephra (op)

Opepe Tephra (Vucetich & Pullar 1973) is only recognised in a peat swamp cut by the Otamangakau Canal (N112/109984). The estimated age from the uniform rate of peat accumulation is 8600 yr B.P., which compares well with a radiocarbon age of 8850 ± 1000 yr B.P. (Healy 1964). The deposition of Opepe Tephra occurred at the time of maximum soil development on Papakai Tephra, making its preservation outside of peat swamps very unlikely.

Poronui Tephra (po)

Poronui Tephra (Vucetich & Pullar 1973) is a rhyolitic tephra erupted from Taupo Volcanic Centre. North of Tongariro, Poronui Tephra is enclosed by Poutu Lapilli and Te Rato Lapilli, but to the east Te Rato Lapilli is thin or absent.

FIG. 2—Poutu reference section on National Park-Taupo Road (N112/239901), showing four rhyolitic tephra: Taupo Pumice (tp), Poronui Tephra (po), Rotorua Ash (rr), Oruanui Formation (ou); and two andesitic marker beds: Poutu Lapilli (pt) and Rotoaira Lapilli (rt).

Poronui Tephra is typically exposed in the Poutu Canal-eastern National Park-Taupo Road region, where it comprises fine yellow ash 10–30 mm thick. It is also present at reference sections Poutu (Fig. 2), Access 10, and Te Ponanga Saddle (Fig. 3), (see Appendix), and extends southwards over half the length of the Desert Road, but does not occur to the west of Tongariro. It thickens northwards to 60 mm on Kapa Road (N102/382012), and eastwards to 80 mm at the head of the Waipakihi Valley (N112/431846).

A ^{14}C age of 9780 ± 170 yr B.P. for Te Rato Lapilli (NZ 1372; Table 2), together with an estimated age of 9700 yr B.P. for Poutu Lapilli, dates Poronui Tephra at about 9740 yr B.P. The preservation of Poronui Tephra as a discrete horizon is attributed to the rapid deposition of overlying andesitic beds.

The ash has been traced northwards and correlated with Poronui Tephra of the Taupo Sub-group. The ferromagnesian assemblage (hypersthene + augite) confirms this correlation. Titanomagnetite analyses of Poronui Tephra at the Iwatahi reference section (N103/735200; see Fig. 1) and one other site (analyses 17, 18) correlate with the rhyolitic ash bracketed by Poutu Lapilli and Te Rato Lapilli at three sites in the Tongariro region (analyses 19–21). At the Iwatahi reference section, Poutu Lapilli has been identified in the paleosol of Poronui Tephra, which is in turn underlain by the grey-green Te Rato Lapilli.

FIG. 3—Te Ponanga Saddle reference section, Te Ponanga Saddle Road (N112/224983), type section for Papanetu Tephra. Rhyolitic tephrae are: Waimihia Lapilli (wm), Poronui Tephra (po), Papanetu Tephra (pa), ?Puketarata Ash (pk); the andesitic units are: Poutu Lapilli (pt) and Te Rato Lapilli (tt).

Papanetu Tephra (pa)

Papanetu Tephra is a new formation name for rhyolitic tephra immediately underlying the Te Rato Lapilli. At the type section on the Te Ponanga Saddle Road (N112/224983; see Appendix), Papanetu Tephra comprises up to 20 mm pale yellow ash with abundant grey lithic fragments, and clear obsidian up to 10 mm. On Kuharua Dome (N102/188082) Papanetu Tephra, below Te Rato Lapilli and above rhyolitic breccia, comprises 0.62 m of rhyolitic ash and coarse obsidian fragments.

The tephra is best displayed in sections along Te Ponanga Saddle Road, where it is commonly 10–20 mm thick but with a range of 2–40 mm. The isopach pattern (Fig. 4) and the coarse obsidian fragments indicate that the source is Kuharua Dome.

Papanetu Tephra is bracketed by two new radiocarbon dates. Twigs from 5 mm of peat above Papanetu Tephra gave an age of 9780 ± 170 years B.P. (NZ 1372, Table 2), the peat gave an age of 9700 ± 210 years B.P. (NZ 1373, Table 2), and twigs from 20 mm of peat immediately underlying the tephra gave an age of 9790 ± 160 years B.P. (NZ 1374, Table 2). The age of Papanetu Tephra is taken as being 9785 years B.P., and the date provides a minimum age for Kuharua Dome.

FIG. 4—Isopach map of Papanetu Tephra (based on 77 measurements). All thicknesses are in mm.

Papanetu Tephra has a ferromagnesian assemblage comprising hypersthene + augite. Three titanomagnetite analyses, including one from the section on Kuharua Dome, are similar except that chromium is higher in the sample from the dome (see Table 4).

Karapiti Lapilli (kp)

Rhyolitic tephra correlated with Karapiti Lapilli (Vucetich & Pullar 1973) underlies Te Rato Lapilli on Kapa Road and at sections further north. Karapiti Lapilli and Papanetu Tephra both directly underlie Te Rato Lapilli, without evidence of significant time break. The age of Karapiti Tephra is therefore considered to be about 9785 years.

Two titanomagnetite samples of Karapiti Lapilli were analysed (analyses 25, 26) and found to be significantly lower in chromium, cobalt and nickel than Papanetu Tephra samples. Karapiti Lapilli and Papanetu Tephra both have a hypersthene + augite ferromagnesian assemblage, so cannot be distinguished on mineralogy.

? Rotorua Ash (rr)

A fine yellow rhyolitic ash that probably correlates with Rotorua Ash (Vucetich & Pullar 1964) occurs about midway between Te Rato Lapilli and Rotoaira Lapilli in sections to the north of Tongariro, and in about

half of all sections elsewhere in the study area spanning this time range. The ash extends as far westwards as Moerangi and southwards almost to Waiouru (see Fig. 1), and reaches a maximum thickness of 60 mm. It occurs typically as small "cream cakes" (Healy 1964, p. 10), or in small pockets to the north of Tongariro (e.g., at reference sections Poutu, Access 10, and Mangatawai, described in appendix. See also Fig. 5). At sections on the National Park-Taupo Road south of Taurewa it occurs as a discrete horizon where overlain by tephra from Mt Ruapehu.

Its wide distribution and its fine grain size suggests a distant source. Two dated andesitic tephtras ($12\,350 \pm 220$ years B.P., NZ 1187; $13\,150 \pm 300$ years B.P., NZ 1186; Table 2) from a section at N112/105987 can be correlated with a section 0.5 km to the north-west (N112/102990), where they bracket the rhyolitic ash, and indicate an age of about 12 500 years B.P. The ferromagnesian assemblage comprising hypersthene + calcic hornblende + biotite + augite suggests correlation with a Rotorua Sub-group tephra, and the Rotorua Ash, with an estimated age of 13 000 years B.P. (Vucetich & Pullar 1964), is a probable correlative.

Three titanomagnetite analyses (analyses 30–32), from the Tongariro region contain significantly higher vanadium, chromium, cobalt and nickel than three near-source Rotorua Ash samples (analyses 27–29). However, the presence of some very large augite and hypersthene in the Tongariro samples may indicate contamination by andesitic tephra.

This tephra constitutes the most valuable time plane in the Tongariro area.

? Puketarata Ash (pk)

At the Mangatawai reference section (N112/250806) a rhyolitic tephra comprising a calcic hornblende + hypersthene + minor biotite ferromagnesian assemblage occurs in a lens 0.19 m thick and 1.46 m long, 0.53 m below ?Rotorua Ash and above Rotoaira Lapilli (Topping 1973). The stratigraphic position, ferromagnesian assemblage, and titanomagnetic composition (analyses 33, 34) identify the tephra as ? Puketarata Ash.

At a section near Wairehu Canal (N112/145983), a rhyolitic tephra containing a biotite + hypersthene + minor calcic hornblende and augite, and occurring between ? Rotorua Ash and Rotoaira Lapilli, is also considered to be ? Puketarata Ash. Rerewhakaaitu Ash (see below) has been correlated with a tephra occurring below Rotoaira Lapilli at the Te Ponanga Saddle reference section, so that the correlation with Puketarata Ash is supported by a section at Palmer Road (N94/542499) where Puketarata Ash is bracketed by Rotorua and Rerewhakaaitu Ashes (Kohn 1973).

Isopachs for Puketarata Ash (Lloyd 1972) show traces of the ash at Wairakei, but a consideration of the exponential fallout pattern of tephra suggests that it may have been deposited as far south as Tongariro.

Rerewhakaaitu Ash (rk)

A 40 mm lens of white to pale yellow fine rhyolitic ash occurs within andesitic tephtras 1 m below ? Rotorua Ash in a section on the lateral moraine on the northern side of Mangatepopo Valley (N112/089822). The ash is

FIG. 5—Tephra section on eastern side, Motuopuhi Island, Lake Rotoaira (N112/198956), showing the rhyolitic ?Rotorua Ash (rr), Papanetu Tephra (pa), Poronui Tephra (po), and the andesitic Poutu Lapilli (pt) and Te Rato Lapilli (tt). The trowel is 0.29 m in length.

correlated with Rerewhakaaitu Ash (Vucetich & Pullar 1964), erupted from the Okataina Volcanic Centre about $14\,700 \pm 200$ years B.P. (NZ 716).

Rerewhakaaitu Ash is considered to be present as the rhyolitic tephra below Rotoaira Lapilli and above Oruanui Ash at the Te Ponanga Saddle reference section (see Appendix), and 0.15 m below Rotoaira Lapilli at the Poutu reference section.

The ferromagnesian mineral assemblage contains biotite + hypersthene + calcic hornblende $\pm$ augite. Rerewhakaaitu Ash samples from near source have a similar ferromagnesian assemblage, but are not known to contain augite (Cole 1970). Titanomagnetite analysis of the ash (without augite) on the moraine in Mangatepopo Valley agrees well with known Rerewhakaaitu Ash samples (analyses 35–38).

Oruanui Formation (ou)

The Oruanui Formation occurs throughout the whole region, and its distribution is consistent with an interpolation of Vucetich & Pullar's (1969,

p. 798) isopach map. The two members—Oruanui Breccia (tephra-flow) and underlying Oruanui Ash (tephra-fall)—have been radiocarbon dated at $20\,600 \pm 300$ years B.P. (NZ 12; Vucetich & Pullar 1969).

The Oruanui Breccia consists of pale brownish grey massive ash and rare lapilli, and is typically seen on the Rotoaira Road (N112/176979), where the upper 2.7 m is clearly exposed. The contact between the two members is best seen at the Poutu reference section (N112/239901). At a more westerly section (N112/125924) a lens of andesitic boulders and cobbles separates two possible flow units. The possibility of more than one flow unit within Oruanui Breccia could also be explained by slumping after a period of erosion.

The Oruanui Ash is a distinctive air-fall unit containing chalazoidites (Vucetich & Pullar 1969). North of Tongariro, the shower-bedded base of the ash overlies either sands and gravels or a very dark brown tuff containing plant fragments.

The two Oruanui members do not occur above an altitude of 1200 m. On the western slopes of Tongariro up to an altitude of 1070 m Oruanui tephra forms the matrix of alluvial deposits, and is interbedded with gravels at a section 13 km SE of Mt Ruapehu (N122/175575). Reworked Oruanui tephra occurs at 1100 m at the head of the Waipakihi Valley (N112/431846), and is 2.4 m thick further down-valley at a height of 1000 m (N112/377795). The ash occurs up to 670 m altitude on Te Ponanga Saddle Road (N102/238004), while Oruanui Breccia is absent above 580 m (N102/244009) in the same area.

The ferromagnesian assemblages of Oruanui samples in the study area comprise hypersthene + augite + calcic hornblende, which is the same as that for Oruanui tephra in the type area. Titanomagnetite analyses from Oruanui Breccia and Ash (analyses 41, 42) compare well with known samples in the Taupo and Rotorua districts (analyses 39, 40).

REWORKED TEPHRA DEPOSITS

Hinuera Formation

Water-laid pumiceous silts, sands and gravels are exposed in several sections to the north of Tongariro, and vary from large scale current-bedding (as at Poutu reference section) to smaller cross-bedding (as at a section east of Pihanga, N112/298951). It is probably reworked Oruanui Formation, and is considered to correlate with Hinuera Formation (Healy 1946; Thompson 1958; Grindley 1959; Schofield 1965; Vucetich & Pullar 1969; Lloyd 1972).

In all instances within the Tongariro area, Hinuera Formation overlies Oruanui Formation and is in turn overlain by Rotoaira Lapilli (Topping 1973). It is therefore younger than 20 600 years B.P. and older than 13 800 years B.P. (the maximum age of Rotoaira Lapilli; Table 2), and can be correlated with Hinuera-2 sediments (Schofield 1965).

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APPENDIX

REFERENCE SECTIONS

Mangatawai: a cutting on the Waiouru-Turangi Road (Desert Road) on the south side of the bridge over Mangatawai Stream, N112/250806.

Ngauruhoe Tephra	0.44 m	very dark grey ash to dark brown fine ash
Taupo Pumice	0.2 m	(in pockets) pale yellow rhyolitic ash, lapilli and blocks
Mangatawai Tephra	0.8 m	dark brown fine ash giving way to dark grey ash with interbedded very dark grey ash containing yellow leaves
Whakaipo Tephra & Waimihia Lapilli	0.24 m	dark yellowish brown ash with pale yellow rhyolitic lapilli, giving way to coarse yellowish brown rhyolitic ash
Papakai Tephra	0.24 m	yellowish brown fine ash with interspersed grey and strong brown stained lapilli; buried soil
Poutu Lapilli	0.54 m 1 m	strong brown weakly shower-bedded lapilli andesitic tephra
Te Rato Lapilli	40 mm	olive grey lapilli
Papanetu Tephra-Karapiti Lapilli		trace light yellowish brown fine ash
?Rotorua Ash	1.9 m 0-40 mm	andesitic tephra pale yellow rhyolitic ash in yellowish brown ash
	0.53 m	andesitic tephra
?Puketarata Ash	0.19 m 1.4 m 0.46 m 0.63 m 0.9 + m	(pocket) fine white rhyolitic ash andesitic tephra alluvium andesitic tephra alluvium

Access 10: a large cutting on the crest of a hill 2.5 km from the Waiouru—Turangi Road (Desert Road) on Hydro Access Road No. 10, N112/301844.

Ngauruhoe Tephra	50 + mm	fine black ash
Taupo Pumice	0.6 m	pale yellow rhyolitic ash, lapilli and blocks
Mangatawai Tephra	0.43 m	dark yellowish brown to black ash
Whakaipo Tephra & Waimihia Lapilli	0.58 m	fine yellowish brown ash with interspersed pale yellow rhyolitic ash
Papakai Tephra	0.4 m	dark brown fine ash; paleosol (erosion break)
Poutu Lapilli	0.36 m	yellowish red stained lapilli
	40 mm	grey to yellowish brown ash
Poronui Tephra	10 mm	fine yellow rhyolitic ash
	0.44 m	andesitic tephra
Te Rato Lapilli	10 mm	grey coarse ash
	50 mm	yellowish brown ash
Papanetu Tephra—Kara-piti Lapilli	0–20 mm	light yellowish brown rhyolitic ash
?Rotorua Ash	1.3 m	andesitic tephra
	20–30 mm	fine pale yellow rhyolitic ash
	1.2 m	andesitic tephra
Rotoaira Lapilli	0.27 m	0.12 m strong brown pumiceous lapilli; 20 mm very dark grey fine ash grading into 80 mm strong brown and black coarse ash; 20 mm very dark grey ash grading into 30 mm olive yellow lapilli and ash
	1.1 m	andesitic tephra
	4.5 m	alluvium or laharic debris, on
	1.4 + m	purplish grey ignimbrite; planar upper surface

Poutu: a large cutting on the National Park—Taupo Road, 5.7 km west of Rangipo, N112/239901. Type section for Poutu Lapilli and Rotoaira Lapilli.

Taupo Pumice	0.40 m	pale yellow rhyolitic ash, lapilli and blocks
Mangatawai Tephra	0.42 m	dark yellowish brown ash becoming dark grey over bottom 0.2 m
Whakaipo Tephra & Waimihia Lapilli	0.3 m	yellowish brown fine ash with interspersed pale yellow rhyolitic ash
Papakai Tephra	0.4 m	strong brown ash with grey lithic lapilli throughout; paleosol
Hinemaiaia Ash	0–30 mm	"cream cakes" of pale yellow brown rhyolitic tephra occur in lower half of this unit
Poutu Lapilli	0.90 m	brownish yellow weakly bedded lapilli
	60 mm	very dark greyish brown to dark olive grey ash
Poronui Tephra	20–30 mm	pale yellow rhyolitic ash
	0.12 m	andesitic tephra
Te Rato Lapilli	0.16 m	very dark grey coarse ash and lapilli and pale yellow lapilli
	0.64 m	andesitic tephra
?Rotorua Ash	0–20 mm	fine yellow rhyolitic ash, usually as "cream cakes" about 20 mm across
	0.71 m	andesitic tephra
Rotoaira Lapilli	0.38 m	0.16 m yellowish red coarse ash and lapilli; 20 mm (10–50 mm) black ash; 0.2 m shower bedded brownish lapilli and coarse ash (erosion)
	0.12 m	yellowish brown ash with scattered strong brown lapilli
	80 mm	light olive brown ash (sandy silt) with sparse strong brown lapilli; a few angular cobbles throughout these two units which are probably water-laid. In places up to 50 mm white rhyolitic ash present; may not be primary
Rerewhakaaitu Ash		

	0.38 m	shower-bedded strong brown and brownish yellow ash and lapilli
Hinuera Formation	0.82 m	current bedded gravelly sands (erosion)
Oruanui Formation	0.39 m	pale brownish grey massive ash with scattered pumice lapilli (Oruanui Breccia)
	0.57 m	0.31 m very pale brown ash, shower bedded and studded with chalazoidites up to 30 mm across; 40 mm pale yellow shower bedded ash; 0.12 m pale yellow shower bedded fine and coarse ash (Oruanui Ash); sharp contact with tuff, lapilli tuff and alluvium
	2 + m	

Te Ponanga Saddle: a cutting on the eastern side of Te Ponanga Saddle Road near the summit, and to the north of Lake Rotopounamu, N112/224983. Type section for Papanetu Tephra.

Ngauruhoe Tephra	0.15 m	dark brown grey fine ash
Taupo Pumice	0.95 m	pale yellow rhyolitic ash, lapilli and blocks
Mangatawai Tephra	0.34 m	dark brown grey ash
Waimihia Lapilli	0.13 m	pale yellow rhyolitic ash
Papakai Tephra	0.43 m	yellow brown fine ash with interspersed grey and strong brown lapilli; paleosol
Poutu Lapilli	0.65 m	grey and strong brown coarse ash and lapilli (erosion)
Poronui Tephra	60 mm	grey ash with a trace of light yellowish brown fine rhyolitic ash
Te Rato Lapilli	0.3 m	dark greenish grey lapilli and coarse ash and pale yellow lapilli
	20 mm	yellowish brown ash and coarse grey lithic ash
Papanetu Tephra	0-20 mm	pale yellow ash with coarse clear obsidian and grey lithic ash
	0.85 m	andesitic tephra (?Rotorua Ash in other Te Ponanga Road sections is about halfway down these units)
?Puketarata Ash	30 mm	isolated pocket of yellow rhyolitic ash
	0.16 m	yellowish brown ash
Unnamed rhyolitic ash	20 mm	isolated pocket of yellow rhyolitic ash
	0.12 m	yellowish brown ash
Rotoaira Lapilli	85 mm	20 mm yellowish red coarse ash and lapilli; 5 mm dark grey ash; 60 mm coarse strong brown ash and lapilli
	0.30 m	yellowish brown ash
Rerewhakaaitu Ash	60 mm	white fine rhyolitic ash
	0.60 m	slightly gravelly sand, yellowish brown silts with minor cobbles and boulders
Oruanui Ash	0.30 m	shower bedded pale brown ash, coarse ash and chalazoidites
	1.5 + m	alluvium; angular andesitic boulders and cobbles in pale brown to grey brown silty matrix

Wairoa: a cutting 450 m east of C Wairoa Trig and 90 m west of Hydro Access Road No. 4 N112/105987.

Taupo Pumice	0.5 m	(variable) pale yellow ash, lapilli and blocks
Mangatawai Tephra	0.22 m	dark brown grey ash
Papakai Tephra	0.37 m	yellowish brown fine ash with sparse lapilli; buried soil (erosion)

Poutu Lapilli	0·58 m	strong brown lapilli
	0·11 m	andesitic tephra
Te Rato Lapilli	0·14 m	greenish grey lapilli and ash
	30 mm	yellowish brown ash and sparse coarse grey lithic ash
	0·14 m	yellowish brown fine and coarse ash
	50 mm	strong brown coarse ash and lapilli
	80 mm	strong brown ash with interspersed coarse ash and lapilli
	0·15 m	yellowish brown ash and sparse lapilli scattered charcoal (NZ 1187, Table 2)

(?Rotorua Ash is present as "cream cakes" in this position in nearby sections, e.g., N112/096989).

	0·13 m	yellowish brown ash with interspersed yellowish red lapilli
	0·25 m	yellowish brown ash; charcoal (NZ 1186, Table 2) scattered over top 80 mm
	20 mm	yellowish red pumiceous and lithic lapilli
	0·25 m	brown to yellow brown ash
	0·1 m	yellowish brown ash with interspersed strong brown pumiceous and dark grey to black lithic lapilli
	0·6 + m	yellowish brown loess and/or tephra

A. RHYOLITIC TEPHRAS

RHYOLITIC TEPHRA MARKER BEDS IN THE TONGARIRO AREA, NORTH
ISLAND, NEW ZEALAND

W. W. Topping and B. P. Kohn

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Topping recognised and mapped the rhyolitic tephtras, supplied the ^{14}C data, and collected most of the samples. The workers worked jointly on the heavy mineral assemblages of these and correlative tephtras from more northerly volcanic centres and Kohn's titanomagnetite analyses confirmed the correlations.

LATE OTIRAN RHYOLITIC TEPHRA MARKER BEDS

Most of the Aranuiian* rhyolitic tephra erupted from Taupo and Maroa volcanic centres and many of these erupted from Okataina Volcanic Centre have been identified within tephra sequences near Tongariro. It is probable therefore that several of the late Otiran** rhyolitic tephra from these centres were also deposited within Tongariro Volcanic Centre. Late Otiran erosion has removed much of the 14-20,000 years BP tephra record in the Tongariro area and a minority of sections expose tephra below the 20,000 year old Oruanui Formation. The rhyolitic tephra will therefore be present in few sections.

Six additional rhyolitic tephra not described in Topping and Kohn (1973) but likely to be of some limited use as marker beds are described and tentative correlations given. Most are known to occur in only one or two sections. Correlation will need to be sustained by a chemical "fingerprint" technique because only one of the presumed correlatives, Rotoehu Ash, is yet dated by radiocarbon; Taupo and Maroa source tephra older than 20,000 years BP have not yet been mapped.

Okareka Ash

A white rhyolitic fine ash, 10 mm thick, is found interbedded with andesitic tephra, peats and possible vivianite deposits, in a pit excavated on the eastern embankment of Otamangakau Canal (N112/107982). This ash occurs 240 mm above reworked Oruanui Breccia, 720 mm below

* Aranuiian Stage - period of warming and warmth following the last major maximum of the glaciers (Suggate 1961); post-glacial; c. 14,000 years BP to present day.

** Otiran Stage - period of cooling and cold of Otira (last) Glaciation (Suggate 1961).

Rotoaira Lapilli and 1.41 m below Rotorua Ash.

The ferromagnesian mineral assemblage of dominant biotite, calcic hornblende, and scarce hypersthene and cummingtonite (Table 3) along with the fine grain size indicate an Okataina source. The implied age (i.e. 13,800-20,000 years BP) suggests correlation with Rerewhakaaitu Ash, Okareka Ash or Te Rere Ash. Of these Te Rere Ash, with a declared ferromagnesian assemblage of hypersthene + calcic hornblende $\pm$ cummingtonite with only traces of biotite and augite (Kohn 1973) is probably not a valid correlative. The other two named tephra have assemblages similar to the unknown ash. Okareka Ash is favoured because Rerewhakaaitu Ash is identified in this area in a younger stratigraphic position (see Poutu and Te Ponanga Saddle reference sections, Appendix 1A). A radiocarbon date (N112/556) of 14,050 years BP obtained from a peat collected 60 mm above the unknown rhyolitic ash is inconclusive.

The correlation could be fully established in either of two ways - (a) by electron microprobe analysis of titanomagnetite grains, glass (Smith and Westgate 1969), or biotite (Desborough, Pittman and Donnell 1973); or (b) by recognition in further pits within Rotoaira Basin where peat for radiocarbon dating lies immediately above or below the ash.

Okaia tephra

The youngest rhyolitic tephra that pre-dates Oruanui Formation in sections north-west of the Tongariro Massif correlates with a Taupo source tephra known informally as Okaia tephra which has an estimated age of 22,000 years BP (C. G. Vucetich, pers. comm.). At a section 3.5 km west of Kuratau (section 193, N102/137137) Okaia tephra lies 210 mm below Oruanui Ash and comprises 120 mm of pale yellow medium to coarse rhyolitic tuff with white medium rhyolitic ash and charcoal fragments scattered within the overlying 70 mm of very dark brown tuff.

Okaia tephra is present in sections up to 5 km further west along the Tokaanu-Taumarunui Road (section 199, N102/079135). It can also be correlated southwards along West Taupo Road from Whangamata Road, the reference section.

The ferromagnesian mineral assemblage comprises hypersthene + calcic hornblende + rare augite.

Pink ash

A pale pink and white fine to medium rhyolitic ash, 400 mm thick at section 195 (N102/115136), and 520 mm thick at section 193 (N102/137137) occurs about 260 mm below Okaia tephra (e.g. section 193). It also occurs near the Turangi Lookout (section 94, N102/248009, see Appendix 1B) as a lens of bedded pink fine and white medium ash 250 mm thick. At this latter section it resembles its probable correlative, a pinkish tephra unit occurring between Okaia tephra and Rotoehu Ash (C. G. Vucetich, pers. comm.) on northern West Taupo Road. The ferromagnesian mineral assemblage (from sections 199 and 94) which comprises hypersthene + calcic hornblende + rare augite appears to confirm a Taupo Volcanic Centre source.

Unnamed ash

A probable rhyolitic fine ash, 60 mm thick, occurs at section 199 (N102/002129) where it is 400 mm below Okaia tephra and 370 mm above 'Pink ash'.

?Rotoehu Ash

Rotoehu Ash has been recognised at sections along Whangamata Road and northern West Taupo Road (C. G. Vucetich, pers. comm.) and it is probably present at the Turangi Lookout section (section 94, N102/248009, see Appendix 1B). Here it occurs as 'cream cakes' and in one 70 mm pocket

of pale yellow fine rhyolitic ash 2.55 m below Oruanui Formation. The ferromagnesian mineral assemblage of hypersthene + augite + calcic hornblende + cummingtonite + biotite (Table 3) is similar to the assemblage for Rotoehu Ash from sites north-west of Lake Taupo (R. Howarth pers. comm.).

Old unnamed ash

A white fine rhyolitic ash bed of 40 mm thickness underlies a black carbonaceous tuff at section 62 (N112/105979) on the western embankment of Otamangakau Canal. A small tree stump in situ on this black tuff has been radiocarbon dated (NZ1337, Table 4) at >47,000 years BP providing a minimum age for this unknown rhyolitic ash.

The ferromagnesian mineral assemblage of this 'Old unnamed ash' comprises hypersthene + calcic hornblende + augite (Table 3).

RHYOLITIC FERROMAGNESIAN MINERAL ASSEMBLAGES

The characteristic ferromagnesian mineral assemblages of thin rhyolitic tephra beds occurring within Tongariro Volcanic Centre have been used to confirm correlation of several tephtras (Topping and Kohn 1973).

Certain mineral assemblages are dominant in particular centres for certain time intervals. For example, cummingtonite is only known from Okataina Volcanic Centre (Kohn 1973), biotite is only known from Okataina and Maroa volcanic centres, and calcic hornblende is known from Okataina and Maroa volcanic centres, and from Taupo Volcanic Centre tephtras older than 20,000 years BP. Tephtras from Taupo Volcanic Centre, pre-20,000 years, contain a hypersthene + calcic hornblende + rare augite ferromagnesian mineral assemblage but may not be distinguished individually. Tephtras erupted from Taupo Volcanic Centre in the last 10,000 years which are the most common in the Tongariro Volcanic Centre contain hypersthene as the dominant ferromagnesian mineral. They can thus be distinguished from Okataina and Maroa source tephtras but cannot be distinguished from others from the same source.

Separation of the ferromagnesian minerals, from a 2-4 ϕ size fraction, was by means of a Frantz Isodynamic Separator. The assemblages are presented in Table 3.

B. ANDESITIC TEPHRAS

TEPHROSTRATIGRAPHY AND CHRONOLOGY OF LATE QUATERNARY ERUPTIVES
FROM THE TONGARIRO VOLCANIC CENTRE, NEW ZEALAND

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TEPHROSTRATIGRAPHY AND CHRONOLOGY OF LATE QUATERNARY ERUPTIVES FROM THE TONGARIRO VOLCANIC CENTRE, NEW ZEALAND

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ABSTRACT

The Tongariro Sub-group is defined to include all andesitic tephra of Aranuiian age erupted within the Tongariro Volcanic Centre from 13 800 years B.P. (NZ1559) to the present day. The source vents include Mounts Ruapehu and Ngauruhoe, Tama Lakes, Blue Lake, Red Crater, North Crater, and upper and lower Te Mari Craters.

Two previously named tephra, Ngauruhoe Tephra and Mangatawai Tephra, are given formation status. The units have accumulated intermittently over the period 0–1819 years B.P. and c. 1819–2500 years B.P., respectively. A further four formations are defined: Papakai Tephra has accumulated intermittently between c. 3400–9700 years B.P.; Mangamate Tephra, with six named members, was erupted mainly from the Tama Lakes–Ngauruhoe area between c. 9700–9780 years B.P.; Okupapa Tephra was erupted from Mount Ruapehu over 9790 years B.P.; and Rotoaira Lapilli, which marks the base of the Tongariro Sub-group, was probably erupted from lower Te Mari Crater 13 800 years B.P.

Volumes are calculated and isopach maps are presented for four of the formations and three of the members.

INTRODUCTION

The lava flows and lahar ring plains of the Tongariro Volcanic Centre have been mapped by Grindley (1960), Grindley and Mathews (1965), and Mathews (1967). These authors grouped volcanic formations which they considered to have been formed during Post-glacial, Last Glaciation and Penultimate Glaciation times. This mapping, together with limited K–Ar dating (Stipp 1968), provides a guide to the geological history of the Tongariro Volcanic Centre. A study of the tephra deposits about the volcanoes, however, allows a greater appreciation of this history.

The probable source vent of a particular tephra can be determined where the tephra distribution pattern is known, and the age of the eruptive event is known where the tephra is radiocarbon-dated from stratigraphic sections containing peat, charcoal or wood. The vent from which a flow was extruded is often known, so that the oldest dated tephra upon such a lava flow or dome provides a minimum age for that flow. Alluvium, lahars, glacial outwash, loess, etc., where interbedded with tephra, can all be dated, and in this way a comprehensive history can be built up. During periods of colder climate weakly consolidated tephra are more susceptible to erosion, and the tephra column therefore has a climatic story within it.

In this paper the stratigraphy and chronology of andesitic tephra erupted from about nine vents (Fig. 1) within the Tongariro Volcanic Centre over the past 14 000 years are described, and the tephra are grouped into a

FIG. 1—Locality map of study area. Numbers refer to reference sections (see Appendix): 1 Mangatawai, 2 Access 10, 3 Poutu, 4 Okupata, 5 Wairoa.

Tongariro Sub-group. The formalised units are considered the minimum number likely to be required in dating volcanic, tectonic and climatic events.

Further chronology is provided by the identification of 13 rhyolitic tephra erupted from Okataina, Maroa, and Taupo Volcanic Centres over the last 20 000 years and interbedded with andesitic tephra. These thin tephra beds have been described elsewhere (Topping & Kohn 1973).

PREVIOUS WORK

A widespread rhyolitic marker, the Taupo Pumice (Baumgart 1954; Healy 1964), was early used to separate the two youngest andesitic units of "intermittent" (Taylor 1953) origin. All andesitic tephra above Taupo Pumice have been referred to as Ngauruhoe ash (Grange & Hurst 1929; Grange & Williamson 1930; Grange 1931; Grange & Taylor 1931; N.Z. Soil Bureau 1954; Gregg 1960 [Ngauruhoe Ash]) and the "thinly bedded dark grey andesite ash containing leaves" (Grange & Hurst 1929, p. 7) below Taupo Pumice has been named Mangatawai Ash by Gregg (1960).

"Fine brown andesite ash" and "andesite lapilli" (Grange & Hurst 1929; Grange & Williamson 1930) underlying Mangatawai Ash were described as the youngest beds of the Tongariro shower (Grange 1931; Grange & Taylor 1931; N.Z. Soil Bureau 1954; Tongariro Ash of Gregg 1960). The youngest beds were mapped as a soil forming ash where not covered by Ngauruhoe Ash and Taupo Pumice (Grange 1931; Grange & Taylor 1931; N.Z. Soil Bureau 1954). Where covered by younger tephra, Thomas (1889) recognised that the "fine brown andesite ash" forms a conspicuous paleosol.

DEFINITION OF FORMATIONS AND MEMBERS

Rhyolitic tephra eruptions tend to be "paroxysmal" (Taylor 1953); bursts of violent activity are separated by long periods of inactivity during which prominent paleosols are usually formed. Rhyolitic tephra formations have been defined from the bracketing paleosols and erosion breaks (Vucetich & Pullar 1964, 1969, 1973; Baumgart 1954; Healy 1964). Although andesitic tephra may have a paroxysmal origin, for example Te Rato Lapilli and Poutu Lapilli, much of the tephra accumulation is "intermittent" (Taylor 1953). The natural vegetation generally accommodates tephra accretions without any one tephra layer being differentially weathered and preserved as a paleosol horizon. The andesitic tephra often do not have the well-developed paleosols which are most appropriate to define formation boundaries.

Most tephra erupted from Mount Ruapehu between about 10–14 000 years B.P. have been very strongly wind-controlled, and most of these have been deposited to the east of the volcano. These eastern deposits accumulated too rapidly for soils to form. Fewer eruptives have gone to the north, and here paleosols are preserved. At a section on the National Park–Taupo Road (N112/037866)* paleosols are quite distinct, each recognised by vertical

*Grid reference based on the national thousand-yard grid of the 1:63 360 topographical map series (NZMS 1)

FIG. 2.—Paleosols developed within tephra erupted northwards from Mount Ruapehu between c. 10–14 000 years B.P. The paleosols are recognised by pronounced cracking, darker colour, and increased clay content. Basal lapilli of Okupata Tephra (oa), ?Rotorua Ash (rr).

and horizontal cracking, darker colour, and increased clay content, and each developed upon ash overlying a basal lapilli (Fig. 2). If adequate sections were available these paleosols could be used to define formations.

In the absence of paleosols north of Tongariro, other criteria have had to be used to define formations. In swamps the presence of peat between tephra allows the tephra to be divided up into formations, the peat accumulation representing time during which a soil would be forming elsewhere. Widespread erosional unconformities also represent time, and are used to define formations.

Thirteen rhyolitic tephra are interbedded with the andesitic tephra within the Tongariro area. Two of the thirteen are widespread, and have been used to define the base and top for three andesitic tephra formations of intermittent origin.

STRATIGRAPHY AND CHRONOLOGY

The **Tongariro Sub-group** is here defined to include all tephra from the present day to 13 800 years B.P. (base of Rotoaira Lapilli) that originated within the Tongariro Volcanic Centre (Grindley 1960).

Rerewhakaaitu Ash, radiocarbon dated at $14\,700 \pm 200$ years B.P. (NZ716; Vucetich 1968) was defined as the base of both the Holocene and Rotorua Sub-group in the Rotorua region, about 140 km north of Tongariro (Vucetich & Pullar 1964). Rerewhakaaitu Ash is interbedded in andesitic tephra below the Rotoaira Lapilli in two sections north of Tongariro (Poutu

and Te Ponanga reference sections, see Appendix) and has been identified within andesitic tephra on a lateral moraine on the northern side of Mangatepopo Valley (Topping & Kohn 1973). The base of the Tongariro Sub-group is therefore slightly younger than the base of the Rotorua Sub-group.

Rotoaira Lapilli has a maximum age of $13\,800 \pm 300$ years B.P. (NZ 1559), making the Tongariro Sub-group equivalent to the Aranui Stage of Suggate (1961), and post Kumara-3 glacial advance in age (Gage & Suggate 1958).

Tephra formations within the Tongariro Sub-group are shown in Table 1.

The widespread and easily recognisable rhyolitic Taupo Pumice is used to define the base and top of Ngauruhoe Tephra and Mangatawai Tephra formations respectively. The top of Mangatawai Tephra has undergone weak paleosol development.

The rhyolitic Waimihia Lapilli (Baumgart 1954; Healy 1964) defines the top of Papakai Tephra Formation, and the base of Papakai Tephra is defined by a widespread erosion contact with Poutu Lapilli, youngest member of the Mangamate Tephra Formation. Peat is present beneath Te Rato Lapilli Member in sections in swamps north-west of Tongariro, thus defining the base of Mangamate Tephra. In these same sections peat is not present between members of the formation.

Okupata Tephra has a well developed paleosol and is separated, in swamp sections, by peat from Mangamate Tephra. Its base is defined by an underlying paleosol (see Fig. 2).

Rotoaira Lapilli is an easily recognisable marker over a large area north and north-east of Tongariro. It usually lies unconformably on older andesitic tephra or Oruanui Formation or Hinuera Formation (see Topping and Kohn, 1973), and marks the base of the Tongariro Sub-group. The top of Rotoaira Lapilli lacks a paleosol or evidence of an erosion break useful to define formation status. However, it can be readily mapped, and because it is a valuable marker it is given formation status.

NGAURUHOE TEPHRA FORMATION

Ngauruhoe Tephra was first described as "... andesite ash and scoria from Ngauruhoe, etc. (Recent) ..." overlying Taupo Pumice by Grange & Hurst (1929, p. 6), and was later named Ngauruhoe ash by Grange & Taylor (1931, p. 7). The name Ngauruhoe Ash (Gregg 1960) has been adopted through general usage, but Ngauruhoe Tephra is proposed here because Ngauruhoe ash contains scoriaceous lapilli horizons closer to Mount Ngauruhoe and Mount Ruapehu. It is given formation status so that prominent beds within the tephra may in the future be defined as members.

The type section is a cutting on the Desert Road on the southern side of the Mangatawai Stream (Mangatawai reference section, N112/250806), where Ngauruhoe Tephra comprises 0.44 m very dark grey to dark brown fine and medium ash.

CRITERIA: The lower contact with Taupo Pumice is gradational and difficult to define; the upper part is the present-day soil, and is still accumulating. Ngauruhoe Tephra is locally over-thickened by accretion of windblown sand and silt on the Desert Road, for example 2-3 m thick at N122/223622 (1068 m); above 1405 m altitude on northern Ruapehu; above 1525 m on southern Ruapehu.

BEST LOCALITIES: Mangatawai reference section (N112/250806), and sections to the south on the Desert Road; section (N112/041735) on road to Iwikau Alpine Village, where seven tephra beds can be recognised within Ngauruhoe Tephra.

SOURCE: Ngauruhoe Tephra has resulted from eruptions from Te Mari craters, Red Crater, Ngauruhoe, and Ruapehu since about 1819 years B.P. (Healy 1964). The thickness distribution pattern (Fig. 3) shows that Ruapehu has contributed more tephra to this deposit than has Ngauruhoe (see also Gregg 1960; Fig. 8) and westerly winds have been dominant during accumulation.

The volume of Ngauruhoe Tephra is about 1.3 km^3 .

MANGATAWAI TEPHRA FORMATION

The name Mangatawai Ash was proposed by Gregg (1960) for the "thinly bedded dark grey andesitic ash containing leaves" of Grange & Hurst (1929, p. 7). The type locality is a cutting on the Desert Road on the south side of the bridge over Mangatawai Stream, where the unit comprises 0.29 m dark brown fine ash giving way to 0.5 m of dark grey medium ash with interbedded dark grey and very dark grey medium ash containing *Nothofagus* sp. leaves. The upper ash layer has undergone weak soil development, and is overlain by Taupo Pumice (c. 1819 years B.P.; Healy 1964). Unnamed andesitic tephrae separate each of Mangatawai Tephra, Whakaipo Tephra (Vucetich & Pullar 1973), Waimihia Lapilli (Baumgart 1954) and the andesitic Papakai Tephra.

As several lapilli units occur within the ash closer to Ngauruhoe the name should more correctly be Mangatawai Tephra, and the unit is here given formation status.

Isopachs for Mangatawai Tephra (Gregg 1960) confirm Grange & Hurst's (1929, p. 7) belief that most of the ash is from Ngauruhoe. Leaves from the lower 80 mm returned an age of 2500 ± 200 years B.P. (Fergusson & Rafter 1959; NZ186), showing that the formation is the result of about 700 years intermittent activity.

PAPAKAI TEPHRA FORMATION

Thomas (1889, p. 352) described a section on the slopes above Papakai, and recognised a paleosol developed on ash and lapilli beds later referred to collectively as the Tongariro shower (Grange 1931; Grange & Taylor 1931) or Tongariro Ash (Gregg 1960). These beds have been considered the

FIG. 3—Isopachs (mm) of Ngauruhoe Tephra (based on 111 measurements).

parent material of present day soils south of the volcanoes, where the younger Taupo Pumice and less widespread, younger andesitic tephras are absent (Grange 1931; N.Z. Soil Bureau 1954).

This tephra unit is here named Papakai Tephra after a Maori settlement SE of the junction of the National Park-Taupo Road and Rotoaira Road. The type section is a large cutting 1.5 km SE of Papakai (N112/125924), where the tephra comprises up to 0.87 m yellowish brown greasy ash with interspersed grey fine to medium lapilli, occurring above Poutu Lapilli and below andesitic ash containing Waimihia Lapilli. Papakai Tephra can best be recognised by seeing the tephra at the type section in conjunction with Poutu, Access 10 and Mangatawai reference sections.

CRITERIA: Papakai Tephra is invariably characterised by its greasy consistency, the prominent vertical and horizontal cracking (denoting a paleosol), and the presence of interspersed grey lapilli. It overlies Poutu Lapilli, and its top is defined either by the first appearance of Waimihia Lapilli or, where Waimihia Lapilli is absent, on the upper limit of both cracking and interspersed lapilli. In many sections the Papakai Tephra grades into Poutu Lapilli; sometimes this lower contact is regular, as in Fig. 4, but more often it is irregular, as a result of either erosion or soil formation. Soil development, assessed on higher clay content, darker colour, and pronounced weathering, is best near the base of Papakai Tephra (e.g., N122/223694).

BEST LOCALITIES: Papakai reference section (N112/125924) and other sections on the National Park-Taupo Road between Papakai and Rangipo; cutting on branch road from Hydro Access Road No. 4 (N112/099984); Poutu, Access 10, and Mangatawai reference sections.

FIG. 4—Section on a branch road from Hydro Access Road No. 4 (N112/099984), showing paleosol development of Papakai Tephra Formation (pp), which at this site is conformable with Poutu Lapilli (pt). Also shown are Te Rato Lapilli (tt), Mangatawai Tephra (mg), and the rhyolitic Taupo Pumice (tp).

FIG. 5—Isopachs (mm) of Papakai Tephra Formation (based on 174 measurements).

AGE: An estimated lower age limit for Papakai Tephra is 9700 years B.P., for Poutu Lapilli obtained from a dated wood sample 0.09 m above Poutu Lapilli within a peat swamp cut by the Otamangakau Canal (see under Poutu Lapilli). The Waimihia Lapilli provides an upper age limit of about 3400 years B.P. Papakai Tephra thus spans about 6300 years.

SOURCE: The thickness distribution pattern (Fig. 5) suggests that a major volume of Papakai Tephra originated from the Ngauruhoe-Tama Lakes region and from one of the northern Tongariro craters (Lower Te Mari Crater, North Crater or Blue Lake). Grange & Hurst (1929, p. 7) considered their "fine brown andesitic ash" unit (Papakai Tephra) and the underlying "layer of andesite lapilli" (Poutu Lapilli) to be from the Tama craters.

Several debris flows came down the Mangatipua Stream during deposition of Papakai Tephra, confirming activity from one of the northern vents. Tephra from Mount Ruapehu is also known to contribute to Papakai Tephra (e.g., section at N112/062783).

The volume of Papakai Tephra is about 1.5 km³.

MANGAMATE TEPHRA FORMATION

Mangamate Tephra is a new formation name for several andesitic tephtras underlying Papakai Tephra Formation and overlying a thin rhyolitic marker bed, Papanetu Tephra (Topping & Kohn 1973). All but one of the six named members were erupted eastwards from Tongariro, and the reference section is thus designated where all can be readily identified in relation to each other and the associated rhyolitic tephtras. The reference section (Access 10) is within a large cutting on the crest of a hill on Hydro Access Road No. 10 (N112/301844), 2.5 km east of the Desert Road. The formation name is taken from the nearby Mangamate Stream. At this section the formation, directly under Papakai Tephra, and conformable with older tephtras, comprises

Poutu Lapilli	0.43 m	yellowish red stained lithic lapilli
Wharepu Tephra	40 mm	grey to yellowish brown ash
Poronui Tephra	10 mm	yellow fine rhyolitic ash
Ohinepango Tephra	30 mm	strong brown medium ash
	40 mm	grey-black medium ash
	40 mm	strong brown and black medium ash
	30 mm	grey-black medium ash
Waihohonu Lapilli	70 mm	yellowish red and grey fine lapilli and coarse ash
unnamed tephra	40 mm	dark yellowish brown coarse ash
Oturere Lapilli	0.1 m	yellowish red coarse lapilli
	20 mm	yellowish red coarse ash
	30 mm	yellowish red coarse lapilli
	20 mm	yellowish red coarse ash
	30 mm	yellowish red coarse lapilli
Te Rato Lapilli	10 mm	grey coarse ash.

The rhyolitic Poronui Tephra which is interbedded with upper members of the Mangamate Tephra Formation has been described as a Taupo Sub-group formation by Vucetich & Pullar (1973). It is not here regarded as part of this andesitic formation.

In a section near Wairehu Canal (N112/145983) a 5 mm thickness of peat separates Te Rato Lapilli, the oldest member of Mangamate Tephra, from Papanetu Tephra, which is separated from Okupata Tephra Formation by a further 20 mm thickness of peat. This hiatus is used to define Te Rato Lapilli as the base of the formation. The basal part of Papakai Tephra has undergone intense soil development, and there is often an erosion surface separating it from Poutu Lapilli. The oldest and youngest members of Mangamate Tephra are easily recognised, and the formation is therefore also easily recognised.

Te Rato Lapilli thickens to the north and west, while the other named members, with the exception of Poutu Lapilli, thin in these directions as they were erupted eastwards from Tongariro. Poutu Lapilli has lobes to NW, NE and SE, and is the most extensive member. All members are most easily identified at Access 10 and in sections near Poutu Canal, where the formation totals less than 1 m, and become more difficult to identify further south, where thickness exceeds 4 m and the individual beds become confusingly alike.

Poutu Lapilli and Te Rato Lapilli are named from reference sections on the National Park-Taupo Road. The other members are each named from localities along the Desert Road where maximum thickness is attained. Minor ash and lapilli beds between Waihohonu Lapilli and Oturere Lapilli are not named or described here, and tephra bracketed by Poutu Lapilli and Te Rato Lapilli on the National Park-Taupo Road in sections near Te Rato School cannot be correlated with members described in this account.

Poutu Lapilli Member

Poutu Lapilli is a new member name applied to a tephra unit of lapilli grade size erupted largely to the north of Tongariro. It is overlain by Papakai Tephra, and conformably underlain by Wharepu Tephra Member and a thin rhyolitic tephra, Poronui Tephra (Vucetich and Pullar 1973; Topping & Kohn 1973).

The reference locality is a large cutting on the National Park-Taupo Road (N112/237901) 5.7 km from Rangipo (Fig. 6). At this section, Poutu Lapilli consists of 0.9 m of brownish yellow bedded coarse ash and lapilli. CRITERIA: Poutu Lapilli consists of finely vesicular grey lapilli and minor andesitic lava fragments. The iron-stained lapilli are bedded with little vertical change in grade-size. The upper contact with Papakai Tephra Formation may be gradational with increase in ash content (see Fig. 4), or may be sharp and conformable (see Fig. 6), or eroded. Some of the grey lapilli within Papakai Tephra may have been reworked from the underlying Poutu Lapilli.

BEST LOCALITIES: Poutu reference section (N112/237901) and other cuttings along the National Park-Taupo Road between Papakai and Rangipo; cutting on branch road from Hydro Access Road No. 4 (grid ref. N112/099984; Fig. 4).

FIG. 6—Poutu reference section on National Park-Taupo Road (N112/239901), type section for Poutu Lapilli member of the Mangamate Tephra Formation (pt), and Rotoaira Lapilli Formation (rt). Rotoaira Lapilli unconformably overlies Hinuera Formation (hi) and Oruanui Formation (ou). Also shown are Papakai Tephra (pp) and Te Rato Lapilli (tt).

AGE: Poutu Lapilli occurs 90 mm below a dated wood sample (N.Z. 1335, Table 2) from a peat swamp cut by the Otamangakau Canal (grid ref. N112/109984). An extrapolation of the uniform accumulation rate for the peat gives an age of 9700 years B.P. for Poutu Lapilli, and a younger age limit for Mangamate Tephra Formation. An age of 9780 ± 170 years B.P. (N.Z. 1372) immediately below Te Rato Lapilli provides a useful check and a maximum age.

DISTRIBUTION: The isopach map for Poutu Lapilli (Fig. 7) shows a trilobed distribution pattern with lobes to the NW, NE and SE. No peat occurs within Poutu Lapilli in a swamp cut by the Wairehu Canal (grid ref. N112/145983), showing that no appreciable time separates these two lobes.

The three lobe axes meet in the vicinity of Blue Lake, which is regarded as the most likely source.

The volume of Poutu Lapilli is about 0.9 km^3 .

Wharepu Tephra Member

Wharepu Tephra is a new name for the second youngest member of the Mangamate Tephra Formation. It is named after Wharepu C Trig, which is 1.5 km west of a section on the Desert Road (N122/219675) where the upper bed is very prominent. At this section the 0.43 m thick Poutu Lapilli

TABLE 2—Radiocarbon ages for andesitic tephra of Tongariro Sub-group.

FOSSIL RECORD NO. NZ14C NO.	14C AGE YEARS B.P. (1950)	EVENTS AGED	SAMPLE DESCRIPTION: STRATIGRAPHIC POSITION	LOCALITY (NZMS1 (1968))*
N112/544 NZ1336	3,200 $\pm$ 50	Provides check on rate of accumulation of peat and thus a more accurate estimate of age of Pou-tu Lapilli	Wood: within peat; 0.66 m below base of Taupo Pumice, 3.46 m above Pou-tu Lapilli	Tongariro, N112/109984; swamp cut by Oramangakau Canal, Tongariro Power Scheme
N112/545 NZ1335	9,560 $\pm$ 100	Minimum age for Pou-tu Lapilli	Wood: small branches from peat 4.03 m below Taupo Pumice and 90 mm above Pou-tu Lapilli	"
N112/551 NZ1373	9,700 $\pm$ 210	Maximum for Te Raro Lapilli	Peat: 5 mm horizon below Te Raro Lapilli and above Papanetu Tephra	Tongariro: N112/145983; swamp cut by Wairerehu Canal, Tongariro Power Scheme. Approx. 0.9 km NW at point where Rotoaira Road crosses canal
N112/550 NZ1372	9,780 $\pm$ 170		Wood: twigs from 5 mm horizon of peat separating Te Raro Lapilli from the underlying Papanetu Tephra	"
N112/552 NZ1374	9,790 $\pm$ 160	Minimum age for Okupata Tephra	Wood: twigs from 20 mm of peat below Papanetu Tephra and above Okupata Tephra	"
N112/549 NZ1338	9,540 $\pm$ 100	Dates lahar; provides a minimum age for Okupata Tephra	Wood: within Ruapehu laharic debris below Mangatawai Tephra and above Okupata Tephra	Tongariro: N112/010820; cuttings on National Park - Taupo Highway immediately north of bridge over Whakapapanui Stream
N112/541 NZ1189	12,450 $\pm$ 340	Provides age for Okupata Tephra and a maximum for Te Raro Lapilli	Charcoal: with Okupata Tephra, 30 mm below Papanetu Tephra	Tongariro: N112/101977; cutting northern side Access Road No. 4, Tongariro Power Scheme, near junction of Papakai and Waitehohi Streams
N112/548 NZ1559	13,800 $\pm$ 300	Maximum age for Rotoaira Lapilli	Charcoal: within andesitic tephra immediately underlying Rotoaira Lapilli Formation	Tongariro: N112/298951; cutting on eastern side of Desert Road, east of Pihanga and 6.4 km south of Turangi

* All samples collected by W.W. Topping

FIG. 7.—Isopachs (mm) of Poutu Lapilli, youngest member of the Mangamate Tephra Formation (based on 188 measurements).

is separated from Papakai Tephra by an erosion break. Wharepu Tephra comprises

0.32 m	grey coarse lithic ash and lapilli with minor brown-stained lapilli
0.1 m	bedded grey and brown coarse ash and lapilli
0.17 m	red-stained fine and medium lithic lapilli
20 mm	brown ash

and overlies Poronui Tephra a 10 mm thick yellow rhyolitic tephra.

Wharepu Tephra consists essentially of two lapilli lobes above a 20 mm horizon of brown fine ash. The brown ash coarsens northwards to a 20 mm horizon of grey medium ash as the two lapilli beds thin. From Mangatawai reference section northwards Wharepu Tephra is of medium ash grade, and cannot be distinguished from the underlying Ohinepango Tephra except for the presence of Poronui Tephra between them. In a few sections along the Desert Road (e.g., N112/231741, N112/243764) both Poronui Tephra and Ohinepango Tephra have been eroded off, but Wharepu Tephra is complete. There is, therefore, a time break between Poronui Tephra and Wharepu Tephra. Because no peat separates Poutu Lapilli and Te Rato Lapilli in a swamp cut by the Wairehu Canal (N112/145983), this time break is not regarded as significant enough to warrant formation status.

A partial isopach map for Wharepu Tephra shows that the uppermost bed was distributed in a more southerly lobe than the second (and thinner) bed, and that the member was probably erupted from the Tama Lakes area.

Ohinepango Tephra Member

Ohinepango Tephra is best represented in sections on the Desert Road near Ohinepango Stream, from which it takes its name. It is characterised by its uniform medium to coarse sand grade size and the alternation of black, and black and brownish yellow or strong brown coloured horizons. It is often very similar to Wharepu Tephra, so that the presence of Poronui Tephra is needed to divide them. At a section where a small unnamed tributary of the Waihohonu Stream is crossed by the Desert Road (N112/240747), Ohinepango Tephra comprises

- 60 mm dark grey-black and strong brown medium ash (Poronui Tephra 1 cm fine yellow rhyolitic ash)
- 70 mm black and brownish yellow medium ash
- 50 mm strong brown and black medium ash
- 50 mm black ash
- 50 mm black and strong brown medium ash
- 10 mm black medium ash.

Ohinepango Tephra is everywhere conformable with the underlying Waihohonu Lapilli except at a section near Waihohonu River Bridge, on the Desert Road (N112/224736), where 0.14 m of gravels separates them. This event is considered to be so localised as not to affect the member status of either unit. Poronui Tephra lies above Ohinepango Tephra north of Mangatawai reference section, but further south the youngest part of Ohinepango Tephra overlies Poronui Tephra.

Partial isopach control shows an ESE-orientated lobe probably from a source in the Tama Lakes-Ngauruhoe area.

Waihohonu Lapilli Member

Waihohonu Lapilli is a new member name applied to a tephra unit which reaches a maximum thickness at a section where a small unnamed tributary of the Waihohonu Stream is crossed by the Desert Road (N112/240747). At this section Waihohonu Lapilli comprises

0.42 m	grey and strong brown fine and medium lithic lapilli
5 mm	light brown ash
0.52 m	strong brown and grey fine to coarse lithic lapilli
0.36 m	strong brown and grey fine, and scattered medium and coarse lithic lapilli.

Waihohonu Lapilli is everywhere conformable with older "unnamed tephra" and the younger Ohinepango Tephra, except where a 0.14 m unit of silt, sand, cobbles, and rare boulders (mudflow?) underlies the latter at a section near Waihohonu River bridge on the Desert Road (N112/224736). Waihohonu Lapilli consists of several beds which coarsen and reach maximum thicknesses at various places along the Desert Road. The light brown ash is a valuable marker within the beds, and the enclosing members are easily recognisable, i.e., the strong brown and dark grey medium to coarse ash of Ohinepango Tephra, and largely ash grade "unnamed tephra".

Partial isopach control suggests a source or sources in the Tama Lakes-Ngauruhoe area.

Oturere Lapilli Member

This new lapilli member is best seen in sections on the Desert Road near Oturere Trig. At the Makahikatoa Stream Bridge on the Desert Road (N112/250787), for example, Oturere Lapilli comprises 0.5 m grey and iron-stained yellow fine to very coarse lapilli conformably overlying 20 mm of Te Rato Lapilli, and in turn underlying "unnamed tephra" and Waihohonu Lapilli.

In the north shower bedding is present, and is best represented at the Access 10 reference section. Oturere Lapilli is readily identified from the overlying yellowish brown to brown ash ("unnamed tephra") and the underlying Te Rato Lapilli.

A partial isopach map shows a lobe axis directed eastwards from a possible Tama Lakes-Ngauruhoe source.

Te Rato Lapilli Member

Te Rato Lapilli is a new member name applied to a tephra unit of lapilli grade stratigraphically below Oturere Lapilli. It is immediately underlain by another rhyolitic tephra, Papanetu Tephra (Topping & Kohn 1973). The reference locality (N112/124928) is a road cutting on the National Park-Taupo Road 1 km SE of Papakai and 0.8 km SE of Te Rato School, where the formation is described as

10 mm	grey ash
0.4 m	very dark grey lithic lapilli and light yellowish brown finely vesiculated lapilli.

CRITERIA: Te Rato Lapilli is the most easily recognisable of the Tongariro eruptives, and is characterised by its very dark grey colour and the presence

of two different types of lapilli. Light, non-vesicular, very dark grey angular fine-grained andesite fragments are mixed with fewer, larger light yellowish brown finely vesicular dacitic lapilli. The unit can be recognised on the lateral margins where only 5 mm thick, but is harder to define accurately near the terminal margin of the lobe. It can be recognised as far north as the Taupo–Napier Highway.

BEST LOCALITIES: National Park–Taupo Road from Papakai to Poutu reference site (N112/237901).

AGE: Wood in the 5 mm of peat immediately underlying the lapilli has been dated at 9780 ± 170 years B.P. (NZ1372, Table 2), which is taken as both the age of Te Rato Lapilli and the older age limit for the formation.

DISTRIBUTION: The thickness distribution pattern (Fig. 8) is a lobe directed to the NNE of the Tongariro Massif. The lobe axis coincides with the lineation of eruptive centres, so that from the isopach map alone this member cannot be positively assigned to a particular vent. Explosive eruptions took place from the Tama Lake–Ngauruhoe region both before and after Te Rato Lapilli deposition; lava flowed from one of the Te Mari craters, and a nuée ardente took place from North Crater, before Te Rato Lapilli

FIG. 8—Isopachs (mm) of Te Rato Lapilli, oldest member of the Mangamate Tephra Formation (based on 143 measurements).

was erupted: any of these vents is thus a possible source. However, the absence of Te Rato Lapilli in sections to the west of Ngauruhoe suggests that North Crater is the most likely source.

The volume of Te Rato Lapilli is about 0.1 km^3 .

OKUPATA TEPHRA FORMATION

The youngest prominent lapilli unit that was erupted northwards from Ruapehu has a distinctive paleosol, and is very prominent along the National Park-Taupo Road south of Taurewa; it is here named Okupata Tephra Formation. It is the youngest of a series of units, each consisting of a basal lapilli with a paleosol developed on the overlying ash, distributed to the north of Ruapehu.

The type section is on the National Park-Taupo Road, 5.8 km SSW of Taurewa (N112/023850; location 4, Fig. 1), where Okupata Tephra comprises

- 80 mm yellowish brown ash with scattered yellow medium and coarse lapilli and a few dark grey fine lithic lapilli, paleosol
- 80 mm yellow fine to coarse lapilli
- 80 mm strong brown fine to coarse lapilli.

At this locality, Okupata Tephra is overlain by undifferentiated Mangamate Tephra and is underlain by a paleosol. Further north (e.g., 1 km SSW of Taurewa, N112/050895), Te Rato Lapilli Member of Mangamate Tephra Formation overlies Okupata Tephra.

The yellow colour of the uppermost lapilli and the strong brown colour of the lowermost lapilli serves to distinguish this formation from underlying lapilli beds.

An isopach map for thicknesses of the basal lapilli of Okupata Tephra (Fig. 9) shows a confined lobe distributed to the north of Ruapehu. The grey fine lithic lapilli within the ash above the basal lapilli are similar to those making up Mangamate Tephra, and are also considered to be from a Tongariro source.

At several sections, the positions of trees living at the time the lapilli were deposited are shown from the ash-filled casts in this layer. Wood from a 20 mm horizon of peat separating Papanetu Tephra (Topping & Kohn 1973) from Okupata Tephra gave an age of 9790 ± 160 years B.P. (NZ1374, Table 2), and charcoal from Okupata Tephra from a section 4 km further west (N112/101977) returned an age of $12\,450 \pm 340$ years B.P. (NZ1189, Table 2).

The volume of the basal lapilli of Okupata Tephra is about 0.2 km^3 .

ROTOAIRA LAPILLI FORMATION

This is a new formation name for a multiple lapilli unit very prominent in sections SE of Lake Rotoaira. The type locality is the Poutu reference section

FIG. 9—Isopachs (mm) of the basal lapilli of the Okupata Tephra Formation (based on 59 measurements).

(see Fig. 6), a large cutting on the National Park-Taupo Road 5.7 km west of Rangipo (N112/239901). At this section Rotoaira Lapilli comprises

0.16 m	yellowish red coarse ash and lapilli
20 mm	(10–50 mm) black ash
0.2 m	shower bedded brownish yellow lapilli and coarse ash.

The lower contact is distinct, the upper contact moderately distinct. Rotoaira Lapilli is rarely conformable with older andesitic tephra near Tongariro, and often lies on eroded Oruanui Formation or Hinuera Formation (Topping & Kohn 1973). It is the oldest andesitic unit conformable with the present day topography in the area south-east of Lake Rotoaira, and defines the base of the Tongariro Sub-group. No time break can be proven above Rotoaira Lapilli, but formation status is given to Rotoaira Lapilli because of the ease with which it can be mapped, and its usefulness as a marker.

CRITERIA: To the north of Tongariro, the black ash separating the two lapilli horizons can be recognised even where Rotoaira Lapilli is only 40 mm thick, and is therefore a valuable character to aid in its identification. The yellowish red colour of the upper lapilli horizon and brownish yellow of the lower can also be recognised as far north as Turangi, and allows this tephra to be distinguished from an otherwise similar younger lapilli unit. Charcoal fragments are rarely present immediately below Rotoaira Lapilli.

BEST LOCALITIES: Poutu and Access 10 reference sections; sections along the eastern part of National Park-Taupo Road; and alongside Poutu Stream near McDonnell's Redoubt (N112/238913).

AGE: Charcoal directly below Rotoaira Lapilli from a section on the Desert Road east of Pihanga (N112/298951), and considered to have been carbonised by this particular eruption, returned an age of $13\,800 \pm 300$ years B.P. (NZ1559, Table 2).

SOURCE: The pattern of thickness distribution (Fig. 10) suggests a northern Tongariro source. The stratigraphic position of Rotoaira Lapilli could not be identified with certainty in sections south of Mangatawai reference section; the isopach map is therefore incomplete. Lava flows were erupted from the Te Mari craters shortly after Rotoaira Lapilli deposition. Chemical analyses and titanomagnetite data for two of the flows exposed in Lower Te Mari Crater are very similar to analyses of Rotoaira Lapilli. A lower Te Mari source is most probable.

The volume of Rotoaira Lapilli is at least 0.2 km^3 .

TEPHRA VOLUME

Volumes for tephra described in this paper have been calculated using the formula $13.08ab^2$ (Cole & Stephenson 1972), where 'a' is the thickness of the tephra at the source and 'b' is the distance over which that thickness is halved. For asymmetrical distribution patterns, radii of circles of the same area as that enclosed within each of the isopachs were determined (Thorarinson 1954). The radii were then plotted against isopach thicknesses on log-

FIG. 10—Isopachs (mm) of Rotoaira Lapilli Formation (based on 73 measurements). Rotoaira Lapilli cannot be mapped any further south than shown because deep sections are lacking.

normal paper, and 'a' read as the intercept of the line with the y-axis. The resulting tephra volume values (km^3) are

Ngauruhoe Tephra	1.3
Papakai Tephra	1.5
Poutu Lapilli	0.9
Te Rato Lapilli	0.1
Okupata Tephra basal lapilli	0.2
Rotoaira Lapilli	0.2

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APPENDIX

REFERENCE SECTIONS

Mangatawai: a cutting on the Desert Road on the southern side of the bridge over Mangatawai Stream, N112/250806. Type section for Ngauruhoe Tephra Formation and Mangatawai Tephra Formation.

Ngauruhoe Tephra	0.44 m	very dark grey medium ash to dark brown fine ash
Taupo Pumice	0.2 m	(in pockets) pale yellow coarse to fine rhyolitic ash, lapilli and small blocks
Mangatawai Tephra	0.79 m	0.29 m dark brown fine ash giving way to dark grey medium ash with interbedded dark grey medium ash containing yellow leaves
Whakaipo Tephra & Waimihia Lapilli	0.24 m	dark yellowish brown fine and medium ash with pale yellow medium rhyolitic ash, giving way to yellowish brown coarse rhyolitic ash
Papakai Tephra	0.24 m	yellowish brown fine ash with interspersed grey and strong brown stained fine to medium lapilli; buried soil
Poutu Lapilli	0.54 m	strong brown fine and medium lapilli and grey lithics

Wharepu Tephra	70 mm	40 mm grey to dark olive-grey medium ash; 30 mm dark olive grey and olive brown medium ash with a few interspersed fine and medium lapilli
Poronui Tephra	Trace	yellow fine rhyolitic ash
Ohinepango Tephra	0.19 m	50 mm dark olive grey and olive brown medium ash; 40 mm very dark grey medium ash; 60 mm very dark grey and brownish yellow medium ash; 40 mm very dark grey medium ash
Waihohonu Lapilli	0.36 m	10 mm grey ash; 70 mm strong brown and dark to very dark grey fine to coarse lithic lapilli; 0.28 m dark grey and strong brown fine and a few medium lithic lapilli
unnamed tephra	50 mm	20 mm dark greyish brown medium ash with interspersed yellow coarse ash; 10 mm coarse yellow ash, fine and medium brownish lapilli; 20 mm dark yellowish brown ash
Oturere Lapilli	0.42 m	strong brown, yellowish brown and dark greyish brown fine to coarse lapilli
Te Rato Lapilli	40 mm	olive grey and olive fine lapilli
Papanetu Tephra-Karapiti Lapilli	Trace	light yellowish brown fine rhyolitic ash
	1.89 m	undifferentiated tephra beds
?Rotorua Ash	Trace-40 mm	pale yellow rhyolitic ash in yellowish brown ash
	0.53 m	undifferentiated tephra beds
?Puketarata Ash	0.19 m	(pocket) white fine rhyolitic ash
	1.14 m	undifferentiated tephra beds
?Rotoaira Lapilli	0.24 m	50 mm dark grey ash; 0.14 m brownish yellow fine to coarse lapilli and grey fine lithics; 50 mm dark and light grey medium to coarse ash
	0.46 m	alluvium
	0.63 m	undifferentiated tephra beds
	0.91 + m	alluvium

Access 10: a large cutting on the crest of a hill 2.5 km from the Waiouru-Turangi Road (Desert Road) on Hydro Access Road No. 10, N112/301844.

Ngauruhoe Tephra	50 + mm	black fine ash
Taupo Pumice	0.6 m	pale yellow rhyolitic ash, lapilli and blocks
Mangatawai Tephra	0.43 m	dark yellowish brown to black ash
Whakaipo Tephra & Waimihia Lapilli	0.58 m	yellowish brown fine ash with interspersed pale yellowish rhyolitic ash
Papakai Tephra	0.4 m	dark brown fine ash; paleosol (erosion break)
Poutu Lapilli	0.36 m	yellowish red stained lapilli
Wharepu Tephra	40 mm	grey to yellowish brown ash
Poronui Tephra	10 mm	yellow fine rhyolitic ash
Ohinepango Tephra	1.40 mm	30 mm strong brown medium ash; 40 mm; grey-black medium ash; 40 mm; strong brown and black medium ash; 30 mm grey-black medium ash
Waihohonu Lapilli	70 mm	yellowish red and grey fine lapilli
unnamed tephra	40 mm	dark yellowish brown coarse ash
Oturere Lapilli	0.2 m	100 mm yellowish red coarse lapilli; 20 mm yellowish red coarse ash; 30 mm yellowish red coarse ash; 30 mm yellowish red coarse lapilli

Te Rato Lapilli	10 mm	grey coarse ash
	50 mm	yellowish brown ash
Papanetu Tephra-	0-20 mm	light yellowish brown rhyolitic ash
Karapiti Lapilli	1.3 m	andesitic tephra
?Rotorua Ash	20-30 mm	pale yellow fine rhyolitic ash
	1.2 m	andesitic tephra
Rotoaira Lapilli	0.27 m	120 mm strong brown pumiceous lapilli;
		20 mm very dark grey fine ash, grading into
		80 mm strong brown and black coarse ash;
		20 mm very dark grey ash, grading into
		30 mm olive yellow lapilli and ash
	1.1 m	andesitic tephra
	4.5 m	alluvium or laharic debris, on
	1.4 + m	purplish grey ignimbrite; planar upper surface.

Poutu: a large cutting on the National Park-Taupo Road, 5.7 km west of Rangipo, N112/239901. Type section for Poutu Lapilli and Rotoaira Lapilli.

Taupo Pumice	0.4 m	pale yellow rhyolitic ash, lapilli and blocks
Mangatawai Tephra	0.42 m	dark yellowish brown ash becoming dark grey over bottom 0.2 m
Whakaipo Tephra,	0.3 m	yellowish brown fine ash with interspersed
Waimihia Lapilli		pale yellow rhyolitic ash
Papakai Tephra	0.4 m	strong brown ash with grey lithic lapilli throughout; paleosol
Hinemaiaia Ash	20 mm	"cream cakes" of pale yellow brown rhyolitic tephra occur in lower half of Papakai Tephra
Poutu Lapilli	0.9 m	brownish yellow weakly bedded lapilli
Wharepu Tephra	60 mm	very dark greyish brown to dark olive grey ash
Poronui Tephra	20-30 mm	pale yellow fine rhyolitic ash
Ohinepango Tephra	60 mm	30 mm strong brown medium ash; 30 mm very dark grey medium ash
Waihohonu Lapilli	30 mm	yellowish red medium and coarse ash and fine lapilli
unnamed tephra	30 mm	brown ash
Oturere Lapilli	10 mm	yellowish brown medium lapilli
Te Rato Lapilli	0.16 m	very dark grey coarse ash and lapilli and pale yellow lapilli
	0.64 m	andesitic tephra
?Rotorua Ash	0-20 mm	yellow fine rhyolitic ash, usually as "cream cakes" about 20 mm across
	0.71 m	andesitic tephra
Rotoaira Lapilli	0.38 m	0.16 m yellowish red coarse ash and lapilli; 20 mm (10-50 mm) black ash; 0.2 m shower bedded brownish lapilli and coarse ash
		(erosion break)
	0.12 m	yellowish brown ash with scattered strong brown lapilli
	80 mm	light olive brown ash (sandy silt) with sparse strong brown lapilli; a few angular cobbles throughout these two units which may be water-laid; in places up to 50 mm white rhyolitic ash present (may not be primary)
Rerewhakaaitu Ash	0.38 m	shower bedded strong brown and brownish yellow ash and lapilli
Hinuera Formation	0.82 m	current bedded gravelly sands
		(erosion break)
Oruanui Formation	0.39 m	pale brownish grey massive ash with scattered pumice lapilli (Oruanui Breccia)

Oruanui Formation— <i>continued</i>	0.57 m	0.31 m very pale brown ash, shower bedded and studded with chalazoidites up to 30 mm across; 0.1 m very pale brown shower bedded ash; 40 mm pale yellow shower bedded ash; 0.12 m pale yellow shower bedded fine and coarse ash (Oruanui Ash); sharp contact with
	2 + m	tuff, lapilli tuff and alluvium.
Okupata: a cutting on the National Park-Taupo Road 0.2 km SW of junction with Hydro Access Road No. 1, N112/023850. Type section for Okupata Tephra.		
Ngauruhoe Tephra	0.22 m	very dark brown fine ash
Taupo Pumice	0.6 m	pale yellow ash, lapilli and blocks
Mangatawai Tephra	0.21 m	dark brown ash; lenses of dark grey ash with beech leaves
unnamed tephra	0.22 m	dark yellowish brown ash
Papakai Tephra	0.21 m	dark yellowish brown ash with a few scattered fine and medium brownish yellow lapilli
Mangamate Tephra	0.22 m	yellowish brown ash with numerous medium dark grey lapilli
Okupata Tephra	0.24 m	80 mm yellowish brown ash with scattered brownish yellow medium and coarse lapilli and a few dark grey fine lapilli; paleosol; 80 mm yellow fine to coarse lapilli; 80 mm strong brown fine to coarse lapilli
unnamed tephra	90 mm	dark yellowish brown ash; paleosol
	80 mm	brownish yellow fine and medium lapilli and grey fine lithics in yellowish brown ash
	70 mm	strong brown fine and medium lapilli and grey fine lithics
	0.14 m	yellowish brown ash; paleosol
?Rotorua Ash	Trace	yellow fine rhyolitic ash
	0.1 m	yellowish red coarse ash, and fine lapilli
	20 mm	dark yellowish brown ash with sparse fine lithics; paleosol
	50 mm	yellowish red fine, medium and coarse lapilli and dark grey fine lithics
	40 mm	brown ash with interspersed strong brown fine and medium lapilli; paleosol
	80 mm	dark yellowish brown ash with interspersed strong brown fine and medium lapilli
	0.2 m	yellowish red lapilli; upper 80 mm fine, lower 0.12 m fine to coarse
	0.13 m	yellowish brown coarse sandy silt with a few reddish yellow fine to medium lapilli
	50 mm	brownish yellow fine lapilli and grey lithics
	70 mm	dark grey and pale brown sandy silt
	0.13 m	yellowish brown silty fine sand
	0.15 m	dark grey and pale brown sands; subangular to subrounded cobbles and boulders of vesicular olivine andesite occur throughout the above five units
	1.5 m	very pale brown reworked Oruanui Formation (erosion break)
Oruanui Breccia	3.6 + m	very pale brown ash and fine to medium lapilli; some chalazoidites.

No. 3 TOPPING - QUATERNARY ERUPTIVES FROM TONGARIRO 423

Wairoa: a cutting 450 m east of C Wairoa Trig and 90 m west of Hydro Access Road No. 4, N112/105987.

Taupo Pumice	0.5 m	(variable) pale yellow ash, lapilli and blocks
Mangatawai Tephra	0.22 m	dark brown grey ash
Papakai Tephra	0.37 m	yellowish brown fine ash with sparse grey lithic lapilli; paleosol (erosion break)
Poutu Lapilli	0.58 m	strong brown lapilli
unnamed tephra	90 mm	grey and strong brown fine lapilli
	5 mm	grey ash
	20 mm	yellow and grey fine lapilli
Te Rato Lapilli	0.14 m	greenish grey lapilli and ash
unnamed tephra	30 mm	yellowish brown ash and sparse grey coarse lithic ash
Okupata Tephra	0.19 m	140 mm yellowish brown fine and coarse ash; 50 mm
	50 mm	strong brown coarse ash and lapilli
unnamed tephra	80 mm	strong brown ash with interspersed coarse ash and lapilli
	0.15 m	yellowish brown ash and sparse lapilli; scattered charcoal (NZ1187; Topping & Kohn 1973 table 2); ?Rotorua Ash is present as "cream cakes" in this position in nearby sections, e.g., N112/096989
	0.13 m	yellowish brown ash with interspersed yellowish red lapilli
	0.25 m	yellowish brown ash; charcoal (NZ1186; Topping & Kohn 1973 table 2); scattered over top 80 mm
?Rotorua Lapilli	20 mm	yellowish red pumiceous and lithic lapilli
unnamed tephra	0.25 m	brown to yellow brown ash
	0.1 m	yellowish brown ash with interspersed strong brown pumiceous lapilli and dark grey to black lithic lapilli
	0.6 + m	yellowish brown tephra and/or loess.

ADDITIONAL NOTES ON ANDESITIC TEPHRAS

Radiocarbon Dates

All radiocarbon dates on wood, charcoal or peat samples collected by the writer during work on this thesis are presented in Table 4 with details on location, stratigraphic position and significance of the ages.

An Estimated Age for Poutu Lapilli

In Topping (1973) and Topping and Kohn (1973) an age of 9,700 years BP was assigned to Poutu Lapilli. Derivation of this age was obtained from a section at Otamangakau Canal (60, N112/109984; Appendix 1B) where > 4 m of peat and thin interbedded tephrae separate Taupo Pumice and Poutu Lapilli (Fig 4).

The radiocarbon date (NZ1335) of $9,560 \pm 100$ years BP for wood 90 mm above Poutu Lapilli together with an age of about 1819 years BP (Healy 1964) for Taupo Pumice provides a uniform rate of peat accumulation of about 0.45 m per thousand years. An extrapolation of this accumulation rate (through 90 mm of peat and tephra) provides an estimated age of 9,700 years BP for Poutu Lapilli. This age can only be correct if the peat accumulated at a constant rate. This assumption is supported by a ^{14}C date (NZ1336) of $3,200 \pm 50$ years BP for a further wood sample from this section and by interpolated ages for two rhyolitic tephrae (Rotoma Ash and Opepe Tephra) which are very similar to dates obtained elsewhere on those two tephrae (Topping and Kohn 1973).

Rate of Intermittent Tephra Accumulation, 9,700-1819 years BP

The rate of peat accumulation was sufficiently fast to trap individual thin (> 3 mm) discrete rhyolitic and andesitic tephrae. Thus the distribution of andesitic tephrae through the peat should provide information

Table 4: Radiocarbon dates obtained from peat, wood and charcoal samples from Tongariro Volcanic Centre

Fossil Record No.	¹⁴ C Age Years B.P. (1950)	Events Aged	Sample Description; Stratigraphic Position *	Locality (NZMS1 (1968))**
N112/544 NZ4336	3,200 [±] 50	Provides check on rate of accumulation of peat and thus a more accurate estimate of age of Poutu Lapilli	Wood: within peat; 0.66 m below base of Taupo Pumice, 3.46 m above Poutu Lapilli	Tongariro, N112/109984; swamp cut by Otamangakau Canal, Tongariro Power Scheme
N112/553 NZ4558	3,110 [±] 75	This date is much too young for the age of the paleosol beneath Okupata Tephra. Either the sample is from the base of the trunk and the date is incorrect, or the date is correct and the sample is actually from the root of a large rimu which grew higher in the section.	Wood: remains of <u>Dacrydium cupressinum</u> (rimu) in growth position sampled from the paleosol immediately beneath Okupata Tephra. Sample considered to be from the base of the trunk.	Tongariro, N112/036866; cutting eastern side National Park-Taupo Road, west of Tongariro and 4 km south of Taurewa
N112/543 NZ4188	4,810 [±] 110	Dates increase in rate of accumulation of Papakai Tephra probably resulting from renewed cone-building eruptions at North Crater	Charcoal: large fragments (<u>Dacrydium cupressinum</u> , rimu), deposited within Papakai Tephra directly after local erosion, and correlated with charcoal in sections at Wairehu Canal	Tongariro, N112/094937; cutting on National Park-Taupo Road 1.3 km south-west of junction with Rotoaira Road
N112/542 NZ4190	4,820 [±] 85	Dates increase in rate of accumulation of Papakai Tephra probably resulting from renewed cone-building eruptions at North Crater	Charcoal: large fragments (<u>Dacrydium cupressinum</u> , rimu), deposited within Papakai Tephra directly after local erosion, and correlated with charcoal in sections at Wairehu Canal	Tongariro, N112/096941; cutting on National Park-Taupo Road 600 m south-west of junction with Rotoaira Road
N112/554 NZ4560	5,690 [±] 100	¹⁴ C age is too young to date the paleosol. Either the age is incorrect or the sample is from a root of a rimu which grew higher in the section	Wood: remains of <u>Dacrydium cupressinum</u> (rimu) in growth position sampled from the paleosol above the rhyolitic Rotorua Ash. Sample considered to be part of a stem and to date the lapilli unit overlying the paleosol.	Tongariro, N112/036866; cutting on western side of National Park-Taupo Road, west of Tongariro and 4 km south of Taurewa

Fossil Record No.	¹⁴ C Age Years B.P. (1950)	Events Aged	Sample Description; Stratigraphic Position*	Locality (NZMS1 (1968))**
N112/549 NZ4338	9,540 [±] 100	Dates lahar; provides a minimum age for Okupata Tephra	Wood: a stem of <u>Libocedrus bidwillii</u> (mountain cedar) within laharic breccia (Muriotu Lahars, Grindley 1960) below part of Papakai Tephra and above Okupata Tephra	Tongariro, N112/010820; cuttings on National Park-Taupo Road immediately north of bridge over Whakapapanui Stream
N112/545 NZ4335	9,560 [±] 100	Minimum age for Poutu Lapilli	Wood: small branches from peat 4-0.3 m below Taupo Pumice and 90 mm above Poutu Lapilli	Tongariro, N112/109984; swamp cut by Otanangakau Canal, Tongariro Power Scheme
N112/551 NZ4373	9,700 [±] 210	Maximum age for Te Rato Lapilli; minimum age for Papanetu Tephra and Karapiti Lapilli	Peat: 5 mm horizon below Te Rato Lapilli and above Papanetu Tephra	Tongariro, N112/145983; swamp cut by Wairehu Canal, Tongariro Power Scheme. Approx. 0.9 km NW of point where Rotoaira Road crosses canal
N112/550 NZ4372	9,780 [±] 170	"	Wood: small branches and stems of <u>Dacrydium colensoi</u> (silver pine) and roots of <u>Podocarpus hallii</u> (Hall's totara) within a 3-10 mm horizon of peat directly below Te Rato Lapilli and above Papanetu Tephra	"
N112/552 NZ4374	9,790 [±] 160	Maximum age for Papanetu Tephra; minimum age for Okupata Tephra	Wood: small branches and stems of <u>Dacrydium colensoi</u> (silver pine) and roots of <u>Podocarpus hallii</u> (Hall's totara) within a 20 mm horizon of peat directly below Papanetu Tephra and above Okupata Tephra basal lapilli	"

Fossil Record No. ¹⁴ C No.	¹⁴ C Age Years B.P. (1950)	Events Aged	Sample Description; Stratigraphic Position*	Locality (NZMS1 (1968))**
N112/539 NZ4187	12,350 [±] 220	Provides a minimum age for Rotorua Ash	Charcoal: small fragments of rimu (<u>Dacrydium cupressinum</u>) charcoal scattered throughout 0.15 m ande- sitic tephra which in neighbour- ing sections immediately overlies Rotorua Ash	Tongariro, N112/105987; 450 m east of C Wairoa Trig, 90 m west of Tongariro Power Scheme Access Road No. 4
N112/541 NZ4189	12,450 [±] 340	Provides age for Okupata Tephra and a maximum for Te Rato Lapilli. The date is considered slightly too old	Charcoal: small fragments of rimu (<u>Dacrydium cupressinum</u>) charcoal scattered within Okupata Tephra, 30 mm below Papanetu Tephra	Tongariro, N112/101977; cutting northern side Access Road No.4, Tongariro Power Scheme, near junction of Papakai and Waitehouhi Streams
N112/540 NZ4186	13,150 [±] 300	Provides a maximum age for Rotorua Ash	Charcoal: small fragments of rimu (<u>Dacrydium cupressinum</u>) charcoal scattered throughout top third of an andesitic tephra unit which in neighbouring sections is 0.13 m below Rotorua Ash	Tongariro, N112/105987; 450 m east of C Wairoa Trig, 90 m west of Tongariro Power Scheme Access Road No. 4
N112/548 (recollection) NZ4159	13,800 [±] 300	Maximum age for Rotoaira Lapilli	Charcoal: fine fragments of rimu (<u>Dacrydium cupressinum</u>) charcoal within andesitic tephra immed- iately underlying Rotoaira Lapilli Formation	Tongariro, N112/298951; cutting on eastern side of Desert Road, east of Pihanga and 6.4 km south of Turangi
N112/556	14,050 [±] 250	Provides a minimum age for an unknown rhyolitic ash which is probably Okareka Ash	Peat: interbedded with andesitic tephras 0.31 m above reworked Oruanui Formation; 1.35 m below Rotorua Ash, 0.66 m below probable Rotoaira Lapilli. The peat horizon dated lies 60 mm above a 10 mm white fine rhyolitic ash	Tongariro, N112/107982; eastern embankment, Otamangakau Canal, Tongariro Power Scheme. 600 m NE of bridge on Hydro Access Road No.4

Fossil Record No.	¹⁴ C Age Years B.P. (1950)	Events Aged	Sample Description; Stratigraphic Position*	Locality (NZMS1 (1968))**
N112/555	> 40,300	Age for a nuée ardente deposit: the last major eruption from a vent (N112/202997) to the south of Tihia	Charcoal: outer few rings of a tree trunk (0.75 m high) in situ on laharic breccia and carbonised by a nuée ardente deposit (c. 3.5 m thick) which overwhelmed and still covers it; 6.70 m below base of Rotoaira Lepilli	Tongariro, N112/202974; large cutting on northern side, and near eastern end, of Rotoaira Road; 300 m north of Lake Rotoaira
N21581				
N112/546	> 47,000	Minimum age for a prominent black carbonaceous tuff (former paleosol) within tuffs below Oruanui Formation	Wood: small tree trunk in growth position on black carbonaceous tuff; 2.25 m below Oruanui Ash	Tongariro, N112/105979; western embankment of Otamangakau Canal, Tongariro Power Scheme
NZ1337				

* Wood identifications by Dr R. N. Patel, Forest Research Institute, Rotorua.
Charcoal identifications by Dr B.P.J. Molloy, Botany Division, D.S.I.R., Christchurch.

** All samples collected by W. W. Topping.

Fig 4 : Derivation of an estimated age for Poutu Lapilli. At section 60 in Otamangakau Canal (N112/109984, Appendix 1B) >4 m of peat and thin interbedded tephra separate Taupo Pumice and Poutu Lapilli. The distribution of these tephra within the peat is shown on the vertical axis. The age of Taupo Pumice (c. 1819 years BP, Healy 1964) and two radiocarbon dates (NZ1335, NZ1336) for wood from the peat, define a constant rate of accumulation which has been extrapolated to give an age of 9,700 years BP for the top of Poutu Lapilli. The interpolated ages for two rhyolitic tephra (Rotoma Ash and Opepe Tephra) within the peat are very close to their previously determined radiocarbon ages (Topping and Kohn 1973) and support the constant rate of peat accumulation. The composite tephra column built up locally during deposition of the peat is shown at left of the diagram.

on the rate of intermittent tephra eruption. The Otamangakau Canal site is NNW of the Tongariro Massif so that the record will not be as accurate as would be a similar site east of the massif, in the direction of the predominant wind. However, it is known (e.g. Paricutin volcano) that intermittent eruptions over appreciable periods of time result in crudely circular (rather than elongate) distribution patterns (c.f. Ngauruhoe Tephra, Papakai Tephra, Topping 1973; Mangatawai Tephra, Gregg 1960). Over a period of thousands of years any uniformly accumulating peat, reasonably close to vents of intermittent activity, should be an approximate record of the rate of the eruptive activity.

Intermittent eruptions following deposition of Poutu Lapilli appear to have been frequent for about 2,300 years before the rate dropped sharply. From that time until 1819 years BP the eruptions were infrequent except for a greater frequency between 2,500 and 2,300 years BP. This latter period corresponds to the deposition of Mangatawai Tephra. The lack of weathering and lack of disruption of fine bedding in the basal part of the Mangatawai Tephra shows that it accumulated rapidly (see Weathering section). However, the tephra record of the lower Papakai Tephra at first seems to contradict the peat record. That part of Papakai Tephra older than Hinemaiaia Ash (6,300 years BP) is the most strongly weathered and the net accumulation rate was very low.

The volume of the Mangamate Formation was sufficient to totally destroy the pre-Mangamate forest over an area of at least $1,000 \text{ km}^2$. Vegetation would have difficulty establishing on the thick, well-sorted non-vesicular lapilli so that active erosion would be widespread. Observation shows that this was indeed so.

Although the rate of intermittent tephra eruption was reasonably high after the Mangamate eruptions most was removed by wind or water and

the net accumulation was nil or very low until vegetation covered the area. It is therefore important to remember when dealing with weathering that the observed field thickness is only a net value and that much of the tephra intermittently erupted during a certain period of time may not be present in the final tephra column.

Correlation Columns

Correlation of andesitic and rhyolitic tephtras from east of the Tongariro Massif across to the western side of the massif is shown in Fig 5. Three more-detailed correlation lines are shown in tabular form in Appendix 3, i.e. (a) a north-south traverse from north-east of Turangi to Waicouru along the Desert Road to the east of the Tongariro Massif; (b) a north-south traverse from Turangi down the western side of the Tongariro Massif; (c) a west-east traverse north of the Tongariro Massif. All sections along the road traverses are included in the tables and their positions can be located on Figs 6, 7, 8 in the back pocket.

KEY

<u>Andesitic Tephra</u>		<u>Rhyolitic Tephra</u>	
ng	Ngauruhoe Tephra	tp	Taupo Pumice
mg	Mangatawai Tephra	wo	Whakaipo Tephra
pp	Papakai Tephra	wm	Waimihia Lapilli
pt	Poutu Lapilli	po	Poronui Tephra
wp	Wharepu Tephra	pa-kp	Papanetu Tephra- Karapiti Lapilli
oh	Ohinepango Tephra	rr	Rotorua Ash
wa	Waihohonu Lapilli	pk	Puketarata Ash
ot	Oturere Lapilli	rk	Rerewhakaaitu Ash
tt	Te Rato Lapilli	OuB	Oruanui Breccia
mn	Mangamate Tephra	OuA	Oruanui Ash
oa	Okupata Tephra		
rt	Rotoaira Lapilli		
A	undifferentiated andesitic tephras		
tuff	undifferentiated andesitic tuffs		
alluv. alluvium			

Fig 5: Correlation columns for andesitic and rhyolitic tephra beds. The sections are located in a semi-circle about the Tongariro Massif and show lateral thickness variation from east (Mangatawai) to west (Okupata). Detailed section descriptions appear in Appendix 1A and three more detailed correlation tables in Appendix 3.

Mangatawai

Access 10

Poufu

Wairoa

Okupata

N112/250806

N112/301844

N112/239901

N112/103987

N112/023850

Thickness
(metres)

PAHOKA LAPILLI

A lapilli unit underlying Mangamate Formation, not formally named in Topping (1973), will be informally referred to in this thesis as 'Pahoka lapilli'.

Pahoka lapilli is best represented at a section where the Desert Road crosses a small unnamed tributary of Waihohonu Stream (N112/240747, section 132). At this section the tephra sequence below Oturere Lapilli comprises:

Formation	Description	Thickness (mm)
Mangamate Tephra	brownish yellow and grey lithic fine to coarse lapilli (<u>Oturere Lapilli</u>)	470
	grey fine non-vesicular lapilli in yellowish brown ash (<u>Te Rato Lapilli</u>)	10
unnamed tephras of Tongariro Sub-group	yellow and black coarse ash, fine lapilli	150
	yellowish brown ash	30
	strong brown and black coarse ash, fine and medium lapilli	60
	yellowish brown ash with interspersed fine lapilli	40
	yellow and grey fine lapilli	20
	yellowish brown ash with interspersed fine lapilli; gradational lower boundary	30
Pahoka lapilli	grey, non-vesiculated, andesitic coarse ash, fine to coarse lapilli and light grey pumiceous fine to coarse dacitic lapilli	480
unnamed tephra	yellowish brown ash with sparse fine lapilli	40

Too few sections are exposed off the Desert Road to justify drawing an isopach map but the available data suggest a main south-easterly directed lobe from a possible source at or near North Crater.

Pahoka lapilli is a little older than Papanetu Tephra (9,790 years BP) and Karapiti Lapilli and is probably between 9,800 and 10,000 years BP. It overlies Ruapehu source tephra east of Ruapehu (e.g. section 171, N122/228655; Appendix 1B).

The andesitic and dacitic lapilli are similar to those for the younger Te Rato Lapilli (erupted from North Crater c. 9,780 years BP) except that in Pahoka lapilli the dacite component is greater than 10% by weight (the approximate proportion for Te Rato Lapilli). Chemical analyses for these two tephra are given in Table 8.

TABLE 8 : Major Element Analyses for Lavas and Tephra of Taupo Volcanic Zone.

All major elements except Na_2O were determined by X-ray fluorescence spectrophotometer. Samples prepared as glass fusion discs following the procedure of Norrish and Hutton (1969). FeO determined by standard titration method of Shapiro and Bramm (1956). Sample locations are given on page 48 and those with VUV numbers are lodged in the Geology Department, Victoria University.

No. VUV Sample No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	11947	11948	11949	11950	11951	11952	11953	11789	11954	11955	11956	11957	11958	11959	11960	-
SiO_2	63.47	57.16	63.10	59.50	53.66	73.78	76.87	73.77	58.99	60.13	59.39	56.09	54.73	56.10	55.41	57.80
TiO_2	0.40	0.66	0.41	0.58	0.71	0.22	0.15	0.23	0.69	0.72	0.76	0.67	0.70	0.70	0.69	0.59
Al_2O_3	17.16	18.33	15.99	16.78	15.68	12.84	12.47	12.20	18.16	16.78	17.27	13.77	14.53	14.29	14.18	14.10
Fe_2O_3	4.55*	7.96*	4.56*	6.71*	2.13											
FeO					6.02	2.69*	0.39	0.65	1.89	2.36	2.47	1.48	2.15	1.89	0.68	1.60
MnO	0.13	0.14	0.10	0.12	0.13	0.06	0.76	0.92	3.93	4.63	4.63	5.56	4.59	5.24	6.10	5.95
MgO	1.53	3.58	1.48	2.65	5.35	0.22	0.15	0.24	0.11	0.13	0.13	0.12	0.12	0.12	0.12	0.15
CaO	4.39	7.01	4.45	5.91	8.49	1.59	1.12	1.62	2.60	3.85	3.33	8.34	8.49	8.09	7.69	6.90
Na_2O^{**}	4.02	3.53	3.61	3.55	2.85	4.07	2.26	4.70	5.52	6.73	6.49	7.23	6.85	6.80	7.22	9.40
K_2O	1.80	1.24	1.89	1.56	0.94	2.98	3.12	3.38	1.64	1.50	1.51	3.10	2.85	2.95	3.34	2.40
P_2O_5	0.18	0.17	0.10	0.12	0.10	0.06	0.04	0.03	0.19	0.19	0.19	0.13	0.12	0.11	0.12	0.10
L.O.I.***	3.32	0.79	2.68	1.53	0.79	2.40	2.43	0.74	3.37	0.32	0.57	0.30	1.36	1.17	0.67	0.23

* Total Fe expressed as Fe_2O_3

** Na_2O : analysed by atomic absorption spectrophotometry

*** Loss on Ignition between 110-1000°C.

100.95

5.

TABLE 8 cont.: Major Element Analyses for Lavas and Tephra of Taupo Volcanic Zone

No. VUV Sample No.	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
SiO ₂	56.44	52.70	52.72	52.49	52.68	52.19	58.88	58.24	57.93	59.86	59.01	61.24	51.80	53.04	53.24	53.81
TiO ₂	0.71	0.73	0.62	0.73	0.73	0.71	0.69	0.70	0.68	0.70	0.70	0.67	0.73	0.73	0.75	0.72
Al ₂ O ₃	14.44	15.41	15.32	15.12	15.09	14.92	16.29	16.11	15.98	16.22	15.83	15.75	14.87	14.96	15.11	14.97
Fe ₂ O ₃	1.09	1.91	1.96	6.81	6.87	3.51	1.29	1.33	1.35	1.64	1.48	1.85	3.93	4.49	4.85	2.20
FeO	5.78	7.35	7.33	2.81	2.80	5.70	5.46	5.63	5.46	5.05	5.36	4.45	5.45	5.15	4.62	6.44
MnO	0.16	0.16	0.16	0.16	0.16	0.17	0.13	0.12	0.12	0.12	0.12	0.11	0.16	0.16	0.15	0.15
MgO	8.35	7.29	7.09	7.09	7.23	7.51	4.06	4.13	4.31	3.43	4.04	3.15	7.06	6.75	6.38	5.83
CaO	7.17	10.30	10.30	10.24	10.28	10.39	7.28	7.45	7.24	6.63	7.13	6.26	10.06	10.08	9.68	9.26
Na ₂ O**	2.72	2.58	2.70	2.50	2.50	2.48	3.34	3.18	3.22	3.32	3.45	3.53	2.61	2.61	2.61	2.86
K ₂ O	1.39	0.68	0.69	0.68	0.67	0.65	1.51	1.45	1.51	1.70	1.59	1.88	0.70	0.70	0.73	0.89
P ₂ O ₅	0.15	0.12	0.12	0.13	0.12	0.13	0.15	0.11	0.15	0.13	0.13	0.12	0.12	0.14	0.10	0.12
L.O.I.***	1.45	0.66	0.11	0.76	0.76	0.06	0.65	0.95	0.23	0.30	0.56	0.31	0.23	0.72	0.85	0.85

Table 8 continued: Lithology and locations for the samples analysed in Table 8.

No.	VUW Sample No.	Lithology and Location
1	11947	Dacite lapilli from Te Kato Lapilli; Ketetahi Springs, N112/135872 (section 157)
2	11948	Andesite lapilli from Te Kato Lapilli; Ketetahi Springs, N112/135872 (section 157)
3	11949	Dacite lapilli from Pahoka Lapilli; Desert Road, 12 km SE of Ngauruhoe, N112/216709 (section 161)
4	11950	Andesite lapilli " " " " " " " " " " " "
5	11951	Waiohoro Lapilli; Desert Road, 12 km ESE of Ngauruhoe, N112/216709 (section 161)
6	11952	Obsidian fragments, Peperetu Tephra; Te Ponanga Saddle Road reference section, N112/224953 (section 87(a))
7	11953	Obsidian fragments, Waiohoro Ash; collected Dr B. P. Kohn
8	11789	Hypersilicic-hornblende rhyolite, Kiharua dome; Analyst, V. Dorerik (1972, unpubl. M.Sc. thesis)
9	11954	Kotoaira Lapilli from type locality, Poutu reference section, N112/237901 (section 17)
10	11955	Andesite from top flow exposed on western side of Lower Te Kari Crater, N112/161872
11	11956	" " bottom " " " " " " " " " "
12	11957	Vesicular olivine andesite, Pukeonake Scoria Cone; N112/063822
13	11958	Olivine andesite, plug 1.4 km north of Pukeonake; N112/065838
14	11959	Olivine andesite, plug 800 m north of Pukeonake; N112/065832
15	11960	Vesicular olivine andesite flow exposed on National Park-Turangi Road 6.7 km NNW of Pukeonake, N112/050895
16	-	Olivine andesite, Pukekaihiore near summit. Analyst, J. A. Ritchie (Steiner 1956)
17	-	Pyroxene andesite, large clearing north of mouth of Papamunuka Stream. Analyst P. T. Seelye (Clark 1960)
18	11961	Basalt; Red Crater flow into South Crater; N112/136828
19	11962	Basalt; Red Crater flow into south-western Oturere Valley; N112/140827
20	11963	Basalt; Red Crater flow into Central Crater; N112/146841
21	11964	" " " " " " " " " Duplicate sample 485
22	11965	Basalt; Red Crater flow into northern Oturere Valley; N112/153830
23	11966	Olivine andesite; Red Crater flow into western Oturere Valley; N112/145825
24	11967	Olivine andesite; Red Crater flow into western Oturere Valley; N112/146826
25	11968	Olivine andesite; Red Crater flow into western Oturere Valley; N112/148823
26	11969	Olivine andesite; Red Crater flow into western Oturere Valley; N112/151819
27	11970	Olivine andesite; Red Crater flow into western Oturere Valley; N112/157823
28	11971	Olivine andesite; Red Crater flow into western Oturere Valley; N112/156828
29	11972	Scoriaceous basalt from upper surface of Red Crater flow into South Crater, N112/156828
30	11973	Scoriaceous basalt from upper surface of Red Crater flow into south-western Oturere Valley; N112/140826
31	11974	Scoriaceous basalt from upper surface of Red Crater flow into northern Oturere Valley; N112/153830
32	11975	Scoriaceous basalt from upper surface of Red Crater flow into Central Crater; N112/146841

GRAIN-SIZE CHARACTERISTICS FOR TE RATO LAPILLI AND POUTU LAPILLI

INTRODUCTION

Granulometric or grain-size analysis is often useful in determining the origin of a tephra deposit. This was first recognised by Moore (1934) who was able to distinguish between relatively well sorted pyroclastic fall (tephra-fall) and poorly sorted pyroclastic flow (tephra-flow) deposits. Murai (1961) has used the shape of the cumulative particle size distribution curve to help subdivide pyroclastic flow deposits into five types. By plotting sorting values (Inman 1952) against median particle diameter Walker (1971) has shown that pyroclastic fall and pyroclastic flow deposits fall into two different fields with little overlap (Fig 15). Base surge deposits cluster in an area away from the central parts of the flow or fall fields (Crowe and Fisher 1973). Sheridan (1971) has shown, by plotting C , the coarsest one percentile against M , the median diameter, that the three types of deposits can be separated on a C - M diagram as used by Passega (1964). The pyroclastic fall and flow fields overlap, however.

Walker and Croasdale (1972) have used grain-size data to differentiate between pyroclastic deposits of strombolian/hawaiian type basaltic activity, and those exemplified by the opening stages of the Surtsey eruption of 1963-4, the surtseyan type. Detailed grain-size data have also been used to determine characteristics and wind directions for individual eruptions, e.g. two plinian-type tephra-fall deposits from Agua de Pau volcano, on São Miguel Island in the Azores (Walker and Croasdale 1971); the Crater Lake eruption, Mount Mazama, Oregon (Fisher 1964); and the Burrell Lapilli eruption, Mt Egmont, New Zealand (Topping 1972).

In this study the Te Rato Lapilli was examined in detail. It is exposed in many sections and is not shower bedded (i.e. there is no

Fig 9: Sampling sites for Te Rato Lapilli (marked by x) and seven further Tongariro Sub-group tephra layers (dots).

alternation of coarse and fine tephra). Samples from 22 sites (Fig 9) were mechanically analysed. For comparison another tephra unit, Poutu Lapilli, was sampled at five sections. A detailed study was not made of Poutu Lapilli as it has a trilobed distribution pattern (representing at least three different wind directions) and is bedded (although without large variation in grain size).

METHODS

All samples were sieved for 12 minutes using a range of sieves from -3.7ϕ to 4.5ϕ (12 to 0.0625 mm) with an interval of 1ϕ between -3 and 4ϕ . Two samples (7, 32) that were sieved in duplicate had means that agreed within ± 0.04 . There was only minor abrasion of the pumice. The grain size data were used to compute the graphic statistics of Folk and Ward (1957) and Inman (1952) (Tables 9,10). Representative histograms and cumulative curves are given (Figs 12,13).

TE RATO LAPILLI

Distribution

Te Rato Lapilli was erupted about 9,780 yr BP from a vent, at the northern end of the Tongariro Massif, probably on North Crater (Topping 1973). The thickness distribution pattern (Fig 8, Topping 1973) indicates a single lobe directed to the northeast (026°) of North Crater.

Types of Lapilli

Te Rato Lapilli contains dark grey (5Y 3/1) non-vesicular andesitic lapilli and fewer, larger, light yellowish brown (2.5Y 6/4) finely vesicular dacitic lapilli. In thin section the andesitic lapilli are very finely vesicular and contain small acicular green-brown hornblendes and rare

Table 9:

Statistical parameters for eight Tongariro Sub-group tephtras. The data in the two left hand columns have been computed by the method of moments; the data in the right hand columns are graphical measures of Inman (1952) and Folk (1968).

Sample No.	Moment Mn	St.Dev.	Percentiles							Statistical Data					
			5	15	25	50	75	85	95	Mean (Mn)	St.Dev. (Mn)	St.Dev. (Mn)	Skew (Mn)	Kurt (Mn)	
<u>Te Rapa Lapilli</u>															
2	-0.15	1.05	-1.53	-0.91	-0.58	-0.22	0.13	0.60	1.02	-0.18	0.75	0.75	0.03	0.08	1.04
7A	-0.15	0.93	-1.39	-0.91	-0.55	-0.18	0.15	0.60	0.99	-0.16	0.74	0.75	0.01	0.04	0.95
7B	-0.22	0.88	-1.42	-0.55	-0.72	-0.25	0.28	0.53	0.92	-0.22	0.73	0.74	0.03	0.06	0.95
14	-0.68	1.07	-2.12	-1.49	-1.22	-0.69	-0.21	0.16	0.78	-0.57	0.85	0.82	0.02	0.02	1.18
18	-0.14	1.02	-1.40	-0.92	-0.68	-0.22	0.32	0.58	0.97	-0.19	0.73	0.75	0.03	0.06	0.97
25	-0.33	1.27	-2.88	-1.87	-1.42	-0.87	-0.35	-0.04	0.77	-0.52	1.01	0.92	-0.09	-0.09	1.32
27	-0.90	1.22	-2.25	-1.79	-1.48	-1.00	-0.42	-0.11	0.73	-0.97	0.87	0.84	0.11	0.06	1.15
31	-0.70	1.10	-2.17	-1.49	-1.23	-0.72	-0.29	0.04	0.79	-0.72	0.83	0.75	0.00	-0.01	1.30
32	-0.35	1.08	-1.74	-1.21	-1.00	-0.40	0.23	0.52	0.97	-0.36	0.84	0.86	0.03	0.06	0.91
32 (3rd)	-0.58	0.78	-1.87	-1.30	-1.03	-0.37	0.27	0.54	0.97	-0.58	0.89	0.92	-0.03	-0.01	0.90
32Derite	-1.14	0.75	-2.90	-1.90	-1.60	-1.05	-0.36	0.00	0.54	-0.98	1.00	0.95	0.01	0.12	1.14
32Andesite	-0.57	0.79	-1.80	-1.28	-1.00	-0.30	0.40	0.60	0.92	-0.53	0.98	0.94	-0.07	-0.04	0.80
36	0.22	0.31	-0.73	-0.31	-0.15	0.23	0.52	0.75	1.44	0.23	0.60	0.53	0.05	-0.01	1.33
57	0.03	0.96	-1.26	-0.69	-0.42	0.03	0.46	0.71	1.36	0.01	0.75	0.72	-0.01	-0.03	1.22
42	0.19	1.19	-1.21	-0.66	-0.37	0.13	0.53	0.79	1.35	0.09	0.83	0.73	0.02	-0.09	1.40
50	-0.56	1.32	-2.19	-1.46	-1.24	-0.64	-0.04	0.16	0.98	-0.51	0.96	0.96	0.03	0.04	1.08
51	-0.26	1.20	-1.80	-1.16	-0.92	-0.34	0.28	0.56	1.30	-0.31	0.91	0.87	0.06	0.06	1.07
53	-0.52	1.06	-1.50	-1.29	-1.09	-0.57	-0.03	0.19	0.94	-0.50	0.82	0.82	0.11	0.13	1.06
57	-0.53	1.14	-2.21	-1.49	-1.19	-0.46	0.10	0.43	0.99	-0.53	0.97	0.97	0.01	0.04	1.02
60	-0.38	1.01	-1.83	-1.21	-0.98	-0.39	0.22	0.51	0.97	-0.36	0.86	0.86	0.01	0.05	0.96
63	-0.01	1.09	-1.46	-0.87	-0.57	-0.06	0.45	0.75	1.66	-0.06	0.88	0.81	0.06	0.00	1.22
136	-0.95	1.11	-2.86	-2.04	-1.61	-0.39	-0.20	0.18	0.76	-0.92	1.10	1.11	-0.06	-0.23	1.05
157	-1.40	1.23	-3.39	-2.72	-2.21	-1.34	-0.58	-0.24	0.54	-1.44	1.21	1.24	-0.08	-0.11	0.99
159	-1.12	1.37	-3.25	-2.43	-1.96	-1.10	-0.33	0.08	0.84	-1.15	1.25	1.25	-0.05	-0.06	1.03
160	-0.53	1.50	-2.92	-1.73	-1.28	-0.53	0.19	0.54	1.51	-0.58	1.25	1.14	-0.08	-0.06	1.25
506	-0.83	1.19	-2.21	-1.52	-1.16	-0.92	-0.42	-0.13	0.74	-0.89	0.82	0.74	0.03	0.06	1.27
<u>Poua Lapilli</u>															
118	-1.18	1.31	-3.15	-2.45	-2.06	-1.22	-0.44	-0.06	0.77	-1.24	1.19	1.19	-0.01	-0.03	0.99
179	-0.22	1.34	-1.61	-1.13	-0.94	-0.44	0.13	0.56	2.69	-0.54	1.07	0.84	0.32	0.13	1.64
197	0.14	1.31	-1.28	-0.81	-0.56	-0.11	0.56	0.91	2.85	-0.00	1.06	0.86	0.31	0.19	1.52
217	-1.15	1.68	-3.10	-2.42	-2.11	-1.43	-0.63	-0.20	2.54	-1.35	1.41	1.11	0.26	0.11	1.56
224	-0.12	0.93	-1.40	-1.00	-0.63	-0.10	0.42	0.67	1.25	-0.15	0.82	0.84	-0.03	-0.03	1.00
<u>Wharenga Tephra</u>															
116	1.08	1.10	0.09	0.45	0.59	0.82	1.40	1.73	3.44	1.00	0.83	0.64	0.50	0.43	1.69
118	-2.28	1.10	-3.45	-3.17	-3.06	-2.34	-1.67	-1.41	-1.02	-2.31	0.81	0.88	0.08	0.06	0.71
<u>Chinepango Tephra</u>															
116	1.08	0.88	-0.05	0.47	0.68	1.03	1.50	1.76	2.55	1.09	0.72	0.64	0.15	0.13	1.31
<u>Waikohou Lapilli</u>															
118	-1.26	0.99	-3.03	-2.12	-1.82	-1.27	-0.67	-0.38	0.22	-1.26	0.93	0.87	-0.03	0.02	1.15
<u>Otutere Lapilli</u>															
115	-1.53	1.52	-3.44	-2.36	-2.46	-1.62	-0.75	-0.26	0.95	-1.61	1.34	1.35	0.09	0.00	1.05
<u>Pahoka Lapilli</u>															
2	-1.33	2.24	-3.76	-3.16	-2.79	-1.95	-0.80	0.54	3.84	-1.52	2.08	1.85	0.44	0.35	1.56
<u>Rotoaira Lapilli</u>															
2	0.38	1.20	-1.31	-0.58	-0.24	0.37	0.91	1.30	1.91	0.36	0.96	0.94	-0.02	-0.00	1.15

feldspar microlites in a black glassy matrix. The dacitic lapilli contain rare, small, acicular, green-brown hornblendes in a vesicular, clear partially devitrified, glassy matrix. Chemical analyses for the andesitic and dacitic lapilli are given in Table 8.

Grain-size Analysis

Maximum Diameters: In many tephra fall deposits of lapilli grade, e.g. Burrell Lapilli (Topping 1969) appreciably larger blocks occur. Such blocks are absent from Te Rato Lapilli. The average of five maximum diameters for each of (a) dacitic lapilli, and (b) andesitic lapilli from each sampling site are given in Fig 10 and the values contoured. Both sets of data show a broad lobe directed north or slightly to the west of north, from the supposed source on North Crater.

Maximum diameters for Te Rato Lapilli were plotted against log distance from a source assumed to be North Crater to compare with data for other eruptions (Fisher 1964, Topping 1972) (Fig 11).

Particle Size Distribution: Histograms for samples of Te Rato Lapilli are unimodal (Fig 12) with up to 89% by weight of the sample (No. 36) falling within the -1.0 to 1.0ϕ (2-0.5 mm) range. Sample 32 was sieved at an $\frac{1}{2}\phi$ interval to check that the histograms for Te Rato Lapilli were indeed unimodal. Dacitic lapilli was hand picked from the andesitic lapilli of this sample and the composite histogram is shown in Fig 12. This dacite comprises 10% by weight of the total sample and it has a coarser mode than the andesitic lapilli. Typical cumulative curves for Te Rato Lapilli are presented in Fig 13 and curves for the two components of sample 32 are shown in Fig 14.

Grade Size Variation: Contoured median diameters (Table 9) decrease outwards in a broad north to north-north-easterly lobe. The pattern is similar to the maps of contoured weight percentages for coarse (4-2 mm)

Fig 10: Distribution of maximum diameters (average of five at each site) for the two components of Te Rato Lapilli:

- (a) dacitic lapilli
- (b) andesitic lapilli

Fig 11: The variation of average maximum particle size with distance from source. 1 - NE lobe of the Crater Lake eruption, Mount Mazama, Oregon (Fisher 1964). 2 - the major downwind depositional axis of the 1783 tephra-fall layer, Mount Asama (Minakami 1942). 3 - NE lobe of Little Glass Mountain eruption, NE California (Fisher 1964). 4 - ESE lobe of the Burrell Lapilli eruption, Mount Egmont (Topping 1972). 5 - dacitic lapilli component of Te Rato Lapilli. 6 - andesitic lapilli component of Te Rato Lapilli.

Fig 12: Typical histograms for Te Rato Lapilli. Sample 32 was sieved at a $\frac{1}{2}\phi$ interval and the dacitic lapilli have been separated from the andesitic component.

Fig 13: Cumulative curves for four samples of Te Rato Lapilli.
 The samples are 2.7 (157), 7.0 (27), 11.3 (32) and
 17.5 km (37) from the probable source, North Crater.

Fig 14: Cumulative curves for the two components of Te Rato Lapilli, sample 32: D - dacite lapilli; A - andesite lapilli. The cumulative curve for the total sample is shown in Fig .

Fig 15: Sorting (σ_ϕ) versus median particle diameter (Md_ϕ) data for eight tephra-fall deposits of the Tongariro Sub-group. The data are superimposed on a contoured plot of air-fall samples from Walker (1971). The dashed boundary curve is the lower limit of tephra-flow deposits (Walker 1971).

and fine (1-0.5 mm) grade sizes. For grade sizes above 2 mm the weight percentages decrease outwards from source. For grade sizes less than 1 mm percentages increase outwards. The 2-1 mm fraction forms a broad belt across the north-east-directed isopach lobe and is intermediate, first increasing then decreasing outwards. (In the Crater Lake eruption at Mount Mazama, Oregon (Fisher 1964) and in the Burrell Lapilli eruption, Mount Egmont (Topping 1972) it is the 4-2 mm fraction that has this intermediate distribution).

Sorting: Inman sorting values (Table 9) decrease and tephra becomes better sorted with increasing distance from source. In Fig 15 data for Te Rato Lapilli have been superimposed on a contoured plot of sorting versus median particle diameter (Walker 1971) to compare the data with data for other eruptions.

Discussion of Results

Te Rato Lapilli has about 10% by weight of dacite and is therefore a polycomponent system (Walker 1971). The difference in modal values between dacitic and andesitic components and the difference in their sorting values (Table 9) shows that Te Rato Lapilli is behaving as a polycomponent system. Walker and Croasdale (1971) found that sorting values (Inman) for pumice (σ_{ϕ} , average = 1.4 ϕ) and crystal (σ_{ϕ} , average = 0.8 ϕ) components of the Foga A pumice deposit in the Azores, a polycomponent system with lithics (σ_{ϕ} , average = 1.7 ϕ) as a minor component, were smaller than sorting values for whole samples (σ_{ϕ} , average = 1.8 ϕ). However, sorting values for whole samples were found to be lower near the vent than 5-10 km away and the difference was attributed to a unimodal distribution where pumice predominates near the vent changing to bimodal further away as crystals increase in importance, and lowest values 20 km or more away where crystals predominate. In the Te Rato Lapilli no noticeable increase in weight

percent of dacitic lapilli occurs towards source. Walker and Croasdale's data do show that even though the dacitic component is small it is likely to increase sorting values for the total sample.

Sorting values (Inman) for whole samples of Te Rato Lapilli range between 0.53 and 1.25 ϕ with the average for the 23 sites being 0.87 ϕ and therefore better sorted than the average of 1.2-1.4 ϕ obtained from 117 tephra by Fisher (1964). The composite samples are very well sorted (for tephra) and the andesitic component, the heavier component, is likely to be slightly better sorted still. These low sorting values suggest deposition during strong winds (Fisher 1964) and this is supported by the elliptical nature of the isopach map and the fact that most of the Te Rato Lapilli samples plot below the axis for the fall-field in Fig 15. Samples from six other Tongariro tephra were sieved (Fig 9): Wharepu Tephra, from sites at which it is of lapilli and ash grade respectively; Ohinepango Tephra of ash grade; and Waihohehu Lapilli, Oturere Lapilli, Rotoaira Lapilli, and Pahoka lapilli (informal name, see p. 44), all of lapilli grade. Partial isopach data for all of these tephra indicate deposition during strong winds and all, except Pahoka lapilli, plot below the tephra-fall axis (Fig 15) supporting this deduction. Pahoka lapilli, a polycomponent system with appreciable dacitic lapilli, has a sorting value (Inman) higher than expected from the isopach data. It is probable that the dacitic component is large enough in this tephra to cause a significant increase in sorting value for the whole sample.

The isopach map for Te Rato Lapilli can best be explained by deposition during south-westerly winds. However, the grade size data do not present north-easterly directed lobes which shows that deposition was more complex, and maximum size data give a broad north-directed lobe suggesting that the initial eruptive burst was carried to the north before winds swung around to the south-south-west. This north-directed lobe for

the coarsest lapilli is too broad to allow a precise intersection of its axis with the axis for the isopach map and thus to define a vent, but it does support an origin from North Crater rather than from the Tama Lakes.

An extrapolation of curve 4 on Fig 11 suggests that the Te Rato Lapilli eruption was of slightly lower magnitude than the Burrell Lapilli eruption of c. 1655 A.D. on Mount Egmont (Druce 1966, Topping 1972). However, the different plots for the dacitic and andesitic lapilli components for Te Rato Lapilli show that this type of plot could only be used for quantitative comparison of eruptives with the same specific gravity and until the specific gravities for the different lapilli types can be equated with terminal fall velocities its potential use is limited (Walker, Wilson, and Bowell, 1971, Walker 1971).

POUTU LAPILLI

Distribution

Poutu Lapilli was erupted about 9,700 yr BP probably from a source near Blue Lake, Northern Tongariro (Topping 1973). The thickness distribution pattern is trilobed (Fig 16).

Types of Lapilli

Most of the lapilli are similar lithologically to the andesitic lapilli of Te Rato Lapilli. Lithic lapilli are minor and bigger than the essential (juvenile) lapilli.

Grain-size Analysis

Size analysis data from five sites (Fig 9) are presented in Table 9 and Appendix 4, and histograms in Fig 17. The average of five maximum sized essential lapilli at each of 12 sites north of Tongariro have been plotted on the Poutu Lapilli isopach map (Fig 16).

Fig 16: The average of five maximum sized essential lapilli at each of 12 sites north of Tongariro superimposed on the Poutu Lapilli isopach map. The maximum size data support the existence of the two northern lobes of the isopach map.

Fig 17: Typical histograms for Poutu Lapilli. Sample 197 is from the NW lobe, sample 118 from the SE lobe, and samples 217 and 224 from the NE lobe.

Discussion of Results

Although data are limited a few tentative conclusions can be drawn. The three lobes within the isopach map show that Poutu Lapilli was deposited under at least three different wind directions. The average maximum size lapilli measurements support the existence of the two northerly lobes revealed by the thickness data. Maximum diameters are slightly coarser for lapilli in the north-west lobe than for fragments at a similar distance from northern Tongariro in the north-east lobe suggesting that winds were stronger during deposition of the north-west lobe.

Samples 197 and 224 are on the north-west and north-east lobes respectively and equal distances from the source. Sample 224 is on a lobe axis, sample 197 is 10 km off the lobe axis yet both have similar median diameters and are equally sorted. This again suggests that the magnitude of the north-west eruption was probably slightly greater than that for the north-east eruption.

Sample 217 on the western flank of the north-east lobe axis and sample 118 on the south-east lobe axis are approximately the same distance from Blue Lake. The coarser sample, 217, has the smaller sorting value showing that the magnitude and/or wind at the time of eruption of the north-east lobe was probably greater than that of the south-east lobe. Therefore, it is probable that deposition of the north-west and north-east lobes was at times of greater winds than existed during formation of the south-east lobe and possibly the strongest winds occurred during formation of the north-west lobe. Histograms for Poutu Lapilli, sample 217 (Fig 17), and Te Rato Lapilli, sample 63 (Fig 12), show that, assuming Blue Lake and North Crater sources respectively, winds were stronger during deposition of Poutu Lapilli.

CONCLUSIONS

Te Rato Lapilli is a polycomponent system comprising essential largely non-vesicular andesitic lapilli and coarser vesicular dacitic lapilli (c. 10% by weight) with rare accessory lithic lapilli. The dacitic component is slightly less well sorted (Table 9) than the andesitic component but the weight percent of dacite does not vary enough to either aid location of an eruptive vent or significantly affect the graphic measures for the andesitic component.

The lapilli are very well sorted in comparison with other tephra deposits and were erupted from a probable North Crater source during strong south-westerly winds. One of the initial eruptive bursts probably took place while the wind was from the south.

The Te Rato Lapilli was of slightly smaller magnitude than the Burrell Lapilli eruption of c. 1655 A.D. on Mount Egmont (Druce 1966, Topping 1972).

Poutu Lapilli, consisting largely of non-vesicular essential andesitic lapilli, was deposited in at least three lobes (NW, NE and SE). If three only depositional phases occurred then the NW lobe was formed by the strongest winds and the SE lobe by the weakest winds. Assuming a Blue Lake source for Poutu Lapilli and a North Crater source for Te Rato Lapilli then the Poutu Lapilli eruptions were of greater magnitude and/or winds were stronger during these eruptions.

The following section "Rhyolitic and Andesitic Volcanism" was first written as part of Topping and Kohn (1973) but is now planned as a separate paper for the Bulletin of the Geological Society of America.

The chronology and stratigraphic control are mainly by WWT (Topping 1973, Topping and Kohn 1973). The rhyolitic tephras were collected in the source areas by BPK, in the Tongariro area by WWT, and the andesitic tephras and lavas by WWT. Titanomagnetite analyses were carried out by BPK and the manuscript was written jointly.

The figures, tables and manuscript, in approximately this form have already appeared in BPK'S PhD thesis (Kohn 1973).

C. RHYOLITIC AND ANDESITIC VOLCANISM

The distribution through time of rhyolitic tephra from the Okataina, Maroa and Taupo volcanic centres is shown in Table 1, p. 25. Most of these tephra have been recognised in the Tongariro Volcanic Centre (Topping and Kohn 1973), and provide dated marker horizons to strengthen the radiocarbon chronology within the Tongariro Volcanic Centre. The eruption of tephra from Okataina and Maroa volcanic centres appear to be unrelated in time with andesitic volcanism whereas the eruption of Karapiti Lapilli, Papanetu Tephra, Poronui Tephra and Opepe Tephra coincided with this volcanism.

Stratigraphic Relation of Rhyolitic and Andesitic Eruptives

The most widespread and persistent andesitic tephra beds, Poutu Lapilli and Te Rato Lapilli, and the several lapilli beds which they bracket were erupted during an active period of andesitic volcanism possibly as short as 90 years (Table 1, p. 32, Fig 4). The rhyolitic eruptions of Karapiti Lapilli, Papanetu Tephra and Poronui Tephra and the extrusion of Kuharua Dome also occurred during this period; and the closeness in time of Poronui Tephra and Te Rato Lapilli has already been remarked upon by Vucetich and Pullar (1973).

After about 7,400 years BP the frequency and duration of andesitic volcanism decreased sharply, and thin tephra accumulated intermittently over the subsequent 2,600 years as a soil (Fig 4). Of the rhyolitic tephra erupted during this period only the Hinemaiaia Tephra, erupted about 6,300 years BP from a source in Taupo Volcanic Centre about 50 km NNE of the Tongariro Volcanic Centre (Vucetich and Pullar 1973), is appreciably thick. That is because it is well preserved by its burial by andesitic ash mainly from the Tama Lakes area.

Andesitic volcanism increased again about 4,800 years BP (NZ1188, NZ1190, Table 4; see p.97-8) with the initiation of cone building tephra eruptions from North Crater and Red Crater on Tongariro and about 2,500 years BP with initiation of eruptions from Ngauruhoe. Ruapehu has also contributed to this tephra deposition through to the present day. The deposition in the Tongariro area of the very large Waimihia Lapilli and Taupo Pumice, and the smaller Whakaipo Tephra and Mapara Tephra (see Appendix 4 for volumes) from the Taupo Volcanic Centre interrupted this intermittent ash accumulation.

Chemical Relationships of the Rhyolitic and Andesitic Eruptives

It is known that element concentrations within the titanomagnetites of rhyolitic tephtras probably reflect the availability of elements which can be readily incorporated into the structure so making them sensitive recorders of changes in magma composition. B. P. Kohn (1973) has shown that Taupo Sub-group tephtras fall into two groups on the basis of their titanomagnetite compositions and the groupings are considered to reflect different magma compositions, viz. the older group of Karapiti Lapilli, Poronui Tephra and Opepe Tephra, and the younger group of Hinemaiaia Ash and younger tephtras. B. P. Kohn has also examined titanomagnetites from andesitic tephtras and associated lavas from Tongariro and Ruapehu erupted over the last 15,000 years and reports two groups - the older >c. 11,000 years BP. The two groupings within each of the rhyolites and the andesites are shown in Figs 18 and 19 and the titanomagnetite analyses are shown in Tables 4 (Topping & Kohn 1973) and 11 (Appendix 4).

The changes in elemental abundances within the titanomagnetites suggest that tephtras erupted from the Tongariro Volcanic Centre during approximately the last 10,000 years BP have been from 'new' magma. The earliest eruptions from this new magma (see analyses for Te Rato

Fig. 19. - Plots of Ni versus Co compositions of titanomagnetites from the rhyolitic Taupo Sub-group tephtras (upper diagram) and andesitic Tongariro Sub-group tephtras and lavas (lower diagram).

Lapilli) are very closely associated in time with eruption of the oldest Taupo Sub-group tephra - Karapiti Lapilli, Papanetu Tephra, and Poronui Tephra - and the eruptions continued beyond deposition of the Opepe Tephra before the rate of andesitic tephra eruption dropped sharply. About 6,300 years BP the eruption of Hinemaiaia Ash from the Taupo Volcanic Zone introduced a change in rhyolitic tephra composition (Kohn 1973).

The oldest tephra from the youngest andesitic magma is indicated, by whole rock chemistry, to be Pahoka lapilli, a tephra which contains both dacitic and andesitic components similar to Te Rato Lapilli (Table 8). Because Pahoka lapilli immediately predates Karapiti Lapilli (stratigraphic evidence), the first rhyolitic eruption from Taupo Volcanic Centre for some 10,000 years, it appears that andesitic eruptions have been the trigger to rhyolitic eruptions.

On the above evidence it is likely that andesite of a new composition moved upwards and its initial eruption about 10,000 years ago may have provided the trigger for eruption of the oldest Taupo Sub-group tephra. Timing of subsequent eruptions of rhyolitic tephra of a new composition was probably controlled by increase of vapour pressure over confining pressure with subsequent healing of fractures and a new build up of pressure. The concurrent intermittent andesitic volcanism probably had no significant effect on the timing of the youngest rhyolitic eruptions.

This interpretation is supported by the observation of Ewart (1963) that these two groups of rhyolitic tephra, which are also identifiable on the basis of vesicularity of pumice and the chemistry of their glasses, were erupted under different pressure conditions - the older magma at 1,000 kbars, and the younger magma at 2,000-3,000 kbars.

PART 2

QUATERNARY HISTORY OF
THE TONGARIRO VOLCANIC CENTRE

A. QUATERNARY ERUPTIVE HISTORY OF THE TONGARIRO VOLCANIC CENTRE

INTRODUCTION

Tephros have recently played and in future will play an increasingly important role in establishing chronology and correlating events within Quaternary geology, archeology, paleovolcanology and stratigraphy (Wellman 1962, Healy et al 1964, Wilcox 1965, Kobayashi and Shimizu 1966, Pullar 1967, Thorarinsson 1967, Ninkovitch 1968, Vucetich 1968, Vucetich and Pullar 1969).

In New Zealand rhyolitic tephros in particular are very widespread and form valuable marker beds. Certain of the andesitic tephros, for example Poutu Lapilli, Te Rato Lapilli and Rotoaira Lapilli, are good time indicators but in general not quite so good as the rhyolites. A major advantage accruing from the accumulation of the andesitic tephros in the Tongariro Volcanic Centre is that they have preserved most of the rhyolitic tephros previously deposited over the area. Puketarata Ash (Lloyd 1972), for example, has not been recognised in rhyolitic tephra sequences south of Wairakei yet it has been identified (Topping and Kohn 1973) in andesitic sequences near Lake Rotoaira over 60 km south of its source in the Maroa Volcanic Centre. Many of the rhyolitic tephros are already dated and charcoal, wood and peat associated with the andesitic tephros have provided dates for a further four of these rhyolitic tephros. These dates together with the andesitic tephrochronology (Topping 1973) provide time planes to date landforms and events within the southern part of the Taupo Volcanic Zone.

Within the Tongariro Volcanic Centre domes, lava flows and lahar deposits younger than 14,000 years BP can be assigned minimum ages from the oldest dated mantling tephros. However, erosion may have removed part or all of the tephra cover from older surfaces. The older tephros (>20,000 years

BP) are best preserved where Oruanui Formation was appreciably thick, particularly at low altitudes around the Rotoaira Basin. Although the voluminous Oruanui Formation has been eroded off some surfaces, particularly above 900 m, its reworked products can be recognised at many sites and thus provide a minimum age.

Numbered sections from which tephra data are quoted during the following discussions are located by the grid reference and are shown in Appendix 2 and on maps N102, N112 and N122 (back pocket). Some of the more important sections are described in Appendix 1. All tephra contacts are conformable unless otherwise stated.

QUATERNARY GEOCHRONOLOGY BEYOND RADIOCARBON DATING

The Tongariro Volcanic Centre (southern part of Taupo Volcanic Zone) was generated probably entirely during Quaternary time. Miocene-Pliocene siltstones, which are capped by lavas of Hauhungatahi Andesite (Hay 1967) west of Ruapehu and which also outcrop in the Ohakune area, were deposited before the end of the late Tertiary marine transgression. At the close of Opoitian time (lowest Pliocene) the sea retreated southwards into the Wanganui Basin which was regarded by Fleming (1953) as a continuation of the Taupo Graben. No volcanic material is present within these siltstones near Waiouru where their age is probably Upper Miocene (Kapitean; Fleming, pers. comm., in Gregg 1960) and the southern part of Taupo Volcanic Zone as we now know it was not operative at that time.

The earliest pebbles of hypersthene andesite in the Wanganui Basin and in Rangitikei Valley were deposited during the late Castlecliffian (early Pleistocene) (Fleming 1953, Te Punga 1952).

Of the nine K/Ar dates obtained within Tongariro Volcanic Centre

(Stipp 1968) the oldest is 0.26 m.y. (GA 3254, Table 1) for a lava at the southern end of the Tongariro Massif. However, the centre is known to be older than that and may be considerably older. For example, two ignimbrite formations, the Whakamaru Ignimbrite (Hatherton 1954) and the Te Whaiti Ignimbrite (Grindley 1960) with ages of about 0.32 m.y. and 0.30 m.y. respectively (B. P. Kohn, pers. comm.) outcrop in the Tongariro Volcanic Centre and overlie andesitic material. Lahars from the Kakaramea-Tihia Massif (Hauhungaroa Lahars (Grindley 1960)) underlie Whakamaru Ignimbrite and they may date back to 0.59 m.y. (see p.120). Andesitic tephras underlie Te Whaiti Ignimbrite in Poutu Tunnel and are therefore older than 0.30 m.y. Andesite lava in Tongariro River is most probably older than this ignimbrite and its reversed polarity suggests it may be older than 0.69 m.y. (see p.216).

Apart from these two ignimbrites and the nine K/Ar dates no other absolute (radiometric) chronology beyond 45,000 years BP (radiocarbon dating) is available for Tongariro Volcanic Centre. Consequently little is known of the early history of the volcanic centre. The age relationships within the last 20,000 years are better known, particularly for the vents on Tongariro. These data, detailed in this chapter, are summarised in Fig 20.

STRUCTURE AND VOLCANIC HISTORY OF THE TONGARIRO VOLCANIC CENTRE

The eruptive centres are considered from north to south, in the order: Kakaramea-Tihia Massif, Rotopounamu Graben, Pihanga, Maungaku, Maungakatote, Tongariro Massif (with vents described from youngest to oldest), Hauhungatahi, Ruapehu, and the Ohakune explosion craters.

Kakaramea-Tihia Massif

The andesite volcanoes at the northern end of the Tongariro Volcanic Centre are aligned NW-SE for some 10 km, sub-parallel with the oldest vents on the Tongariro Massif. Most of the activity from the Kakaramea-Tihia Massif

Fig 20: Quaternary Eruptive Activity within the Tongariro Volcanic Centre. The eruptive vents are listed in approximate north-south order of occurrence and their locations are shown in Fig 2. The chronology used to date the tephra eruptions (t), lava extrusions (l) and lahars (L) was obtained from radio-carbon dated andesitic and rhyolitic tephra, two fission track dated ignimbrites, and the Brunhes-Matuyama magnetic polarity boundary and is shown at the right hand side of the figure.

The dashed lines are reasonably certain, the dotted lines are estimated ranges, and the queried lines are guestimates only.

h - historic eruptions;	ng - Ngauruhoe Tephra;
mg - Mangatawai Tephra;	mn - Mangamate Tephra;
pt - Poutu Lapilli;	tt - Te Rato Lapilli;
R - a reversely magnetised andesite lava flow;	
GA - numbers are K/Ar dates from Stipp, 1968 (Table 1).

Andesitic Tephra Rhyolitic Tephra

(Fig 2) at the north-western end of this belt was probably earlier than the major cone-building eruptions from Pihanga, at the south-eastern end. Kakaramea (1,280 m) and Tihia (1,147 m) are more dissected than Pihanga and lavas dated by Stipp (1968) from these sources have ages of 0.222 ± 0.001 m.y. and 0.192 ± 0.023 m.y. respectively (Table 1). The Kakaramea-Tihia Massif has several youthful cones and craters which have probably been active within the last 50,000 years. Much of the topographic relief is due to recent fault movement on the Taupo Fault belt (Grindley 1960).

Kakaramea

No tephtras likely to be from the Kakaramea area were observed above Oruanui Formation (20,000 years BP) in any sections north and north-west of the massif. There is no reason to suppose that volcanic activity has been more recent near Kakaramea^{trig} than at craters at the eastern end of the massif.

Tihia

Lava flows and volcanic breccia from Tihia exposed at sections on Te Ponanga Saddle Road (e.g. sections 91, 92, N112/238004, N112/241007) are older than Oruanui Formation (i.e. > 20,000 years BP). The youngest eruptive deposit yet recognised comes from the eastern end of the Kakaramea-Tihia Massif. This was the product of a nuée ardente which overwhelmed and carbonised vegetation and was above the Curie temperature when it came to rest (section 79, N112/202974; see p.224). The nuée ardente was from its distribution probably erupted from the southern of the two vents WSW of Tihia and charcoal from the deposit was radiocarbon dated (NZ1581) at >40,300 years BP.

In slips and sections on Tihia and neighbouring peaks (e.g. section 379, N102/215006) Rotorua Ash (c. 12,500 years BP) is usually the oldest dated tephra. The exception is Rotoaira Lapilli (13,800 years BP) which is

present in a section on the northern slopes of Tihia (381, N102/218006). Tephra older than Rotoaira Lapilli are likely to have been removed by erosion and frost-heave, either when the tree-line was being lowered during Otiran glacial advances (see section on late Quaternary erosion, p.161) or soon after deposition if, in fact, the tephra had fallen during the times of lowered tree-line.

A dome-shaped hill on the north-eastern slopes of Tihia has, exposed on its flank, a tephra section (94, N102/248009). This section includes two rhyolitic tephra - a Taupo source rhyolite older than 20,000 years BP and a still older ash which is probably Rotoehu Ash. If this topographic high is a buried dome it must be $>42,000$ years old.

Rotopounamu Graben

Between Tihia and the western flanks of Pihanga the Rotopounamu Graben is aligned NNE-SSW, sub-parallel with the youngest vents on the Tongariro Massif. The graben contains two recognisable craters (at N112/218947 and N112/220955; here referred to as the Onepoto Craters); a possible explosion crater, Lake Rotopounamu; and two more northerly peaks, Puketopo (c. 930 m, N112/232977), and Pukemohono (c. 795 m, N112/245976).

The Rotopounamu Graben was formed after major eruptive activity ceased, and the western fault in particular, with hot springs on its extension into Lake Rotoaira (E. Cudby, pers. comm.), is probably very young ($< 2,000$ years BP?).

Lake Rotopounamu

Lake Rotopounamu is a small lake (Fig 2), about 1 km^2 in area and with a maximum depth of 7.5 m, situated in the central part of the graben. Fault lines of uncertain age occur to the east and west of the lake. The

lake may be consequent on ponding of drainage and so post-date the faulting or it may have been an explosion crater (Cowan 1927, Gregg 1960). A section (214, N112/228969) on the northern shore of the lake, and on the lower slopes of Puketopo Cone, contains Te Rato Lapilli. This places a minimum age of 9,780 years BP for the lake-filled depression that is if it originated as an explosion crater.

Onepoto Craters

On the two unnamed craters south of Lake Rotopounamu (here referred to as the Onepoto Craters), the oldest tephra identified is Rotorua Ash at 12,500 years BP (section 326, N112/215948). In sections at lower altitudes, at the south-western base of the southern of the Onepoto Craters (section 327, N112/209942) and on the western flank of the northern crater (section 83, N112/214969), Rotoaira Lapilli is present. A minimum age of 20,000 years BP for these two craters is suggested by a deposit underlying Oruanui Breccia on Motuopuhi Island. These slightly weathered brownish yellow coarse lapilli, >1.6 m thick, are believed to have been erupted from one of the Onepoto Craters.

Puketopo Cone

At sections on Te Ponanga Saddle Road west of Puketopo Cone Rotoaira Lapilli (section 86, N112/221978) and Oruanui Ash (section 87, N112/224983) are present, and Oruanui ash is reworked above andesite lava in a further section (85, N112/219977) placing a minimum age of 20,000 years BP on eruptions from this cone.

It is probable therefore that Oruanui Formation has been removed by erosion elsewhere within and on the flanks of the Rotopounamu Graben and that 20,000 years BP is a minimum age for all eruptions from vents within that graben.

Pihanga

Pihanga (1,304 m), at the south-eastern end of the northern group of andesites, is dome-shaped and little dissected. An andesite boulder from Poutu Stream on the southern side of Pihanga, and assumed to be from Pihanga, has been K/Ar dated by Stipp (1968) at 0.125 ± 0.004 m.y. (Table 1).

On the northern side of the summit of Pihanga, at the head of Kahurau Stream, there is a large slip which was once regarded as a crater (e.g. Thomas 1889). (The true crater is immediately to the south). At the top of the slip grey scoriaceous block and ash beds, which dip northwards down the Kahurau Stream, are truncated by younger scoriaceous strong brown block beds which dip southwards into the crater. These younger beds are capped by lava. Within this crater (N112/251943, section 282), recent erosion has exposed 4.2 m of lapilli and finely laminated ash beds which were laid down in water, probably in a small crater lake. The age of this deposit is unknown. Papanetu Tephra, at 9,790 years BP, is the oldest dated tephra recognised on top of Pihanga. Older tephtras have been removed by erosion: fortuitous preservation is required if older tephtras are to be found above 1,200 m (see altitudinal limitations on Oruanui Formation, p. 25).

Numerous sections around the base of Pihanga (e.g. section 427, N112/225929; and section 43, N112/296958) expose Oruanui Formation which is considered to place a minimum age of 20,000 years BP on the youngest tephra eruptions from Pihanga.

Maungakatote and Maungaku

Maungakatote (848 m) and Maungaku (964 m) are andesite cones about 10 and 15 km respectively west-north-west of Lake Rotoaira. Clark (1960) records labradorite, labradorite-pyroxene, and pyroxene andesites from

these cones, and the writer has sampled hornblende andesite on the eastern side of Maungakatote. An andesite flow from Maungakatote peak overlies Whakamaru Ignimbrite (drill hole data; Dr N. Briggs, pers. comm.) and both cones are therefore probably younger than 0.32 m.y.

Tongariro Massif

Ngauruhoe

Ngauruhoe, New Zealand's most active volcanic vent, is a composite cone about 900 m high within the southern part of the Tongariro Massif. Its peak is 2,251 m high, and its 30° outer slopes terminate in a crater about 400 m across. Gregg (1960) gives a list of eruptions recorded from 1839 to 1959 and gives detailed descriptions of changes in the summit sub-craters during this time. The most recent lava flows are those of July 1870, February 1949 (c. $546,750 \text{ m}^3$, Battey 1949), and June-September 1954 (13 flows with a volume of the order of $5,800,000 \text{ m}^3$; Gregg 1956). Somewhat older lava flows reach the base of the cone on all sides except the east. The flows are all of aa lava and much of the rest of the cone is likely to have been built up by block and ash flows similar to those which accompanied the 1949 and 1954 eruptions.

Ngauruhoe is surrounded by ridges of andesite up to 1,560 m altitude which Cotton (1944) considered to be part of a dissected somma ring. The three moraine-bounded valleys which radiate outwards from Ngauruhoe suggest a once larger volcano in this position and the age of the morair ($>15,000$ years BP) would provide a minimum age for explosion and/or collapse of that cone.

Partial isopach maps for members of the Mangamate Formation suggest that some of these members were erupted from a vent or vents beneath Ngauruhoe about 9,700 years BP. Isopachs for Mangatawai Tephra (Gregg 1960, p. 39) are centred about Ngauruhoe. The basal leaf-bearing part

of the formation accumulated rapidly, after which ash deposition to the present has been at a slower rate (and mainly from Ruapehu). No tephras are known to have been erupted from the Ngauruhoe area between c. 9,700 and 2,500 years BP. The Ngauruhoe cone is considered to have begun eruption 2,500 years ago and to have completed most of its growth during deposition of Mangatawai Tephra. The largest lava flows, including those between the Makahikatoa (section 422, Appendix 1C) and Mangatepopo (section 165) moraines, were extruded during deposition of Mangatawai Tephra. The short time taken for the build-up of Ngauruhoe is consistent with similar cones overseas, for example Parícutin.

Te Mari Craters

The two craters north of Te Mari Trig on northern Tongariro have been referred to by Cussen (1891) and Gregg (1960) as 'lower Te Mari Crater' and 'upper Te Mari Crater', and collectively as 'Te Mari Craters'. This usage is followed here (Fig 21).

The Maoris had often seen lower Te Mari Crater in eruption (R.T. Batley in Cowan 1927, p. 148) and eruptions have been reported from Te Mari Craters in 1855 (Hochstetter 1864, p. 130), 1869 (Hill 1892), June 1886 (Hill 1892), November 1892 to January 1893 (John Chase in "New Zealand Herald", Auckland, 6 December 1892; Hill 1894), November-December 1896 (Friedländer 1899, Hill 1897, Lowe 1897), and possibly in 1928 (Thompson 1928).

At section 271 (N112/193904) on the National Park-Taupo Road, 4 km NE of Te Mari Craters, andesite gravels and sands occur above and below Taupo Pumice and above the leaf-bearing basal Mangatawai Tephra. The deposits are probably from the Te Mari Craters and suggest that at least one of the craters has been intermittently active for 2,500 years.

Rotoaira Lapilli Formation (Topping 1973) was most probably erupted from lower Te Mari Crater about 13,800 years BP. Chemical and

Fig 21: Vents of the Tongariro Massif. Note the NNE-SSW alignment of the vents and the Recent faults. Central Crater and South Crater have been named previously as craters but are not regarded as craters by the present writer. Photo by courtesy of Lands and Survey Dept.

titanomagnetite analyses for the lapilli are similar to those for two of the lavas exposed within the lower crater (analyses At section 468 (N112/175873), 1 km north-east of lower Te Mari Crater, Rotoaira Lapilli is greater than 8 m thick. Two of the nine lapilli beds were distributed north-eastwards and the others to the south-east. Lava which outcrops 4 km NNE of the lower crater (section 275, N112/181913) was probably extruded directly after the emission of the north-eastward-directed lobes of Rotoaira Lapilli and lava at N112/176916 (sections 27, 28) is slightly younger again.

Immediately north of lower Te Mari Crater a large leveed aa flow (>90 m thick) probably began as a cumulodome. At the distal end of the flow there are two large collapse features and five younger explosion craters. A 1.57 m pit excavated near the terminal end of the flow (section 272, N112/170905) showed Waimihia Lapilli overlying the blocky surface of the flow. A pit at the distal end (section 148, N112/166877) exposes at least 0.45 m of Papakai Tephra above the lava. The lava age is therefore likely to be between 9,700 and 6,000 years BP.

The youngest lavas from Te Mari Craters are from the upper crater; one has flowed into the lower crater and the others have flowed north-west down into Okahukura Bush. The flows are younger than Taupo Pumice and were therefore erupted within the last 1819 years BP. Tree-ring dating shows that the flows were extruded many years before 1764 A.D. and probably closer to 1528 A.D. (see p. 206)

Activity from the Te Mari Craters probably began 14,000 years BP and has continued through to the present.

Red Crater

Red Crater is a recent vent lying within a small scoria cone on the central part of the Tongariro Massif and 3 km NNE of Ngauruhoe. Dark red and black scoria, locally welded, overlies massive light grey old Tongariro

Fig 22: A large dike exposed in the south-eastern wall of Red Crater which has fed a young lava flow in the southern part of Oturere Valley. The draining of the lava has left a tunnel selvedged by chilled lava.

lavas and the cone is intruded by dikes, presumed radial. One of these dikes feeding a young aa flow in the southern part of the Oturere Valley drained of lava leaving a lava tunnel selvedged by basalt (Fig 22). The vent has remained active with ash eruptions reported in 1855 (Hochstetter 1864) and April 1926 (Thompson 1926).

All flows from Red Crater are aa lava which can be divided into an older group erupted before Taupo Pumice and a younger group of five flows which were erupted post-Taupo Pumice (Figs 23, 24, 25). The oldest exposed flow from the cone flowed south-eastwards and filled the floor of the formerly glaciated Oturere Valley. It is younger than 9,700 years BP because the thick Mangamate Tephra, although present elsewhere on eastern Tongariro, does not cover the lava. No Papakai Tephra has yet been observed in sections overlying the flow so that the flow could be as young as 2,500 years BP.

Three pits excavated on the south-eastern lower slopes of Red Crater are described in Appendix 1B (section nos. 477, 479, 481). At site 477 (see Fig 24) the lava is covered by > 0.97 m lapilli and ash beds of Mangatawai Tephra, providing a minimum of 2,500 years old for the lavas.

Darker coloured (black) lavas have flowed to the south-west into South Crater, south into the head of Oturere Valley, north into the broad crater-like depression mapped by Cussen (1891) as "Central Crater", and two flows eastwards into northern Oturere Valley. Taupo Pumice has not been found on any of these flows which are therefore regarded as younger than 1819 years BP (an average age for Taupo Pumice; Healy 1964).

The pre-Taupo Pumice flows from Red Crater are olivine andesites. They have a hyalopilitic texture and comprise phenocrystic olivine, plagioclase, hypersthene and augite with few to sparse feldspar microlites within a blackish-brown glassy matrix. The post-Taupo Pumice flows differ from the older flows by containing greater amounts of small phenocrystic

Fig 23: Red Crater lava analyses plotted as $\text{FeO} + 0.9\text{Fe}_2\text{O}_3 + \text{MnO}$: $\text{Na}_2\text{O} + \text{K}_2\text{O}$: MgO . The six lavas erupted before 1819 years BP (i.e. before Taupo Pumice) are andesites (A) and are clearly distinguished chemically from the four basalt lavas (B) erupted <1819 years BP (i.e. since Taupo Pumice). The analyses are presented in Table 8 and the location of the samples is shown in Fig 24.

Fig 24: Andesite and basalt lava flows extruded from Red Crater. Sites from which lava and scoria samples were collected for analysis (Table 8) are: 474 (11961, 11972), 475 (11962, 11973), 485 (11963, 11964, 11975), 484 (11965, 11974), 476 (11966), 477 (11967), 478 (11968), 480 (11969), 482 (11970) and 483 (11971). Descriptions of tephra sections 477, 479 and 481 appear in Appendix 1B. Photo by courtesy of Lands and Survey Dept.

Fig. 15: Geology of the Tongariro Massif (after W. H. Matthews, 1967) with units from rhyolitic and andesitic tephrochronology. The 1500 A.D. age for the Upper Te Wawa flows is an estimate only (see p. 205). The upper part of the North Crater cone is now shown and it probably formed between 4,800 and 2,000 years BP. The glacial moraines are to be older than 14,700 years BP. The map is slightly modified from an original draughtsman E. Souter.

olivine and abundant feldspar microlites in a blackish glassy matrix which is mainly hyalopilitic but tends towards hyalo-ophitic. Chemically the younger flows are basalts (Table 8) as previously described by Healy (1962). They are chemically quite distinct from the olivine andesites (Fig 23).

A white and yellow clay bed is a useful marker within Ngauruhoe Tephra deposits in Oturere Valley (sections 481, 495, 496; Appendix 1B). It contains lithic fragments in some sections and thickens towards the Emerald Lakes craters, the probable source. Because the lithic fragments are concentrated towards the top of the deposit it is probable that the hydrothermal clays were erupted from fumaroles or small vents before larger phreatic explosions enlarged the vents. The Emerald Lakes are two of a line of small explosion craters trending north-east from Red Crater. Debris ejected from these craters rests on the basalt flow in Central Crater. The explosions are therefore younger than 1819 years BP, and they are almost certain to equate with the white and yellow clay bed described earlier. If the rates of tephra accumulation at sites (495, 496) 4 km south-east of Red Crater have been constant throughout the formation of Ngauruhoe Tephra then the phreatic eruptions from the Emerald Lakes craters occurred about 1250 years BP and the lava flows into Central Crater and northern Oturere Valley occurred between 1250 and 1819 years BP.

Similar white and yellow clays which occur within Mangatawai Tephra (section nos 477, 479, see Appendix 1B) were probably also erupted from the Red Crater-Emerald Lakes area. Within Ngauruhoe Tephra and Mangatawai Tephra the white and yellow clays (hydrothermal alteration products ejected during phreatic eruptions) are valuable markers provided that the relationship to Taupo Pumice (younger or older than) can be determined. At least two tephra units erupted from Red Crater can be recognised within Ngauruhoe and Mangatawai Tephra, i.e., the "120 mm greyish brown medium to very

coarse lapilli" of section 481 and the "200 mm red medium and coarse ash" of section 477. These were probably erupted at the same time as red scoriaceous beds which are now exposed in the upper interior portions of the cone.

The altitude and blocky nature of the youngest Red Crater lavas has precluded the accumulation of ash grade tephra on their upper surfaces so that tephrostratigraphy cannot be used to give their relative ages. Scoriaceous medium lapilli from the upper surface of each of the four flows were analysed for comparison with the unweathered lava in each case. As the lavas are not vegetated and probably exist under similar weathering conditions then the amount of weathering of the scoriaceous lapilli compared with the unweathered parent rock could give the relative ages of the lavas. A comparison of Parker's Indices for the weathered and unweathered rocks (see Appendix 5) give a tentative order for extrusion of the flows into; one northern Oturere Valley, second southern Oturere Valley, third Central Crater, and last into South Crater. If this order is correct then the oldest three were probably erupted within 600 years of deposition of Taupo Pumice over the area.

Blue Lake

Blue Lake, toward the north-eastern end of the Tongariro Massif, and of 1,686 m altitude, is a circular vent with a diameter of about 400 m and occupied by a lake with a maximum depth of c. 16 m. The higher slopes north of Blue Lake and near Rotopaunga Trig, over 120 m above the lake, are mantled by welded agglomerate which is considered to be the product of fire-fountaining of lava at high temperature to a considerable height (e.g. 600-750 m; Mathews 1967) above the crater (Healy 1963). The degree of welding decreases with distance from source and the beds are considered to have accumulated rapidly because prismatic joints cross several layers

without interruption showing that they cooled as a unit (Mathews 1967).

Patches of fresh black vesicular scoria to the west of Blue Lake may be the product of local *nuée ardente* eruptions (Healy 1965).

Although the crater looks youthful no tephra beds within Ngauruhoe or Mangatawai Tephras can yet be ascribed to eruptions from Blue Lake. Poutu Lapilli, youngest member of the Mangamate Tephra, comprises three lobes (Fig 7, Topping 1973) the axes of which intersect at Blue Lake. Large blocks lithologically similar to Poutu Lapilli fragments occur near N112/166833, 1.6 km south-east of Blue Lake, again supporting the eruption of Poutu Lapilli from Blue Lake at about 9,700 years BP.

North Crater

North Crater (1,830 m) is a flat-topped cone near the north-western end of the Tongariro Massif. To the north, south and north-east, cliffs of lava and welded agglomerate define a crater rim about 1,100 m in diameter within which a large pool of lava has ponded and cooled. Mathews (1967) has suggested that "the ponded lava must have been relatively viscous, exerting a hydrostatic pressure insufficient to break down the impounding walls; or relatively cool, congealing against the walls and adding to their strength before it flooded to its full height". Although the lava was fluid enough to form a horizontal upper surface it flowed only 300 m beyond the point where it appears to have overtopped the western crater rim. Shortly prior to this flow and possibly at earlier times the ponded lava must have been fluid enough to sustain fire-fountaining to a considerable height (e.g. 600-750 m; Mathews 1967) and to form welded agglomerates.

An explosion pit about 300 m in diameter and 60 m deep is present in the north-western sector of North Crater (Fig 26). Included in the debris surrounding the pit are large blocks up to 9 m across. Radial contraction fractures in these blocks show that they were ejected while solid but

Fig 26: The explosion pit in the north-western sector of North Crater. Lavas and agglomerates of the southern rim of North Crater are in the background. The pit is about 300 m in diameter and 60 m deep, and the andesite flow which is exposed in its walls is thought to have formed the unusually flat floor of North Crater (Fig 21).

Fig 27: One of several large blocks, up to 9 m across, included in the debris surrounding the explosion pit on North Crater. The radial contraction fractures in these blocks show that they were ejected while solid but hot.

hot (Fig 27). The volume of debris is consistent with the volume of the pit (Mathews 1967) so that it is probable that the development of the explosion pit was a late phase in the cooling of the mass of lava directly underlying the summit plateau.

Taupo Pumice blocks are present at the south-western corner of North Crater and in the explosion pit and give a minimum age of 1819 years BP for the last major eruptions from North Crater. There may have been, however, an ash eruption from North Crater during September 1927 (New Zealand Herald, Auckland, 5, 6, 10 September 1927, in Gregg, 1960). Mathews (1967) described a thin lens of ash interbedded with breccias below the west rim of North Crater and composed of glass, a few plagioclase microlites and a trace of quartz. In the present study the lens of ash could not be located after careful search so these breccias remain undated.

A probable North Crater lava near Otukou Quarry (N112/138951), 9 km north of North Crater, has been K/Ar dated (Stipp 1968) at c. 0.071 m.y. (Table 1). Block breccia exposed on the National Park-Taupo Road at N112/132922 (section 59) is older than 20,000 years BP and lava exposed on the western bank of the Mangatipua Stream (N112/145894) is older than 12,500 years BP. Te Rato Lapilli can be recognised at sites up to 1,320 m (N112/139872) on northern slopes of the cone showing that most of the cone is older than 10,000 years BP and isopach data suggest that Te Rato Lapilli was actually erupted from North Crater.

Several metres thickness of black pumiceous blocks and ash at N112/124893 (section 159), exposed in a stream 3.4 km north of the crater, were probably deposited from one or more nuées ardentes about 10,000 years BP (the nuée deposit is overlain by 300 mm rock fragments in ash matrix (mud flow), 110 mm yellowish brown ash with minor strong brown fine lapilli, and Papanetu Tephra).

Although most of the North Crater cone was constructed by 10,000

years BP there is circumstantial evidence for a considerably younger age for the upper part of the cone. Papakai Tephra (3,440-9,700 years BP; Topping 1973), although largely deposited from one or more vents in the Ngauruhoe-Tama Lakes area, has had a noticeable component added from one or more of the northern Tongariro vents - North Crater, Blue Lake or Te Mari Craters. The rhyolitic Hinemaiaia Ash (age c. 6,300 years BP: Table 1, Topping and Kohn 1973) occurs towards the base of Papakai Tephra at sites to the north of Tongariro showing that most of this ash deposition was between 3,440 and 6,300 years BP. Mudflow and debris flow deposits (described under Lahars section, p.122) deposited during Papakai Tephra time must also be from one of these northern craters. Charcoal from two sites north-west of Tongariro (N112/096941, N112/091937) and dated at $4,820 \pm 85$ (NZ1190) and $4,810 \pm 110$ (NZ1188) respectively and also present in the same stratigraphic positions at sites in the Rotoaira Basin (e.g. sections 311, 312, 315) mark an increase in the rate of tephra accumulation after the slow deposition of the basal Papakai Tephra. While the initiation of cone-building eruptions from Ngauruhoe may be the cause of this increase in tephra deposition it is far more likely due to renewed cone-building eruptions from North Crater. Identification of the rhyolitic ash reported by Mathews (1967) as Waimihia Lapilli would support this younger age for the upper cone.

Tama Lakes

The two Tama Lakes, generally distinguished as either Lower Tama Lake or Upper Tama Lake, occupy one and two respectively of six explosion craters on the saddle between the Tongariro Massif and Ruapehu. Grange and Hurst (1929) recognised that these craters were the source of young tephra eruptions and recent work (Topping 1973) has shown that five members of the Mangamate Formation and possibly also Pahoka lapilli were erupted from craters in the Ngauruhoe-Tama Lakes area between 9,700 and

c. 10,000 years BP.

Pyroclastic debris surrounding Lower Tama Lake includes many blocks of dark grey to black, fine-grained, non-vesiculated or very finely vesiculated andesite similar in appearance to the andesite lapilli in the members of the Mangamate Formation. One or two rare breadcrust bombs show that such blocks were hot when ejected. A thin lava flow, exposed on a saddle (N112/109763) north-east of the Lower Tama Lake, has "a glassy tachylitic vesicular texture, consistent with [its] being quenched by contact with snow or glacier ice" (Grindley 1965) and is lithologically similar to these blocks. The latter observation suggests that build up of pressure (magmatic or superheated steam) beneath such thin flows caused their fragmentation and eruption before they had finally cooled. The lava would need to be hot enough to form bombs and hot enough not to have formed joint planes and fractures within the lava flow prior to the time of disruption.

It is not known whether there was sufficient ice and snow on the Tongariro Massif c. 9,700 years BP to cause rapid quenching of lava flows, as suggested by Grindley (1965). Glacial moraines with a minimum age of 9,100 years BP are known from Hawaii (Porter 1973) but there is not yet any evidence of a cold phase in New Zealand at this time. The erosion break above Mangamate Tephra is here interpreted as being due to lack of protective vegetation and to be without climatic significance. No cold phase has been recognised in peats of this age west of Lake Rotoaira (M. S. McGlone, pers. comm.).

Pukeonake Scoria Cone

Pukeonake Scoria Cone, 1,225 metres in altitude and 5.6 km west of Mount Ngauruhoe (Fig 28), is largely tussock-covered and rises about 143 metres above the surrounding Tongariro ring plain. To the north of

Fig 28: Pukeonake Scoria Cone from the west with Pukekaikiore dome and Ngauruhoe cone beyond.

Fig 29: Two olivine andesite plugs viewed from the summit of Pukeonake Scoria Cone. These three features mark a north-south fissure from which lava was extruded mainly westwards over an area of about 55 km² over 20,000 years BP.

Pukeonake (its name means 'even sloping hill') are two further vents (Fig 29), now residual plugs.

Grange and Hurst (1929), reporting on their work within the Tongariro Subdivision, described Pukeonake as an olivine basalt cone on the eastern margin of an extensive sheet of vesicular olivine basalt to the west of Pukekaihiore. To the north they mapped two plugs. Clark (1960) has shown these 'basalts' to be olivine andesites on chemical grounds. In 1960 Grindley proposed the new formation name 'Pukeonake Andesite' and described Pukeonake and the two more northerly vents as scoria cones. He considered them to be surrounded by Waimarino Lahars and thus to date from Last Glaciation (Grindley 1965).

A road constructed in 1958 for quarrying of the cone gives ready access, and exposures created by the quarrying, together with those of recent rill erosion on the outer eastern slopes and the crater breached by the Pukeonake Stream provide the volcanic history of the cone.

The outer slopes of the cone are steepest to the east (25°) and south-east (23°) and least steep to the south-west (17°), averaging 21° . The external slopes reflect the dips within the scoriaceous beds of the cone being $33-35^{\circ}$ to the south-east and $31-32^{\circ}$ to the south-west. Outwards from the centre of the cone external slopes increase and decrease in accordance with, but to a lesser extent than, the structural dips.

The cone, approximately $1,150 \times 900$ m is elongated NE-SW. This elongation together with the south-western slopes being the least steep suggest that for much of the formation of the cone wind was from the NE. However, this slight elongation could also be due to two or more close vents along this line.

Scoria cones similar to Pukeonake usually form over comparatively short periods of time. However, Pukeonake has a distinctive discordant unconformity representing an unknown period of time. On the northern

side of Pukeonake Stream quarrying of c. 4,000 tons of scoria from the cone (MacInnes, pers. comm.) has exposed 41 m (laterally) of scoriaceous block and lapilli, and tuffaceous beds dipping towards the centre of the cone. Dark grey to black scoriaceous block and lapilli beds with blocks up to 1.35 m long alternate with beds in which blocks sit in a matrix of more scoriaceous (most of vesicles 1-2 mm across) yellow-grey andesite of lapilli and coarse ash grade sizes. About 90 m further downstream, younger tephra, dipping south-east at $31-33^{\circ}$, comprise beds of grey-brown medium to coarse tuffs with scattered, scoriaceous lapilli and beds of coarse lapilli and small blocks in coarse ash matrix. Blocks, rarely larger than 100 mm, and lapilli, are of dark grey-black vesiculated olivine andesite scoria or are more pumiceous and yellow. Some beds are of black scoriaceous blocks usually of 150 mm across, but up to 300 mm. Orange lapilli beds and lapilli and ash beds of yellow-green and red also occur.

At two places on the upper external south-eastern slopes the unconformity between older and younger beds is seen. Black lapilli and block beds (rare blocks up to 330 mm across), beds of black, yellow, and orange scoriaceous lapilli interbedded with coarse ash beds dip downslope. They are unconformably overlain by 3.7 m of yellow lapilli and yellow and red coarse ash beds (with blocks of up to 120 mm) dipping craterwards. These younger yellow-green and red beds are also exposed near the centre of the cone.

Black scoriaceous blocks and lapilli near the south-eastern and eastern upper sections of the cone stand in vertical exposures, are almost welded, and are likely to have been produced by fire-fountaining. One large spindle bomb, 1.13 m in length, is exposed on the eastern interior portion of the cone showing that at least some of the scoria was molten when thrown into the air. Olivine crystals in the scoria exposed in the interior of the cone have been altered to bright pink iddingsite, possibly by gaseous

oxidation. These crystals within the scoria increase in abundance towards the top of the interior exposures, showing likely tapping of progressively more basic magma.

Age and Interpretation of the History of the Cone

Headward erosion of the Pukeonake Stream has exposed within the cone a complete section of tephra beds overlying the scoria beds of the cone (section 164, Appendix 1B). The oldest tephra exposed, the rhyolitic Oruanui Formation, provides a minimum age of 20,000 years BP (NZ12, NZ1056, Pullar and Heine 1972) for the final eruptions of the cone.

The basal shower-bedded part of Oruanui Ash and the chalazoidite-containing ash dip up to 17° on scoriaceous olivine andesite beds and are overlain by a wedge of massive Oruanui Ash (tephra-fall) and Oruanui Breccia (tephra-flow) (Fig 30). These deposits are overlain by three beds of accretionary lapilli or pisolites of the type named chalazoidites by Berry (1928). These are separated and overlain by finely laminated water-laid beds containing sedimentary structures (Figs 31, 32).

Chalazoidites can form in three ways (Moore and Peck 1962):

- (a) absorption of a rain drop by newly deposited ash during light rain (Scrope 1829, Lacroix 1904);
- (b) accretion of ash around a nucleus blown by the wind or rolling down a slope (Stearns 1925); and
- (c) accretion of moist ash in an eruptive cloud to form mud-pellet rains (Perret 1924, Stearns 1925).

The widespread occurrence and the finely laminated character of the chalazoidites within the Oruanui Ash (Seinde Island Pumice of Berry 1928) support an origin by (c). Chalazoidites occurring within Oruanui Formation elsewhere in the Tongariro area form only one bed within the Oruanui Ash Member and are not size graded. The three beds within Pukeonake Scoria

Fig 30: Oruanui Formation infilling the former crater of Pukeonake Scoria Cone and overlain by subhorizontal andesitic tephra.

Fig 31: Three beds of chalazoidites within finely laminated water-worked Oruanui tephra exposed within the former crater of Pukeonake Scoria Cone.

Fig 32: Detail of one of the three chalazoidite beds of Fig 31 showing the very crude grading.

Cone are crudely graded although this may be due to water sorting. The chalazoidites within the three beds are considered to be too numerous to have been derived from Oruanui ash exposed on higher surfaces of the crater and are considered to represent tephra-fall eruptions younger than the tephra-flow deposits of the Oruanui Breccia Member.

Sometime after final eruption of scoria at Pukeonake, the Oruanui Ash Member was erupted as a series of showers (including a chalazoidite shower) over the Tongariro area. The basal shower-bedded ash lined a conical vent within the crater and this was partially filled by massive Oruanui Ash and probable tephra-flow deposits of Oruanui Breccia. Rain-water could not drain from the closed basin sealed by the ash but formed a small crater lake. Three subsequent showers of chalazoidites which fell into this lake were each, in turn, overlain by finely laminated sub-horizontal beds of water-reworked ash. After the Oruanui eruptions and rapid infilling of the lake, subaerial andesitic tephra from Mount Ruapehu and the Tongariro Massif have continued to accumulate to the present day.

In this interpretation the chalazoidites above the Oruanui Breccia represent deposits which have been fortuitously preserved within the crater but have been removed elsewhere in Tongariro Volcanic Centre by erosion during late Otiran cold climates (Suggate 1965, Suggate and Moar 1970). They may therefore equate with bed 3 (chalazoidite tuff and tuffaceous sandstone) of the Wairakei Breccia at Wairakei 70 km to the NE (Grindley 1965, Vucetich and Pullar 1969).

Chalazoidites occur above and below the Oruanui Breccia at Pukeonake Scoria Cone. Where the Oruanui Breccia Member (tephra-flow) is absent, for example near Ohakune 35 km south of Pukeonake (sections 456, 255, 256; N121/912511, N121/980454, N121/986452) the chalazoidites may therefore be younger or older than the tephra-flow member. The Aokautere Ash, a

rhyolitic tephra mapped by Cowie (1964) near Palmerston North 140 km south of Pukeonake, and correlated with Oruanui Ash by Vucetich and Pullar (1969) includes the shower bedded base of Oruanui Ash. However, the upper part of Aokautere Ash, equating with the chalazoidite-containing ash near Ohakune, probably contains tephra younger than the Oruanui Breccia Member and should not be considered a correlative of the Oruanui Ash Member alone.

Geologic Setting of Pukeonake Scoria Cone

The Pukeonake Scoria Cone was formed by fire fountaining at the intersection and widest part of a N-S fissure, defined by Pukeonake and the two plugs north of it with a deeper-seated E-W fracture running from Pukeonake to Pukekaikiore dome and Mt Ngauruhoe. Voluminous olivine andesites which flowed westwards from the fissure covered an area of about 55 km². The oldest flows, e.g. those exposed at Mahuia Rapids, are non vesicular. The younger flows are vesicular and can be seen in several road cuttings between Mahuia Rapids and Taurewa (N112/050895). The olivine andesites control the topography and outcrop at many places along Pukeonake Stream, Papamanuka Stream, and Whakapapanui Stream below the Makahikatoa Stream confluence.

The western ring plain of Tongariro should therefore not have been mapped as Rangipo Lahars (Grindley 1960) i.e. as "andesite conglomerate building [the] deeply dissected ring-plain of Tongariro" but as olivine andesite lavas. Grindley (1960) mapped olivine-augite-labradorite andesite flows at Mahuia Rapids as part of his Pukekaikiore Andesite Formation. However, there is no evidence that these lavas were erupted from Pukekaikiore and they should be included in Grindley's (1960) Pukeonake Andesite Formation, redefined to include lavas.

The olivine andesites from Mahuia Rapids, Pukeonake Scoria Cone, the two plugs north of Pukeonake, and lava exposed at N112/049836 (section 337) all contain phenocrystic olivine, plagioclase, and pyroxene in a groundmass which is usually hyalopilitic (with microlites of feldspar and occasional small pyroxene crystals in a matrix of brown to black glass), but becomes almost holocrystalline in the Mahuia Rapids olivine andesite. The olivine andesite flow erupted from a vent near the summit of Pukekaikioire dome about 14,700 years BP contains pyroxene and abundant olivine phenocrysts in a hyalopilitic groundmass. This lava differs from the other olivine andesites because it lacks feldspar phenocrysts. It is also slightly different on the basis of chemistry (Table 8). ^(p. 48)

The Older Tongariro Centres

Mathews (1967) has noted that the older Tongariro flows are thicker and have more regular bedding than the younger flows most of which are of the aa type. Many flows younger than 20,000 years BP such as the youngest Ngauruhoe flows and the flow north of lower Te Mari Crater have well developed central troughs and levees, or larger flows such as the Te Mari Crater flows forming the western shoreline of Lake Rotoaira, and the oldest Red Crater flow in Oturere Valley show pronounced transverse arcuate furrows.

Geomorphically Tongariro Massif varies from Kear's (1957) "residual mountain stage" in the Tama Lakes area, where narrow radiating ridges are separated by relatively broad valleys, to "planeze stage" on the eastern and western sides where the interfluves are wider than the valleys, and to "volcano stage" near the northern side where stream erosion is minimal. Mathews (1967) used these observations to argue that Tongariro has never been a single large cone, in contrast to Marshall (1905, p. 183) and Speight (1908, p. 100) who believed that the summit has been destroyed by

explosion, and to Taylor (1855, p. 225), Crawford (1869, p. 21), and Grange and Hurst (1929, pp 6-7) who considered Tongariro to be a large collapse structure.

Mathews has used dips on old lavas and breccias as evidence of six vents along a north-westerly line between Tongariro Trig and the southern wall of the upper Oturere Valley. Three other old vents, also aligned to the north-west are Pukekalkiore dome; a second vent presumed to be close to breccias which are now almost covered on the southern side of Ngauruhoe cone; and a third vent mapped by Mathews (1967) at the top of Tama ridge (N112/125780) 800 m north-north-east of Upper Tama Lake. Both alignments are therefore subparallel to the Pihanga-Kakaramaea line of vents and it is possible, from the available K/Ar dates (Stipp 1968), that the vents on both massifs were active at the same time. It is also interesting that the apparent youngest vents of the Pihanga-Kakaramaea lineament are aligned to the NNE as are all the youngest vents on the Tongariro Massif.

Two further vents, on the northern sides of Oturere and Mangahouhounui valleys, can be recognised from morphology and from the dips of lavas exposed in valley walls (Mathews 1967). However, several further features named and described as craters - South Crater (Thomas 1889, Grange and Hurst 1929); Central Crater (Cussen 1891, Grange and Hurst 1929); Oturere Crater (Speight 1908, Grange and Hurst 1929); and an "ancient crater" at the head of Mangahouhounui Stream (Grange and Hurst 1929) - have little evidence apart from their circular or semi-circular outline to suggest their origin as craters. All have probably been largely reshaped as cirques, or at least modified by glacial erosion.

An unnamed peak (N112/171862), 1 km east of upper Te Mari Crater, was the source of lava flows extruded earlier than 13,800 years BP (sections 468, 24, 25; N112/175873, N112/208899, N112/204901) and perhaps more

than 20,000 years BP (sections 24, 25).

Pukekaikio

Pukekaikio, 2 km north-west of Ngauruhoe, is a dome-shaped mass consisting of numerous labradorite andesite flows. The complex joint patterns and draping nature of the younger flows suggest, but do not prove, that Pukekaikio is a multiple flow cumuldome rather than a remnant of a much larger volcano. The dome has been modified to north and south by the glaciers which occupied Mangatepopo and Makahikatoa Valleys. Mathews (1967) records a possible glacially grooved surface at the north-western base of Pukekaikio (N112/092816).

Several authors (Gregg 1960, Grindley 1960, Hay 1967) have attributed the vast olivine andesite flows which occur west of Tongariro and outcrop on the National Park-Taupo Road and at Mahuia Rapids to a vent on Pukekaikio. It is more likely, however, that these flows were extruded shortly before 20,000 years BP from a fissure defined by Pukeonake Scoria Cone and the two small plugs north of the cone (see p. 106-7).

One or more young flows of olivine andesite have been extruded from a vent near the summit of Pukekaikio. The black scoriaceous aa breccia is exposed near the terminal margin where the Mangatepopo-Whakapapa Village track crosses a small stream (N112/076812, section 368, see Appendix 1D). The unnamed basal lapilli (0.15 m at section 368) is known from section 369 in Mangatepopo Valley (N112/089822, see Appendix 1C) where it is 0.17 m thick. Here it overlies 0.36 m "brown grey medium and coarse ash, fine lapilli"; 0-40 mm of rhyolitic Rerewhakaaitu Ash (Topping and Kohn 1973); and 0.58 m dark grey and brownish grey medium and coarse ash. The unweathered tephra (0.36 m) above, and the similar tephra (0.58 m) directly below the Rerewhakaaitu Ash are also present in the crater of Pukeonake Scoria Cone and are almost certain to have been erupted from Pukekaikio

Fig 33: Hauhungatahi, 12 km north-west of Ruapehu (Fig 2), consists of a low cone of olivine andesite (tussock covered) which overlies and protects Miocene (Kapitean Stage) marine siltstones. The andesite-siltstone contact is at the break in slope, the upper limit of forest, about 520 m above the surrounding Ruapehu ring-plain.

dome immediately prior to extrusion of the olivine andesite flow. The age of the flow is therefore similar to that of the Rerewhakaaitu Ash, 14,700 years BP (NZ716, Vucetich and Pullar 1969).

Hauhungatahi

Hauhungatahi (Fig 33), 12 km north-west of Ruapehu, consists of a low cone of olivine andesite (Clark 1960; Hauhungatahi Andesite Formation of Hay, 1967) which has protected Miocene (Kapitean Stage) marine siltstones from erosion to the level of the Ruapehu ring-plain about 520 m below.

The only tephra section providing information on the age of Hauhungatahi is a road section 1.5 km south of Erua Ski Village (N111/898717, section 242) where blocks of vesiculated olivine andesite from Hauhungatahi lie within andesitic tephra 0.40 m below Oruanui Ash, and hence are older than 20,000 years BP.

Ruapehu

Most tephras erupted from Ruapehu between c. 10,000-14,000 years BP have been strongly wind-controlled and most have been deposited to the east of the volcano. Less frequent emanations have drifted north. The eastern deposits, in general, accumulated too continuously for prominent soils to form between eruptions; e.g. c. 10 km east of the summit (N122/171664, section 462) over 50 ash and lapilli units are present with no paleosols or erosion breaks within the sequence (Topping 1973). The number of available sections to the east of Ruapehu is inadequate to allow plotting of isopachs for any of these units.

The Mangamate Formation and Pahoka lapilli can be recognised as far south as the Waikato River bridge on Desert Road (N122/228655, section 171) where they overlie the Ruapehu tephras described above. The Waimihia Lapilli Member is present in the southern area of the Rangipo Desert

(N122/165595; 460; 10 km south-east of Ruapehu); Rotorua Ash is probably present in a section on Desert Road 9 km north of Waiouru (N122/197528; 285(a)); and Taupo Pumice is present in sections south-east of Ruapehu. Oruanui Formation is present in road cuttings to west and south of Ruapehu and has been identified from within gravels at a section 13 km south-east of Ruapehu (N122/175575) but is apparently absent from sections along Desert Road. These four radiocarbon dated rhyolitic tephra provide the only chronology to date lavas, lahar deposits, etc, west, south-west, south and south-east of Ruapehu. In these areas some of the more prominent Ruapehu source lapilli units will need to be radiocarbon dated.

A very extensive, and one of the youngest, aa flows on Ruapehu extends northwards almost to the Chateau. Two sections (Nos 346, 347; N112/041726, N112/041729) through the flow expose up to 0.93 m of tephra older than Mangatawai Tephra overlying the aa breccia. Strong brown and yellowish brown lapilli occurring within the lower part of the Papakai Tephra in one of these sections (347) has been recognised elsewhere within Papakai Tephra (344, N112/062783) and has a Ruapehu source. The stratigraphic position of this lapilli suggests an age for the Ruapehu lava of between 5,000-10,000 years BP. The source is probably the northern crater of Friedländer (1899) and the lava was extruded after deposition of Okupata Tephra basal lapilli and probably after deposition of the Murimotu Lahars lower down on the northwestern slopes (see under lahars, p. 128).

This northern crater is likely to have been the source of the numerous tephra erupted between 10,000 and 14,000 years BP becoming relatively inactive about 10,000 years ago just before eruption of the voluminous Mangamate Tephra from vents on the Tongariro Massif. The northern

vent continued sporadic activity, however, as shown by extrusion of a large aa flow on northern Ruapehu, the formation of a hot lahar, and eruption of several tephra all between 12,450 and 5,000 years BP. By 2,500 years BP little tephra was being erupted from Ruapehu and the lack of laharic deposits of this age north-west of Ruapehu suggest that the northern crater had been filled-in with debris and that there was no longer a crater lake in this vent.

Tephra erupted from Ruapehu since 2,500 years BP was probably from the vent occupied by the present Crater Lake. Radiocarbon dating of the earliest of the recent lahars within the Whangaehu River valley would give a reasonable age for the initiation of that vent. Most of the activity from Crater Lake vent has been since 1819 years BP from which time more tephra has been erupted than from Ngauruhoe.

Lava flows from a small parasitic cone (crater floor has a width of c. 50 m) at 1,500 m on northern Ruapehu and mapped as post-glacial by Grindley (1960) are capped by 0.93 m of tephra older than Mangatawai Tephra. The flows are probably older than 5,000 years BP and younger than 9,700 years BP (section 465; N112/093747). No tephra sections on the eastern lobe have been found.

Ohakune Explosion Craters

The southernmost vents of the Tongariro Volcanic Centre occur near Ohakune, about 19 km south-west of the summit of Ruapehu. Two explosion craters or maars (Ollier 1967) form the Rangatau Lakes 4.5 km south-west of Ohakune; and at least five craters (Gorton 1968) occur 1 km north-west of Ohakune. Tephra and lavas from these craters consist of pyroxene and olivine andesites (Clark 1960).

Oruanui Ash is interbedded with andesitic tephra above slightly weathered scoriaceous ejecta erupted from the northern of the two Rangatau Lakes (N121/885469, section 505, Appendix 1D). Oruanui Ash is also present in two sections (Appendix 1D) near the rim of the largest of the other craters: at a section in a quarry (456, N121/912511) 0.13 m of Oruanui Ash and > 0.1 m of older andesitic ash mantle olivine andesite scoria, and in a railway cutting (section 455, N121/907518) Oruanui Ash and 0.18 m of andesitic ash overlie ash and lapilli erupted from the largest crater.

The age for all of the Ohakune craters is therefore likely to be a little older than 20,000 years BP, and perhaps 25,000 years BP.

AGES FOR RHYOLITIC AND DACITIC DOMES BASED ON TEPHRA COVER BEDS

Puketarata Dome (Lloyd 1972) [c. 13,500 years BP]

Puketarata Ash, which was erupted from Puketarata Dome towards the end of dome building, is considered to be the youngest tephra erupted from the Maroa Volcanic Centre and to have an age of c. 10,000 years BP (Lloyd 1972). At a section near Wairehu Canal (310(a), N112/145983), 12 km north of Tongariro, Puketarata Ash occurs c. 80 mm below andesitic tephra dated at $13,150 \pm 300$ years BP (NZ1186, Table 4, p. 37) and 0.16 m above Rotoaira Lapilli which has been dated elsewhere at $13,800 \pm 300$ years BP (NZ1559). Puketarata Ash and Puketarata Dome therefore have an estimated age of 13,500 years BP.

Kuharua Dome [c. 9,785 years BP]

Kuharua Dome (Fig 34), 12 km north-west of Turangi, is the southernmost of four rhyolitic domes (Daorerk 1972) near the south-western end of Lake Taupo. Papanetu Tephra which has been dated at c. 9,785 years BP (NZ1372, NZ1374, Table 2, Topping and Kohn 1973) was erupted from Kuharua Dome (Fig 4, p. 25) towards the end of dome formation. A pit excavated at about N102/188082 (section 320) shows 0.62 m of Papanetu Tephra directly below Te Rato Lapilli and directly overlying rhyolitic bedrock.

Pukekaikiore Dome (12 km north-west of Turangi; not to be confused with the dome of the same name west of Mt Ngauruhoe) [> 9,790 years BP]

In a section on this rhyolitic dome (324, N102/217125) Te Rato Lapilli and a trace of Papanetu Tephra can be recognised within yellowish brown ash. The lower contact with bedrock can not be seen. Pukekaikiore therefore has a minimum age of $9,790 \pm 160$ years BP (NZ1374) and is thus older than Kuharua Dome; probably considerably older.

Fig 34: Kuharua Dome, 12 km north-west of Turangi, was extruded about 9,785 years BP and was the site of eruption of the rhyolitic Papanetu Tephra. The ridge in front of Kuharua consists of andesite lava flows from the Tihia-Kakaramea Massif. Manganamu Dome (Fig 35) is at the right hand side of the photo.

Fig 35: Manganamu Dome, a small dacitic dome 4 km west of Turangi, which was extruded within the past 1819 years BP, i.e. since eruption of Taupo Pumice.

Fig 36: Koroī Dome, about 90 m high and of dacitic composition, was extruded near the south-eastern end of Lake Taupo (Fig 2) probably about 1819 years BP.

Manganamu Dome (4 km west of Turangi; not to be confused with a dacitic dome of the same name 5 km south-west of Tauhara, Fig 35) [$< 1,819$ years BP]

Independent thorough search by Mr W. M. Prebble (oral comm.) and by the author have revealed no Taupo Pumice on this dacitic dome. It is therefore very probable that Manganamu was extruded within the last 1819 years BP.

Koroī Dome [c. 1,819 years BP]

Koroī Dome (Fig 36; Thomas 1889 for name) has a composition of hypersthene dacite (Daorerk 1972). It is about 90 m in height and has been extruded at the southern end of a rhyolitic lava flow which is considerably older than 9,780 years BP (224, N102/358078). The oldest tephra exposed in four pits dug on top of Koroī Dome was 0.3 m of Taupo Pumice and this tephra directly overlay fresh dacitic lava. The age of the dome is thus unlikely to be much older than 1819 years BP.

Horohoro Dome [$> 14,000$ years BP]

This small dacitic dome about 90 m in height and 11 km east of Lake Rotoaira is older than 13,800 years BP (NZ1559). In a pit excavated on the north-eastern side of the dome (276, N112/348901) Rotoaira Lapilli and 0.35 m of older andesitic ash were the oldest tephras exposed.

Motuopuhi Island [$> 20,000$ years BP]

This island in Lake Rotoaira is considered, on mineralogical grounds, to be a dacite (Clark 1960). An exposure on the eastern shore (319, N112/198956) of the island has 1.5 m of Oruanui Breccia and at least 1.61 m of coarse andesitic lapilli above dacitic lava. The andesitic lapilli (probably from one of the two craters immediately south of Lake Rotopounamu) is of unknown age. However, Oruanui Breccia with an age of about 20,000 years BP (Vucetich and Pullar 1969) provides a minimum age for the dacitic lava.

B. LAHARS OF THE TONGARIRO VOLCANIC CENTRE

The term lahar is here applied to any unsorted or poorly sorted deposit of volcanic debris that moved and was deposited as a mass and owed its mobility to water (Mullineaux and Crandell 1962). It refers to both the mass flowage and the resulting deposit (A.G.I. 'Dictionary of Geological Terms' 1962).

Lahar deposits are generally poorly sorted, unstratified, and often contain large boulders, but structures characteristic of alluvium are generally absent. The clasts within laharic breccia are usually more angular than in alluvium at comparable distances from the source volcano. The preservation of angularity over considerable distances probably results from transport in a suspension whereby stones are buffered by a viscous matrix that greatly reduces abrasion (Mullineaux and Crandell 1962). There is frequently, however, a gradation from angular, through subangular to subrounded (and smaller) clasts both from central to lateral parts of a lahar deposit and with increasing distance from source, and this possibly reflects decreasing viscosity of the matrix. The laharic breccia thus changes laterally to laharic conglomerate. Lahars close to source are commonly ungraded but on less steep slopes vertical grading, from coarse at the base to fine at the top, is common (Crandell 1957). Reverse grading characterises some laharic breccias (Schmincke 1967) and may form during inertia flow (Bagnold 1954, Sanders 1965). Whether the grading of the lahar deposits is normal or reversed it differs from the vertical alternation of grain sizes typical of alluvial beds.

Lahars can be subdivided into mudflows and debris flows. The definitions of Varnes (1958), followed here, are that mudflows consist of at least 50% sand, silt and clay sized particles, and debris flows have a greater proportion of coarse debris. A single deposit may

grade from debris flow at the base to mudflow at the top. At the snout of a mudflow the water may drain away carrying with it some of the material and depositing it as alluvium. There may therefore be a transition from laharic breccia and/or laharic conglomerate to alluvium.

Lahars can form in many ways (Anderson 1933, Macdonald 1972) and although most lahars are cold, 'hot lahars' are a common product of volcanic activity (Mullineaux and Grandell 1962). The main origins are listed below:

A Associated with eruptions

- (a) Through a crater lake, e.g. Ruapehu, 23 June 1969.
- (b) Melting of ice and snow, e.g. by lava at Mt Lassen, 1915.
- (c) Following heavy rains
- (d) Accompanied by heavy rains
- (e) Introduction of autobrecciated lavas into streams (Curtis 1954)
- (f) Descent of glowing avalanches or tephra flows into streams, e.g. Bezymianny Volcano, 1956 (Gorshkov 1959).
- (g) Explosion-induced avalanches of old rock material into streams.
- (h) Brecciation of lava flowing over snow or ice or very wet ground on the slope of the volcano (Fiske, Hopson and Waters 1963).
- (i) Extrusion of material already brecciated in the conduit before reaching the ground surface (Parsons 1967).

B Not directly related to eruptions

- (a) Collapse of the dam of a crater lake, e.g. Ruapehu Crater Lake, 24 Dec., 1953; Tangiwai Disaster.
- (b) Heavy rains falling on unconsolidated ejecta, e.g. Mayon Volcano, Philippines, 1968.
- (c) Rapid melting of snow and ice; Mount Shasta, California in 1926 and 1931.

- (d) Movement of water-saturated material down the slope of the mountain set off by an earthquake.

Around Mt Egmont Grant-Taylor (1964) has used the term 'ringplain' (Morgan and Gibson 1927) for "the whole of the area composed of waterlaid breccias and conglomerates from the lower limit of andesitic lava flows.... to the outer edge of the ... lowlands." Grindley (1960) has adopted this usage for the Tongariro Volcanic Centre where he has defined five formations within the laharic deposits of the local ringplains - one each for the Kakaramea-Tihia and Tongariro massifs, and three for Ruapehu. One informal Recent lahar assemblage from Mt Ruapehu is also identified.

Kakaramea-Tihia Massif

The oldest of these formations, Hauhungaroa Lahars, occurs as the remnants of a ringplain to the west and north-west of Kakaramea. The lahars are overlain by Whakamaru Ignimbrite (Blank 1965) and therefore pre-date 0.32 m.y. They occur up to an altitude of 1,063 m (Grindley 1960) in the Hauhungaroa Range. Since deposition, the lahar deposits have been uplifted about 550 m with respect to the lower slopes of Kakaramea. A very approximate age of about 0.6 m.y. is derived for the lahars from an assumed relative uplift rate of 0.94 m/kyr (calculated from the present height displacement (550 m) of Whakamaru Ignimbrite (0.32 m.y.) on either side of the Hauhungaroa Fault). This lahar age of 0.6 m.y. is over twice that of the oldest of the K/Ar dated lavas (0.26 m.y.) obtained from the Tongariro Volcanic Centre by Stipp (1968, Table 1) but it is supported by paleomagnetic determinations on local lavas (see p.216).

Several lahars have descended the eastern and more northerly slopes of Tihia during late Quaternary times. At Te Ponanga Saddle Road

(section 93, N102/244009) Rotocaira Lapilli and 70 mm of younger andesitic tephra are sandwiched between two mudflow units which consequently pre-date and post-date 13,800 years BP. Further north-east on the same road (section 73, N102/256015) the approximate minimum age for a stratigraphically younger mudflow unit is 10,000 years BP. These three lahars comprise lava and pyroclastic debris previously much weakened by hydrothermal activity. Two historic lahars, one in 1846 (Cowan 1901) and another in 1910 A.D. (Keam 1961) have their sources along the Waihi Fault scarp in the Hipaua Thermal area to the north of Tihia.

Pihanga

East of Pihanga laharic breccia in section 40 on Desert Road (N112/297947) was emplaced from Pihanga at least 13,800 years BP, and probably c. 15,000 years BP.

Two Aramuan debris flow units from Pihanga have also been recognised. One deposit, 4 km north-east of Pihanga (section 71, N112/293968), comprises > 3.6 m of horizontally-bedded, uniform pebbly sands with black, grey, red and purple pebbles. This deposit is separated from Te Rato Lapilli by 190 mm of andesitic tephra and has therefore a minimum age of about 10,000 years BP. About 6.1 km NNE of Pihanga (section 72, N102/276010) the second deposit, 800 mm of grey and brown fine to coarse sand with lenses of pebbly sands, directly underlies Papanetu Tephra. This debris flow occurred 9,790 years BP and is slightly younger than the above-mentioned deposit. Both probably originated from the northern summit area of Pihanga.

Tongariro Massif

The majority of the laharic breccias and conglomerates making up the Tongariro ringplain (Rangipo Lahars) are proven to be older than 20,000

years BP (e.g. N112/074925, section 56; N112/125924, section 58; N112/239901, section 17) but more exact age limits are not yet possible. One of these deposits (section 56) has hydrothermally altered clasts some of which contain pyrite and it is likely to have originated from an area of active fumaroles.

Minor lahars from young vents on the Tongariro Massif have been deposited within the last 20,000 years. On the left bank of a tributary of Mangatipua Stream, northern Tongariro (section 138, N112/144897), deposits of five lahars (330, 710, 1,100, 460, and 490 mm thick, oldest to youngest) directly overlie Poutu Lapilli and have an age of about 9,700 years BP. These deposits are represented by > 2.35 m of bedded gravels at a section 2.3 km further NNE (section 29, N112/156919). The lahars may be from Blue Lake or North Crater, source vents for the youngest and oldest members of Mangamate Formation, and therefore active at the time of deposition of the lahars, or they may be from the Te Mari Craters which are also in the catchment area of Mangatipua Stream.

A historic mudflow, Mangatipua Formation, descended from Ketetahi Springs about 1895 A.D. (p. 205). Ketetahi Springs consist of hot springs and fumaroles at a height of 1,350 m on northern Tongariro. It is possible that the hydrothermally altered pyroclastic debris may have slid at a time of heavy rain or during a large earthquake on 17 or 21 August 1895 (Hill 1911; Trans. N.Z. Inst. 28, Appendix p. 768, 1896).

Ruapehu

The oldest assemblage of laharic breccias and conglomerates of the Ruapehu ringplain mapped by Grindley (1960), form the Waimarino Lahars and the three younger less widespread lahar assemblages form Murimotu Lahars, Hautapu Lahars, and "lahars of Whangaehu River". The disposition of these

lahars as fan-shaped deposits reveals parts of the upper cone or crater rim breached at the time of their deposition and the approximate position of the crater at that time.

A laharic unit 3 km south of National Park (section 238, N111/907765) and mapped as Waimarino Lahars by Hay (1967) overlies Oruanui Ash. The Waimarino Lahars were therefore still forming 20,000 years ago. About 1 km further south (section 239, N111/907756) a bouldery lahar unit is conformably overlain by 230 mm of strong brown andesitic ash and by Oruanui Ash and is therefore older than 20,000 years BP. In general, Waimarino Lahars, west of Ruapehu, become progressively older to the south. Waimarino Lahars in railway cuttings from 1.5 km south of Horopito to the Taonui Viaduct (Hay 1967) are all, with the exception of one unit, older than Oruanui Ash (N121/882562). One of the largest of these laharic units, exposed at N121/844553, is inversely graded (Schmincke 1967; also Fig 37).

In Whangaehu Valley Grindley (1960) mapped two younger lahar terraces (Hautapu and Murimotu lahars) and a fan-shaped, unnamed assemblage of Recent "lahars of Whangaehu River". Six of the Recent lahars from Crater Lake have been confined to Whangaehu River. The latest of these, at 8 p.m. on 24 December 1953, began with crevassing movements in ice which are considered (Healy 1954) to have caused collapse of an ash barrier which had been holding water in Crater Lake at a level above normal. Lake level dropped approximately 6 m in 150 minutes (Stilwell et al 1954) as the water rushed through the previously blocked ice cave down into Whangaehu Valley. The lahar reached the railway bridge near Tangiwai (N122/072435) 20 km to the south c. 10.10-10.20 p.m., about five minutes before the Wellington-Auckland express train arrived at the bridge. One pier of the bridge was washed away and six carriages plunged into the river with the loss of 151 lives. Maximum discharge at the bridge was estimated to be $850 \text{ m}^3/\text{sec}$

Fig 37: An inversely graded lahar unit of the Waimarino Lahars Formation exposed on the National Park-Raetihi Road 30 km south of National Park, N121/844553.

Fig 38: Conical mounds formed by one or more lahars of the Murimotu Lahars Formation near the junction of State Highways 47 and 48.

and one of the railway carriage frames was carried about 2.4 km downstream (Stilwell et al 1954).

Similar cold lahars from Crater Lake travelled down Whangaehu River in 1859, 1861 and 1925. In 1889 and 1895 lahars in the same river originated from eruptions through Crater Lake (The Soil Conservation and Rivers Control Council, Wellington, New Zealand; 1957) and on 23 June 1969 further eruptions through the lake initiated four small mudflows on northern Ruapehu.

On the southern side of Ruapehu a few tens of sections only, mainly road cuttings, have been examined so that conclusions regarding the lahars on that side can only be tentative. It can be said, however, that Hautapu Lahars are older than the youngest Waimarino Lahars. Their minimum age, if known, would probably date movement on the fault east of Whangaehu River and so date the beheading of Hautapu Stream by Whangaehu River.

Much of the laharic debris mapped by Hay (1967) as Murimotu Lahars is now known to be part of the Waimarino Lahars Formation. Alongside the Mangaehuehue Stream (N121/966459), 6 km south-east of Ohakune, lahars mapped as Murimotu Lahars (Hay 1967) are almost certainly younger than 20,000 years BP. Road sections, exposing Murimotu Lahars (Grindley 1960) up to 17 km west of Waicuru are younger than 20,000 years. Therefore, until the chronology of the accompanying Ruapehu tephra is known the Waimarino Formation is probably best regarded as older than 20,000 years and the Murimotu Formation younger than 20,000 years BP. Consequently, Murimotu Lahars (Hay 1967) present in sections 3.5 km south of Raetihi and separated from Oruanui Ash by 0.85 m of ash and/or loess should be mapped as Waimarino Lahars. Oruanui Formation is present in several road cuttings up to 8 km south-east of Ohakune so that these lahars also belong to the Waimarino Formation.

Murimotu Lahars, NW Ruapehu

Deposits of at least three lahars outcrop in cuttings along the National Park-Turangi Road, from Mahuia Rapids (N112/010820) south to the Whakapapa Stream Bridge (N111/974785) and form conical mounds in the central region, e.g. near the junction of State Highways 47 and 48 (Fig 38). The conical hills, up to 9 m high, occur in three belts about 5 km long (Cowan 1927) and have been ascribed to various origins - Hill (1891) considered the mounds to be blisters on the surface of a lava flow which had flowed over water-saturated ground; Cowan (1927) considered them to be bubbles within lava; Bossard (1928) considered the bubbles to be the "result of explosions of volatiles within relatively substantial lava flows with comparatively rich gas-content..."; Park (1926) considered the mounds to have been deposited by a retreating Waimarino Glacier; and, finally, Grange and Hurst (1929) suggested that the mounds were formed from lahars and Grange (1931b) compared them with historic mudflow deposits in Java and Japan. Healy (1965) has described a section from a quarry within one of the mounds on the western side of Bruce Road (N112/003791) and suggested that one or more lahars and one or more nuées ardentes came down the Whakapapa Valley "probably from a crater or crateral hollow which lay to the north of the present crater lake" (northern crater of Friedländer (1899)).

Mangatawai Tephra and Papakai Formation mantle the mounds but Okupata Tephra which is known to have been deposited over this area about 12,450 yrs BP (NZ1189), is absent.

Immediately north of Mahuia Rapids (N112/010820, section 104) a 1.8 m laharic unit of angular to subrounded pebbles, cobbles and boulders within a purplish grey sandy silt matrix contains branches and stems of Libocedrus bidwillii (mountain cedar), a root(?) of Cyathodes sp, and Dacrydium colensoi (silver pine) (Dr R. N. Patel, pers. comm.). This unit overlies

Fig 39: Laharic breccias of the Murimotu Lahars Formation outcropping on the National Park-Taupo Road just north of Whakapapanui Stream, N112/010820 (section 104). A lahar unit, containing wood, radiocarbon dated (NZ1338) at $9,540 \pm 100$ years BP, overlies the basal lapilli of Okupata Tephra and an older lahar unit. Taupo Pumice is exposed at the top of the section.

Okupata Tephra (Fig 39). The radiocarbon date (NZ1338) $9,540 \pm 100$ yrs BP for wood from within this lahar unit at this site (section 104) dates the lahar. In the same section Okupata Tephra overlies and is separated from the remainder of the Ruapehu tephra sequence (c. 10,000-14,000 years BP) by a further unit of laharic breccia (Fig 39). These lahars therefore occurred over a period of up to 3,000 years.

The 9,540 year old laharic breccia at section 104, and another wood-containing laharic breccia unit at Whakapapa Stream Bridge (N111/974785) may belong to one broad mudflow, or be distributaries of one large mudflow, or be parts of two smaller mudflows. In the latter two cases the flows cut through the then existing bush and were then deflected from the Whakapapa Stream channel to either side of the earlier deposited central mound field.

Because several lahars over a 3,000 year time span descended only one valley draining the summit area it is likely that these lahars originated from one (northern) crater. The presence of hydrothermally altered clasts within some of the flows suggest an origin of clasts and lahars from an area of active fumaroles. One of the largest flows - forming the central mound field - came to rest above the Curie point (see page 221) and is likely to have been initiated by displacement of a crater lake either by lava or a growing lava dome. It is probable therefore that these laharic breccias descended from an active (or then recently active crater) at the northern end of the Ruapehu summit area. The occurrence of a large aa flow on northern Ruapehu, with a probable age of between 5,000 and 10,000 years BP and post-dating the lahars, supports that suggestion. Okupata Tephra and the underlying Ruapehu source tephras (back to at least 14,000 years BP) were probably also erupted from this northern vent.

The lahars are then seen as being caused by releases of water from a crater lake (northern crater of Friedländer, 1899) as the rate of

tephra eruption became more sporadic. Some tephras and one large aa flow were still erupted, however, and after a period of relative inactivity, another lava extrusion (c. 12,000 years BP?) into the crater caused a hot lahar to descend the north-western slopes.

C. FAULTING WITHIN THE TONGARIRO VOLCANIC CENTRE

The structural setting of the Tongariro Volcanic Centre has been described by Gregg (1960, 1961) and Grindley (1960, 1965) and is summarised in the Introduction (p.8-13).

Sixteen kilometres east of the Taupo Graben in the Kaimanawa Range, Te Whaiti Ignimbrite (Grindley 1960) overlies greywacke and argillite basement at 1,200 m (Ignimbrite Saddle, N113/471859; Grindley 1960). The writer has observed a new exposure of ignimbrite 5 km further west at 1,155 m (N112/427848). At the Poutu Tunnel (N112/299869), inside the graben, the same ignimbrite outcrops at about 570 m. The occurrence of ignimbrite at different altitudes in the Kaimanawa Range suggests that some partial warping accompanied the block faulting. Since the time of eruption of Te Whaiti Ignimbrite was about 0.30 m.y. ago (fission track age : B. P. Kohn, pers. comm.), this deformation must have proceeded at an average rate of subsidence of 2.1 m/kyr for the southern part of the Taupo Volcanic Zone with respect to the Kaimanawa Range.

Local deformation is known in historic times within the graben. Hochstetter's (1864; Plate 2) sketch map of the Tongariro area shows two peninsulas extending into Lake Rotoaira (Fig 40), one at the south-eastern end, and another at the north-western end connecting with Motuopuhi Island. Between 1864 and 1933, the date of publication of a map of the Tongariro area by Grange and Williamson, the south-eastern peninsula had disappeared from view (tree stumps are present in situ in shallow water along the eastern shore, c. N112/233921) but the north-western peninsula persisted (Fig 40). Since 1933 the end of the peninsula has become separated to form Motuopuhi Island. The area of Lake Rotoaira is therefore gradually extending as this part of the graben becomes further depressed.

Fig 40: Changes in the shape of Lake Rotoaira over the past 110 years. (a) probable shape of the lake in 1864 based on a sketch by Hochstetter; (b) as mapped by Grange and Williamson (1933) - the south-eastern peninsula has disappeared; (c) as at 1974: the end of the former north-western peninsula is now Motuopuhi Island. Movement on the two faults shown in the figure has been since eruption of Taupo Pumice (i.e. 1819 years BP).

Recent faulting in the Tongariro area has been "mentioned" in Maori legends. Gordon (1888) records two changes in the course of the Tokaanu River; the earliest "about ten generations ago", and a second change during which a pa (fortified Maori village) disappeared into Lake Rotoaira.

The fault along which Onepoto Stream flows has formed a gorge up to 65 m deep and hot springs, present on the extension of the fault into Lake Rotoaira at N112/207937 (E. Cudby, pers. comm.), suggest that the latest movement may be <2,000 years BP.

Where faults cut tephra sequences the youngest displaced tephra provides a maximum age for the most recent movement. An example is; a conspicuous fault extending from the upper western slopes of Tongariro northwards over Kakaramea to the Waihi Fault which has a vertical scarp of up to 15 m (Fig 40). This unnamed fault has displaced Taupo Pumice (1819 years BP) at the eastern end of section 58 (N112/125924). Comparable movement is evident at another fault scarp about 12 m high and about 1.3 km east of, and parallel to, the south-eastern shore of Lake Rotoaira. In the latter example Taupo Pumice is overthickened at the foot of the fault scarp (Fig 41) suggesting that this fault also post-dates Taupo Pumice.

While such faulting is likely to be partly due to tectonic processes it is possible that part of the subsidence is collapse resulting from the discharge of large volumes of tephra (Taylor 1855). The evidence for a local eruptive source for Taupo Pumice is indicated by the large size of the Taupo Pumice blocks preserved on top of North Crater (the average of five maximum block diameters is 578 mm). In Rotoaira Basin Taupo Pumice deposits are very thick compared with areas further north. The direction of lodgement of a large rimu (Dacrydium cupressinum) tree felled by a *nūē* ardente at a point 4.3 km ESE of Lake Rotoaira also suggests a local source for some of the Taupo Pumice *nūē* ardente deposits (Pullar and Patel 1972).

Fig 41: The fault scarp about 1.3 km east of, and parallel to, the south-eastern shore of Lake Rotoaira (position shown in Fig 40). The overthickening of Taupo Pumice at the foot of the fault scarp suggests that the fault movement post-dates deposition of Taupo Pumice.

Fig 42: A patch of fused red and green pumice in the lower part of tephra-flow deposits of Taupo Pumice. Note the white pumice below the fused patch showing that it does not have a fumarolic origin, and the charcoal towards the left of the section (30, N112/135921).

Several patches of fused red and green pumice scattered to the north and west of Lake Rotocaira (e.g. section 30, Fig 42) show locally high temperatures which may indicate close proximity to a source. Such red patches may be several metres across. In section they can be seen to be without "roots" and they do not therefore have a fumarolic origin. The red patches may be fulgarites formed during locally disturbed atmospheric conditions when lightning strikes the pumice breccia. However, two of the blocks of fused pumice from section 30 show distinctive wood impressions and it is more likely that dead tree-trunks (e.g. matai, Podocarpus spicatus) were ignited by the hot tephra and burned at $>900^{\circ}\text{C}$ and remelted some of the already very hot rhyolitic pumice. The fact of fault movements to both east and west of the lake since eruption of Taupo Pumice adds further support to the suggestion of a local source for some of the Taupo Pumice eruptions.

Most of the faults are downthrown towards Tongariro Massif although there are exceptions. The fault which cuts block breccia at section 59 (Fig 43) is down-faulted to the west away from Tongariro. Displacement of the base of Mangatawai Tephra on the northern side of this section shows that movement is likely to have occurred $<2,500$ years BP. Near the Waihohonu terminal moraines (approx. N112/182752) a normal fault dipping eastwards away from Tongariro and with a vertical displacement of 2.3 m, moved before deposition of Mangatawai Tephra, probably about 2,600 years BP.

One of the faults which cut the northern wall of Waihohonu Valley is also downfaulted to the east away from the Tongariro Massif. At section 502 (N112/167782) vertical fault displacement is 1.04 m. At section 503 (N112/163775) the overthickening of beds within the upper part of Mangamate Tephra Formation on the downthrown side shows that this fault movement took place towards the end of deposition of the formation, c. 9,700-9,740 years BP. The ages for at least four other faults on eastern Tongariro cannot

Fig 43: A Recent fault cutting tephra and block breccia at a section on the National Park-Taupo Road (59, N112/132922). The normal fault, which downthrows to the west away from the Tongariro Massif, displaces the base of Mangatawai Tephra on the northern side of the road cutting showing that movement is $<2,500$ years BP. The prominent lapilli unit about midway up the tephra sequence is Te Rato Lapilli.

Fig 44: A large fissure of rhyolitic "Oruanui tephra", up to 520 mm wide and striking at 356° , which cuts lapilli and tuff deposits older than Oruanui Formation in Poutu Canal (section 97, N112/267896). Note the general parallelism of the sides of the fissure.

yet be determined as tephra sections have not been found on the fault lines. However, one of these faults is older than the oldest andesite lava from Red Crater in Oturere Valley. This lava is older than 2,500 years BP and younger than 9,700 years BP so that this fault movement may also have been associated with the Mangamate Tephra eruptions.

Not all local faults strike NNE. A normal fault which displaces Rotoaira Lapilli at a section (no. 44, N112/293967) north-east of Pihanga dips south at 70° and may represent a complimentary fault of the NNE-trending Taupo Fault Belt.

Superficial Fissure Fillings

In the Lake Rotoaira area there are a number of dike-like fissures filled with rhyolitic tephra. Several are seen in one only outcrop but two are exposed on both sides of Poutu Canal. One fissure in Poutu Canal (section 1, N112/291879) with a strike of 52° , was several centimetres wide and cut alluvial (possibly laharic breccia) deposits. A larger fissure in Poutu Canal (section 97, N112/267896, Fig 44), up to 520 mm wide, striking at 356° , cuts lapilli and tuff deposits older than Oruanui Formation. This, and a similar fissure at section 17 (N112/239901, Fig 45) have pull-apart character.

Several small irregular fissures filled with Taupo pumice are present in the Tongariro area (Fig 46) and are similar to features described from Italy by Losacco and Parea (1969). Some of the fissures bifurcate or anastomose and they taper towards the ends. Lapilli are often present in the wider upper part of the fissure and medium to fine ash in the lower end indicates downward migration. These irregular fissures probably do not have great lateral extent. In a few sections (e.g. Taupo Pumice at section 397, N112/431846; and Oruanui Formation at section 293, N111/883909) tephric

Fig 45: A small fissure of rhyolitic "Oruanui tephra" which cuts the shower bedded base of the Oruanui Ash at the Poutu reference section (17, N112/239901). Note the general parallelism of the sides of the fissure.

Fig 46: A small irregular fissure of rhyolitic tephra cutting andesitic tephra below Taupo Pumice at a section on Desert Road, north-east of Pihanga (section 44, N122/293967). Lapilli fill the upper part of the fissure, ash the lower part.

material has been fed into one or more large sub-horizontal beds ("sills"). These "sills" may be conformable, over short distances, with enclosing beds. Fissures and sills are probably still actively growing. Apparently much tephra migrates with groundwater down such fissures.

However, the two fault-like fissures in Poutu Canal, with generally uniform width and with pull-apart character, may not be erosional features. It is probable that they formed during the tectonism accompanying eruption of the large rhyolitic tephra-flows. At section 17 (Fig 45) the fissure cuts the shower bedded base of Oruanui Ash showing that it is associated with the eruption of a flow unit, and not with the eruption of air fall units. Some of the Taupo Pumice was probably erupted from within Tongariro Volcanic Centre. Eruptive sources of Oruanui Formation (within Taupo and Maroa volcanic centres) were certainly close enough for the associated tectonism to affect the Rotoaira area.

The width of both types of fissures has probably increased by subsequent erosion and deposition in the same way as "solution pipes" developed in limestone (Fleming 1953). These can be seen in various stages of development in thick deposits of Taupo Pumice near Waikato Falls (N112/306836).

D. GLACIATION IN THE TONGARIRO VOLCANIC CENTREIntroduction

Park (1910a, b, c, d, 1916, 1926) described striated boulders and the till-like character of deposits to be north-west of Mt Ruapehu and in the valley of the Hautapu River to the south-east of Ruapehu as evidence for an extensive glaciation of the Tongariro National Park volcanoes. However, Speight (1908), Marshall (1910), Trechmann (1917) and Moore (1917) could find no evidence to support an extension of the six glaciers on Mt Ruapehu during the Pleistocene. Grange (1931b) was able to show that the "morainic mounds" of Park's "Waimarino Glacier" near the junction of National Park-Taupo Road and Bruce Road were lahar mounds. Cotton (1944) and Te Punga (1952) considered conglomerates in Hautapu River, up to 75 km south-east of Ruapehu, which were attributed by Park to the "Hautapu Glacier" also to be laharic deposits.

Taylor (1927, 1928) found many striae at 2,100 m and considered that evidence of Pleistocene glaciation would be found down to 1,350 m. During regional geological mapping Grange and Williamson (1930) found a striated boulder at 1,326 m on the ridge to the north of Wahianoa Stream within subangular coarse conglomerate and noted that similar conglomerates are exposed in the upper part of the Whakapapa Valley. Polished, striated lava occurs at 1,275 m in the bed of the Wairere Stream, northern Ruapehu, and these authors noted that the valley of the Wahianoa Stream (Fig. 47) with its U-shaped section down to 1,110 m and conglomerates along its sides has all the appearance of a glaciated valley.

Willett (1950) has proposed, on climatic and biological evidence, that the Pleistocene snowline in New Zealand was depressed by about 1,050 m

corresponding to a reduction in temperature of about 6°C^* . He estimated the Pleistocene snowline on Ruapehu to have been down to 1,330 m altitude. An area of about 56 km^2 would have been above this limit and "periglacial tundra" would have covered a large area within the Tongariro Volcanic Centre. However, recognition of glacial deposits as moraine is likely to be difficult because of subsequent volcanic activity. Moraines are seldom associated with the six glaciers presently on Mount Ruapehu (Cowan 1927, Odell 1955a, b). Striae on boulders are likely to be readily removed by erosion because the andesite is soft and relatively coarse-grained (Taylor 1927). The occurrence of striated boulders is not a sufficient criterion alone for designating a deposit as till: Grange (1931b) has recorded striated boulders from within a lahar deposit and the largest andesitic block found by Park (1916) in the Rangitikei Valley and now regarded as having a laharic origin (Gotton 1944, Te Punga 1952), was also abundantly striated (probably as the result of the passage of the laharic debris over its upper surface after it was deposited from the flow).

Moraines on the Tongariro Massif

Mathews (1967) recognised evidence for glaciation of the Mount Tongariro Massif and mapped large paired moraine ridges bounding Mangatepopo Valley, north Waihohehu Valley, and Makahikatoa Valley and tentatively identified (from aerial photographs) a small moraine on the north side of Oturere Valley. A tephra section on one of the Mangatepopo moraines gave him an estimated minimum age of 4,000 years BP for these moraines and he suggested from the lack of dissection of the moraines that

* Wardle (1970) considers, however, that the depression of the snowline in the Fox Glacier area of the Southern Alps may have been between 540 and 810 m.

they correlated with the youngest of the Pleistocene moraines of South Island, the Poulter (Gage and Suggate 1958) or Hawea (McKellar 1960) moraines of slightly more than 15,000 years ago.

During mapping of tephras on Tongariro the writer made a thorough search for till and found several convincing exposures. In Makahikatoa Valley till is exposed where a young Ngauruhoe lava flow (overlying 1.43 m of Mangatawai Tephra and estimated to be about 2,000 years BP) has deflected the stream against the southern valley wall. Mathews (1967) has described this section (N112/083792) as "... an obscurely bedded deposit consists of boulders of up to [0.75 m] in diameter. Many are faceted and have snubbed corners; some have fine striations. They are set in an abundant, firm, and poorly sorted matrix including everything from small angular to rounded stones grading in size down to silt and clay. The boulders are rarely in contact with one another and are commonly separated from the stony matrix by clay-rich films. Lenses of bedded sand up to [0.9 m] long and [0.3 m] thick dip from 0° to 40° to the west (downstream). It is not conceivable that such lenses accumulated with steep dips, and it must be presumed that they have been rotated into this position, perhaps in a frozen state in which they were sufficiently coherent to retain their identity. Many veinlets of clay are also present and these, too, dip westward at moderate to steep angles. They are interpreted as clastic dikes injected into gash fractures formed by shear beneath an overriding westerly-flowing ice tongue. By whatever mechanism these can be explained, the clay films, the dislocated lenses of sediments, and the clay veinlets are features known to be present in undoubted tills elsewhere, but, as far as I am aware, they are unknown in lahars."

Of the criteria given by Mathews, the poor sorting, firm abundant matrix, lack of contact between boulders and cobbles, the clay partings around boulders and cobbles, and the clay veinlets were found to be the most diagnostic. Boulders were mainly angular to subangular and fine

Fig 47: The U-shaped Wahianoa Valley, eastern Ruapehu. Morainic till is exposed in many places on the valley walls and many of the boulders are striated (e.g. see Fig 48).

Fig 48: A small fine-grained, glassy andesite boulder which has been faceted, polished and striated during its transport in glacial ice. The boulder is from the northern lateral moraine of Wahianoa Valley about half way between the valley floor and the crest of the ridge at the site of Fig 47.

Fig 49: An exposure of morainic till on the southern side of Makahikatoa Stream (section 422, N112/083792) where the stream has been deflected against the southern lateral moraine by a lava flow which was extruded from Ngauruhoe c. 2,000 years BP. The till at this location has been described by Mathews (1967).

Fig 50: An exposure of morainic till on the southern side of Waihohonu Valley (c. N112/175754).

Fig 51: An exposure of morainic till on the southern side of Mangahouhounui Valley (section 501, N112/198839).

Fig 52: A striated boulder exposed within probable morainic till on the western side of the Oturere Valley (N112/185803).

striae were found only on very fine grained polished andesites on eastern Ruapehu (Fig. 48). In the Tongariro moraines several boulders were found with coarse striae and grooves. Differences in clast lithologies were also useful in distinguishing tops of morainal ridges from old ridges with lava cores and with no morainal covering.

Exposures of till were found on the southern sides of Makahikatoa Stream, Waihohonu Valley and Mangahouhounui Valley (Figs 49, 50, 51). One only striated boulder (Fig. 52) was observed on the western side of Oturere Valley in a possible moraine mapped by Mathews (1967). The ridge is not an old lava flow that has become covered by its own weathering products because boulders and cobbles exposed on its upper surface have different lithologies and so it is likely to be moraine.

The Mangatepopo and Waihohonu moraines are particularly pronounced paired ridges (Figs 53, 54). The writer believes that this is due to restriction of the glacier by valley walls of andesite. Andesite can be seen to underlie the morainal ridges closer to source, and forms a bluff at N112/183754, on the inside of the northern Waihohonu moraine near the terminal moraine so that it probably underlies both ridges for almost their whole extent. While andesite is considered to underlie the northern lateral moraine of Mangatepopo Valley it is probably absent from beneath the lower southern lateral and terminal moraines of the same valley. The Makahikatoa moraines have subdued relief and are unlikely to have lava cores. The Mangahouhounui moraines (Fig. 55) are extensions of ridges of andesite flows one of which is exposed on the southern valley wall at N112/201838. At this site a recent tree-fall has removed a large slab of vegetation and exposed a "probable" glacially striated outcrop (Fig. 56). Initially all of the glaciated valleys would likely have been U-shaped. Oturere Valley has been filled with lavas erupted from Red Crater within the past 9,700 years BP and the three moraine-bounded valleys radiating outward from Ngauruhoe are

Fig 53: Lateral and terminal moraines of the Mangatepopo Valley. Rerewhakaaitu Ash (14,700 years BP) is interbedded with andesitic tephtras erupted from the vent at the summit of Pukekaikiore dome (at right) in a section (369, N112/089822) at the foot of the northern lateral moraine just up-valley of the section of ridge shown in the photo. The valley has been partially filled with lava flows from Ngauruhoe. The largest and oldest of these flows is about 2,000 years BP.

Fig 54: Lateral and terminal moraines of the Waihothonu Valley extending eastwards from Ngauruhoe. The upper part of the valley (Fig 57) has been partially filled with alluvium from the Ngauruhoe cone.

Fig 55: Lateral moraines of Mangahouhounui Valley, north-eastern Tongariro Massif.

Fig 56: Andesite lava with probable glacial striae and grooves exposed on the southern wall of Mangahouhounui Valley by a recent tree-fall (N112/201838).

being filled with lavas from that cone. However, Waihoehonu Valley still retains part of its glacially eroded shape (Fig. 57).

Till Deposits on Ruapehu

One of the formerly glaciated valleys on eastern Ruapehu, the Wahianoa Valley, still retains its U-shape (Fig. 47). Towards the head of the valley the valley walls are underlain by lava flows but further downstream they are covered with moraine. Many of the boulders in the moraine have coarse striations and those of a grey very fine-grained glassy andesite lava are often polished and have striae subparallel in two or three directions (Fig. 48).

Till was observed above 1,530 m on the Ohakune Mountain Road (N122/019623) and there is a possible roche moutonnée at c. 1,320 m alongside the Mangawhero Stream and the Ohakune Mountain Road (N122/005613). At N122/132666 (section no. 463) laminated silts and clays (the oldest are probably varves) overlie till at 1,500 m on the southern side of a branch of the Mangatoetoeenui Stream. The present summit area of Mt Ruapehu is almost 5 km². Although the northern crater (Friedländer 1899) and the cone containing the Crater Lake post-date the Otiran glacial advances most of Ruapehu is now essentially similar to what it must have been like 22,000 years ago. Similar morainic deposits should therefore be associated with each of the six present-day glaciers on Ruapehu, particularly in the Mangaturuturu River area and in the Whakapapa Valley, but these were not examined in the present study.

Minimum Age for the Moraines

The age of the moraines is not yet certain but it appears that they are at least older than 15,000 years BP.

Fig 57: The head of the Waihohonu Valley showing the U-shaped cross section. Young lava flows (left) and alluvium from Ngauruhoe are filling the upper part of the valley.

Fig 58: Downcutting of a small stream at 1,500 m on eastern Ruapehu (section 463, N122/132666) has exposed a sequence of laminated silts and clays, >8 m thick and probably varved towards the base. The sediments overlie moraine and were probably deposited in a small proglacial lake. Two groups of beds (u=upper group, l=lower group) appear to contain rhyolitic tephra. Mr M. S. McGlone for scale.

At a section (N112/089822, section no. 369, see Appendix 1C) on the inside of the northern lateral moraine of Mangatepopo Valley, Rerewhakaaitu Ash is interbedded with andesitic tephtras (Topping and Kohn 1973). The andesitic tephtras were probably erupted from Pukekaikioire dome which extruded an olivine andesite aa flow about 14,700 years BP (section no. 368, see Appendix 1D). These andesitic tephtras overlies Oruanui Formation in the nearby Pukeonake Scoria Cone but this formation was not exposed during excavation into the moraine and it may not be present. It seems unlikely that Rerewhakaaitu Ash should be preserved where it fell 14,700 years BP if the terminal moraine formed about 15,000 years BP.

The oldest dated tephtra about 50 m to either side of the section examined by Mathews (1967) in the Makahikatoa Valley is Rotorua Ash with an age of about 12,500 years BP (Topping and Kohn 1973) but further tephtras overlying the moraines are believed to date back to c. 14,000 years BP (section no. 422, Appendix 1C). A section on the inside of the southern Waihehohu moraine (N112/165759; section no. 494) has many tephtras exposed below Rotorua Ash. On the inside of the northern lateral moraine of the Mangahouhounui Valley the oldest exposed tephtra is Rotoaira Lapilli of c. 13,800 years BP (NZ1559). However, Rotoaira Lapilli is the oldest tephtra exposed elsewhere on Tongariro on surfaces believed to be considerably older than 14,000 years BP. Older tephtras on these moraines may have been stripped off during the earlier cooler climate of the late Otiran glacial advances and redeposited as loess and colluvium on lower slopes (see sections on loess and erosion).

At 1,500 m on eastern Ruapehu (N122/132666, section no. 463) a sequence of laminated silts and clays, >8 m vertically and probably varved towards the base, has been exposed by downcutting of a small stream (Fig.58). This sequence should record any warming following the formation of the moraines. Diapiric structures and drag folds within the sediments

(Fig 59) suggest a later readvance of ice (Corybeare and Crook, 1968).

Two groups of these laminated silts and clays appeared to contain rhyolitic tephra (upper and lower samples of Fig. 58). It was considered likely that the upper sample might correlate with Oruanui Formation, so magnetites from the two samples were analysed by Mr P. R. Kyle on the electron microprobe for comparison with magnetites from the Oruanui Formation. Of the 18 magnetite grains scanned from the upper sample 16 grains are andesitic and two are in excellent agreement with the two magnetite species present in the Oruanui Formation (Table 13). All magnetites from the lower sample are dissimilar to those of Oruanui Formation, and dissimilar to analyses for the Mangaoni Lapilli (Kohn 1973) which at the time of sampling were the only possible rhyolitic tephra correlatives between 20,000-40,000 years BP. There are now, however, at least three Taupo or Maroa source tephra recognised within this age range (Vucetich, pers. comm.) and the author has mapped two of these tephra into the Tongariro area. While not conclusive, the magnetite data suggest that the upper sample was deposited about 20,000 years BP*. If the underlying till was formed during the later Kumara-2 glacial advance of Suggate and Moar (1970) then the ice readvance suggested by the diapiric and drag folds within the laminated silts and clays may equate with one of the two Kumara-3 glacial advances.

Glacial Deposits of other Ages

All the glacial tills discussed so far are considered to be of the same age. Mathews (1967) has recognised till from beneath an old Tongariro

* Oruanui Ash within the crater of Pukeonake Scoria Cone is shower bedded and dips up to 17° . It seems unlikely, therefore, that there was a year-round cover of snow or ice at 1,225 m about 20,000 years BP.

TABLE 13: Electron microprobe analyses for two magnetite species found within the Oruanui Formation. These two magnetite species are also present within a sample of laminated silts and clays above moraine at 1,500 m on eastern Mt Ruapehu (N122/132666; Fig

	Oruanui Formation					Oruanui Formation					Two magnetite grains from upper sample of laminated silts and clays from a site at 1,500 m on Mt Ruapehu (N122/132666).				
	Magnetite Type 1					Magnetite Type 2					Oruanui Type 1				
	1	2	3	Mean		1	2	3	Mean		1	2	3	Mean	
SiO ₂	0.08	0.08	0.06	0.07		0.09	0.06	0.08	0.08		0.09	0.08			
Al ₂ O ₃	1.65	1.58	1.64	1.62		1.47	1.52	1.42	1.47		1.57	1.49			
TiO ₂	9.15	9.10	9.03	9.09		10.6	10.5	10.8	10.6		8.97	10.6			
FeO	81.4	82.6	82.7	82.2		82.0	81.4	81.6	81.7		82.6	81.4			
MnO	0.45	0.42	0.45	0.44		0.59	0.61	0.59	0.60		0.44	0.57			
MgO	0.76	0.68	0.69	0.71		0.59	0.61	0.56	0.59		0.73	0.60			
Sum	93.49	94.46	94.57	94.13		95.34	94.70	95.05	95.04		94.40	94.74			
FeO ^a	48.4	49.3	49.5	49.1		47.0	46.6	46.4	46.7		49.6	46.6			
FeO	37.8	38.2	38.1	38.0		39.7	39.4	39.6	39.7		38.0	39.5			
Total	98.69	99.36	99.47	99.03		100.04	99.30	99.45	99.74		99.40	99.44			
Usp %	25.4	25.2	24.8	25.1		29.3	29.3	30.0	29.6		24.6	29.5			

^a Analyses recalculated by the method of Carmichael (1967)

Analyst = P. R. Kyle, VUW.

Fig 59: Diapiric structures and drag folds within the upper part of the sequence of sediments shown in Fig 58. Camera lens cap (left centre) for scale .

Fig 60: Parallel grooves and striae at c. 2,520 m (N122/056669) near the Glacier Hut, upper northern slopes of Mt Ruapehu. The glacially eroded grey andesite contrasts with the non-glacially eroded, strong brown weathered surface of the lower part of the andesite.

lava flow in Mangatepopo Stream (N112/097825). Stipp (1968) has dated lava just to the east of this site at c. 0.104 ± 0.002 m.y. (K/Ar date GA3257, N112/100826; Table 1) and the till is therefore likely to be older than 0.1 m.y.

On the Mangaehuehue Glacier Mr L. O. Krenek (in Odell, 1955b, p. 605) has recorded lateral moraine almost 75 m above the present level and terminal moraines about 450 to 540 m from the present snout of the glacier. Two ridges within Wahianca Valley at about 1,350 m altitude may also be moraines. These and any other young moraines that may subsequently be found are going to prove very difficult to date.

Similarly, the time at which parallel grooves and striae were formed at the present snout of the Whakapapa Glacier (Ward 1929) or at c. 2,520 m near the Glacier Hut (Fig. 60) cannot yet be determined. However, localised glacial erosion of the surface of a strong brown, weathered lava shows that this particular glacial advance was the first for a considerable time and may represent the first advance since the Otiran Glacial Stage.

Cirques

Glacial erosion is likely to have played a major role in the destruction of the older Tongariro cones and the large crater-like features on the Tongariro Massif. South Crater, and the head of Mangahouhounui Valley (i.e. above 1,500 m) are, for example, probably cirques. It is not known whether the northern end of the massif was glaciated. The Te Mari Craters and the upper part of the North Crater cone are of post-glacial age and flows from these vents are likely to have filled any U-shaped valleys that may have been formed.

No tephra containing abundant rock fragments of old lava were erupted from the Ngauruhoe area between the end of the Otiran (c. 14,000 years BP) and the commencement of the present Ngauruhoe cone (c. 2,500

years BP). Yet, during the Otiran the site of the present Ngauruhoe must have been occupied by a cone (moderately dissected), say 1,800 m high, which was large enough to support three glaciers flowing down the Mangatepopo, Makahikatoa, and Waihoehonu valleys. The work of those glaciers probably speeded up destruction of that cone.

E. LATE OTIRAN/EARLY ARANUIAN VEGETATION IN THE TONGARIRO
AREA, CENTRAL NORTH ISLAND, NEW ZEALAND

M. S. McGlone and W. W. Topping

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Late Otiran/early Aranuian Vegetation in the Tongariro Area, Central North Island, New Zealand

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ABSTRACT

Pollen analysis and charcoal identifications of a tephra sequence in the Tongariro area, North Island, New Zealand, show that between 20 000 and 14 000 years B.P. there was a change from *Nothofagus* forest, grassland, and shrubland to podocarp-broadleaf forest. This implies a change to a warmer climate during that period.

INTRODUCTION

The correlation of several rhyolitic marker beds in the Tongariro area by heavy mineral analysis, titanomagnetite analysis, radiocarbon dating, and stratigraphy with tephras erupted from the Okataina, Maroa, and Taupo volcanic centres (Topping & Kohn, in press) has provided valuable time planes within late Otiran and early Aranuian deposits north of the Tongariro massif. This note is an attempt to use these time planes in the study of vegetation history in the central Volcanic Plateau.

SITE LOCATION AND TEHPROCHRONOLOGY

Seven peat and tephra samples covering the time span from c. 12 350 years B.P. to greater than 20 000 years B.P. were collected for pollen analysis from three sites (Fig. 1). Pollen sample numbers 1-5 came from site A, number 6 from site B, and number 7 from site C. All sites lie c. 610 m above sea level. They are shown in relation to four of the rhyolitic tephras in Table 1.

TABLE 1—Tephrochronology

Tephra	Inferred stratigraphic age (years before 1950)	Site location	Pollen sample number	Stratigraphic position of pollen samples
Rotorua Ash ¹	c. 12 500	(A) N112/145983; swamp cut by Wairehu Canal, Tongariro Power Scheme. Approximately 0.9 km N.W. of point where Rotoaira Road crosses canal. Altitude c. 610 m ditto	1	0–20 mm above Rotorua Ash
			2	0–10 mm below Rotorua Ash
			3	90–110 mm above Puketarata Ash
Puketarata Ash ²	c. 13 500	ditto	4	0–10 mm above Puketarata Ash
			5	0–10 mm below Puketarata Ash
Oruanui Ash ³	c. 20 000	(B) N112/096989; section on access road, Tongariro Power Scheme, on western side of Wanganui River. Altitude c. 610 m	6	0–40 mm below Oruanui Ash
Unnamed rhyolite ash ⁴	> 20 000	(C) N102/137137; section on southern side of Turangi-Taumarunui Road, 3.5 km west of Kuratau. Altitude c. 580 m	7	0–10 mm above unknown rhyolite ash; 210 mm below Oruanui Formation

¹ Age is based on NZ1187; 12 350 $\pm$ 220 yr B.P. for a sample taken above the ash, and on NZ1186; 13 150 $\pm$ 300 yr B.P., for a sample taken 130 mm below the ash (Topping & Kohn, in press).

² NZ1186 (see above) provides a youngest age for this ash. A date of 13 800 $\pm$ 300 yr 2.S. (NZ1559) for Rotoaira Lapilli (Topping, in press) provides an oldest age.

³ Age based on NZ12 and NZ1056 (Pullar & Heine 1971).

⁴ The ferromagnesian assemblage and stratigraphic position suggest correlation with one of the younger members of the Mangaoni Formation (Vucetich & Pullar 1969) in which case the age of the ash would probably be 25–30 000 yr B.P. Titanomagnetite analysis of the ash does not support this correlation (B. P. Kohn, pers. comm.) so that it may therefore have a local source.

FIG. 1—Location of sample sites.

RESULTS

POLLEN ANALYSIS

Despite the high tephra and low organic content of most of the samples, well preserved pollen was obtained from all. The results of the analysis are given in Table 2. The pollen spectra show a change from a situation in which *Nothofagus fusca* type, Gramineae, and *Phyllocladus* pollen are most abundant (in the older samples 7 and 6), to one in which *Podocarpus* pollen predominates (in the younger samples 5–1). With decreasing age in samples 5–1 there is a gradual change in which such pollen types as *Nothofagus fusca* type, *Nothofagus menziesii*, and *Phyllocladus* become very much reduced in abundance while there is a steady increase in the amount of *Dacrydium cupressinum* pollen. At the same time many additional tree and shrub pollen types make an appearance.

TABLE 2—Results of Pollen Analyses

SITE	A					B	C
Approximate age (yr B.P.)	12 500			13 500		20 000	>20 000
Pollen sample number	1	2	3	4	5	6	7
	PERCENTAGES (Pollen sum=total pollen)						
Pollen grains of woody plants	77	75	90	68	66	72	69
Pollen grains of <i>Nothofagus</i> and tree conifers	53	51	58	40	36	31	36
Pollen grains of herbaceous plants	23	25	10	32	34	28	31
POLLEN TYPE	PERCENTAGES (Pollen sum= <i>Nothofagus</i> and tree conifers)						

NOTHOFAGUS AND TREE CONIFERS

<i>Dacrydium colensoi</i> type	tr	tr	1	1	—	—	—
<i>Dacrydium cupressinum</i>	24	28	14	13	7	+	—
<i>Nothofagus fusca</i> type	6	6	5	14	17	83	94
<i>Nothofagus menziesii</i>	2	1	3	9	8	10	5
<i>Podocarpus dacrydiodes</i>	1	1	1	—	—	tr	—
<i>Podocarpus ferrugineus/spicatus</i>	66	64	77	62	68	7	1
<i>Podocarpus totara</i> type	tr	tr	—	—	—	—	—

OTHER WOODY VEGETATION

<i>Aristotelia</i>	tr	tr	—	—	tr	—	—
<i>Carpodetus serratus</i>	+	+	+	—	—	—	—
Compositae	2	1	tr	1	4	+	—
<i>Coprosma</i>	4	7	9	12	15	13	11
<i>Coriaria</i>	1	—	—	1	1	—	—
<i>Cyathodes colensoi</i>	—	—	—	—	tr	2	5
<i>Cyathodes empetrifolia</i>	—	—	+	—	—	—	+
<i>Cyathodes fraseri</i>	—	—	—	—	—	—	—
<i>Dacrydium bidwillii/biforme</i> type	22	20	23	22	29	50	13
<i>Dracophyllum</i>	—	+	+	+	—	9	tr
<i>Griselinia</i>	+	—	+	—	—	—	—
<i>Hoheria</i> type	4	3	4	4	3	—	—
<i>Leptospermum</i>	tr	—	tr	1	tr	—	—
<i>Metrosideros</i>	tr	tr	tr	—	+	—	—
<i>Muehlenbeckia</i>	+	tr	tr	—	tr	—	—
<i>Myrsine</i>	1	4	3	4	7	+	—
<i>Nestegis</i>	tr	—	tr	+	1	—	—
<i>Phyllocladus</i>	4	5	10	14	17	60	61
<i>Pseudopanax</i>	tr	—	+	+	tr	—	—
<i>Pseudowintera</i>	—	—	tr	—	tr	—	—
<i>Quintinia</i>	—	—	+	+	—	—	—
<i>Rubus</i>	+	—	—	1	—	—	—

HERBS

<i>Anisotome</i> type	—	+	—	—	—	—	—
<i>Astelia</i>	—	—	—	—	—	1	—
<i>Calorophus</i>	tr	2	1	1	tr	27	—
<i>Centella uniflora</i>	+	2	+	1	+	—	—

	1	2	3	4	5	6	7
Centrolepidaceae	1	1	tr	2	4	—	+
<i>Chenopodium</i>	—	—	+	tr	—	1	—
Cyperaceae	34	38	5	39	72	—	—
<i>Euphrasia</i>	2	1	tr	tr	+	—	—
<i>Gentiana</i>	1	—	tr	tr	—	+	+
Gramineae	4	4	8	33	15	52	83
<i>Gunnera</i>	—	—	—	—	+	—	—
<i>Haloragis</i>	2	1	1	3	3	9	—
<i>Lilacopsis</i>	—	+	+	—	—	—	—
<i>Oreomyrrhis</i>	—	—	—	—	+	—	—
<i>Plantago</i>	—	—	—	—	+	+	—
Scrophulariaceae	—	—	—	—	—	—	2
<i>Selliera radicans</i>	—	—	+	—	+	—	—
<i>Stylidium</i>	—	—	tr	—	—	—	—
<i>Tillaea</i>	4	3	3	6	5	1	—
Umbelliferae	—	—	—	—	—	+	+
SPORES							
<i>Cyathea</i> type	14	14	7	5	5	—	—
<i>Dicksonia squarrosa</i>	1	3	1	—	—	—	—
<i>Gleichenia</i>	45	50	67	56	82	674	16
<i>Lycopodium</i>	+	tr	tr	tr	1	—	4
Monoletic fern spores	3	6	2	3	6	1	3
<i>Pteridium</i>	—	1	—	—	—	—	—
DERIVED							
Casuarina	—	—	—	—	—	+	—
Total pollen counted (excluding spores)	475	448	396	558	572	373	228

tr = less than 1%

+ = noted after count made

Although these results indicate transition from *Nothofagus* forest, *Phyllocladus* shrubland, and grassland to podocarp forest in the general region, it is not clear whether the 2 older sites (B and C) lay above or below the upper forest limits of the time. Moar (1970) has demonstrated that modern pollen samples taken above a tree line are generally dominated by tree pollen. The relatively low percentages of tree pollen, and the high percentages of Gramineae pollen in samples 7 and 6, raise the possibility that the tree line lay at a lower altitude than sites B and C. Alternatively, the tree line may have been higher than the sites but, as at the present time, much scrub-covered and open ground lay beneath it.

The pollen types from samples 1–5 include many representatives of genera commonly found in podocarp-broadleaf forest on the Volcanic Plateau such as *Carpodetus serratus*, *Griselinia*, *Nestegis*, *Quintinia*,

Metrosideros, and *Dicksonia squarrosa*. As most of these plants are not wind pollinated, podocarp-broadleaf forest was almost certainly established in the locality.

CHARCOAL

The localities (see Fig. 1 also) where charcoal of *Dacrydium cupressinum* (identified by B. P. J. Molloy, Botany Division, DSIR) was found in the Tongariro area are as follows:

- (1) Small fragments directly beneath Rotoaira Lapilli (NZ1559; $13\,800 \pm 300$ yr B.P.), N112/298951; cutting on eastern side of Desert Road (Turangi-Waiouru Road), east of Pihanga, and 6.4 km south of Turangi. Altitude c. 427 m.
- (2) Small fragments directly beneath Rotoaira Lapilli; N112/268989; site is 2.8 km S.W. of Turangi, 180 m S.E. of road to V.H.F. Hut (base of Pihanga). Altitude c. 427 m.
- (3) Small fragments scattered throughout 0.15 m andesitic tephra which in neighbouring sections immediately overlies Rotorua Ash; N112/105987; 450 m east of c. Wairoa Trig, 90 m west of Tongariro Power Scheme Access Road No. 4 (NZ1187; $12\,350 \pm 220$ yr B.P.). Altitude c. 610 m.
- (4) Small fragments scattered throughout top third of an andesitic tephra unit which in neighbouring sections is 130 mm below Rotorua Ash. Location and altitude as above (NZ1186; $13\,150 \pm 300$ yr B.P.).

The oldest of these dates for this charcoal (c. 13 800 yr B.P.) gives the earliest known occurrence of *Dacrydium cupressinum* in the area.

DISCUSSION

Willett (1950) suggests that during the last glaciation the average temperature fell by as much as 6°C. Gage (1965) regards the figure of 6°C as still being reasonably accurate. Wardle (1970) questions the basis on which Willett made his estimates, however, and makes the suggestion that the lowering of the snow line during the Pleistocene may have been considerably less. If the 6°C figure is accepted, such a drop would be sufficient, according to Willett, to depress snowlines by approximately 1050 m. In turn this would lead to a similar depression in height of tree line. If this depression is applied to the present tree line on Ruapehu (c. 1500 m), the Otiran tree line would have been at about 430 m. Sites A, B, and C would have been then between 150 and 180 m above tree line. As noted above, the pollen spectra from these sites do not contradict Willett's hypothesis, but neither can they be regarded as unambiguous evidence for such a depression of the tree line. McIntyre (1970), however, provides pollen analytical data from a deposit near Wellington which, he suggests, indicates that the tree line was at or below present day sea level 19 000 years ago. This would imply a depression of the tree line by about 1050 m.

The Rotoaira Lapilli of the Tongariro tephra sequence (age, $13\,800 \pm 700$ yr B.P.) is the oldest andesitic tephra conformable to the present surface over a large area to the north-east of Tongariro. It therefore represents the beginning of relatively stable conditions in the area. This stability of the soil surface and the establishment of podocarp-broadleaf forest at altitudes of at least 610 m, point to a warmer climate than that which existed 6000 years before. As there is a gap of approximately 6000 years, between the Puketarata Ash (samples 4 and 5) and the Oruanui (sample 6), we have no evidence to date the beginning of the climatic amelioration exactly. The date of 13 800 yr B.P. gives, however, a youngest age for this event which is in agreement with Suggate's (1965) date of c. 14 000 yr B.P. for the end of the Otiran.

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F. LATE QUATERNARY LOESS DEPOSITS

Deposits (280-430 mm thick) interpreted as loess are interbedded in several sections in a sector from west to north-east of the Tongariro Massif, with tephra older than Rotoaira Lapilli (13,800 years BP) and younger than Oruanui Formation (20,000 years BP).

The loess is light yellowish brown, darker in colour than the rhyolitic Oruanui Formation and lighter in colour than the Aranui ash grade andesitic tephra. The loess beds are massive and without either the sedimentary structures expected of fine alluvium or the bedding and vertical change in grade size characteristic of tephra-fall deposits. The beds mantle underlying beds, have a subaerial origin, and are therefore considered to be loesses.

The loess beds comprise silt to sand grade sizes and in some cases (e.g. section 220, Appendix 1B) include rhyolitic lapilli (2-30 mm) which have probably been reworked from the underlying Oruanui Formation. The rhyolitic lapilli are vesicular enough to have been transported by wind just as lapilli from the Taupo Pumice are presently being incorporated into loessic "Ngauruhoe Tephra" on top of Pukeonake Scoria Cone and in Desert Road sections east of Ruapehu (e.g. 283, N122/223622). The presence of lapilli and the angularity of the sand grade size suggests short transport distance. The loess beds often contain rootlet channels. They are little weathered and their lighter colour with respect to the andesitic tephra is due both to their lesser degree of weathering and rhyolitic ash content.

In some sections up to three loess beds can be recognised interbedded with tephra (e.g. 220, Appendix 1B). However, they cannot yet be correlated individually as there are too few sections with the complete tephra sequence from Rotoaira Lapilli to Oruanui Formation. Rerewhakaitu Ash (14,700 years BP) occurs in a few sections but it is the only dated tephra between

13,800 and 20,000 years BP so that no ages can be assigned to the individual loess beds.

The youngest loess has a paleosol which contains charred fragments of Dacrydium cupressinum (rimu) probably charred during the Rotoaira Lapilli eruptions. At that time, 13,800 years BP (NZ1559), loess accumulation had largely ceased and the area north and north-east of the Tongariro Massif supported a podocarp dominated forest (McGlone and Topping 1973). No paleosols have been recognised within, or at the top of, the older loess units.

Loess derived from Aranuian tephras and alluvium is currently being incorporated into "Ngauruhoe Tephra" in areas of limited vegetation cover (e.g. top of Pukeonake Scoria Cone and Desert Road sections east of Ruapehu). Cool climate is not therefore a prerequisite for loess formation but sparse vegetation is probably essential.

The presence of rhyolitic lapilli in a loess (e.g. section 220, Appendix 1B) shows an earlier local exposure of Oruanui Formation. Consequently, it is not yet certain whether there is a definite number of loess beds which represent individual climatic episodes, e.g. glacial retreats, or whether the number of beds varies from site to site and represents localised erosion and deposition of Oruanui Formation under generally cool-climate conditions. Further detailed pollen analysis of peats in the Rotoaira Basin is probably the best way of resolving the issue.

G. EROSION OF TEPHRA DEPOSITSLate Quaternary Erosion

Several erosional unconformities can be recognised within tephra sequences of Tongariro Volcanic Centre. The most widespread erosion breaks are immediately above Oruanui Breccia, above Poutu Lapilli, above Taupo Pumice and below Rotoaira Lapilli. Localised erosion, inferred from unconformable contacts, is also recognised between Wharepu Tephra and Poronui Tephra and immediately above the Rotoaira Lapilli. These erosion surfaces do not all have the same origin.

At the present time erosion is inordinately more active where the vegetation cover is incomplete. The vegetative cover in the past may have been depleted while the vegetation zones were lowered during cooling climatic conditions, or by tephra burying and so destroying the vegetation, or, more recently by man destroying vegetation by fire. However, close to source on higher slopes most eruptions may be accompanied by erosion and redeposition as shown by Druce (1966) for recent eruptions from Mount Egmont.

Most rhyolitic tephra fall eruptions and certain of the andesitic lapilli eruptions were voluminous enough to destroy vegetation by burial over large areas. Vucetich and Pullar (1963) give a conservative estimate of 0.45 m as the thickness of tephra required to destroy forest vegetation and Druce (pers. comm. in Vucetich and Pullar 1963) found that Burrell Lapilli of 0.38 m thickness caused complete destruction of mountain cedar (Libocedrus bidwillii) and Hall's totara (Podocarpus hallii) on Mount Egmont. (A "humic horizon" found at many sites beneath the Burrell Lapilli has been interpreted as being leaf fall induced by scorching of the plants by a preceding ash shower (Druce 1966)).

Foliage may be stripped from trees by falling lapilli. Trees bared of leaves will enable heavy rains to channel the upper surface of the

tephra and saturated ash may become unstable and slide until vegetation again stabilises the area.

Erosion following rhyolitic tephra flow eruptions is usually greater than that following tephra fall eruptions. Airfall tephra may be sufficiently thick to destroy much of the vegetation by burial but the *nuees ardentes* destroy all the vegetation, including dead standing trees killed by the preceding tephra fall eruptions which would otherwise help prevent mass movement of tephra. Heavy falls of rain often accompany large eruptions and these will accentuate the damage resulting from the blocking of natural drainage systems by thick pumice deposits of *nuee ardente* origin.

Two widespread rhyolitic tephra flow units, Taupo Pumice and Oruanui Breccia, occur within Tongariro Volcanic Centre. The upper surface of Taupo Pumice is usually eroded and the deposits contain abundant charred logs showing that all vegetation was destroyed at those sites. The upper surface of Oruanui Formation is almost invariably eroded, the youngest tephra fall beds being preserved fortuitously within the crater of Pukeonake Scoria Cone only.

The Rotoaira Lapilli deposit has been eroded at two sites (Poutu reference section, N112/239901; section 220, N112/257897; see Appendix 1A) where the unit was thick enough (0.38 m) to have partially destroyed the vegetation. The presence of charcoal under Rotoaira Lapilli at several widely scattered sites indicates that forest fires, initiated during eruptions from the Te Mari craters, caused some destruction of the vegetation. However, the thick tephra, rather than destruction by fire, was the major contributing cause of the erosion because the tephra is not eroded where its thickness is < 0.38 m.

Below Wharepu Tephra, an erosional unconformity, recognised by the absence of Poronui Tephra and the upper part of Ohinepango Tephra (see Table for stratigraphic relationships), is recorded locally, mainly in Desert Road sections (Topping 1973). The finely bedded undisturbed

character of Wharepu Tephra and Ohinepango Tephra and the thin yet unbroken horizon of the rhyolitic Poronui Tephra show that no substantial vegetation stabilised the surface during deposition of Mangamate Formation and that local erosion need only have been due to heavy rain on an unprotected surface.

Between Poutu Lapilli, youngest member of Mangamate Formation, and the overlying Papakai Formation an erosional unconformity is very common in tephra sections and erosion was widespread at this time. In some Desert Road sections (e.g. 163, N122/223694; 169, N122/219675) Poutu Lapilli (300-900 mm thick in nearby sections), with prominent subhorizontal bedding, has been almost completely truncated. At many other sites the contact is quite irregular and at rare sections (e.g. Poutu reference section, Fig. 6, Topping 1973; also Fig. 4) the contact is almost conformable. Overseas there is considerable evidence for cooler global climatic conditions at about 9,700 years BP, for example, climate was cooler about 9,500 years BP in Siberia (Kind 1972) and glacial moraines in Hawaii formed prior to 9,100 years BP (Woodcock in Porter 1973). However, pollen analysis on peat samples from above and below Mangamate Tephra at the Wairehu Canal section (No. 310) does not support a cooling (M. S. McGlone, pers. comm.). Any global cooling at this time would therefore need to be of short duration. The erosion break (unconformity) present in many sections above Poutu Lapilli is probably due to short term erosion before the vegetation had a chance to recolonise the area. There is no evidence for any soil formation between the members of Mangamate Formation and no major vegetation is likely to have established during deposition of the formation. The thickness of the youngest member, Poutu Lapilli, is itself sufficient to have buried the previous vegetation over a very large area from the north-west (clockwise) around to the south-east of the Tongariro Massif and tephra of the total formation must therefore have devastated more than 1,000 km²

of the pre-Mangamate forest. Rain water would have readily drained through the non-vesicular Poutu Lapilli (which lacked fines) so that both lack of water retention (c.f. the largely unvegetated Onetapu Desert, east of Ruapehu) and the widespread area devastated meant that vegetation required an appreciable time to stabilise the upper surface of Mangamate Tephra, and erosion may locally have been prolonged. The truncated surface, seen in the Desert Road sections mentioned earlier, was probably cut in a manner similar to the present-day erosion of the non-vegetated, sub-horizontal, tephra sequences on Rangipo Desert. On steeper slopes the erosion surfaces would be more irregular. However, some of the erosional irregularities of the upper surface of Poutu Lapilli are due to the lifting action of roots of plants that established during deposition of earliest Papakai Tephra between 9,700 and 6,300 years BP.

At least three erosion breaks which occur between 14,000 and 20,000 years^{BP} (Rotoaira Lapilli and Oruanui Formation) cannot be explained by thickness of tephra cover and must have another origin possibly that of cold climate. The erosional unconformities truncate tephra and loess beds and are not related to destruction of the vegetation. Some of these erosion breaks, e.g. as at section 220 (N112/257897, see Appendix 1B), can only be recognised where they truncate lapilli units. In sections on National Park-Taupo Road south of Taurewa and at the western end of Lake Rotoaira (34, N112/176979) the erosion surfaces are more irregular and they are commonly lined by subangular to subrounded andesitic cobbles and boulders (Fig. 61). At sections south of Taurewa the andesites are vesicular olivine andesites which have been derived from lavas that underlie Oruanui Formation in this area. The cobbles and boulders have probably been transported only short distances but their occurrence suggests much surface runoff and incomplete vegetation cover.

Suggate (1965) and Suggate and Moar (1970) suggest that glacial advances within the late Otira Glacial in north Westland, South Island,

Fig 61: Subangular to subrounded andesite cobbles and boulders lining erosional unconformities within reworked tephra deposits at a section on Rotoaira Road, at the northern end of Lake Rotoaira (N112/176979, section 35). The water-reworked silts and sands are derived mainly from the underlying Oruanui Formation (20,000 years BP) and they are overlain by probable loess, and Rotoaira Lapilli (13,800 years BP).

New Zealand, occurred: Before 22,300 - c. 18,000 yr BP (later Kumara 2 advance, K2.2)

c. 17,000 - c. 16,000 yr BP (earlier Kumara 3 advance)

and c. 14,500 - c. 14,000 yr BP (later Kumara 3 advance).

Rotoaira Lapilli, dated at 13,800 yrs BP (NZ1559) is the oldest andesitic tephra accordant with the present surface over a large area to the north-east of Tongariro. It therefore marks the base of the Aranuiian Stage (Suggate 1961) and the erosion break directly beneath Rotoaira Lapilli probably corresponds to Suggate and Mear's (1970) later Kumara-3 advance. At Poutu reference section (No. 17, see Appendix 1A) Rerewhakaaitu Ash underlies this erosion break and it places a maximum age of 14,700 years BP (NZ716) on the later Kumara-3 advance. Lack of age control on andesitic tephras erupted between 14,700 and 20,000 years BP has meant that erosional unconformities during this time span cannot yet be dated by the means at hand.

Pollen from 210-220 mm below Oruanui Ash and overlying an "unnamed rhyolitic ash", now informally known as the Okaia tephra and believed to be about 22,000 years old (C. G. Vucetich, pers. comm.) indicates a cool-climate flora of Nothofagus forest, Phyllocladus shrubland, and grasslands. Pollen analysis indicates slightly less cool conditions at 20,000 years BP (McGlone and Topping 1973) with a sudden warming to podocarp-broadleaf forest taking place about 14,500 years BP (N112/556). These data are consistent with Suggate and Mear (1970).

Present-day Erosion

Within the Tongariro area erosion is particularly active at the present time. On the Rangipo Desert, east of Ruapehu, pedestalled "islands" of tussock and scrub are being isolated and undermined by wind erosion, and

dune bedding can be recognised within reworked Ngauruhoe Tephra in at least one Desert Road section. On many of the eastern slopes of Tongariro, erosion has removed all tephras deposited since 13,800 years BP and the present deflation is exposing colluvium and morainic deposits (Fig. 62). Where "islands" of vegetation persist, tephra sequences are complete from Rotoaira Lapilli to Ngauruhoe Tephra, showing that this widespread erosion was initiated within the past 1819 years BP.

Except for the truncation of Mangamate Formation (due to the destruction of the pre-Mangamate Formation vegetative cover) the most widespread erosion within the park during the last 14,000 years occurs today.

This erosion is probably due to (a) destruction of the forest cover by the Taupo Pumice eruptions, (b) pre-European and early European fires, (c) recent climate change and (d) noxious animals.

(a) Destruction of the Forest Cover by the Taupo Pumice Eruptions

Taupo Pumice nuée ardente deposits in the Tongariro area contain many charred logs showing that most of the vegetation was destroyed by the eruptions. For example, Nothofagus menziesii (silver beech) occurs in situ below Taupo Pumice at 1,020 m on northern Tongariro (N112/133893) 60 m above the present totara (Podocarpus hallii) forests (V. E. Neall, pers. comm.). Taupo Pumice is thin to absent on the south-western slopes of Ruapehu where the beech forest which grows up to 1,500 m altitude was probably not adversely affected by the eruptions. The basal Mangatawai Tephra (2,500 years BP) contains beech leaves at 1,500 m (Gregg 1960) and, apart from the south-western slopes of Ruapehu, the present upper limit of forest is at about 1,410 m. It is likely that the forest which established following the complete destruction by the Taupo Pumice flows has not yet spread up to the former tree-line. Beech (Nothofagus) forest is known to migrate very slowly but this is not so for podocarp-broadleaf

Fig 62: On the northern side of Mangahouhounui Valley, NE Tongariro, "islands" of vegetation and the tephra beds they protect are being destroyed by wind erosion. The removal of the tephra is exposing colluvial deposits over 13,800 years old.

Fig 63: Old tree trunks, larger than the present subalpine scrub, lie on an actively eroding surface on top of the ridge north of Mangahouhounui Valley, north-eastern Tongariro (N112/198844). At the left side of the photo a tephra sequence through to the present day is still preserved; in the foreground the surface is developed in Mangamate Formation (9,700-9,780 years BP); and at upper right all deposits younger than 13,800 years BP have been removed by erosion.

forest. The Podocarpus hallii (Hall's totara) forests on northern Tongariro, and the rimu-kamahi (Dacrydium cupressinum - Weinmannia racemosa) and totara-kaikawaka (P. hallii - Libocedrus bidwillii) forests of Hauhungatahi are examples of communities which one would have expected to find as forest cover over the Tongariro National Park area today instead of the present Chionochloa rubra tussocklands. Today's active erosion was not initiated by eruption of Taupo Pumice even though most of the forest cover was destroyed by the nuées ardentes. Presumably, therefore, a forest cover was able to establish soon after eruption of Taupo Pumice and we need to find a more recent cause for forest destruction.

(b) Pre-European and Early European Fires

Widespread fires, pre-European to as recently as 1920 (Tongariro National Park Handbook 1965, p. 29), have swept through the park and have probably destroyed the forest cover and prevented this cover from regenerating. Southern beech forest (Nothofagus solandri var cliffortioides) in the northern part of the park (particularly west of Tongariro) forms "islands" within Chionochloa rubra tussock grasslands consistent with, but not proof of, stands of vegetation which have survived these fires. The beech would only migrate slowly from these "islands", if at all, and podocarp forest would probably have difficulty establishing in a tussock cover. Maori fires probably destroyed the forest cover initially but it is known that much of the tussock grasslands were fired between 1900 and 1920 in an effort to introduce heather (Calluna vulgaris) as a suitable cover for grouse.

(c) Recent Climate Change

The remains of shrubs preserved within Mangatawai Tephra on Hauhungatahi have stem and root diameters larger than any of the subalpine scrub species currently growing at the site. Also, tree trunks considerably larger than the present subalpine scrub lie on eroded tephra ground surfaces on the northern side of Mangahouhounui Valley at N112/198844 (Fig. 63).

Two possible reasons for these observations could be invoked. Either there has been a climatically controlled lowering of the tree-line since 2,500 years BP and probably quite recently, as suggested by Bray (1971), Park (1970) and others, or the vegetation at these sites has been destroyed by recent fires and the tree-line is still ascending to its former height.

Much of today's active erosion would possibly either not have been initiated, or if initiated would have healed over, if the post-Taupo Pumice vegetation still covered the area. Once the vegetative cover has been removed, however, erosion can quickly remove the tephra, particularly Taupo Pumice (e.g. the old Ketetahi Track, N112/131920) and Mangamate Tephra (on eastern Tongariro) possibly because these particular deposits lack silt and clay, are therefore less well bonded and offer less resistance to erosion. Papakai^{Tephra} is the only Aranuiian tephra that is likely to be incompetent under loading. The greasy silt (allophanic) could be expected to cause slippage of tephra younger than 9,700 years BP but field observation does not support this suggestion.

(d) Noxious Animals

Noxious animals, such as red deer, pigs, opossums, wild horses and cattle which have appeared in the area since man, have probably caused much destruction through browsing, and the formation of tracks which by exposing unvegetated surfaces to heavy rains is the cause of many slips.

Probably much of the erosion occurs during periods of heavy rain such as 21 March 1933 when 178 mm of rain fell overnight at Chateau Tongariro, and 29-31 October 1945 when 220 mm fell at the Chateau in 46 hours and 304 mm in 3 days (The Soil Conservation and Rivers Control Council, Wellington, 1957). Many of the slips appear to be of the same age and it is noticeable that those on south-facing aspects are regenerating with difficulty, if at all.

Destruction of the forest cover by the Taupo Pumice eruptions of

1819 years BP is not considered to be the major cause of the present widespread erosion. Forest which subsequently covered the Taupo Pumice has been removed over large areas of the park by Maori and early European fires, and later tussock fires. Recent climate change may be causing an increased frequency of heavy rain storms or it may be inhibiting regeneration of the forest cover but this is considered to be secondary to the destruction by fires and noxious animals, which are considered the probable major causes of the erosion.

H. TEPHRA WEATHERING

Lavas, pyroclastic and epiclastic deposits are subject to weathering and since that is in part time-dependant a knowledge of the qualitative changes undergone during weathering provides a means of estimating the age of a deposit. However, determination of the amount of weathering and the number of variables that control it make accurate quantification of a rate difficult.

The weathering rate is known to be affected by rock permeability, temperature, amount of water movement or leaching, pH of the soil (particularly the amount of carbonic acid), degree of oxidation and its fluctuation, composition of the minerals and rocks being weathered, and their surface area and particle size. An increase in surface area, usually because of a smaller particle size, allows a more rapid rate of weathering so that aa breccias would weather at a faster rate than massive lavas, and well-jointed lavas faster than less jointed lavas.

Although it is difficult to estimate the age of any one lava or tephra deposit within Tongariro Volcanic Centre from the amount of weathering it has undergone a comparison of weathering forms can be used to give relative ages for similar deposits. For example, the youngest aa flows from Ngauruhoe, erupted in 1954, are darkest in colour while older flows of similar composition grade through grey to brownish greys as the outer surfaces become weathered.

An additional factor of importance in an area such as Tongariro Volcanic Centre is hydrothermal alteration of tephtras, lavas and breccias. These deposits can be converted readily to clays by the action of hot springs and they are then very susceptible to landsliding. Examples are the Ketetahi Springs, the north-eastern slopes of Tihia, the Hipaua Thermal area near the Waihi Fault, and an area close to Wanganui River

at N112/099990. Hydrothermally altered debris may also be ejected from fumaroles or craters during small phreatic eruptions, as in the formation of the Emerald Lakes explosion craters (Appendix 1B).

Weathering of Tephra

Tephra have several advantages over other deposits when considering the relative importance of criteria as indices of weathering. The time for a particular stage of weathering to develop is known for soils and paleosols in tephra successions. The weathered forms of tephra of different chemical compositions, e.g. rhyolitic and andesitic, of the same radiocarbon age or similar stratigraphic position can be compared. Also, the fine bedding and/or thinness of certain andesitic tephra allows no disruption due to rooting of vegetation and soil forming processes.

The term paleosol, as used here, refers to a buried soil. Many tephra deposits undergo soil formation but not all soils upon burial form paleosols. Soils form at times when ash deposition is slow or non-existent so that recognition of paleosols within tephra sequences is important in indicating where time breaks occur in the accumulation record.

Some general conclusions can be made regarding the weathering of tephra:

- (1) The rate of weathering varies with the chemical composition of the tephra. Andesitic tephra weather more rapidly than dacitic and rhyolitic tephra and less rapidly than basaltic tephra.
- (2) Weathering rates increase with decreasing particle size (increasing surface area).
- (3) The weathering rate of lapilli increases with vesicularity, a special case of increasing surface area.

- (4) The weathering characteristics of most tephra beds generally reflect the amount of time that bed was exposed at the surface during soil-forming processes. However, some beds can be shown to have been weathered since burial.

The four factors above do not have equal weighting. For example, Te Rato Lapilli comprises two types of lapilli, mainly very dark grey (5Y 3/4), non-vesicular, andesite lapilli with fewer (c. 10% by weight), larger, pale yellow (2.5Y 7/4), moderately vesicular (3), dacite lapilli (1). The dacite is less basic and larger (2) than the andesite lapilli yet it is slightly weathered, from white to pale yellow, while the andesite lapilli are unweathered. In this example the vesicularity of the dacite lapilli is the major factor responsible for its greater degree of weathering.

During soil formation the andesitic glass is rapidly altered and destroyed. The average particle size is reduced and the colloid content (greasiness when the moistened tephra is rubbed between the thumb and fingers) is increased. When a tephra becomes buried the amount of soil formation it has undergone usually can be assessed on three main properties, colour, colloid content and "cracking". Normally a combination of properties is required and this evidence must be supported by a knowledge of the distribution and relative age relationships of the beds. A radiocarbon chronology of every tephra unit is also very helpful, but inessential. Each criterion is considered below:

(a) Colour

During weathering the original light to dark grey colours of the andesitic tephrae are changed to the oxidised colours of yellowish brown, strong brown, and yellowish red. Colour is one of the most useful features by which to recognise and correlate a specific andesitic tephra. Although colour is often an indication of the amount of tephra pedogenesis in some cases the colour can be shown to be due to changes since burial.

Fig 64: A generalised tephra column (0-9,780 years BP) for the Tongariro area with members of Mangamate Formation detailed. At Iwatahi, 55 km further north-east, four members of Mangamate Tephra are absent so that Poronui Tephra directly overlies unweathered dark grey ash, Te Rato Lapilli. There is therefore insufficient time for significant soil weathering to have occurred between deposition of Te Rato Lapilli and Poronui Tephra.

In the Mangamate Formation (Fig 64) the youngest member, Poutu Lapilli, is typically a strong brown (7.5YR 5/6) colour. By contrast andesitic lapilli of the oldest member, Te Rato Lapilli, have a very dark grey colour (5Y 3/1) even where the bed is only 20 mm thick and of medium ash grade (Iwatahi section, N102/735200, Fig 1, Topping and Kohn 1973; 23 km south-east of Taupo township). Te Rato Lapilli at this section forms an almost continuous horizon which has not been disrupted by soil forming processes. The dark grey colour is retained because the immediately overlying rhyolitic Poronui Tephra was erupted soon after deposition of Te Rato Lapilli.

In sections near Tongariro, two further members of Mangamate Formation, Wharepu Tephra and Ohinepango Tephra, also have their original unweathered colours of dark olive grey (5Y 3/2) and very dark grey (7.5YR 3/1). Their colour and their fine undisturbed bedding (e.g. Mangatawai and Access 10 reference sections, Appendix 1A) show that no vegetation colonised, and that no soils were formed on their upper surfaces. Moreover, no widespread erosion occurred after deposition of either of these members.

In similar sections the rhyolitic Poronui Tephra is 10-20 mm thick and usually forms a continuous uniformly thin horizon. The lack of disruption by plant roots suggests that no vegetation established above Poronui Tephra or the overlying Wharepu Tephra. In sections within Wairehu Canal (e.g. 310, Appendix 1B) peat is present immediately above and below Mangamate Formation but is not interbedded within the formation. This reinforces the conclusion that no time breaks of sufficient duration occurred to allow soils to form during deposition of Mangamate Formation.

Yet, Oturere Lapilli the second-to-oldest member of Mangamate Formation (overlying Te Rato Lapilli) has a strong brown (7.5YR 5/6)

or even yellowish red (5YR 4/6) colour (e.g. Access 10 reference section, Appendix 1A). In this case the weathering of Oturere Lapilli must have occurred after its burial.

In general, colour of ash grade tephra usually indicates weathering during soil formation but in lapilli colour can be a post-burial feature. The strong brown to yellowish red colours of many lapilli units was not a result of soil formation at their upper surface but was due to deposition of iron oxides and hydroxides on the outer surfaces of the buried lapilli far below the level of soil formation (for example, Oturere Lapilli 0.66 m below in the case of Access 10 reference section). Post-burial weathering is dependent upon the vesicularity and the degree of sorting (whether there is a mixture of several grade sizes and how this affects permeability). In Wharepu Tephra, Ohinepango Tephra, and Te Rato Lapilli the particles are well sorted and non-vesicular and are free draining. Where drainage is impeded in less well sorted tephra (usually more vesicular) weathering products from soils higher in the section are deposited on the outer surface of the particles. The deposition of weathering products is also due to vertical textural changes within tephra beds. The upper half of the Okupata Tephra basal lapilli is yellow (10YR 7/8) while the lower half is strong brown (7.5YR 5/6) and this difference is probably due to the deposition of iron oxides and hydroxides near the lapilli-fine ash textural boundary, and analogous to deposits of iron ('iron pans') at the base of Burrell Lapilli on Mount Egmont (Tonkin 1970).

The soil that developed subsequent to Mangamate Formation is now the most conspicuous paleosol (lower part of Papakai Tephra, Fig 65) in the Tongariro Sub-group tephra. Papakai Tephra, mostly a strong brown (7.5YR 5/6) colour (e.g. Poutu reference section), consists of a greasy (allophanic) silt, has much vertical and horizontal cracking, and the discrete ash beds which it is assumed were deposited during its

Fig 65: Paleosol development within Papakai Tephra is particularly strong in the lowermost part of the formation, i.e. between c. 9,700 and 6,300 years BP (lower part of the trowel). The "cream cakes" (level with the handle of the trowel) are of the rhyolitic tephra marker bed, Hinemaiaia Ash (c. 6,300 years BP). The little-weathered dark grey ash in the upper part of the photo is basal Mangatawai Tephra (c. 2,500 years BP) and Taupo Pumice (c. 1819 years BP) is at the top. Poutu reference section, N112/239901 (see Appendix 1A).

accumulation have lost identity during the soil formation. It is probable that the iron oxides deposited as coatings on the Oturere lapilli were from the weathered Papakai Tephra.

(b) Greasiness

A buried soil will often have a "greasy" feel because of its marked allophane content and/or organic matter; greasy here refers to non-cohesiveness of silty clay and clay grade sizes when moistened and rubbed between thumb and fingers. However, as with other individual criteria used to assess weathering there are exceptions. Almost unweathered tephra such as the fine beds within the shower bedded base of Oruanui Ash (Poutu reference section, Appendix 1A) may also have a greasy feel. Although some time break is indicated by bioturbation at the fine ash-coarse ash boundary (J. A. Westgate, pers. comm.) there is no evidence to indicate significant time for weathering within Oruanui Ash.

(c) Cracking and Surface Weathering

When tephra sections (e.g. road cuttings) dry out, paleosols (buried soils) shrink differentially, because of their clay content, with respect to less weathered tephra and become "cracked". In road cuttings paleosols may either erode more readily or be more resistant than the less weathered tephra. In ash grade andesitic tephra of intermittent origin paleosols often fret more than the enclosing tephra. In contrast, andesitic or rhyolitic coarse ash and lapilli of paroxysmal origin often have paleosols that are more massive and form resistant ledges relative to the less weathered coarse ash and lapilli which contain less clay-sized material and less organic matter.

Although such cracking is a good indication of paleosol development caution is needed as there are exceptions. Fine ash layers sandwiched within lapilli beds may weather superficially in road cuttings to

resemble paleosols; "pseudopaleosols". For example, a fine ash horizon within Poutu Lapilli at section 32 (N112/150978, Fig 66) has the appearance of a paleosol and it is known to be the lateral facies of a lapilli shower which is not separated by significant time from its enclosing beds (e.g. in sections in Wairehu Canal there is peat above and below Mangamate Formation but none within the formation). Similarly, in sections to the north of Tongariro the fine andesitic ash bed above Poromui Tephra and below Poutu Lapilli is cracked. And this ash bed is the lateral facies of unweathered dark olive grey (5Y 3/2) and very dark grey (7.5YR 3/1) medium ash with fine undisturbed bedding (Wharepu Tephra) which is known to have been erupted shortly before Poutu Lapilli.

Weathering as a Function of the Rate of Tephra Accumulation

Much of the ash grade andesitic tephra accumulated intermittently and the plant cover was able to accommodate the individual tephra accretions within the developing soil with apparent uniform weathering. Thus much of the ash grade tephra, although weathered, does not retain soil character upon burial. Where the tephra accumulation rate was very slow the soil remained in one position for a considerable period of time and when buried this soil is preserved as a prominent paleosol. The rate of tephra accumulation therefore has an important bearing on the degree of paleosol development. This is best seen by considering tephtras erupted from Ruapehu between c. 10,000-14,000 years BP.

(i) Rate of accumulation of Ruapehu source tephtras, 10-14,000 years BP

To the east of Ruapehu (N122/171664, section 462) there are more than 50 lapilli and ash units which are little weathered, without paleosols, and have therefore accumulated rapidly. At section 171 (N122/228655 Appendix 1B) 15 km east of Ruapehu, for example, each Ruapehu tephra

unit older than c. 9,800 years BP consists primarily of a basal lapilli overlain by medium to coarse ash which is usually grey and unweathered.

At most sections north of Tongariro the ash facies of these same tephra units, together with a few local Tongariro source tephras, are moderately weathered and are without paleosols. Within these tephra sections the "cream caked" nature of Rotorua Ash shows that at these sites all the tephra units between 13,800 and 9,800 years BP have undergone some soil development but the soil was able to keep pace with more or less continuous tephra accretion (10 mm in 37 years at section 17).

At road sections west of the Tongariro Massif Ruapehu tephras of the same age have several prominent paleosols (Topping 1973, Fig 2). The tephra accretion at these sites was not uniform and soils were formed during times of little or no tephra deposition. The paleosols are made more obvious in these sections (e.g. Okupata reference section, Appendix 1A) because in most cases their soil development was terminated by paroxysmal lapilli eruptions.

The degree of paleosol development can therefore be equated with the rate of intermittent tephra accumulation. West of Tongariro (e.g. section 99) the intermittent tephra (i.e. lapilli beds excluded) from about 9,800-14,000 years BP accumulated at a rate of about 10 mm in 91 years compared with a rate of about 10 mm in 37 years at sections north of Tongariro (e.g. section 17). The difference in accumulation rates has resulted in obvious paleosols west of Tongariro and their apparent absence north of Tongariro.

Further rates of tephra accumulation are given in Fig 67 for sections at different points of the compass with respect to the Tongariro Massif. These data also support the observation that soil development was marked where rates of tephra accumulation were low and especially north-

Fig 66: A "pseudopaleosol" formed by superficial cracking of fine ash sandwiched between beds of the Poutu Lapilli Member. The enclosing lapilli beds are not separated by significant time and the fine ash is the lateral facies of a further lapilli bed. Section 32 (N112/150978).

Fig 68: The paleosol developed at the top of Mangatawai Tephra. The basal part of the formation consists of finely bedded unweathered dark grey to very dark grey medium ash. There is weak paleosol development below the base of Mangatawai Tephra and greater paleosol development throughout Papakai Tephra. The greatest paleosol development within Papakai Tephra is at the base of the formation, between the "cream cakes" of Hinemaiaia Ash (c. 6,300 years BP; near head of geological hammer), and the under lying Poutu Lapilli Member (c. 9,700 years BP).

Fig 67: Rates of intermittent tephra accumulation with respect to direction from the Tongariro Massif. The figures represent the number of years taken for the accumulation of 10 mm of tephra. The original field thicknesses upon which the data are based are consolidated net thicknesses and differ from the total thicknesses of newly fallen unconsolidated, uneroded tephra. The tephra beds and their periods of accumulation are:

- (a) Ngauruhoe Tephra (1,840 years);
- (b) Mangatawai Tephra (680 years);
- (c) Papakai Tephra (6,300 years);
- (d) base of Mangamate Tephra to Rotorua Ash (2,720 years);
- (e) Rotorua Ash to top of Rotoaira Lapilli (1,300 years);
- (f) Papakai Tephra older than Hinemaiaia Ash (3,400 years), and (in brackets) Papakai Tephra younger than Hinemaiaia Ash (2,900 years).

west to south-west from the source vents, i.e. toward the source of the predominant winds (Fig 67). Mangatawai Tephra, with the highest rate of accumulation, is least weathered; and Papakai Tephra, with the lowest rate, is most weathered.

(ii) Mangatawai Tephra

If all of Mangatawai Tephra had been of intermittent origin then it should be little weathered. However, the upper part commonly has the form of a paleosol (Fig 68) just below Taupo Pumice. The unweathered dark grey (5YR 4/1) to very dark grey (5YR 3/1) medium ash containing yellow (10YR 7/8) to white fossil beech leaves which comprises most of Mangatawai Tephra is finely bedded and has not been disturbed by soil development. Mangatawai Tephra is the only tephra bed in the Tongariro Sub-group with abundant sub-fossil leaves and it is probable that the high tephra accumulation rate prevented the leaves from being destroyed through normal oxidation processes. Although Mangatawai Tephra accumulated during 680 years at least half of the formation accumulated rapidly, probably in a matter of days to weeks. The rate of tephra accumulation during soil development (10 mm in 220 years at section 57, north of Tongariro) is about a tenth of the accumulation rate (10 mm in 22 years, section 57) for the whole formation. An accumulation rate of 10 mm in 220 years is sufficiently slow (c.f. Papakai Tephra data, Fig 67) to expect an obvious paleosol at the top of Mangatawai Tephra as seen in tephra sections.

(iii) Papakai Tephra

The average rate of tephra accumulation for Papakai Tephra is less than 10 mm in 140 years (Fig 67) and the whole formation can be characterised by its paleosol development (Topping 1973), and discrete andesitic tephra beds are not preserved (e.g. Poutu reference section).

Of several rhyolitic tephra deposited during this period only Hinemaiaia Ash (Topping and Kohn 1973) is preserved. It is therefore a valuable marker within Papakai Tephra and can be used to show that rates of tephra accumulation were generally two to three times slower for the first 3,400 years of Papakai Tephra deposition (9,700-6,300 years BP) than for the last 2,900 years of deposition (6,300-3,400 years BP) (Fig 67). The greater degree of paleosol development near the base of the formation can be clearly seen in many sections around Tongariro (e.g. Poutu reference section, Fig 65).

In many sections around Tongariro Hinemaiaia Ash is absent and is inferred to have been churned up during soil formation. Where present it is usually as "cream cakes" (Fig 65) - remnants of an original bed that has since been disrupted during soil formation. It is present in lenses only NNW of Tongariro in thick Papakai Tephra preserved as a result of subsequent eruptions from one or more of Te Mari Craters, Blue Lake and North Crater. Hinemaiaia Ash is best preserved at Desert Road sections east of the Tama Lakes where later ashes erupted from craters in the Tama Lakes-Ngauruhoe area preserved the rhyolite and prevented soil processes from disrupting it. Thus the presence and character of a thin rhyolitic tephra within a soil-forming tephra tells us much about the rate of tephra accretion to that soil.

There are at least two other qualifying factors in declaring rates of soil formation more complex than just a dependence upon rate of tephra accumulation that can be exemplified by Papakai Tephra. This tephra is probably relatively more weathered than other slowly accumulating tephras because: (1) it was largely erupted as fine ash from non-cone-building vents (Tama Lakes-Ngauruhoe area) in comparison with the medium ash grade tephra erupted from cone-building vents from Ngauruhoe (Mangatawai Tephra), and (2) the climate may have been warmer during Papakai Tephra

deposition than either before or afterwards.

Because weathering of ash grade andesitic tephra is so dependent upon rate of accumulation and much of the weathering of lapilli units is post-burial no climatic implications, similar to those determined for the rhyolitic tephra by Vucetich (1968), can yet be obtained from the andesitic tephra.

Conclusions

All tephra undergo some weathering, the amount being determined mainly by chemical composition, particle size range (distance from source), external and internal surface areas (vesicularity), the period of time the bed was exposed at the surface, and various climatic factors. The amount of soil development previously undergone by tephra can be assessed in strict stratigraphic context on a combination of colour, greasiness, cracking on drying^{out} (there are exceptions to the individual factors), and degree of disruption of the bedding.

If the accumulation rate for andesitic ash is known the presence or absence of a paleosol can be predicted. In the Tongariro area Mangatawai Tephra is least weathered and has the fastest accumulation rate; Papakai Tephra is most weathered and has the slowest accumulation rate. North of Tongariro tephra deposition (mainly from Ruapehu vents) from 13,800 to 12,500 years BP is twice as fast as the rate between 12,500 and 9,800 years BP.

The degree of paleosol development varies according to the distribution of the tephra from the source vents and their related particle sizes: soils were least well developed ESE of Tongariro where the rate of tephra accumulation was highest and were best developed in the west to south quadrant where the rate of tephra accumulation was lowest.

I. TREE-RING DATING ON NORTHERN TONGARIRO

Principles of Tree-ring Chronology

In temperate regions growth rings are formed within the woody tissue, xylem, in stems and roots of coniferous and dicotyledenous trees. The cambium layer just inside the bark differentiates xylem tissue towards the inside and phloem, food-conducting tissue, towards the outside. In the spring when growth begins the xylem cells formed are large and thinwalled (Fig. 69) and comprise the "earlywood" portion of the growth ring. Towards the end of the growing season the xylem cells become progressively smaller and thicker walled. This dense tissue, the "latewood", forms a distinct boundary against the lighter earlywood of the following year's xylem. The earlywood and latewood together form the growth ring and in temperate regions where there is one growing season a year usually a single and annual ring forms.

The growing season in New Zealand does not fall within one calendar year so that the date given to a ring will be that of the year in which the growth ring was completed.

Where two or more growth rings are formed in the one season then all except the last ring are false rings. The narrow latewood band of a false ring usually lies on the inside of a wider latewood band and in normal ring sequences the latewood-earlywood transition is usually less distinct than the boundary between latewood and earlywood of the following growth ring. False rings are considered to be due to abrupt environmental changes such as mid growing season droughts, late frosts, as well as injuries by insects, fungi, or fire (Kozlowski 1971). Xylem increments may be missing from certain sections of the tree - particularly in the lower stem of trees which are old or becoming suppressed. These "missing" rings are rarely missing over the entire surface of a stem or a branch so that the

'61 1862 1863 '64

Fig 67: Cellular detail (35x) of part of the ring sequence for Phyllocladus alpinus tree XI. Note the 1861-1864 signature where two broad rings with dense latewood (1862, 1863) are enclosed by two narrower rings (1861, 1864). (Ring indices for XI(iii) are: 1861 - 0.57, 1862 - 1.32, 1863 - 1.72, 1864 - 0.60). This signature was particularly useful for cross-dating.

term "locally absent" (Stokes and Smiley 1968) is preferred by the present author.

If a tree lives under optimum growing conditions then successive growth rings are likely to be of uniform width and the sequence of rings (the ring series) is said to be complacent. If one or more varying climatic factors inhibits growth then the ring widths are likely to vary and the ring series is sensitive. The matching of patterns within sensitive ring series allows cross-dating (Douglass 1941) and if one ring in one of the trees can be dated the chronology can be extended from tree to tree. Such cross-dating is impossible in any area unless there is uniformity of tree-ring patterns. The regularity of tree-ring patterns can be tested by "circuit uniformity", the similarity of patterns on different radii of the same tree section, "vertical uniformity", the similarity of patterns at different heights within the same stem, and "site uniformity", the similarity of patterns from within different trees.

When a tree is erect the form of growth rings is nearly concentric. However, when a tree is tilted subsequent growth rings form eccentrically and the non-conformity between them is used to date the tilting (Lawrence 1950, LaMarche and Wallace 1972). The wood produced by the tree to correct for the tilting (reaction wood) is either compression or tension wood. In conifers, or softwoods, compression wood is formed on the underside of the stem where it results in wider growth rings; and by contrast in angiosperms, or hardwoods, tension wood is formed on the upper side of the stem where it results in wider growth rings. Reaction wood can usually be distinguished microscopically from normal wood (Jane 1970).

Previous Dendrochronology in New Zealand

Previous dendrochronology in New Zealand has been notably unsuccessful in cross-dating. Bell (1958) and Bell and Bell (1959, cited in Scott 1972) studied 17 New Zealand tree species and found that cross-dating was only possible between some specimens of Agathis australis (kauri) and Podocarpus totara (totara), and then only in the Auckland area. Elder (in Batley 1956) found no circuit uniformity in mountain beech (Nothofagus cliffortioides) and Scott (1964) failed to cross-date archeological specimens of Libocedrus bidwillii (kaikawaka), Podocarpus darydioides (kahikatea) and Podocarpus spicatus (matai). Cameron (1960) was not able to cross-date mature rimu (Dacrydium cupressinum) or young rimu and kahikateas near Rotorua. For Hall's totara (Podocarpus hallii) in Central Otago (Wells 1972) there is good circuit uniformity but no vertical or site uniformity. Dr D. Scott (pers. comm. in Wells 1972) reached the same conclusion for Hall's totara in the Mackenzie Country, Central Otago.

Scott (1972)* attempted cross-dating in the Lake Tekapo area, South Island and on Mount Ruapehu. At Lake Tekapo he found that circuit uniformity in Phyllocladus alpinus, and Pinus nigra var. maritima was good but variable in Podocarpus hallii, Discaria toumatou, and Nothofagus solandri. There was found to be no similarity in tree ring patterns for the different species. Vertical uniformity was not tested. On Mount Ruapehu, Scott did not check for circuit and vertical uniformity. Tree ring patterns for Phyllocladus alpinus and Nothofagus solandri showed some similarities but there were no similarities between ring patterns from Lake Tekapo and Ruapehu. Correlations between ring indices and climate were found to be weak at both localities.

New Zealand podocarps (including totara, rimu and kahikatea) usually lack circuit uniformity (Hutchinson 1926). They also possess fused or

* Fieldwork for the present study began in March 1972 before Scott's paper was published.

"split" rings "where one of the narrow limiting bands of thicker walled cells divides into two bands of equal size and general character with a thin band of thin walled cells intervening" (Hutchinson 1926, Barker 1928), and may form two or three rings each year (Hutchinson 1926, Lloyd 1963, Cameron 1960). However, the conditions under which podocarps form more than one ring a year are not yet known. Wells (1972) has shown, however, that ring growth in P. hallii in Central Otago is annual and that a second flush during the growing season does not result in an extra ring.

Methods

Tree cores (5 mm diameter) were obtained with '8" and '16" Swedish increment borers and cross sections were cut with a small chain saw.

An x-ray technique (mentioned in Fritts 1972; Ellis 1971, Parker and Henoch 1971) was first attempted. Cores and cross sections about 5 mm in thickness were x-rayed for 45 seconds at 25 pkV in a Faxitron Model 805 x-ray unit (Field Emission Corporation). The developed Agfa Gevaert D7 Structurix film was then passed through an optical densiometer and a pattern of peaks corresponding to the denser latewood obtained. This technique was abandoned for cross-correlating because of difficulty in defining peaks in the central portions of slabs (where ring widths are 0.1-0.3 mm); the possibility of locally absent rings being missed where growth rings wavered from the vertical (so that x-rays passed through the latewood obliquely); and the necessity to change instrumental settings (amperage, sensitivity, and speed) during the course of each optical densiometer traverse.

Visual examination of slabs and cores under the microscope was found to be simpler, more direct, and reliable. Cores were mounted, and cores

and cross sections sanded with progressively finer grades of sand paper until cell detail was clear under a binocular microscope. Counting of rings was from the centre outwards using methods described in Glock (1937) and Stokes and Smiley (1968) and ring widths were measured to ± 0.01 mm with an eyepiece micrometer. Ring widths (mm) were plotted against ring number, for specimens from the mudflow and for younger cores without bark attached, and plotted against calendar year for specimens with bark attached. Skeleton plots (Stokes and Smiley 1968) and tracing paper overlays with lines connecting upper ends of ring width lines were used to correlate ring patterns. To aid correlation, ring indices (Stokes and Smiley 1968) were calculated: a trend line for tree growth was calculated from 10-year running means and indices determined by calculating the width of each ring as a percentage of the growth trend in that year.

Cross-dating on Northern Tongariro

Cores examined were from four tree species growing at 830-1,000 m within subalpine scrub on northern Tongariro. Kanuka (Leptospermum ericoides), abundant in the area, had indistinct rings, and broadleaf (Griselinia littoralis) and mountain fivefinger (Neopanax colensoi), not very abundant, had distinct rings. Phyllocladus alpinus (Wardle 1969), or mountain toatoa, is both abundant in the area, and has very distinct growth rings (Patel 1968) which are annual (Wardle 1963a, Lawrence and Lawrence 1965, Wells 1972). This species was therefore used to attempt cross-dating.

Two living Phyllocladus alpinus trees (X1, X2) from a site at 990 m altitude alongside Mangatipua Stream (site X in Fig 70) were felled and three cross-sections cut from each. Ring widths were measured along two radii in each section. Circuit (Fig 71) and vertical (Fig 72) uniformity were shown to be good. P. alpinus was therefore considered a reliable

Fig 70: Tongariro Massif, northern slopes, with aa flows from Te Mari Craters (solid lines) and a mudflow from Ketetahi Springs (dashed lines) outlined. X and Y mark sites of trees cored for correlation and tree-ring dating of the Mangatipua Mudflow. (Photo by courtesy of Lands and Survey).

Fig 71: Circuit uniformity: ring width patterns along two radii at the same height in a Phyllocladus alpinus tree (tree X2 from site X), showing similarity of pattern which does not differ greatly from radius to radius.

Fig 72: Vertical uniformity: ring width patterns at three different heights (X1(iii), basal section; X1(ii), mid section; X1(i), uppermost section) within a *Phyllocladus alpinus* tree (X1) showing similarity at different heights.

Fig 73: Cross-correlation of ring width patterns (solid lines) for two living *Phyllocladus alpinus* trees (Y3, Y4) at site Y and correlation of these with the ring width pattern (dashed) for a log of *Phyllocladus alpinus* (log Xb) from the Mangatipua Mudflow. The date of 1894 A.D. for the outermost ring of the log places the death of the tree between the 1894 and 1895 growing seasons.

Fig 74: Ring index patterns for three logs (Xa, Xb, Xc) from the Mangatipua Mudflow showing correlation with two patterns ((ii) and (iii)) from Phyllocladus alpinus tree X1. The outermost ring, 1894 A.D., for logs Xa (Phyllocladus alpinus) and Xc (Podocarpus hallii or P. totara) puts the time of death of these two trees between the 1894 and 1895 growing seasons. Fig 74 also shows a possible correlation of log Xb (Phyllocladus alpinus) which would put the death of tree Xb between the 1899 and 1900 A.D. growing seasons (c.f. Fig 73 where death of tree Xb would have been between the 1894 and 1895 growing seasons).

species in this area. Four further trees (X3-X6) at this site were cored.

At a lower site, 830 m altitude (site Y in Fig 70), one core was taken from each of six living P. alpinus trees (Y1-Y6). Ring patterns for these trees correlate well with those obtained at site X and site uniformity for this species was therefore established for northern Tongariro.

At site X five dead trees were examined. Growth rings for two of the species were indistinct (one probably Leptospermum ericoides or L. scoparium; identifications for the logs supplied by Dr R. N. Patel, FRI, Rotorua) and they were not used. Of the remaining three (labelled Xa, Xb, Xc), two were Phyllocladus alpinus (Xa, Xb) and one was Podocarpus hallii or P. totara (Xc). All three cross-correlate with P. alpinus trees already examined (Figs 73, 74) and the time of death for each established as being after the (Xa) 1894, (Xb) 1894 or 1899, and (Xc) 1894, growing seasons.

Discussion

Phyllocladus alpinus trees on northern Tongariro possess circuit, vertical and site uniformity, and living trees have been cross-dated with logs of the same species and of Podocarpus hallii (P. totara?) within a mudflow. The cross-dating extends over a period of at least 100 years. These trees must therefore be reflecting changes in one or more factors within the local climate (Douglass 1941). Glock (1955) shows that such relationships can be very complex with many factors involved, for example, temperature; precipitation; depth, porosity, water holding capacity, pH, and structure of the soil; topography; etc., and that ring series are most sensitive where one of these factors begins to have a limiting effect on tree growth.

Scott (1972) has shown for Mount Ruapehu an annual precipitation range of 180-290 cm and a positive correlation (by multiple linear regression analysis) between ring indices of P. alpinus and moisture

Fig 75: Ring index plots for *Phyllocladus alpinus* trees from northern Tongariro (X1(iii), X1(ii), Y3, Y4) and from Ruapehu (average of two cores, Scott 1972) showing general similarity of patterns without coincidence of peak positions.

availability in the previous autumn. These findings are likely to hold for northern Tongariro where the precipitation is probably similar.

Ring index plots for P. alpinus trees on Tongariro are compared with similar plots (Scott 1972) for P. alpinus from Mt Ruapehu in Fig 75. There does not appear to be significant correlation but this may be due to the different methods used. Scott (1972) fitted a negative exponential curve to the series of ring measurements to remove the growth trend in his calculation of ring indices. In the discussion of his paper he suggested that fitting a trend line derived from a 5 to 10 year moving average might remove the shorter growth trends and improve correlation. On northern Tongariro a 10 year running mean was used, as recommended by Scott, and the ring index patterns do not therefore need to agree in detail with those of Scott. (A 5 year running mean was calculated as a check and gave a pattern similar to the ring index pattern calculated from a 10 year running mean).

If the ring width pattern for Phyllocladus alpinus on northern Tongariro holds for areas such as Ruapehu, then the 1861-64 signature in particular (Fig 69) should be readily recognisable and be particularly useful for cross-dating.

Dating of the Mangatipua Mudflow

The Mangatipua Mudflow

Debris from a mudflow considered (W. P. Mead, pers. comm.) to have been erupted from Ketetahi Springs in the 1890s and to have reached Lake Rotocaira can still be recognised on the lower part of the Ketetahi Track (c. N112/147900) where angular to subrounded pebbles, cobbles, and boulders, many hydrothermally altered to a whitish yellow colour, are present within a silt-clay matrix. Higher up the mountain (X in Fig 70) the debris exceeds 1.5 m thickness and the subalpine vegetation has been destroyed. The deposit,

Fig 76: A section through Mangatipua Mudflow, exposed on the western bank of Mangatipua Stream, N112/147887, near site X (Fig 70). The prominent log in the foreground is log Xb (Phyllocladus alpinus).

here formally named the Mangatipua Mudflow, is best represented by sections on either side of Mangatipua Stream at N112/147887 (Fig 76) where it overlies, in downward succession:

weakly iron-stained sandy silt (and/or tephra)	0.25 m
pebbly sandy silt	0.12 m
dark brown silt loam (paleosol) grading into	0.40 m
sandy silt with blocks of andesitic lava near the	
top of a recent aa flow from upper Te Mari Crater	

A pit excavated in the mudflow about 20 m north-east of the stream where the sub-alpine vegetation was not destroyed gives the following sequence:

dark brown loam, humus-rich present day soil	60 mm
angular to subrounded pebbles and cobbles	
within a dull yellow sandy silt matrix	
<u>(Mangatipua Mudflow)</u>	0.15 m
dark brown sandy silt loam (paleosol)	40 mm
brown and grey sand; compact	60 mm
grey, brown-grey, and red medium and coarse sand;	
loose	90 mm
dark brown silt loam (paleosol), resting on	0.40 m
sandy silt containing andesitic blocks at top	
of the upper Te Mari Crater aa flow	

The lava flow overlies Taupo Pumice (Gregg 1960, Fergusson & Rafter 1959) and the deposits in the two sections just described are therefore younger than 1819 years B.P. (Healy 1964).

Historic Eruptions from the Te Mari Craters

The deposits listed beneath the Mangatipua Mudflow and above the paleosol overlying the aa flow are probably tephrae erupted from the Te Mari Craters. These craters were active during August 1869 (Hill 1892,

Gregg 1960) and again in late 1892 (Hill 1894) and in December 1896 (Hill 1897, Lowe 1897, Friedländer 1899). The geological evidence is insufficient to assign the deposits to any one of these periods of activity. The paleosol would suggest the older age but "pseudo-paleosols" could be formed locally by humification of leaves either stripped from trees during eruptions (Druce 1966) or dropped as a result of toxic fumes (Dickson 1965); many sections would need to be examined to exclude such a possibility.

The only obvious differences in ring width patterns for trees from sites X and Y is a reduced width for the 1869-70 ring of those trees closer to Te Mari Craters (site X).

Tephra-fall eruptions cause ring width reductions which last for as little as one year, e.g. kaikawaka (Libocedrus bidwillii), rimu (Dacrydium cupressinum), and kanuka (Leptospermum ericoides) trees which survived the Burrell Lapilli eruption on Mount Egmont (Druce 1966), to a decade or more, as in the case of old Douglas firs (Pseudotsuga taxifolia) which survived a lapilli eruption from Mount St Helens, Washington (Lawrence 1954). In Druce's example the reduction in growth was attributed to crown damage with possible decrease in return of nutrients from litter, and in Lawrence's case to a combination of crown damage, toxic concentration of soluble salts leached from the lapilli, and reduced aeration. Toxic volcanic gases may also give such a reduction.

It is possible that eruptions from Te Mari Craters during August 1869 resulted in reduced growth in Phyllocladus alpinus trees at site X.

Age of the Mangatipua Mudflow

A comparison of ring patterns (Figs 73,74) for the Phyllocladus trees partially buried by the mudflow at site X, with trees at site Y (e.g. Fig 73), unaffected by the mudflow, allows three possible conclusions:

1) The removal of competing vegetation upslope of the light-demanding trees with its consequent increase in light caused no increase in growth rate (Glock 1955, p. 102; Lawrence 1950, Mathews 1951).

2) Although the two Phyllocladus trees which were felled for the cross-dating studies were partially covered by the debris this caused no reaction wood.

3) If the mudflow caused a reduction in growth rate the flow must have been during 1869-70. However, this age is considered too great for the mudflow (W. P. Mead, pers. comm.) and the reduction in growth rate is probably due to activity from the Te Mari Craters.

The youngest (outermost) ring for each of the logs cross-dated from the mudflow should have grown in the last growing season prior to the mudflow. Some inner bark is present on specimen Xa; no bark is present on either of the other two specimens but because the youngest ring preserved is almost unbroken it is probable that no rings have been removed. The date of the youngest earlywood (springwood) in each of the logs is thus: 1894 for specimen Xa and specimen Xc and 1894 or 1899 for specimen Xb. There are therefore two possible ages for the Mangatipua Mudflow. It is most probable that the mudflow occurred between late summer and spring of 1895, with the correct age of the outer earlywood in Xb being 1894 A.D. It is also possible, though less likely, that trees Xa and Xc were killed between late summer and spring of 1895 and brought down in a mudflow between summer and spring of 1900 A.D.

Estimated Age for a Young Lava Flow from Upper Te Mari Crater

An aa flow from upper Te Mari Crater, informally referred to as 'upper Te Mari lava flow' in this account, has flowed down into Okahukura Bush (Fig 70) "within tolerably recent times" (Cockayne 1908). The lava is

younger than Taupo Pumice (1819 years BP, Healy 1964) and wood collected from beneath the lava was radiocarbon dated at less than 200 years BP (Fergusson and Rafter 1959) and was considered (Gregg 1960) to be from the root of a tree younger than the lava flow.

Two days were spent examining the margins of the lava flow and four trees were cored in an effort to determine its age. No burn scars (Druce 1957) were recognised. A Hall's totara (Podocarpus hallii) and a broadleaf (Griselinia littoralis) from the eastern margin of the flow were cored to see if removal of competing vegetation (Glock 1955, p. 102) affected the growth rate: there was either no such effect or, more likely, the cores were not long enough.

A Podocarpus hallii, apparently tilted by a block of the lava flow, had four cores taken from it, and a nearby P. hallii (position estimated to be near N112/150896) distorted by a block of lava had three cores removed. No compression wood was recognised. A wedge was later extracted from each tree with a small chainsaw. Microscopic examination again revealed no compression wood.

The tilted P. hallii was either tilted by the flow or it may have grown towards light from a nursery position close under a block of the flow (if the wedge had gone right to the centre of the tree then tilting by the flow would be recognised by the initiation of compression wood some distance out from the centre). One wedge showing 0.21 m of the tree radius, was about 226 years old (230 rings - 4 false rings) giving an average radial growth rate of c. 11 rings/cm. Because the tree has a radius of 39.8 cm the total number of rings is likely to be about 430. Allowing 14* years for the tree to grow to 0.90 m height - the height of the section above ground - and if the tree was not tilted by the lava flow, then the lava was probably extruded prior to 1542-14 i.e. 1528 A.D. If the tree was tilted by the lava then the age of the lava is slightly more recent than 1528 A.D.

A ^{minimum} maximum age for the lava flow is possible from the oldest tree growing on the lava. The larger Phyllocladus tree felled at site X (see Fig 70), tree X1, had an age, near the base of the trunk, of 1802 A.D. However, this tree was growing on a 0.40 m thick paleosol so that the lava flow is therefore considerably older than 1802 A.D.

The age of the oldest log from the mudflow provides a minimum age for the lava. The innermost growth ring for log Xb (Fig 74) was dated at 1764 A.D. This section was not at the base of the tree which therefore began growing an unknown number of years prior to 1764 A.D.

It is extremely unlikely that a tree seedling could successfully establish within a year of the lava extrusion. Ecesis periods (time for vegetation to colonise a barren surface) for glacial moraines vary from about 20 to 43 years (Bray and Struik 1963, Mathews 1951). Ecesis periods for aa lava flows could be considerably greater (Eggler 1966) but will depend on the amount of tephra that is deposited between the blocks or in hollows on the upper surface of the lava.

The upper Te Mari lava flow was therefore extruded many years before 1764 A.D. and probably closer to 1528 A.D.

- * Four young totaras about 1 m high growing in bush margins near Taurewa, west of the Tongariro Massif, were uprooted to determine the approximate age for a totara (Podocarpus hallii) at 0.90 m height. The number of growth rings at the base and at 0.90 m height in each tree were counted and the average difference found to be about 14 years:

Tree No.	No. of Rings at Base	No. of Rings at 0.90 m	Age of Tree at 0.90 m
1	17	3	14
2	15	3	12
3	17	5	12
4	25	9	16

J. PALEOMAGNETIC STUDIES IN TONGARIRO VOLCANIC CENTRE

Introduction

The development of a geomagnetic polarity scale for the last 5 m.y. (Cox 1969) has supplemented the use of K/Ar dating in determining chronology, with results from one method used to confirm results from the other. In New Zealand the change from the Matuyama reversed epoch (Fig. 77) to the normal polarity of the Brunhes normal epoch at 0.69 m.y. ago has been shown to be useful to separate ignimbrites in central North Island (Cox 1971) and this boundary also should be a valuable time plane within the andesitic lavas of the Tongariro Volcanic Centre.

Within the Brunhes normal epoch at least three short term reverse polarity events, or geomagnetic excursions (Watkins 1972), have so far been recognised (Fig. 77). The Laschamp event (Bonhommet and Babkine 1967, Bonhommet and Zähringer 1969) is older than $8,730 \pm 300$ years BP (Brousse, Delibrias, Labeyrie and Rudel 1966), and probably less than 22,000 years BP (Bonhommet and Zähringer 1969). This event probably correlates with the Gothenburg event, a reversal in varved marine clay and silt from Gothenburg, Sweden which has an upper boundary at 12,400 years BP (Mörner, Lanser and Hospers 1971) and with a lower boundary at probably less than 13,300 years BP (Denham and Cox 1971).

An unnamed second reverse event (geomagnetic excursion) at about 31,000 years BP has been recognised by Barbetti and McElhinny (1972) from archeomagnetic investigations of aboriginal fireplaces in Australia. One oven with reverse polarity was radiocarbon dated at $30,780 \pm 520$ years BP. Four other radiocarbon dates, two of which were from normally polarised ovens, suggest that the geomagnetic excursion has an estimated duration of less than 4,000 years.

The third reverse event, the Blake event, was suggested by Smith and Foster (1969) at between 0.108 and 0.114 m.y. using data from deep sea cores and it has also been recognised in further deep sea cores by Wollin et al (1971).

Current Chronology in Taupo Volcanic Zone

Within the Tongariro Volcanic Centre most chronology for andesitic and rhyolitic tephra is from radiocarbon ages (Topping 1973, Topping and Kohn 1973). One of the most useful of the rhyolitic tephra in the Tongariro area is the Oruanui Formation which was erupted from the Maroa Volcanic Centre about 20,000 yr BP (Vucetich and Pullar 1969). Lavas younger than Oruanui Formation can be dated from the overlying tephra but older lavas are difficult to date because there are no distinctive dated tephra older than 20,000 yr BP in the area and erosion has in many places removed older tephra. Stipp (1968) has K/Ar dated nine lavas from Kakaramea, Tihia, Pihanga, Tongariro, and Ruapehu with ages between 0.03 and 0.26 m.y. (Table 1). Also, the Whakamaru Ignimbrite (Hatherton 1954) and the Te Whaiti Ignimbrite (Grindley 1960) have recently been fission track dated at 0.32 m.y. and 0.30 m.y. respectively (B. P. Kohn, pers. comm.). Ages for some lavas can thus be estimated from their relationship with one of these andesitic lavas or ignimbrites or from the degree of dissection of the volcanic cone (Kear 1957, Mathews 1967).

When fieldwork was carried out, the Laschamp reverse polarity event was regarded as being between 10,000 and 30,000 yr BP. Accordingly, several lavas (from young cones) which had the Oruanui Formation as the oldest, or one of the oldest, tephra mantling them were cored to see if they had reverse polarity and therefore had an age of between 20,000 and 30,000 yr BP. Although the age of the Laschamp event is still not

Fig 77: The geomagnetic time-scale for the last 1 m.y. The Laschamp event is not accurately dated and is probably the same as the Gothenburg event at c. 12,400-13,300 years BP.

definitely known it is probable that it may correlate with the Gothenburg event at c. 12,400 to 13,300 years BP (Mörner et al 1971, Denham and Cox 1971). A reversed polarity for any of the flows older than 20,000 yr BP would therefore not correlate with the Laschamp event. It could however indicate extrusion during the geomagnetic excursion (unnamed) at about 31,000 yr BP (Barbetti and McElhinny 1972), an event unknown to the writer at the time of sampling.

Sample Locations

(a) Beggs Pool, 11939

Four orientated cores were taken from an andesitic lava flow which outcrops in the Tongariro River at Beggs Pool (N112/305838; Fig 78). The lava has been mapped as part of the Tongariro Andesites Formation by Grindley (1960) who considers it to be one of the oldest lavas exposed within the Tongariro Volcanic Centre and to be of Nukumaruan age (c. 1.8-1.1 m.y., fission track ages, D. Seward, pers. comm.). Although the andesitic lava is in close proximity to the Te Whaiti Ignimbrite (c. 0.3 m.y., B.P. Kohn, pers. comm.), the stratigraphic relationship between the two cannot yet be established (B. R. Paterson, pers. comm.). However, the presence of andesitic tephra beneath the Te Whaiti Ignimbrite in the Poutu Tunnel, Tongariro Power Scheme, is evidence that the Tongariro Volcanic Centre was active earlier than 0.26 m.y. ago, the oldest K/Ar date so far obtained in the area (Table 1).

(b) Wanganui River, 11940

Four cores were drilled at Wanganui River (N112/096987; Fig 78) where the river has cut through an andesitic lava flow from Maungakatote

Fig 78: Localities within Tongariro Volcanic Centre sampled during this paleomagnetic study.

cone. Grindley (1960) has mapped lavas from this cone as part of the Pihanga Andesite Formation of mid-Pleistocene age. The lava flow sampled overlies Whakamaru Ignimbrite (drill hole data, N. Briggs pers. comm.) which was erupted c. 0.32 m.y. ago (B. P. Kohn, pers. comm.).

(c) Mahuia Rapids, 11941

Olivine andesite lava at Mahuia Rapids (N112/007819, Fig 78) in the Wairere Stream has been mapped as Pukekaikioire Andesite Formation by Grindley (1960) who considered the lavas to have been erupted from Pukekaikioire dome during the penultimate glaciation. However, the writer considers these lavas to have been erupted from a north-south fissure, defined by Pukeonake Cone and two more northerly outcrops (plugs?) of olivine andesite (see pages 106-7), Oruanui Formation, at c. 20,000 yr BP, is the oldest tephra exposed within the crater of Pukeonake Cone and occurs above olivine andesite lavas in many sections along Pukeonake Stream. Four cores were taken to see whether the flow at Mahuia Rapids was extruded during a reverse polarity event.

(d) Okupata, 11942

Vesicular olivine andesite lava outcropping 3.8 km south of Taurewa on the National Park-Taupo Road (N112/037866, Fig 78) is mapped as Tongariro Andesite Formation by Grindley (1960) but is considered by the writer to have been extruded from the same fissure as the flow at Mahuia Rapids. Oruanui Formation overlies the lava and four cores were obtained to see whether the flow had been extruded during a reverse polarity event.

(e) Te Rato, 11943

Block lava outcropping on the National Park-Taupo Road (N112/132922, Fig 78) 1.6 km south-east of Te Rato School is a part of Grindley's (1960)

North Crater Andesite Formation of Last Glaciation age. Oruanui Formation overlies the lava in the eastern part of the northern side of the cutting. One core was taken from each of three blocks within the flow to check whether the lava was extruded during a reverse polarity event.

(f) Papanetu Stream, 11944

A section on the western side of Te Ponanga Saddle Road (N102/238004, Fig 78) 100 m north of Papanetu Stream has exposed purplish volcanic breccia on the eastern slopes of Tihia. Oruanui Ash directly overlies the breccia. Three cores were taken from the matrix and one core from each of two clasts within the breccia. An alignment of NRM directions for clasts and matrix would show that temperatures were above the Curie temperature for the breccia after it came to rest and, if hot, the sample polarities would show whether the breccia formed during a reverse polarity event.

(g) Bruce Road, 11945

Conical lahar mounds (Murimotu Lahars Formation of Grindley, 1960) are conspicuous on the lower northern slopes of Mt Ruapehu near the junction of National Park-Taupe Road and Bruce Road. A mudflow origin was first suggested by Grange and Hurst (1929) and Grange (1931), and Healy (1965) has described deposits of at least four flows (one possibly a nuée ardente) within one of the mounds. Okupata Tephra occurs in cuttings 3 km further north and from isopach data it is obvious that it was deposited over the area now covered by the mounds. As it does not mantle the mounds the lahar must be younger than $12,450 \pm 340$ years BP (NZ1189, Table 2, Topping 1973). Wood from one of the lahar units exposed in a road cutting 3 km further north (N112/010820) has been radiocarbon dated at $9,540 \pm 100$ years BP (NZ1338, Table 2, Topping 1973). The relationship to the lahar mounds is not established. However, this

dated lahar unit and another unit 5 km to the south-west both contain wood and it is likely that these two lahars destroyed sectors of vegetation to either side of the central mound field which, being earlier, deflected them outwards. The lahar mounds probably therefore have an age between 12,450 and 9,540 years BP.

Two of the mounds on Bruce Road have strong red and purple colours suggesting a high temperature origin and three cores were taken from each of four boulders and one core from each of a further 12 small boulders to determine whether the clasts within one of the mounds (at N112/007787, Fig 78) came to rest above their Curie points.

(h) Tokaamu Intake, 11946

Nuee ardente deposits from a peak WSW of Tihia are exposed in road cuttings on Te Ponanga Saddle Road (N112/202974, Fig 78) 500 m north of the Tokaamu Tunnel Intake on the northern shore of Lake Rotoaira. The deposits contain charcoal and the remains of an upright tree trunk 0.75 m high which was carbonised by the nuees ardentes. Charcoal from this tree has been radiocarbon dated at >40,300 years BP (NZ1581). One core was taken from each of five black vesiculated andesite clasts within the nuee ardente deposits to determine whether the temperature of the clasts was above the Curie point when they came to rest.

Methods

Cores of 25 mm diameter were obtained with a portable, water-cooled diamond drill. Cores at each site were collected from within a radius of about 3 metres. Blocks within the block flow and clasts within the nuee ardente and laharc deposits were firmly enough embedded within their matrices for coring to be carried out in the field. Cores were orientated with a Brunton compass.

A selection of the cores were measured on a 5 cycles/sec spinner magnetometer slightly modified from the design of Foster (1966) and incorporating two fluxgate detectors. Six cores were thermally cleaned at 150°C using VUW Physics Department thermal demagnetising equipment at Moores Valley, Wainuiomata. The intensity of NRM for all samples (Table 14) is thought sufficiently high and NRM directions close enough (Figs 79, 80) to make thermal cleaning unnecessary.

Results

Paleomagnetic data on untreated cores measured in the spinner magnetometer and for the six cores thermally cleaned at 150°C are presented in Tables 14, 15. The NRM directions for lava flows and clasts are presented in Figs 79, 80.

Lava from Wanganui River (11940, Fig 79), Mahuia Rapids (11941, Fig 79), Okupata (11942, Fig 79), and Te Rato (11943, Fig 80), and an outcrop of volcanic breccia (11944, Fig 80), all known to be older than 20,000 years BP, have normal polarity and therefore were not extruded during either the Laschamp reverse polarity event (Bonhommet and Babkine 1967, Bonhommet and Zähringer 1969) or during the geomagnetic excursion at about 31,000 years BP (Barbetti and McElhinny 1972) but during the Brunhes normal epoch.

The lava at Beggs Pool (11939, Fig 79), of the Tongariro Andesites Formation (Grindley 1960), has reversed polarity. The stratigraphic relationship suggests that the Tongariro Andesites Formation is older than the Te Whaiti Ignimbrite (c. 0.3 m.y.; see p. 211) and therefore is most likely to have been erupted during the Matuyama reverse epoch.

This conclusion is consistent with Malahoff (1969) who, while commenting on magnetic patterns for New Zealand volcanoes, stated:

(a) Beggs Pool, 11939.

(b) Wangamui River, 11940.

(c) Mahuia Rapids, 11941.

(d) Okupata, 11942.

Fig 79: NRM directions of andesite lavas within the Tongariro Volcanic Centre (sites located in Fig 78). Equal areas plot. Dots = normal, negative, up; circles = reverse, positive, down.

(e) Block lava, Te Rato, 11943.

(f) Volcanic breccia, Papanetu Stream, 11944.

(g) Laharic breccia, Bruce Road, 11945

(h) Nuée ardente deposit, Tokaanu Intake, 11946.

Fig 80: NRM directions for: (e) block lava at Te Rato; (f) volcanic breccia at Papanetu Stream (the two matrix cores are almost superimposed); (g) clasts within a lahar mound on Bruce Road; and (h) clasts within a nuée ardente deposit at Tokaanu Intake (sites located in Fig 78). Equal areas plot.
Dots = normal, negative, up; circles = reverse, positive, down.

Table 15: Paleomagnetic results for Quaternary andesitic eruptives and laharic breccia.
Data for individual samples are listed in Appendix 5.

Locality	Temp.	N(n)	Mean Dec.	Mean Inc.	K	α_{95}	R
<u>Beggs Pool N112/305838;</u> lava of Tongariro Andesites Formation, Tongariro River	NRM	2	215.5	56.1	150.6	12.7	1.993
<u>Wangamui River N112/096987;</u> lava from Maungakatote cone	NRM 150°C	4 2	19.2 16.2	-63.1 -61.5	420.1 213.4	3.4 10.6	3.992 1.995
<u>Mahuia Rapids N112/007819;</u> olivine andesite lava	NRM	3	10.3	-52.2	>1000	2.6	2.998
<u>Okupata N112/037866;</u> vesicular olivine andesite	NRM	4	12.6	-59.2	127.0	6.2	3.976
<u>Te Rato N112/132922;</u> block lava of North Grater Andesite Formation	NRM 150°C	3(4) 1(2)	352.8 331.8	-57.6 -69.2	38.4 204.8	11.4 10.8	3.921 1.995
<u>Bruce Road N112/007787;</u> lahar mound of the Murimotu Lahars Formation	NRM 150°C NRM NRM NRM NRM NRM	1(3) 1(2) 1(3) 1(3) 1(3) 6 7	181.8 181.2 196.5 164.2 190.8 200.8 205.3	-7.9 -6.1 -7.1 -16.2 -53.5 19.0 41.2	272.8 105.0 910.8 290.8 892.4 1.7 8.3	5.1 15.2 2.8 4.9 2.8 70.2 21.6	2.992 1.990 2.997 2.993 2.997 3.021 6.275
<u>Tokaanu Intake N112/202974;</u> nuée ardente deposit from peak WSW of Tihia	NRM	5	351.0	-65.2	175.8	4.8	4.977

N Number of samples or clasts

n Number of specimens

Dec Declination in degrees east

Inc Inclination (negative, up, normal; positive, down, reversed)

K Fisher precision parameter

α_{95} Semi-angle of cone of 95% confidence about mean direction

R Vector sum of unit vectors parallel to directions of magnetisation

"....The total force anomaly over ... Ruapehu ... cannot be interpreted by the magnetisation of the cone itself (Malahoff 1968); one must assume either a lesser magnetised mass within the cone (such as a volcanic plug with temperatures above the Curie point), or blocks reversely magnetised and within the cone, or both conditions simultaneously."

An age of c. 0.22 m.y. for a lava below the break in slope of northern Ruapehu led Stipp (1968) to conclude that "by about 0.22 m.y. ago a huge massif had been constructed." If Malahoff's (1969) anomalous magnetic pattern is not due entirely to rocks presently above the Curie point then some of the oldest flows may have been erupted during the Matuyama reverse epoch.

NRM and Temperature of Emplacement

Aramaki and Akimoto (1957) have shown that fragments in pyroclastic flow (*nuée ardente*) deposits have uniform orientation of their NRM (natural remnant magnetism) if the temperature of emplacement of the deposit was higher than the Curie point of the constituent ferromagnetic minerals. In mudflows the temperature of deposition was lower than the Curie point and the fragments show a random orientation of NRM. Chadwick (1971) has similarly differentiated volcanic breccias emplaced at relatively high temperatures from breccias formed at lower temperatures and Mullineux and Crandell (1962) have shown that a recent lahar from Mount St Helens, Washington was near the Curie point when the debris came to rest.

For a volcanic breccia (Papanetu Stream, 11944) from Mt Tihia in the Tongariro Volcanic Centre matrix cores and one of the two lithic clasts cored have normal polarity and plot together (Fig 80). The matrix was above the Curie point when the breccia came to rest. One of the lithic clasts may have been above the Curie point but the other lithic

clast, with reverse polarity and a random distribution, was cold. The breccia formed during the Brunhes normal epoch, not during a reverse event.

Of the 16 clasts cored from within a lahar mound at Bruce Road (11945, Fig 80) five have normal polarity and 11 are reversed. Although there is a reasonable scatter all plot within a sector from $N120$ to $N270^{\circ}$. None plot in the position of the present field. Such a distribution probably means that the lahar came to rest above the Curie point and probably near the end or the beginning of a reverse magnetic event (Barbetti and McElhinny 1972). The age limits for the formation of the mound, 9,540-12,450 years BP allow that the lahar descended the north-western slopes of Mt Ruapehu near the end of the Gothenburg event. The four normal clasts which plot closely may belong to a subsequent lahar, also above the Curie point, which descended soon after the earlier reversed lahar.

More clasts - including some from the younger nuée ardente deposit exposed in one of the mounds and many clasts from a further mound - would need to be cored to confirm this interpretation and the position of the normally magnetised clasts within the mound noted to see whether they are closer to the outside and therefore from a hot lahar subsequent to the Gothenburg event.

Clasts from nuée ardente deposits (Tokaamu Intake, 11946) erupted more than 40,300 years BP (NZ1581) from a peak WSW of Tihia plot closely (Fig 80) showing that the clasts were above their Curie points when they came to rest. Data from Aramaki and Akimoto (1957) suggest that this temperature may have been above $400-550^{\circ}\text{C}$. The structure of the charcoal from the deposits indicate a minimum temperature of 400°C and a maximum of 600°C (W. J. Cousins, PEL, pers. comm.).

NRM directions for cores from the massive andesitic flows (Fig 79) plot closely whereas the scatter is greater for the block

breccia (Fig 80). For the individual blocks of the block breccia the exterior portions are likely to be at or below the Curie point when the flow came to rest and the central portions of the blocks are likely to be above the Curie point. The core samples, because they include part of the exterior of the blocks, will include a portion with part of its NRM acquired before the flow finally comes to rest. The NRM directions for individual clasts are therefore likely to be slightly more scattered than for massive flows. In the block breccia there is also the possibility of post-depositional change in block positions. This post-depositional change is likely to be even greater for a hot lahar where clasts will rotate slightly as water drains from the matrix.

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APPENDIX 1A Reference Sections

Mangatawai	(No. 115)
Access 10	(22)
Poutu	(17)
Te Rato	(57(a))
Okupata	(99)
Wairoa	(45)
Te Ponanga Saddle	(87(a))

B Additional Tephra Sections

Wairehu Canal, southern side	(310, 310(a))
" " northern side	(311)
Otamangakau Canal	(60)
" " western embankment	(62)
Poutu Damsite	(220)
Tongariro River Bridge	(171)
Turangi Lookout	(94)
Pukeonake Scoria Cone	(164)
Upper Bruce Road	(269) ← p. 295, this volume.
Oturerere Valley	(495)
" "	(496)
" "	(477)
" "	(479)
" "	(481)

C Tephra Sections Associated with Moraines

Mangatepopo Valley	(369)
Makahikatoa Valley	(422)
Waihohonu Valley	(494)
Mangahouhounui Valley	(499)
" "	(498)

D Tephra Sections Used to Date Lavas, Craters, Domes

Pukekaikioere aa flow	(368)
Ohakune explosion craters	(455)
" " "	(456)
Rangatau Lakes	(505)
Kuharua Dome	(320)
Pukekaikioere Dome	(324)
Herohoro Dome	(276)
Motuopuhi Island	(319)

The soil colour notation is that of the "Munsell Soil Color Charts", 1954 edition.

Pahoka lapilli is enclosed within brackets in the 'Formation' column as a reminder that it is an informal name and that the lapilli unit has informal status.

The dates of publication for the topographic sheets are given in Appendix 2.

APPENDIX 1AReference Sections

Mangatawai (section no. 115): a cutting along the Desert Road on the southern side of the bridge over Mangatawai Stream; N112/250806.

Altitude: 823 m. Type section for Ngauruhoe Tephra Formation and Mangatawai Tephra Formation.

Formation	Description	Thickness (mm)
Ngauruhoe Tephra	very dark grey (10YR 3/1) medium ash (medium sand) to dark brown (10YR 3/3) ash (fine sandy silt)	440
Taupo Pumice	pale yellow (2.5Y 7/4) coarse to fine rhyolitic ash, lapilli and fine blocks (in pockets)	200
Mangatawai Tephra	290 mm dark brown (10YR 3/3) fine ash (silt loam) grading down to dark grey (10YR 3.5/1) medium ash (fine sand) with interbedded dark grey (5YR 4/1) and very dark grey (5YR 3/1) medium ash (fine sand) containing yellow (10YR 7/8) beech leaves	790
Whakaipo Tephra	dark yellowish-brown (10YR 4/4) fine and medium andesitic and rhyolitic (?) ash (silt loam) with pale yellow (2.5Y 7/4) medium rhyolitic ash (medium sand) grading to yellowish brown (10YR 5/6) coarse rhyolitic ash (<u>Waimihia Lapilli</u>)	240
Papakai Tephra	yellowish brown (10YR 5/6) fine ash (silty clay loam) with interspersed grey and strong brown (7.5YR 5/6) fine to medium lapilli; buried soil	240

Formation	Description	Thickness (mm)
Mangamate Tephra	strong brown (7.5YR 5/6), and grey lithic, fine and medium lapilli (<u>Poutu Lapilli</u>)	540
	40 mm grey to dark olive grey (5Y 3/2) medium ash; 30 mm dark olive grey (5Y 3/2) and olive brown (2.5Y 4/4) medium ash with a few interspersed fine and medium lapilli (<u>Wharepu Tephra</u>)	70
Poronui Tephra	yellow (10YR 7/6) fine rhyolitic ash	trace
Mangamate Tephra	50 mm dark olive grey (5Y 3/2) and olive brown (2.5Y 4/4) medium ash; 40 mm very dark grey (7.5YR 3/1) medium ash; 60 mm very dark grey (7.5YR 3/1) and brownish-yellow (10YR 6/8) medium ash (medium sand); 40 mm very dark grey (7.5YR 3/1) medium ash (<u>Ohinepango Tephra</u>)	190
	10 mm grey ash; 70 mm strong brown (7.5YR 5/6) and dark to very dark grey (5Y 3.5/1) fine to coarse lithic lapilli; 280 mm dark grey and strong brown (7.5YR 5/6) fine and a few medium lithic lapilli (<u>Waihohonu Lapilli</u>)	360
	20 mm dark greyish brown (2.5Y 4/2) medium ash with interspersed yellow (2.5Y 7/6) coarse ash; 10 mm brownish yellow (10YR 6/6) coarse ash fine lapilli; 20 mm dark yellowish brown (10YR 4.5/4) ash (sandy silt)	50

Formation	Description	Thickness (mm)
	strong brown (7.5YR 5/6), yellowish brown (10YR 5/4) and dark greyish brown (2.5Y 4/2) fine medium and coarse lapilli (<u>Oturere Lapilli</u>)	420
	olive grey (5Y 4/2) andesitic and olive (5Y 4/3) dacitic fine lapilli (<u>Te Rato Lapilli</u>)	40
Papenetu Tephra and/ or Karapiti Lapilli	light yellowish brown (2.5Y 6/4) fine rhyolitic ash	trace
	brownish yellow (10YR 6/6) ash, coarse ash, fine lapilli	60-140
(Pahoka Lapilli)	yellowish brown (10YR 5/8) dacitic and grey (10YR 5/1) andesitic fine, medium and coarse lapilli; 10 mm grey fine ash base	320
	yellow (10YR 7/8) coarse ash, fine lapilli within ash	90
	pale yellow (2.5Y 7/4) and grey coarse ash 50 mm brownish yellow (10YR 6/8) coarse ash, fine lapilli in minor brownish yellow to dark greyish brown (10YR 4/2) ash; 60 mm brownish yellow (10YR 6/8) fine lapilli	90 110
	greyish brown (10YR 4.5/2.5) ash, strong brown (7.5YR 5/6) fine and medium lapilli	120
	strong brown (7.5YR 5/6) fine, medium and a few coarse lapilli	110

Formation	Description	Thickness (mm)
	yellowish brown (10YR 5/4) ash grading down into a grey medium ash; interspersed brownish yellow (10YR 6/6) fine and medium lapilli	120
	brownish yellow (10YR 6/6) fine and medium lapilli	50
	grey (10YR 5.5/1) ash	10
	slightly greyish yellow brown (10YR 5/4) medium ash with a few interspersed brownish yellow (10YR 6/6) medium and coarse lapilli	90
	strong brown (7.5YR 5/6) fine lapilli (grey (10YR 5.5/1) base)	30
	dark yellowish brown (10YR 4/6) ash, brownish yellow (10YR 6/6) fine lapilli	90
	strong brown (7.5YR 4/6) to yellowish red (5YR 4/6) fine, medium and coarse lapilli	150
	brownish yellow (10YR 6/8) fine lapilli, coarse ash; gradational lower boundary	120
	dark grey to dark greyish brown (10YR 4/1.5) and yellowish brown (10YR 5/4) fine lapilli	90
	very dark grey (2.5Y 3/1) fine and medium lapilli and strong brown (7.5YR 5/6) iron- stained lithic lapilli	140
	yellowish brown (10YR 5/6) ash with a few interspersed yellowish red (7.5YR 6/6) fine lapilli	60
Rotorua Ash	pale yellow (2.5Y 7/4) fine rhyolitic ash, in yellowish brown (10YR 5/6) andesitic ash	0-40

Formation	Description	Thickness (mm)
	slightly grey yellowish brown (10YR 5/4) ash with interspersed reddish yellow (7.5YR 6/8) fine lapilli (almost a discrete lapilli layer in centre)	110
	reddish yellow (7.5YR 6/6) coarse ash, fine lapilli	50
	30 mm dark greyish brown (10YR 4/2) ash grading into yellowish brown ash with interspersed reddish yellow (7.5YR 6/8) coarse ash and fine lapilli which are less abundant towards the base	90
	yellowish brown (10YR 5/4) medium ash (medium sand)	100
	dark greyish brown (2.5Y 4/2) and brownish yellow (10YR 6/8) medium ash; moderately sharp lower contact	60
	brownish yellow (10YR 6/6) and dark greyish brown (2.5Y 4/2) coarse ash, fine lapilli; bottom 60 mm is slightly finer and contains a few fine and medium lapilli	120
Puketarata Ash	white fine rhyolitic ash occurs in a pocket 190 mm thick and as a lens 1.46 m long where the tephras have been slightly re- worked by water (the units above and below Puketarata Ash can be correlated to non- water laid parts of the sequence)	0-190
	yellowish brown (10YR 5/4) ash with inter- spersed strong brown (7.5YR 5/6) fine and medium lapilli	40

Formation	Description	Thickness (mm)
	40 mm strong brown (7.5YR 5/6) medium and coarse ash; 100 mm strong brown (7.5YR 5/6) and dark grey coarse ash, fine lapilli	140
	yellowish brown (10YR 5/4) ash with strong brown (7.5YR 5/8) fine lapilli	40
	strong brown (7.5YR 5/8) coarse ash, fine and medium lapilli	70
	30 mm yellowish brown (10YR 5/4) medium and coarse ash grading into 30 mm dark grey, then strong brown (7.5YR 5/6), coarse ash	60
	yellowish brown (10YR 5/4) ash with scattered strong brown coarse ash in upper 30 mm; ash coarsens downwards into yellow (10YR 7/8) and dark greyish brown (2.5Y 4/2) medium ash (medium sand)	150
	strong brown (7.5YR 5/8) coarse ash, fine lapilli and dark greyish brown (2.5Y 4/2) coarse ash	40
	strong brown (7.5YR 5/8) medium and coarse lapilli, grey fine and medium lithic lapilli in ash matrix, grading into (by absence of lapilli)	30
	yellowish brown (10YR 5/4) medium ash (fine sand) grading into	140
	strong brown (7.5YR 5/8) and dark greyish brown (2.5Y 4/2) fine lapilli; a few medium lapilli which are more common over lower half	110
	strong brown (7.5YR 5/6) fine ash grading to medium ash	130
	greyish brown (2.5Y 5/2) ash, strong brown (7.5YR 5/6) medium and coarse lapilli	190

Formation	Description	Thickness (mm)
?Rotoaira Lapilli	50 mm dark grey (10YR 4/1) ash; 140 mm brownish yellow (10YR 6/8) fine, medium and coarse lapilli, grey fine lithics; 50 mm dark grey and light grey (2.5Y 7/2) medium and coarse ash (medium and coarse sand)	240
	greyish brown (10YR 5/2) ash, strong brown fine, medium and coarse lapilli, grey medium and coarse lithics, with a few sub-angular to sub-rounded cobbles up to 200 mm across (alluvium?)	460
	reddish yellow (7.5YR 6/6) coarse ash, fine, medium and coarse pumiceous lapilli	160
	greyish brown (10YR 5/2) ash (medium and coarse sand)	40
	brownish yellow (10YR 6/8) fine, medium and coarse pumiceous lapilli; dark grey medium and coarse lithics within lowermost 200 mm; lower 70 mm comprises dark grey and yellow (10YR 8/6) fine lapilli	430
	grey sands and greyish brown silty matrix with subangular to subrounded boulders, cobbles and pebbles; a few yellowish red lapilli scattered within lowermost 300 mm (alluvium)	910 ⁺

Access 10 (section no. 22): a large cutting on the crest of a hill 2.5 km from the Waiouru-Turangi Road (Desert Road) on Hydro Access Road No. 10; N412/301844. Altitude: 648 m. Type section for Mangamate Tephra Formation.

Formation	Description	Thickness (mm)
Ngauruhoe Tephra	black (5YR 2/1) fine ash	50 ⁺
Taupo Pumice	pale yellow (2.5Y 7/4) rhyolitic ash, lapilli and blocks	600
Mangatawai Tephra	dark yellowish brown to black (5YR 2/1) ash	430
Whakaipo Tephra, and Waimihia	dark yellowish brown (10YR 4/4) fine ash with interspersed pale yellow (2.5Y 7/4) medium and coarse rhyolitic ash (<u>Waimihia Lapilli</u>)	580
Papakai Tephra	dark brown (7.5YR 4/2) fine ash; paleosol (erosion break)	400
Mangamate Tephra	yellowish red (5YR 4/8) stained lapilli (<u>Poutu Lapilli</u>)	360
	10 mm grey ash; 30 mm yellowish brown ash (<u>Wharepu Tephra</u>)	40
Poronui Tephra	yellow (10YR 7/6) fine rhyolitic ash	10
Mangamate Tephra	30 mm strong brown (7.5YR 5/8) medium ash (medium sand); 40 mm grey-black medium ash; 40 mm strong brown and black medium ash; 30 mm grey-black medium ash (<u>Ohinepango Tephra</u>)	140
	yellowish red (5YR 4/8) and grey fine lapilli (<u>Waihohonu Lapilli</u>)	70
	dark yellowish brown (10YR 4/4) coarse ash	30-40

Formation	Description	Thickness (mm)
	100 mm yellowish red (5YR 4/6) coarse lapilli; 20 mm coarse ash; 30 mm yellowish red coarse lapilli; 20 mm yellowish red coarse ash; 30 mm yellowish red coarse lapilli (<u>Oturere Lapilli</u>)	200
	grey (5Y 4.5/1) coarse ash (<u>Te Rato Lapilli</u>)	10
	yellowish brown (10YR 5/6) ash	50
Papanetu Tephra and/or Karapiti Lapilli	light yellowish brown (2.5Y 6/4) rhyolitic ash	0-20
	yellowish brown (10YR 5/6) ash	60
(Pahoka Lapilli)	greyish brown (10YR 5/2) lapilli with 10 mm grey ash at base	250
	yellow (10YR 7/8) coarse ash in a dark yellowish brown (10YR 4/4) ash matrix	80
	brownish yellow (10YR 6/8) and grey coarse pumiceous ash	30
	dark yellowish brown (10YR 4/4) ash coarsening to yellowish red (5YR 4/8) coarse ash, fine lapilli	30 50
	dark yellowish brown (10YR 4/6) ash (silt loam) with fine scattered lapilli; a few coarse lapilli towards top	60
	strong brown (7.5YR 5/8) coarse ash, fine to medium lapilli	90
	dark yellowish brown (10YR 4/6) fine and coarse ash (loamy coarse sand) with interspersed brownish yellow (10YR 6/8) fine lapilli	70

Formation	Description	Thickness (mm)
	dark yellowish brown (10YR 4/6) ash with fine to medium brownish yellow (10YR 6/8) lapilli	20
	dark yellowish brown (10YR 4/6) to yellowish brown (10YR 5/5) fine and coarse ash, with scattered brownish yellow fine lapilli; a few brown (10YR 5/3) coarse lapilli in upper half of unit (coarse sandy loam)	150
	strong brown (7.5YR 5/6) fine, medium and medium to coarse lapilli (most c. 10 mm across but some up to 55 mm)	110
	brownish yellow (10YR 6/6) coarse ash in yellowish brown (10YR 5/6) minor fine ash matrix (coarse sand)	90
	brownish yellow (10YR 6/6) and olive grey (5Y 4/2) coarse ash (coarse sand)	50
	dark yellowish brown (10YR 4/6) and olive grey (5Y 4/2) coarse ash, fine lithic lapilli	110
	yellowish brown (10YR 5/6) ash (sandy loam)	40
Rotorua Ash	pale yellow (2.5YR 8/4) fine rhyolitic ash	20-30
	dark yellowish brown (10YR 4/6) ash - a few 'cream cakes' of black medium ash (medium sand) in upper part; fine lithic lapilli scattered over the central 20 mm (loamy sand)	80
	brownish yellow (10YR 6/8) fine lapilli, coarse ash in dark yellowish brown matrix; a 5 mm layer of dark grey-black coarse ash 20 mm from top of unit	70
	dark yellowish brown (10YR 4/6) medium ash (fine sand) passing to, at about 100 mm depth, medium and coarse ash of similar colour but with olive	

Formation	Description	Thickness (mm)
	yellow (2.5Y 6/6) coarse ash; some strong brown (7.5YR 5/6) fine to medium lapilli over bottom 20 mm	190
	dark yellowish brown (10YR 4/6) fine ash, brownish yellow (10YR 6/8) coarse ash and fine lapilli (sandy loam)	40
	brownish yellow (10YR 6/8) and grey coarse ash, fine lapilli	100
	dark yellowish brown (10YR 4/6) fine and medium ash (sandy loam)	30
	brownish yellow (10YR 6/6) fine to medium lapilli in fine and medium ash	30
	yellowish brown (10YR 5/5) fine and medium ash (fine sandy loam)	270
	brownish yellow (10YR 6/8) medium and coarse ash, fine and medium lapilli, coarsening towards base	40
	olive yellow (2.5Y 6/6) and dark greyish brown (2.5Y 4/2) medium ash (fine sand)	70
	olive yellow (2.5Y 6/6), brownish yellow (10YR 6/8), and dark greyish brown (2.5Y 4/2) coarse ash	50
	yellowish brown (10YR 5/4) ash with interspersed brownish yellow (10YR 6/8) coarse ash	60
	dark greyish brown (2.5Y 4/2) fine ash (silt) with interspersed strong brown (7.5YR 5/6) fine, medium and coarse lapilli	130
Rotoaira Lapilli	120 mm strong brown (7.5YR 5/7) fine, medium and coarse lapilli; 20 mm very dark grey (2.5Y 3/0) fine ash grading into 80 mm strong brown	

Formation	Description	Thickness (mm)
	(7.5YR 5/6) and black coarse ash, fine lapilli; 20 mm very dark grey (2.5Y 3/0) fine to medium ash (fine sand) grading into 30 mm olive yellow (2.5Y 6/6) fine to medium lapilli in ash	270
	pale olive (5Y 6/3) gleyed(?) ash with a few reddish yellow (7.5YR 6/6) fine and medium lapilli in top third and scattered reddish yellow medium lapilli in bottom third; in places bottom 40 mm is dark grey medium ash (medium sand)	440
	strong brown (7.5YR 5/8) coarse, very coarse and medium lapilli (many 30-40 mm across)	70
	light yellowish brown (2.5Y 6/4) ash (clayey silt loam)	500
	andesitic cobbles and pebbles and medium reddish yellow (7.5YR 6/6) lapilli (reworked tephra + alluvium?)	100
	unsorted subangular to subrounded boulders and cobbles in a matrix of pebbly silty sand (laharic breccia or alluvium?)	4.5 ⁺ m
	(unconformity)	
Te Whaiti Ignimbrite	pale purplish grey tuff; planar upper surface (c. 0.3 m.y.)	1.4 ⁺ m

Poutu (section no. 17): a large cutting on the National Park-Taupo Road, 5.7 km west of Rangipo; N112/239901. Altitude : 594m. Type section for Poutu Lapilli Member (Mangamate Formation), and Rotoaira Lapilli Formation.

Formation	Description	Thickness (mm)
Taupo Pumice	pale yellow (2.5Y 7/4) rhyolitic ash, lapilli and blocks	400
Mangatawai Tephra	dark yellowish brown (10YR 4/4) ash with dark grey medium ash (fine sand) in lower half	420
Whakaipo Tephra and Waimihia	yellowish brown (10YR 5/6) fine ash with medium pale yellow (2.5Y 7/4) rhyolitic ash scattered throughout (<u>Waimihia Lapilli</u>)	300
Papakai Tephra	strong brown (7.5YR 5/6) fine ash with grey fine lithic lapilli; paleosol	400
Hinemaiiaia Ash	cream cakes of pale yellow brown fine rhyolitic ash occur in lower half of Papakai Tephra	20
Mangamate Tephra	brownish yellow (10YR 6/6) weakly bedded coarse ash, fine and medium lapilli (<u>Poutu Lapilli</u>) 10 mm very dark greyish brown (2.5Y 3/2) grading to 50 mm dark olive grey (5Y 3/2), medium ash (medium sand) (<u>Wharepu Tephra</u>)	900 60
Poronui Tephra	pale yellow (2.5Y 8/4) rhyolitic ash	20-30
Mangamate Tephra	30 mm strong brown (7.5YR 5/6) medium ash (medium sand); 30 mm very dark grey (5Y 3/1) medium ash (<u>Ohinepango Tephra</u>) yellowish red (5YR 4/8) medium and coarse ash, fine lapilli (medium, coarse and very coarse sand) (<u>Weihoihomu Lapilli</u>)	60 30

Formation	Description	Thickness (mm)
	brown (10YR 4/3) ash	30
	yellowish brown (10YR 5/7) medium lapilli (Oturere Lapilli)	10
	very dark grey (5Y 3/1) coarse ash, fine lithic lapilli and pale yellow (2.5Y 7/4) fine and medium finely vesiculated dacitic lapilli (<u>Te Rato Lapilli</u>)	160
	yellowish brown (10YR 5/6) fine ash	60
(Pahoka Lapilli)	strong brown (7.5YR 5/8) stained coarse grey pumiceous lapilli; slight grey ash base	10
	strong brown (7.5YR 5/6) coarse ash (coarse and very coarse sand)	140
	yellowish brown (10YR 5/6) fine ash with interspersed light yellowish brown (2.5Y 6/4) coarse ash	100
	yellowish red (5YR 4/8), and less abundant very dark greyish brown (10YR 3/2), coarse ash, fine lapilli grading downwards to fine and medium lapilli; very dark greyish brown component increases in concen- tration downwards	110
	yellowish brown (10YR 5/6) ash and fine lapilli (light yellowish brown when broken)	50
	yellowish red (5YR 5/6) fine, medium and a few coarse lapilli in yellowish brown (10YR 5/6) ash	40
	yellowish brown (10YR 5/6) ash and scattered yellow (10YR 7/6) fine lapilli	50
	discontinuous single lapilli - thick layer of yellowish red (5YR 5/8) medium and coarse lapilli and grey lithics	15

Formation	Description	Thickness (mm)
	yellowish brown (10YR 5/8) coarse ash; lower 20 mm is medium ash	80
Rotorua Ash	yellow (2.5Y 8/6) fine rhyolitic ash, usually as cream cakes about 20 mm across	0-20
	yellowish brown (10YR 5/6) ash with interspersed brownish yellow (10YR 6/6) coarse ash (very coarse sandy silt)	80
	yellowish red (5YR 5/6) coarse ash to fine lapilli	20
	very dark greyish brown (2.5Y 3/2) coarse ash (very coarse sand) and fine lapilli	10
	yellowish brown (10YR 5/6) coarse ash	50
	very dark greyish brown (2.5Y 3/2) coarse lithic ash	30
	strong brown (7.5YR 5/8) and very dark greyish brown (2.5Y 3/2) medium to coarse ash	40
	strong brown (7.5YR 5/6) and yellowish red (5YR 5/8) coarse ash, fine lapilli in yellowish brown (10YR 5/8) ash matrix	10
	yellowish brown (10YR 5/6) ash (sandy silt) with sparse yellow (2.5Y 8/6) coarse ash	130
	similar to overlying tephra but with a greyer brownish yellow colour due to increased percentage of mafic crystals and lithic ash	100
	yellowish brown (10YR 5/4) ash (sandy silt) with scattered strong brown (7.5YR 5/7) fine lapilli (erosion break)	90
	strong brown (7.5YR 5/7) lapilli interspersed throughout dark grey medium ash	60

Formation	Description	Thickness (mm)
Rotoaira Lapilli	160 mm yellowish red (5YR 5/8) coarse ash, fine lapilli; 20 mm (10-50 mm) black medium ash (fine sand); 200 mm shower bedded brownish yellow (10YR 6/8) lapilli and coarse ash	380
	(erosion break)	
	yellowish brown (10YR 5/6) fine and medium ash (silty sand) with scattered strong brown (7.5YR 5/7) lapilli	120
	light olive brown (2.5YR 5/4) ash (sandy silt) with a few strong brown (7.5YR 5/7) lapilli; a few angular pebbles through this and the overlying unit which may therefore be water reworked	
Rerewhakaaitu Ash	in places white fine rhyolitic ash is present within the above unit (may be reworked)	0-50
	shower bedded strong brown (7.5YR 5/6) and brownish yellow (10YR 6/8) ash and lapilli	380
Hinuera Formation	current bedded gravelly sands	820
	(erosion break)	
Oruanui	pale brownish grey massive ash and pumice lapilli tuff (<u>Oruanui Breccia</u>)	390
	310 mm very pale brown (10YR 7/3) ash (slippery silt) shower bedded and studded with chalazoidites up to 30 mm across; 100 mm very pale brown (10YR 7/3) shower bedded ash (sandy silt); 40 mm pale yellow (2.5Y 6.5/4) shower bedded fine ash (greasy silt); 120 mm pale yellow (2.5Y 5.5/4 to 6.5/4) shower bedded fine and coarse ash (<u>Oruanui Ash</u>)	570

Formation	Description	Thickness (mm)
	sharp contact with greyish brown silt, black sand, strong brown stained lapilli and angular pebbles and cobbles (alluvium)	200
	90 mm greyish brown tuff containing sparse lithic lapilli on 150 mm dark reddish brown (2.5YR 3/4) lapilli tuff	240
	dark yellowish brown (10YR 4.5/4) tuff shot through with yellowish red (5YR 5/8) and grey lapilli; small charcoal fragments	160
	yellowish red (5YR 5/8) and grey lithic medium lapilli tuff	370
	yellowish red (5YR 4/6) to dark yellowish brown (10YR 4/6) fine tuff (indurated greasy silt) containing charcoal	150
	subangular to subrounded boulders, cobbles and pebbles in a silt-sand matrix (laharic breccia?)	900 ⁺

The normal fault at the eastern end of this section probably post-dates Taupo Pumice.

Te Rato (section no. 57(a)): A cutting on the southern side of the National Park-Taupo Road 0.6 km south-east of Te Rato Lapilli; N112/124928. Altitude : 701 m. Type section for Te Rato Lapilli Member (Mangamate Formation).

Formation	Description	Thickness (mm)
Ngauruhoe Tephra	very dark brown (10YR 2/2) fine ash (fine sandy silt; soil), gradational boundary	200
Taupo Pumice	pale yellow (5Y 7/3) rhyolitic ash, lapilli and blocks; upper 50-60 mm stained to yellowish-brown (10YR 5/7)	c. 1.3 m
Mangatawai Tephra	30 mm dark brown (10YR 3/3) ash (fine sandy silt; buried soil); 160 mm dark greyish-brown (2.5Y 3.5/2) fine ash (fine sandy silt); 110 mm very dark grey (2.5YR 3/2) bedded ash containing beech leaves (fine sand)	300
Waimihia	olive brown (2.5Y 4/4) to light yellowish-brown (2.5Y 6/4) andesitic ash with interspersed white rhyolitic ash (<u>Waimihia Lapilli</u>) (fine sandy silt); gradational boundary	160
Papakai Tephra	strong brown (7.5YR 5/7) fine ash with grey lithic and strong brown-stained fine to medium lapilli (greasy silt); strong cracking (buried soil); gradational boundary	370
	(erosion break)	
Mangamate Tephra	mainly brownish yellow (10YR 6/6), in places yellowish red (5YR 4/8), andesitic lithic lapilli: 160 mm fine, medium and coarse lapilli; 60 mm coarse ash and fine lapilli; 240 mm fine to very coarse lapilli; 60 mm fine and medium lapilli;	

Formation	Description	Thickness (mm)
	180 mm fine, medium and coarse lapilli (<u>Poutu Lapilli</u>); sharp boundary	700
	yellowish brown (10YR 5/5) ash with interspersed fine lithic lapilli; trace of grey fine ash at base	20
	dark grey and yellowish red (5YR 4/5) stained coarse ash, fine lithic lapilli	90
	5 mm grey fine ash; 15 mm olive (5Y 5/3) fine and medium ash (sandy silt); 20 mm olive brown (2.5Y 4/4) and grey coarse ash (coarse sand); 20 mm olive brown (2.5Y 4/4) ash; sharp boundary	60
	10 mm grey medium ash (fine sand) on very dark grey (5Y 3/1) fine and medium andesitic lithic lapilli and light yellowish brown (2.5Y 6/4) finely vesicular fine to coarse dacitic lapilli (<u>Te Rato Lapilli</u>)	410
	yellowish brown (10YR 5/6) fine ash with grey coarse lithic ash and grey fine lithic lapilli interspersed (very coarse sandy silt)	10
Papanetu Tephra	pale yellow (5YR 7/3) coarse obsidian-rich ash (coarse sand)	5
	yellowish brown (10YR 5/6) coarse ash (very coarse sandy silt) tending towards discrete strong brown (7.5YR 5/6) coarse ash, fine lapilli; gradational lower contact	80
	brownish yellow (10YR 6/6) coarse ash, fine and a few medium lapilli; with the lower 20 mm a	

Formation	Description	Thickness (mm)
	yellowish red (5YR 4/6) more compact coarse ash, fine lapilli	70
	yellowish brown (10YR 5/5) ash with coarse ash and fine lapilli throughout (pebbly coarse sandy silt)	40
	grey and strong brown (7.5YR 5/6) coarse ash (very coarse sand) with 5 mm grey medium ash at both top and bottom of unit	40
	yellowish brown (10YR 5/6) coarse and fine ash (sandy silt)	30
	strong brown (7.5YR 5/6) and grey coarse ash and fine lapilli (discrete); sharp contact	90
	dark yellowish brown (10YR 4/6) fine ash with yellowish brown (10YR 5/8) coarse ash (coarse sandy silt)	80
	dark yellowish brown (10YR 4/6) medium and fine ash (fine sandy silt)	60
Rotorua Ash	horizon of pale yellow (2.5Y 7/4) cream cakes of fine rhyolitic ash (silt)	10
	yellowish brown (10YR 5/8) fine and medium ash (sandy silt) with a few strong brown (7.5YR 5/6) fine lapilli	60
	strong brown (7.5YR 5/6) fine to medium lapilli in yellowish-brown (10YR 5/8) ash	30
	dark yellowish brown (10YR 4/6) fine ash with strong brown (7.5YR 5/7) coarse ash (coarse sandy silt)	50
	dark yellowish brown (10YR 4/6) ash, strong brown (7.5YR 5/7) coarse ash; a few strong brown (7.5YR 5/6) lapilli towards top	40

Formation	Description	Thickness (mm)
	strong brown (7.5YR 5/6) and grey lithic fine to medium lapilli	20
	yellowish red (5YR 4/8) coarse ash, fine lapilli	60
	dark yellowish brown (10YR 4/6) fine and medium ash (sandy silt) with scattered strong brown (7.5YR 5/6) fine and medium lapilli	60
	dark yellowish brown (10YR 4.5/4) ash (sandy silt) with strong brown (7.5YR 5/8) fine to coarse lapilli scattered throughout lower 110 mm	310
	grey and dark greyish brown (2.5Y 4/2) fine ash (silt) with strong brown (7.5YR 5/8) fine to coarse lapilli interspersed	130
	pale yellowish brown and grey medium sand with andesitic cobbles and small boulders (alluvium)	90
	120 mm dark purplish grey sand and andesitic gravel; 20 mm grey fine sand (alluvium)	140
Rotoaira Lapilli	light yellowish brown (2.5Y 6/4) and grey coarse ash	10-50
	dark yellowish brown (10YR 4/6) cobbly sands grading down into river alluvium	120 ⁺

Okupata (section no. 99): a cutting on the National Park-Taupo Road
200 m south-west of the junction with Hydro Access Road No. 1; N112/023850.
Altitude: 884 m. Type section for Okupata Tephra Formation.

Formation	Description	Thickness (mm)
Ngauruhoe Tephra	very dark brown (10YR 2/2) fine ash (silt)	220
Taupo Pumice	pale yellow (2.5Y 7/4) rhyolitic ash, lapilli and blocks	c. 600
Mangatawai Tephra	dark brown (10YR 3/3) fine ash (silt); lenses of dark grey (10YR 4/1) medium ash (very fine sand) with beech (<i>Nothofagus</i> sp.) leaves	210
	dark yellowish brown (10YR 4/4) fine ash (greasy silt)	220
Papakai Tephra	dark yellowish brown (10YR 4/6) fine ash (greasy silt) with a few scattered brownish yellow (10YR 6/8) fine and medium lapilli	210
Mangamate Tephra	yellowish brown (10YR 5/6) fine ash (greasy silt) with numerous dark grey (7.5YR 4/0) medium lapilli	220
Okupata Tephra	80 mm yellowish brown (10YR 5/6) fine ash (greasy silt) with scattered brownish yellow (10YR 6/8) medium and coarse lapilli and a few dark grey (7.5YR 4/0) fine lapilli; 80 mm yellow (10YR 7/8) fine to very coarse lapilli (up to 50 mm across); 80 mm strong brown (7.5YR 5/6) fine to coarse lapilli	240
	dark yellowish brown (10YR 4/6) fine ash (silt); paleosol	90
	brownish yellow (10YR 5.5/8) fine and medium lapilli and grey fine lithics in yellowish brown (10YR 5/8) ash	80

Formation	Description	Thickness (mm)
	strong brown (7.5YR 5/6) fine and medium lapilli and grey fine lithics	70
	yellowish brown (10YR 5/6) ash	140
Rotorua Ash	yellow (10YR 7/8) fine rhyolitic ash	trace
	yellowish red (5YR 5/8) coarse ash, fine lapilli	100
	dark yellowish brown (10YR 4/6) ash with sparse interspersed fine lithics (fine pebbly silt); paleosol	20
	yellowish red (5YR 5/8) fine, medium and coarse lapilli and dark grey fine lithic lapilli	50
	brown (10YR 5/3) ash with interspersed strong brown (7.5YR 5/8) fine and medium lapilli; paleosol	40
	dark yellowish brown (10YR 4/6) ash with interspersed strong brown (7.5YR 5/6) fine and medium lapilli	80
	yellowish red (5YR 5/8) lapilli; upper 80 mm fine, lower 120 mm fine to coarse	200
	yellowish brown (10YR 5/4) ash (coarse sandy silt) with interspersed reddish yellow (7.5YR 7/7) fine to medium lapilli (pebbles; reworked tephra)	130
	brownish yellow (10YR 6/6), and grey lithic, fine lapilli	50
	dark grey (10YR 4/1) and pale brown (10YR 6/3) sands and grey vesicular andesitic gravel (alluvium)	70
	yellowish brown (10YR 5/8) silty fine sand (alluvium)	130
	dark grey (10YR 4/1) and pale brown (10YR 6/3) sands (alluvium); subangular to subrounded pebbles, cobbles and boulders of vesicular olivine andesite occur throughout the above five units)	150

Formation	Description	Thickness (mm)
	very pale brown (10YR 6.5/3) reworked	
	Oruanui Formation	1.50 m
	(erosion, gullies cut)	
Oruanui	very pale brown (10YR 7/3) fine rhyolitic ash with sparse fine to medium lapilli and rare chalazoidites (<u>Oruanui Breccia</u>)	3.6 ⁺ m

Wairoa (section no. 45): a cutting 450 m east of C Wairoa Trig
and 90 m west of Hydro Access Road No. 4; N112/105987. Altitude: 625 m.

Formation	Description	Thickness (mm)
Taupo Pumice	pale yellow (2.5Y 7/4) rhyolitic ash, lapilli and blocks	500
Mangatawai Tephra	dark brown (10YR 3/3) to dark grey (10YR 4/1) fine ash	220
Papakai Tephra	yellowish brown (10YR 5/6) fine ash with sparse grey and strong brown (7.5YR 5/6) fine to medium lapilli; paleosol	370
	(erosion break)	
Mangamate Tephra	strong brown (7.5YR 5/6) coarse ash, fine and medium lapilli (<u>Poutu Lapilli</u>)	580
	grey and strong brown (7.5YR 5/6) coarse ash, fine lapilli	90
	grey fine ash	5

Formation	Description	Thickness (mm)
	grey and yellow (10YR 7/8) coarse ash, fine lapilli	20
	10mm grey medium ash grading into dark greenish grey andesitic fine lapilli and coarse ash with pale yellow (2.5Y 7/4) fine dacitic lapilli (<u>Te Rato Lapilli</u>)	140
	yellowish brown (10YR 5/6) ash and scattered grey coarse lithic ash	30
Okupata Tephra	140 mm yellowish brown (10YR 5/6) fine and coarse ash with scattered brownish yellow (10YR 5.5/8) fine lapilli; 50 mm strong brown (7.5YR 5/6) coarse ash, fine and medium lapilli (<u>basal lapilli</u>)	190
	strong brown (7.5YR 5/6) fine ash with interspersed coarse ash and fine lapilli	80
	strong brown (7.5YR 5/6) coarse ash, fine and medium lapilli, some iron-stained to a yellowish red (5YR 4/8)	80
	yellowish brown (10YR 5/6) fine ash, sparse fine to medium lapilli; scattered charcoal which was radiocarbon dated (NZ1187) at 12,350 $\pm$ 220 years BP (Topping & Kohn 1973)	150
	(Rotorua Ash is present as cream cakes in this position in nearby sections, e.g. N112/096989, section no. 52).	
	yellowish brown (10YR 5/6) ash with interspersed yellowish red (5YR 5/8) fine and medium lapilli	130

Formation	Description	Thickness (mm)
	yellowish brown ash with scattered charcoal throughout upper 80 mm (charcoal was radio- carbon dated (NZ1186) at 13,150 [±] 300 years BP (Topping & Kohn 1973))	250
?Rotoaira Lapilli	yellowish red (5YR 5/8) coarse pumiceous, and grey lithic, lapilli	20
	brown fine ash (silt) grading to yellowish brown (10YR 5/6) with depth (tephra and/or loess)	250
	yellowish brown (10YR 5/6) fine ash with inter- spersed strong brown (7.5YR 5/8) fine to medium lapilli and dark grey to black fine lithic, lapilli	100
	yellowish brown (10YR 5/4) clayey fine silt (?fine ash) with many dark rootlet channels (loess and/ or tephra)	600 ⁺

Te Ponanga Saddle (section no. 87(a)): a cutting on the eastern side of Te Ponanga Saddle Road near the summit, and to the north of Lake Rotopounamu; N112/224983. Altitude = 744 m. Type section for Papanetu Tephra Formation.

Formation	Description	Thickness (mm)
Ngauruhoe Tephra	dark brown grey fine ash	150
Taupo Pumice	pale yellow (2.5Y 7/4) rhyolitic ash, lapilli and blocks	950
Mangatawai Tephra	dark brown grey fine ash	340
Waimihia	pale yellow (2.5Y 7/4) medium rhyolitic ash (<u>Waimihia Lapilli</u>)	130

Formation	Description	Thickness (mm)
Papakai Tephra	yellowish brown (10YR 5/6) fine ash (greasy silt) with interspersed grey and strong brown (7.5YR 5/8) fine lapilli; paleosol	430
Mangamate Tephra	grey and strong brown (7.5YR 5/8) coarse ash, fine and medium lapilli (<u>Poutu Lapilli</u>)	650
Poronui Tephra	light yellowish brown (2.5Y 6/4) fine rhyolitic ash within 60 mm of grey andesitic ash	trace
Mangamate Tephra	dark greenish grey (5GY 4/1) andesitic fine lapilli and coarse ash with sparse pale yellow (5Y 7/3) medium finely vesicular dacitic lapilli (<u>Te Rato Lapilli</u>)	300
	yellowish brown (10YR 5/4) ash and grey coarse lithic ash	20
Papanetu Tephra	pale yellow (2.5Y 7/4) ash with coarse clear obsidian and grey lithic ash	0-20
	yellowish brown (10YR 5/6) fine ash with numerous coarse ash grains	20
	strong brown (7.5YR 5/6) coarse ash, fine lapilli (mainly 1-3 mm but rarely up to 6-8 mm)	80
	grey ash	10
	strong brown (7.5YR 5/8) coarse ash and fine and medium lapilli; trace of grey ash at base	50
	yellowish brown (10YR 5/4) ash with interspersed fine and medium lapilli	30
	yellowish brown (10YR 5/4) ash, yellow, grey and white fine lapilli (Rotorua Ash is present as cream cakes within this unit in other Te Ponanga Saddle road sections)	120

Formation	Description	Thickness (mm)
	strong brown (7.5YR 5/8) fine and a few medium lapilli with grey angular fine lithic lapilli	70
	yellowish brown (10YR 5/4) ash with interspersed yellow (10YR 7/8) fine lapilli	70
	50 mm brownish yellow (10YR 5.5/8) fine lapilli; 60 mm strong brown (7.5YR 5/8) fine and sparse medium lapilli in yellowish brown (10YR 5/4) ash	110
	yellowish brown (10YR 5/6) fine ash	110
Puketarata Ash	isolated pocket of yellow (2.5Y 7/6) fine rhyolitic ash	30
	yellowish brown (10YR 5/6) fine ash	160
	isolated pocket of yellow (2.5Y 7/6) fine rhyolitic ash	20
	yellowish brown (10YR 5/6) ash	120
Roteaira Lapilli	20 mm yellowish red (5YR 5/8) coarse ash and fine lapilli; 5 mm dark grey ash; 60 mm strong brown (7.5YR 5/8) coarse ash and fine lapilli	85
	yellowish brown (10YR 5/6) to light olive brown (2.5Y 5/4) ash, sparse yellow coarse (10YR 7/8) ash and fine lapilli	300
Rerewhakaaitu Ash	pocket of white fine rhyolitic ash	60
	slightly pebbly sands, yellowish brown silts with minor cobbles and boulders (alluvium?)	600
Oruanui	shower bedded very pale brown (10YR 7/3) fine and coarse ash and chalazoidites (Oruanui Ash)	300
	angular andesitic boulders, cobbles and pebbles in a pale brown to grey brown silty matrix (breccia)	1,50 ⁺ m

APPENDIX 1BAdditional Tephra Sections

Wairehu Canal (southern side; section nos. 310, 310(a)): road cuttings on southern side of Wairehu Canal by a bridge 0.7 km west of point where Te Ponanga Saddle Road crosses canal; N112/145983. Altitude: 610 m.

Formation	Description	Thickness (mm)
Taupo Pumice	pale yellow (2.5Y 7/4) rhyolitic ash, lapilli and blocks (top stripped off)	500
	very dark brown peat + wood	40
	yellow ash	20
	very dark brown peat	190
?Waimihia	white medium rhyolitic ash (<u>?Waimihia Lapilli</u>)	10
Papakai Tephra	very dark brown peat; lower 90 mm possibly contains more ash	1.39m
Mangamate Tephra	bedded brown fine and medium lithic lapilli (<u>Poutu Lapilli</u>)	400
	grey coarse andesitic ash and white coarse dacitic ash, fine lapilli (<u>Te Rato Lapilli</u>)	340
	dark brown peat (+ ash?) containing small branches and stems of <u>Dacrydium colensoi</u> and roots of <u>Podocarpus hallii</u> (identified by Dr R. N. Patel, F.R.I., Rotorua). Peat (NZ1373) and wood (NZ1372) were radiocarbon dated at 9,700 $\pm$ 210 and 9,780 $\pm$ 170 years B.P. respectively (Topping & Kohn 1973)	3-10
Papanetu Tephra	pale grey to white coarse rhyolitic ash (coarse sand); sharp upper and lower boundaries	5-15

Formation	Description	Thickness (mm)
	dark brown peaty ash (silt) containing charcoal fragments and small branches and stems of <u>Dacrydium colensoi</u> and roots of <u>Podocarpus hallii</u> (identified by Dr R. N. Patel); wood was radio-carbon dated (NZ1374) at 9,790 [±] 160 years B.P. (Topping & Kohn 1973)	20
70kupata Tephra	20 mm coarse ash, fine lapilli; 10 mm dark brown ash; 50 mm coarse ash, fine lapilli; sharp contacts (<u>?basal lapilli</u>)	80
	brown peaty ash (sandy silt)	40
	pale brown coarse ash	50
	dark brown peat and/or fine ash	10
	pale grey fine ash grading down into fine lapilli, coarse ash	70
	dark brown fine ash or peat (clayey silt) with white flecks of ash	110
Rotorua Ash	fine white rhyolitic ash with black rootlet channels	40
	grey and greyish brown medium ash (medium sand)	10
	dark brown peaty ash with white medium ash flecks	25
	pale yellow brown fine pumiceous lapilli	20
	dark brown fine and medium ash with peat (?) (sandy silt)	8
	pale whitish brown medium ash and brownish grey fine ash	10
	dark brown fine ash, white medium ash (gritty sandy silt)	40
	brown fine lapilli grading down to coarse ash	50

Formation	Description	Thickness (mm)
	brown medium and fine ash (sandy silt); gradational lower boundary	80
	brown medium ash (medium sand)	20
	brown fine and medium ash (silty sand)	10
Puketarata Ash	white to pale yellow fine rhyolitic ash	10
	black lithic fine lapilli and coarse ash in brown fine ash (gritty sandy silt); lithic fragments coarsen upwards	30
	brown ash (fine sandy silt)	40
	blue-green indurated ash (sandy silt)	10-20
	purplish grey ash (very fine sand) with a 10 mm pale whitish grey ash horizon in the centre of the unit	80
?Rotoaira Lapilli	angular grey medium andesitic lithic lapilli and coarse ash	40
	bedded rhyolitic ash (reworked Oruanui Formation)	540 ⁺

Wairehu Canal (northern side; section no. 311): shallow section on northern side of Wairehu Canal near bridge 0.7 km west of point where Te Ponanga Saddle Road crosses the canal; N112/145984. Altitude: 610 m.

Formation	Description	Thickness (mm)
Ngauruhoe Tephra	black fine ash (silt; soil)	130
Taupo Pumice	pale yellow (2.5Y 7/4) rhyolitic lapilli and blocks; upper 300 mm has a high percentage of lithic fragments	630

Formation	Description	Thickness (mm)
Mangatawai Tephra	dark greyish brown (10YR 4/2) to dark grey fine and medium ash (very fine sand); many yellowish red (5YR 5/8) rust mottles	160
Waimihia	dark brown (10YR 4/3) fine andesitic ash (very fine sandy silt) with interspersed white medium rhyolitic ash; lower 20 mm is a horizon of white (5YR 8/2) medium rhyolitic ash (<u>Waimihia Lapilli</u>)	110
Papakai Tephra	dark brown (10YR 4/3) fine andesitic ash; sharp contact with	60
	horizon of small charcoal fragments	20
Papakai Tephra	dark brown (7.5YR 3/2) fine ash (silty clay) - almost no peat as tephra does not darken in colour on exposure to air	170
Mangamate Tephra	dark brown (7.5YR 3/2) fine and medium lapilli (<u>Poutu Lapilli</u>)	540

Otamangakau Canal (Section no. 60): peats and interbedded tephras between Taupo Pumice and Poutu Lapilli exposed (and subsequently removed) during excavation of the Otamangakau Canal, Tongariro Power Scheme; N112/109984. Altitude: 613 m.

Formation	Description	Thickness (mm)
Taupo Pumice	pale yellow rhyolitic ash, lapilli and blocks	900
	peat	250
(a)	peat with a trace of yellow ash	20
	peat	10
(b)	yellow ash	10
(c)	peat with yellow ash	30
(d)	yellow ash	40
	peat	
	(wood dated (NZ1336) at 3,200 $\pm$ 50 years B.P. was obtained 400 mm from top of this peat unit)	490
(e)	yellow fine ash coarsening with depth	20
	peat	310
(f)	ash	20
	peat	870
(g)	yellow ash	10
	peat	240
(h)	medium to coarse yellowish brown ash	10
	peat	580
?Rotoma Ash	(i) white ash (rhyolitic)	20
	peat	70
(j)	white ash (rhyolitic?)	3
	peat	60
(k)	yellow ash with minor peat sandwiched in the centre	30
	peat	5
(l)	yellow ash	20
	peat	10
(m)	yellow ash	30
(n)	peat with trace of yellow ash	20
(o)	yellow ash	20

Formation	Description	Thickness (mm)
	peat	10
(p)	yellow ash	20
	peat	20
(q)	yellow ash	70
	peat	60
(r)	ash	5
	peat	30
(s)	ash	5
	peat	20
(t)	yellow ash	10
	peat	40
(u)	yellow tephra with minor peat sandwiched in centre	20
	peat	30
70pepe Tephra	(v) white ash (rhyolitic?)	trace
	peat	70
	(w) yellow ash	20
	peat	30
	(x) yellow ash	140
	peat	130
	(y) yellow ash	10
	peat; wood (radiocarbon dated (NZ1335) at 9,560 $\pm$ 100 years B.P.) was sampled 10 mm above base of this peat unit	100
	(z) yellow ash	10
	peat	70
Mangamate Tephra	greyish brown coarse ash, fine and medium lapilli (Poutu Lapilli)	820
	yellow fine ash	5
	greyish brown coarse ash	50
	yellowish grey ash	10
	5 mm grey medium ash grading into grey andesitic and white dacitic coarse ash, fine lapilli (Te Rato Lapilli)	150
	undifferentiated andesitic tephtras (erosion break)	1.14 m

Formation	Description	Thickness (mm)
Oruanui	pale brown medium and fine rhyolitic ash with pumiceous lapilli and chalazoidites (<u>Oruanui</u> <u>Breccia</u>)	2.35 ⁺ m

The yellow ash horizons were all of fine grained ash mixed with organic matter. Samples a, d, e, f, g, h, i, k, q, r, s and x were sent to Mr M. S. McGlone, Botany Division, D.S.I.R., Christchurch for pollen analysis.

Otamangakau Canal (western shore, section no. 62): a tephra sequence exposed on the western embankment of Otamangakau Canal 300 m north of the bridge on Hydro Access Road No. 4; N112/105979. Altitude: 613 m.

Sequence below Oruanui Ash comprises:

brownish grey to dark brownish grey tuff	110
dark brown tuff becoming lighter brown with depth	310
yellowish brown to yellowish grey fine tuff	600
black tuff; paleosol	270
grey fine tuff (indurated silt)	210
yellowish grey coarse tuff	20
grey fine tuff (indurated silt)	160
pale yellowish grey coarse tuff	20
grey tuff (indurated silt)	110
grey sands and gravels containing wood	340
pale grey fine sandy clay	60
grey sand	40
black tuff; paleosol; wood in situ on this paleosol was radiocarbon dated (NZ1337) at > 47,000 years B.P.	70
dark brown fine tuff with white medium to coarse ash specks	120
dark brown fine tuff with white medium to coarse ash flecks and strong brown fine lapilli	130
pinkish brown fine tuff with numerous white flecks and mafic crystals	400
pinkish blue coarse ash, fine lapilli	80
brown fine tuff	350 ⁺

Poutu Damsite (section no. 220): large cutting on National Park-Taupo Road, 3.3 km WSW of Rangipo, at junction with Access road to Poutu Damsite; N112/257897. Altitude: 579 m. Description from base of Retoaira Lapilli.

Formation	Description	Thickness (mm)
	yellowish brown fine ash (silt) with sparse white medium rhyolitic lapilli; paleosol at top with occasional fragments of charcoal (tephric loess?)	310
	greyish yellow brown medium ash (fine sand); grading to greyish brown medium ash and white fine rhyolitic lapilli	190
	greyish yellow brown medium ash (fine sand); gradational lower boundary	100
	very dark grey medium ash (fine sand) with rare white fine rhyolitic pumice	80
	greyish brown fine ash (silt)	170
	very dark grey medium ash (very fine sand)	80
	greyish brown medium ash (fine sand) with dark grey lithic, and rare rhyolitic pumiceous fine lapilli	30
	30 mm brownish yellow coarse ash and dark lithic ash coarsening to 80 mm brownish yellow fine and sparse medium pumiceous lapilli; 20 mm grey ash; 50 mm brownish yellow coarse ash, fine and sparse medium to coarse lapilli; 10 mm grey ash; 100 mm brownish yellow coarse ash, fine to coarse lapilli with 10 mm grey lithic fine lapilli concentrated at base; 50 mm greyish brown medium and coarse ash grading to 60 mm brownish yellow fine and sparse	180

Formation	Description	Thickness (mm)
	medium lapilli, grey and pale grey lithic	
	coarse ash, fine lapilli; 10 mm grey medium ash	
	(medium sand) with sparse pale grey pumiceous	
	medium lapilli; 40 mm reddish yellow pumiceous fine	
	lapilli with interspersed strong brown pumiceous	
	medium lapilli; 20 mm grey lithic coarse ash;	
	30 mm strong brown coarse ash; 80 mm strong	
	brown pumiceous coarse ash, fine, medium and	
	coarse lapilli, grey lithic coarse ash, fine lapilli	590
	(erosional unconformity)	
	pale brown fine and medium ash (fine sandy silt) with	
	abundant fine to coarse white rhyolitic lapilli	
	(loess?)	280
	yellowish brown fine and medium ash (sandy silt;	
	loess?)	230
	black angular lithic coarse ash, fine and rare medium	
	lapilli in yellowish brown fine ash (silt; loessic?)	
	matrix	60
	pale yellowish brown fine ash (silt) becoming paler	
	with depth; scattered fine, medium and sparse	
	coarse rhyolitic lapilli; strong brown fine and	
	medium lapilli throughout lower 110 mm (loess)	430
	(erosional unconformity)	
	30 mm grey coarse and medium ash; 50 mm strong brown	
	and grey coarse ash, fine lapilli; 10 mm grey	
	lithic coarse ash (very coarse sand); 100 mm	
	strong brown coarse ash, fine to coarse lapilli;	
	10 mm grey lithic coarse ash; 90 mm strong brown	
	coarse ash, fine and medium lapilli	290

Formation	Description	Thickness (mm)
	(erosional unconformity)	
	light yellowish brown rhyolitic ash and scattered white pumice lapilli (reworked Oruanui Breccia; loess)	780
	pale brown rhyolitic ash (loess?)	920 ⁺

Tongariro River Bridge (section no. 171): stream sections left bank
of Tongariro River just upstream from bridge on Desert Road; N122/228655.
Altitude: 1,036 m.

Formation	Description	Thickness (mm)
Ngauruhoe Tephra	black to dark brownish grey medium and fine ash	1.20 m
Taupo Pumice	pale yellow rhyolitic ash, lapilli and blocks; bright pink in places	1.20 m
Mangatawai Tephra	200 mm greyish brown ash grading to dark grey medium ash containing beech leaves	420
	brown ash with scattered medium lapilli in centre of unit	90
Waimihia	white fine rhyolitic ash (<u>Waimihia Lapilli</u>)	40
Papakai Tephra	yellowish brown ash with sparse white rhyolitic medium ash; upper 90 mm dark, possibly a paleosol	190
Mangamate Tephra	grey and strong brown (iron-stained) fine, medium and a few coarse lithic lapilli (<u>Poutu Lapilli</u>)	260
	190 mm grey and strong brown fine and a few medium lithic lapilli; 10 mm brown fine ash (<u>Wharepu Tephra</u>)	200
	(inferred erosion break)	

Formation	Description	Thickness (mm)
	grey and yellow fine lithic lapilli (<u>Waihohehu Lapilli</u>)	170
	20 mm grey ash with scattered fine to coarse yellow pumiceous lapilli; 40 mm bedded grey and yellow fine lapilli	60
	10 mm grey fine lithics; 250 mm grey and yellow fine and medium lithic lapilli (<u>Oturere Lapilli</u>)	260
	yellowish brown ash with a few yellow fine pumiceous lapilli	90
	greyish yellow fine and coarse ash	60
(Pahoka Lapilli)	20 mm grey rounded fine lithic cobbles (water reworked lapilli); 60 mm flat, platy, angular grey lithic fine cobbles (lapilli broken down in situ); a few grey medium to coarse lithic lapilli	80
	yellowish brown coarse and medium ash with a few yellow medium pumiceous lapilli; fine lithic lapilli common in lower half	120
	pale yellow coarse and medium pumiceous lapilli	50
	pale yellow fine pumiceous lapilli, black fine lithic lapilli	30
	grey and greyish yellow medium and coarse ash with grey fine lithic lapilli scattered through bottom 60 mm	160
	brownish yellow fine and medium pumiceous lapilli, grey fine to medium lithic lapilli; grey medium ash interspersed through top 20 mm	100
	30 mm grey coarse and medium ash; 40 mm yellow pumiceous and grey lithic fine and medium lapilli; 10 mm grey medium ash	80

Formation	Description	Thickness (mm)
	10 mm pale yellowish brown ash; 70 mm grey fine lithic lapilli becoming yellow towards the base	80
	grey coarse and medium ash with sparse grey fine to medium lithic lapilli	70
	yellow fine angular lithic lapilli giving way abruptly to grey medium and coarse ash, fine lithic lapilli	50
	50 mm grey medium and coarse lithic ash; 120 mm yellow fine, medium and coarse lapilli and grey fine lithic lapilli	170
	yellow angular, platy, fine lithic lapilli	20
	grey fine lithics in minor grey medium ash matrix	50
	grey medium ash with interspersed grey fine to medium lithic lapilli	80
	strong brown fine, medium and coarse pumiceous lapilli, grey fine and medium lithic lapilli	150
	grey medium and coarse ash	50
	brownish yellow fine and medium pumiceous lapilli	60
	grey medium and coarse ash	100
	strong brown fine, and sparse medium, pumiceous lapilli, grey fine lithic lapilli	130
	grey medium and coarse ash, sparse grey fine lithic lapilli	50
	pale yellow medium and fine pumiceous lapilli	50
	grey fine and medium ash	40
	yellowish brown fine and medium lapilli	40
	black coarse and medium ash	60

Formation	Description	Thickness (mm)
	grey fine lithic lapilli, coarse ash in a medium ash matrix which is grey over upper 20 mm yellowish brown over lower 20 mm	40
	30 mm dark grey medium ash; grading to 30 mm greyish yellow brown medium ash and interspersed fine lapilli	60
	dark grey medium ash and interspersed strong brown fine lapilli	30
	strong brown fine to coarse pumiceous lapilli	50
	grey medium ash and interspersed grey fine lithic lapilli	20
	grey fine lithic lapilli in yellowish brown medium ash matrix	40
	greyish brown medium ash with sparse brown medium lapilli; white fine ash in central part of unit	110
	grey platy, angular fine lithic lapilli and ash	30
	20 mm grey medium ash; 30 mm greyish brown medium ash; 30 mm yellowish brown fine lapilli	80
	20 mm grey medium ash; 50 mm greyish brown medium ash with minor fine lapilli; 40 mm yellowish brown medium ash and fine lapilli	110
	20 mm grey medium ash and minor yellow fine lapilli; 80 mm yellow fine lapilli	100
	10 mm grey medium ash grading into 110 mm yellowish brown coarse and fine ash	120
	grey coarse and fine ash	90
	laharic breccias	9.45 m
	yellow fine and medium lapilli	570
	grey boulders in indurated sandy matrix (alluvium)	190

Formation	Description	Thickness (mm)
	grey gritty volcanic sandstone containing sparse red fine pebbles	230
	laharic breccias (?) (section to top of waterfall)	c.5.10 m
Rest of section is described below the waterfall at the junction of the two streams; measurements approximate only.		
	gravelly laharic breccias	5.70 m
	tuff	900
	tuffs and lapilli tuffs	2.70 m
	laharic breccia containing large boulders	2.10 m
	brown fine tuffs, lapilli tuffs (minor lapilli content), strong brown lapilli tuffs	4.20 ⁺ m

Turangi Lookout (section no. 94): north-facing section opposite
lookout over Turangi on Te Ponanga Saddle Road; N102/248009. Altitude
564 m. Section measured from top of Mangamate Tephra Formation.

Formation	Description	Thickness (mm)
	(erosion surface)	
Mangamate Tephra	grey and strong brown coarse ash, fine and medium lapilli (<u>Poutu Lapilli</u>)	530
	yellowish brown medium ash (<u>Wharepu Tephra</u>)	40
Poronui Tephra	light yellowish brown fine rhyolitic ash	0-10

Formation	Description	Thickness (mm)
Mangamate Tephra	yellowish brown fine ash (clayey silt)	30
	greenish grey andesitic coarse ash, fine lapilli and pale yellow fine and medium dacitic lapilli (Te Rato Lapilli)	260
	yellowish brown ash with interspersed grey coarse ash, fine lapilli	10
Papanetu Tephra	pale yellow rhyolitic ash with coarse grey lithic ash and clear obsidian	0-10
	yellowish brown ash and fine lapilli	210
	70 mm brownish yellow fine lapilli; 5 mm grey medium ash; 10 mm brownish yellow fine lapilli	85
	yellowish brown ash	30
	brownish yellow fine and medium lapilli in yellowish brown ash	30
	yellowish brown ash with sparse yellow fine lapilli	70
Rotorua Ash	yellow fine rhyolitic ash	trace
	yellowish brown ash with sparse yellow fine lapilli	70
	brownish yellow coarse ash, fine lapilli in minor yellowish brown ash matrix	80
	yellowish brown ash with sparse yellow fine lapilli in upper 160 mm; lower 50 mm becoming greyer and with brownish yellow fine lapilli	320
Rotoaira Lapilli	10 mm strong brown and black coarse ash, fine lapilli; 3 mm grey ash; 60 mm strong brown and black coarse ash, fine lapilli	73
	yellowish brown ash, becoming paler with depth (loess?)	860

Formation	Description	Thickness (mm)
	yellowish brown ash with interspersed grey lithic coarse ash, fine lapilli	50
	yellowish brown ash	90
	strong brown fine and medium lapilli	80
	light yellowish brown fine ash (tephric loess?)	330
	yellowish brown to greyish yellow brown silt-sand matrix, andesitic pebbles and cobbles, reworked pumice (alluvium)	900
	(erosion break)	
Oruanui	pale brownish grey rhyolitic ash and sparse lapilli (Oruanui Breccia)	1.23 m
	(erosion break)	
	yellowish brown ash with strong brown coarse lapilli scattered over central part	560
	lens of bedded pink fine and white medium rhyolitic ash	250
	yellowish brown fine and medium ash and sparse strong brown medium lapilli; paleosol at top	900
	strong brown medium lapilli in yellowish brown ash	20
	yellowish brown ash with manganese flecks and sparse strong brown medium lapilli	820
	pale yellow fine rhyolitic ash; one pocket, the remainder as cream cakes	0-70

Pukeonake Scoria Cone (section no. 164): Tephra section exposed within the crater near the head of Pukeonake Stream; N112/064823.
Altitude: 1,204 m.

Formation	Description	Thickness (mm)
Ngauruhoe Tephra	dark brown (10YR 3/3) fine and medium ash (fine sandy silt) sparsely interspersed with coarse ash; pockets of reworked pale yellow (2.5Y 8/3) coarse rhyolitic ash and fine lapilli of Taupo Pumice; gradational boundary to	1,03 m
Taupo Pumice	pale yellow (2.5Y 8/3) fine ash coarsening to lapilli with depth; blocks (up to 180 mm across) scattered throughout; charred wood of 15 mm diameter common in lower half of deposit; distinct straight lower boundary	580
Mangatawai Tephra	dark brown (10YR 4/3) fine ash with a few rust coloured mottles along former rootlet channels; basal 250 mm consists of dark grey (5Y 4/1) medium ash (medium to fine sand) and beech leaves; gradational contact with	420
	dark brown (10YR 3/4) fine ash with sparse rust mottles along cracks and old rootlet channels; gradational lower contact	430
Papakai Tephra	brown (7.5YR 4/3) fine ash with scattered strong brown (7.5YR 5/6) fine (4-10mm) pumiceous lapilli; sharp contact with	540
Mangamate Tephra	grey (N5.5/0) dense lithic lapilli; distinct lower boundary dark yellowish brown (10YR 4/6) fine ash, sometimes ironstained to a yellowish red (5YR 5/8); grey to	210

Formation	Description	Thickness (mm)
	dark grey lithic lapilli scattered throughout	
	lower half of unit; sharp lower contact	380
Okupata Tephra	130 mm brownish yellow (10YR 6/6) fine to coarse pumiceous lapilli and fine grey lithics - almost divided in two by an ash rich horizon; 80 mm strong brown (7.5YR 5.5/8) fine and medium pumiceous lapilli (discrete in central part, indurated at top and bottom due to iron pan formation)(basal lapilli)	210
	light yellowish brown (2.5Y 6/4) ash with sparse grey fine lithic lapilli	90
	reddish yellow (7.5YR 6/8) coarse ash, fine lapilli and grey fine lithic lapilli	50
	strong brown (7.5YR 5/6) fine to coarse lapilli; grey fine lithic lapilli	170
	brownish yellow (10YR 6/6) ash with interspersed fine lithic lapilli	80
	brownish yellow to yellowish brown (10YR 5.5/6) medium ash and grey fine lithics	30
	strong brown (7.5YR 5/6) fine and medium lapilli	100
	light yellowish brown (10YR 6/4) ash with coarse lithic ash	110
(Rotorua Ash?)	yellowish andesitic ash possibly including some fine rhyolitic ash	30
	reddish yellow (7.5YR 6/8) fine and sparse medium lapilli; grey (7.5YR 5/4) ash at base	140
	brownish yellow (10YR 6/6) medium ash with inter- spersed fine and medium lapilli and grey fine lithic lapilli (the lapilli sometimes in 3 or 4 discrete horizons	210

Formation	Description	Thickness (mm)
	80 mm yellowish red (5YR 5/8) fine to medium lapilli; 180 mm reddish yellow (7.5YR 6/8) fine and medium lapilli	260
	brown (10YR 5/3) coarse ash with numerous grey coarse lithic ash, fine lapilli	100
	yellowish brown (10YR 5.5/8) fine lapilli and grey fine lithic lapilli	60
	mainly grey medium ash grade tephra, sometimes greyish yellow brown; interspersed grey fine lithic lapilli	2.40 m
	1.15 m finely laminated water-laid rhyolitic silts, clays, and sands; 640 mm, three massive beds of crudely graded chalazoidites with interbedded laminated rhyolitic sediments; 690 mm laminated rhyolitic sediments (reworked tephra considered by the writer to be correlatives of bed 3, Wairakei Breccia Formation (Grindley 1965, Vucetich and Pullar 1969))	2.48 m
Oruanui	rhyolitic fine and medium ash, sparse fine to medium pumice lapilli and chalazoidites (<u>Oruanui Breccia</u> and/or <u>Oruanui Ash</u>)*	4.05
	basal shower bedded fine to coarse rhyolitic ash (<u>Oruanui Ash</u>)	110
	beds of scoriaceous olivine andesite blocks of Pukeonake Scoria Cone	

*Airfall chalazoidites of Oruanui Ash (which is correlated by the writer with bed 1, Wairakei Breccia Formation (Grindley 1965, Vucetich and Pullar 1969)) directly overlie the shower bedded basal beds towards the eastern end of the exposure.

Upper Bruce Road (section no. 269): a section on the western side of Bruce Road 2 km above the Chateau Tongariro, northern Mt Ruapehu; N112/041735. Altitude: 1,260 m.

Formation	Description	Thickness (mm)
Ngauruhoe Tephra	180 mm dark brown to black medium ash (fine sand);	
	10 mm dark brown to black medium and coarse ash;	
	20 mm light grey coarse ash;	
	70 mm dark brown medium ash;	
	110 mm black medium ash;	
	90 mm dark brown fine and medium ash;	
	30 mm black medium ash;	
	260 mm greyish brown medium and fine ash (sandy silt)	770
Taupe Pumice	pale yellow rhyolitic ash and lapilli	90
Mangatawai Tephra	250 mm greyish brown fine ash (silt);	
	230 mm black medium ash (medium sand) with beech leaves, and brownish grey medium ash (very fine sand)	480

The 10, 20, and 110 mm beds within Ngauruhoe Tephra are readily identified around the upper Bruce Road, northern Ruapehu and with detailed work would probably warrant member status.

Oturere Valley (section no. 495): a section towards the southern side of Oturere Valley above the earliest lava extruded from Red Crater; N112/174804. Altitude: 1,332 m.

Formation	Description	Thickness (mm)
Ngauruhoe Tephra	80 mm pale brownish grey medium ash;	
	50 mm grey medium ash;	
	40 mm pale brownish grey ash;	
	50 mm grey medium ash;	
	100 mm pale brown grey medium ash;	
	10 mm grey medium ash;	
	120 mm pale yellowish brown to grey medium ash;	
	30 mm yellow and white fine ash (hydrothermal clay*);	
	40 mm yellowish brown medium ash;	
	30 mm grey medium ash;	
	50 mm brownish yellow coarse lithic ash and reworked Taupo Pumice;	
	50 mm brown and strong brown coarse ash, fine scoriaceous lapilli;**	
	10 mm grey medium ash and greyish brown fine ash	660
Taupo Pumice	pale yellow rhyolitic ash, lapilli and blocks	3+ m

* The yellow and white fine ash is considered to be the product of a small phreatic eruption. It contains lithic fragments in more westerly sections and thickens towards the Emerald Lakes explosion craters from which it was probably erupted. Lithic lapilli and blocks from these craters lie on the upper surface of the young Red Crater as flow in Central Crater. The "50 mm brown and strong brown coarse ash, fine scoriaceous lapilli"*** present near the bottom of Ngauruhoe Tephra thickens westwards towards Red Crater its probable source.

Oturere Valley (section no. 496): section just south-west of Oturere Hut in Oturere Valley; N112/177803. Altitude: 1,320 m.

Formation	Description	Thickness (mm)
Ngauruhoe Tephra	330 mm tephra (not described here);	
	60 mm brownish yellow fine ash (clay*) and dark grey medium lithic ash;	
	20 mm white fine ash (clay*);	
	20 mm brown and strong brown coarse ash, fine lapilli (reworked?);	
	40 mm brown and strong brown coarse ash, fine lapilli;**	
	90 mm greyish brown ash;	
	30 mm putty grey fine ash***	590 ⁺

The white and yellow fine ashes (clays*), assumed to be from hydrothermal eruptions at Emerald Lakes, the brown and strong brown coarse ash, fine lapilli unit,** assumed to be from Red Crater and older putty coloured ash*** are all distinctive and would provide useful markers for detailed mapping.

Oturere Valley (section no. 477): a pit excavated on the south-eastern slopes of Red Crater 500 m from the vent; N112/146826. Altitude: 1,560 m.

Formation	Description	Thickness (mm)
	(present eroded surface)	
Taupo Pumice	pale yellow fine and medium rhyolitic ash (mainly fine sand); lowest 40 mm consists almost entirely of crystals	280

Formation	Description	Thickness (mm)
Mangatawai Tephra	30 mm grey brown medium and coarse ash; grading into 120 mm greyish fine and medium scoriaceous lapilli; 70 mm brownish grey medium ash and lapilli; 140 mm greyish brown to brown scoriaceous fine to very coarse lapilli; 200 mm very dark grey medium ash; 200 mm pale yellowish brown ash (hydrothermally altered?) with grey fine lithic lapilli; 200 mm red medium and coarse ash	960 ⁺

Otureru Valley (section no. 479): section on lower south-east
slopes of Red Crater, 1 km from the vent; N112/148822. Altitude:
1,494 m.

Formation	Description	Thickness (mm)
Mangatawai Tephra	(description from base of "140 mm greyish brown to brown scoriaceous lapilli" bed of section no. 477): 210 mm dark grey and grey brown medium to coarse ash; 50 mm white and yellow fine ash (hydrothermal clay?); 360 mm brown and grey coarse ash; 30 mm yellow and pale yellow fine ash (hydrothermal clay?); 100 mm grey and grey brown fine ash (silt) grading to medium ash (fine and medium sand) with a few	

Formation	Description	Thickness (mm)
	fine lithic lapilli in the central part of the unit;	
	40 mm very pale grey brown ash;	
	320 ⁺ mm pale brown pumiceous fine lapilli, dark grey medium and fine ash	1.11 ⁺ m

Sections 477 and 479 show typical detail of beds within Mangatawai Tephra close to source. The yellow and white fine ashes are probably clays of hydrothermal origin and may represent vent-clearing phreatic eruptions after periods of intense fumarolic activity, probably at Red Crater.

Many of the tephra beds are distinctive enough to allow detailed local mapping.

Oturere Valley (section no. 481): bank of dry stream in the upper central part of Oturere Valley; N112/153823. Altitude: 1,422 m.

Formation	Description	Thickness (mm)
	sands and gravels (alluvium)	600
	(erosional unconformity)	
Ngauruhoe Tephra	140 mm yellow and pale yellow fine ash (hydro- thermal clay*);	
	50 mm yellow ash;	
	240 mm brown and grey medium ash (fine sand);	
	140 mm grey and brown ash with fine lapilli towards the base;	
	210 mm: 80 mm greyish brown fine and medium lapilli, 10 mm greyish brown ash, 120 mm greyish brown medium to very coarse lapilli**;	780

Formation	Description	Thickness (mm)
	(inferred erosion break: lower Ngauruhoe Tephra beds missing here)	
	sands, comprising mainly crystals reworked from Taupo Pumice (alluvium)	340
	(erosion break)	
Taupo Pumice	pale yellow rhyolite ash and fine lapilli	550 ⁺

Tephra beds from the Emerald Lakes explosion craters (*), estimated age 1250 A.D., and Red Crater (**) are indicated as in the descriptions of section nos. 495 and 496.

Two erosional unconformities, an inferred erosion break, and two associated alluvial deposits are represented in the section. The uppermost erosion break may equate with the initiation of erosion which has continued to the present day on eastern Tongariro. If so, it is younger than 1250 years BP estimated for the formation of Emerald Lakes.

APPENDIX 1CTephra Sections Associated with Moraines

Mangatepopo Valley (section no. 369): section to north of
Mangatepopo Stream on lower slopes of a lateral morainal ridge;
N412/089822. Altitude: 1,146 m.

Formation	Description	Thickness (mm)
Taupo Pumice	pale yellow rhyolitic ash and lapilli	200
Mangatawai Tephra	220 mm dark greyish brown fine ash; 360 mm very dark grey to black medium ash (fine sand) with leaves; 80 mm pale brownish grey ash with rare charcoal on lower contact; 100 mm dark greyish brown ash; 90 mm yellowish brown fine scoriaceous lapilli; 470 mm yellowish brown to greyish brown ash grading down into purplish grey ash	1.32 m
	greyish yellow brown fine ash	300
Papakai Tephra	90 mm greyish yellow brown fine ash with inter- spersed pale yellow coarse ash; 340 mm greyish yellow brown ash with sparse yellow fine lapilli	430
Mangamate Tephra	grey fine to coarse angular lithic lapilli with rare very coarse lapilli (50 mm across)	540
	yellowish brown to brownish yellow fine and coarse ash	220
	grey andesitic pebbles with rare boulders and cobbles (alluvium) (erosional unconformity)	420

Formation	Description	Thickness (mm)
Okupata Tephra	yellowish red fine to coarse lapilli (bottom of basal lapilli of <u>Okupata Tephra?</u>)	90
	greyish yellow brown sandy silts with interbedded pebbles (reworked tephrae)	760
Rotorua Ash	yellow fine rhyolitic ash	0-30
	strong brown and dark grey fine lapilli	140
	very dark grey ash	40
	strong brown fine lapilli	40
	brown grey medium ash and coarse lithic ash (gritty sand)	30
	strong brown fine and medium lapilli	40
	brown grey medium and coarse ash (slightly gritty sand)	50
	yellowish brown to brownish yellow fine and medium lapilli in ash	40
	brownish grey coarse and medium lithic ash and fine lapilli	70
	yellowish red fine to coarse lapilli	170
	brown grey medium and coarse ash, fine lapilli (sands and gritty sands)	360
Rerewhakaaitu Ash	white to pale yellow fine rhyolitic ash (see Topping & Kohn 1973 for identification)	0-40
	dark grey and brownish grey medium and coarse ash (medium and coarse sands)	580

The identification of Rerewhakaaitu Ash interbedded with andesitic tephrae on the inside of the northern lateral moraine of Mangatepope Valley provides a minimum age of c. 14,700 years BP (NZ716, Vucetich and Pullar 1969) for glacial ice at this site. The brownish grey and dark

grey medium and coarse ashes above and below Rerewhakaaitu Ash can be correlated with similar tephra occurring within the crater of Pukeonake Scoria Cone. These beds were probably erupted from a recent crater near the summit of Pukekaiore dome prior to extrusion of an olivine andesite aa flow (see section 368).

Makahikatoa Valley (section no. 422): sections exposed on both northern and southern sides of the Makahikatoa Stream. A young lava flow from Ngauruhoe has deflected the stream against the southern lateral moraine of Makahikatoa Valley; N112/084792. Altitude: 1,190 m. About 70 m upstream from a section of morainic till described by Mathews (1967) (see Fig. 49).

(a) Section beneath recent Ngauruhoe lava flow:

Formation	Description	Thickness (mm)
Mangatawai Tephra	500 mm greyish brown ash; 930 mm dark grey medium ash (fine to medium sand) with interbedded beech leaves	1.43 m
	70 mm yellow and pale grey fine ash; 230 mm dark grey brown fine ash and peaty silt (containing wood); 90 mm grey brown fine ash and peaty silt	390
Papakai Tephra	220 mm brown fine ash, with yellow fine and medium lapilli; 460 mm brown fine ash and brown grey lithic coarse ash - fine lapilli, with sparse yellow pumiceous medium lapilli towards the base	680

Mangamate
Tephra

(b) downstream a few metres section description continues

Formation	Description	Thickness (mm)
Mangamate Tephra	brownish grey non-vesicular medium and coarse lapilli, grey andesitic lithic coarse lapilli and blocks	650
	yellowish brown fine and coarse ash	190
	brownish yellow to strong brown fine lapilli and grey fine lithic lapilli	70
Okupata Tephra	70 mm yellowish brown ash, grey lithic fine and medium lapilli;	
	110 mm brownish yellow coarse ash to coarse lapilli; 40 mm strong brown fine to coarse lapilli (<u>basal lapilli</u>)	180

The remainder of the Ruapehu tephra sequence, back to c. 14,000 years BP, is not described here. Rotorua Ash is present in this and neighbouring sections giving a minimum age of c. 12,500 years BP for the glacial moraine.

(c) The Ruapehu source tephtras (c. 10,000-14,000 years BP) are also present above an exposure of till on the southern bank of the stream about 50 m downstream of the site described by Mathews.

Waihoehonu Valley (section no. 494): section on the inside of the southern lateral moraine of Waihoehonu Valley; N112/165759. Altitude: 1,130 m.

Formation	Description	Thickness (mm)
Mangamate Tephra	brown fine ash with interspersed strong brown fine and medium lapilli; contains ohalazoidites	40
	80 mm grey, brownish grey and strong brown lapilli;	
	180 mm grey lapilli; 240 mm grey and strong brown lapilli; 280 mm grey, brownish grey and strong brown lapilli (<u>Oturere Lapilli</u>)	780

Formation	Description	Thickness (mm)
Mangamate Tephra	dark grey angular coarse ash (<u>Te Rato Lapilli</u>)	30
	yellowish brown ash with interspersed grey	
Karapiti Lapilli	coarse ash to medium lapilli containing a trace (0.5 mm) of pale yellow rhyolitic fine ash	90
(Pahoka Lapilli)	brownish grey and yellow coarse ash, fine, medium and coarse lapilli	160

The section, exposed by trenching on a gentle slope, revealed Rotorua Ash and many older andesitic tephtras. The underlying morainic till is therefore older than 12,500 years BP (Topping and Kohn 1973) and probably considerably older.

Mangahouhounui Valley (section no. 499): section on the north-facing outer slope of the northern ridge of Mangahouhounui Valley; N112/197844. Altitude: 1,185 m.

Formation	Description	Thickness (mm)
Mangamate Tephra	630 mm strong brown fine to coarse lapilli with a few grey very coarse lithic lapilli - finer average grain size towards top; 20 mm grey lithic coarse ash, fine lapilli; 60 mm strong brown fine to coarse lapilli (<u>Poutu Lapilli</u>)	710
	100 mm grey medium and coarse ash; 70 mm strong brown and grey medium and coarse ash, fine lapilli; 70 mm strong brown stained medium and coarse ash; 20 mm grey medium and coarse ash (<u>Wharepu Tephra</u>)	260

Formation	Description	Thickness (mm)
	strong brown stained medium and coarse ash (<u>Wharepu Tephra-Ohinepango Tephra</u>); Poronui Tephra is usually in the middle of this bed	50
	grey medium and coarse ash (<u>Ohinepango Tephra</u>)	60
	170 mm grey, strong brown and pale brown fine, medium and coarse lapilli; 110 mm grey medium and coarse ash with sparse grey and brown fine and medium lapilli; 180 mm bedded grey and strong brown medium and coarse ash, fine lapilli; 10 mm grey coarse and medium ash, fine lapilli (<u>Waihohonu Lapilli</u>)	470
	yellowish brown to brownish yellow ash and lapilli; white clays present 0-10 mm and 40-50 mm from base of unit	70
	strong brown to brownish yellow coarse ash, fine and medium lapilli (<u>Oturere Lapilli</u>)	160
	grey and yellow coarse ash, fine and medium lapilli (<u>Te Rato Lapilli</u>)	260
Papanetu Tephra- Karapiti Lapilli	pale yellow fine rhyolitic ash	10
	brown fine ash; paleosol	30
(Pahoka Lapilli)	grey and yellow medium and coarse lapilli	30
	yellow to pale yellow and grey coarse ash (erosional unconformity) undifferentiated andesitic tephra	

Formation	Description	Thickness (mm)
Rotorua Ash	white fine rhyolitic ash	20
	undifferentiated andesitic tephra white to pale yellow fine rhyolitic ash	0-5
Rotoaira Lapilli	30 mm grey fine ash; 160 mm strong brown medium and coarse lapilli in brown ash; 20 mm grey lithic coarse ash, fine and medium lapilli; 200 mm strong brown medium and coarse lapilli in brown ash; 30 mm grey fine ash; 30 mm strong brown fine to coarse lapilli; 70 mm grey fine ash and strong brown lapilli; grading into 280 mm strong brown medium and coarse lapilli; 50 mm purplish grey medium ash; 170 mm yellowish red to yellow medium to very coarse lapilli, rare blocks up to 90 mm across; 5 mm grey fine ash; 80 mm brownish yellow coarse ash, fine and medium lapilli; 10 mm grey fine ash	1.14m
ON	bouldery sands	

The oldest tephra exposed at this site, Rotoaira Lapilli, provides a minimum age of 13,800 years BP (NZ1559) for deposits, considered to be morainic, draped over this lava cored ridge.

In this area there is evidence of considerable erosion, initiated within the last 1819 years BP (i.e. since Taupo Pumice). Large tree trunks (Fig. 63) lying on the eroded surface indicate a previous higher tree-line in an area where the present vegetation is subalpine scrub and tussock.

Mangahouhounui Valley (section no. 498): a section exposed north of Mangahouhounui Stream on the lower slopes of what I interpret as a moraine-covered lava-cored ridge; N112/196840. Altitude : 1,090 m.

Formation	Description	Thickness (mm)
Mangamate Tephra	 grey, and pale yellow pumiceous, coarse ash, fine and medium lapilli (<u>Te Rato Lapilli</u>)	260
Papanetu Tephra- Karapiti Lapilli	pale yellow to white fine rhyolitic ash	10
	undescribed andesitic tephrae (erosional unconformity)	450
Rotoaira Lapilli	450 ⁺ mm (indistinct upper limit) brownish yellow ash, fine to coarse pumiceous and lithic lapilli; 50 mm grey medium ash (very fine sand); 260 mm brownish yellow to yellow mainly coarse to very coarse pumiceous lapilli; 5 mm grey medium ash; 160 mm brownish yellow coarse ash, fine and medium lapilli; 10 ⁺ mm grey medium ash	935 ⁺

The last major retreat of glacial ice from this site in Mangahouhounui Valley was prior to 13,800 years BP.

APPENDIX 1DTephra Sections Used to Date Lavas, Craters, Domes

Pukekaikioire aa flow (section no. 368): a stream section on the Mangatepopo-Whakapapa Village track west of Pukekaikioire dome and overlying the olivine andesite flow erupted from a vent near the summit of the dome; N112/076812. Altitude: 1,120 m.

Formation	Description	Thickness (mm)
Mangamate Tephra	grey fine to very coarse angular lithic lapilli	260
	yellowish brown ash with dark grey fine angular lithic lapilli scattered within bottom 70 mm	200
	yellow and grey coarse ash (coarse sand; water reworked tephra)	420
	60 mm brownish yellow fine to coarse pumiceous lapilli; 80 mm yellowish red fine to coarse pumiceous lapilli (<u>basal lapilli</u>)	140
Okupata Tephra	greyish brown fine to medium ash which coarsens to medium ash about half way down unit; in places a 40 mm brownish grey ash horizon is present 40 mm below the top of the unit	320
	brown fine lapilli with grey ash matrix within top 10-20 mm	70
	greyish brown medium and coarse ash (gritty sand)	90
	yellowish brown and grey fine to coarse lapilli	190
	yellowish brown ash	60
	40 mm yellow coarse ash, fine lapilli; 50 mm strong brown coarse ash, fine lapilli	90
	brown ash with interspersed yellow coarse ash	40

Formation	Description	Thickness (mm)
	strong brown coarse ash, fine lapilli	180
	dark grey to greyish brown ash with a few scattered strong brown to yellowish red fine lapilli	50
	yellowish red fine and medium lapilli in minor ash matrix	40
	dark grey to greyish brown ash with scattered yellowish red medium and fine lapilli	130
	yellowish red fine and medium lapilli	140
	greyish yellow brown ash, grading into greyish yellow brown ash with grey fine lithics and yellowish brown fine lapilli	80 90
	yellowish brown and grey (lithic) fine and medium lapilli	150
Pukekaikio Andesite (Grindley 1960)	blocks of olivine andesite aa flow erupted from a vent near the summit of Pukekaikio dome	1.17 ⁺ m

The unnamed basal lapilli (150 mm at this site) above the aa flow is known from section 369 (where it is 170 mm thick) to overlie 360 mm of brown grey medium and coarse ash and fine lapilli and 0-40 mm of Rerewhakaaitu Ash. It therefore post-dates 14,700 years B.P. The lava flow (section 368) was thus erupted probably slightly less than 14,700 years B.P.

Ohakune explosion craters (section no. 455): section on the southern side of the railway track on the western rim of the largest of the Ohakune explosion craters; N121/907518. Altitude: 615 m.

Formation	Description	Thickness (mm)
	yellowish brown ash	1.20 m
Oruanui	pale yellowish brown to yellowish white rhyolitic fine ash; medium ash at base (<u>Oruanui Ash</u>)	130
	yellowish brown ash	180
	yellowish brown ash with coarse lithic lapilli	260
	brownish yellow coarse ash, fine and a few medium lapilli and dark grey lithic lapilli	260
	strong brown and grey fine to very coarse lapilli in yellowish brown fine ash grading towards base into fine and medium, and a few coarse, lapilli	630
	very dark grey fine and medium lithic lapilli with brown fine ash matrix	250

Oruanui Ash occurs within andesitic tephra overlying ejecta from one of the explosion craters north of Ohakune. The crater is therefore older than 20,000 years B.P.

Ohakune explosion craters (section no. 456): the upper part of a section in a quarry, southern side of the railway line on the southern rim of the largest of the Ohakune explosion craters; N121/912511. Altitude: 603 m.

Formation	Description	Thickness (mm)
	dark brown fine ash; granular structure, soil	30
	yellowish brown fine ash	1.14 m
	yellowish brown ash with sparse brownish yellow coarse ash and fine lapilli	580

Formation	Description	Thickness (mm)
Oruanui	pale yellowish brown to yellowish-white fine rhyolitic ash containing chalazoidites; medium ash at base (<u>Oruanui Ash</u>)	130
	yellowish brown fine ash	100 ⁺

Tephra and lava flows exposed on the southern rim of the largest explosion crater north of Ohakune are older than 20,000 years B.P.

Rangatau Lakes (section no. 505): road cutting through rim of the more northerly of the Rangatau Lakes, 2.8 km southwest of Ohakune; N121/885469. Altitude: 570 m.

Formation	Description	Thickness (mm)
	yellowish brown ash	1.74 m
Oruanui	very pale yellowish brown fine and medium rhyolitic ash (<u>Oruanui Ash</u>)	180
ON	andesitic ash, lapilli and blocks from the explosion crater (maar)	

The more northerly of the two maars south-west of Ohakune is older than 20,000 years B.P.

Kuharua Dome (section no. 320): section on northern side of Kuharua Dome; N102/188082. Altitude: 810 m.

Formation	Description	Thickness (mm)
Mangamate Tephra	 greenish grey brown and yellowish brown (10YR 5/8) medium to coarse ash (<u>Te Rato Lapilli</u>)	120

Formation	Description	Thickness (mm)
Papanetu Tephra	dark yellowish brown (10YR 4/6) fine and medium ash; the upper 70 mm contains abundant medium and coarse ash grade clear grey obsidian fragments and blue-grey coarse lithic ash, and grades down into ash with rare medium ash grade obsidian	620

Haparangi
Rhyolite,
ha (Grindley
1960)

rhyolitic bed rock of Kuharua Dome

Both this section and two other tephra sections on Kuharua Dome show Papanetu Tephra directly overlying rhyolitic lava. The thickness (e.f. section 87; appendix) and isopach data (Topping and Kohn 1973, Fig. 4) show that the tephra was erupted from Kuharua Dome towards the end of dome formation. The radiocarbon age (NZ1372, NZ1373, NZ1374, see Table 2, p. 26) of about 9,785 years B.P. for Papanetu Tephra is therefore the age of completion of dome building.

Pukekaikioe Dome (section no. 324): exposure on the upper southern slopes of Pukekaikioe Dome (rhyolitic) 12 km north-west of Turangi; N102/217125. Altitude: 696 m.

Formation	Description	Thickness (mm)
Taupo Pumice	pale yellow ash, lapilli and blocks	450
Waimihia?	dark yellowish brown (10YR 4/4) ash grading down to yellowish brown (10YR 5/6) ash containing scattered pale yellow (2.5Y 7/4) medium and coarse ash, fine lapilli (mainly <u>Waimihia Lapilli?</u>)	290

Formation	Description	Thickness (mm)
Mangamate Tephra	greenish grey and yellowish brown medium ash (<u>Te Rato Lapilli</u>)	100
Papanetu Tephra	yellowish brown ash with medium ash grade obsidian fragments	0-5

Papanetu Tephra provides a minimum age of 9,790 years BP (NZ1734) for extrusion of Pukekaikio Dome.

Horohoro Dome (section no. 276): pit excavated on the north-eastern lower slopes of this small dacitic dome, situated 11 km east of Lake Rotoaira; N112/348901. Altitude: 630 m.

Formation	Description	Thickness (mm)
Mangatawai Tephra	(not described)	460
Whakaipo Tephra- Waimihia	yellowish brown fine andesitic ash with interspersed yellow medium and coarse rhyolitic ash and fine lapilli (<u>Whakaipo Tephra</u> and <u>Waimihia Lapilli</u> in unnamed andesitic ash)	540
Papakai Tephra	(not described)	550
Mangamate Tephra	strong brown lapilli and coarse ash (<u>Poutu Lapilli</u>)	420
	undifferentiated fine and medium ashes	130
	greenish grey lapilli and coarse ash (<u>Te Rato Lapilli</u>)	120
(Pahoka Lapilli)	greyish brown lapilli (overthickened?)	300
	yellowish brown coarse ash	220
	strong brown fine lapilli in yellowish brown ash; basal 80 mm has no ash matrix	170

Formation	Description	Thickness (mm)
	yellowish brown fine ash and coarse lithic ash	60
	grey lithic coarse ash, fine lapilli	80
	yellowish brown ash	40
Rotorua Ash	yellow fine rhyolitic ash as cream cakes	0-20
	yellowish brown ash with grey coarse lithic ash	340
	yellowish brown ash and scattered fine lapilli; indistinct contacts	70
	yellowish brown ash	110
Rotoaira Lapilli	strong brown fine to medium lapilli	80
	yellowish brown weathered andesitic ash	350 ⁺

Horohoro Dome is therefore known to be older than 13,800 years B.P.
(age of Rotoaira Lapilli).

Motuopuhi Island (section no. 319): section on south-eastern embayment of Motuopuhi Island, northern end of Lake Rotoaira; N112/198956. Altitude; 555 m.

Formation	Description	Thickness (mm)
Taupe Pumice	pale yellow rhyolitic ash, lapilli and blocks	900
Mangatawai Tephra	dark brownish grey ash	300
Waimihia	brownish grey ash with interspersed pale yellow rhyolitic ash; gradational boundaries (andesitic ash + <u>Waimihia Lapilli</u>)	360
Papakai Tephra	yellowish brown fine ash (greasy silt) with inter- spersed grey and strong brown fine lapilli; paleosol	300
Mangamate Tephra	strong brown coarse ash fine and medium lapilli (<u>Poutu Lapilli</u>)	670
	greenish grey and yellowish brown medium ash (medium sand) (<u>Wharepu Tephra</u>)	30
Poronui Tephra	pale yellow fine rhyolitic ash	0-10
Mangamate Tephra	yellowish brown ash with fine to medium lithic lapilli	30
	dark greenish grey andesitic fine lapilli, coarse ash and pale yellow dacitic medium lapilli (<u>Te Rato Lapilli</u>)	330
	yellowish brown ash and grey fine lithic lapilli	10
Papanetu Tephra	light grey rhyolitic fine and medium ash	10

Formation	Description	Thickness (mm)
	yellowish brown ash; brownish yellow coarse ash throughout upper 80 mm; sparse fine lapilli in lower 60 mm	140
	yellowish brown coarse ash, fine lapilli; slightly indurated	20
	grey (lithic) and brownish yellow coarse ash, fine lapilli	50
	strong brown fine lapilli	40
	grey medium ash	10
	strong brown coarse ash, fine lapilli	40
	yellowish brown fine ash, coarse ash and fine lapilli	20
	line of grey (lithic) and brownish yellow medium lapilli	10
	yellowish brown ash	100
Rotorua Ash	yellow rhyolitic fine ash	40
	yellowish brown fine ash	40
	30 mm yellowish red coarse ash, fine lapilli; 30 mm strong brown and grey fine to medium lapilli	60
	yellowish brown fine ash with scattered brownish yellow coarse ash	80
	yellowish brown fine and coarse ash, fine lapilli	20
	yellowish brown ash, brownish yellow fine lapilli	70
	yellowish brown fine ash	390
Rotoaira Lapilli	30 mm yellowish red coarse ash, fine lapilli; 10 mm grey medium ash (fine sand); 90 mm brownish yellow fine and medium lapilli with sparse strong brown pumiceous coarse lapilli at the base	130

Formation	Description	Thickness (mm)
	greyish yellow brown ash with numerous pale yellowish brown fine lapilli (white-grey when broken; reworked Motuopuhi dacite?)	600
?Rerewhakaaitu Ash	some white rhyolitic fine ash also appears in this unit - the stratigraphic position, >13,800 yrs BP, and ferromagnesian assemblage of biotite, a; hypersthene, a; hornblende, c; and augite, S; suggests correlation with Rerewhakaaitu Ash	10
	brownish yellow coarse ash, fine lapilli	30
	yellowish brown fine ash, pale brown lapilli (white grey when broken) and numerous grey lithic fine lapilli	100
	30 mm brownish yellow fine and medium lapilli; 50 mm brownish yellow coarse ash, fine to medium lapilli; in places this unit becomes 70 mm grey lithic fine lapilli and brownish yellow to strong brown fine, medium, and sparse coarse pumiceous lapilli	80
Hinuera	rhyolitic silts and sands with occasional layers of very pale brown rhyolitic pumice pebbles (re-worked fine to medium lapilli)	1.12 m
Oruanui	pale brown rhyolitic ash and sparse pumiceous lapilli (<u>Oruanui Breccia</u>) (inferred hiatus)	1.50 ⁺ m

Formation	Description	Thickness (mm)
	yellowish brown and grey fine and medium lapilli	360
	brownish yellow coarse to fine lapilli, rare blocks	230
	pale yellow (soft) coarse and medium lapilli, rare blocks	1.02 ⁺ m
ON	pale grey pumiceous dacite of Motuopuhi Island (upper contact with tephra under water and not seen).	

The three andesitic lapilli units below Oruanui Breccia were probably erupted from one of the two craters immediately south of Lake Rotopounamu. The Oruanui Breccia provides a minimum age of 20,000 years BP for extrusion of the dacitic lava that forms the island.

APPENDIX 2Section Locations Used in this Thesis

All grid references are based on the national thousand-yard grid of the 1:63,360 topographic map series (NZMS1).

The dates of publication of sheets used in this study are:

Ngauruhoe	N112 - 1968 (1st Edition)
Tokaanu	N102 - 1971 (2nd Ed)
Ruapehu	N122 - 1971 (2nd Ed)
Waimarino	N111 - 1971 (1st Ed)
Taumarunui	N101 - 1972 (1st Ed)
Ohakune	N121 - 1968 (1st Ed)
Kaweka	N113 - 1970 (2nd Ed)
Rangitaiki	N103 - 1969 (2nd Ed)
Taupo	N94 - 1969 (1st Ed)

<u>Section No.</u>	<u>Grid Ref.</u>	<u>Section No.</u>	<u>Grid Ref.</u>	<u>Section No.</u>	<u>Grid Ref.</u>
1	N112/291879	36,88	N112/230990	71	N112/293968
2	N112/289880	37,94	N102/248009	72	N102/276010
3	N112/282889	38	N112/303926	73	N102/256015
4	N112/285886	39	N112/300941	74	N112/191972
5	N112/284888	40	N112/297947	75	N112/191972
6	N112/283888	41	N112/297948	76	N112/193973
7	N112/275890	42	N112/298951	77	N112/197972
8	N112/272890	43	N112/296958	78	N112/200974
9	N112/274893	44	N112/293967	79	N112/202974
10	N112/272896	45	N112/105987	80	N112/206971
11	N112/270895	46	N112/101977	81	N112/208968
12	N112/266896	47	N112/083931	82	N112/211969
13	N112/277896	48	N112/140958	83	N112/214969
14	N112/252898	49	N112/140962	84	N112/217973
15	N112/249898	50	N112/095975	85	N112/219977
16	N112/242900	51	N112/102990	86,63	N112/221978
17	N112/239901	52	N112/096989	87	N112/222981
18	N112/294879	53	N112/094986	87(a)	N112/224983
19	N112/296876	54	N112/099984	88,36	N112/230990
20	N112/298873	55	N112/254907	89	N112/232992
21	N112/298871	56	N112/074925	90	N112/234997
22	N112/301844	57	N112/122930	91	N102/238004
23	N112/210899	58	N112/125924	92	N102/241007
24	N112/208899	59	N112/132922	93	N102/244009
25	N112/204901	60	N112/109984	94,37	N102/248009
26	N112/185908	61	N112/106979	95	N102/259008
27	N112/176916	62	N112/105979	96	N102/258005
28	N112/174916	63,86	N112/221978	97	N112/267896
29	N112/156919	64	N112/069918	98	N112/031856
30	N112/135921	65	N112/061933	99	N112/023850
31	N112/097941	66	N112/061912	100	N112/021843
32	N112/150978	67	N112/050895	101	N112/020836
33	N112/158980	68	N112/048894	102	N112/014827
34	N112/176979	69	N112/046890	103	N112/010821
35	N112/188973	70	N112/037866	104	N112/010820

<u>Section No.</u>	<u>Grid Ref.</u>	<u>Section No.</u>	<u>Grid Ref.</u>	<u>Section No.</u>	<u>Grid Ref.</u>
105	N111/993803	140	N102/271000	177	N112/137750
105(a)	N111/994802	141	N112/274999	178	N102/235048
106	N111/974785	142	N112/117923	179	N102/227062
107	N111/905806	143	N112/115915	180	N102/227064
108	N111/901819	144	N112/111907	181	N102/226068
109	N112/291873	145	N112/135915	182	N102/227070
110	N112/297848	146	N112/138912	183	N102/228094
111	N112/289861	147	N112/156864	184	N102/226105
112	N112/287858	148	N112/166877	185	N102/246116
113	N112/254816	149	N112/168877	186	N102/239128
114	N112/253810	150	N112/161872	187	N102/216107
115	N112/250806	151	N112/161872	188	N102/198121
116	N112/250787	152	N112/161872	189	N102/197122
117	N112/248779	153	N112/160859	190	N102/172143
118	N112/243764	154	N112/155852	191	N102/143134
119	N112/045907	155	N112/136855	192	N102/143137
120	N112/040928	156	N112/137856	193	N102/137137
121	N112/036930	157	N112/139872	194	N102/126137
122	N112/032930	158	N112/130885	195	N102/115136
123	N112/025928	159	N112/124893	196	N102/106133
124	N112/029933	160	N112/134902	196(a)	N102/104132
125	N112/028938	161	N112/216709	197	N102/098129
125(a)	N112/023941	162	N112/215704	198	N102/090131
126	N112/020945	163	N122/223694	199	N102/079135
127	N111/998936	164	N112/064823	200	N102/074137
128	N112/003791	165	N112/080819	200(a)	N102/063138
129	N112/014787	166	N112/080819	201	N102/058139
130	N112/017856	167	N112/065838	202	N102/057142
131	N111/	168	N112/065832	202(a)	N102/054147
132	N112/240747	169	N122/219675	203	N102/047155
133	N112/231741	170	N122/223671	204	N102/043167
134	N112/224736	171	N122/228655	205	N102/037164
135	N112/222732	172	N112/149745	206	N102/031160
136	N112/153902	173	N112/102751	207	N102/025153
137	N112/150901	174	N112/105758	208	N102/015141
138	N112/134897	175	N112/109763	208(a)	N102/007130
139	N112/288992	176	N112/135750	209	N102/002129

Section No.	Grid Ref.	Section No.	Grid Ref.	Section No.	Grid Ref.
210	N102/179194	245	N121/884581	282	N112/251943
211	N102/175178	246	N121/843553	283	N122/223622
212	N102/175161	246(a)	N121/841554	284	N122/210585
213	N102/175156	247	N121/903496	285	N122/197533
214	N112/228969	248	N121/882519	285(a)	N122/197528
215	N112/233964	249	N121/833550	286	N122/194524
216	N112/214963	250	N121/835546	287	N111/902827
217	N112/214960	251	N121/941481	288	N111/903829
218	N112/217966	252	N121/948479	289	N111/905832
219	N112/298817	253	N121/966459	290	N111/882880
220	N112/257897	254	N121/972456	291	N111/885894
221	N112/268992	255	N121/980454	291(a)	N111/888897
222	N112/266991	256	N121/986452	291(b)	N111/887899
223	N112/267993	257	N121/986452	292	N111/888901
224	N102/358078	258	N121/994444	293	N111/883909
225	N133/705290	259	N122/004434	294	N111/881914
226	N102/258003	260	N122/014424	295	N111/878919
226(a)	N102/259002	261	N122/053426	297	N101/886034
227	N112/292998	262	N122/116427	298	N101/873056
227(a)	N112/292988	263	N122/147432	299	N101/872058
228	N102/368031	264	N122/148433	299(a)	N101/870058
229	N102/382012	265	N122/149433	300	N101/864063
230	N112/430974	266	N112/037749	301	N101/863064
230(a)	N112/414969	267	N112/036749	302	N101/862066
233	N122/227649	268	N112/041736	308	N112/304841
234	N112/094747	269	N112/041735	309	N112/302846
234(a)	N112/094745	270	N112/238913	310(a)	N112/145983
235	N112/065756	271	N112/193904	310	N112/145983
236	N112/045754	272	N112/170905	311	N112/145984
237	N111/907778	273	N112/171911	312	N112/143984
238	N111/907765	274	N112/181914	313	N112/156971
239	N111/907756	275	N112/181913	314	N112/152973
240	N111/907753	276	N112/348901	315	N112/151974
241	N111/908749	277	N102/247015	316	N112/149976
242	N111/898717	278	N112/061859	317	N112/147971
243	N121/896677 to 904677	279	N112/077856	318	N112/144968
244	N121/895669	280	N112/079863	319	N112/198956
		281	N112/258974	320	N102/188082

<u>Section No.</u>	<u>Grid Ref.</u>	<u>Section No.</u>	<u>Grid Ref.</u>	<u>Section No.</u>	<u>Grid Ref.</u>
321	N102/185079	356	N112/042812	392	N112/344761
322	N102/189086	357	N112/051817	393	N112/377795
323	N112/282801	358	N112/054819	394	N112/403826
324	N102/217125	359	N112/133853	395	N112/434845
325	N112/209946	360	N112/130856	396	N113/462852
326	N112/215948	360(b)	N112/131854	397	N112/431846
327	N112/209942	360(a)	N112/132852	398	N112/373822
328	N102/338064	361	N112/134848	399	N112/273720
329	N102/306018	362	N112/143851	400	N112/268719
330	N112/011820	363	N112/148846	401	N112/002726
331	N112/014819	364	N112/082816	402	N111/980716
332	N112/022816	365	N112/078814	403	N111/954724
333	N112/027843	366	N112/090813	404	N122/059665
334	N112/032842	367	N112/077813	405	N122/064655
335	N112/044835	368	N112/076812	406	N122/064658
336 & (a)	N112/046835	369	N112/089822	407	N122/055663
337	N112/049836	370	N112/145885	408	N122/055651
338	N112/052835	370(a)	N112/145885	409	N111/972764
339	N112/068842	371	N112/278799	410	N112/012793
340	N112/064847	372	N112/138829	411	N112/012796
341	N112/059849	374	N112/301829	412	N112/015801
342	N112/046765	375	N112/209983	413	N112/014808
343	N112/056779	376	N102/210005	414	N112/013810
344	N112/062783	377	N102/212006	415	N112/011814
344(a)	N112/073808	378	N102/214006	416	N111/
345	N112/012713	379	N102/215006	417	N111/981740
346	N112/041726	380	N102/217005	418	N111/971765
347	N112/041729	381	N102/218006	419(a)	N111/980736
348	N112/060820	382	N102/218015	419(b)	N111/980737
348(a)	N112/055816	383	N102/216018	419(c)	N111/956748
349	N112/054816	384	N102/211002	420	N112/073807
349(a)	N112/053816	385	N112/129841	421	N112/069798
350	N112/049817	286	N112/151843	422	N112/084792
351	N112/047816	387	N112/178803	423	N112/072797
352	N112/045816	388	N112/166833	424	N112/232925
353	N112/045814	389	N112/146856	425	N112/230927
354	N112/045813	390	N112/259700	426	N112/227928
355	N112/044812	391	N112/329734	427	N112/225929

<u>Section No.</u>	<u>Grid Ref.</u>	<u>Section No.</u>	<u>Grid Ref.</u>
428	N121/895680	470	N103/734420
429	N121/882562	471	N122/117596
430	N121/860608	472	N122/113643
431	N121/867591	473	N122/113649
432	N121/867589	474	N112/136828
433	N121/806524	475	N112/140827
434	N121/805444	476	N112/145825
435	N121/806440	477	N112/146826
436	N121/814475	478	N112/148823
437	N121/816475	479	N112/148822
438	N121/833477	480	N112/151819
439	N121/891478	481	N112/153823
440	N121/948542	482	N112/157823
441	N121/974564	483	N112/156828
442	N121/976577	484	N112/153830
443	N121/986587	485	N112/146841
444	N121/993595	486	N113/470986
450	N122/019623	489	N112/177756
451	N122/017622	490	N112/186746
452	N122/007614	491	N112/191761
453	N122/006610	492	N112/174764
454	N121/996602	493	N112/168764
455	N121/907518	493(a)	N112/162763
456	N121/912511	494	N112/165759
457	N122/116517	495	N112/174804
458	N122/098553	496	N112/177803
459	N122/097565	497	N112/198828(?)
460	N122/165595	498	N112/196840
461	N122/175575	499	N112/197844
462	N122/171664	500	N112/199844
463	N122/132666	501	N112/198839
464	N121/918504	502	N112/167782
465	N112/093747	503	N112/163775
466	N112/089720	504	N112/201724
466(a)	N112/089721	505	N121/885469
467	N112/177870	506	N112/173980
468	N112/175873	507	N112/107982
469	N112/170866		

APPENDIX 3

Key to Accompany Tables 5, 6 and 7

All thicknesses are in centimetres

Pk	Puketarata Ash (rhyolitic)
Rk	Rerewhakaaitu Ash (rhyolitic)
OuB	Oruanui Breccia Member (tephra flow)
OuA	Oruanui Ash Member (tephra fall)
Ou	undifferentiated Oruanui Formation
?Re	probable Rotoehu Ash
TW	Te Whaiti Ignimbrite Formation
Hi	Hinuera Formation
A	composite thickness for andesitic tephra below Mangamate Formation and above Rotorua Ash
B	composite thickness for andesitic tephra below Rotorua Ash and above Rotoaira Lapilli
47(2)19	re Papakai Tephra : top to bottom of bed - 47 cm of Papakai Tephra 2 cm pocket or cream cakes of Hinemaiaia Ash, 19 cm of Papakai Tephra
r	unnamed rhyolitic tephra
t	unnamed andesitic tephra : individual or grouped beds
T	unnamed andesitic tuff or lapilli tuff : single or multiple beds
b	probable loess beds
L	laharic breccia, debris flow and mudflow deposits
a	alluvium
vb	volcanic breccia
tf	andesitic tephra flow deposit
b,t	undifferentiated loess and tephra beds
(r)	reworked tephra (mainly fluvial)
?	origin of bed uncertain
* **	unnamed bed(s) interbedded within a named tephra sequence
x ⁺	minimum thickness (in centimetres)

- tr trace only, <5 mm thick
- p pocket or lens
- (c) tephra unit occurs as cream cakes
- erosional unconformity
- no measurement recorded.

Where solid horizontal lines are missing from a stratigraphic column the thickness stipulated is a composite measurement for all units between the enclosing solid horizontal lines.

APPENDIX 4

Table 3. Relative abundances of ferromagnesian minerals from rhyolitic tephrae present in the Tongariro Volcanic Centre. Samples are also included from the type localities for Rotoma Ash and Puketarata Ash.

Relative Abundance Symbols

A = very abundant	> 50%
a = abundant	30-50%
C = very common	10-29%
c = common	5-9%
S = scarce	1-4%
R = rare	< 1%

Abbreviations

T.L.	- type locality
a	- ash grade tephra
L	- lapilli grade tephra
c	- "cream cakes"
p	- pocket
sh.b.	- shower bedded
xmm	- thickness of bed
x-ymm	- position of sample within thick tephra
*	Cumingtonite
?	Correlation not certain
(large)	- large grains, likely to be contaminants
sc	- rhyolitic ash scattered with finer andesitic ash

TABLE 3: (continued)

Section No.	Location	Grid Reference	Hypersthene	Augite	Calcic Hornblende	Biotite
<u>Whakaipo Tephra</u>						
229	Kepa Road, 8 km east of Turangi (90mm, L)	N102/382012	A	C	-	-
170	Desert Road, 15 km east of Ruapehu (20mm, c, a)	N122/223671	A	C	-	-
<u>Waimihia Lapilli</u>						
460	Rangipo Desert, 11 km SE of Ruapehu (30mm, a)	N122/165595	A	S	-	-
229	Kepa Road, 8 km east of Turangi (410mm, L)	N102/382012	A	C	-	-
170	Desert Road, 15 km east of Ruapehu (120mm, scattered, a)	N122/223671	A	C	-	-
453	Blyth Track, 6 km SW of Ruapehu (30mm, a)	N122/006610	A	a	-	-
<u>Hinemaiaia Ash</u>						
229	Kepa Road, 8 km east of Turangi (70mm, a)	N102/382012	A	C	-	-
58	National Park-Taupo Road, 1 km SE of Te Rato School (60mm, p, a)	N112/125924	A	C	-	-
170	Desert Road, 15 km east of Ruapehu (10mm, sc. a)	N122/223671	A	C	-	-
118	Desert Road, 11 km east of Ngauruhoe (60mm, a)	N112/243764	A	S	-	-
<u>Rotoma Ash</u>						
-	Democrat Road, Reremahakaaitu (810mm, a, T.L.; 280-430mm)	N86/934824	C	R	A	-
-	-ditto- (480-570mm)	"	C	R	A	-
60 ?	Otanangakau Canal, 16 km NNW of Ngauruhoe (20mm, a)	N112/109984	A	C (large)	C	C (large)

TABLE 3: (continued)

Section No.	Location	Grid Reference	Hypersthene	Augite	Calcic Hornblende	Biotite
<u>Poronui Tephra</u>						
229	Kepa Road, 8 km east of Turangi (60mm,a)	N102/382012	A	S	-	-
397	Waipahihi River Valley, 4.3 km east of Ngauruhoe	N112/431846	A	C	-	-
<u>Papanetu Tephra</u>						
87(a)	Te Ponanga Saddle Road, 18 km NNE of Ngauruhoe (20mm, a, T.L.)	N112/224983	A	c	-	-
73	Te Ponanga Saddle Road, 3 km west of Turangi (30mm,a)	N102/256015	A	C	-	-
<u>Karaiti Lapilli</u>						
486	Fletcher's Road, 17 km east of Turangi (220mm,a; upper sample)	N113/470986	A	S	-	-
"	-ditto- (lower sample)	"	A	C	-	-
<u>?Rotorua Ash</u>						
58	National Park-Taupo Road, 1 km SE of Te Rato School (40mm,a)	N112/125924	A	R	R	C
24	Poutu Canal, 17 km ENE of Ngauruhoe (20mm,a)	N112/298874	A	R	C	c
15	National Park-Taupo Road, 14 km NE of Ngauruhoe (20mm,a)	N112/249898	A	R	C	c
340	Wairehu Canal, 16 km north of Ngauruhoe (40mm,a)	N112/145983	A	R	C	c
62	Otamangakau Canal, 16 km NNW of Ngauruhoe (40mm,a)	N112/105979	A	R	C	S
421	Mangatopopo-Whakapapa Village track, 5 km W of Ngauruhoe (60mm,a)	N112/069798	A	S	S	S
<u>Puketarata Ash</u>						
-	Palmer Road, 5 km NW of Wairakei (500mm, a,L; 180-250mm)	N94/542499	a	-	C	a
-	Palmer Road, (500 mm,sh.b., a,L)	N94/542499	a	-	a	a

TABLE 3: (continued)

Section No.	Location	Grid Reference	Hypersthene	Augite	Calcic Hornblende	Biotite
-	Wairakei-Putaruru Highway, 11 km N. of Wairakei (4.57 m, L, T.L.)	N94/516544	a	-	a	C
115 ?	Desert Road, 11 km east of Ngauruhoe (190m, p.a.)	N112/250806	a	-	A	c
87(a)?	Te Ponanga Saddle Road, 18 km NNE of Ngauruhoe (30m, p.a.)	N112/224983	A	S	C	S
340(a)?	Wairehā Canal, 16 km north of Ngauruhoe (10m, a)	N112/145983	a	S	S	A
		<u>Unknown ash</u>				
87(a)	Te Ponanga Saddle Road, 18 km NNE of Ngauruhoe (20m, p.a.) (below Pk.A., above Et. Lapilli)	N112/224983	A	c	-	-
		<u>Rerewhakaaitu Ash</u>				
369	Mangatepopo Valley, 3.5 km WNW of Ngauruhoe (40m, a)	N112/089822	C	-	c	A
87(a)	Te Ponanga Saddle Road, 18 km NNE of Ngauruhoe (60m, p.a.)	N112/224983	c	-	c	A
17 ?	National Park-Taupo Road, 13.5 km NE of Ngauruhoe (50m, a)	N112/239901	a	c	-	A
70 ?	National Park-Taupo Road (30m, p.a.)	N112/037866	A	c	R	c
349 ?	Motuofuhi Island, Lake Rotoaira (20m, p.a.)	N112/198956	a	S	c	a
		<u>70kareka Ash</u>				
507 ?	Otamangakau Canal, 16 km NNW of Ngauruhoe (40m, a)	N112/107982	S	-	c (S*)	A
		<u>Oruanui Breccia</u>				
58	National Park-Taupo Road, 1 km SE of Te Rato School (4.00 m, a)	N112/125924	A	c	c	-

TABLE 3: continued

Section No.	Location	Grid Reference	Hypersthene	Augite	Calcic Hornblende	Biotite
<u>Oruanui Ash</u>						
58	National Park-Taupo Road, 1 km SE of Te Rato School (1,080mm,a)	N112/125924	A	C	R	-
209	Turangi-Taumarunui Road 29 km WNW of Turangi (water-reworked,a)	N102/002129	A	S	C	-
<u>Okaiia tephra</u>						
193	Turangi-Taumarunui Road, 18 km NW of Turangi (100mm,a)	N102/137137	A	R	C	-
195	Turangi-Taumarunui Road, 19 km NW of Turangi (210mm,a)	N102/115136	A	S	C	-
<u>Pink ash</u>						
195	Turangi-Taumarunui Road, 19 km NW of Turangi (400mm,a)	N102/115136	A	S	C	-
94	Te Ponanga Saddle Road, 4 km west of Turangi (250mm,p.a.)	N102/248009	A	C (large)	C	-
<u>Rototoehu Ash</u>						
94	Te Ponanga Saddle Road, 4 km west of Turangi (70mm,p.c.a.)	N102/248009	A	C	S (S*)	S
<u>Old unnamed ash</u>						
62	Otamangakau Canal, 16 km WNW of Ngauruhoe (40mm,a)	N112/105979	A	S	S	-

Table 10: Grain-size cumulative percentage data for eight Tongariro Sub-group tephras

Sample No.	Class Limit	Cumulative Percentage										Rest
		-4.20	-3.70	-3.00	-2.00	-1.00	0.00	1.00	2.00	3.00	4.00	
<u>Te Rato Lapilli</u>												
2		0.00	0.00	0.35	2.09	13.50	60.28	84.13	93.13	98.44	99.70	100.00
7A		0.00	0.00	0.00	1.02	13.70	52.11	85.24	93.96	99.16	99.27	100.00
7B		0.00	0.00	0.00	1.15	14.55	51.88	87.34	99.73	99.39	99.43	100.00
14		0.00	0.00	0.48	6.43	33.86	50.76	84.27	98.73	98.77	99.09	100.00
18		0.00	0.00	0.00	1.12	13.69	60.97	85.58	97.98	98.27	98.88	100.00
25		0.00	0.00	4.36	13.70	44.79	84.83	97.57	98.03	98.23	98.71	100.00
27		0.00	0.00	0.36	11.82	50.15	86.50	97.65	97.95	98.08	98.38	100.00
31		0.00	0.00	1.17	6.69	36.71	83.40	97.53	98.15	98.52	98.97	100.00
32		0.00	0.00	0.00	2.88	24.09	66.40	95.82	98.12	98.76	98.98	100.00
32 Dacite		0.00	0.00	3.89	14.44	50.30	83.80	97.47	99.19	99.59	99.79	100.00
32 Andesite		0.00	0.00	0.00	2.36	23.54	61.34	90.67	97.35	98.15	98.56	100.00
36		0.00	0.00	0.00	0.00	2.38	37.44	81.54	99.81	99.10	99.22	100.00
37		0.00	0.00	0.00	0.70	9.79	48.71	82.34	90.66	93.71	99.12	100.00
42		0.00	0.00	0.00	0.43	9.50	43.85	90.04	95.30	95.64	97.75	100.00
50		0.00	0.00	0.53	8.51	35.19	75.91	95.25	97.19	97.42	98.06	100.00
51		0.00	0.00	0.47	3.50	21.52	64.87	93.53	97.47	97.78	98.46	100.00
53		0.00	0.00	0.77	3.19	30.80	75.81	96.06	98.49	98.74	99.17	100.00
57		0.00	0.00	0.00	7.62	32.78	72.01	95.13	98.52	98.75	99.18	100.00
60		0.00	0.00	0.44	3.64	25.91	66.85	95.71	99.05	99.25	99.45	100.00
63		0.00	0.00	0.00	1.56	13.31	52.51	90.78	97.05	98.23	98.95	100.00
136		0.00	0.25	4.09	16.38	46.45	79.77	98.05	99.79	99.82	99.82	100.00
157		0.00	2.35	12.57	30.04	60.32	89.51	97.18	99.54	99.72	99.79	100.00
159		0.00	1.66	9.21	24.17	52.99	82.72	97.30	98.55	98.91	99.12	100.00
160		0.00	1.90	4.91	12.31	33.00	69.31	93.52	95.31	96.96	97.81	100.00
506		0.00	0.00	0.73	8.23	46.74	87.52	97.37	97.93	98.01	98.36	100.00
<u>Poutu Lapilli</u>												
118		0.00	0.00	7.68	26.88	56.49	75.36	97.44	98.61	98.90	99.12	100.00
179		0.00	0.00	0.00	1.93	21.86	71.67	91.81	93.49	95.67	97.42	100.00
197		0.00	0.00	0.68	11.47	55.00	86.04	91.90	95.52	97.59	99.00	100.00
217		0.00	0.87	6.78	29.47	65.30	87.65	91.20	93.79	96.01	97.44	100.00
224		0.00	0.00	0.00	0.88	16.16	53.95	73.55	98.75	99.33	99.62	100.00
<u>Whareni Tephra</u>												
116		0.00	0.00	0.00	0.04	0.31	3.72	62.37	90.34	94.04	96.20	100.00
118		0.00	1.80	32.22	59.35	95.48	98.63	98.98	99.13	99.23	99.39	100.00
<u>Ohinerango Tephra</u>												
116		0.00	0.00	0.00	0.00	0.24	5.94	48.50	91.06	97.96	98.79	100.00
<u>Waihohehu Lapilli</u>												
118		0.00	0.00	5.41	18.55	61.43	93.75	99.20	99.57	99.67	99.73	100.00
<u>Otureru Lapilli</u>												
115		2.27	2.27	15.46	37.81	69.69	82.09	95.30	97.76	98.80	99.10	100.00
<u>Pahoka Lapilli</u>												
2		0.00	6.18	21.00	48.85	72.94	82.42	85.32	88.91	92.56	95.43	100.00
<u>Rotoaira Lapilli</u>												
2		0.00	0.00	0.00	1.29	9.18	34.30	77.26	96.37	97.24	98.21	100.00

Volumes of Tephra Deposits

Volumes for tephra described in this paper have been calculated using the formula, $13.08ab^2$ (Cole and Stephenson 1972), where 'a' is the thickness of the tephra at the source and 'b' is the distance over which that thickness is halved. For asymmetrical distribution patterns radii of circles were determined which had the same area as that enclosed within each of the isopachs (Thorarinsson 1954). (It can be shown mathematically that the formula holds for calculation of volume of an ellipse (R. Allis pers. comm.): if d and b are the major and minor radii of the ellipse where the thickness is halved then the circle is the special situation where d = b). The radii were then plotted against isopach thicknesses on log-normal paper and 'a' read as the intercept of the line with the y-axis.

<u>Tephra</u>	<u>Volume (km³)</u>
<u>Andesitic tephra:</u>	
Ngauruhoe Tephra	1.3
Papakai Tephra	1.5
Poutu Lapilli	0.9
Te Rato Lapilli	0.1
Okupata Tephra, basal lapilli	0.2
Rotoaira Lapilli	0.2
Mangatawai Tephra + andesitic tephra above Waimihia Lapilli	1.2
<u>Rhyolitic Tephra:</u>	
Kaharoa Ash	1.7
Taupo Lapilli	6.2
Rotongaio Ash	0.2
Mapara Tephra	0.7*
Whakaipo Tephra	0.8*
Hatepe Lapilli	1.2
Waimihia Lapilli (wm2)	6.2

<u>Tephra cont.</u>	<u>Volume (km³)</u>
Whakatane Ash	1.1
Hinemaiaia Ash	5.0* (considered maximal by Vucetich and Pullar 1973)
Mamaku Ash	2.3
Rotoma Ash	5.1
Opepe Tephra	5.0* (considered maximal by Vucetich and Pullar 1973)
Poronui Tephra	3.5*
Papanetu Tephra	0.02
Karapiti Lapilli	5.0*
Waiohau Ash	3.4
Rotorua Ash	0.9
Puketarata Ash	0.06
Rerewhakaaitu Ash	1.8
Okareka Ash	4.5
Te Rere Ash	2.8
Oruanui Formation	17.4
<u>Basaltic Tephra:</u>	
Tarawera basalt	0.3
Rotokawau Ash	0.4

* These values are from Vucetich and Pullar (1973).

The tephra volumes should only be regarded as relative and not absolute volumes. They do not record the volume of newly fallen tephra which Thorarinsson (1954) states may be up to three times larger. The calculations have been based on isopach data from Vucetich and Pullar 1964, 1969; Topping 1973; Topping and Kohn 1973; and Cole 1972.

Table 11: Titanomagnetite analyses of andesitic tephra and lavas of the Tongariro Volcanic Centre

ANDESITIC TEPHRA AND LAVA													
Analysis No.	Sample	Locality	Grid Reference	Ti%	Mg%	Mn%	Ca%	V	Cr	Co	Ni	Zr	Cu
1	Ngauruhoe Tephra	Desert Road	N112/250787	5.06	1.96	0.45	0.47	5184	914	175	289	98	101
2	Mangatawai Tephra	Makahikitoa Bridge Desert Road basal 40 cm	N112/250787	3.33	1.79	0.21	1.08	3572	726	136	239	121	200
3	Papakai Tephra	Desert Road ash within paleosol	N112/250787	6.73	1.64	0.50	0.17	4552	812	187	277	85	108
4	Poutu Lapilli	National Park-Taupo Road	N112/239901	5.77	1.15	0.43	0.66	4954	1706	163	322	103	170
5	Poutu Lapilli	S.E. of Blue Lake	N112/166833	2.64	1.54	0.38	1.45	3136	958	198	289	56	269
6	Poutu Lapilli	Desert Road	N112/298951	2.97	0.79	0.28	2.64	3206	764	128	225	74	93
7	Poutu Lapilli	Iwatahi Gully in paleosol on Poronui Tephra	N103/735200	5.39	1.47	0.38	0.46	4913	562	142	217	138	96
8	Te Rato Lapilli	Te Ponanga Road	N112/221978	3.64	0.66	0.30	1.17	4337	960	163	284	70	121
9	Te Rato Lapilli	Ketetahi Springs finely vesiculated lithic fragments	N112/139872	5.06	1.35	0.33	0.62	4203	1502	156	248	88	171
10	Te Rato Lapilli	Okahukura Bush (N. Tongariro) pumiceous lapilli	N112/153902	3.31	1.09	0.35	0.44	1628	93	72	53	16	52
11	Te Rato Lapilli	Iwatahi Gully	N103/735200	6.57	1.00	0.43	0.16	4363	475	104	176	204	91
12	Okupata Tephra	National Park-Taupo Road upper ash	N112/037866	6.91	1.63	0.25	0.30	5797	2212	176	366	108	75
13	Okupata Tephra	National Park-Taupo Road	N112/037866	5.72	1.80	0.24	0.63	5019	1843	192	338	76	118
14	Unnamed tephra (below Okupata T)	National Park-Taupo Road basal lapilli	N112/037866	5.39	1.90	0.25	0.27	4981	2284	209	446	76	105
15	Unnamed tephra (below Okupata Tephra)	Near Hydro Access Road	N112/105987	5.87	1.87	0.26	0.34	5367	2242	202	380	74	248

Table 11 continued: Titanomagnetite analyses of andesitic tephra and lavas of the Tongariro Volcanic Centre

Analysis No.	Sample	Locality	Grid Reference	Ti%	Mg%	Mn%	Ca%	V	Cr	Co	Ni	Zr	Cu
16	Unnamed tephra (below Okupata T)	National Park-Taupo Road	N112/069918	6.41	1.99	0.31	0.27	6899	2509	221	453	67	95
17	Rotoaira Lapilli	National Park-Taupo Road	N112/239901	7.13	1.46	0.24	0.24	6401	1941	186	393	95	164
18	Rotoaira Lapilli	Rotoaira Road	N112/158980	7.41	1.80	0.35	0.27	9870	2472	219	499	108	180
19	Te Mari Lava Flow	Lower Te Mari Crater upper flows	N112/161872	7.14	1.50	0.28	0.30	7037	1791	225	371	108	133
20	Te Mari Lava Flow	Lower Te Mari Crater lower flows	N112/161872	7.24	1.18	0.26	0.29	6120	1345	198	314	119	136
21	Unnamed andesitic tephra below Rotoaira Lapilli	Desert Road	N112/291879	7.98	1.74	0.36	0.13	5326	2056	315	531	198	181
22	Unnamed andesitic tephra below Rotoaira Lapilli	Poutu Canal	N112/289880	6.29	1.92	0.30	0.23	11893	1951	202	387	127	79
23	North Crater - young lava	North Crater	N112/136855	8.42	1.07	0.29	0.15	8809	2470	173	280	106	110
24	Blue Lake lava	Blue Lake, western rim	N112/148946	6.91	0.99	0.23	0.13	10077	6325	221	470	114	122
25	Old North Crater lava	North Crater, eastern rim	N112/143851	7.54	0.90	0.29	0.18	8236	21107	221	411	197	108

APPENDIX 5Relative Ages of Four Red Crater Basalt Flows

Four basalt flows erupted from Red Crater within the past 1819 years BP have very similar chemical analyses (Table 8). Since precipitation primarily determines the rate of weathering of tephra (Ruxton 1968a, Hay and Jones 1972) a comparison of the chemical analyses for similarly sized small (10-20 mm) scoriaceous fragments on the upper surface of the basalt flows with the subsurface relatively unweathered basalt should give a probable order of extrusion for the basalts (Atkinson and Swindale 1971). No vegetation covers the flows and the precipitation can be assumed to be approximately the same for all flows.

Ruxton (1968b) has suggested that the mole ratio of silica to alumina is the most useful means of quantifying the degree of chemical weathering of rocks. However, Parker (1970) notes that "although silica does tend to be mobile during weathering, its movement within a profile is often irregular, and the total proportion lost is usually small." Kramer (1968) considered weathering to be an exchange of Na, Ca, Mg, and K for H in the mineral structure with or without a loss of Si and Parker (1970) therefore considers Na, Ca, Mg and Ca more suitable elements than Si as a base for a weathering index.

An index proposed by Parker (1970: here termed 'Parker's Index', P.I.) takes into consideration the individual mobilities of the most major elements, based on bond strength considerations and is expressed as:

$$\left(\frac{(Na)_a}{(Na-O)_b} + \frac{(Mg)_a}{(Mg-O)_b} + \frac{(K)_a}{(K-O)_b} + \frac{(Ca)_a}{(Ca-O)_b} \right) \times 100$$

where $(X)_a$ indicates the atomic proportion of element X, defined as atomic percentage divided by atomic weight, and $(X-O)_b$ is the bond strength of element X with oxygen. Using bond strength values from Nicholls, 1963

(in Parker 1970), the expression becomes:

$$\left(\frac{(\text{Na})_a}{0.35} + \frac{(\text{Mg})_a}{0.9} + \frac{(\text{K})_a}{0.25} + \frac{(\text{Ca})_a}{0.7} \right) \times 100$$

Parker's Indices (Table) have been calculated from chemical analyses of four Red Crater basalts and from scoriaceous basalt lying on the surface of those flows. The percentage difference between Parker's Index within each lava flow (presumed unweathered) and the weathered scoria (presumed to have had the same original composition as the underlying flow rock) gives an order of extrusion for the flows: 1 (oldest) - flow into northern Oturere Valley, 2 - flow into southern Oturere Valley, 3 - flow into Central Crater, and 4 (youngest) - flow into South Crater. The percentage differences are so close however that this order of extrusion should be considered tentative rather than absolute.

Table 12: A tentative order of extrusion for four basalts extruded from Red Crater 1819 years BP derived from differences between Parker's Indices for weathered and unweathered rock of the same flow. The Parker's Index values have been calculated from chemical analyses which appear in Table

Lava (L) and Scoria (Sc) Samples	Parker's Index	Difference	% Difference	Relative Age
474 L	73.0	0.8	1.10	D
474 Sc	72.2			
475 L	73.6	2.3	3.13	B
475 Sc	71.3			
484 L	72.8	3.3	4.53	A
484 Sc	69.5			
485 L	71.5	1.7 2.2	2.38 3.06	C
485 Sc	69.8			
485 L (dup.)	72.0			

Table 14:

Paleomagnetic data for andesitic eruptives and laharic breccia within the Tongariro Volcanic Centre - data for individual clasts.

345.

Locality	Core Sample No.	Temp.	Dec.	Inc.	Intensity (emu/cm ³ x 10 ⁻³)	Mean Dec.	Mean Inc.	K	α 95	R
<u>Beggs Pool</u>										
N112/305838; lava of Tongariro	11939A	NRM	223	+55	0.114	215.5	56.1	150.6	12.7	1.993
Andesites Formation, Tongariro River	11939C	NRM	207	+57	0.0929					
<u>Wanganui River</u>										
N112/096987; lava from	11940A	NRM	17	-66	2.30					
Maungakato cone	11940B	NRM	17	-62	2.50	19.2	-63.1	420.1	3.4	3.992
	11940C	NRM	15	-59	2.01					
	11940D	NRM	28	-64	2.12					
"	11940A	150°C	23	-64	1.99	16.2	-61.5	213.4	10.6	1.995
	11940B	150°C	11	-59	2.07					
<u>Mahia Rapids</u>										
N112/007819; olivine andesite	11941A	NRM	7	-51	3.00	10.3	-52.2	>1000	2.6	2.998
lava	11941B	NRM	12	-51	3.53					
	11941D	NRM	12	-55	3.88					
<u>Okupata</u>										
N112/037866; vesicular olivine	11942A	NRM	13	-58	6.05					
andesite	11942B	NRM	11	-51	6.39	12.6	-59.2	127.0	6.2	3.976
	11942C	NRM	18	-68	5.43					
	11942D	NRM	10	-59	5.70					
<u>Te Rato</u>										
N112/132922; block lava of	11943A	NRM	349	-51	2.22					
North Crater	11943B	NRM	10	-45	9.09					
Andesite Formation	11943C(1)	NRM	343	-67	5.78	352.8	-57.6	38.4	11.4	3.921
	11943C(2)	NRM	340	-65	5.42					
	11943C(1)	150°C	321	-71	5.20	331.8	-69.2	204.8	10.8	1.995
	11943C(2)	150°C	340	-67	5.80					

/continued

Table 14: continued

Locality	Core Sample No.	Temp.	Dec.	Inc.	Intensity (emu/cm ³ x 10 ⁻³)	Mean Dec.	Mean Inc.	K	α	R
Papanetu Stream										
N102/238004;	11944M(1)	NRM	244	-84	2.10					
volcanic breccia	11944M(2)	NRM	252	-85	1.98					
eastern slopes of	11944J(1)	NRM	343	-78	10.4					
Tihia	11944J(2)	NRM	166	+10	127					
M = matrix										
L = lithic elasts										
Bruce Road										
N112/007787;	11945C1(a)	NRM	180	-2	8.95					
lahar mound of the	11945C1(b)	NRM	183	-10	8.95					
Murimotu Lahars	11945C1(c)	NRM	182	-11	8.98					
Formation	11945C1(a)	150°C	179	-1	8.92					
C = clast	11945C1(c)	150°C	183	-11	8.84					
	11945C2(a)	NRM	196	-7	4.22					
	11945C2(b)	NRM	195	-9	5.73					
	11945C2(c)	NRM	198	-5	4.87					
	11945C3(a)	NRM	162	-13	1.60					
	11945C3(b)	NRM	164	-20	1.53					
	11945C3(c)	NRM	167	-16	1.56					
	11945C4(a)	NRM	191	-53	1.42					
	11945C4(b)	NRM	194	-56	1.41					
	11945C4(c)	NRM	188	-52	1.37					
	11945CN1	NRM	210	23	0.243					
	11945CN2	NRM	241	39	180					
	11945CN3	NRM	265	13	304					
	11945CN4	NRM	146	23	101					
	11945CN5	NRM	239	-77	230					
	11945CN6	NRM	125	19	163					

/continued

Table 14: continued

Locality	Core Sample No.	Temp.	Deco.	Inc.	Intensity (emu/cm ³ x 10 ⁻³)	Mean Dec.	Mean Inc.	K	α_{95}	R
Tokaamu Intake N112/202974; ruée ardente deposit from peak WSW of Tihia	11945CLE	NRM	210	51	0.611					
	11945CLF	NRM	188	-10	0.198					
	11945CLG	NRM	170	70	0.368					
	11945CLH	NRM	229	28	0.190	205.3	44.2	8.3	21.6	6.275
	11945CLI	NRM	199	52	0.312					
	11945CLJ	NRM	222	46	0.237					
	11945CLK	NRM	202	39	0.154					
	11946A	NRM	356	-58	3.10					
	11946B	NRM	359	-71	1.96					
	11946C	NRM	352	-64	6.18	351.0	-65.2	175.8	4.8	4.977
	11946D	NRM	336	-65	1.96					
	11946E	NRM	353	-67	2.01					

Dec Declination in degrees east
Inc Inclination (negative, up, normal; positive, down, reversed)
K Fisher precision parameter
 α_{95} Semi-angle of cone of 95% confidence about mean direction
R Vector sum of unit vectors parallel to directions of magnetisation