VINCENT ERNEST NEALL

SOME ASPECTS OF WESTERN TARANAKI GEOLOGY AND PEDOLOGY

Thesis submitted for the degree of
Doctor of Philosophy
in Geology

Victoria University of Wellington
May 1973

FRONTISPIECE

Vertical aerial photograph of Mt. Egmont and the Pouakai Range to the NNW showing

(a) older lavas of Mt. Egmont cone (comprising West Ridge and Bobs Ridge lava flows) truncated in their upper part by

(b) the "amphitheatre" between Bobs Ridge and Fanthams Peak - a collapse structure from which the Opua Formation lahar originated.

(c) Younger stands of vegetation destroyed by a debris flow originating from the Okahu Gorge region about 80 years ago.

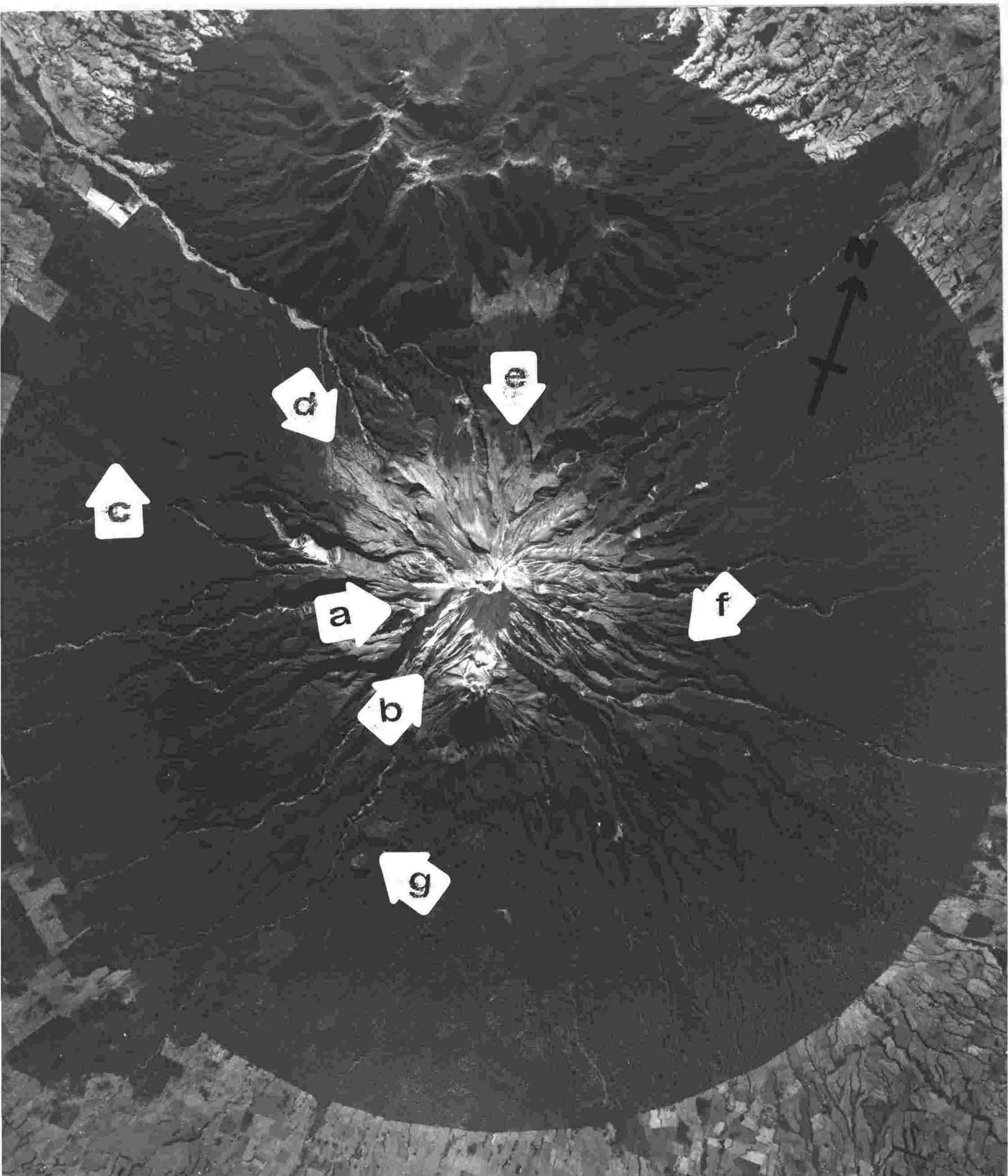
(d) The depressed bushline on the north-western Egmont slopes, due to the 80 year old debris flow spreading 9 kms to the present National Park boundary.

(e) One of the younger lava flows on Mt. Egmont which descends Minarapa Stream.

(f) The Dray Track lava flows to the east of Mt. Egmont, with distinctive levees to each side.

(g) Two cumulo-domes on the southern flanks, named the Beehives.

- Lands and Survey Department photo.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INTRODUCTION

The North Island of New Zealand is the southern end of an island arc structure which stretches 3000 km northwards to Samoa. It comprises the Hikurangi Trench to the east of the North Island (Houtz, et.al. 1967), a central negative gravity anomaly (Robertson and Reilly 1958) and two volcanic zones to the west of the gravity anomaly (Cole 1967). The volcanic zones comprise the Ohakune-White Island zone of calc-alkaline volcanoes and a western zone of more alkaline volcanoes from Northland to Taranaki. The Taranaki volcanoes are principally high potash low magnesia hornblende-andesites (Hatherton 1968a) which extend 25 km south from New Plymouth to Mt. Egmont.

Volcanological investigations on the Taranaki andesites have previously been limited to petrological, geomorphic and Recent tree-ring dating studies. The following work involves detailed studies on the tephrochronology, lahar stratigraphy, weathering and soil formation in western Taranaki together with a detailed interpretation of Quaternary volcanic and climatic events.

CHAPTER 1

THE VOLCANIC HISTORY OF WESTERN TARANAKI

Mount Egmont and the ranges extending northwards to New Plymouth (Fig.1) have a volcanic history that has lasted from early Pleistocene times almost to the present day (Table 1). Prior to this, Taranaki was covered by a shallow sea beneath which a sequence of Tertiary sediments was deposited. Oil and gas within Eocene paralic beds have flowed into Tertiary structures which have been subsequently drilled and commercially developed (e.g. 35 million cubic feet of natural gas per day is produced at Kapuni, Hay 1967). More recently an offshore oil and gas field has been discovered 53 km offshore to the south-west, with two horizons producing 45 and 42.5 million cubic feet of gas per day (A.N.Z. Bank 1970).

The lavas extruded from Mt. Egmont and its adjacent volcanoes cover a comparatively small area at high altitude and below the 900m (3,000 ft) contour they merge into a thick apron of fragmentary volcaniclastics termed the ringplain (Grant-Taylor 1964a). The outskirts of the Taranaki volcanic ringplains are bounded to the west by the coast and to the east by uplifted upper Tertiary mudstones from Urenui south to Hawera.

With time the volcanic history has followed a NNW to SSE trend in Taranaki and is referred to as the Taranaki Volcanic Succession. Progressing southwards along the succession each volcano is seen to be associated with a progressively more

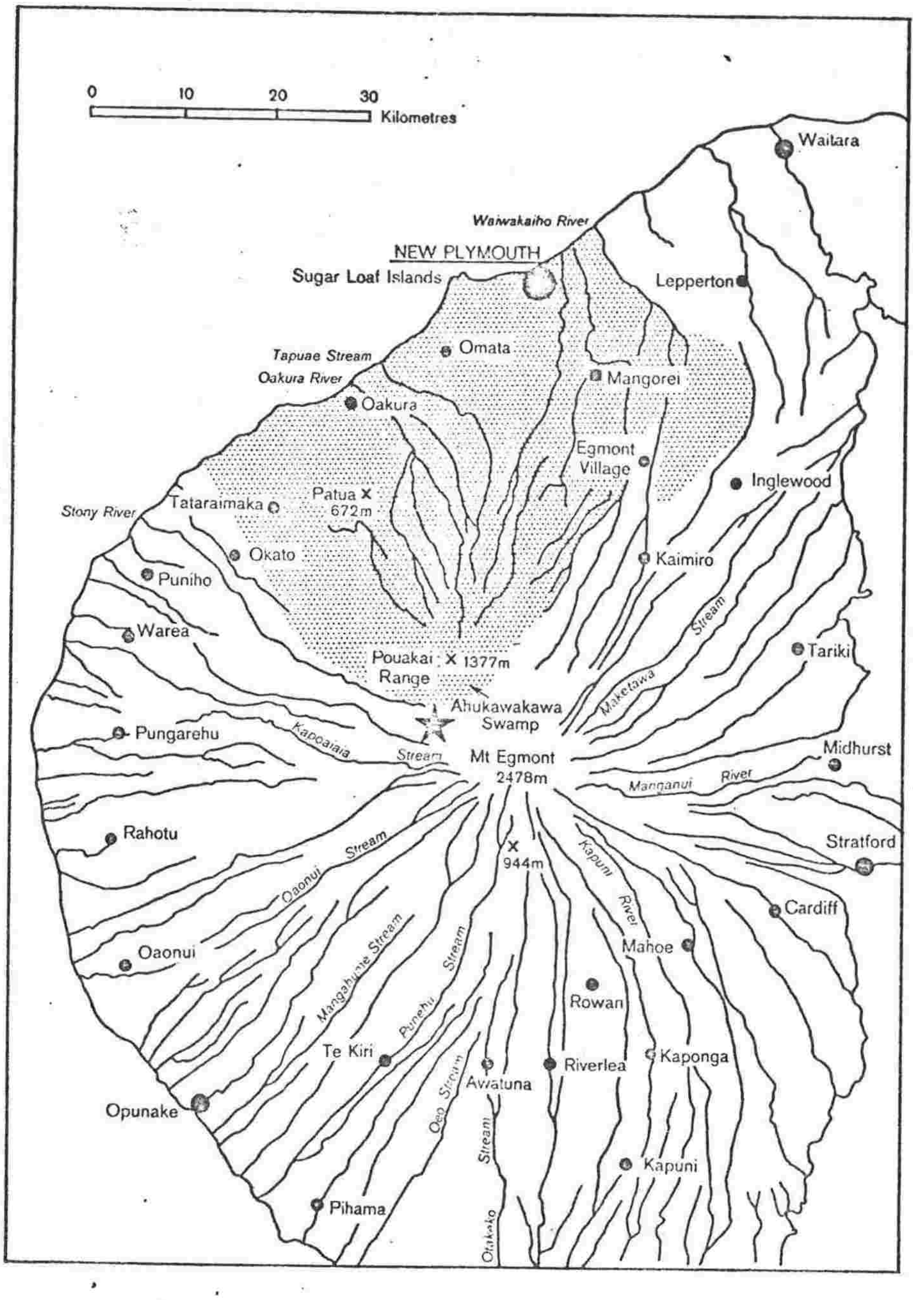

FIGURE 1 - Locality map of Taranaki, showing radial drainage pattern to Mt. Egmont. Dotted area refers to Pouakai Range ringplain. Star locates ecosystem study site described in detail in Chapter 8.

TABLE 1 - VOLCANIC EVENTS IN TARANAKI

Age of event			
Years before present.	Geological period (or yrs A.D.)		
250	RECENT 1755 A.D.	Tahurangi Ash eruption (Druce 1970)	Debris flows along south side of Ahukawakawa Swamp and down Stony River.
350	1655A.D.	Burrell Lapilli eruptives (Druce 1970)	Large flood in Okato region.
	1500A.D.	Newall eruptions - hot nuees ardentes	
700			
1,500	HOLOCENE	Scattered ash and lapilli eruptions to the east of Egmont summit.	
3,000		Widespread stability	
		Final construction of upper Egmont cone - emplacement of (with decreasing age) Sharks Tooth, Dray Track, Skeets Ridge and Minarapa Stream lava flows.	
		Collapse of south-west sector of Egmont cone to form "amphitheatre" between Bobs Bluff and Fanthams Peak.	Eruption of Oakura Tephra. Extrusion of cumulodomes.
7,000		Construction of basal portions of present Egmont cone e.g. West Ridge, Bobs Ridge flows.	Eruption of Okato Tephra
10,000			Collapses led to debris flow deposits in upper Newall Road region.
15,000	PLEISTOCENE	Beginning of new Egmont cone - emplacement of Dawson Falls, Warwicks and Humphries Castle lava flows.	
35,000		Cone collapsed forming Pungarehu lahar mounds. Construction of an early Egmont cone.	Construction of Fanthams Peak and Pukeiti cone.
70,000		Activity at Egmont started - mainly laharic breccias preserved.	
250,000		Pouakai Volcano - diorites and andesites with extensive ringplain of laharic breccias, and eruptions of ashes preserved in New Plymouth region.	
500,000		Kaitake Volcano - andesite, diorite and associated breccias (now hydrothermally altered).	
1.75 million		Paritutu and the Sugar Loaves - dacitic cumulodomes	
12 million - 60 million	TERTIARY	Deposition of Tertiary sediments (mudstones, sandstones, limestones and coal) which contain oil and gas structures e.g. Kapuni.	

recent and youthful landscape. In the north is Paritutu and the Sugar Loaves at New Plymouth, positioned slightly to the north-east of the principal volcanic line. Further south are Kaitake, a disembowelled extinct volcano; Pouakai, a severely eroded, extinct volcano; and Egmont, a classic strato-volcano of interbedded lavas and breccias (Fig.2). Except for the dacites at the Paritutu centre, all of the cones are composed of andesite lavas but diorites are exposed in the core regions of Pouakai and Kaitake.

Mohakatino Formation

The earliest evidence of andesitic volcanism in Taranaki is preserved as andesitic tuff in the Mohakatino Formation of Southland age in northern Taranaki. Glennie (in Arnold 1959) concluded from the distribution of the pyroclastic material in the formation that the source area was in the Tasman Sea and this origin is supported by the discovery of a large circular magnetic anomaly about 45 km off the Taranaki coast (Hatherton 1968b). A similar but twin-peaked anomaly also regarded as Miocene age occurs 60 km south of Egmont in northern Cook Strait but there is no bathymetric evidence of its existence (Hatherton 1968a and b).

Paritutu and the Sugar Loaves

The first volcanic centre to be preserved onshore in Taranaki is at the New Plymouth foreshore. It comprises Paritutu and the offshore islands named the Sugar Loaves (Fig.3). Early geologists regarded these volcanic remnants as a cone-sheet system (Hutton 1944), but more recent work by Arnold

FIGURE 2 - View from the north-west along the Taranaki Volcanic Succession. Kaitake Range in foreground, Pouakai Range in centre and Mt. Egmont behind.

FIGURE 3 - Paritutu and the Sugar Loaf Islands at New Plymouth, from the south. Raised marine bench in foreground.

(1959) suggests they represent a growing volcano which became pierced by a series of highly viscous, craterless cumulodomes. Grant-Taylor (1964b) regards the volcanics as erosion remnants of a former volcano which have proved resistant to marine erosion. However the phenocrysts within the lavas are aligned in circular or curved patterns around most of the Sugar Loaves, supporting Arnold's theory.

Paritutu is thought to represent a plug or spine of lava that was extruded in nearly solid form, like a piston, in much the same way as the spine was thrust up from the summit of Mt. Pelée on the Caribbean island of Martinique in 1902 A.D. A zone of crushed rock around the base of Paritutu probably marks the circular fault up which the spine was extruded. The rocks have been K/Ar dated at 1.76 million years B.P. (Dr. J.J. Stipp, pers.com.).

Surrounding the lavas at Paritutu are breccias named "Lower Pouakai Agglomerate" (Clarke 1912, Gibson and Morgan 1927). Arnold (1959) suggests the "Agglomerate" was derived by uparching and intrusion of a semi-rigid igneous mass. The presence of Pliocene sandy musdtone blocks up to 70,000 m^3 (Arnold 1959) was explained by this mechanism. A recent find by the author of a marine bivalve Protothaca crassicosta (Deshayes), identified by Dr. A. Beu, N.Z. Geological Survey, Lower Hutt, within the breccia near Mikotahi indicates the breccia was probably deposited under subaqueous conditions. A submarine breccia flow is considered a likely alternative to explain the large size of Tertiary blocks in the breccias.

It is probably due to these volcanic extrusions fracturing the underlying Tertiary sediments that oil has seeped upwards along small fissures to form oil seeps and gas vents on the

New Plymouth foreshore. For about 65 years, oil has flowed in small quantities from this field, yielding some 100,000 gallons of crude oil and 3½ million cubic feet of gas per year (A.N.Z. Bank 1970) until 1971 when the field was closed.

Kaitake

Fifteen kilometres (8 miles) south-west of New Plymouth is the Kaitake Range where volcanic activity began about 575,000 yr B.P. (Stipp, pers.com.). Advanced erosion has reduced the volcano to a circular area of radiating ridges which rise to the central point Patuha, 673 m (2,243 ft) in altitude. There is little evidence preserved today of the activity associated with this volcano because most of the rock outcrops are covered in bush. Of the few rocks exposed, most are andesites and diorites which have been hydrothermally altered to quartz and kaolinite with small quantities of pyrite. Gold, silver and copper have been reported from the Boars Head Mine, on the north-west side of the Range, but the workings were quickly abandoned.

Three ringplain surfaces have been attributed to slope away from the Kaitake Range; they are, in decreasing order of age, the New Plymouth, Eltham and Inglewood Lahars, (Grant-Taylor 1964a and b, Hay 1967). However detailed tephrochronological studies in the region immediately south of New Plymouth do not support the existence of three separate ringplains. The Tapuae-Manganui Ridge (Gibson and Morgan 1927) is undoubtedly composed of a highly weathered and thus older breccia than the Pouakai ringplain breccias, but other than the Kaitake

Range being the nearest likely source, little conclusive evidence is available. On the seaward north-western slopes of the Kaitake Range are a number of planar surfaces preserved on a few ridges which may represent uplifted marine benches and not ringplain surfaces.

Pouakai

Ten kilometres (6 mls) to the south-east of the Kaitake Range is the Pouakai Range, an extensive mountainous area rising to 1,377 m (4,591 ft) altitude, with a diameter of between a half and two thirds that of Egmont. About 250,000 years ago (Stipp, pers.com.) an extensive ringplain of volcanic breccias was formed around Pouakai volcano (termed the Maitahi surface by Grant-Taylor 1964a and Hay 1967), by huge lahars which descended from the upper Pouakai slopes prising underlying Tertiary sediments into "rafts" within the breccias.

The southern Pouakai ringplain has been eroded by more recent lahars from Egmont and the upper parts of the original volcano have also been eroded so that only the lower and middle portions remain. During the last stadial many of the tephras covering the upper slopes of the Pouakai Range were eroded and redeposited as dunes and mounds at lower altitudes (see Chapter 3 "Katikara Formation"). The large Ahukawakawa Swamp between Egmont and Pouakai was regarded as a caldera by Gibson and Morgan (1927) but there is little evidence of any circular faulting to support an explosion or collapse origin.

Some of the older tephras in the vicinity of New Plymouth may have been erupted from the Pouakai Range.

Egmont

Little is known of when activity commenced at the Egmont centre but some of the oldest deposits are exposed in the coastal cliffs of southern Taranaki, particularly between Manaia and Hawera. Early tephras preserved in the Okato-Oakura region suggest activity at the Egmont centre began at least 50-70,000 years ago. It appears that a substantial cone had been constructed by 35,000 years B.P. and that about this time an eruption occurred leading to large scale collapse. The bulk of the volcanic cone slid westwards as a huge lahar flow to beyond the present coastline forming the Pungarehu Formation. This formation now stretches from Okato south to near Te Kiri and is typical of other lahar deposits elsewhere in the world. In particular it shows many thousands of various sized mounds developed on its upper surface. This type of lahar produced by volcanic collapse appears to have been a repetitive and common occurrence with the Taranaki volcanoes and much controversy exists as to its origin.

About 20,000 years ago, whilst a new cone was being constructed at the Egmont centre, magma also burst to the surface between Kaitake and Pouakai to form Pukeiti cone. Lava flows on Egmont were extruded and include that at Dawson Falls and the remnant Warwicks and Humphries Castles. Fanthams Peak is also known to have existed at this time because it deflected later lahar flows to the south-west and has protected a strip of older ringplain between Auroa and Mangawhero Roads (here named the "Mangawhero Ridge"), near Awatuna.

The remainder of the present upper cone has been built since 16,000 yr B.P. accompanied by frequent collapses of unstable materials to the north, east and west and eruption of volcanic ash and lapilli layers over most of Taranaki. Two of these ashes now form the topsoil throughout most of the province - the Oakura and Okato tephras. At least two lahars have reached the present coastline since 16,000 yr B.P. and the younger one, dated at less than 7,000 years old, was clearly derived from the large "amphitheatre" which now exists between Bobs Ridge and Fanthams Peak.

Over the last 500 years a multitude of events have occurred on Egmont which tend to obscure the earlier geology. About 1500 A.D. hot incandescent nuées ardentes (the Newall eruptions) flowed downhill from the western rim of Egmont summit and much of the native bush on the north-western slopes was reduced to carbonised logs. Fires also swept 3 km (2 mls) northwards across the western slopes of the Pouakai Range (Druce 1970, p.53). This was followed 150 years later by the eruption of the Burrell lapilli, an air-fall pumice (Topping 1972). Maori ovens (umus) have been found beneath both these eruptives (Oliver 1929; Topping, pers.com.). About 300 years ago the present summit of Mount Egmont, a tholoid, was also emplaced. The last eruption occurred about 1750 A.D.

In the intervals between the latest short-lived eruptions, Egmont has also suffered severe erosion probably due to heavy rainstorms. At least 20% of the surfaces in Egmont National Park (excluding the Kaitake and Pouakai ranges) are less than 500 years old. The loosely jointed lava flows, some resting on loose gravel, are relatively unstable and at least 11 debris flows have originated over the last 500 years from minor lava flow collapses. The western crater rim was the source for a number of these flows. Following the 1500 A.D. eruptions, debris washed down Stony River in a large flood covering 30 km^2 of what is now valuable farmland in the Okato district. The latest debris flow occurred about 100 years ago and reduced the native bush to ground level from Pyramid Stream to the Park boundary.

"POUAKAI GROUP"

The term "Pouakai Series" was proposed by Clarke (1912) for the succession of pyroclastic, igneous and sedimentary rocks (including lignites) within the New Plymouth Subdivision. The "flow rocks" which constitute Paritutu and the Sugar Loaf Islands near New Plymouth, were also included within the "Series". Gibson and Morgan (1927) realised the "Pouakai Series" could be subdivided into upper and lower divisions which were recognised as "stages" by Fleming (1953). They regarded the divisions as almost wholly volcanic, but the upper part was thought to be of both volcanic and sedimentary origin.

Fleming (1953) considered a group name was necessary for the products of the Taranaki and Tongariro-Ruapehu volcanoes so that they could be separated from the older Wanganui Series rocks beneath. A regional unconformity separates the two units. Fleming used the term <u>Pouakai Group</u> as a lithologic name for the several formations of the Hawera Series on the west coast of the North Island for two reasons. Firstly the term "Pouakai Series" was the oldest stratigraphic name based on a place name in the general area involved, and secondly because the term had been used as a "group" to include two sets of pyroclastic, igneous and sedimentary rocks in Taranaki. Apart from the preliminary subdivision by Morgan and Gibson, no further subdivision has been suggested except for sets of geomorphic surfaces proposed by Grant-Taylor (1964a and b; Hay 1967) which I consider are of equivalent status to sub-groups.

More recently K/Ar dates of the principal volcanic rocks of New Plymouth Subdivision i.e. the original "Pouakai Series", indicate that Paritutu is 1.76 m yr old and the Kaitake Range 500,000 yr B.P. (Dr. J.J. Stipp, pers.com.). In addition fission-track dating of tuffs within the Wanganui Series has been accomplished (D. Seward and B.P. Kohn, pers.com.). The fission track dates on the tuffs from the Wanganui Series, below the regional unconformity i.e. below the base of the Pouakai Group defined by Fleming, indicate that the upper Wanganui Series is considerably younger than the Paritutu volcanics. The possibility that Kaitake and Pouakai are also older than the unconformity cannot be overlooked. It is here proposed that "Pouakai Group" include all the Quaternary volcanic flow rocks, volcaniclastics, tephras and associated sediments in Taranaki. The upper contact of the Group is defined as present ground surface, the lower contact is defined as the base of the volcanics at Paritutu centre, New Plymouth.

REFERENCES

A.N.Z. Bank, 1970: New Zealand's sources of power. Australia and New Zealand Banking Group Limited, Melbourne. Australia, 28pp.

Arnold, H.C., 1959: The Sugar Loaf intrusions near New Plymouth. N.Z. Journal of Geology and Geophysics 2: 735-45.

Clarke, E. de C., 1912: The Geology of the New Plymouth Subdivision. N.Z. Geological Survey Bulletin n.s. 14. 58pp.

Cole, J.W., 1967: Quaternary volcanic zones in the North Island of New Zealand and their relationship to structure. Bulletin Volcanologique, Tome XXX: 189-97.

Druce, A.P., 1966: Tree-ring dating of Recent volcanic ash and lapilli, Mt. Egmont. N.Z. Journal of Botany 4(1): 3-41

Fleming, C.A., 1953: The Geology of Wanganui Subdivision. N.Z. Geological Survey Bulletin n.s.52. 362 pp.

Gibson, W.; Morgan, P.G., 1927: The Geology of the Egmont Subdivision. N.Z. Geological Survey Bulletin n.s.29. 99pp.

Grant-Taylor, T.L., 1964a: Geology of Egmont National Park. Pp. 13-26 in Scanlan, A.B. (ed.): "Egmont National Park". Egmont National Park Board, New Plymouth. 87pp.

Grant-Taylor, T.L., 1964b. Volcanic history of western Taranaki. N.Z. Journal of Geology and Geophysics 7: 78-86.

Hatherton, T., 1968a: "Miogeosynclinal" Andesites. Earth and Planetary Science Letters 4: 441-7.

Hatherton, T., 1968b: A source for volcanic material in the Mohakatino Beds. N.Z. Journal of Geology and Geophysics 11(5): 1207-10.

Hay, R.F., 1967: Sheet 7 - Taranaki. "Geological Map of New Zealand 1: 250,000". N.Z. Department of Scientific and Industrial Research, Wellington.

Houtz, R.E.; Ewing, J.L.; Ewing, M.: Lonardi, A.G., 1967: Seismic reflection studies of the New Zealand Plateau. Journal of geophysical research 72: 4713-29.

Hutton, C.O., 1944: Some igneous rocks from the New Plymouth area. Transactions of the Royal Society of New Zealand 74: 125-53.

Oliver, W.R.B., 1931: An ancient Maori oven on Mount Egmont. Journal of the Polynesian Society 40(2): 73-80.

Robertson, E.I.; Reilly, W.I., 1958: Bouger Anomaly Map of New Zealand. N.Z. Journal of Geology and Geophysics 1 (3): 560-4.

Topping, W.W., 1973: Burrell Lapilli eruptives, Mount Egmont, New Zealand. N.Z. Journal of Geology and Geophysics 15 (3): 476-90.

CHAPTER 2

TEPHROCHRONOLOGY AND TEPHROSTRATIGRAPHY OF WESTERN TARANAKI (N108-109), NEW ZEALAND.

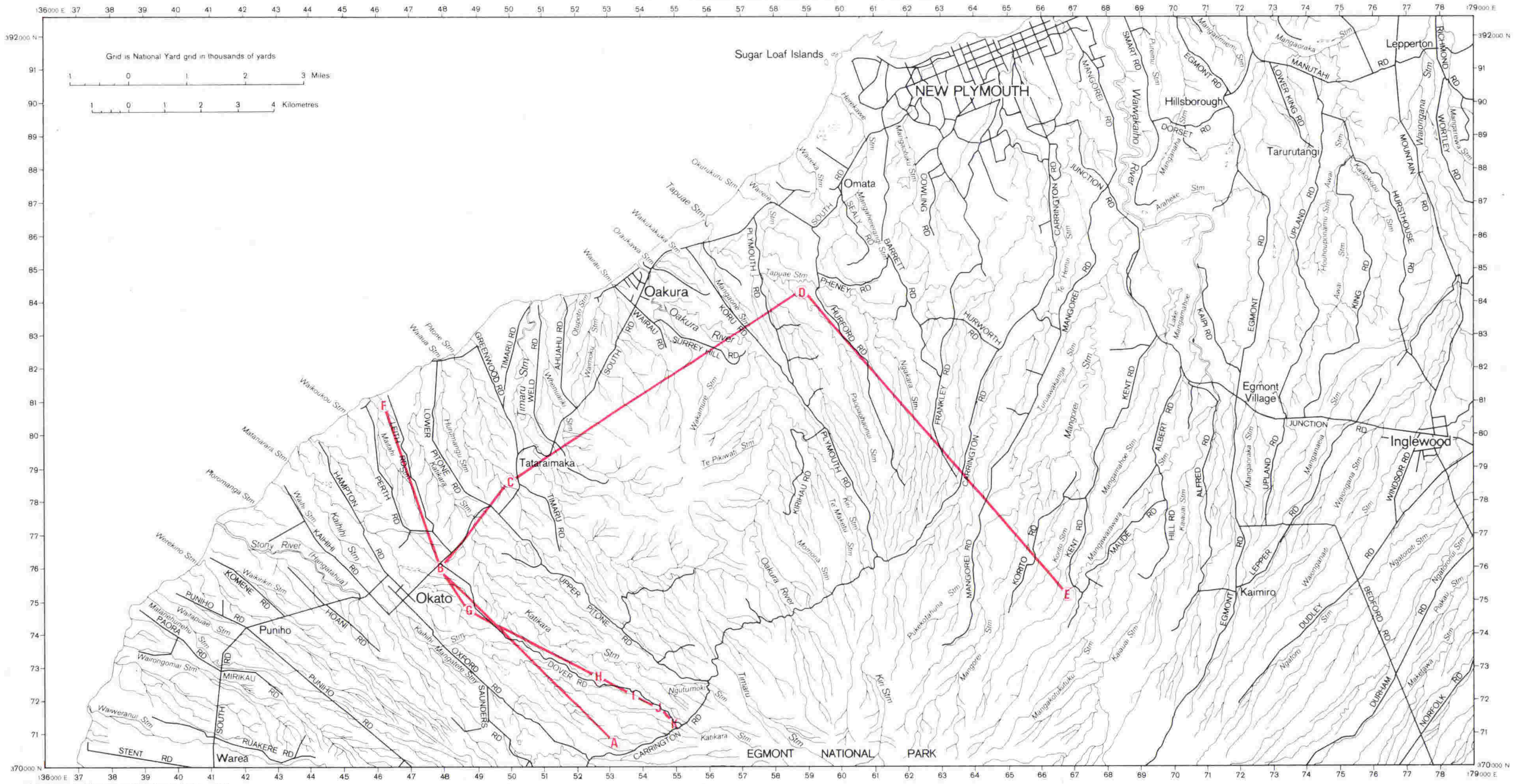

FIG. 3—Detailed locality map showing location of principal sections and the correlation lines in Fig. 29 and 30. A to E are described in the Appendix: A in Section 3, B in Section 6, C in Section 1, D in Section 2, E in Section 4.

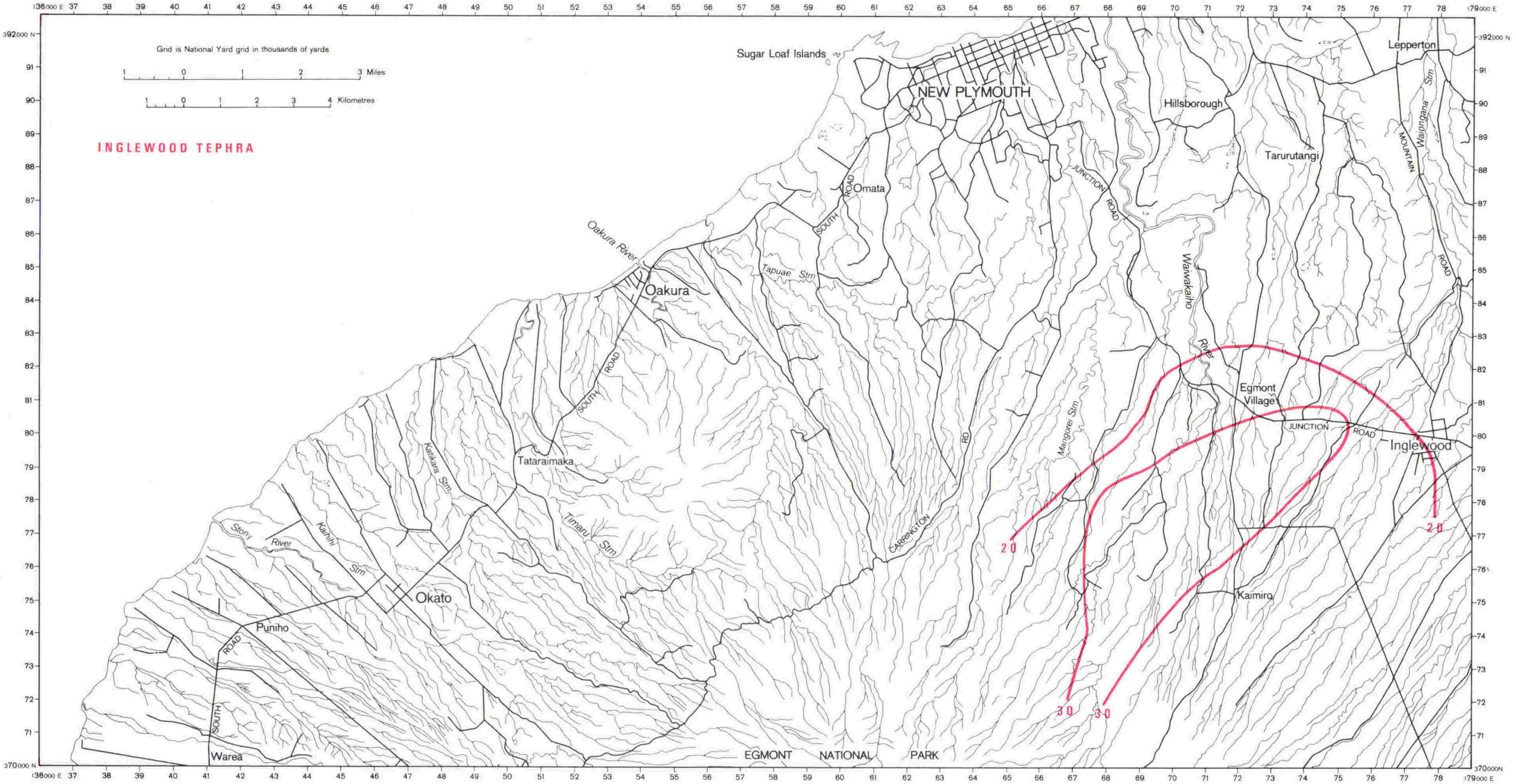

Fig. 4—Inglewood Tephra isopach map. Thickness values in cm.

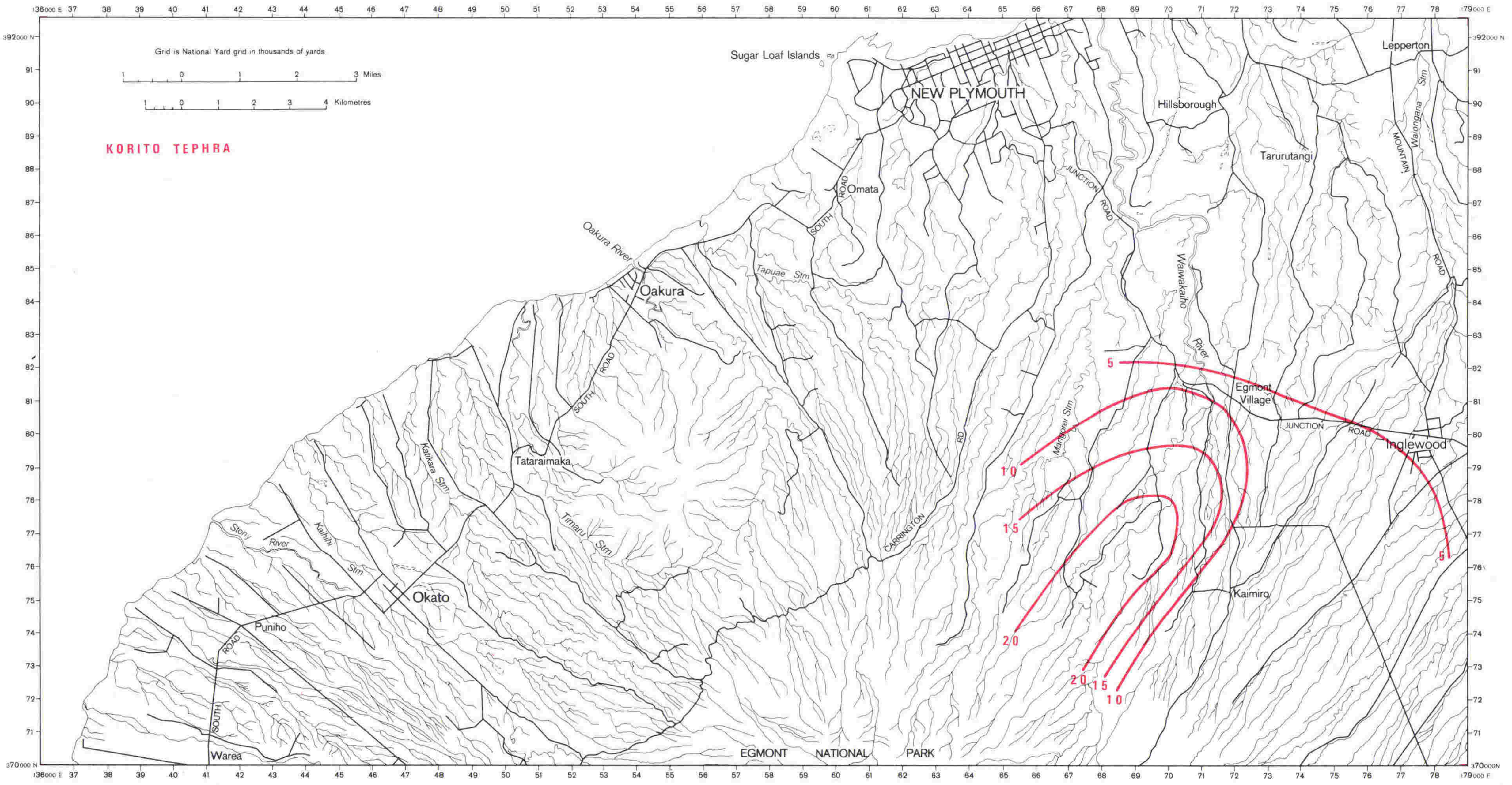

FIG. 5—Korito Tephra isopach map. Thickness values in cm.

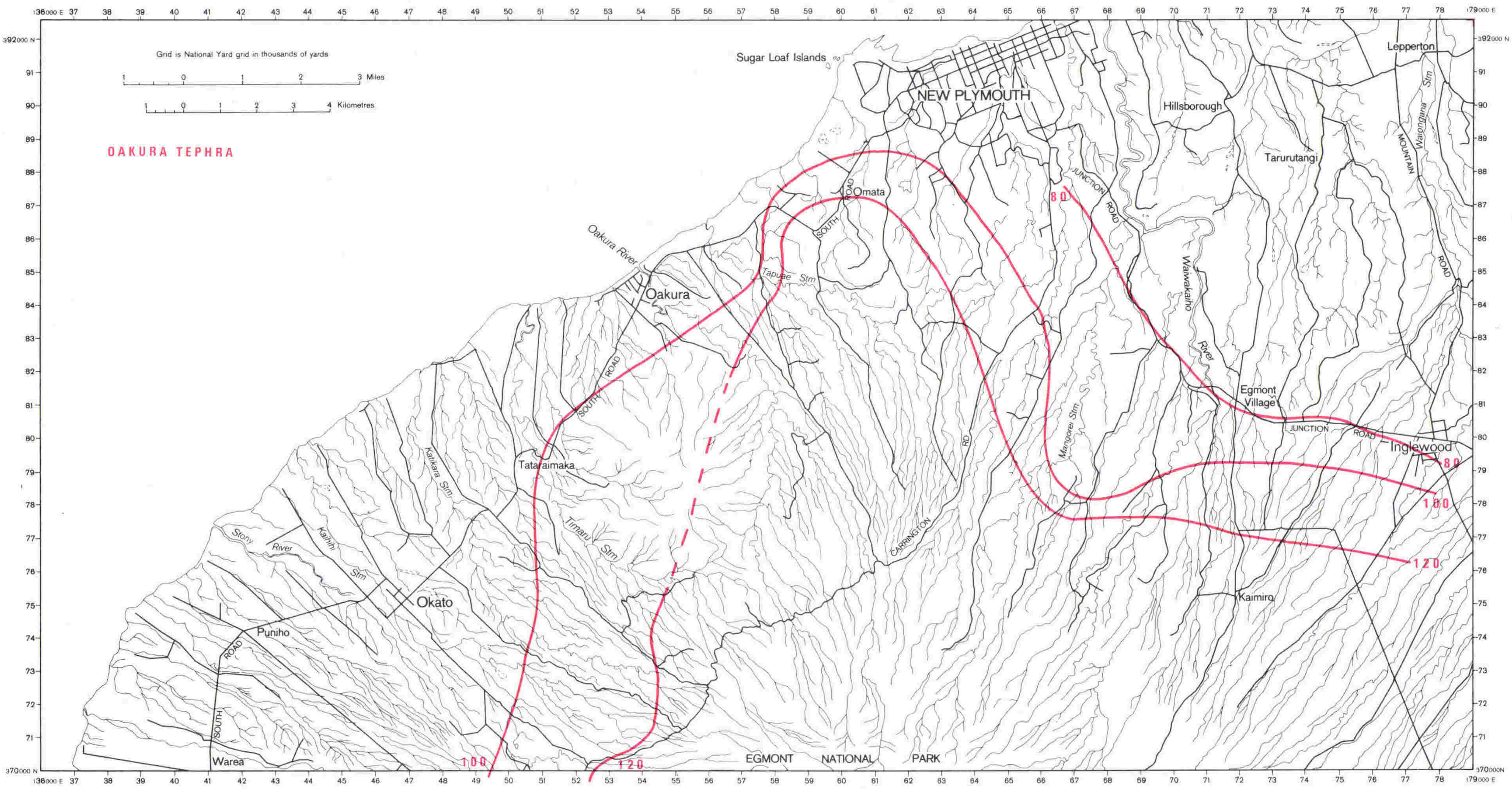

FIG. 6—Oakura Tephra isopach map. Thickness values in cm.

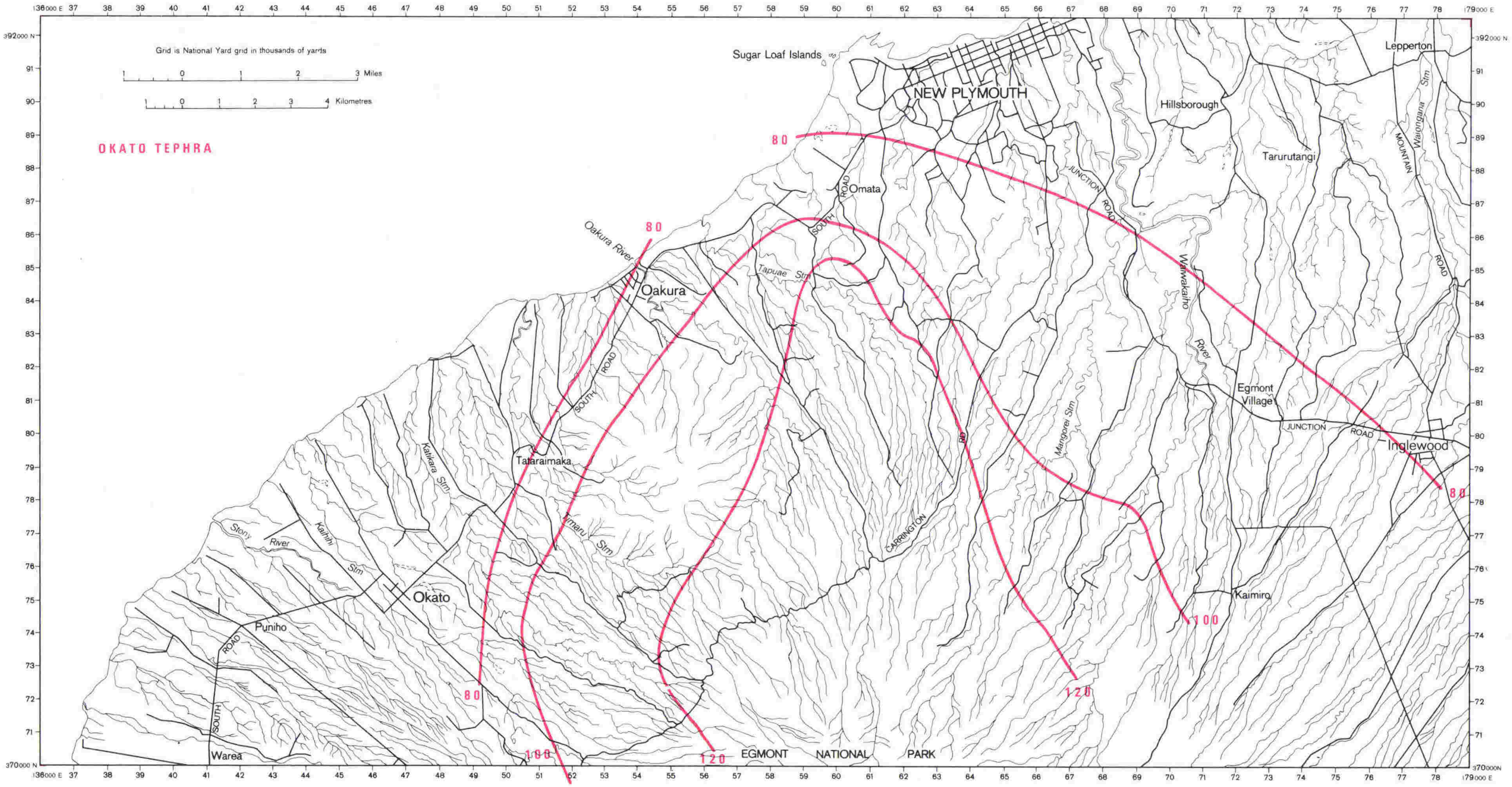

FIG. 7—Okato Tephra isopach map. Thickness values in cm.

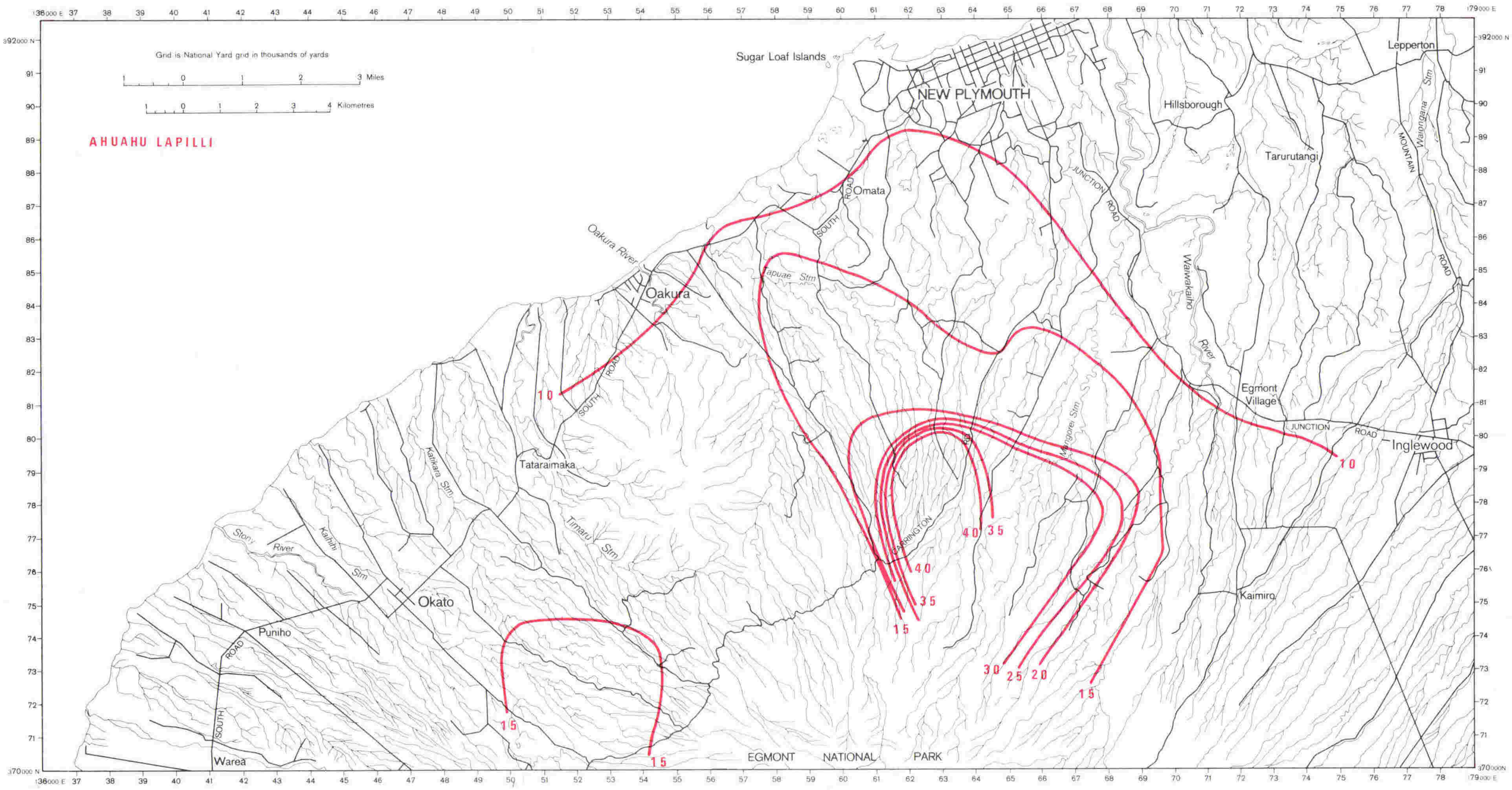

Fig. 8. Ahuahu Lapilli isopach map. Thickness values in cm.

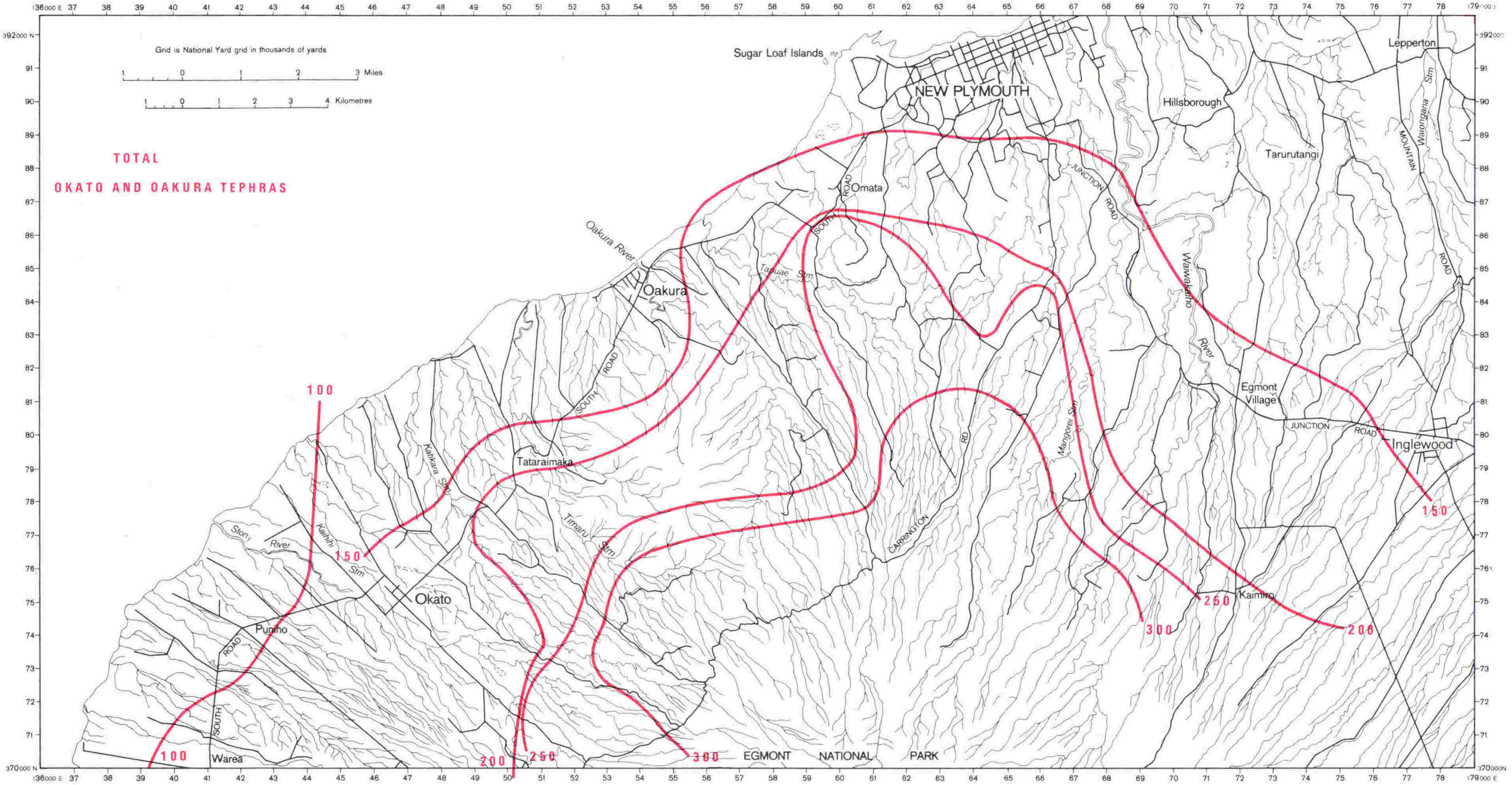

FIG. 9—Combined Oakura and Okato Tephras (previously termed the "Egmont Shower"). Thickness values in cm.

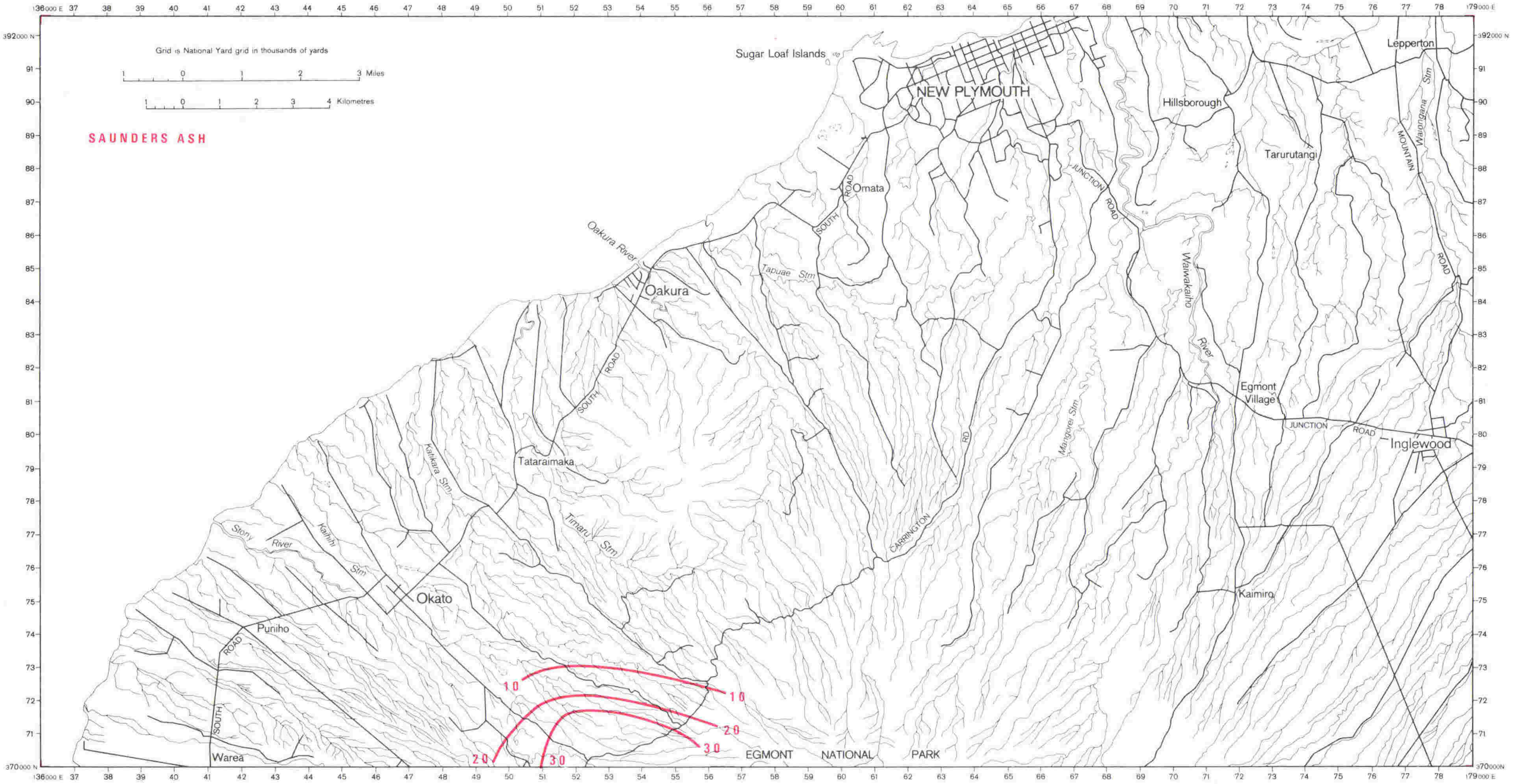

Fig. 10 Saunders Ash isopach map. Thickness values in cm.

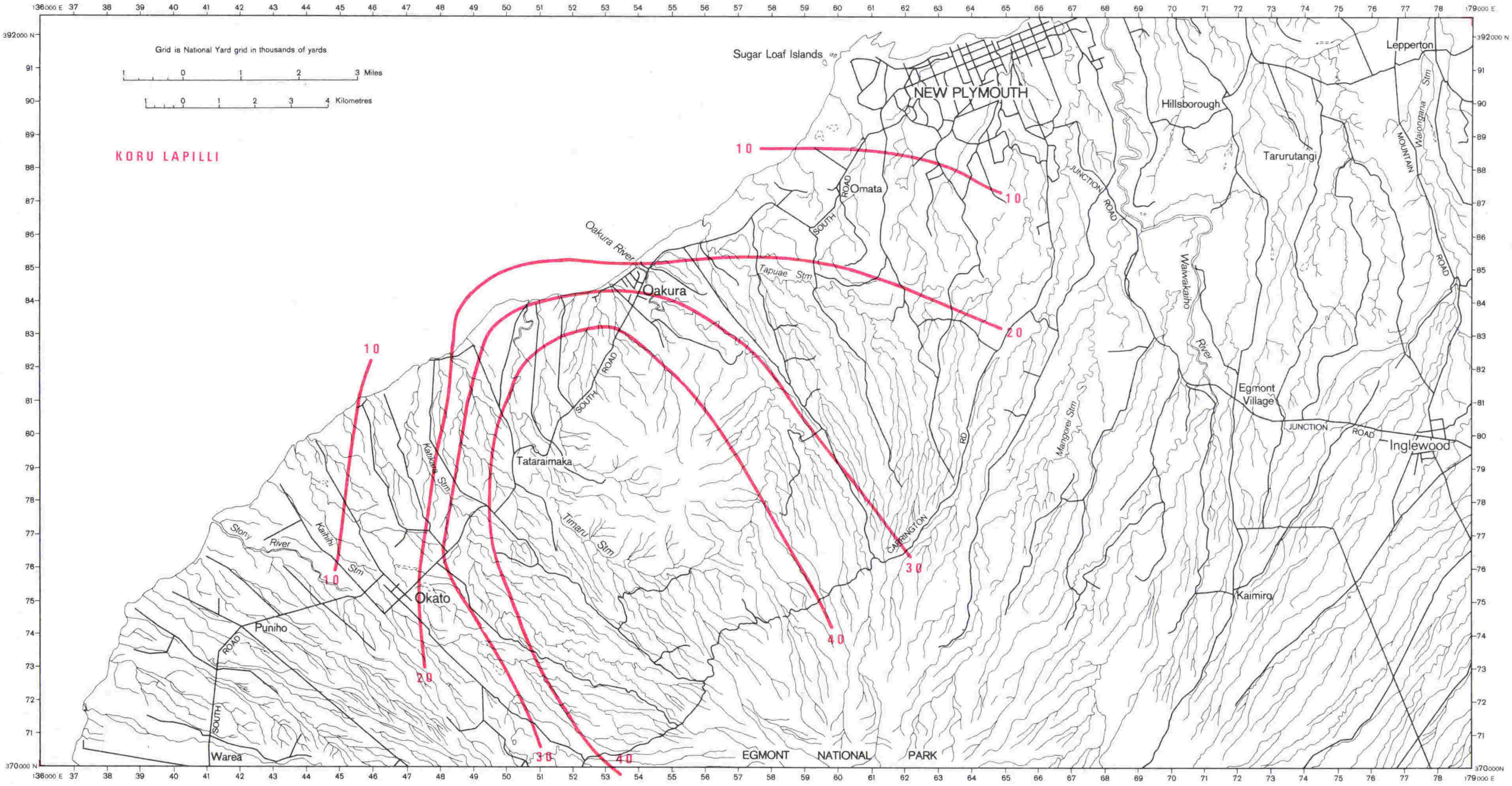

FIG. 11—Koru lapilli isopach map. Thickness values in cm.

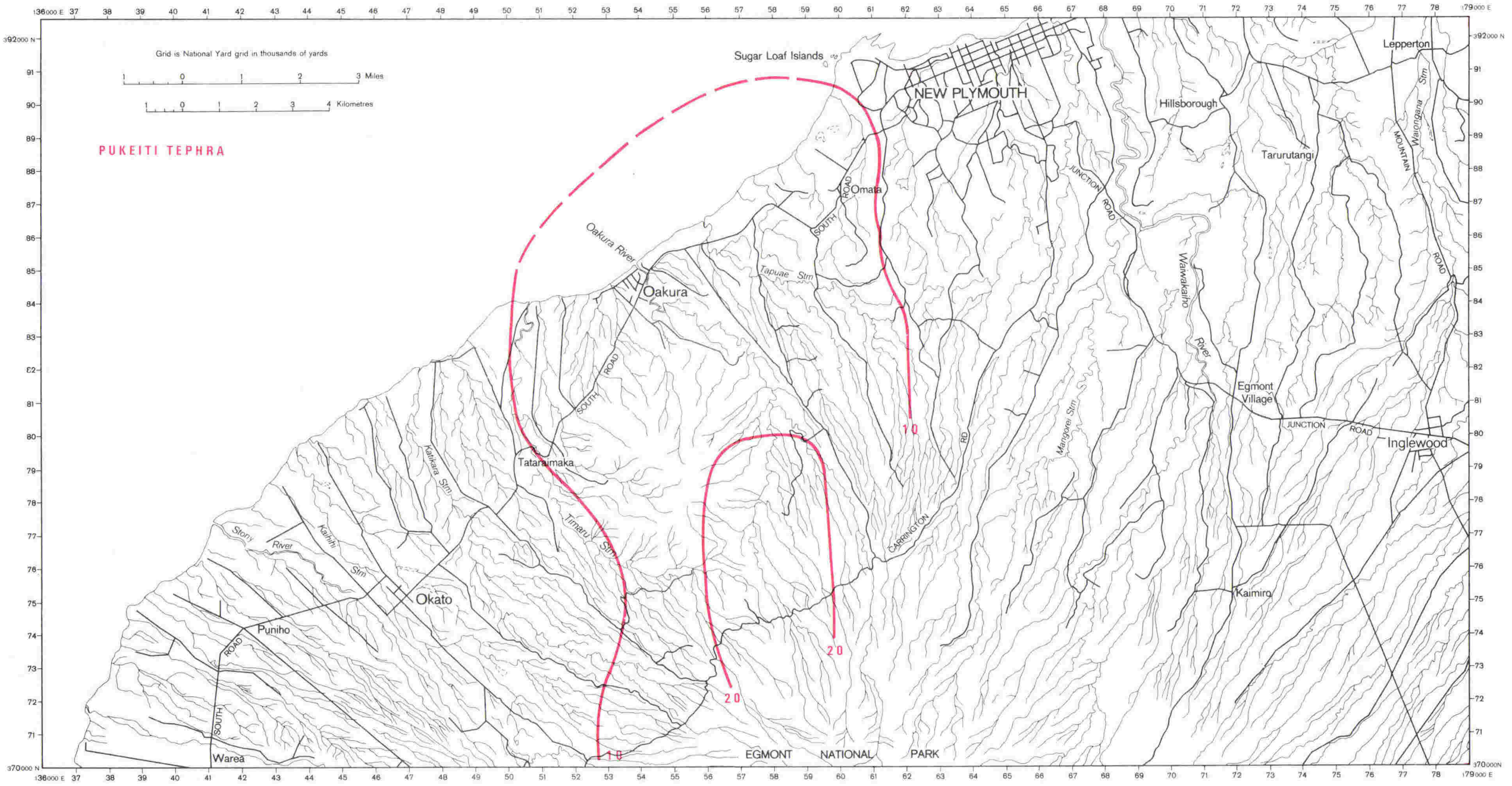

Fig. 12—Pukeiti Tephra isopach map. Thickness values in cm.

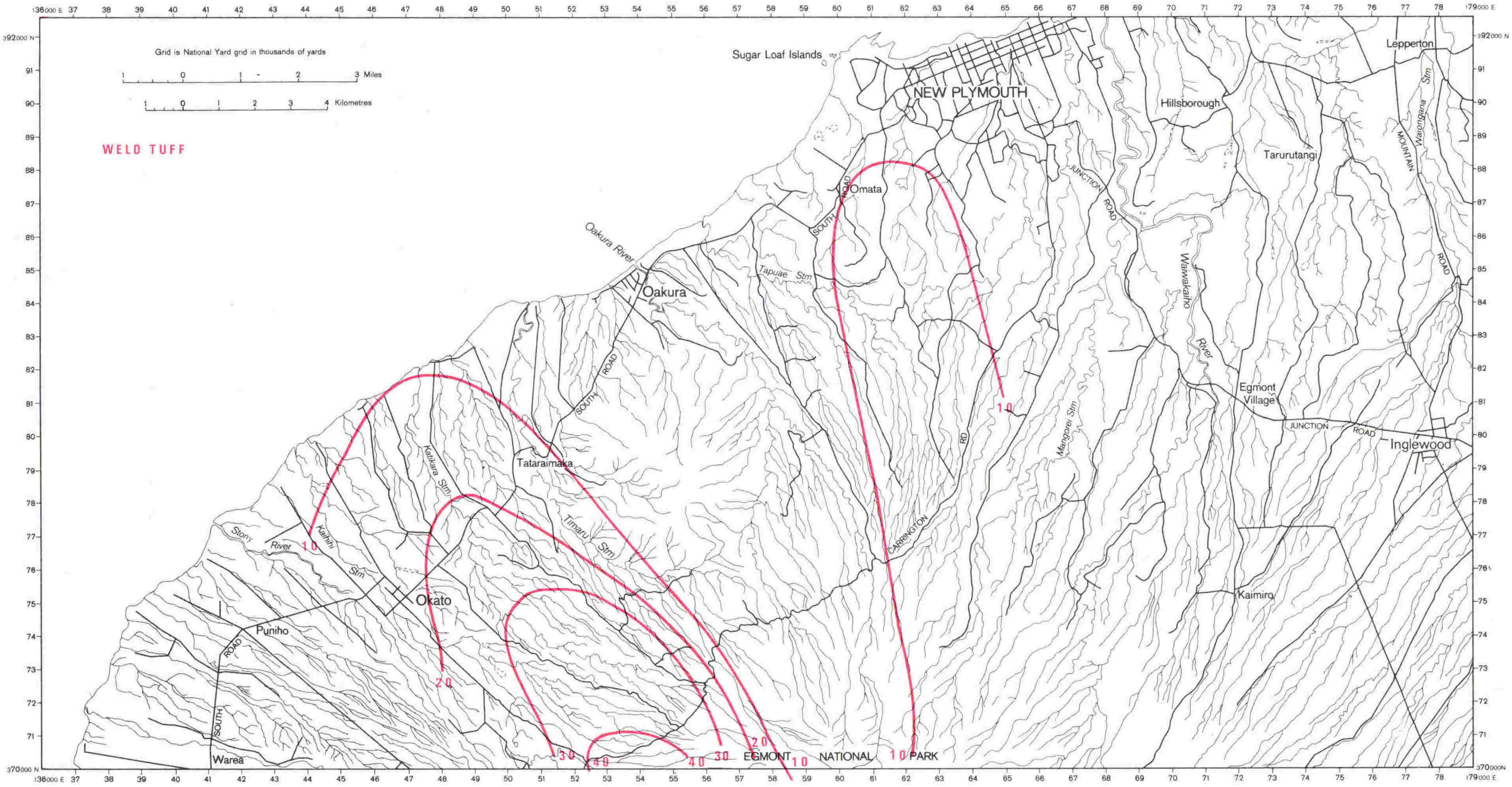

Fig. 13.—Weld tuff isopach map. Thickness values in cm.

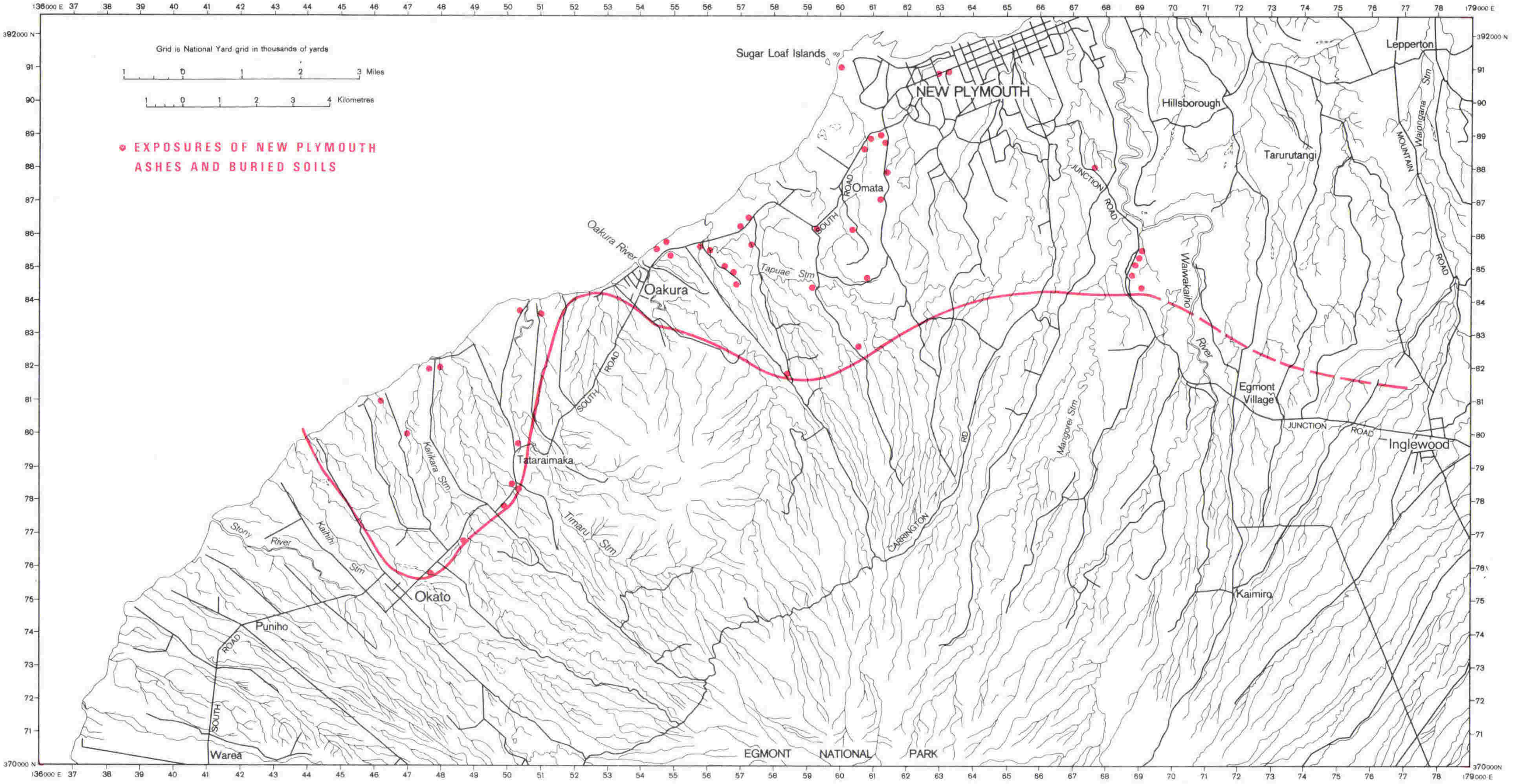

Fig. 14—Distribution of occurrences of New Plymouth Ashes.

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TEPHROCHRONOLOGY AND TEPHROSTRATIGRAPHY OF WESTERN TARANAKI (N108–109), NEW ZEALAND

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(*Received 26 May 1971; revised 16 June 1972*)

ABSTRACT

Ten newly named formations and members of ash and lapilli, erupted from Mt Egmont and the Pouakai Range, comprise the principal tephras mantling the western Taranaki landscape. They are overlain by nine restricted younger eruptives, previously described by Druce, which are also summarised in this paper. The Newall Ash and Lapilli are considered to have been deposited by nuées ardentes between 1500–1550 A.D., in contrast with the Burrell Lapilli, an airfall deposit of 1655 A.D.

The newly named tephras include the "Egmont Shower", here split into two separate formations, one considered to be less than (NZ1144) 6,970 ± 76 yr B.P., and the other between (NZ1144) and (NZ942) 16,100 ± 220 yr B.P. The underlying Saunders Ash is considered to be a nuée ardente deposit preserved between much thicker tephras, it contains charcoal dated (NZ942) at 16,100 ± 220 yr B.P. The other newly named tephras are richly allophanic, stratigraphically overlie the Rapanui Formation near New Plymouth and are thought to have been erupted from Mt Egmont. They overlie, with major disconformity, the oldest tephras described: the New Plymouth Ashes and Buried Soils, which form massive halloysite bearing deposits and were probably erupted from the Pouakai Range volcano.

INTRODUCTION

In the Central Volcanic Region of New Zealand, the major late Quaternary volcanics are predominantly rhyolitic lava flows, ignimbrites, pumice breccias, and tephras. Of 25 major eruptions during the last 40,000 years

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(Healy in press), three have covered over 12,000 km² with pumice ash to a minimum thickness of 30 cm, and one has been identified about 300 km to the south at Taita, near Wellington (Vucetich and Pullar 1969). Widespread Quaternary tephras are also represented in deep sea sediments 1,000 km to the east of New Zealand, and have been correlated with the eruption of ignimbrites from the Central Volcanic Region (Ninkovitch 1968).

Rhyolitic volcanicity is generally violent in contrast to the gradual buildup of composite andesite cones and the associated eruption of comparatively small volumes of tephras. In Taranaki, 125 km to the WSW of the Central Volcanic Region, the andesitic volcanoes Pouakai and Egmont, have been active since mid-Pleistocene times. Older tephras were erupted from Pouakai centre and are preserved on the Pouakai ringplain, north of a line between Okato and Inglewood (Fig. 1). Younger tephras from Egmont centre are preserved on the ringplain, south of a line between Okato and Inglewood. In addition, the younger Egmont tephras have also been deposited on the older Pouakai tephras to the north, and due to recent laharic erosion from Egmont centre, some of the Egmont tephras are only preserved on the Pouakai ringplain. The best tephra sections are preserved on the fringes of the volcanoes below the 1,000 ft (300 m) contour. The Taranaki constructional surfaces show tephra thicknesses which are more or less proportionate to their age. The tephras and limited nuée ardente deposits form distinctive marker beds and are useful in dating constructional surfaces and landforms adjacent to the source areas. This paper presents the stratigraphy of the principal late Quaternary tephras and nuée ardente deposits originating from the Taranaki volcanoes. The area studied is mostly 200 km² of the older Pouakai ringplain, preserved south of New Plymouth, extending in an arc from Okato in the west to Inglewood in the east (Fig. 1). The tephras and nuée ardente deposits described in this paper and exposed between Okato and Opunake (N118) will be discussed in a later paper relating to the age of lahars in western Taranaki.

TERMINOLOGY

Terms used in this paper are defined as follows:

Volcaniclastic Fisher (1961) uses this term to include the "entire field of clastic rocks composed in part of, or entirely of volcanic fragments". The rock may therefore be formed by any mechanism. A shorter, more precise definition is suggested for New Zealand usage, to include "all fragmental rocks of volcanic origin". The term encompasses all pyroclastic, autoclastic and detrital volcanic deposits.

Pyroclastic Wentworth and Williams (1932) defined "pyroclastic" as "an adjective applied to rocks produced by explosive or aerial ejection of material from a volcanic vent". Pyroclastic rocks are considered to be of two kinds: (a) tephras deposited from eruptive clouds by aerial ejection, and (b) flow deposits erupted in the form of nuées ardentes.

Ash, lapilli and blocks Size descriptive terms for pyroclastic rocks are those of Fisher (1961) who modified Wentworth and Williams' (1932) usage to agree with sedimentary terminology.

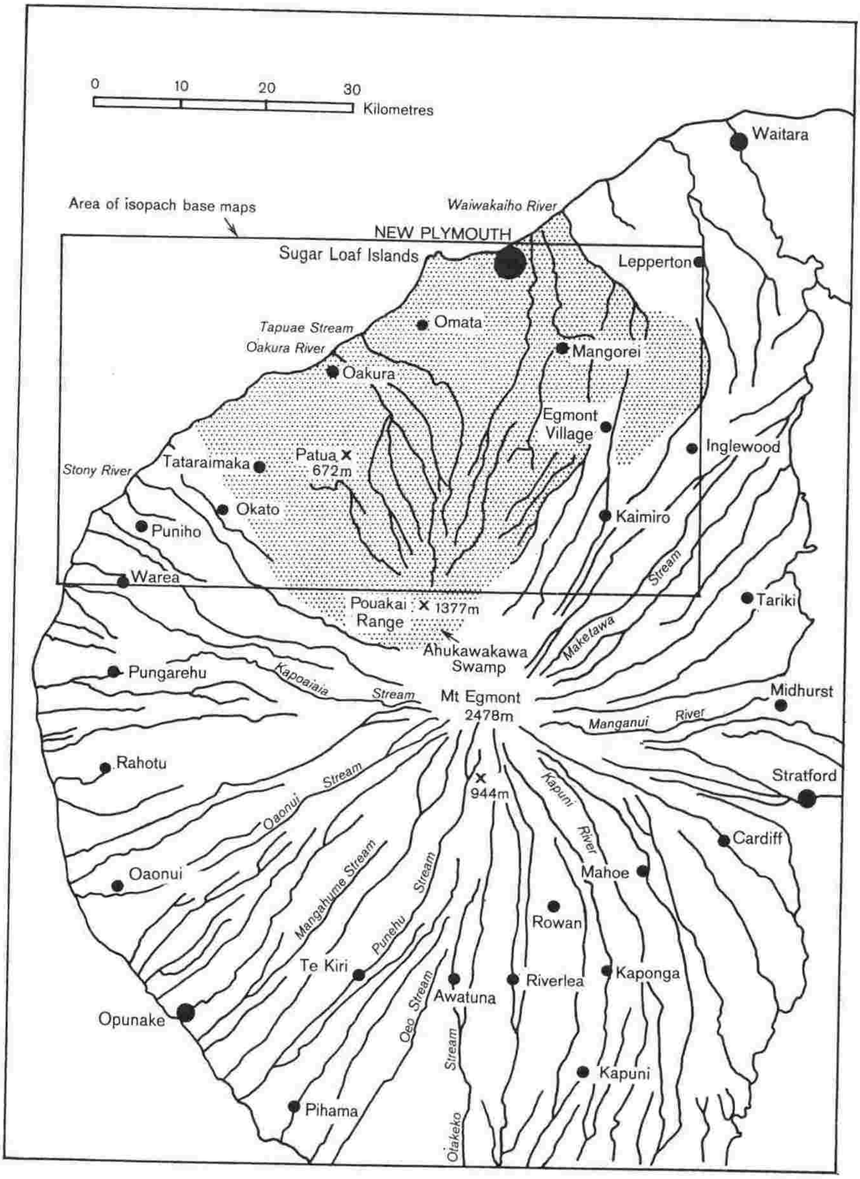

FIG. 1—Locality map of Taranaki showing; (a) distribution of Pouakai Range ring-plain in study area (stippled), (b) region of isopach base maps (enclosed)

Volcaniclastic Limits		Sedimentological Limits	
Block	>64 mm	Boulder Cobble	>256 mm 256–64 mm
Lapilli	64–2 mm	Pebble Granule	64–4 mm 4–2 mm
Coarse ash	2–0·0625 mm	Very coarse to fine sand	2–0·0625 mm
Fine ash	<0·0625 mm	Silt and clay	<0·0625 mm

Tuff An indurated rock composed of pyroclastic fragments <2 mm diameter. Lapilli tuff can be used to qualify tuffs containing fragments between 2 and 64 mm.

Tephra The term 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". Thorarinsson does not specifically exclude flow deposits, but because such deposits "flow from a crater during an eruption" (A.G.I. Glossary 1960), they are not considered to be "tephra" and are here classified separately as "flow deposits".

PREVIOUS WORK

Oliver (1931) remarks on Maori myths which are the first record of an historic eruption from Mt Egmont. The first field evidence of recent activity was recognised by A. W. Burrell, of Stratford, who found pumice fragments in the forks of living matai (*Podocarpus spicatus*) and rimu (*Dacrydium cupressinum*) trees, in 1883. In 1929 a party of workmen constructing the road to Stratford Mountain House, uncovered a Maori oven buried beneath a pumiceous lapilli (now named the Burrell Lapilli, Oliver 1931). Apart from reconnaissance soil surveys (4 miles to 1 inch soil maps), no further work on the recent pyroclastics was done until Druce (1966) studied the distribution of ash and lapilli layers in the soils and peats on the flanks of Mt Egmont. Nine eruptives identified by Druce were considered to have been erupted since 1600 A.D. (Table 1). The most widespread member, the Burrell Lapilli, was found to cover the bases of kaikawaka (*Libocedrus bidwilli*) trees which survived the eruption. Some of these trees were cored and showed closely spaced tree-rings, beginning in the year 1655 A.D., which were attributed to growth retardation as a result of the eruption. Three other members are assigned the same age because of their conformable contacts with the Burrell Lapilli, with no soil development between them. The four members are included within the Burrell Formation.

TABLE 1—Taranaki tephrochronology, stratigraphic column

FORMATIONS	NAMED MEMBERS	UNNAMED ASHES	SYMBOLS	AUTHOR	AGE
TAHURANGI FORMATION	TAHURANGI ASH		Ta	Druce (1966)	1755 AD
BURRELL FORMATION	PUNIHO LAPILLI 2		Pl 2	Druce (1966)	1655 AD
	PUNIHO LAPILLI 1		Pl 1		1655 AD
	BURRELL LAPILLI		Bl		1655 AD
	BURRELL ASH		Ba		1655 AD
NEWALL FORMATION	WAIWERANUI ASH		Wa	Druce (1966)	Revised Age 1500 - 1550 AD
	WAIWERANUI LAPILLI		Wl		
	NEWALL LAPILLI		Nl		
	NEWALL ASH		Na		
		Unnamed Ash Beds			
INGLEWOOD TEPHRA			Il		
KORITO TEPHRA			J		
EGMONT SHOWER OAKURA TEPHRA		Unnamed Ash	Eg 1	Grange and Taylor 1931, 1933	<6,970 ± 76 rs. B.P. this paper (NZ 1144)
	Basal lapilli		Eg 1 lap.		
STENT ASH				Wellman (1962)	
OKATO TEPHRA		Unnamed Ash	Eg 2	Grange and Taylor 1931, 1933	
	AHUAHU LAPILLI		Aa		
SAUNDERS ASH			Gg		16,100 ± 220 yrs. B.P. this paper (NZ942)
CARRINGTON TEPHRAS			Ct		
KORU TEPHRA	Koru ash		Ka		
	Koru lapilli		Kp		
PUKEITI TEPHRA			Pk		
WELD TEPHRA	Weld ash		Wd		
	Weld tuff		Wt		
		Unnamed Ash Unnamed Lapilli			
NEW PLYMOUTH ASHES AND BURIED SOILS			NPA & NPBS		

From the rate of peat accumulation between the Burrell Lapilli and the present ground surface, Druce inferred the date of the later Tahurangi Ash eruption to be 1755 A.D. Four members beneath the Burrell Formation are grouped within the Newall Formation. During the eruption of the Newall Ash and Lapilli most of the forest on the NW side of Mt Egmont was destroyed. Terrestrial ratas subsequently re-established on the fresh surfaces, and two were dated by dendrochronology as having been established in the years 1627 and 1630 A.D. A sharp decrease in the tree ring annual increments of a kaikawaka now growing on Fanthams Peak was dated at 1604 A.D., and Druce considered this was most probably a result of the Newall eruptions. This date has been further revised (*see* section on Newall Ash, below, and Table 2).

More recently Topping (1972) has shown the anomalous distribution of the Burrell Lapilli was determined by changing wind vectors. The Burrell Lapilli, Waiweranui ash and Tahurangi ash show distribution patterns indicative of air-fall origin, in contrast to the other eruptives described by Druce (1966) which were probably deposited by nuées ardentes to the west of Egmont summit. The influence of the latest tephras from Egmont on soil development in the Dawson Falls region is described by Tonkin (1970).

The soil-forming Egmont and Stratford ash showers were mapped by Grange and Taylor (1933) in the first work done on the older tephras. Their broad distribution is summarised by Gibbs (1968). Clarke (1912), Gibson and Morgan (1927), and Grant-Taylor (1964a, 1964b, 1970) describe the volcanic and sedimentary rocks of the region. Gow (1967, 1968) made detailed petrological studies of selected andesites and iron sands from Mt Egmont.

METHOD OF STUDY

All major road cuttings, north of a line from Okato to Inglewood, and south of New Plymouth, up to the 2,400 ft (600 m) contour of the Pouakai Range were studied, and 600 sections examined in detail. First, a reconnaissance was made, then each cutting was examined and recorded in a continuous succession to avoid miscorrelation. The mapping carried out was considered sufficiently detailed (sections averaging 0·25 km apart) for reliable lithological correlation between road cuttings. This distance is in contrast to the larger scale rhyolitic mapping by Vucetich and Pullar (1969) who studied 300 sections over 25,000 km^2.

Cuttings which face south remain wet throughout much of the year, support thick vegetation, and are relatively useless. The cuttings which face north and are subjected to wetting and drying show preferential weathering of strata. They are best examined during the winter months because the individual layers are brightly coloured when moist, but less distinctive, massive, and hard when dry. For this reason much of the correlative work was carried out from 1968–70 during the winter and spring months (August to December).

USE OF BURIED SOILS

Rhyolitic eruptions occupied a minute part of the total time represented in sections exposed in the central North Island. Over the last 10,000 years eruptions have averaged one per 625 years (Healy in press), and were separated by accumulations of organic matter and soil development. The andesitic volcanism in Taranaki has been more frequent but less violent, with one small eruption, on average, at least every 500 years. However, the increased frequency of recent andesitic eruptions, averaging one per 150 years, probably indicates better preservation of eruptives, which may have accumulated at this rate in the past. The Taranaki eruptions have resulted in the accretion of conformable tephras on the continually vegetated topography to form the highly allophanic, yellow-brown loams of present day soils. Numerous root channels throughout the entire ash column confirm the continual vegetation cover.

Buried soils are most frequently recognised by a well developed, blocky structure and darker colours, which are best developed beneath coarse lapilli horizons. The clearest buried soils show the above characters, plus organic matter accumulations and increased abundance of root channels. The less well developed buried soils are marked only by blocky structure, darker colour, and susceptibility to weathering in road cuttings.

Within consolidated massive older ash in the New Plymouth area are several dark horizons which are interpreted as buried soils. The buried soils are weakly resistant to fretting, whereas the relatively unweathered ash upon which the soil is developed, is more resistant and projects from the sides of cuttings. Apart from enumeration of the buried soils from the top downwards, it was not possible to subdivide these older ashes because of lack of distinctive lithologic markers. They are grouped as the New Plymouth Ashes and Buried Soils. With increasing distance from source, most of the ashes and their buried soils become thin and merge together. To the north of New Plymouth they thin into a single layer, mantling Tertiary sediments without any distinctive soil breaks preserved.

TYPE LOCALITIES

Optimum thickness, rather than a maximum thickness, is the main criterion for the selection of the type localities. The site selection depended on the number and accessibility of sections (invariably cuttings on the well roaded ringplain), and the tephra lithology and soil morphology. In Taranaki, the character of each tephra changes towards the source vent, where thick deposits exist in densely bushed country and prove difficult to correlate with the deposits clearly exposed on the lowland ringplain. Also, the tephras are invariably difficult to trace near their source because of the disproportionately greater volume of other volcanic rocks. Thus the type sections have been chosen on the ringplain where the correlation is proven and distinctive, and not near the vent where the tephras are of unusual appearance. Secondary reference sections have been designated where necessary, to show lateral variation.

STRATIGRAPHIC UNITS

Where numerous tephras of small volume and limited areal extent are erupted from closely spaced vents, their distribution can only be determined for a limited sector of the ringplain. Most widespread tephras provide good stratigraphic control. Tephra units have been named after localities around the ringplain. The individual Carrington Tephras are the products of many small scale eruptions of restricted importance and they have been collectively grouped into a larger single unit.

The method of tephra nomenclature used in the Central Volcanic Region has been followed in Taranaki, in accordance with Gregg (1961). The units named in detail in this paper are all lithologically distinctive and are extremely useful in correlation studies.

Nearly all formations are bounded both above and beneath by a buried soil, which is usually developed within the top 10 cm of tephra, rather than accumulated organic materials built upon the formation. The tephra formation must be carefully defined because it may range in thickness from several centimetres to several metres. The differentiation and subsequent naming of lavas, flow-breccias and tephras of an eruptive episode into members (Cole 1970) each lithologically mapable, yet closely allied according to their age, introduces a vague time-stratigraphic connotation.

CONTACTS BETWEEN FORMATIONS

On fairly stable lowland surfaces below the 1,000 ft (300 m) contour, most tephra formations are conformable and show planar contacts. At higher altitudes, on more dissected topography, wavy boundaries between tephras are more common, with rare angular unconformities. The recognition of buried soils between the formations indicates that nearly every boundary marks a period of non-deposition, with associated weathering: a paraconformity of Dunbar and Rodger's (1957) terminology.

The lower contact of the Saunders Ash is an angular unconformity at altitudes greater than about 300 m, especially at the southern end of Carrington Road. Where the Saunders Ash thins on the lowlands, however, the unconformity is exposed between the overlapping younger Okato Tephra and the older Carrington Tephras, in the larger gullies. In the large treads between the gullies, the unconformity is a plane surface, and is marked at the contact by friable, crumbly ash above and older, firmer, blocky ash below. All the remaining contacts are conformable.

Boundaries are often marked by a coarse lapilli horizon resting on a buried soil. Because they are little weathered and are extremely porous, the lapilli horizons tend to conduct water and are often iron stained. With increasing altitude, when annual rainfall exceeds about 180 cm, and invariably with greater proximity to source, each coarse lapilli bed is strongly iron stained and some are cemented into an iron pan. The Koru lapilli at Pukeiti has orange and black (iron and manganese) coatings to each individual lapilli, with a thin iron pan at the base of the layer.

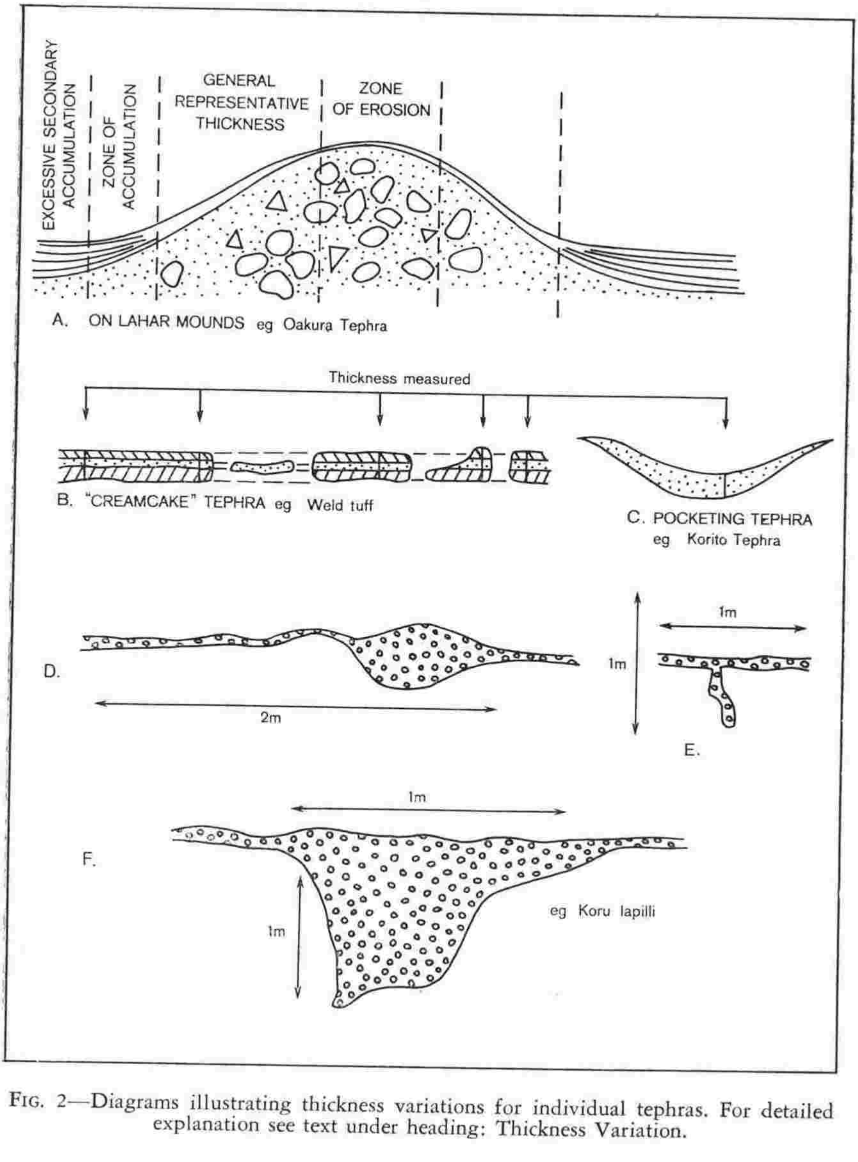

FIG. 2—Diagrams illustrating thickness variations for individual tephras. For detailed explanation see text under heading: Thickness Variation.

THICKNESS VARIATION

Some of the tephra marker beds are preserved as pockets or discontinuous "cream cakes" (for usage *see* Healy *et al.* 1964, p. 10) and show variations in thickness along a single cutting (e.g., from 0 to 30 cm). The discontinuous "cream cakes" were measured from the maximum vertical thickness where the entire "cream cake" is preserved (Fig. 2B). The variability in thickness of some beds, here termed "pocketing", led to consistent measurements being taken of the maximum thickness of a layer, because it is at this point that all the unit is preserved (Fig. 2C). Elsewhere it may have been removed, or there may have been no total cover of tephra because it landed on a vegetated surface. Alternatively, the thicker portions may be zones of accumulation. A few tephras definitely overthicken at one or two localities, quite differently to "pocketing", e.g., Koru lapilli (Fig. 2D, 2E). At the junction of Weld and Main South Coastal Road, the normally 8 cm thick Koru lapilli reaches 1 m thickness (Fig. 2F). Such anomalies in the general distribution pattern are attributed to trees which were present on the surface, which led to interception and concentration of the original fall. At the above site, the lapilli may have accumulated at the base of a large tree or possibly a fallen log, and subsequently moved into the position of the rotting wood.

The base of the tephra stratigraphic column is marked by a major paraconformity above the New Plymouth Ashes and Buried Soils. Below this contact, tephra correlation is difficult and impracticable, owing to lack of marker beds. Beneath these lower ashes the Lower Pouakai Agglomerate (of Gibson and Morgan 1927) is exposed in the sea cliffs north of Oakura River mouth.

ISOPACH MAPS

The principal topographical features on the isopach base maps are shown on Fig. 3.

Thicknesses in centimetres are used to determine the isopachs presented in Figures 4 to 13 below. It is difficult to select reliable thicknesses for thin (centimetre thick) andesitic tephras, and modal values have been used. For individual tephras on lahar mound topography, measurements about half way across the side of the mound are considered most reliable (Fig. 2A). This is because the tephras have been stripped from the apex of the mound and tend to accumulate on the apron surrounding it. A subsequent movement of ash into gentle depressions and along the sides of gullies is also apparent. Thickness values from such localities were avoided. Most of the isopach lines have been constructed with emphasis on the thicker values, which are considered more reliable. The accuracy of the points plotted is proportional to thickness, and may vary up to 10 percent.

SYSTEMATICS

The tephras and nuée ardente deposits are described in the order youngest to oldest because, with increasing age, they are less distinctive, less well preserved, and increasingly difficult to correlate. The base of the described stratigraphic column is the uppermost buried soil of the New Plymouth Ashes and Buried Soils. All the tephras stratigraphically above the dated Saunders Ash (NZ942, 16,100 ± 220 yr B.P.), i.e., from the Okato Tephra to the ground surface, are here termed Holocene. The previously described Tahurangi, Burrell and Newall Formations are included in the systematics because additional information has been added to their original descriptions.

Ashes mentioned in the systematics are of varying friability. To differentiate two grades of friability, "firmly friable" is used where there is a slightly greater resistance to pressure than there is in "friable" samples.

TAHURANGI FORMATION (after Druce 1966)

Type section in foundation cutting of the new Manganui Hut. Alt: 4,150 ft (1,245 m) N119/670619*.

MEMBER: TAHURANGI ASH (Ta)

CRITERIA: Dark brown, fine sandy loam developed on fine grey to black ash. The eruption produced a laterally restricted air-fall deposit varying from 1 to 10 cm in thickness, which has been accurately delineated by Tonkin (1970).

BURRELL FORMATION (after Druce 1966)

Two members are described at one type section and two at another type section.

MEMBER: PUNIHO LAPILLI 2 (Pl 2)

Formally named by Druce (1966). Grant-Taylor previously referred to a single shower in this region as the Puniho Lapilli (1964a), then called it Puniho Ash, then Puniho Grit (1964b). From insufficient information it was presumed the latter three names were for the same shower, and they constitute what Druce has now mapped separately as Puniho Lapilli 1 and/or 2.

CRITERIA: Dark brown (slightly reddish) soil, on lapilli and ash with sparse small carbonised wood fragments.

TYPE SECTION: NW of Puniho Hill (15 m SW of signpost at junction of Puniho Track with track around the mountain) where lapilli is 13 cm thick. Alt: 3,140 ft (942 m). N118/601635.

From the closely spaced isopachs along either side of the deposit, the western distribution pattern which is topographically controlled and the presence of charcoal fragments, this eruption is regarded as being of a "nuée peléenne d'explosion dirigee" (Lacroix 1930), strongly directed to the west of the present Mt Egmont summit.

MEMBER: PUNIHO LAPILLI 1 (Pl 1)

Formally named by Druce (1966) but was presumably also referred to by Grant-Taylor (1964a and b).

CRITERIA: Brown to dark brown soil on lapilli and ash, with small sparse carbonised wood fragments.

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

TYPE SECTION: As for Puniho Lapilli 2 where Puniho Lapilli 1 is 15 cm thick.

This pyroclastic deposit is considered to have been emplaced by a small "nuée peléenne d'explosion dirigee" (Lacroix 1930), strongly directed to the west of Mt Egmont summit because of its similar properties to Puniho Lapilli 2.

MEMBER: BURRELL LAPILLI (Bl)

Formally designated by Druce (1966); first recognised by A. W. Burrell in 1883 and described by Oliver (1931) as a lapilli bed overlying a Maori oven. It has also been referred to as the "Burrell Shower" by Grange and Taylor (1933) and by Gibbs (1968).

CRITERIA: Loose, white pumice blocks, lapilli and coarse ash with some lithic andesite fragments.

TYPE SECTION: Foundation cutting at new Manganui Hut where member is 25 cm thick. Alt: 4,150 ft (1,245 m). N119/670619.

From the generally eastern distribution pattern, the burial of the bases of certain kaikawaka trees (Druce 1966), and the occurrence of pumice fragments in the forks of matai trees, recent work by Topping (1972) indicates that this eruption was an air-fall tephra eruption. From sorting values at localities along the axis of distribution, the eruption to the ESE is thought to have been influenced by strong SW winds.

MEMBER: BURRELL ASH (Ba) Named by Druce (1966)

CRITERIA: Greyish brown coarse and fine ash; usually firm, shower-bedded in places, with abundant small carbonised wood fragments on western side of mountain.

TYPE SECTION: As for Burrell Lapilli, where Burrell Ash is 18 cm thick.

From the irregular distribution of this member and the presence of carbonised wood, the ash is considered to have been deposited by a small "nuée ardente vulcanienne" (Lacroix 1930) directly to the west of the present Mt Egmont summit, with a small proportion of air-fall material scattered laterally in the other directions.

NEWALL FORMATION

Named by Druce (1966) to include four members, one of which was previously recognised by Grange and Taylor (*in* Druce 1966), and Gibbs (*in* Wellman 1962). As with the Burrell Formation, all members are conformable and are considered to have erupted over a short period of time. Druce (1966) estimated the date of deposition of the Newall Formation as about 1604 A.D. Subsequent to this work Mr Druce and the author examined sections in the Ahukawakawa Swamp and concluded from the peat thickness between the Newall and Burrell Ashes that a greater time period than 50 years separated the Newall and Burrell Formations. Since then two radiocarbon dates have been obtained from trees charred by the Newall eruptions (Table 2). A sample from the type section of Newall Lapilli was dated (NZ1141) at 447 ± 40 yr B.P., and a sample from a charred log buried beneath 3 m of river alluvium on upper Saunders Road was dated (NZ941) at 404 ± 44 yr B.P. Both dates suggest an amendment to the age of the formation to between 1500–1550 A.D.

MEMBER: WAIWERANUI ASH (Wa) First described by Druce (1966)

CRITERIA: Fine ash with brown to dark brown, fine sandy loam.

TYPE SECTION: NW of Puniho Hill (15 m SW of signpost at junction of Puniho Track with track round the mountain where member is 5 cm thick. Alt: 3,140 ft (942 m). N118/601635.

The deposit probably represents a small tephra eruption.

TABLE 2—Radiocarbon dates from Taranaki reported in this paper

NZ^{14}C Dating No.	NZ Fossil Record No.	Grid Ref. (+ map ed.)	Age (in yr B.P.)	Interpretation
NZ 941	N118/513	N118/520688 (1965)	404 ± 44	Log carbonised by Newall eruptives and later overlain by alluvium. Wood identified as *Podocarpus ferrugineus.*
NZ 942	N108/506	N108/534704 (1962)	16,100 ± 220	Charcoal within Saunders Ash, identified as *Dracophyllum* sp.
NZ 1141	N118/505	N118/540679 (1969)	447 ± 40	Newall charcoal from type locality, identified as *Myrsine* sp.
NZ 1143	N118/509	N118/512658 (1965)	12,550 ± 150	Wood from base of debris flow sequence, without Okato Tephra preserved between NZ1143 and NZ1144.
NZ 1144	N118/510	N118/526665 (1969)	6,970 ± 76	Buried forest covered by debris flow deposit which is overlain by Oakura Tephra.

MEMBER: WAIWERANUI LAPILLI (Wl) First described by Druce (1966)

CRITERIA: Dark greyish brown blocks, lapilli and coarse ash; loose; with variable amounts of carbonised wood (usually much less than in bed below).

TYPE SECTION: As for Waiweranui Ash.

The occurrence of charcoal, the unilobed distribution of the member to the west, and the closely spaced isopachs on either side of the deposit indicates the origin was a small "nuée peléenne d'explosion dirigee" (Lacroix 1930) with maximum thickness of 60 cm.

MEMBER: NEWALL LAPILLI (Nl)

This member was previously described as "Newall Ash" by Grange and Taylor (*in* Druce 1966) and Gibbs (*in* Wellman 1962). Formally named by Druce (1966).

CRITERIA: Dark grey, coarse ash; loose; abundant carbonised wood, including logs up to 23 cm diameter lying in plane of bed.

TYPE SECTION: North bank of Stony River, 100 m east of top end of Saunders Road. Alt: 1,250 ft (375 m). N118/540679.

VARIATION: The deposit is generally white and loose, coarse ash near source, but in the richly allophanic soils developed on the ashes in western Taranaki, it forms discontinuous "cream cakes" in the red brown friable topsoil, e.g., on upper Newall Road.

The abundant charred logs together with a distribution pattern similar to Waiweranui Lapilli, suggest this deposit resulted from a moderate sized "nuée ardente vulcanienne" (Lacroix 1930), comparable with those described from the Mt Mayon eruption, Phillipines, in 1968 A.D. (Moore and Melson 1969). The maximum thickness of the deposit is about 80 cm.

MEMBER: NEWALL ASH (Na) Formally named by Druce (1966)

CRITERIA: Greyish brown, coarse and fine ash; usually firm, with abundant small carbonised wood fragments on west side of Egmont and east side of Fanthams Peak; logs on ground charred on upper surface only.

TYPE SECTION: As for Newall Lapilli. The maximum thickness of this member is about 30 cm.

The Newall Ash is clearly exposed 5 to 10 m beneath the present ground surface in cliffs alongside the Maero Stream and Stony River, where it has been covered by later debris flows. The charred logs in the deposit have been traced eastwards along Stony River, between the Maero and Pyramid Streams. The immediate thickening of the overlying debris flow deposits (maximum thickness 20 m) in this area coincides with the axis of the Newall Ash and Lapilli members, and indicates the existence of a former valley along which these ash flows travelled. Furthermore, much of the river alluvium spread over 20 km^2 to both sides of Stony River, between the 1,000 ft (300 m) contour and the coast, was deposited after the Newall eruptions. This suggests a large proportion of the western side of Mt Egmont crater has collapsed over the last 400 years.

The partial charring by the Newall Ash does not suggest such a hot eruption as the Newall Lapilli, but the distribution pattern is the same, indicating a similar mode of emplacement.

UNNAMED ASH AND LAPILLI BEDS

Within the eastern boundary of Egmont National Park, a series of small tephra showers of relatively limited distribution are preserved. These are not described in this paper because they are not widespread stratigraphic markers, and are poorly exposed, but they have been figured by Druce (1966, fig. 4). The uppermost lapilli in this sequence has been mapped as "unnamed lapilli" by Tonkin (1970).

INGLEWOOD TEPHRA (Il)

Inglewood Tephra is a new formation, here named after the township 15 km SE of New Plymouth. The tephra is a creamy pumiceous lapilli, containing blocks near to source, and is nearly always preserved within 30–100 cm of the ground surface in the Inglewood region.

The upper contact is nearly always topsoil, developed on the present day ground surface, but adjacent to Egmont National Park a thin accretion of the unnamed ashes mentioned above, overlies the formation. The base of the tephra is marked by a sharp contact between the richly pumiceous lapilli above, passing downwards into the finer yellow- and reddish-brown buried soil developed on the olive-yellow coarse ash of the Korito Tephra. The Inglewood Tephra is not shower bedded and no charcoal has yet been obtained from the formation. The unit mantles the present day topography and is probably not older than about 5,000 years.

CRITERIA: Creamy coloured, pumiceous lapilli and blocks, with minor grey, dense andesite lapilli.

TYPE SECTION: The type section is designated on Maude Road, 0·2 km above the junction with Kent Road (*see* Section 4 of Appendix and Fig. 15), N109/673752 (2nd ed. 1965), where the formation thickness varies from 50–115 cm in a "pocketting" fashion. Here it is dominated by creamy, pumiceous lapilli, with minor grey, dense, andesite lapilli and a small proportion of coarse ash also present in the matrix.

DISTRIBUTION AND SOURCE: The lapilli is found within the topsoil from Korito Road in the west to at least as far as Dudley Road in the SE, indicating a relatively recent origin. The isopach map (*see* Fig. 4) shows a unilobed directional pattern to the north. The preservation on the northern slopes of the Pouakai Range precludes a pyroclastic flow emplacement. This unit is very similar to the Burrell Lapilli in lithology and distribution pattern type, and was a tephra blown to the north by a southerly wind component.

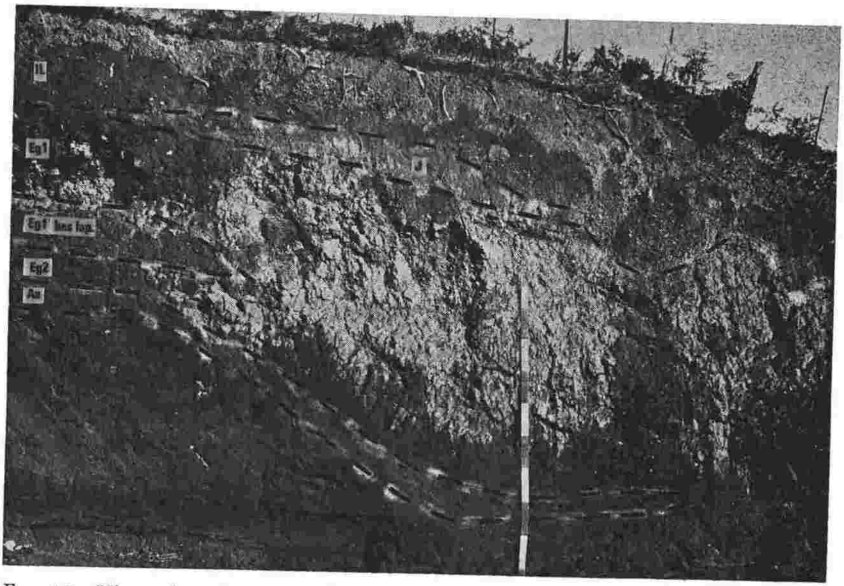


FIG. 15—View of section exposed on Maude Road immediately to south of junction with Kent Road (Section 4 of Appendix). Type locality for Inglewood Tephra (Il) and Korito Tephra (J). Eg 1 = Oakura Tephra; Eg 1 bas lap. = Oakura Tephra basal lapilli member; Eg 2 = Okato Tephra upper ash member; Aa = Ahuahu Lapilli.

REFERENCE LOCALITY: Southern end of Korito Road, last road cutting on west side of road (*see* Section 7 of Appendix, and Fig. 16) N109/650745.

VARIATION: The lapilli coarsens to pumiceous blocks, with very little ash matrix, at the top of Maude Road. North of the main road between Inglewood and New Plymouth the lapilli diminishes to ash size grade, and is preserved as white speckles in the topsoil. To the west the bed thins, and occurs as white blocks loosely bound within friable red-brown allophanic ash.

KORITO TEPHRA (J)

Korito Tephra is a new formation, here named after Korito Road, Taranaki County, where the formation was first discovered. The tephra is a distinctive pale yellow coarse ash (devoid of fine ash) which occurs as pockets in most road cuttings between Korito Road and Inglewood.

CRITERIA: Fine, soft, olive-yellow pumiceous ash, with a sharp basal contact to reddish brown ash beds. Sharp upper contact beneath Inglewood Tephra.

TYPE SECTION: Designated on Maude Road, at the same locality as for the Inglewood Tephra (*see* Section 4 of Appendix and Fig. 15), N109/673752. Here the formation is richly pumiceous and averages 30 cm thickness, with a sharp contact to the overlying Inglewood Tephra. The lower contact with the Oakura Tephra is also sharp. The formation is very similar to the Inglewood Tephra in distribution and composition, except that it is a good deal finer. Both formations are separated by a buried soil.

FIG. 16—Detail of Inglewood Tephra and Korito Tephra on Korito Road (Section 7 of Appendix). Length of tape is 2·5 m (in 25 cm divisions). Il=Inglewood Tephra; J=Korito Tephra; Eg 1=Oakura Tephra

DISTRIBUTION AND SOURCE: Similar distribution pattern to the Inglewood Tephra (Fig. 5) but slightly less widespread. The distribution is to the north with an axis along Maude Road. An airfall origin from Egmont is most probable.

REFERENCE LOCALITY: Southern end of Korito Road, as for Inglewood Tephra (*see* Section 7 of Appendix and Fig. 16) N109/650745.

VARIATIONS: The deposit is of coarse ash grade and is of mottled appearance towards source. Near its outer limit it forms small coarse ashy pockets beneath the Inglewood Tephra, but remains remarkably similar in texture at most localities.

EGMONT SHOWER

Grange and Taylor (1933, p. 33) used the term "Egmont Shower" for the oldest of three ash showers, which gives rise to soil exposed in "a belt of four to ten miles wide, bordering the coast from Waitara to Hawera". An implicit point in the designation of the shower is that it was deposited "later" than the mudflows, which form the multitude of dome-shaped hills between Okato and Opunake. This eliminates the large thickness of ashes exposed beneath the Saunders Ash from comprising the Egmont Shower. The Oakura Tephra forms the upper half of the unit proposed by Grange and Taylor, and although it is not continuously preserved on the ground surface between Okato and Opunake, it can be traced, to dip beneath a younger lahar in the coastal cliffs north of Opunake. The unit "Egmont Shower" as defined by Grange and Taylor (1933) and mapped by Gibbs (1968), occupies an important stratigraphic position. It should not be confused with the "Egmont Ash" (Fleming 1953) which has become an obscure stratigraphic term for a number of reddish-brown deposits forming the topsoil between Wanganui and Hawera. It may be correct that some portions of the "Egmont Ash" do contain part of the "Egmont Shower". However the percentage of quartz (between 1–9%) in the Egmont Ash at the Soil Bureau Reference Site for the Egmont Black Loam (near Hawera), suggests a possible wind borne origin. Further "foreign" minerals present in this reference profile do not occur in the near volcanic source ash profiles at Patua and Stratford (Table 3). The transitional nature of the lateral boundary of the "Egmont ashes" (Gibbs 1968) northwards into the Mairoa ashes, and in the east to the Tongariro ashes, has not yet been elucidated.

OAKURA TEPHRA (Eg 1)

A new formation is named after the township on the coast of western Taranaki, 8 km SW of New Plymouth. The tephra is predominantly coarse and fine ash, which is richly allophanic and grades downwards to a basal lapilli. The character of the unit shows no distinctive properties, but occupies an important stratigraphic position and is the most widespread tephra formation yet mapped in Taranaki.

The upper contact of the formation throughout the region forms present day ground surface except between New Plymouth and Inglewood where it is overlain by the Inglewood Tephra and Korito Tephra. The basal contact is marked by the base of the lapilli bed and near source is sharp. However, at a distance of about 2–5 km from the coastline the lapilli diminish in grain size to become indistinguishable from the ash above. The Oakura Tephra can still be recognised from the tephra beneath by its slightly darker, reddish colour and its less well developed structure and consistence which are reflected in its incapacity to form vertical sections in road cuttings because it erodes rapidly. North of Opunake the formation is bounded above and beneath by laharic debris.

Radiocarbon dating (NZ1144, Table 2) from buried forest layers beneath Oakura Tephra at the top of Newall Road indicate a maximum age for the formation of about 7,000 years. However, the total time span for the deposition of the ash is still unknown.

CRITERIA: Yellowish red, highly allophanic, friable ash. Texture varies from coarse sandy clay loam near source to fine sandy clay loam at distances greater than about 15 km from Mt Egmont summit. Very weakly developed blocky structure breaking to crumbs. Basal lapilli present in near source deposits consist of creamy pumice and dense grey andesite fragments, surrounded by reddish brown, ashy matrix. Gradational boundary between lapilli and upper ash. Basal contact sharp and straight, where lapilli is exposed.

TYPE SECTION: Designated at the large cutting south of the Omata Dairy Factory on Hurford Road (*see* Section 2 of Appendix and Fig. 17, 18) N108/593842 (1962).

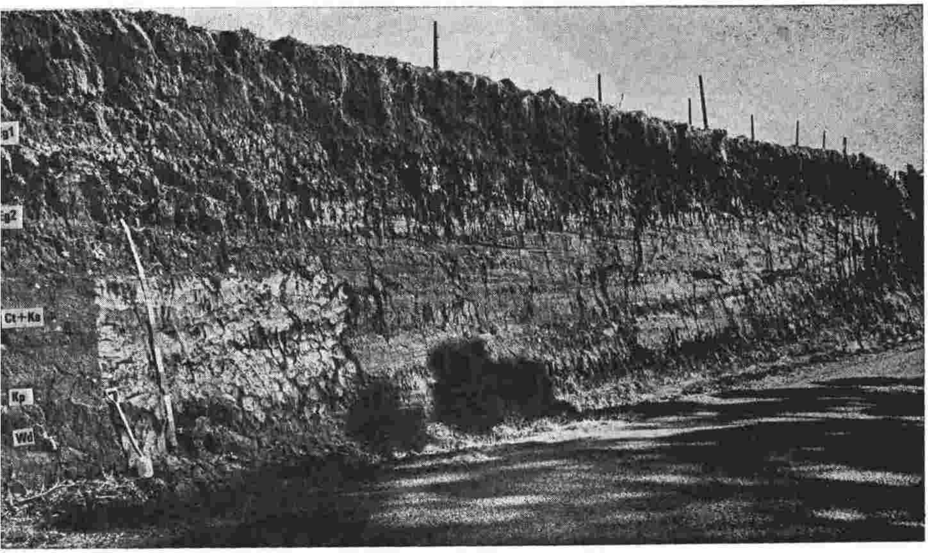
TABLE 3—Selected sand mineralogy from Soil Bureau reference sites

	Egmont					Stratford				Patua			
	Depth (cm)					Depth (cm)				Depth (cm)			
	0–7.5	7.5–15	20–35	46–56	74–89	0–7.5	7.5–15	18–30	41–54	0–7.5	15–28	38–54	56–74
Quartz	c	c	S	S	c								
Feldspars													
Acid				R	c								
Andesine	A	A	A	A	C	A	a	a	a	a	A	C	A
Micas													
Muscovite	R	R	R	R	S								
Biotite	R	R	R	R		R	R	R	R		R	R	R
Epidotes													
Zoisite, clinozoisite			R										
Saussurite		R	R	R									
Sericitic aggregates			R										
Accessory silicates													
Zircon				R									
Tourmaline					R								
Garnet					R								

From N.Z. Soil Bureau Bulletin 26 (3), 1968

Frequency of minerals in sand fraction

A = very abundant .. .. >50%
a = abundant 30–50%
C = very common.. .. .. 10–29%
c = common 5–9%
S = scarce 1–4%
R = rare .. .. <1%



. 17—General view of section directly south of Omata Dairy Factory, Hurford Road (Section 2 of Appendix). Type Locality for Oakura Tephra (Eg 1), Okato Tephra (Eg 2), and Pukeiti Tephra. Ct + Ka = Carrington Tephras + Koru ash; Kp = Koru lapilli; Wd = Weld ash. Tape is 2·5 m length.

The following section exposed:

127 cm of coarse and fine ash with many 3 cm creamy pumice lapilli and 1 cm light, grey, dense andesite lapilli. The ash is friable with a structure of weak, large blocks which break readily to small blocks and crumbs. Grading to

13 cm of brownish yellow and grey lapilli, with a moderately distinct basal contact into coarse ash with a few lapilli.

DISTRIBUTION AND SOURCE: The formation extends as far north as Waitara although at this distance the unit is obscure (*see* Fig. 6). It is the youngest widespread ash, and mantles most land surfaces in Taranaki, outside Egmont National Park. Within the park the ash becomes buried beneath large thicknesses of loose detrital andesite breccias and conglomerates which have originated from Egmont summit since the deposition of the Oakura Tephra. The distribution shows a broad lobe towards New Plymouth suggesting a southerly vector influenced deposition.

REFERENCE LOCALITIES: Cutting on Main South Coastal Road opposite Timaru Road (*see* Section 1 of Appendix and Fig. 19, 20) N108/503784 (1962).

Cutting 0·1 km down Plymouth Road from junction with Koru Road (*see* Section 5 of Appendix and Fig. 21, 22) N108/585817.

VARIATIONS: At most localities the tephra shows a single lapilli bed at its base. However, particularly along Carrington Road and at other road cuttings near source, further lapilli beds wedge into the central part of the ash. No buried soils have been recognised within the ash.

STENT ASH

Recent work in 1971 shows the marker bed Stent Ash (Wellman 1962), previously found only in coastal sections, also occurs at a few other scattered localities. It overlies a buried forest near the top of Newall Road, dated (NZ1144, Table 2) at 6,970 ± 76 yr B.P.

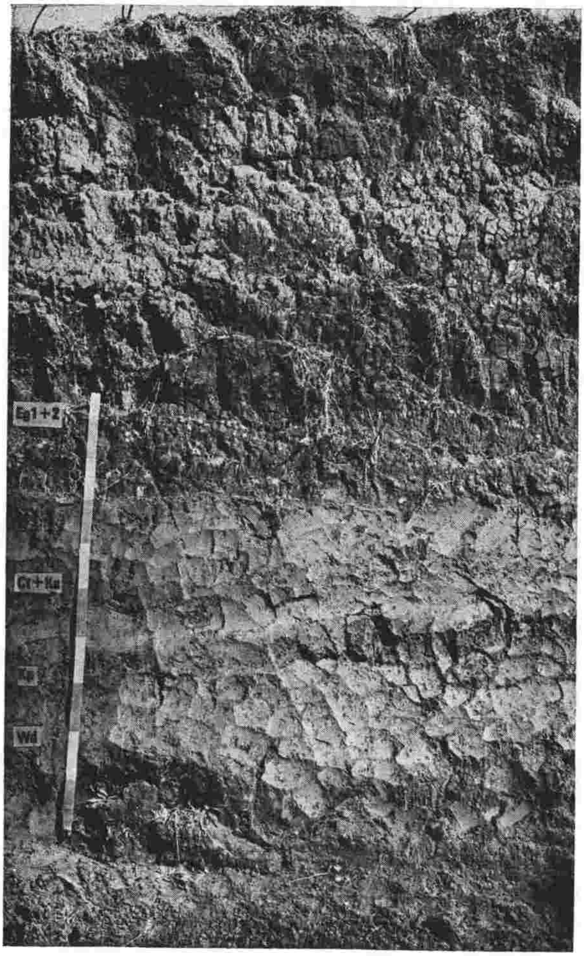


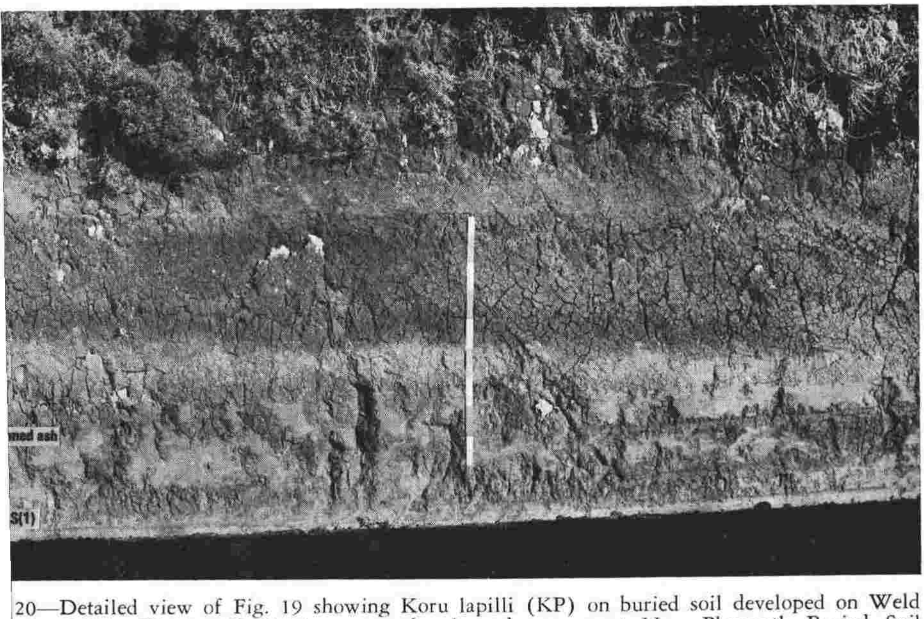
FIG. 18—Detailed view of Fig. 17, showing Oakura and Okato Tephras (Eg 1 + 2), Carrington Tephras and Koru ash (Ct + Ka), Koru lapilli (Kp) on Pukeiti Tephra and Weld ash (Wd).

OKATO TEPHRA (Eg 2)

A new formation is here named after the township 30 km SW of New Plymouth. It is very similar to the Oakura Tephra consisting of coarse, highly allophanic ash but with a more distinctive basal lapilli. The ash of the formation is indistinctive, macroscopically, from the ash above, but the basal lapilli bed is a very useful marker which, together with the Koru lapilli, can be used for widespread correlative work. The Okato Tephra constitutes the lower half of the "Egmont Shower".

The basal lapilli is sufficiently important to be assigned member status as the Ahuahu Lapilli. It is named after the road 3 km south of Oakura. Separate isopach maps are presented for the Oakura Tephra (*see* Fig. 6), Okato Tephra (Fig. 7), and the Ahuahu Lapilli (Fig. 8), apart from the total Oakura and Okato Tephras (previously the "Egmont Shower") isopach map (Fig. 9).

19—General view of section at junction of Upper Timaru Road and Main South Coastal Road (Section 1 of Appendix). Type locality for Koru lapilli and Weld Tephra. Tape is 2·5 m in length. Ct + Ka = Carrington Tephras + Koru ash; Kp = Koru lapilli; Wd = Weld ash is unlabelled; Wt = Weld tuff; NPBS(1) = New Plymouth Buried Soil No. 1 (uppermost).



20—Detailed view of Fig. 19 showing Koru lapilli (KP) on buried soil developed on Weld ash (Wd), Weld tuff (Wt), unnamed ash and uppermost New Plymouth Buried Soil (NPBS(1)).

The upper contact is sharp near source, when the ash is overlain by the basal lapilli of the Oakura Tephra. However, along the coast the upper lapilli diminishes to coarse ash grade and then the two units are almost inseparable. Although a difference in structure and consistence exists between the Okato and Oakura ashes at this distance, the boundary between them is not sharp and thus thickness measurements of each unit are unreliable. The basal contact is distinctive and sharp where the basal lapilli is preserved. In the Carrington–Saunders Road region the lapilli rests upon the Saunders Ash, the upper Carrington Tephras, or on redeposited ash. Northwards the basal lapilli progressively overlies older ashes of the Koru Tephra and then New Plymouth ashes, so that north of Oakura a widespread disconformity separates the friable Oakura and Okato Tephras from the older, firmer, blocky ashes. South of Okato the formation is bounded both above and below by a sequence of laharic breccias.

CRITERIA: Strong brown, highly allophanic, firmly friable coarse and fine ash. Texture varies from coarse sandy loam to fine sandy loam at distances greater than about 1 km from Mt Egmont summit. Blocky structure with rare prisms developed, breaking to small blocks and crumbs; passing gradationally to Ahuahu Lapilli.

TYPE SECTION: Designated at the large cutting south of the Omata Dairy Factory on Hurford Road (*see* Section 2 of Appendix and Fig. 17, 18), N108/593842. The formation is exposed beneath the Oakura Tephra and shows:

51 cm coarse ash with blocky structure with prisms developed in places;
76 cm of more resistant coarse ash, forming prisms which break to large blocks and then crumbs. Lapilli show a marked increase in the lowermost 5 cm;
10 cm reddish-yellow and light grey lapilli, averaging 1–2 cm. (Ahuahu Lapilli)

REFERENCE LOCALITIES: Cutting on Main South Road opposite Timaru Road (*see* Section 1 of Appendix and Fig. 19, 20) N108/503784.

Cutting 0·1 km down Plymouth Road from junction with Koru Road (*see* Section 5 of Appendix and Fig. 21, 22) N108/585817.

Radiocarbon dating (NZ942, Table 2) of the Saunders Ash from a sample of charcoal immediately beneath the Okato Tephra sets a maximum age of the formation about 16,000 years. The dating (NZ1143 and 1144, Table 2) of a debris flow sequence at the top of Newall Road, without the Okato Tephra preserved in it, suggests the formation is older than 12,000 years.

MEMBER: AHUAHU LAPILLI (Aa)

CRITERIA: Reddish-yellow, well rounded lapilli averaging 1 cm across; lapilli very abundant often with little ashy matrix; porous iron stained layer with a sharp straight basal boundary.

VARIATIONS: Near to source, particularly along the southern end of Carrington Road, allophanic ash may approach 50% of the volume of the lapilli member. At intermediate distances the lapilli size is very similar to the Koru lapilli and the two may be confused, but the latter is distinguished by the underlying Pukeiti Tephra. A small lapilli wedges into the centre of the ash, along Carrington Road, but because it occurs only in this vicinity and does not show a buried soil developed beneath, it is not considered worthy of separate status.

DISTRIBUTION AND SOURCE: Away from source, when the basal contact of Ahuahu Lapilli is exposed, the upper contact becomes obscure because the marker bed above the basal lapilli of the Oakura Tephra progressively thins and disappears. However an isopach map is presented for the formation (*see* Fig 7) together with an isopach map for the individual marker bed, Ahuahu Lapilli (*see* Fig. 8). In places, below the Ahuahu Lapilli is a redeposited coarse ash with current bedding. This deposit should not be confused as a further tephra underlying the Okato Tephra.

The above formations are readily distinguished from the underlying ashes. None of the following formations have been previously described.

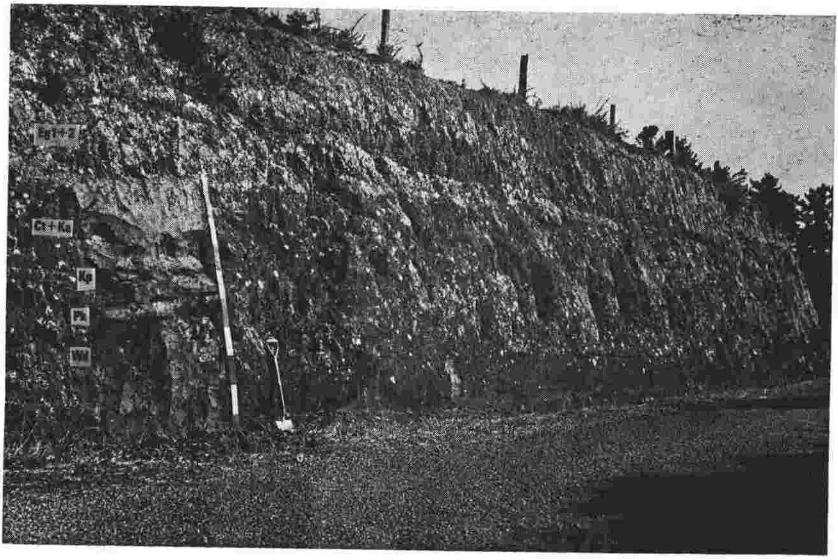


FIG. 21—General view of section exposed on Plymouth Road, 0·1 km north of junction with Koru Road (Section 5 of Appendix). Reference locality for Oakura and Okato Tephras (Eg 1 + 2) and the Koru lapilli (Kp). Ct + Ka = Carrington Tephras + Koru ash; Pk = Pukeiti Tephra; Wd = Weld ash.

SAUNDERS ASH (Gg)

Saunders Ash is a new formation first recognised along upper Saunders Road between the junctions with Okahu and Carrington Roads. The unit is a very distinctive olive-yellow colour in contrast with the yellow brown ashes both above and below. It occupies an important stratigraphic position because it lies in an intermediate position in the tephra sequence and is one of the few ashes containing dated charcoal. The upper boundary is nearly always with the base of the Okato Tephra except where the redeposited ashes overlie the Saunders Ash. The lower boundary nearly always passes into the restricted Carrington Tephras. Infrequently the ash passes both upwards and downwards into a local sandy ash deposit not described in this paper.

CRITERIA: Olive-yellow coarse ash with generally abundant charcoal fragments. Cemented, hard and massive, with sharp, wavy boundaries above and below.

TYPE SECTION: Designated at a cutting on Carrington Road, 0·85 km due east of the junction with Oxford Road (*see* Section 3 of Appendix and Fig. 23), N108/534704. The formation does not weather easily, and projects in the vertical sections as:

38 cm of a "pocketing" olive-yellow coarse ash, with 2 cm charcoal fragments.
A cemented, hard, massive bed which resists weathering. Sharp upper and lower contacts bound the formation.

Distribution and Source: The ash is restricted to a narrow region around the Carrington–Oxford–Saunders Roads region. Recent fieldwork has isolated rare, small pockets of Saunders Ash on the oldest lahar deposits further south, indicating a wider distribution than is presented in the isopach map (*see* Fig. 10), and clearly indicating an origin from Mt Egmont.

Reference Locality: A similar exposure to the type section is found immediately to the north, along Carrington Road. N108/534704.

The charcoal preserved within the Saunders Ash at the type locality is dated at 16,100 ± 220 yr B.P. (NZ942, Table 2). The complete charring of wood at a distance of 12 km from the Mt Egmont source, indicates the material was exceptionally hot when deposited and was probably not an airfall deposit. It is suggested that the Saunders Ash was a pyroclastic flow deposited by a nuée ardente. This is consistent with the restricted distribution of the ash and its unusual physical character. Along Saunders Road, midway between the junctions with Carrington and Okahu Roads, the ash is preserved as a nearly horizontal layer beneath a rounded hill of volcanic sand and ash. In the vicinity, other such mounds show weak current bedding with the concentration of black mafic sand grains into thin bands alternating with thicker yellow-brown ashy sands. The unusual and highly irregular distribution of these deposits indicate they are not tephras and although some sections look as if primarily deposited, they should not be confused with the overlying Okato Tephra.

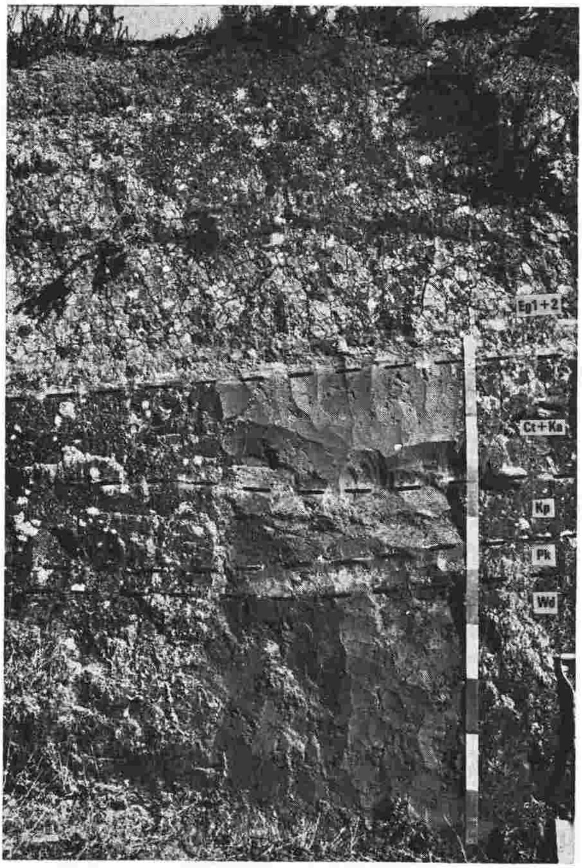


Fig. 22—Detailed view of Fig. 21 showing Oakura and Okato Tephras (Eg 1 + 2) overlying Carrington Tephras and Koru ash (Ct + Ka), on Koru lapilli (Kp), on Pukeiti Tephra (Pk) on Weld ash (Wd).

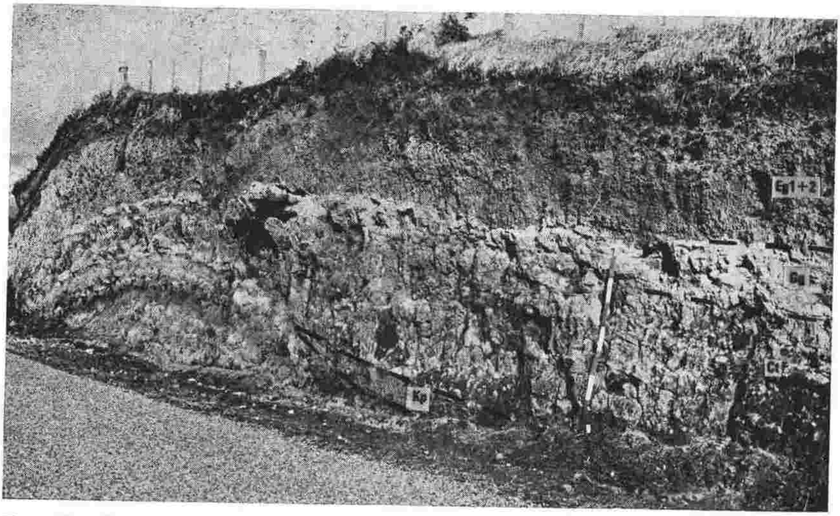


FIG. 23—General view of section on Carrington Road, 0·85 km due east of Oxford Road junction (Section 3 of Appendix). Projecting horizon in cutting is Saunders Ash (Gg) at its type locality; wedge of ?Koru lapilli (Kp) at side base of cutting. Eg 1 + 2 = Oakura + Okato Tephras; Ct = Carrington Tephras.

VARIATIONS: The ash shows a wide variation in colours, depending upon the moisture content, from a deep greenish-grey colour when wet, to an almost creamy colour when dry. The preservation of this ash near Pouakai Hut (alt. 4,200 ft; 1,260 m) suggests a continual cover of vegetation was present at this time to prevent the loose pyroclasts from being eroded immediately they were deposited.

CARRINGTON TEPHRAS (Ct)

This name is proposed for a sequence of relatively localised tephras of restricted correlative usage that are exposed in road cuttings along Carrington Road and upper Maude Road. The individual tephras are of limited use and are not considered worth assigning specific formational names. Each tephra eruptive is typified by coarse yellowish red lapilli which sharply grade upwards into a fine blocky yellow brown or brown ash, the latter being susceptible to weathering. Because of this, together with the vertical cracking, each ash layer is interpreted as having a buried soil developed on its upper surface.

A total of nine ash and lapilli showers were counted on upper Maude Road beneath the Okato Tephra, but only five are preserved in the Carrington Road area.

The upper contact of the tephras is immediately beneath the Saunders Ash. The lower contact is rarely seen but is marked by the Koru Ash in a few cuttings in upper Pitone and Dover Roads. No charcoal has been obtained from these beds so that only an approximate guess according to accumulation rates can be extrapolated. An estimated time interval in the order of 20,000 years is considered required for the deposition of these beds.

CRITERIA: Thin lapilli beds grading upwards to thin ashes, with sharp basal contacts, preserved between the Saunders Ash and the Koru Tephra.

TYPE SECTION: Designated on Carrington Road, at the same locality as the Saunders Ash type section (*see* Section 3 of Appendix and Fig. 23) N108/534704. Here a total of 200 cm of thin lapilli beds each grade upwards into small ashes, with sharp lower boundaries.

DISTRIBUTION AND SOURCE: The few outcrops of these tephras are restricted to road cuttings high on the flanks of the Pouakai Range. Insufficient thickness data are available for isopach construction and thus the origin of these tephras is still in doubt. However, their presence high in the Pouakai Range, near Pouakai Hut, resting conformably beneath the present day surface probably indicates an origin from Egmont.

KORU TEPHRA (Ka + Kp)

A new formation is here named after Koru Pa, 14 km SW of New Plymouth, where the formation was first recognised and where it is typically exposed. However, the locality was not chosen as a type because the upper and lower contacts are not well exposed. The Koru Tephra is exposed in most road sections from Okato to Inglewood, immediately beneath the Okato Tephra. Two informal members are recognised within this formation: the upper is Koru ash, which grades downwards into the Koru lapilli. The latter is the key marker horizon for most of this tephra work.

TYPE LOCALITY: Because of the imperceptible boundary between the lowermost Carrington Tephras and the uppermost Koru ash at most ringplain localities, the type section of the Koru Tephra was designated, without choice, at a road cutting 0·1 km south of Pukeiti Rhododendron Trust (*see* Section 8 of Appendix and Fig. 24, 25) N108/565742. This is the only cutting where the upper contact of the ash can be clearly defined in relation to the lower Koru lapilli. At this locality the Koru ash consists of coarse ash with a few lapilli fragments; sandy clay loam, friable with blocky structure; sharp, straight basal boundary to Koru lapilli. The lapilli attains 56 cm thickness and is unlike its typical occurrence in most other exposures.

SOURCE: The apparent thickening of the tephra towards the Pouakai Range is deceptive because the axis of thickening passes to the south of Pouakai summit and appears to continue towards Mt Egmont, although the deposit in this region is no longer preserved. The deposit probably represents an early eruption from Egmont but has not been preserved on the Egmont ring plain because of recent lahar activity.

MEMBER: **Koru ash (Ka)**

CRITERIA: Strong brown coloured ash with many fine mafic crystals, friable, with moderately developed blocky structure.

DISTRIBUTION: From meagre data, the ash shows a fairly even thinning away from source throughout the mapped area.

MEMBER: **Koru lapilli (Kp)**

CRITERIA: Rounded, yellowish red lapilli, averaging 2 cm across. Soft, pumiceous, porous lapilli and hard, grey, dense andesite lapilli in equal proportions. Lapilli loose, densely packed together, with very little matrix. Horizon generally excessively iron stained, sometimes resulting in iron pan formation and cementing of lapilli. Very distinct, sharp, straight lower boundary.

FIG. 24—Detail of Koru lapilli and Pukeiti Tephra at best locality for both tephras 0·1 km south of Pukeiti Rhododendron Trust (Section 8 of Appendix). For general view see Fig. 25. Divisions on tape =25 cm Ka=Koru ash; Kp = Koru lapilli; Pk=Pukeiti Tephra.

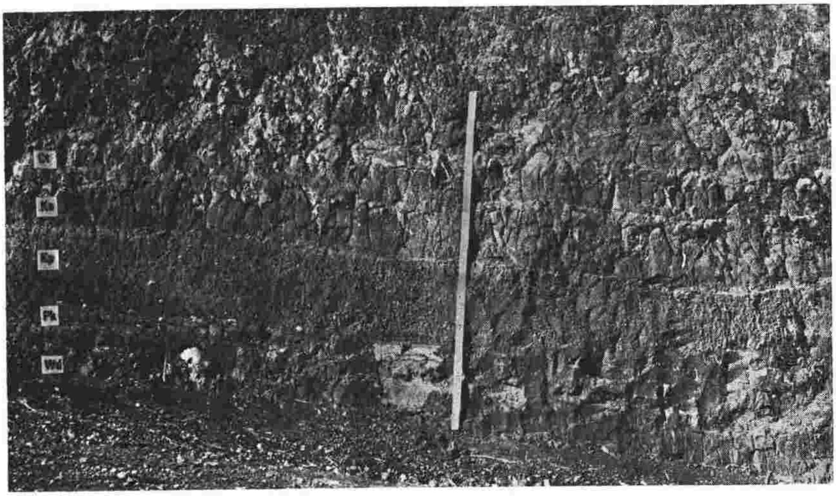


FIG. 25—A more general view than Fig. 24 of section 0·1 km south of Pukeiti Rhododendron Trust (Section 8 of Appendix). Type locality for Koru ash (Ka). Best locality for Koru lapilli (Kp) and Pukeiti Tephra (Pk). Ct = Carrington Tephras; Wd = Weld ash.

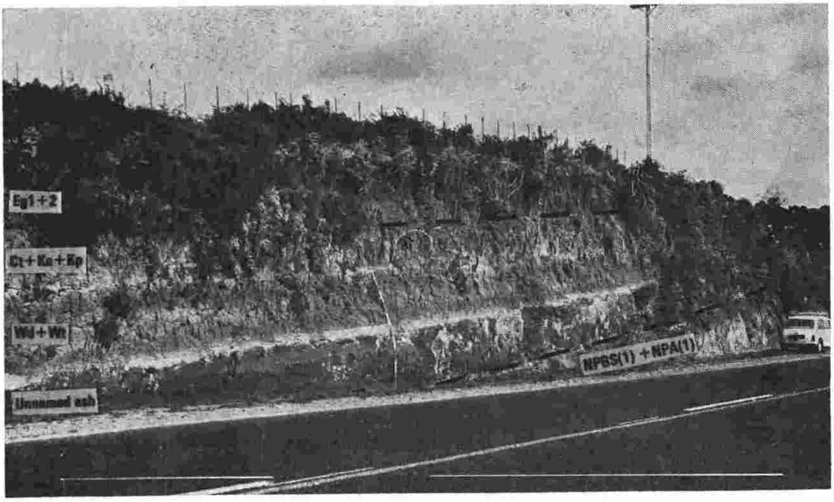


FIG. 26—General view of section on Main South Coastal Road, 0·6 km north of Okato Memorial Clock (Section 6 of Appendix). Reference locality for Koru lapilli (Kp) and Weld Tephra (Wd + Wt). Eg 1 + 2 = Oakura and Okato Tephras; Ct + Ka + Kp = Carrington Tephras + Koru ash + Koru lapilli; NPBS(1) + NPA(1) = Uppermost New Plymouth Buried Soil and Uppermost New Plymouth ash.

The upper boundary of the lapilli is most frequently gradational into the Koru ash. For isopach work, the upper contact was taken where the lapilli form about 50% of the deposit. The lower contact is sharp, straight, and distinctive, upon a buried soil developed on the Pukeiti Tephra.

REFERENCE LOCALITIES: 1. A section showing the Koru lapilli is well exposed at the road cutting on the Main South Road between Okato and Oakura, at the junction with Upper Timaru Road (*see* Section 1 of Appendix and Fig. 19, 20) N108/503784. Here it is overlain by:

36 cm of soft, friable coarse and fine ash with moderately developed blocks passing gradationally down to the Koru lapilli;

36 cm of yellowish red lapilli which are densely packed yet loose, on a sharp straight lower boundary to older ash.

2. Cutting 0·1 km down Plymouth Road from junction with Koru Road (*see* Section 5 of Appendix and Fig. 21, 22) N108/585817.

3. Cutting on Main South Coastal Road, 0·8 km north of Okato Memorial Clock (*see* Section 6 of Appendix and Fig. 26) N108/477758.

DISTRIBUTION: The lapilli bed shows a strong NW distribution pattern with an axis lying along a line from just south of Pouakai summit to Ahuahu Road (*see* Fig. 11). The deposit is considered to be typical, of an airfall pyroclast origin (tephra), and the unidirectional distribution is attributed to a SE wind vector.

VARIATIONS: The lapilli coarsens to almost small blocks near its best locality. Away from the Pouakai Range it becomes finer, always showing an increasing quantity of ashy matrix around fine lapilli rather than disappearing to ash grade altogether.

PUKEITI TEPHRA (Pk)

A new formation is here named after Pukeiti hill because of the nearby best exposure. No tephras appear to have originated from Pukeiti cone, and the naming of this unit does not imply an origin at Pukeiti. The tephra is a white, coarse, pumiceous ash which forms a distinctive marker beneath the Koru lapilli.

CRITERIA: Olive-yellow, coarse pumiceous ash, often occurring as white speckles away from source.

TYPE SECTION: Designated at the large cutting along Hurford Road to the south of Omata Dairy Factory (*see* Section 2 of Appendix and Fig. 17, 18) N108/593842.

15 cm of a yellowish brown friable coarse ash with a sharp distinct wavy boundary to

5 cm of olive-yellow pumiceous coarse ash on a distinct wavy boundary on older ash.

The upper boundary of the tephra is marked by a small buried soil developed beneath the sharp, straight boundary of the Koru lapilli. The lower boundary is marked by the base of the white Pukeiti Tephra, resting upon the yellowish brown ash of the Weld Tephra.

VARIATION: Where the tephra is extremely thin it forms distinct white speckles when the surrounding ash is moist. The layer is more difficult to view during the dry summer months.

BEST LOCALITY: The tephra is well exposed alongside the Pukeiti Rhododendron Trust, where it reaches 26 cm in thickness (*see* Section 8 of Appendix and Fig. 24), and clearly underlies the Koru lapilli.

REFERENCE LOCALITIES: Cutting on Main South Coastal Road opposite Upper Timaru Road (*see* Section 1 of Appendix and Fig. 19, 20) N108/503784.

Cutting 0·1 km down Plymouth Road, from junction with Koru Road (*see* Section 5 of Appendix and Fig. 21, 22) N108/585817.

DISTRIBUTION AND SOURCE: The ash covers an area from north of Okato to New Plymouth, showing an axis of elongation from Pouakai summit, NW to an area between Oakura and Omata (*see* Fig. 12). The source area cannot be determined from the isopach map.

The Pukeiti Tephra is a useful stratigraphic marker because of its association with the Koru lapilli. The presence of the white speckles in the tephra beneath the lapilli, away from source, distinguishes the Koru lapilli from the Ahuahu lapilli.

WELD TEPHRA

A new formation, here named after Weld Road, the locality where the formation was first recognised. The formation contains two informal members. The upper member, Weld ash, contains richly allophanic ash, whilst the lower, Weld tuff, is an extremely well-cemented, grey and yellow, laminated ash and lapilli.

TYPE LOCALITY: The designated type locality for Weld Tephra is at the cutting on the Main South Coastal Road opposite Upper Timaru Road (*see* Section 1 of Appendix and Fig. 19, 20) N108/503784, where the formation is exposed as:

91 cm of firmly friable coarse and fine ash with well developed large blocks (Weld ash) with a sharp straight boundary to
30 cm of grey ash and orange, grey and black lapilli layers forming "creamcakes" with a straight, sharp lower boundary (Weld tuff).

The upper contact of the formation is marked by a thin buried soil (infrequently preserved), formed beneath the white Pukeiti Tephra.

REFERENCE LOCALITY: Cutting on Main South Coastal Road, 0·8 km north of Okato Memorial Clock (*see* Section 6 of Appendix and Fig. 26) N108/4777758 (1962).

MEMBER: **Weld ash (Wd)**

The upper, massive, allophanic ash is given informal member status.

MEMBER: **Weld tuff (Wt)**

The lower, laminated and cemented tuff is given informal member status.

BEST LOCALITY: Weld tuff is best exposed on the Main South Coastal Road between Oakura and Okato, 1·1 km NE of the Dover Road junction (Fig. 27), (grid reference N108/487769), on gently seaward dipping, tephra mantled ringplain (Maitahi Surface), west of Kaitake Range. Beneath 25 cm of Koru lapilli, the Weld Tephra is comprised as follows:

Thickness (in cm)	Description	Formation	Member	Symbol
	— — — — — — PARACONFORMITY — — — — — —			
110			Weld ash	Wd
	two brick hard horizons comprised of			
5	7.7YR/N/5 (grey) ash, well cemented on			
5	10YR/8.4 (very pale brown) speckled layer with grey lapilli, averaging 3 mm across on			
4	10YR/4.1 (dark grey) coarse ash on		Weld tuff	Wt

Thickness (in cm)	Description	Formation	Member	Symbol
4	10YR/7.8 (yellow) ash with speckled grey lapilli on			
1–2	10YR/4.1 (dark grey) ash, well cemented on			
5	10YR/7.8 (yellow) fine lapilli with speckled grey colours on			
	— — — — — — — PARACONFORMITY — — — — — — —			
60	greasy, yellow-brown, massive to blocky ash, to base			

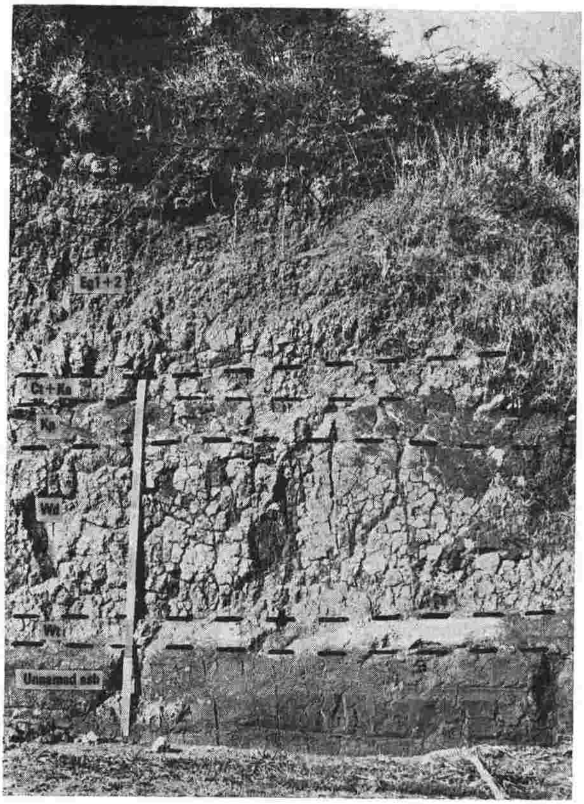


FIG. 27—Best Locality for Weld tuff on Main South Coastal Road 1·1 km NE of Dover Road junction. Tuff at this locality described in detail in text. Tape is 2·5 m in length. Eg 1 + 2 =Oakura + Okato Tephras; Ct + Ka =Carrington Tephras + Koru ash; Kp = Koru lapilli; Wd = Weld ash; Wt = Weld tuff.

CRITERIA: A brick-hard layer, generally laminated grey ashes with orange and grey lapilli layers, generally forming "creamcakes." Sharp, straight, upper and lower contacts.

DISTRIBUTION AND SOURCE: The Weld tuff thickens appreciably from west of the Kaitake Range southwards. The axis of thickening is linear, from upper Oxford Road NW to Tataraimaka. The isopach map (*see* Fig. 13) shows considerable thickening to the south indicating a source area in the Egmont centre.

VARIATION: The tuff is continuous near Okato, but northwards as it thins, it forms discontinuous "creamcakes". Near New Plymouth on Barrett Road there are three occurrences of a bed which is considered a correlative of the Weld tuff. It is a brick-hard layer, but is a pale yellow colour in contrast to the pale grey and orange colours elsewhere.

The Weld tuff is a distinctive marker bed and is the lowest unit which can be traced laterally with any degree of reliability. This formation most probably represents the earliest tephras erupted from the Egmont centre.

UNNAMED ASH

A yellow brown massive ash which is of firm consistence with a very large blocky structure lies beneath the Weld tuff. It is very similar to the Weld ash but is separated from the Weld Tephra Formation by a buried soil. The ash is not distinctive enough to be used for widespread correlative work, does not occupy an important stratigraphic position, and therefore remains unnamed at present.

NEW PLYMOUTH ASHES AND BURIED SOILS (NPA + NPBS)

All the ashes beneath the above unnamed ash are grouped informally into a new division, the New Plymouth Ashes and Buried Soils. Except for the enumeration of the buried soils from the top downwards, there are no distinctive marker beds for stratigraphic control. The base is infrequently exposed in the coastal cliffs showing the ash resting on Lower Pouakai Agglomerate. The uppermost ashes are exposed at the base of most road cuttings in the Okato–Oakura district, but further north, in the environs of New Plymouth city, they form the bulk of the subsoil, capped by a thin veneer of Okato and Oakura Tephras.

The New Plymouth ashes when dry show 10YR/7.4 to 7.6 (very pale brown to yellow) colours. The ashes appear little weathered and are resistant to erosion. They are generally massive in character, consisting of weak prisms breaking to moderately sized blocks. The lower boundaries of buried soils are sharp, straight and very distinct. The Buried Soils dry to 7.5YR/7.2 to 6.2 (pinkish grey) colours. They generally show well developed prisms, up to a few feet in height, which break to small–medium blocks and sometimes loose nuts. The lowermost boundaries are straight or wavy, and gradational as they pass down into the unweathered ash. They are less distinctive than are the lower boundaries of the New Plymouth Ashes.

It is undesirable at present to designate a type locality for these tephras. An excellent locality for them was exposed in a 10 m shaft at the site of the new New Plymouth Hospital but has since been concreted over. Samples

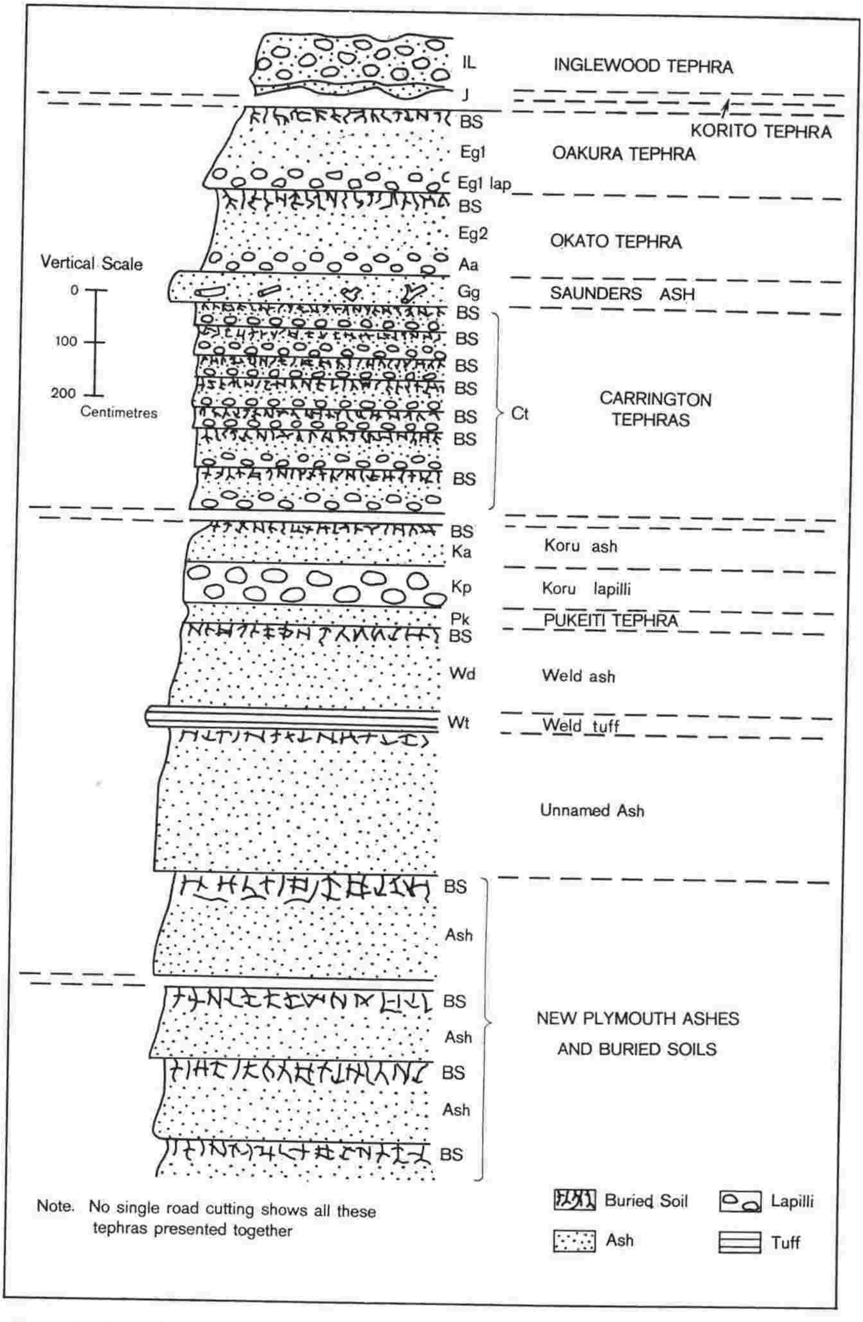


FIG. 28—Weathering profile of ashes in vertical sections. The diagram is composite from information at four localities. At no locality are all formations exposed together.

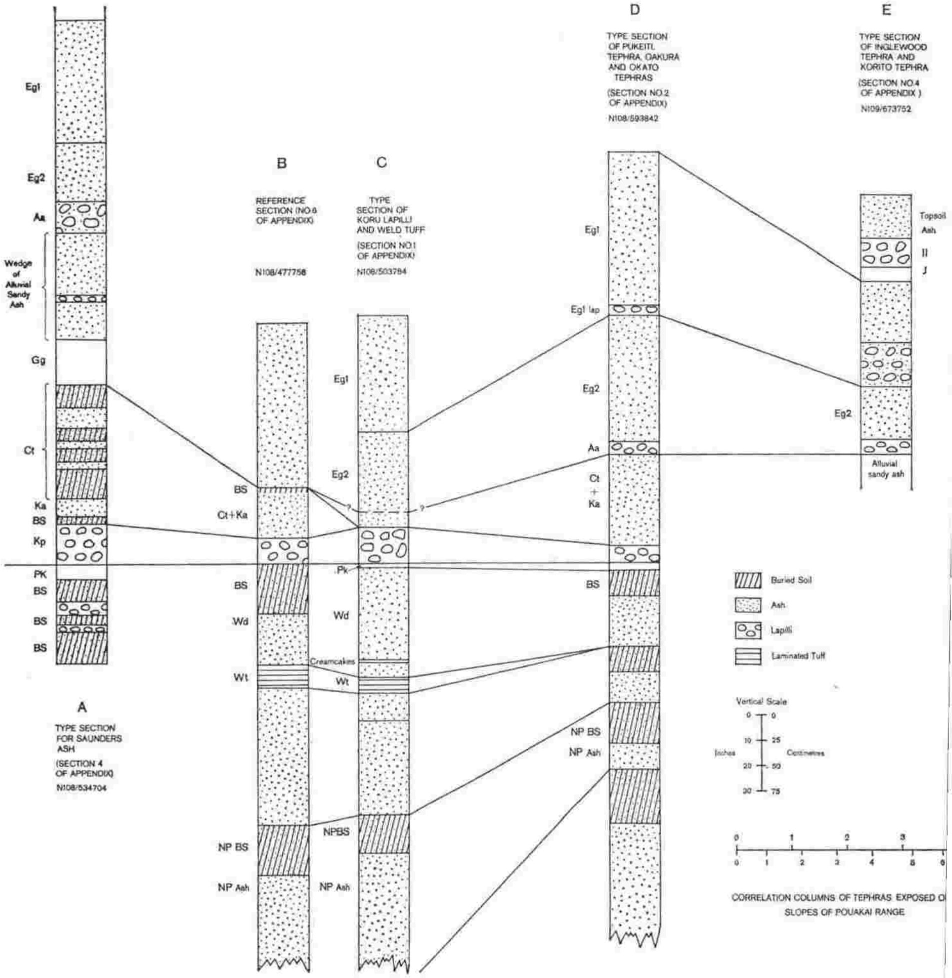


FIG. 29—Correlation columns A to E, from near Okato to Maude Road (*see* Fig. 3). Section to E are described in detail in Appendix (A in Section 3, B in 6, C in 1, D in 2, E in Base level is the lower contact of Koru lapilli, except for the right hand column where of Ahuahu Lapilli is considered base level.

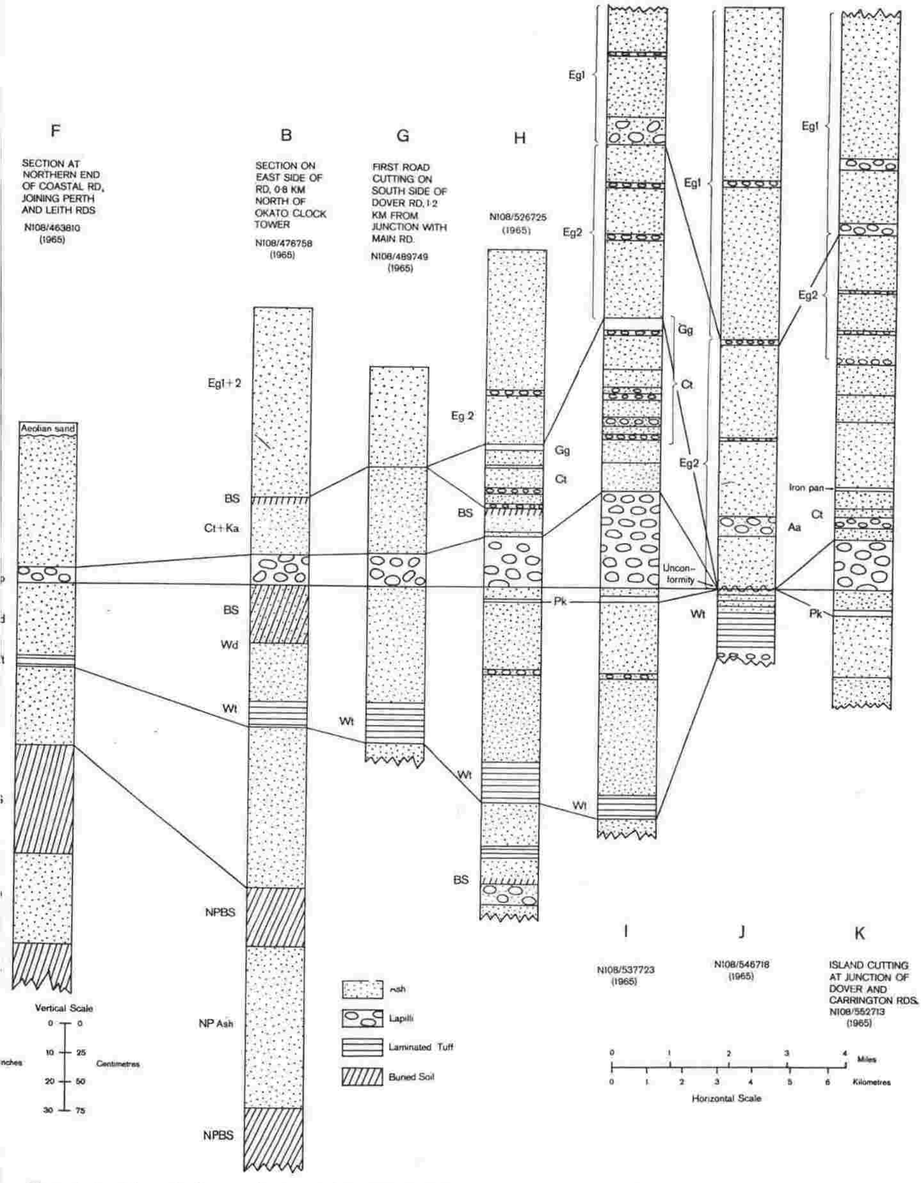


FIG. 30—Correlation columns F to K (with B for comparison), from coast SE along Dover Road (*see* Fig. 3). Base level is the lower contact of Koru lapilli.

have been collected by Dr K. Birrell (N.Z. Soil Bureau, DSIR) at regular intervals, and clay studies on these older ashes were published by Gradwell and Birrell (1954).

BEST LOCALITIES: A readily accessible cutting which shows the features of the five uppermost buried soils is on Croydon Road, 0·5 km SE of the junction with the Main South Road, north of Oakura. Grid ref. N108/562853 (1962). The terrain is a gently seaward-dipping, tephra mantled ring plain (Maitahi Surface, Grant-Taylor 1964a, b), north of the Kaitake Range.

A second best locality is 0·5 km north of the Oakura River Mouth (N108/545855). Exposed at the top of a 30 m high cliff are at least 13 New Plymouth Ashes and Buried Soils. From the beach, the soils appear very distinctive but access to the exposure is difficult and precludes this site from being a suitable type section.

REFERENCE LOCALITIES: Cuttings which expose the uppermost New Plymouth Ashes and Buried Soils include the cutting on the Main South Coastal Road, opposite Upper Timaru Road (*see* Section 1 of Appendix), the cutting exposed 0·1 km down Plymouth Road from the junction with Koru Road (*see* Section 5 of Appendix) and the cutting 0·8 km north of Okato Memorial Clock on Main South Coastal Road. None of these three localities is considered sufficiently well exposed to designate as a type sequence for the ashes and buried soils.

CRITERIA: Firm, yellow brown massive ash with strong blocky structure, with irregular grey friable horizons. Generally containing some halloysitic clay minerals in contrast to the total absence of halloysite in the tephras above.

DISTRIBUTION AND SOURCE: Figure 14 shows the distribution of the New Plymouth Ashes and Buried Soils. They are restricted to the old ring plain surfaces of the Pouakai Range, show a major disconformity to the tephras above, and thus are presumed to have originated from the Pouakai Range.

AGE: A substantial time break is considered to be represented at the top of the New Plymouth Ashes and Buried Soils. This assumption is based on the different character of ash beneath and above this boundary. X-ray and D.T.A. techniques indicate that all the clays within the ashes above this boundary do not contain halloysite but are richly allophanic. Those beneath the boundary still contain large quantities of allophane but also show increasing quantities of halloysite down the sequence. Further work at the New Plymouth Hospital site is presented by Gradwell and Birrell (1954). It is difficult to assess the age of these ashes because they are almost certainly beyond the range of radiocarbon analysis. Three or four of the uppermost ashes are very poorly exposed overlying the Rapanui Formation near the base of Paritutu. A further section exposed at the mouth of the Waiwakaiho River shows 8 ashes and buried soils overlying the Ngarino Formation. This allows an estimate to be made of the age of the upper 4 ashes as younger than 100,000 years (suggesting the upper boundary of these ashes may be in the order of 70,000 years old). Thus the lowermost ashes are greater than 100,000 years.

EXPOSED VERTICAL SECTIONS

Figure 28 shows an idealised diagram of the weathered vertical sections of all the tephras described in this paper. The diagram is composite and hence hypothetical because all the information has been incorporated from all the sections described in the Appendix. Lines of junction between separate sections are represented by dotted horizontal lines. Most weathered vertical sections examined were road cuttings or coastal cliff exposures.

CORRELATION COLUMNS

Correlation columns are shown along two lines in Fig. 29, 30. Figure 29 illustrates the lateral variation of tephra units along a correlation line selected on the outer margin of the Pouakai ring plain. Because of the restricted distribution of the lapilli marker above the Koru ash, most sections on the ring plain show undifferentiated Koru ash plus Carrington Tephras between the marker beds (Koru lapilli and Ahuahu Lapilli). Figure 30 shows a typical correlation line from any point on the coast up to an altitude of about 1,500 ft (450 m).

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REFERENCES

A.G.I. GLOSSARY 1960: "Glossary of geology and related sciences". (2nd ed.). American Geological Institute, Washington, D.C. 325 p. + Supplement 72 p.

CLARKE, E. DE C. 1912: The Geology of the New Plymouth Subdivision, *N.Z. Geological Survey Bulletin 14*. 58 p.

COLE, J. W. 1970: Description and correlation of Holocene volcanic formations in the Tarawera–Rerewhakaaitu region. *Transactions of the Royal Society of New Zealand, Earth Sciences 8* (*7*): 93–108.

DRUCE, A. P. 1966: Tree-ring dating of Recent volcanic ash and lapilli, Mt Egmont. *N.Z. Journal of Botany 4* (*1*): 3–41.

DUNBAR, C. O.; RODGERS, J. 1957: "Principles of Stratigraphy". J. Wiley, New York. 356 p.

FISHER, R. V. 1961: Proposed classification of volcaniclastic sediments and rocks. *Geological Society of America Bulletin 72*: 1409–14.

FLEMING, C. A. 1953: The geology of Wanganui Subdivision. *N.Z. Geological Survey Bulletin 52*. 362 p.

GIBBS, H. S. 1968: Volcanic-ash soils in New Zealand. *N.Z. Department of Scientific and Industrial Research Information Series 65*.

GIBSON, W.; MORGAN, P. G. 1927: The Geology of the Egmont Subdivision. *N.Z. Geological Survey Bulletin 29*. 99 p.

GOW, A. J. 1967: Petrographic studies of iron sands and associated sediments near Hawera, south Taranaki. *N.Z. Journal of Geology and Geophysics 10* (*3*): 675–95.

——— 1968: Petrographic and petrochemical studies of Mt Egmont andesites. *N.Z. Journal of Geology and Geophysics 11* (*1*): 166–90.

GRADWELL, M.; BIRRELL, K. S. 1954: Physical properties of certain volcanic clays. *N.Z. Journal of Science and Technology B36*: 108–22.

GRANGE, L. I.; TAYLOR, N. H. 1933: Report on soil surveys for 1932–33. *N.Z. Department of Scientific and Industrial Research, Annual Report 1932–33*.

GRANT-TAYLOR, T. L. 1964a. Volcanic history of western Taranaki. *N.Z. Journal of Geology and Geophysics* 7: 78–86.

——— 1964b. Geology of Egmont National Park. Pp. 13–26 *in* SCANLAN, A. B. (ed.): "Egmont National Park." Egmont National Park Board, New Plymouth. 87 p.

——— 1970: Geology of Egmont National Park. Pp. 69–82 *in* SCANLAN, A. B. (ed.): "Egmont National Park". Egmont National Park Board, New Plymouth. 86 p. (Revised ed.)

GREGG, D. R. 1961: Stratigraphic nomenclature of late Quaternary pyroclastic deposits in New Zealand. *N.Z. Journal of Geology and Geophysicss 4 (1)*: 44–7.

HEALY, J. (in press): The tempo of rhyolitic volcanism in New Zealand. *Proceedings of Volcanological Conference on Island of Thera, Greece.*

HEALY, J.; VUCETICH, C. G.; PULLAR, W. A. 1964: Stratigraphy and chronology of Late Quaternary volcanic ash in Taupo, Rotorua, and Gisborne districts. *N.Z. Geological Survey Bulletin 73*. 88 p.

LACROIX, A. 1930: Remarques sur les matériaux de projection des volcans et sur le genèse des roches pyroclastiques qu'ils constituent. *Livre Jubilaire 1830–1930, Centenaire de la Societe Geologique de France, Tome II*: 431–72.

MOORE, J. G.; MELSON, W. G. 1969: Nuées ardentes of the 1968 eruption of Mayon volcano, Philippines. *Bulletin Volcanologique 33 (2)*: 600–20.

NINKOVICH, D. 1968: Pleistocene volcanic eruptions in New Zealand recorded in deep-sea sediments. *Earth and Planetary Science Letters 4*: 89–102.

OLIVER, W. R. B. 1931: An ancient Maori oven on Mount Egmont. *Journal of the Polynesian Society 40 (2)*: 73–9.

THORARINSSON, S. 1954: The tephra fall from Hekla on March 29, 1947 II (3). *In* EINARSSON, J.; KJARTANSSON, G.; THORARINSSON, S. (Ed.): "The Eruption of Hekla, 1947–48". Societas Scientiarum Islandica and the Museum of Natural History, Reykjavik. 68 p.

TONKIN, P. J. 1970: The soils of the southeastern sector of Egmont National Park. *Earth Science Journal 4 (1)*: 36–57.

TOPPING, W. W. 1972: The Burrell Lapilli Eruptives, Mount Egmont. *N.Z. Journal of Geology and Geophysics. 15 (3)*: 476–90.

VUCETICH, C. G.; PULLAR, W. A. 1969: Stratigraphy and chronology of late Pleistocene volcanic ash beds in central North Island, New Zealand. *N.Z. Journal of Geology and Geophysics 12 (4)*: 784–837.

WELLMAN, H. W. 1962: Holocene of the North Island of New Zealand: a coastal reconnaissance. *Transactions of the Royal Society of New Zealand, Geology 1*: 29–99.

WENTWORTH, C. K.; WILLIAMS, H. 1932: The classification and terminology of pyroclastic rocks. *Bulletin of the National Research Council, Washington. 89*: 19–53.

APPENDIX

SECTION DESCRIPTIONS

Colours described in the section descriptions are of the Munsell Colour notation.

Section 1

Location: Cutting opposite junction of Upper Timaru Road, with Main South Coastal Road, between Oakura and Okato. On west side of road. (*See* C on Fig. 3 and 29.)

Altitude: 300 ft (90 m).

Rainfall: 60 inches (1,525 mm).

Terrain: Gently seaward-dipping, tephra-mantled ringplain. On the Maitahi Surface, west of Kaitake Range.

Angle of Slope: 2°–3°

Grid Reference: N108/503784 (1962).

Additional Points of Importance: Type Locality for the Koru lapilli and Weld Tephra. Reference Section for Oakura, Okato and Pukeiti Tephras.

Thickness (in cm)	Description	Formation	Member	Symbol
102	5YR/4.8 (yellowish red), coarse sandy loam, friable, with weak blocky structure. Coarse ash with numerous lapilli of distinct, dense light grey and white andesite and creamy andesitic pumice, mostly between 1–2 cm across, showing increased proportions to base. Many small black mafic crystals, about 5 mm long. Many roots. Moderately distinct, irregular boundary, shown by preferential drying and weathering.	OAKURA TEPHRA		Eg 1
	— — — — — — — PARACONFORMITY — — — — — — —			
90	Buried soil developed on 7.5YR/5.6 (strong brown), moderately sandy loam, firmly friable, with well developed blocks in places forming vertical prisms. Coarse ash with many fine, distinct, white, grey and cream lapilli of andesite rock, with many finer black mafic crystals. Distinct, undulating boundary.	OKATO TEPHRA		BS (buried soil) Eg 2
	— — — — — — — DISCONFORMITY — — — — — — —			
36	Buried soil developed on 7.5YR/5.6 (strong brown), coarse sandy loam, soft and friable, with moderately developed blocks. Coarse ash with increasing percentages of dark and light grey lapilli towards base. Distinct gradational boundary to	CARRINGTON TEPHRAS plus	Koru ash	Ct+Ka BS
36	5YR/5.8 (yellowish red), lapilli, averaging 1·5 cm across, larger fragments about 2·5 cm. Lapilli soft, loose and densely packed with very little matrix. Layer appears exceedingly porous and is heavily iron stained. Lapilli show white feldspar and black hornblende crystals set in an orange matrix. Very distinct, straight lower boundary, in places filling small hollows.		Koru lapilli	Kp
	— — — — — — — PARACONFORMITY — — — — — — —			
20	Buried soil developed on 7.5YR/5.6 (strong brown), fine ash, with white, very soft speckles. White pumiceous material often concentrated into pockets: shows black manganese staining in places. Weak wavy boundary.	PUKEITI TEPHRA		BS Pk
	— — — — — — — PARACONFORMITY — — — — — — —			
91	7.5YR/5.6 (strong brown), firmly friable, sandy loam with well developed large blocks, forming plates on exposed surfaces. Coarse ash with no lapilli, but speckles of white, grey and black crystals visible in ash. Distinct, straight lower boundary into	WELD TEPHRA	Weld ash	Wd

Thickness (in cm)	Description	Formation	Member	Symbol
30	10YR/5.6 (yellowish brown), firm to hard layer, in places laminated into grey ash, and orange, grey and black lapilli layers. Forming "creamcakes". Lapilli more concentrated towards top. Massive structure. Distinct straight lower boundary.		Weld tuff	Wt
	— — — — — — PARACONFORMITY — — — — — —			
	Buried soil developed upon			BS
127	7.5YR/5.6 (strong brown) sandy loam, friable. Coarse ash with a few lapilli fragments. Very large vertical prisms breaking to large blocks and then crumb, with many vertical cracks. Single brick hard, 5 cm thick grey sandy, "creamcake" horizon, in centre of ash. Slightly wavy, almost straight boundary.			Unnamed Ash
	— — — — — — MAJOR PARACONFORMITY — — — — — —			
50	10YR/5.6 (yellowish brown) drying very distinctively to 10YR/6.3 (pale brown). Coarse ash with a few creamy lapilli fragments in upper portion. Very friable with little structure, mainly loosely held coarse nuts, coarse sandy loam. Irregular, gradational boundary to		New Plymouth Buried Soil (1)*	NPBS(1)
	7.5YR/5.8 (strong brown) firm, massive greasy coarse sandy loam. Coarse ash with many orange and grey lapilli fragments. Equivalent horizon on opposite (east) side of road displays strong vertical cracks and prisms developed. Beneath is a sharp, straight boundary into another New Plymouth Buried Soil. To base.		Uppermost New Plymouth Ash (1)*	NPA(1)

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*New Plymouth Ashes and Buried Soils are divided into (1) Uppermost, and (2) Layers immediately beneath Uppermost.

Section 2

Location: Large cutting to south of Omata Dairy Factory, across bridge and about 500 m south along Hurford Road. West side of cutting. (*See* D on Fig. 3 and 29).

Altitude: 380 ft (114 m).

Rainfall: 60 inches (1,525 mm).

Terrain: Gently seaward-dipping, tephra mantled ringplain. On Maitahi Surface to north of Kaitake Range.

Angle of Slope: 2°–3°

Grid Reference: N108/593842 (1962).

Additional Points of Importance: Type locality for Oakura and Okato Tephra Formations (previously designated Egmont Shower) and the Pukeiti Tephra Formation.

Thickness (in cm)	Description	Formation	Member	Symbol
127	5YR/5.8 (yellowish red) coarse sandy loam, friable with weak large blocks breaking to small blocks and crumb. Coarse ash with many 3 cm creamy pumice fragments and 1 cm light grey, dense andesite lapilli. Many roots. Wavy, moderately distinct boundary to	OAKURA TEPHRA		Eg 1
13	10YR/6.8 (brownish yellow) and grey lapilli, very soft with many black mafic crystals. Massive "creamcake" structure, resistant to weathering of sandy loam texture. Moderately distinct wavy boundary.		Basal lapilli	Eg 1 lap
	— — — — — — — PARACONFORMITY — — — — — — —			
51	7.5YR/5.6 (strong brown) coarse, sandy loam, firm, blocky structure in places prisms developed. Coarse ash. Moderately straight, distinct, gradational boundary into more resistant	OKATO TEPHRA		Eg 2a
76	7.5YR/5.8 (strong brown), sandy loam, firmly friable with vertical cracks and prisms developed breaking to large blocks and then crumb. Coarse ash, few lapilli, but marked increase in lowermost 5 cm where gradational boundary into			Eg 2b
10	5YR/6.8 (reddish yellow) and 10YR/7.2 (light grey) lapilli, averaging 1–2 cm. Wavy pattern in vertical section. Not densely packed, and matrix consists of similar ash as above. Straight, sharp, distinct boundary.	AHUAHU LAPILLI		Aa
	— — — — — — — DISCONFORMITY — — — — — — —			
	Buried soil developed on			BS
38	10YR/5.6 (yellowish brown), coarse sandy loam. Massive coarse ash showing large, firmly friable blocks. Very distinct, wavy gradational contact with increasing abundance of lapilli to	CARRINGTON TEPHRA plus	Koru ash	Ct+Ka
18	10YR/5.1 (grey) hard, and 5YR/5.8 (yellowish red) soft lapilli, averaging 1–2 cm across. Densely packed, well rounded. Straight, distinct boundary.		Koru lapilli	Kp
	— — — — — — — PARACONFORMITY — — — — — — —			
15	10YR/5.6 (yellowish brown) friable, sandy loam, with moderately developed blocks breaking to crumb. Fine ash. Sharp, distinct, wavy boundary to	PUKEITI TEPHRA		
5	2.5YR/8.8 (yellow) to 6.8 (olive-yellow), coarse ash, containing light yellow, grey and black crystals in a brownish matrix. Very soft, pumiceous material with no structure. Distinct, wavy boundary.			Pk

Thickness (in cm)	Description	Formation	Member	Symbol
	— — — — — — PARACONFORMITY — — — — — —			
	Buried soil developed on			BS
56	10YR/5.6 (yellowish brown) sandy loam, firmly friable with moderately developed blocky structure. Coarse ash. Weak straight boundary.	WELD TEPHRA		
	— — — — — — PARACONFORMITY — — — — — —			
25	7.5YR/5.6 (strong brown) coarse sandy loam, friable weak blocks breaking to small nuts, coarse ash. Gradational wavy boundary into			BS
66	7.5YR/5.8 (strong brown) coarse sandy loam. Coarse ash with many 7.5YR/N6/ (grey) lapilli. Friable, with moderately developed large blocks. Straight, but very distinctive, sharp, weathering boundary		Unnamed Ash	
	— — — — — — MAJOR PARACONFORMITY — — — — — —			
50	10YR/6.6 (brownish yellow) drying to 10YR/6.3 (pale brown) sandy loam. Well developed friable blocks of coarse ash forming prisms in places. Gradational contact into		New Plymouth Buried Soil (1)*	NPBS(1
38	7.5YR/5.6 (strong brown) coarse sandy loam, with well developed large firm blocks of coarse ash sometimes forming prisms. Sharp, wavy boundary.		Uppermost New Plymouth Ash (1)	NPA(1)
	— — — — — — PARACONFORMITY — — — — — —			
75	10YR/6.6 (brownish yellow) drying to 10YR/6.3 (pale brown) sandy loam. Well developed friable blocks of coarse ash on		New Plymouth Buried Soil (2)*	NPBS(2
150	7.5YR/5.6 (strong brown), older, unweathered, massive blocky coarse ash.		New Plymouth Ash (2)	NPA(2)

*New Plymouth Ashes and Buried Soils are divided into (1) Uppermost, and (2) Laye immediately beneath Uppermost.

Section 3

Location: Second cutting to south of Evans' Farmhouse (third house along Carringt Road, from Oxford Road), 0·85 km due east of junction between Carrington a Oxford Roads. On south side of road. (*See* A on Fig. 3 and 29).

Altitude: 1,080 ft (324 m).

Rainfall: 110 inches (2,890 mm).

Terrain: Irregular hummocky dissected surface, on lower flanks of Pouakai Range.

Angle of Slope: Averaging 10°

Grid Reference: N108/534704 (1962).

Additional Points of Importance: Type locality for Saunders Ash and Carrington Tephr Radiocarbon date (NZ942) obtained from this locality, from Saunders A 16,100 ± 220 y B.P. (Table 2)

Thickness (in cm)	Description	Formation	Member	Symbol
76	7.5YR/4.4 (brown to dark brown), coarse sandy loam, friable, weakly blocky. Coarse ash with numerous angular grey lapilli. Moderately distinct, gradational wavy boundary into	OAKURA TEPHRA		Eg 1
15	10YR/8.6 (yellow) soft subrounded lapilli and 7.5YR/N6/ (light grey to grey) angular lapilli, averaging 2 cm across, largest 4 cm. Horizon pocketing. Lapilli loose, granulated sugary looking, with white clay coatings on peds like plant roots. Wavy gradational boundary to		Basal lapilli	Eg 1 lap
	— — — — INTERPRETED PARACONFORMITY — — — —			
			Interpreted	BS
76	7.5YR/5.6 (strong brown) coarse sandy loam, firm moderately sized blocks of coarse ash breaking to small blocks. Wavy gradational boundary to pocketing basal lapilli, often scattered and not discernible from ash above. Cream and grey lapilli, giving overall light yellow colour to the horizon, with black mafic crystals and loose soft creamy pieces of pumice, and hard grey andesite stones, up to 4 cms across. Weakly distinct straight boundary	OKATO TEPHRA	Ahuahu Lapilli	Eg 2 Aa
	— — — — — — PARACONFORMITY — — — — — —			
188	10YR/5.6 (yellowish brown) coarse sandy loam, wedging outwards to the east. Firm, strong large prisms of coarse ash breaking to small blocks.		Buried Soil Developed on Redeposited Sand and Ash	
	— — — — — Sharp, straight, distinct boundary — — — — —			
38	5YR/6.6 (olive-yellow) sand, "pocketing", with 2 cm charcoal fragments. Hard, massive coarse ash, well cemented. Sharp, wavy, very distinct boundary	SAUNDERS ASH		Gg
	— — — — — — UNCONFORMITY — — — — — —			
50	7.5YR/5.6 (strong brown) with white speckles, small friable blocks of coarse ash	CARRINGTON TEPHRA	Buried soil on ash	Ct
	— — — — — — PARACONFORMITY — — — — — —			
	10YR/5.6 (yellowish brown) coarse lapilli studded ash, firm large blocks with gradational contact to	CARRINGTON TEPHRA	Buried soil	
	10YR/6.6 (brownish yellow) overall colour, fine lapilli mottled orange, brown and black in hard, massive cemented ash	CARRINGTON TEPHRA	Unweathered lapilli tuff	Ct

Thickness (in cm)	Description	Formation	Member	Symbol
	— — — — — — PARACONFORMITY — — — — — —			
36	10YR/5.8 (yellowish brown) sandy loam, strongly blocky, coarse ash, on coarse grey and cream lapilli, up to 2 cm across	CARRINGTON TEPHRA	Buried soil Unweathered lapilli	Ct
	— — — — — — PARACONFORMITY — — — — — —			
8	10YR/5.8 (yellowish brown) strongly blocky, sandy loam, coarse ash, on	CARRINGTON TEPHRA	Buried soil	
5	hard, cemented massive coarse lapilli averaging 20 mm. 10YR/6.6 (brownish yellow), consisting of mottled fine orange, brown and black lapilli		Unweathered lapilli tuff	Ct
	— — — — — — PARACONFORMITY — — — — — —			
38	7.5YR/5.6 (strong brown) sandy loam, firm, well developed blocks of coarse ash. Wavy indistinct gradational boundary into	CARRINGTON TEPHRA	Buried soil	Ct
102	7.5YR/5.6 (strong brown), coarse sandy loam, unweathered lapilli-studded ash of firm prisms breaking to medium sized blocks to base.	?KORU TEPHRA		

Section 4

Location: 0·2 km uphill along Maude Road, from the junction with Kent Road. Sectio exposed in sharp corner on west side of road. (*See* E on Fig. 3 and 29).

Altitude: 1,250 ft (375 m).

Rainfall: 100 inches (2,540 mm).

Terrain: Irregular rolling surface with steep gullies and rounded hillocks. On the lowe northern slopes of the Pouakai Range.

Angle of Slope: Averaging 10°

Grid Reference: N109/673752 (1965).

Additional Points of Importance: Type Locality for Inglewood and Korito Tephra Form ations. Reference Section for Oakura and Okato Tephra.

Thickness (in cm)	Description	Formation	Member	Symbol
50–115	7.5YR/N7/ (light grey) dense andesite lapilli averaging 2 cm across, with 5YR/6.6 (olive-yellow) pumiceous lapilli drying to creamy colours, averaging 3 cm across, in 7.5YR/4.4 (dark brown) coarse ash matrix which is friable, weakly blocky, sandy clay loam. Black-grey colours towards top where influence of organic topsoil. Sharp distinct boundary.	INGLEWOOD TEPHRA		Il

Thickness (in cm)	Description	Formation	Member	Symbol
	— — — — — — PARACONFORMITY — — — — — —			
30	sandy, pumiceous loose sand, 10YR/6.8 (brownish yellow) coarse ash, with black mafic crystals giving an overall olive-yellow colour. Sharp distinct boundary.	KORITO TEPHRA		J
	— — — — — — PARACONFORMITY — — — — — —			
127	5YR/4.4 (reddish brown), firmly friable, sandy clay loam. Blocky, coarse ash breaking to crumb. Distinct gradational boundary to	OAKURA TEPHRA		Eg 1
50	10YR/8.1 (white) and 10YR/6.8 (brownish yellow) rounded lapilli sharp, wavy contact.		Basal lapilli	Eg 1 lap.
	— — — — — — PARACONFORMITY — — — — — —			
50	5YR/4.4 (reddish brown), firmly friable, sandy clay loam. Blocky coarse ash breaking to crumb. Distinct gradational boundary to	OKATO TEPHRA		Eg 2
30	5YR/5.8 (yellowish red) lapilli. Many with black manganese stains, all well rounded, firmly compacted and pocketing. Porous horizon, with large spaces between individual lapilli.		Ahuahu Lapilli	Aa
	— — — — — — Sharp, distinct, wavy boundary — — — — — —			
180	10YR/5.4 (yellowish brown), firm massive coarse ash to base.		Redeposited Sandy Ash	

Section 5

Location: Cutting 0·1 km down Plymouth road, from junction with Koru Road. On west side of road cutting.

Altitude: 500 ft (150 m).

Rainfall: 70 inches (1,780 mm).

Terrain: Gently seaward dipping, tephra mantled ringplain. On Maitahi Surface to NE of Kaitake Range.

Angle of Slope: 4°

Grid Reference: N108/585817 (1962).

Additional Points of Importance: Reference section for Oakura, Okato and Pukeiti Tephras and Koru lapilli. Also reference section for Uppermost New Plymouth Ashes and Buried Soils.

Thickness (in cm)	Description	Formation	Member	Symbol
178	7.5YR/4.4 (brown to dark brown) sandy clay loam, friable, weakly blocky breaking to fine crumb. Coarse ash with many white and cream lapilli. Straight to slightly wavy boundary to	OAKURA TEPHRA		Eg 1
20	5YR/5.1 (grey) and 7.5YR/7.8 (reddish yellow) coarse lapilli and coarse ash. Yellow lapilli soft, pumiceous, and averaging about 2 cm across, composing 75% of lapilli. Remainder dense grey andesite fragments. Straight, sharp, distinct boundary.		Basal lapilli	Eg 1 lap
	— — — — — — PARACONFORMITY — — — — — —			
127	10YR/5.8 (yellowish brown) sandy clay loam with well developed large firm blocks breaking to crumbs. Coarse ash.	OKATO TEPHRA		Eg 2
	— — — — — — Sharp, distinct boundary — — — — — —			
10–13	Many hard 5YR/5.1 (grey) and 10YR/6.8 (brownish yellow) lapilli, averaging 2 cm across, in coarse ashy matrix. Distinct, sharp, straight boundary.	OKATO TEPHRA	Ahuahu Lapilli	Aa
	— — — — — — DISCONFORMITY — — — — — —			
56–61	10YR/6.6 to 6.8 (brownish yellow) sandy clay loam. Coarse ash containing many grey, light cream, brownish yellow and orange lapilli, and many black mafic crystals. Firm, massive ash with large blocks towards the top, breaking to fine crumb. Straight, gradational, distinct boundary into	CARRINGTON TEPHRAS plus	Koru ash	Ct+Ka
30	5YR/5.1 (grey) hard and 10YR/6.8 (brownish yellow) soft lapilli. Hard andesite fragments dry to 7.5YR/N8/ to N7/ (white to light grey) colours. Many show 5YR/5.8 (yellowish red) coatings indicating heavy iron stained horizon. Firmly compacted so lapilli are loosely adhered together; with pressure fall freely as loose balls. Distinct, straight sharp boundary.		Koru lapilli	Kp
	— — — — — — PARACONFORMITY — — — — — —			
10	10YR/6.8 (brownish yellow) sandy clay loam. Firmly friable, moderately blocky fine ash with fairly sharp, straight boundary into	PUKEITI TEPHRA		Pk
10	soft pumiceous coarse ash. Consists of soft 2.5YR/8.6 (yellow) pumiceous material and black crystals with 10YR/6.8 (brownish yellow) coatings. Sharp, straight very distinct boundary.			

Thickness (in cm)	Description	Formation	Member	Symbol
	— — — — — — PARACONFORMITY — — — — — —			
150–175	5YR/5.8 to 4.8 (yellowish red) sandy clay loam, tending to 10YR/5.8 (yellowish brown) to the top. Firmly friable massive blocky coarse ash breaking to large crumbs. Undulating, fairly distinctive boundary.	WELD TEPHRA plus	Unnamed Ash	Wd+Wt
	— — — — — — MAJOR PARACONFORMITY — — — — — —			
15–25	5YR/6.3 (light reddish brown) speckles when dry, distinctive, with many old root channels showing 5YR/7.1 (light grey) colours. Sandy clay loam friable with moderately sized blocks breaking to crumbs. Coarse ash with a few lapilli present. Horizon susceptible to erosion in vertical cutting. Gradational, straight, distinct boundary into		Uppermost New Plymouth Buried Soil (1)*	NPBS(1)
18–56	10YR/8.6 (yellow) sandy clay loam, friable with moderately large blocks of coarse ash breaking to crumbs. Straight, sharp distinct boundary.		Uppermost New Plymouth Ash (1)	NPA(1)
	— — — — — — PARACONFORMITY — — — — — —			
90	5YR/6.3 (light reddish brown) speckles, similar to Uppermost New Plymouth Buried Soil, friable, moderately blocky weakly resistant paleosol. Coarse ash with a few lapilli present. Distinct, straight, gradational boundary to		New Plymouth Buried Soil (2)*	NPBS(2)
15	10YR/8.6 (yellow) sandy clay loam, with moderately large blocks of coarse ash breaking friably to crumbs.		New Plymouth Ash (2)	NPA(2)
	— — — — — — PARACONFORMITY — — — — — —			
25	Older ashes and buried soils, containing many fine black mafic crystals to base. All are similar to the two uppermost New Plymouth Ashes and Buried Soils. Lowermost material obscured by accumulation of fallen debris at base of roadcut.		Older New Plymouth Ashes and Buried Soils	

New Plymouth Ashes and Buried Soils are divided into (1) Uppermost, and (2) Layers immediately beneath Uppermost.

Section 6

Location: Between Dover Road Junction and Okato Township, on Main South Coastal Road, 0·8 km NE of Okato Memorial Clock, on east side of road. (*See* B on Fig. 3 and 29.)

Altitude: 300 ft (90 m).

Rainfall: 60 inches (1,525 mm).

Terrain: On gently seaward-dipping, tephra-mantled ringplain surface, to the west of the Pouakai Range. On Maitahi Surface.

Angle of Slope: 2°–3°

Grid Reference: N108/477758.

Additional Points of Importance: Reference Section for Koru lapilli and Weld Tephra.

Thickness (in cm)	Description	Formation	Member	Symbol
165	Upper ash (Oakura Tephra) 5YR/4.8 (yellowish red), lower ash (Okato Tephra) 10YR/5.8 (yellowish brown), show gradational contact and are undifferentiated. Sandy clay loam. Coarse ash with a few grey lapilli, friable, the upper portion tending to be weakly blocky, lower portion moderately blocky. Wavy, weak boundary.	OAKURA and OKATO TEPHRAS		Eg 1+2
	— — — — — — DISCONFORMITY — — — — — —			
50 25	10YR/5.6 (yellowish brown), sandy clay loam, firm, with moderately coarse blocks showing platy structure on exposed surface. Gradational boundary with increasing lapilli content in the coarse ash to 10YR/6.8 (brownish yellow) notably coarse ashy horizon, with numerous cream, orange and grey speckled lapilli, averaging 0.5 cm across, friable and loose. Sharp, straight distinct boundary.	CARRINGTON TEPHRAS plus	Koru ash Koru lapilli	Ct+ Ka Kp
	— — — — — — PARACONFORMITY — — — — — —			
50 50	Well developed buried soil on Unweathered coarse ash, with similar characters except that buried soil is more friable and shows less well developed structure. Both show 7.5YR/4.4 (brown to dark brown) colours, moderately coarse blocks with plates developed on exposed surfaces. Sandy clay loam texture.	WELD TEPHRA	Weld ash	Bs Wd
	— — — — — Straight, very distinct, abrupt boundary — — — — —			
23	Laminated, brick hard horizon. Cemented grit showing three 10YR/7.1 to 6.1 (light grey to grey) coarse and fine ash bands interbedded with two 10YR/8.6 (yellow) lapilli bands. (Colours when dry.) Almost continuous feature, with a few "cream cakes". Straight, very distinct, abrupt boundary.	WELD TEPHRA	Weld tuff	Wt

Thickness (in cm)	Description	Formation	Member	Symbol
	— — — — — — PARACONFORMITY — — — — — —			
140	10YR/5.6 (yellowish brown) sandy clay loam. Coarse ash with distinct abundant mottles of grey rock fragments, creamy pumice, black mafic crystals and soft white speckles. Friable, massive with weak blocks. Straight to slightly wavy, very distinct boundary.		Unnamed Ash	
	— — — — — — MAJOR PARACONFORMITY — — — — — —			
50	When dry 10YR/7.2 (light grey), sandy clay loam, with small well developed firmly friable blocks of coarse ash. Gradational wavy boundary into		Uppermost New Plymouth Buried Soil (1)*	NPBS(1)
140	when dry 10YR/8.6 (yellow) unweathered sandy clay loam, firmly friable with moderate sized, well developed blocks of coarse ash. Straight, distinct, relatively sharp boundary.		Uppermost New Plymouth Ash (1)	NPA(1)
	— — — — — — PARACONFORMITY — — — — — —			
65	when dry 10YR/7.2 (light grey), sandy clay loam with small well developed firmly friable blocks of coarse ash. To base.		New Plymouth Buried Soil (2)*	NPBS(2)

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*New Plymouth Ashes and Buried Soils are divided into (1) Uppermost, and (2) Layers immediately beneath Uppermost.

Section 7

Location: 3·8 km due SW of junction of Korito and Kent Roads, last well exposed cutting at top of Korito Road, (*see* Fig. 3).

Altitude: 1,500 ft (450 m).

Rainfall: 100 inches (2,540 mm).

Terrain: Irregular, rolling surface with steep gullies and rounded hillocks. On the lower northern slopes of the Pouakai Range.

Angle of Slope: Averaging 10°.

Grid Reference: N109/650745 (1965).

Additional Points of Importance: Reference Section for Inglewood and Korito Tephra Formations.

Thickness (in cm)	Description	Formation	Member	Symbol
100–115	7.5YR/N7/ (light grey) dense andesite lapilli fragments, averaging 2 cm across, and 5YR/6.6 (olive-yellow) pumiceous lapilli, often drying to creamy colour, averaging 2·5 cm across Coarse ashy matrix 7.5YR/4.4 (dark brown) with blackish colours to topsoil, coarse sandy clay loam, friable, weakly blocky. Distinct boundary.	INGLEWOOD TEPHRA		I1

Thickness (in cm)	Description	Formation	Member	Symbol
	— — — — — — — PARACONFORMITY — — — — — — —			
38	10YR/6.8 (brownish yellow) and black mafic crystals forming sandy, loose, pumiceous lapilli. Laterally pocketing to coarse ash. Straight to slightly wavy, sharp, distinct boundary.	KORITO TEPHRA		J
	— — — — — — — DISCONFORMITY — — — — — — —			
125	friable, greasy, blocky massive coarse ash to base.	OAKURA TEPHRA		Eg 1

Section 8

Location: Cutting 200 m south of Pukeiti Rhododendron Reserve Main Gate, on Carrington Road. Cutting on south side of road, at sharp corner, before descent to bridge.

Altitude: 1,250 ft (375 m).

Rainfall: 135 inches (3,430 mm).

Terrain: Irregular steeply dissected, bush covered slopes of Pouakai Range.

Angle of Slope: 15°

Grid Reference: N108/565742 (1962).

Additional Points of Importance: Type Locality for Koru ash. Best Locality for Koru lapilli and Pukeiti Tephra.

Thickness (in cm)	Description	Formation	Member	Symbol
150	7.5YR/4.4 (brown to dark brown) sandy clay loam. Coarse ash with many 1 cm grey lapilli. Friable and weakly blocky to gradational boundary	Topsoil plus OAKURA TEPHRA		Eg 1
30	scattered grey and 10YR/8.6 (yellow) lapilli with coarse ashy matrix. Sharp boundary.		Basal lapilli	Eg 1 lap.
	— — — — — — — PARACONFORMITY — — — — — — —			
90	10YR/3.4 (dark yellowish brown) sandy clay loam, friable with moderately developed medium blocks of coarse ash. Gradational boundary to	OKATO TEPHRA		Eg 2
18	10YR/7.1 (light grey) hard angular lapilli averaging 40% of layer, and 7.5YR/7.8 (reddish yellow) soft, rounded lapilli averaging 60%. Sharp, distinct undulating boundary to		Ahuahu Lapilli	Aa
15	7.5YR/4.4 (brown to dark brown) sandy clay loam, friable with very well developed prisms of coarse ash breaking to blocks.			
	— — — — ANGULAR UNCONFORMITY — — — —			
65	(Tephras, undifferentiated, except lowermost unit). Straight, distinct boundary	CARRINGTON TEPHRA		Ct

Thickness (in cm)	Description	Formation	Member	Symbol
	— — — — — — — PARACONFORMITY — — — — — — —			
23	7.5YR/4.4 (brown to dark brown) coarse ash with grey andesite lapilli and black shining mafic crystals. Sandy clay loam, friable with well developed blocky structure. Straight sharp boundary		Buried soil	Bs
	— — — — — — — Straight, sharp boundary — — — — — — —			
8	7.5YR/6.8 (reddish yellow) friable coarse ash with numerous soft pumiceous lapilli. A few grey andesite lapilli towards the sharp, straight, very distinct base	Lowermost CARRINGTON TEPHRA		Ct
	— — — — — — — PARACONFORMITY — — — — — — —			
30–40	5YR/5.8 to /4.8 (yellowish red) sandy clay loam. Coarse ash with a few lapilli fragments. Friable with blocky structure. Sharp, straight very distinct boundary to	KORU TEPHRA	Koru ash	Ka
56	7.5YR/6.8 (reddish yellow) lapilli. Loose balls of lapilli consist of soft orange rounded pumice and angular, dense, grey andesite, which is heavily iron stained. Very porous, basal 8 cm of lapilli also show manganese staining Straight, sharp, very distinct lower boundary		Koru lapilli	Kp
	— — — — — — — PARACONFORMITY — — — — — — —			
10	10YR/7.2 (light grey) sandy clay, with many small distinct manganese stained root channels. Buried soil developed. Greasy massive horizon when wet but develops vertical prisms on drying out. Heavy iron pan developed in lower 5 cm.	PUKEITI TEPHRA		Pk
	— — — — — — — Distinct, sharp boundary — — — — — — —			
8	10YR/5.8 (yellowish brown) sandy clay loam, friable, weakly blocky.			
	— — — — — — — Distinct, sharp boundary — — — — — — —			
8	vari-yellow coloured 10YR/8.8 to /7.8 soft pumiceous ash horizon. Sandy clay loam.			
	— — — — Distinct, straight, sharp boundary — — — —			
8	10YR/5.8 (yellowish brown) coarse ash into			
15	10YR/7.2 (light grey) coarse ash to base.			

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CHAPTER 3

STUDIES ON TARANAKI TEPHRAS

TEPHROCHRONOLOGICAL IMPLICATIONS ON EGMONT RINGPLAIN SURFACES

Detailed tephrochronological studies of the widespread Egmont tephras has allowed the mapping of ringplain surfaces in greater detail than previous 1:250,000 geological mapping (Hay 1967). In particular the units Opunake and Stratford lahars can be re-examined. Most of the Opunake lahars to the west and south of Mt. Egmont have been subdivided into four principal formations, and these are discussed elsewhere. In addition the following points are noted with regard to the 1:250,000 (1967) map.

Areas incorrectly mapped as Stratford lahars include an unnamed strip north-west of Okato, to the north of Stony River, strips along Timaru and Oakura streams and a strip along the eastern side of German Hill. The latter surface consists of river alluvium overlain by Inglewood and Korito tephras and is probably less then 4,000 years old. The former surfaces are all correlatives of the Opunake lahars.

The Mangawhero ridge, 13 km south of Mt. Egmont is considerably older than the surrounding Opunake lahars and appears to be older than the Stratford lahars mapped in the Inglewood region. In road cuttings through the ridge, the Koru lapilli occurs at the base of most exposures indicating the ridge was preserved south of Fanthams Peak as later Egmont lahars were directed to either side of it by an early "Fanthams Peak cone" which has been in existence over a minimum period of 35,000 years.

In an excavation on the upper surface of Pukeiti cone the Oakura and Okato tephras rest upon agglomerate. This indicates the cone has a minimum age of 16,000 years and unless tephras older than the Okato Tephra have since been eroded, the cone is probably younger than 20,000 years.

The extent of ash cover preserved within Egmont National Park indicates that almost the entire ringplain and cone of Mt. Egmont above the 300 m contour has originated in the last 16,000 years.

MAXIMUM SIZE DIAMETERS

Maximum size diameters for the Burrell Lapilli, Oakura Tephra basal lapilli, Ahuahu Lapilli, Koru lapilli and Korito Tephra (coarse ash) were measured according to Fisher's (1964) method. The five largest diameters were averaged at points along the axis of each lobe except for the Ahuahu Lapilli where samples close to source were not on the main axial lobe of distribution.

The curves (Fig. 4) indicate that all the eruptions involved a similar energy release between that released in the Little Glass Mountain pumice-fall eruptions in the United States (Fisher 1964) and the 1783 Mt. Asama eruption, Japan (Minakami 1942). Only the Inglewood Tephra was as powerful as that at Mt. Asama and appears to have been the most powerful eruption to have occurred in Taranaki. The Oakura Tephra basal lapilli, Ahuahu Lapilli and Koru lapilli are all more widespread than the Inglewood Tephra but the eruptions which produced them involved lower energy release, although they were higher than that of the Little Glass Mountain pumice-fall eruption. The latter eruption was of similar size to the Korito Tephra and Burrell Lapilli (Topping 1972) eruptions. Thus none of the tephra eruptions from Egmont released more energy than the 1783 Mt. Asama eruption and have never approached the size of the Crater-Lake pumice-fall (Fisher 1964).

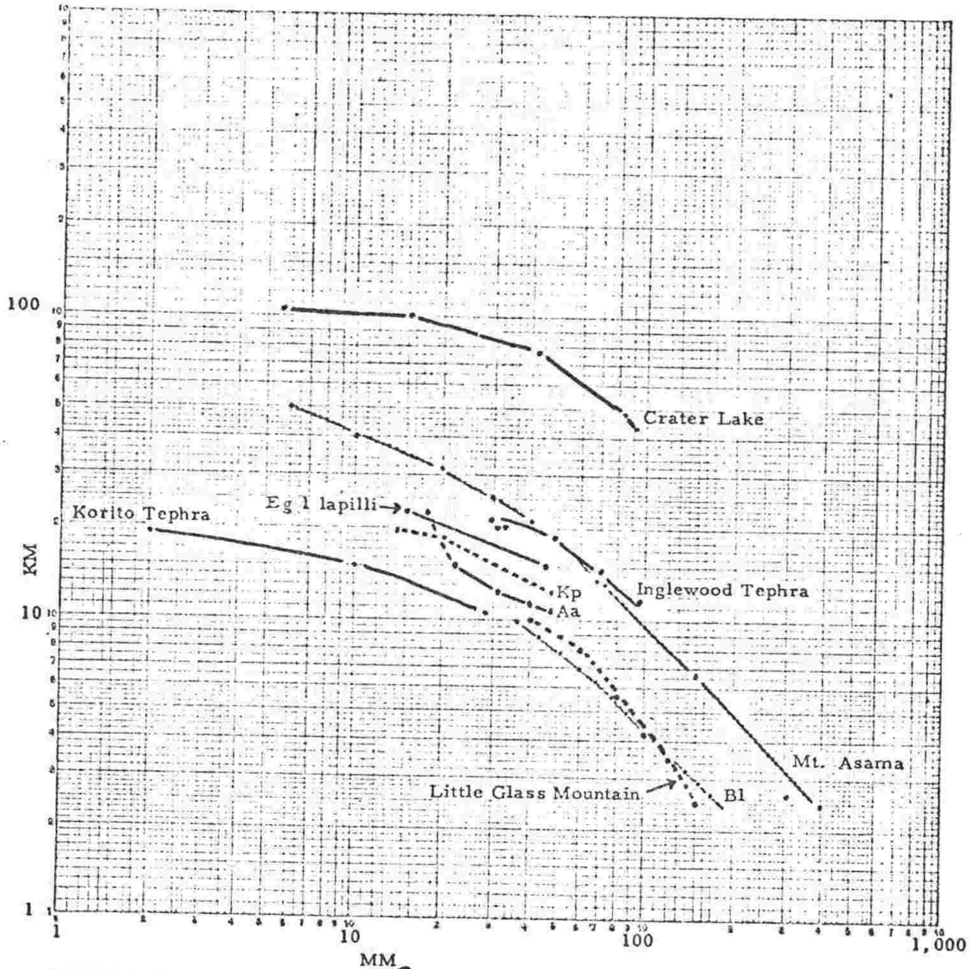


FIGURE 4 - Maximum size diameters (in mm) of pumice fragments with distance from source (in km). Bl=Burrell Lapilli;Eg 1 lapilli=Oakura Tephra basal lapilli;Aa=Ahuahu Lapilli;Kp=Koru Lapilli. Data from the Crater Lake and Little Glass Mountain eruptions is from Fisher (1964), and Mt. Asama data is from Minakami (1942).

TEMPERATURE STUDIES ON CARBONISED WOOD FORMATION

Abundant carbonised wood within Taranaki tephras is restricted to the Saunders Ash, Newall Ash and Newall Lapilli. In the Saunders Ash the fragments comprise complete stems and twigs of a scrub-type vegetation e.g. Dracophyllum sp. but are not large anough to obtain sufficient material for laboratory studies. However within the Newall Ash and Lapilli there are numerous carbonised logs up to 1 m in diameter which could be used in studies to estimate the minimum temperature required to char the wood.

The Newall Ash and Newall Lapilli members are largely restricted to an elongate distribution which follows the course of Stony River (Druce 1966), yet each eruptive averages only about 8 cm thick. Together with narrow but elongate isopachs these features indicate that the two eruptives were probably emplaced by hot glowing avalanches or nuées ardentes (Neall 1972). To find the minimum temperature required for carbonising the logs now preserved in the Newall deposits, samples were collected from the Newall Ash deposit. For comparative purposes samples were also collected from the Taupo Pumice in the Central North Island. The carbonised wood samples were first submitted to Dr. B. Molloy, Botany Division, D.S.I.R., Lincoln, who identified the original species of woods. Present day living samples of these wood species were air-dried and then heated to temperatures between 300° and 800°C, at 100°C intervals, within a layer of the respective lithologies to prevent combustion.

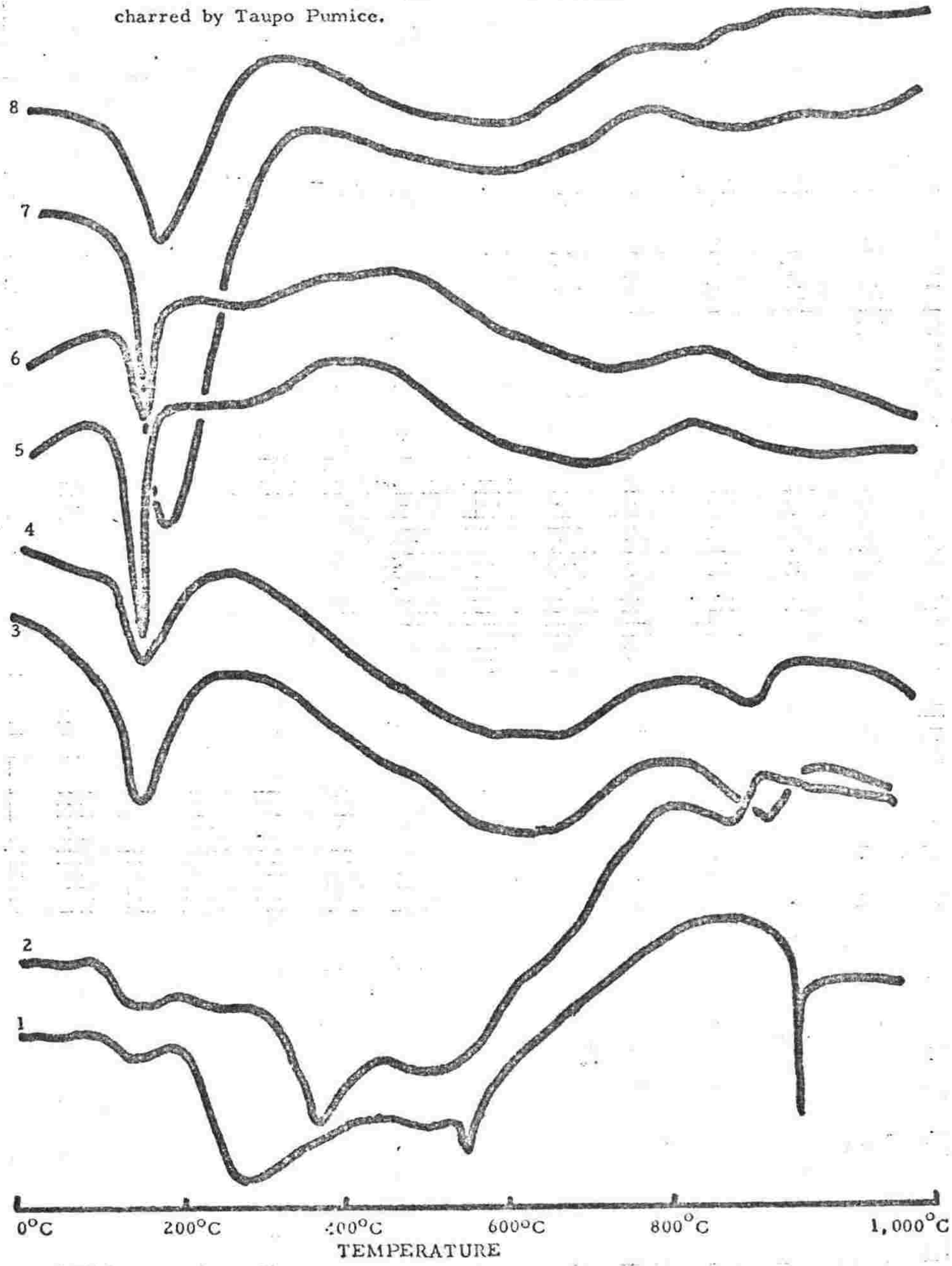
(a) DTA METHOD

Air-dried samples of living miro (Podocarpus ferrugineus), rimu (Dacrydium cupressinum), hinau (Elaeocarpus dentatus), and Myrsine sp. heated to the above temperatures were examined by the DTA method. Traces between different woods showed large differences in peak intensities which frequently obscured smaller peaks distinguished in other species, but a certain number of peaks are common to most samples. The sequence obtained from miro samples is presented in Fig.5. To show the similarity of various woods an untreated sample of rimu is included (trace 1).

The initial endothermic peak between 100° and 200°C is due to removal of water. Untreated wood samples show a strong endothermic peak between 350° and 365°C (attributed to clarain and/or vitrain) which is absent from samples heated above this temperature. A second endothermic peak between 495° and 525°C (attributed to graphite) is diagnostic in samples heated to less than 525°C but remains weak in samples heated above 500°C. Between these two peaks is an exothermic peak at about 420°C attributed to lignin and in the untreated rimu sample an endothermic peak between 250 and 300°C is also due to lignin. An exothermic peak at about 760°C is considered to be formation of carbolignin, and is more distinctive in the lower temperature curves.

The minimum temperature of wood carbonisation in the Newall Ash and Taupo Pumice was extrapolated by comparing the representative unknown sample curves with the heated control sample curves (Fig.5). It is however not possible to make an accurate estimate of the temperature required for carbonisation from these curves, other than being able to distinguish samples charred to

FIGURE 5 - DTA traces of wood and carbonised wood samples. 1= Rimu (Dacrydium cupressinum), no treatment. 2= Miro (Podocarpus ferrugineus), no treatment. 3= Miro heated to 300°C. 4= Miro heated to 400°C. 5= Miro heated to 600°C. 6= Miro heated to 800°C. 7= Miro, collected from Stony River, charred by Newall eruptions. 8= Hinau (Elaeocarpus dentatus), from Rangitaiki Plains, charred by Taupo Pumice.



above or below 400°C when the clarin/vitrain endothermic peak between 350° and 365°C is present or absent.

(b) INFRA-RED ANALYSIS

Six representative samples of carbonised woods were examined by the Infra-red method (Fig.6). Three samples were of rimu

(1) not heated,

(2) heated to 400°, and

(3) to 600°C, together with the following three samples.

(4) charred wood from rimu considered to have been knocked over by the Newall Ash but charred only on its upper surface. The sample was collected from the south bank of Stony River. The tree could not have been exposed to a large amount of heat because of the slight charring, so that a minimum temperature exposure of between 0° and 300°C was expected.

(5) a sample of completely carbonised miro, from the Newall eruptions, dated (NZ941) at 404 ± 44 yr B.P. The sample was collected below alluvium about 1 km from the type locality of the Newall Ash and Lapilli. Sample was also used in calorific determinations (Sample E, Fig.7).

(6) a sample of hinau, completely carbonised within the Taupo Pumice, collected from a nuée ardente deposit on the Rangitaiki Plains (also Sample C, Fig.7).

Curves 1,2 and 3 show general background transmittance which decreases with higher temperatures. The strong peak at 3400cm^{-1} is usually attributed to H-bonded OH groups of phenolic OH and COOH; at 2900cm^{-1} to aliphatic C-H stretching of CH_2 and/or CH_3; at 1720cm^{-1} to C=O stretching of COOH and ketones; at 1610cm^{-1} to aromatic C=C and H-bonded C=O of ketones and at 1510cm^{-1} to aromatic C=C vibrations (Goh,1970,p.681; Stevenson

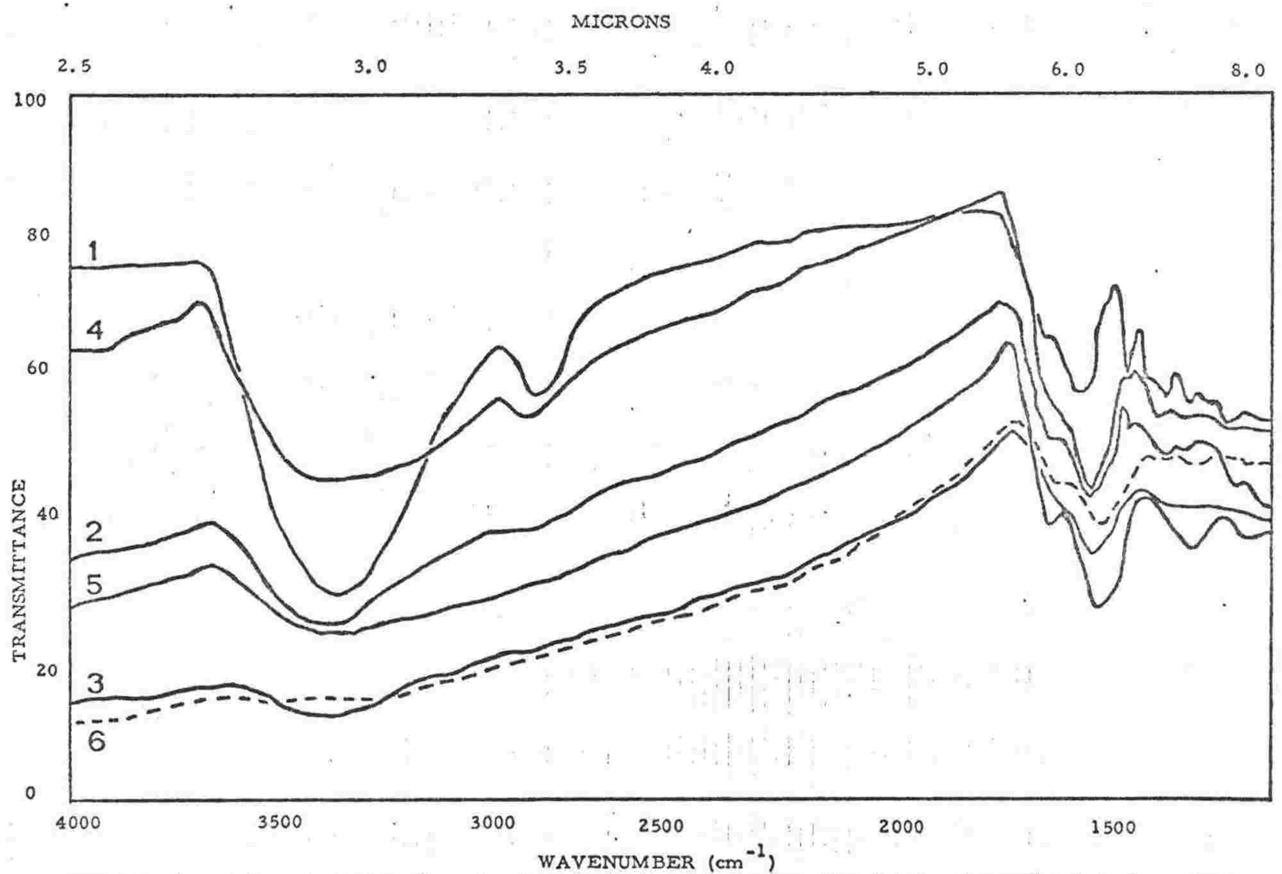


FIGURE 6 - Infrared spectra of wood and carbonised wood samples. For details of samples 1 to 6 see text.

and Goh 1971; Dr.K.M. Goh, pers.com.). The aliphatic C-H bond 2900cm^{-1} peak is lost with heating to 400°C although Schnitzer (1965) reported that it disappears from chars above 540°C. The OH absorption in the 3400cm^{-1} range is quickly reduced below 400°C but is not eliminated and continues to be weakly present at 600°C.

The three naturally charred samples 4,5 and 6, when plotted in Fig.6 show temperature ordering expected from their respective modes of formation i.e. $4<5<6$. Sample 4 broadly follows the untreated rimu sample except for less prominent 3400 and 2900cm^{-1} peaks, indicating it was heated to between 0° and 400°C. Sample 5 possesses a curve indicative of heating to 400°C. Sample 6 is likely to have been heated between 400 and 600°C.

(c) STANDARD COAL ANALYSES

A third method of determining the temperature required to carbonise selected woods from various eruptives was attempted using six trial samples submitted to the N.Z. Coal Research Association, Wellington, for standard coal analysis. The results are presented in Table 2. The calorific value of miro (D) and hinau (A) woods (Fig.3) was similar but rimu heated to 400°C (F) gave a considerably larger value than hinau taken to the same temperature (B). This confirms that temperature estimates are dependent on the type of wood and cannot be reliably made from unidentified charcoals. Because of the similarity of the unheated miro and hinau analyses, charring temperature estimates for both Newall Ash and Taupo Pumice were obtained from the same combined miro-hinau curves and not from projections constructed from the rimu value (F). Weight-gain at 70% R.H. and 20°C,

TABLE 2 - Standard coal analyses of wood and carbonised wood samples.

Sample		A	B	C	D	E	F
Wood		Hinau	Hinau	Hinau	Miro	Miro	Rimu
Treatment		None	Charred at 400°C	From Taupo Pumice	None	From Newall Ash	Charred at 400°C
Gain at 70% R.H. & 20°C	%	2.1	0	1.1	1.6	1.0	0.9
AIR-DRIED BASIS							
Moisture	%	9.6	7.6	11.6	10.4	14.9	6.7
Ash	%	0.8	3.4	6.6	0.1	4.2	3.4
Volatile Matter	%	75.9	49.2	22.0	74.7	29.0	38.7
Fixed Carbon	%	13.7	39.8	59.8	14.8	51.9	51.8
Calorific Value	Btu/lb	7620	9270	10050	7980	9520	10780
Sulphur	%	-	0.20	0.29	0.06	0.10	0.53
DRY, ASH-FREE BASIS							
Volatile Matter	%	84.7	55.3	26.9	83.5	35.8	43.0
Fixed Carbon	%	15.3	44.7	73.1	16.5	64.2	57.0
Calorific Value	Btu/lb	8500	10420	12290	8920	11770	11990
Sulphur	%	-	0.22	0.35	0.07	0.12	0.59

moisture % and sulphur % were plotted against temperature but no relationship to temperature was established. Temperature estimates however could be made from the limited data available on calorific values, volatile matter, fixed carbon and ash contents (Fig.7), and minimum temperature estimates are presented in Table 3.

From the trial analyses it appears that ash % is relatively constant between all three woods examined and may prove useful in accurately plotting a detailed temperature curve. Air-dry sample calorific values, volatile matter and fixed carbon are considered more reliable than on an ash-free basis because they give a minimum temperature for carbonisation.

Although the infra-red and standard coal analysis methods were restricted to six samples with each method, they do indicate the Taupo Pumice carbonised wood was heated to a higher temperature than Newall Ash wood (Table 3). From the above evidence minimum temperatures considered to have carbonised the unknown woods were $520^{\circ} \pm 100^{\circ}C$ for the Newall Ash and $700^{\circ} \pm 100^{\circ}C$ for the Taupo Pumice.

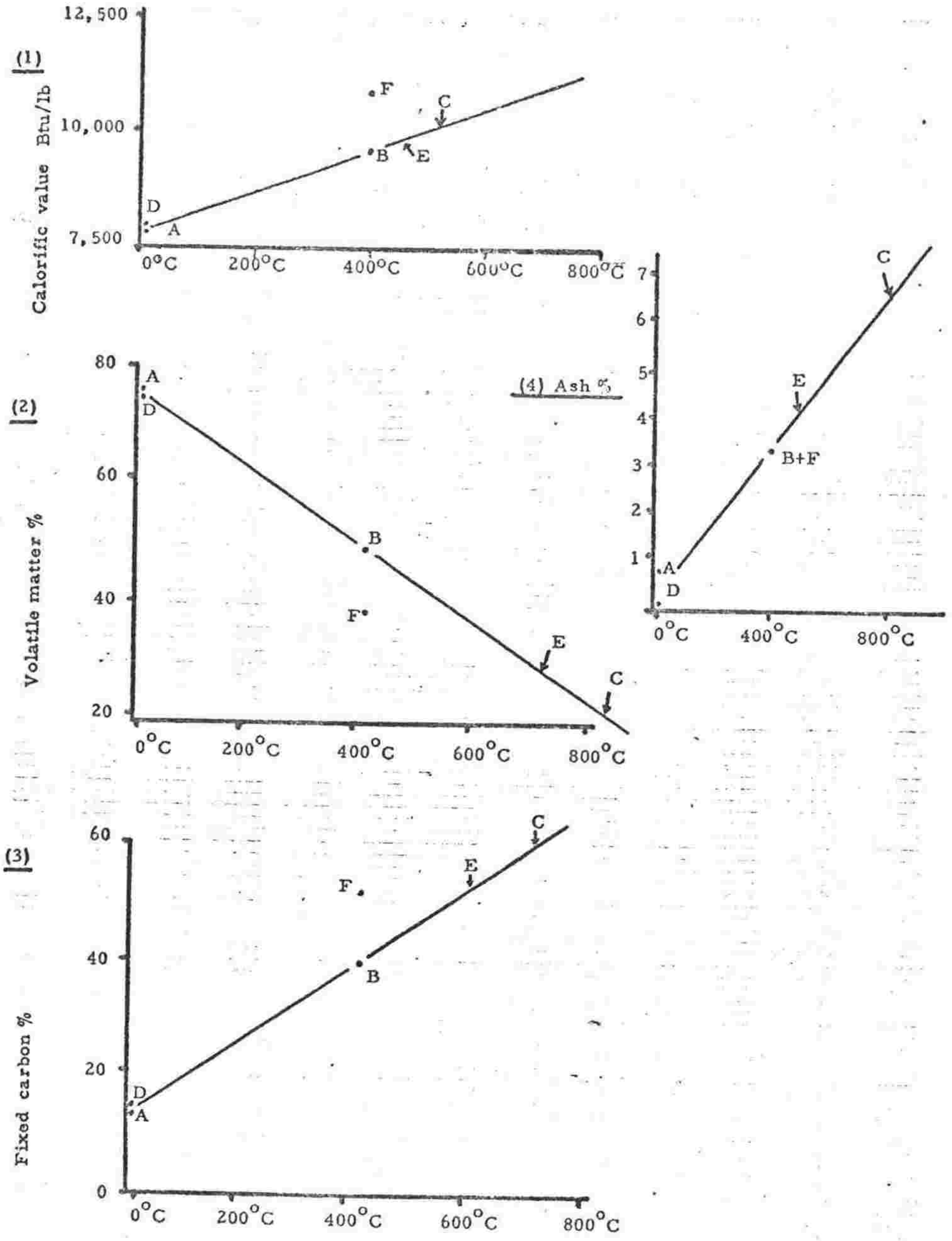


FIGURE 7 - Calorific values (in Btu/lb), volatile matter%, fixed carbon and ash% of selected wood and charcoal samples. Letters A-F refer to samples in Table 2.

(A = Hinau (Elaeocarpus dentatus), untreated wood.
B = Hinau, charred to 400°C.
C = Hinau from Taupo Pumice on Rangitaiki Plains.
D = Miro (Podocarpus ferrugineus), untreated wood.
E = Miro from Newall Ash in Maero Stream, Mt. Egmont.
F = Rimu (Dacrydium cupressinum), charred to 400°C.)

TABLE 3 - Estimated temperatures of eruptives required to carbonise wood samples, from various methods. In degrees Celsius.

Method	Newall Ash	Taupo Pumice
DTA	>400	>400
Infra-red	c.400	400-600
Calorific values	460	580
Volatile Matter	650	770
Fixed Carbon	580	700
Ash	520	880
Concluded Likely Temperature	500±100	600±100

WEATHERING RATES OF LATE QUATERNARY PUMICEOUS LAPILLI IN TARANAKI

The weathering rate of Taranaki pumiceous lapilli, established from major element analyses of dated pumiceous lapilli horizons, provides a basis for the approximate aging of undated pumiceous lapilli. The weathering rate is established from the previously dated Burrell Lapilli, Oakura Tephra basal lapilli and Ahuahu Lapilli making it possible to extrapolate ages of undated horizons.

SAMPLE DETAILS

Distributions and descriptions of the pumiceous lapilli are as follows. Sample location data are presented in Table 4. The Burrell Lapilli, distributed to the east of Mt. Egmont summit (Druce 1966; Topping 1972), contains moderately hard white pumice apparently unweathered, although above 1,000m altitude the exterior surfaces of the lapilli are iron stained. Samples of large lapilli and blocks were collected from near source.

The Inglewood Tephra (Neall 1972), distributed across the northern ringplains of Pouakai and Egmont, between Inglewood and New Plymouth contains relatively fresh pumice similar to that in the Burrell Lapilli.

The Oakura Tephra (Neall 1972) contains a basal lapilli horizon restricted in distribution to the middle and upper slopes of the Pouakai Range and is best exposed along Carrington Road. The basal lapilli is a light yellow colour and most lapilli crumble easily.

Ahuahu Lapilli is most widespread immediately south of New Plymouth (Neall 1972) and shows an axis of thickening along Frankley Road. It is bright orange and shows considerable amounts of iron staining and sometimes above 450m altitude shows a weak iron pan developed in the ash between lapilli. The pumice (Neall 1972) is soft, although lapilli still retain their individual shapes.

The Koru lapilli is stratigraphically the lowest lapilli sampled, and shows an axis of thickening to the north-west of Egmont although being widespread on most pre-25,000 year surfaces. Near source the lapilli are large and abundant and are readily dislodged into individual round "pellets". Lithic fragments remain hard, relatively unweathered and do not crumble whilst the pumiceous lapilli crumble easily. However away from source the lapilli lose their individual form and become cemented together into a porous layer or show boundaries which merge into the surrounding ash. The porous nature of the lapilli layer has resulted in heavy iron and weak manganese staining.

METHOD

Each pumiceous lapilli horizon sampled contains >60% pumiceous lapilli or blocks with the remainder comprising dense lithic andesite fragments. The pumiceous lapilli were washed in water to remove adhering materials and then dried at 110°C. Major element analyses (except for Na) of all pumiceous lapilli were determined by the X-ray fluorescence (XRF) method and matrix correction tables of Norrish and Hutton (1969). Na was determined by atomic absorption (AA) and Mg and Al were determined by both methods.

ASSUMPTIONS

In order to establish a weathering sequence for a particular rock type the initial chemical composition of each weathered sample should be known. This is relatively easily established for saprolites resting upon material from which they were derived, such as basalt lava flows in Hawaii (Atkinson and Swindale 1971) and andesite flows in California (Hendricks and Whittig 1968 a and b). Because of the accretionary nature of andesitic eruptions compared to rhyolitic volcanicity (Neall 1972), most lapilli horizons in Taranaki are less than 50 cm thick and no part of the horizon remains relatively unweathered. It is therefore necessary to assume that the initial composition of rocks and volcanic glasses from Egmont have remained the same during the period over which the lapilli were erupted. This assumption is supported by evidence from Egmont lava lithologies which show constant composition between the recent lavas of Egmont cone and andesitic conglomerates (resting upon the Rapanui Formation near Hawera) derived from a previous Egmont cone (Gow 1968).

All clay formation from Egmont derived lapilli is assumed to be derived from weathering of volcanic glass. It has been shown that allophane can also originate from feldspars (Fieldes and Furkert 1966), but in the sequence of pumiceous lapilli examined there is little etching of these crystals. In this study allophane derived from other sources is considered insignificant. Hydrothermally altered clays are not found with the pumiceous lapilli. No end products contain smectite and/or vermiculite which could otherwise make silica-to-alumina mole-ratios unsuitable as a weathering index (Ruxton 1968a). No alumina is assumed to have been lost or gained from or to the lapilli during weathering, so all major element compositions for silica loss calculations have been recalculated to constant alumina values.

It is assumed that those tephras buried by younger eruptives have not retained appreciable quantities of elements by solution from above. All the younger tephras crop out within 50 cm from ground surface and form the parent material of many present day soils, but the Ahuahu and Koru lapilli are buried beneath 2-5m of younger ashes. If contamination of older lapilli has occurred from percolating solutions it will have reduced the values of apparent rates of weathering measured from chemical analyses, and the rates must therefore be regarded as minimal for the older horizons. Separate lysimeter studies (see Chapter 8) indicate that increments of elements from the atmosphere are much less than loss of elements through drainage. All the lapilli samples come from well drained sites with rainfall between 1.3 and 2.6 x 10^3mm per annum, except for the Burrell Lapilli sample sites where rainfall is 5.2 and 6.5 x 10^3mm per annum.

RESULTS

The pumiceous lapilli show silica contents which decrease from 55 to 34% (Table 4) indicating an exponential rate of silica loss. Na and K show rapid initial removal which tapers off in older horizons, whilst Ca and Mg show inconclusive trends. Ca removal is significant only in the Koru lapilli. Loss on ignition values show that the main process of weathering is hydrolysis.

WEATHERING INDICES

Numerous weathering indices have been formulated to express the relative weathering of rocks. Reiche (1943)

TABLE 4 - Major element analyses of selected Taranaki pumiceous lapilli.

SAMPLE		LOCALITY	Total Fe as Fe_2O_3	MnO	TiO_2	CaO	K_2O	P_2O_5	SiO_2	Al_2O_3	MgO	Na_2O	Loss on ignition
Burrell Lapilli	- pumiceous fragment	Manganui Hut N119/670619 (1957)	6.95	0.15	0.72	7.56	2.60	0.29	54.62	19.51	3.19	3.36	1.0
Burrell Lapilli	- lithic fragment	Manganui Hut N119/670619	7.38	0.16	0.79	6.30	2.58	0.27	56.18	19.48	3.35	3.26	0.6
Burrell Lapilli	- pumiceous fragment	Stratford Mtn. House N119/701615	7.15	0.15	0.71	7.65	2.58	0.30	55.48	18.90	3.27	3.14	1.2
Inglewood Tephra	- pumiceous fragment	Korito Road N109/650745 (1965)	6.97	0.17	0.71	7.23	1.68	0.32	51.40	20.43	1.98	3.13	4.9
Inglewood Tephra	- pumiceous fragment	Eureka Gardens N109/724807	7.04	0.16	0.71	7.15	1.58	0.33	51.83	21.55	1.98	3.22	5.2
Oakura Tephra (basal lapilli)	- pumiceous fragment	Maude Road N109/673752	10.06	0.17	0.57	7.67	0.95	0.33	43.75	22.74	3.21	2.01	8.5
" "	"	Carrington Road N108/534704 (1962)	9.46	0.15	0.91	7.72	1.13	0.27	45.97	22.65	3.38	2.22	8.0
Ahuahu Lapilli	- pumiceous fragment	Maude Road N109/673752	12.22	0.16	1.34	6.70	0.33	0.35	37.27	24.40	3.58	1.21	13.1
Ahuahu Lapilli	- pumiceous fragment	Carrington Road N108/534704	13.22	0.15	1.42	7.68	0.27	0.34	37.94	25.75	4.22	1.23	10.5
Koru lapilli	- pumiceous fragment	Pukeiti N108/565742	11.87	0.22	1.29	5.42	0.12	0.43	32.92	27.00	3.52	0.57	17.1
Koru lapilli	- pumiceous fragment	Timaru Road N108/503784	12.06	0.18	1.25	5.55	0.12	0.47	36.58	27.13	3.45	0.67	14.0

formulated a weathering potential index (WPI) and Ruxton (1968a) plotted it against a product index (PI) where

$$\text{WPI} = \frac{100\ (K_2O + Na_2O + CaO + MgO - H_2O^+)}{SiO_2 + Al_2O_3 + Fe_2O_3 + TiO_2 + FeO + CaO + MgO + Na_2O + K_2O}$$

$$\text{and PI} = \frac{100\ SiO_2}{SiO_2 + TiO_2 + Fe_2O_3 + FeO + Al_2O_3}$$

The Taranaki pumiceous lapilli analyses plotted against these indices are presented in Fig.8. Because FeO and Fe_2O_3 were not separately determined, the total iron value was used in the WPI formula. Loss on ignition values were used in place of H_2O^+. Five clay analyses separated from fine detrital ash have been plotted in this figure to define the lower end of the curve.

Ruxton (1968a) used a weathering index (WI) as a measure of percentage weathering in relation to fresh rock, by assigning the WPI value for fresh rock a value of 0 and the most weathered sample 100. Simpler measures of weathering such as silica loss and silica-to-alumina mole-ratios show good correlation with the WPI and PI values determined from total silicate analysis (Ruxton 1968a). To derive WI values for the Taranaki pumices, the Koru lapilli sample was assigned a value of 100 and a fresh rock value of 0 was assigned to an analysis of a lithic fragment in the Burrell Lapilli. Silica-to-alumina mole-ratios, WI, total element loss % and silica loss % values relative to the unweathered Burrell Lapilli lithic fragment are presented in Table 5. The WI values are plotted against silica-to-alumina mole-ratios in Fig.9.

FIGURE 8 - Progressive weathering of Taranaki pumiceous lapilli and associated clay separates. WPI and PI represent weathering indices of Reiche (1943), see text.

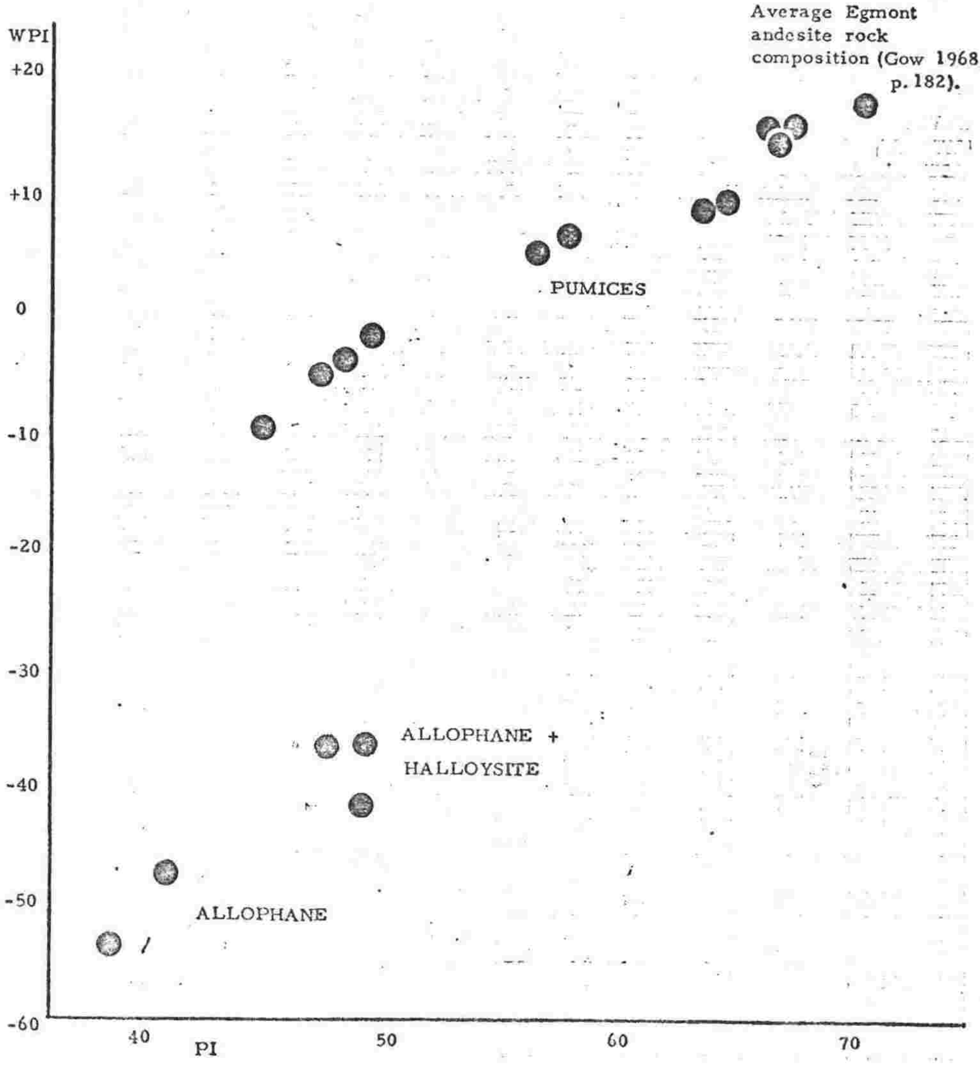


TABLE 5 - Weathering indices of selected Taranaki pumiceous lapilli.

		WPI	PI	WI*	$\frac{SiO_2}{Al_2O_3}$	Total* element loss%	Silica loss%*	Parker's Index
Burrell Lapilli	- pumice	15.96	66.77	5.05	2.80	5.03	6.69	81.0
Burrell Lapilli	- lithic	15.00	67.01	0	2.88	0	0	77.3
Burrell Lapilli	- pumice	15.62	67.45	3.13	2.94	2.82	3.04	79.3
Inglewood Tephra	- pumice	9.77	64.65	22.10	2.52	34.91	20.55	67.0
Inglewood Tephra	- pumice	9.19	63.89	28.71	2.41	25.81	18.69	66.8
Oakura Tephra	- pumice	5.89	56.72	57.66	1.92	50.41	53.45	55.5
Oakura Tephra	- pumice	6.91	58.19	51.29	2.03	35.61	43.88	59.2
Ahuahu Lapilli	- pumice	-1.45	49.54	81.50	1.53	74.04	81.28	40.9
Ahuahu Lapilli	- pumice	3.18	48.43	84.69	1.47	45.92	78.41	45.1
Koru lapilli	- pumice	-9.01	45.05	100	1.22	100	100	30.0
Koru lapilli	- pumice	-4.84	47.53	92.19	1.35	75.86	84.26	31.2

* Burrell Lapilli lithic fragment assigned value of 0 and Koru lapilli pumice assigned value of 100.

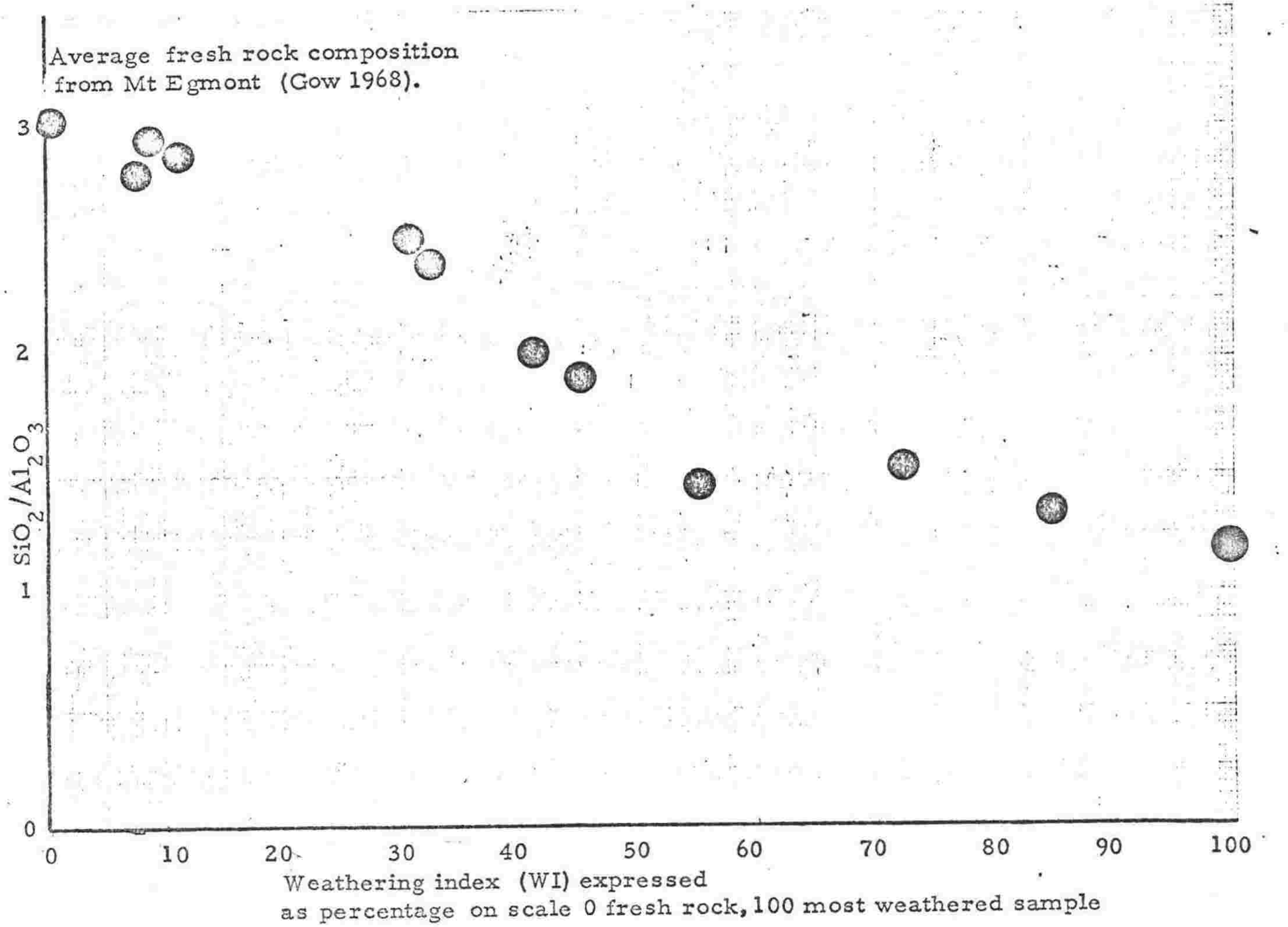


FIGURE 9 - Weathering of selected Taranaki pumiceous lapilli.

Silica-to-alumina ratios plotted against a recalibrated WI.

Another index which relates the atomic weights to atomic proportions of four major elements (Parker 1970) is hereafter referred to as "Parker's Index (PKI)". It is defined as

$$\frac{(Na)_a}{(Na-0)_b} + \frac{(Mg)_a}{(Mg-0)_b} + \frac{(K)_a}{(K-0)_b} + \frac{(Ca)_a}{(Ca-0)_b} \quad x\ 100$$

where $(X)_a$ indicates the atomic proportion of element X, defined as atomic percentage divided by atomic weight, and $(X-0)_b$ is the bond strength of element X with oxygen. Calculated PKI's of the Taranaki pumices prove the index is a useful measure of relative weathering (Table 5).

AGE OF UNDATED PUMICE HORIZONS

The Burrell Lapilli has been dated by tree-ring methods as having been erupted in 1655 A.D. (Druce 1966). The Oakura Tephra is considered to be about 4,000 years old and the Ahuahu Lapilli is dated about 14,000 yr B.P. (Neall 1972). Weathering curves for the three pumice horizons were plotted using each of the weathering indices calculated, and the Inglewood Tephra and Koru lapilli indices were then plotted on these curves. To determine the age of the Koru lapilli, chemical analyses of clays extracted from the uppermost New Plymouth Ashes by Claridge's (1969) method, were also used in plotting the weathering curve. From extrapolated tephra accumulation rates an age is established for the uppermost New Plymouth Ashes of between 70 and 100,000 yr B.P. This age is confirmed by the ashes resting upon the Rapanui marine bench (about 80-120,000 yr B.P.) at New Plymouth. The weathering curves established from WPI, PI and PKI values indicate the relationship between weathering and time is not linear but exponential (Fig.10), a feature also found in New Guinea (Ruxton 1968b).

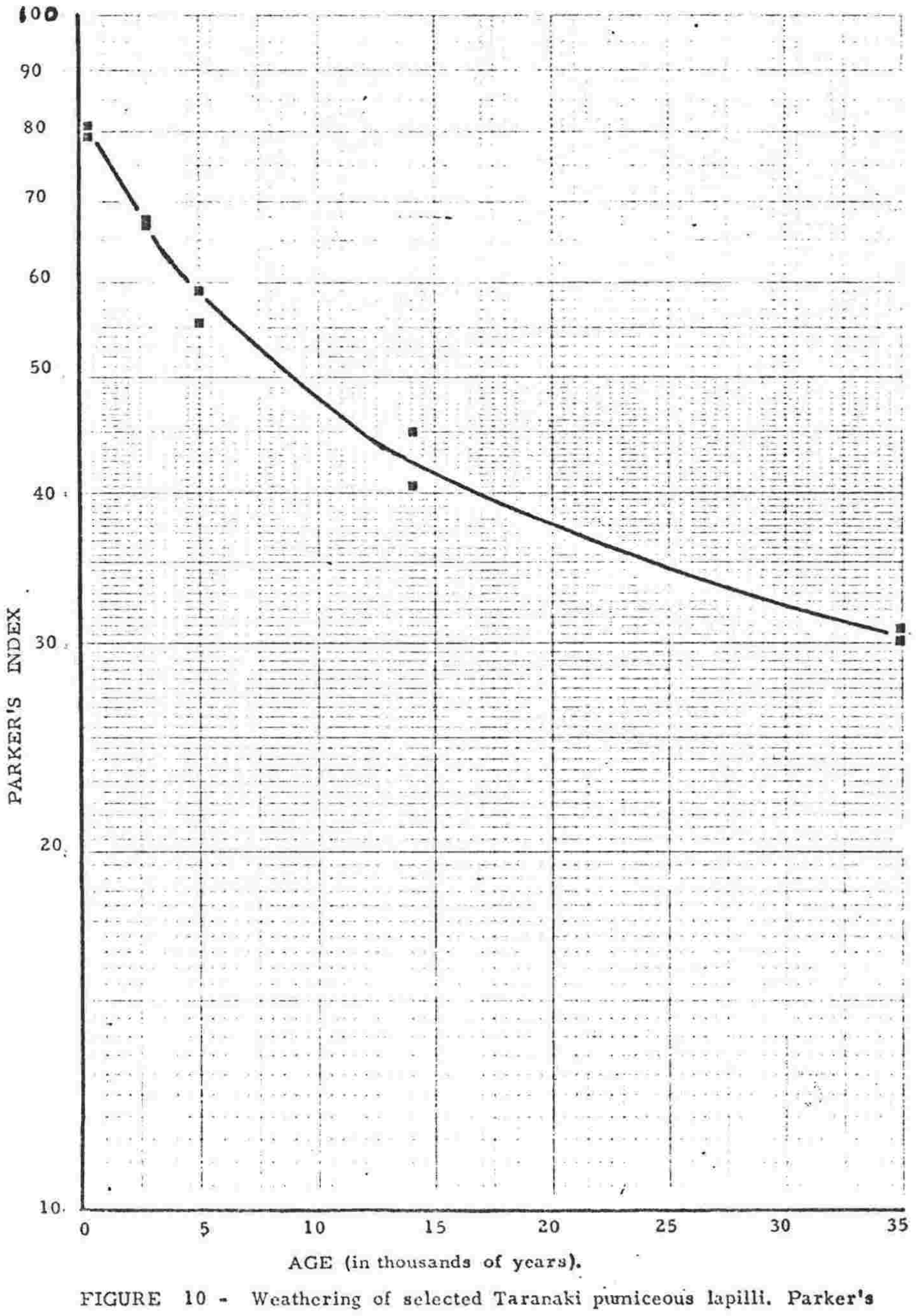


FIGURE 10 - Weathering of selected Taranaki pumiceous lapilli. Parker's Index plotted with age of lapilli.

Silica-to-alumina mole-ratios suggest the Koru lapilli is younger than 25,000 years, and WPI values show it is between 25,000 yr old (if New Plymouth Ashes are assumed to be 70,000 yr B.P.) and 24,000 yr old (if New Plymouth Ashes are 100,000 yr B.P.). PKI and PI curves show ages of 46-59,000 yr B.P. (based on the younger age of the New Plymouth Ashes) and 52-64,000 yr B.P. (with the older age) for the Koru lapilli. From recent information of a radiocarbon date on wood, from immediately above the New Plymouth Ashes, the SiO_2-Al_2O_3 ratios and WPI values are considered most reliable.

An estimated age for the Inglewood Tephra can be gauged more accurately than the Koru lapilli because of the more restricted time range between dated pumice horizons. PKI and WPI curves suggest an age of 3,000 yr B.P. and the PI curve suggests 2,700 yr B.P.

WEATHERING OF GLASS

Fresh volcanic glass within the Burrell Lapilli was analysed by the electron probe method. Comparison with analyses of clay sized allophanic products indicate losses of mobile constituents of about 70 grams (Table 6). Assuming constant chemical composition of glass over the period of weathering, a total loss of 70 gm per 100 gm of ash (i.e. 100 gm reduced to 30 gm) is assumed for the conversion of glass to allophane. Egmont andesites contain an average 58% groundmass (derived from averaging Gow's (1968) samples D7, D8 and E1, collected from Mt. Egmont) so 58 parts of glass in fresh ash can become 18 parts allophane and 100 parts of fresh ash become 60 parts fresh crystals and allophane. The rate of decrease of glass as measured by

TABLE 6 - Chemical composition of Taranaki weathered lapilli, fresh volcanic glass and clay separates recalculated to constant alumina.

		SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	Subtotal	Loss on ignition	Total
Burrell Lapilli	- pumice	47.5	17.0	6.0	2.8	6.6	2.9	2.3	85.1	0.9	86.0
Burrell Lapilli	- lithic	49.0	17.0	6.4	2.9	5.5	2.8	2.3	85.9	0.5	86.4
Burrell Lapilli	- pumice	49.9	17.0	6.4	2.9	6.9	2.8	2.3	88.2	1.1	89.3
Inglewood Tephra	- pumice	42.7	17.0	5.8	1.6	6.0	2.6	1.4	77.1	4.1	81.2
Inglewood Tephra	- pumice	41.0	17.0	5.6	1.6	5.7	2.5	1.3	74.7	4.1	78.8
Oakura Tephra	- pumice	32.7	17.0	7.5	2.4	5.7	1.5	0.7	67.5	6.4	73.9
Oakura Tephra	- pumice	34.5	17.0	7.1	2.5	5.8	1.7	0.9	69.5	6.0	75.5
Ahuahu Lapilli	- pumice	25.9	17.0	8.5	2.5	4.7	0.8	0.2	59.6	9.1	68.7
Ahuahu Lapilli	- pumice	25.0	17.0	8.7	2.8	5.1	0.8	0.2	59.6	6.9	66.5
Koru lapilli	- pumice	20.7	17.0	7.5	2.2	3.4	0.4	0.1	51.3	10.8	62.1
Koru lapilli	- pumice	22.9	17.0	7.6	2.2	3.5	0.4	0.1	53.7	8.8	62.5
Fresh volcanic glass		67.6	17.0	1.9	0.2	2.8	3.7	4.6	97.8	-	97.8
Clay fraction from Oakura Tephra		10.7	17.0	0.1	0.04	0.01	0.5*	tr	28.4	15.4	43.8
Clay fraction from Ahuahu Lapilli		12.0	17.0	0.3	0.04	0.03	1.2*	tr	30.6	15.5	46.1

tr = trace <0.002

* Samples extracted using sodium thiosulphate.

the rate of loss of mobile constituents was rescaled from 100-60 to 100-0 and then expressed as percentage of original glass remaining (Table 7). Assuming little contamination of older samples, then a half life (t½) for the glass can be estimated from Table 7 of about 50-60,000 years. This half-life is considerably longer than that of dacitic glass in New Guinea under humid tropical conditions where glass t½ varies between 1,650 and 5,600 years depending on rainfall and ground water control (Ruxton 1968b). The Taranaki glass is however weathering rapidly compared to volcanic glass elsewhere in New Zealand and its t½ is much shorter than rhyolitic glass in the Central North Island (B.P.Kohn, pers.com.).

SILICA LOSS

Silica losses from a land surface of pumiceous lapilli, expressed per cm^2 area, were calculated relative to the "unweathered" Burrell Lapilli lithic fragment. Calculations assume

(1) constant Al_2O_3 composition,

(2) an initial bulk density of 0.75 for the pumiceous lapilli, and

(3) 400 mm thickness of pumiceous lapilli at each sample point.

Silica losses per cm^2 of pumiceous lapilli (Table 7) average 0.57 $mg/cm^2/yr$ during the Holocene, under 1.5-2.5 x 10^3mm rainfall, but the older Koru lapilli (c.35,000 yr B.P.) shows a reduced rate (0.18 $mg/cm^2/yr$) indicating an exponential relationship between silica loss and time.

TABLE 7 - The loss of mobile constituents from pumiceous lapilli in Taranaki.

Pumiceous horizon (or lithic*)	Age (yr B.P.)	Total element loss (gm/100gm fresh ash)	Percentage of original glass remaining	Silica loss (in $mg/cm^2/yr$) of pumiceous lapilli	Silica loss (in mg/100g glass/yr)
Burrell Lapilli (pumiceous)	350	1.3	96.8		
*Burrell Lapilli (lithic)		0.4	99.0	0	0
Burrell Lapilli (pumiceous)		1.2	97.0		
Inglewood Tephra (pumiceous)	2,500	5.2	87.0	0.54	3.96
Inglewood Tephra (pumiceous)		5.1	87.3		
Oakura Tephra (basal lapilli) (pumiceous)	4,000	8.9	77.8	0.72	5.65
Oakura Tephra (basal lapilli) (pumiceous)		7.9	80.3		
Ahuahu Lapilli (pumiceous)	14,000	13.2	67.0	0.45	2.51
Ahuahu Lapilli (pumiceous)		10.6	73.5		
Koru lapilli (pumiceous)	35,000	17.9	55.3	0.18	1.14
Koru lapilli (pumiceous)		14.1	64.8		

Silica losses obtained from volcanic ash soils overseas include:

(i) $4 mg/cm^2/yr$ on a 4,000 yr old soil at St. Vincent, developed under humid tropical conditions with 2.3×10^3mm annual rainfall and a mean annual temperature of 25°C (Hay 1960),

(ii) 3.8-3.9 $mg/cm^2/yr$ under 2.54×10^3mm annual rainfall in Hawaii (Hay and Jones 1972),

(iii) 4-6 $mg/cm^2/yr$ under $2\text{-}4 \times 10^3$mm annual rainfall in New Guinea (Ruxton 1968b).

The much lower rate of silica loss in the Taranaki pumiceous lapilli is probably a function of grain size, because all the overseas examples involved weathering of finely comminuted tephra.

By assuming that the principal loss of silica is from volcanic glass, rates of silica loss have also been calculated per 100g of fresh glass (Table 7). The calculation assumes that the composition of glass remained constant during the period of time the lapilli were erupted. The fresh glass analysis is from the Burrell Lapilli and was determined by electron probe analysis. The rates confirm a much higher rate of silica loss in the Holocene (averaging 4mg/100g glass/yr) compared to the average rate over the last 35,000 years of 1.14 mg/100g glass/yr.

KATIKARA FORMATION

DEFINITION

A new formation is here proposed for redeposited tephras which crop out over 250 km^2 on Pouakai ringplain, Taranaki. The formation is named from Katikara Stream which originates near Pouakai peak at 1,377 m altitude (4,591 ft) and flows northwestwards to the coastline between Okato and Oakura. The name was chosen because this stream is adjacent to where the formation was first discovered and where it is also widespread. The formation is defined to encompass all the redeposited tephras on Pouakai ringplain deposited between the Oakura and Koru tephras. The variable nature of the lithology has required two reference or subsidiary sections to be designated in addition to the type locality. The type section is named on Saunders Road between the junctions of Wiremu (prior to 1970 called Okahu) and Carrington Roads, at grid reference N118/510698 (1965). The section is a 6 m high and 35 m long exposure through the formation, exposed on a sharp corner to the south side of the road (Fig.10). Here there is exposed

50 - 120 cm Oakura Tephra

50 cm Okato Tephra

3 - 4 m Katikara Formation with grey "creamcakes" about 1 m above Saunders Ash

7 - 10 cm Saunders Ash with charcoal

at least 30 cm + Katikara Formation to base of section.

The formation comprises yellowish brown (10YR 5/6) massive firm sandy ash with weak vertical joints. The material contains fine rhizomorph channels throughout with faint cross-bedding.

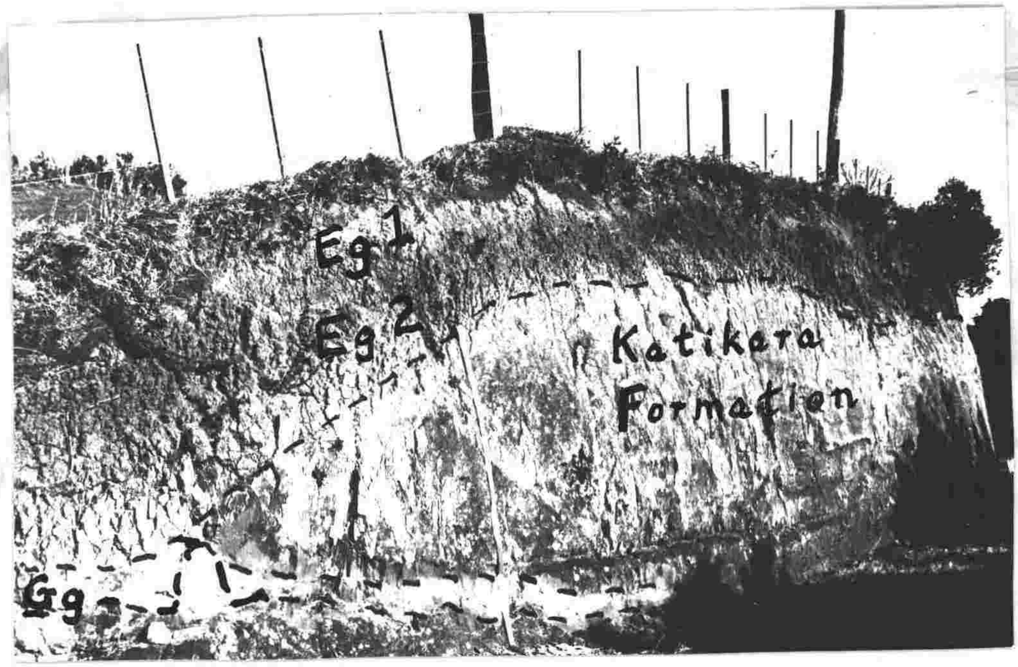


FIGURE 11 - View of type locality of Katikara Formation, at N118/510698 (1965). Saunders Ash (Gg) is preserved through base of hill.

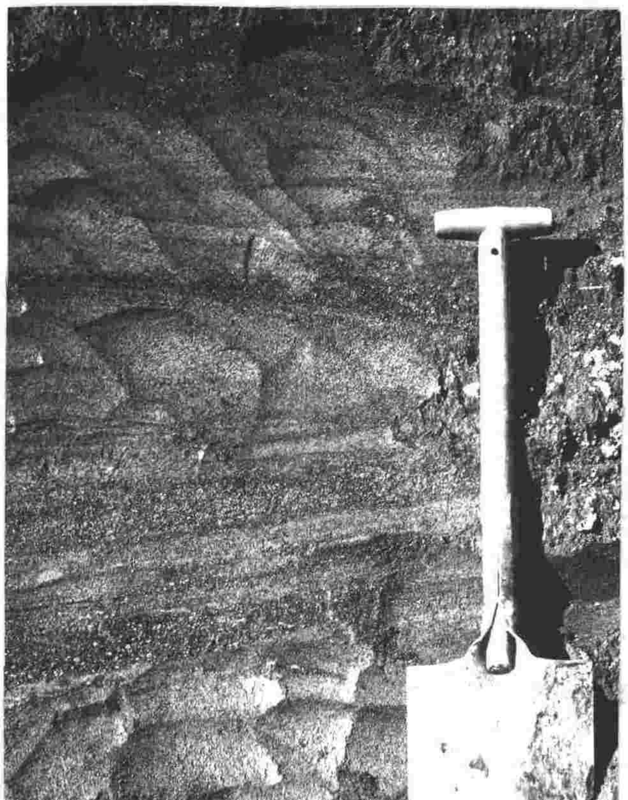


FIGURE 12 - Current bedding visible within Katikara Formation on Highway 3 at N109/693837(1965). Spade is approximately 1m long.

The Saunders Ash has slightly wavy and gradational upper and lower contacts within the Katikara Formation. Ash "creamcakes" (see Neall 1972), within the formation average 2-3 cm and are preserved in a near horizontal plane.

The formation wedges away on both sides of the hill. At the eastern extremity of the wedge is a large andesite boulder, approximately 60 cm across, which immediately underlies the Saunders Ash (see Fig. 11).

The following reference sections are designated in conjunction with the type section.

1. Section on Carrington Road, on south side of type locality for Saunders Ash and Carrington Tephras (see Section 3 of Appendix in Neall, 1972). The formation here is wedged between the Ahuahu Lapilli and Saunders Ash. It is absent from the crest of the section but to the south is in excess of 3 m thick, with the base unexposed. Weak but distinctive cross-bedding is visible within the deposit.
2. Section on State Highway 3, approximately 300 m south of the New Plymouth Crematorium and alongside Mangamahoe Nurseries. Here the formation is exposed in 6 m high sections on both sides of the road, grid reference N109/693837 (1965). Well developed current bedding is visible (Fig.12) where black bands rich in mafics (mainly magnetite and augite) alternate with 7.5YR 5/6 strong brown ash beds. The coarser bands with fragments up to 1 cm across, average about 2.5 cm thick whilst finer alternations may be only 3 mm thick. The mafic minerals adhere only loosely and easily fret from vertical faces by weathering. Thus together with the colour contrast the mafic beds tend to accentuate the laminations. The beds dip 24° to the north-west.

DISTRIBUTION

The Katikara Formation is restricted to ringplain surfaces graded to the Pouakai Range (see Appendices B1 and B2) and on the north-west side of the Range the formation is most commonly above the 200 m contour. It is well exposed in road cuttings along Carrington Road, especially between Dover and Saunders road junctions, and also between the 200 m and 400 m contours on Pitone and Dover roads. It also occurs along Albion Road and isolated pockets occur on Upper Timaru, Weld and Ahuahu roads. The formation appears absent in the vicinity of Pukeiti.

To the north and north-east sides of the Pouakai Range the formation is more widespread and thicker. It extends from the Pouakai Range almost to the present coastline at Omata, and extends towards the coast along all the major river systems, especially the Oakura River and Tapuae Stream. The formation does not extend northwards beyond the southern fringes of New Plymouth city and to the south has not been located beyond the Waiwakaiho and Stony rivers.

GEOMORPHOLOGY

The formation is associated with two principal ringplain surfaces. On the lower slopes of the Pouakai Range, below the 200 m contour, it is associated with a gently seaward dipping, thickly tephra mantled surface (termed "Maitahi lahars" by Hay 1967). It has extensive planar interfluves separated by characteristic box-shaped gullies which form an intricate dendritic drainage system. On the interfluves are thin accumulations of the formation with little modification of the pre-depositional surface. A few isolated hills of the formation between Okato and Omata resemble surfaces on the higher slopes of the Pouakai Range where the pre-depositional surface has been modified. The base of the formation is sharp but conformable with the underlying tephras.

The other ringplain surface (termed "Lepperton lahars" by Hay 1967) occurs above the 200 m contour and consists of a more dissected topography with rolling hills, steep slopes, V-shaped gullies and no planar interfluves (Fig. 13A). On this surface the Katikara Formation is often greater than 2 m thick and has modified the pre-existing landscape, frequently forming new ridges or circular mounds (Fig. 13B). The ridges tend to be slightly sinuous rather than straight and occur in a radial orientation to the Pouakai Range, i.e. they parallel the major drainage systems. Some hills have been buried by the deposits and new ridge crests are displaced to one side of them (Fig. 13C). At many localities where the formation is discontinuous an erosion break which defines its base is seen to be widespread. (Fig. 14).

THICKNESS

The largest mounds observed within the formation occur along Kent Road where they reach 10 m thick. The mounds can easily be mistaken for lahar mounds until their composition is examined. Towards New Plymouth, 10 m high ridges of similar material are well exposed between Mangorei and Plymouth roads, where they range from 500 to 1,000 m in length and average about 100 m width (Fig.15). In many areas the ridges as viewed on aerial photo-

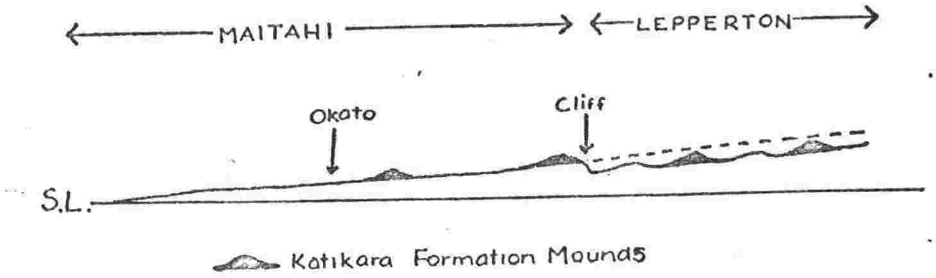


FIGURE 13A - Cross-section of Maitahi and Lepperton surfaces in the Okato district.

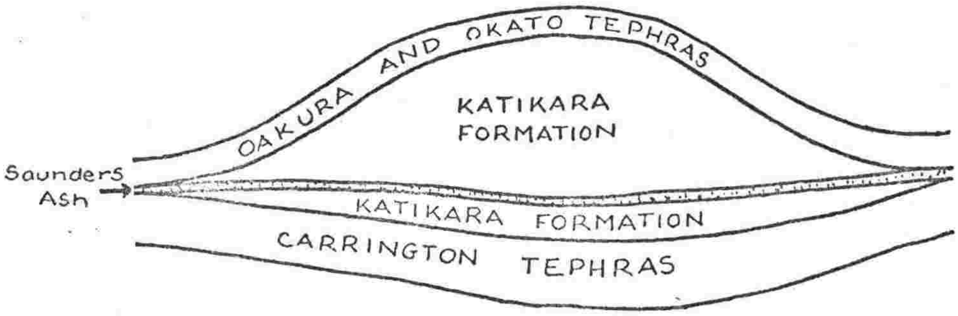


FIGURE 13B - Cross-section of exposure at type locality of Katikara Formation (N118/510698).

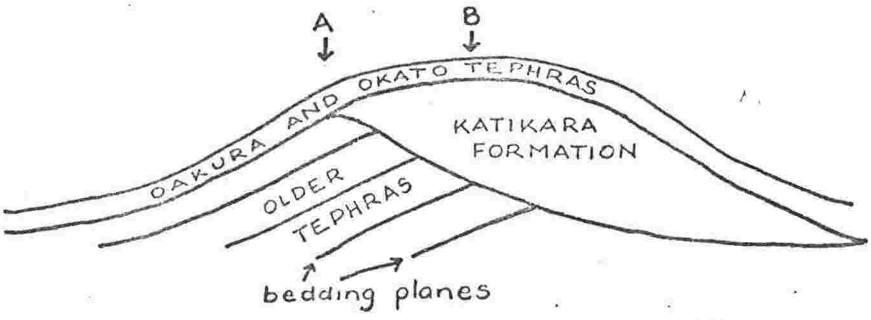


FIGURE 13C - Cross-section of exposure on Dover Road, at N108/535724. Note displacement of hill crest from position A to position B.

FIGURE 14 - Section at N108/525704(1962), on Carrington Road, 50m north of Oxford Road junction. Note disconformity overlain by Saunders Ash, Okato and Oakura Tephras.

FIGURE 15 - Oblique aerial photograph looking north-westwards toward New Plymouth. Most ridges in the foreground are composed of Katikara Formation.

graphs may be mistaken for remnants of a former widespread surface. Because of the variable thickness of the formation it is difficult to accurately estimate its volume. Assuming a 1 m average thickness the formation totals 0.25 km^3.

LITHOLOGY

Initial investigations suggested the formation was an air-fall eruptive because of its similar appearance to most tephras in Taranaki, but detailed studies now indicate the material is redeposited. The general lithology is similar to massive blocky ash of sandy loam texture, but on close inspection weak cross-bedding is discernible. At a few localities lenses of stones and wood occur at the base of the deposit and may measure up to 5 cm across. In the vicinity of Carrington Road between Frankley and Saunders Road junctions, two thin grey ash layers are preserved near the top of the formation, in the form of "creamcakes". The formation generally rests sharply upon the Saunders Ash, where it is present, but in the region between Oxford and Saunders Roads the Saunders Ash is preserved within the base of the formation. Here the upper and lower contacts of the Ash are not sharp but rather gradational, although they remain distinctive due to the colour differences. This indicates the base of the formation is time-transgressive. At the Mangamahoe reference section the most well developed bedding within the formation is exposed, and clearly differs from the weak cross-bedding evident elsewhere. Although the grain sizes are not necessarily very different between the upper and lower parts of each bed, the base is always marked by the heavier mafic grains. A sample from this locality was dry sieved and had a sorting coefficient

(So) of 1.3 compared to a value of 2.3 obtained from the weakly bedded material.

Heavy mineral grains sampled from the formation are principally augite and magnetite, with minor hornblende and hypersthene, indicating an andesitic source. Associated studies of the tephra column in Taranaki indicate that the first occurrence of halloysite is at about 70,000 years B.P., and that all the tephras above this time plane are richly allophanic. Clay fractions separated from the formation and analysed by XRD and DTA techniques show that although the dominant clay is allophane, there is some halloysite present. This suggests that the deposits are derived from older halloysite-bearing tephras as well as younger allophanic tephras. However, the tephras have not been transported over a sufficiently large distance for heavy mineral grains to be rounded or worn in any way.

The base of the formation is always sharp but the upper contact is often difficult to distinguish because of the similar structure and colour of the Okato Tephra above.

AGE

The formation is always overlain by the Oakura Tephra and except for rare sections it is overlain by the Okato Tephra. This indicates that the bulk of the formation is older than 12,550 years, but that near Oxford-Carrington road junction in particular, it may be as young as 7,000 years old. Isopachs drawn from thicknesses measured between the top of the Oakura Tephra and the base of the Okato Tephra (incorrectly termed "Total" Oakura and Okato Tephras in Fig. 9, Neall, 1972) show up to 30% discrepancy with isopachs of the individual tephras combined. This difference is attributed to small indistinguishable pockets of the Katikara Formation which appear to occur between the Okato and Oakura tephras.

In sections along southern Carrington Road, the Saunders Ash is preserved at or within and near the base of the formation. Elsewhere beyond the distribution of the Saunders Ash the formation rests upon the Carrington Tephras, and in the vicinity of Barrett, Frankley and northern Carrington roads rests directly on a highly weathered volcanic breccia which forms the Tapuae-Manganui Ridge (Gibson and Morgan 1927). This indicates the Saunders Ash was erupted about the same time as deposition of the formation commenced, in places on an eroded surface. Because the Saunders Ash is dated (NZ942) at 16,100 ± 220 yr B.P. and is preserved near the base of the formation, then the formation is probably less than 20,000 yr B.P. The bulk of the formation was deposited between the Okato Tephra and Saunders Ash, between 14 and 16,000 yr B.P., which corresponds to the Earlier and Later Kumara 3 advances (Suggate and Moar 1970).

ORIGIN

Four likely origins (or combinations of them) for the formation were considered likely by the author.

1. The laminated beds in the vicinity of Mangamahoe Nurseries are almost identical to current bedding produced by fluvial processes. The general occurrence of the formation in both valleys and on ridges, displaced radially to the Pouakai Range makes a fluvial origin for the entire formation unlikely. This is because it invokes a widespread and very large flood which is likely to have admixed coarser materials, and produced more prominent bedding in the formation. It could

also be expected to occur on the Egmont ringplain. It is proven that the deposits in the Mangamahoe region were deposited by water, but because the bulk of the formation elsewhere contains only weak cross bedding, it is unlikely that all of it was deposited by this process.

2. The restriction of the deposits to the Pouakai ringplain does suggest that its origin is due in part to the presence of the volcano, either primarily as a volcanic environment or due to its orographical effect. The widespread recognition of base surge deposits (Moore 1967; Fisher & Waters 1969) produced during volcanic eruptions and nuclear atmospheric tests deserves consideration as a possible origin for these deposits. If a base surge originated from Egmont, there should be features on the Egmont ringplain landscape produced by this event, instead of being confined to the Pouakai Range. The Pouakai Range is likely to have been extinct for 250,000 years and is not considered a possible source area for a base surge. The bulk of base surge dunes reported by Moore, tend to be concentric to the source area (<u>see</u> Figs. 11 and 12 Moore 1967), and not radial as in the case of the Katikara Formation. Thus this origin is considered unlikely.

3. Slightly sinuous dunes, very similar to the formation, were produced by nuées ardentes which descended the Walibou River during the 1902 eruption of La Soufriere on St. Vincent (Plate IX Anderson, 1903). However for similar reasons to origin no.2, such a mechanism should have produced similar features on the Egmont ringplain, and the Pouakai Range is unlikely to have been active at this time. The

charcoal bearing Saunders Ash is considered to be a flow deposit which probably originated as a nuée ardente (Neall 1972) which descended the Stony River catchment from Egmont summit. The gradational boundary between this ash within the Katikara Formation together with weak bedding could be interpreted as indicative of a continuous event which involved a hot mode of emplacement. If the formation was deposited by a nuée ardente then charcoal could be expected to occur in the formation besides it occurring in the Saunders Ash, whereas in fact only rare wood fragments are found. In addition, the presence of grey "creamcakes" within the deposit indicates incorporation of undisturbed air-fall eruptives within the deposit, which is difficult to preserve in the centre of a single nuée ardente deposit. This origin is thus considered untenable for these reasons.

4. The possibility that the deposits were of aeolian origin was initially dismissed because simple deflationary dunes were considered most likely to have formed near the coast where sand dunes now form under the influence of mainly westerly winds. The bulk of the formation on the other hand, tends to have accumulated on the seaward sides of previous hills at higher altitudes, which suggests an origin from the high flanks of the volcano. The presence of an erosion break beneath the formation (and/or the Saunders Ash) at widespread localities above 300 m altitude indicates that erosion was widespread prior to the deposition of the formation. The incorporation of a nuée ardente deposit (Neall 1972) within the formation precludes the other three origins, but is consistent with an aeolian origin. This

together with weak cross-bedding is considered the best evidence that the mounds and dunes could have accumulated by aeolian processes.

CONCLUSION

During the last stadial it is apparent that widespread erosion occurred along all stream channels draining Pouakai Range above the 200 m contour. It is to be expected that during this time there would have been a lowering of the bush line in Taranaki, and Willett (1950) concluded that the permanent snowline dropped to 1,290 m (4,300 ft), i.e. below the present summit heights of the principal Pouakai peaks. It is not clear whether the Pouakai Range was unvegetated at this time, but charcoal samples from the Saunders Ash (dated (NZ 942) at 16,100 ± 220 yr B.P.) have been identified as <u>Dracophyllum</u> sp.(Neall 1972), suggesting that the dominant vegetation was a subalpine scrub. Thus the great thickness of tephras which mantled the Pouakai Range would have become susceptible to erosion once the vegetation cover became sparse or was removed during periods of cooler climate.

The presence of halloysite in the deposits indicates that older tephras were admixed with younger eruptives and presumably this could occur if older tephras were eroded and redeposited by predominantly aeolian processes. In places it is clear the deposits were resorted by fluvial action which could be expected if rain fell on exposed dune surfaces. It is concluded that the formation represents the products of resorted tephras which have been redeposited on the flanks of the thickly tephra-mantled Pouakai volcano during a period of cooler climate, when the bush line was lowered. The formation can be considered to be a

Taranaki correlative of the Mokai Sands found in the Central North Island (Vucetich & Pullar 1971).

The boundary between the Maitahi and Lepperton surfaces is generally distinct being marked by a small cliff which faces inwards towards the mountain (Fig.13A). It nearly always extends seawards down the major river channels. Occasionally it is obscured by dunes and mounds of the Katikara Formation burying the cliff. It is suggested that the Lepperton surface in western Taranaki simply represents the equivalent of the Maitahi surface which was severely eroded and modified on the higher flanks and in major river systems of Pouakai volcano.

The lack of any similar deposits on Egmont ringplain is notable and two possible explanations are suggested. First, there is a distinct possibility that Egmont was not as high as Pouakai during the last stadial. There is evidence from my tephrochronological studies on Egmont surfaces to suggest that much of the cone has been constructed during Holocene time (i.e. during the last 12,000 years) and thus there may not have been a source area for such deposits to the south. Second, there is a limited cover of tephras at higher altitudes on Egmont due principally to the relative youthfulness of the surfaces and also to the altitude and angle of slope which preclude tephras being easily established in topsoil above the 1,200 m (4,000 ft) contour. Thus during the last climatic cooling there may have been insufficient source material at high enough altitude on Egmont, fine enough to be influenced by aeolian processes i.e. most material was coarse sandy debris.

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REFERENCES

Anderson, T., 1903: Recent volcanic eruptions in the West Indies. The Geographical Journal - March: 265-81.

Atkinson, I.A.E.; Swindale, L.D., 1971: Age determinations of Recent Hawaiian lavas using measurements of weathering changes. Nature,London 233 (5319): 406-7.

Claridge, G.G.C., 1969: Physico-chemical methods for soil analyses. N.Z. Soil Bureau Information Series 23: 39pp.

Druce, A.P., 1966: Tree-ring dating of Recent volcanic ash and lapilli, Mt. Egmont, N.Z. Journal of Botany 4 (1): 3-41.

Fieldes, M.; Furkert, R.J., 1966: The nature of allophane in soils. Part 2 - Differences in composition. N.Z Journal of Science 9 (3): 608-22.

Fisher, R.V., 1964: Maximum size, median diameter, and sorting of tephra. Journal of Geophysical Research 69 (2): 341-55.

Fisher, R.V.; Waters, A.C., 1969: Bed forms in base-surge deposits: Lunar implications. Science 165: 1349-52.

Gibson, W.: Morgan, P.G., 1927: The Geology of the Egmont Subdivision. N.Z. Geological Survey Bulletin n.s. 29. 99pp.

Goh, K.M., 1970: Organic Matter in New Zealand Soils-Part 1. Improved methods for obtaining humic and fulvic acids with low ash content. N.Z. Journal of Science 13 (4): 669-86.

Gow, A.J., 1968: Petrographic and petrochemical studies of Mt. Egmont andesites. N.Z. Journal of Geology and Geophysics 11(1): 166-90.

Hay, R.F., 1967: Sheet 7-Taranaki. "Geological Map of New Zealand 1: 250,000". N.Z. Department of Scientific and Industrial Research, Wellington.

Hay, R.L. 1960: Rate of clay formation and mineral alteration in a 4,000-year-old volcanic ash soil on St. Vincent, B.W.I. American Journal of Science 258: 354-68.

Hay, R.L.; Jones, B.F., 1972: Weathering of basaltic tephra on the island of Hawaii. Geological Society of America Bulletin 83: 317-32.

Hendricks, D.M.; Whittig, L.D., 1968a: Andesite Weathering. I-Mineralogical transformations from andesite to saprolite. Journal of Soil Science 19 (1): 135-46.

Hendricks, D.M.; Whittig, L.D., 1968b: Andesite weathering. II-Geochemical changes from andesite to saprolite. Journal of Soil Science 19(1): 147-53.

Minakami, T., 1942: On the distribution of volcanic ejecta, 2. The distribution of Mt. Asama pumice in 1783. Bulletin of the Earthquake Research Institute Tokyo University 20: 93-106.

Moberley, R., Jnr., 1963: Rate of denudation in Hawaii. Journal of Geology 71: 371-5.

Moore, J.G., 1967: Base surge in recent volcanic eruptions. Bulletin Volcanologique 30: 337-63.

Neall, V.E., 1972: Tephrochronology and tephrostratigraphy of western Taranaki (N108-109), New Zealand. N.Z. Journal of Geology and Geophysics 15 (4): 507-57.

Norrish, K.; Hutton, J.T., 1969: An accurate X-ray spectrographic method for the analysis of a wide range of geological samples. Geochimica et Cosmochimica Acta 33: 431-53.

Parker, A., 1970: An index of weathering for silicate rocks. Geological Magazine 6: 501-4.

Reiche, P., 1943: Graphic representation of chemical weathering. Journal of Sedimentary Petrology 13: 58-68.

Ruxton, B.P., 1968a: Measures of the degree of chemical weathering of rocks. Journal of Geology 76: 518-27.

Ruxton, B.P., 1968b: Rates of weathering of Quaternary volcanic ash in north-east Papua. 9th International Congress of Soil Science Transactions, 4: 367-76.

Suggate, R.P.; Moar, N.T., 1970: Revision of the chronology of the Late Otira Glacial. N.Z. Journal of Geology and Geophysics 13 (3): 742-6.

Schnitzer, M., 1965: The application of infrared spectroscopy to investigations on soil humic compounds. Canadian Spectroscopy 10: 121-7.

Stevenson, F.J.; Goh, K.M., 1971: Infrared spectra of humic acids and related substances. Geochimica et Cosmochimica Acta 35: 471-83.

Topping, W.W., 1972: Burrell Lapilli eruptives, Mount Egmont, New Zealand. N.Z. Journal of Geology and Geophysics 15(3): 476-90.

Vucetich, C.G.; Pullar, W.A., 1969: Stratigraphy and chronology of late Pleistocene volcanic ash beds in central North Island, New Zealand. N.Z. Journal of Geology and Geophysics 12 (4): 784-837.

Willett, R.W., 1950: The New Zealand Pleistocene snow line, climatic conditions, and suggested biological effects. N.Z. Journal of Science and Technology 32(B): 18-48.

CHAPTER 4

LAHARS - THEIR GLOBAL OCCURRENCE, ORIGINS AND ANNOTATED BIBLIOGRAPHY

SUMMARY

The origin of use of the term lahar is reviewed. Lahars are divided into 9 main groupings according to their origins and the source of water required for their formation. Lahars may be initiated by -

(a) an eruption through a crater lake

(b) admixing of a nuée ardente type of flow with running or ponded water

(c) action of heavy rains on products of eruptions either recently ejected or accompanying an eruption

(d) collapse of a crater lake by a non-eruptive mechanism

(e) release of ponded water from beneath an ice cover (type jökulhlaup)

(f) melting of snow and ice directly accompanying an eruption

(g) phreatic explosions or directed blasts

(h) heavy rains disassociated with eruptions

(i) earthquake collapses.

A review of the historical occurrences of each type is presented, followed by reference to some Quaternary and other lahars.

INTRODUCTION

Lahars (volcanic mudflows and debris flows) have devastated areas surrounding volcanoes at many places in the world during the last 1,000 years, especially in the circum-Pacific region. The largest known modern lahar, in 1955, travelled a distance of 90 km from Mt. Bezymianny, Kamchatka (Gorshkov, 1959). Large fields of lahar mounds around the bases of a number of volcanoes in Java, e.g. Mts. Raung, Galounggoung and Keloet, and in New Zealand, e.g. Mts. Egmont and Ruapehu, testify to lahars of catastrophic proportions during the Quaternary Period.

Escher (1922, p.293) listed early literature on Indonesian lahars published in Dutch, and Anderson (1933) reviewed much of the literature available at that time. The present review supplements Anderson's work and of the publications prior to 1933 only the more significant are referred to.

DEFINITIONS

1. LAHAR

The Indonesian term lahar was first used in English literature by Escher (1922) when discussing the possibility of the 1912 Mt. Katmai eruption having been initiated by the collapse of a crater lake. After describing the nature of the lahars from Keloet (or Klut) volcano and how they compared with the Katmai deposits, he proposed that volcanic mudflows be classified as follows:-

(a) Specific volcanic mudflows: Type

1. By an eruption through a crater lake:
lahar (hot lahar) (hot mudflow) Klut (Java)

2. By melting of an ice-cap by an eruption:
jökulhlaup Iceland

(b) Not specific volcanic mudflows:

3. By heavy rains on loose materials:
murgang (cold lahar) (cold mudflow)

Many of the early lahar descriptions are in Dutch, and English translations became available in the 1920s, e.g. Wing Easton and Kemmerling (1923); Palmer's translation of Escher (1925). The term lahar was more fully accepted in English literature after the potential size of tillite-like lahar deposits was appreciated (Scrivenor, 1929; Cotton, 1944; van Bemmelen, 1949).

The earliest precise definition known to the writer is by van Bemmelen (1949) where the lahar is described as "a mudflow containing debris and angular blocks of chiefly volcanic origin". He remarked that the blocks were up to many cubic metres in size, angular, and had not settled in the matrix. This definition (incorporating Escher's murgang and jökulhlaup) has been generally accepted in geological literature. The AGI Glossary (1960) definition of lahar as a "landslide or mudflow of pyroclastic material on the flanks of a volcano" is unacceptable. Non-pyroclastic rocks such as lava fragments and various kinds of detrital deposits may easily become incorporated within a lahar, especially during the emptying of a crater lake.

Van Bemmelen's original definition allowed for lava blocks and Fisher (1960) reported significant amounts of non-volcanic materials in some lahars.

The author proposes a more flexible definition - a large mudflow or debris flow mostly composed of volcaniclastic detritus, often including large blocks, on or surrounding the flanks of a volcano. Escher's classification of lahars is here modified and extended. The term *murgang* has been abandoned because such flows are frequently identical to debris flows in non-volcanic areas. Types recognised since Escher's classification (e.g. Anderson, 1933) are incorporated.

1. *Specific volcanic mudflows and debris flows*	*Examples*
Initiated by:	
(a) an eruption through a crater lake (type *lahar*)	Klut, Java; 1919. Ruapehu, NZ; 1969.
(b) admixing of a nuée ardente type of flow with running or ponded water	Merapi, Java. Soufrière, St. Vincent; 1902.
(c) action of heavy rains on products of eruptions either recently ejected or accompanying an eruption	Vesuvius, Italy; 1906. Fuego, Guatemala; 1963. Agung, Bali; 1963.
(d) collapse of a crater lake (non-eruptive)	Ruapehu, NZ; 1953
(e) release of ponded water from beneath an ice cover (type *jökulhlaup*)	Katla, Iceland; 1958

	Examples
(f) melting of snow and ice directly accompanying an eruption	Cotopaxi, Ecuador; 1877 Villarica, Chile; 1964
(g) phreatic explosions or directed blasts	Bandai-san, Japan; 1888 Bezymianny, USSR; 1955
2. Non-specific volcanic mudflows and debris flows	
Initiated by:	
(a) heavy rains	Egmont, NZ; 1935
(b) earthquake collapses	Fuego, Guatemala; 1917 White Island, NZ; 1914

2. DEBRIS FLOW

The subdivision of lahars according to the percentage of component fragments into mudflows or debris flows has required definition of *debris flow*.

Sharpe (1938) defined *debris slide* as a "rapid downward movement of predominantly unconsolidated and incoherent earth and debris in which the mass does not show backward rotation but slides or rolls forward, forming an irregular hummocky deposit which may resemble morainal topography". At the same time he defined *debris avalanche* as a flowing slide in which flow exceeded slip owing to increased water in the material transported.

The deposits resulting from prehistoric flows and slides show little evidence of their mode of transport so a general term was needed for them. Sharp and Nobles (1953) used debris flow as a general term for all types of rapid flowage of debris in which mud controlled the flow behaviour, and this usage was later accepted by Crandell and Mullineaux (1967) and Waldron (1967). Varnes in Eckles (1958) restricted mudflows to material with at least 50% sand, silt and clay sized particles, and debris flows to material with a greater proportion of coarse debris. In this paper the term debris flow is used in the sense proposed by Varnes.

TYPE 1(a): LAHARS INITIATED BY ERUPTIONS THROUGH CRATER LAKES

Lahars associated with crater lakes have probably caused more loss of life and damage to property than any other type of mud or debris flow. Lahars are more common in Indonesia, where the word originated, than anywhere else, and are well documented. The high incidence is attributed to tropical rainfall filling all volcanic depressions with water. Of 21 Indonesian volcanoes with recorded lahars or inferred Quaternary lahars, 12 possess or have possessed a crater lake (van Padang, 1951). Lahars generated by eruptions through crater lakes are referred to as hot lahars in Indonesia, even if the crater lake water was cold (van Bemmelen, 1949, p.191; Zen and Hadikusumo, 1964).

Keloet (Java) - Between 1000 and 1920 A.D., 26 lahars resulted from collapse of or eruptions through the crater lake.

During the 1919 eruption documented by Wing Easton and Kemmerling (1923), the lahar reached a maximum distance of 38.25 km from its source, covering 131.22 km. More than 5,000 lives were lost. A photo of the crater after the eruption appears in "Illustration" (1919, pp. 116-7). Prior to the eruption the crater lake contained about 40 million m^3 of water. In 1923 tunnels and shafts were established to control the lake level and by siphoning, the capacity was reduced to 2 million m^3 (van Padang, 1960, fig. 7). During the 1951 eruption the tunnels were destroyed (Zen and Hadikusumo, 1965) although no great lahars resulted. In 1954 a new drainage tunnel system, built on a seepage principle, failed to drain the lake sufficiently, leaving 23.5 million m^3 of water in the lake. On 26 April 1966, a violent explosion expelled some 20 million m^3 of crater water, initiating lahars that killed 282 people over 45 km^2. By May 1966, the crater lake was empty and the tunnels were blocked by pyroclastics (Hadikusumo, 1967).

Raung (Java) - This volcano is thought to have had a crater lake prior to 1838. A swarm of hillocks as its western foot extend for 60 km and are considered to represent the missing western sector of the cone (van Padang, 1951).

Galounggoung (Java) - Escher (1925, translated by Palmer, 1929) attributed the Ten Thousand Hills of Tasikmalaja to a huge landslide caused by collapse of a crater lake on Mt. Galounggoung. Lyell (1867, pp. 6-8) records that in two eruptions in 1822, hot water and mud travelled more than 38 km from the mountain, and the countryside was "covered to such a depth with bluish mud that people were buried in their houses".

Lyell continues "the face of the mountain was utterly changed, its summit being broken down, and one side, which had been covered with trees, became an enormous gulf in the form of a semi-circle". Over 4,000 persons were killed. Mudflows occurred again on Galounggoung on 18-19 October 1894, with no casualties (van Padang, 1951).

The following data (van Padang, 1951) has established the role of crater lakes in the production of lahars.

Kawah Idjen (Java) - An eruption occured in the crater lake in 1817.

Una Una (Celebes) - A possible eruption through the crater lake, between 1898 and 1900, produced a mudflow; 2.2 million m^3 of ash and mud were spread over 303,000 km^2.

Klabat (Celebes) - The summit contains a crater lake. Lahar deposits surround the base.

Api Siau (Celebes Sea) - On 14 June 1892, explosions led to a mudflow. In June 1921, the volcano contained a crater lake.

Awu (Celebes Sea) - Mudflows originated from the summit in 1711, 1812, 1856 and 1892. The summit now contains a crater lake 1050 x 825 m diameter, with a depth of 150 - 172m.

Peak of Ternate (off Halmahera, east of Celebes) - Three parasitic craters are filled with water. Mudflows were produced in 1561 (or 1562), 1862 and 1897.

Kaba (Sumatra) - A twin volcano with 3 craters and 4 lakes. A mudflow in 1833 was associated with explosions in the central crater.

The above data has established that nearly half of all known Indonesian eruptions have involved casualties attributable to lahars.

Zao (Japan) - The summit contains a crater lake. Eruptions produced mudflows in 1821, 1867, 1875, 1895 and 1939 (Kuno, 1962).

Haku-san (Japan) - The crater lake boiled and caused a mudflow on 28 September 1579 (Kuno, 1962).

Kusatu-Sirane (Japan) - In 1932 the waters of Lake Yu-gama, mixed with ash and sulphur formed a mudflow to the east and killed two persons (Kuno, 1962).

Agua (Guatemala) - On 10 September 1841, mudflows destroyed Ciudad Vieja, the former capital. The disaster was attributed by some to draining of a crater lake, by others to heavy rains on the loose debris of the volcano mantle (Mooser, et.al., 1958). Cotton (1944) quotes Russell, ... "The crater presents all the characteristics of a former lake basin, and upon the side of the mountain an immense ravine can be clearly seen, departing from a place where the rim of the crater is broken, and extending in the direction of Ciudad Vieja".... Meyer-Abich (1956) considered the slide remnants on the northern wall near the top indicate without doubt the violent discharge of a former crater lake, which possibly had been formed during extremely heavy rains.

La Soufrière (St. Vincent) - On 5 May 1902, fishermen crossing the summit noticed the water in the crater lake discoloured and agitated. By 7 May the crater was emitting a continuous roar and the river beds draining the mountain to the east and west (Rabaka and Wallibou) had become raging torrents of boiling mud and water up to 15 m deep. This activity was attributed to partial discharge of the crater lake (Bullard, 1962). On 7 May the eruption climaxed with a nuée ardente and mudflows of a different nature, the deposits of which were later examined by Anderson (1903).

Nilahue (Chile) - During April 1907, a mudflow coincided with the disappearance of a nearby crater lake Volcan Carran (Casertano, 1963).

Ruapehu (New Zealand) - on 23 June 1969, small eruptions through the crater lake generated four mudflows which flowed radially from the summit. Earlier lahars of this type are recorded in 1889 and 1895 (Healy, 1954).

NOTE: Early hypotheses proposed for the mode of emplacement of the products of the 1912 eruption of Mt. Katmai, included a mudflow origin (Escher, 1922), but the deposits have since been proved to be of a primary nuée ardente origin (Fenner, 1923).

TYPE 1(b): LAHARS INITIATED BY ADMIXING OF NUÉE ARDENTE DEPOSITS WITH RUNNING OR PONDED WATER

Lahars of this type are often secondary effects of eruptions, being generated at the lateral and distal margins of nuées ardentes.

Merapi (Java) - Nuées ardentes have been erupted from Merapi, with production of associated mudflows in 1587, 1672, 1822-3, 1832-5, 1846-7, 1888, 1930-1 (van Padang, 1951).

Semeru (Java) - Mudflows associated with normal explosions and nuées ardentes were recorded in 1875, 1911 and 1946 (van Padang, 1951).

Lamongan (Java) - Mudflows were generated by normal explosions in November 1893 (van Padang, 1961).

Hibok-Hibok (Phillipines) - On 1 September 1948, a cauliflower-type cloud erupted from the summit crater. Nuées ardentes and a lahar swept down the north-east side of the mountain devastating an area of about 8 km^2 (MacDonald and Alcaraz, 1956).

Avachinsky (Kamchatka) - Avalanches of incandescent loose materials often produced mudflows on the volcano during eruptions in 1926 and 1938 (Vlodovetz and Piip, 1959).

Asama (Japan) - On 5 August 1783, a nuée ardente rushed down the northern slope of Asama, and on reaching the river Agatuma-gawa produced a secondary hot mudflow, killing 1,300 persons (Kuno, 1962).

Jorullo (Mexico) - The volcano formed on 29 September 1759. Numerous nuées ardentes flowed down the western slopes in the early days of the eruptions and were accompanied by mudflows which destroyed nearby haciendas and sugar plantations. Flows continued until 1774 (Mooser, et.al., 1958).

Santa Maria (Guatemala) - Hot mudflows accompanied eruptions in 1929. Mud covered an area 10 km long and between 100 m - 1.5 km wide. Blocks up to 20 m^3 in size and not appreciably rounded were carried by the mudflow, while stumps of trees were carbonised. This suggests the mudflows were caused by admixing of nuée ardente material with water from streams which were running high, immediately following the rainy season (Anderson, 1933).

Mt. Pelée (Martinique) - On 5 May 1902, three days before the destruction of St. Pierre by a nuée ardente, a torrent of boiling mud destroyed a sugar mill and killed about 25 workmen, two miles north of St. Pierre. The cause of the mudflow was later ascertained to be the formation of a dam of ash in the headwaters of the Rivière Blanche, at an altitude of about 1,000 m. The water gradually became heated (how or by what is not specified), broke the dam and rushed down the valley (Bullard, 1962). On 14 October, explosions projected material which caused further mudflows in the Rivière Blanche. Robson and Romblin (1966) also record earlier mudflows in this river during eruptions in 1851-2.

La Soufrière (St. Vincent) - During the major ash eruption in 1902, ash dammed streams on many occasions, particularly between 23-25 May. When the water broke the dams it formed hot lahars of type 1(b) and cold lahars of type 1(c) (Anderson, 1903). A renewal of ash eruption on 3 September initiated another mudflow.

Tungarahua (Ecuador) - Mudflows were produced in 1886 and between 1916-25. On 5 April, 1918, "big nuées ardentes and lahars caused landslides and phreatic explosions" (Hantke and Parodi, 1966).

TYPE 1(c): LAHARS INITIATED BY THE ACTION OF HEAVY RAINS ON RECENTLY EJECTED PRODUCTS ACCOMPANYING OR SHORTLY FOLLOWING AN ERUPTION

Such rain lahars are common in tropical regions and are referred to in Indonesia as cold lahars.

Vesuvius (Italy) - The town of Herculaneum was covered by a mudflow from Vesuvius in 79 A.D. The resulting deposit exceeds 20 m thickness, and shows no stratification, consisting of fine ash, lava fragments and pumice which penetrated every crevice. The mudflow was similar to others which have devastated numerous towns on the slopes of Vesuvius in nearly all its violent eruptions. The lack of human skeletons in overwhelmed Herculaneum has been taken as evidence that Pompeii was destroyed a few days earlier, giving the citizens of Herculaneum warning in sufficient time to escape (Bullard, 1962). The water in these mudflows is supplied by heavy rains which accompany most eruptions and convert ash to incoherent mud. On 17 December 1631, mudflows on Vesuvius destroyed numerous villages and nine towns including St. Giorgio a Cremano, Portici and Resini (the town built upon the ancient Herculaneum). During April 1906, ash, sand and boulders were carried by hot avalanches for 3-4 km from the summit. On 27 April, heavy rain fell saturating the ash to the point of flowing. Torrents of liquid mud continued to flow down through gullies onto surrounding farmlands until October, 1908 (Perret, 1924, pp. 102-4).

Agung (Bali) - During the 1963 eruption, tropical torrential rain fell in the higher regions immediately after the eruption, sweeping the accumulated deposits of nuées ardentes to lower regions, devastating many acres and killing 200 people where the lahars left their river courses at bends. From topographic maps, it appears that lahars have accompanied past eruptions on Mt. Agung (Zen and Hadikusumo, 1964).

Lamington (Papua) - Mudflows were an aftermath of the 1951 explosive eruption. As soon as heavy rain fell around the summit area, a deep channel was cut through the fresh ash beds and a series of great mudflows began sweeping through river channels to the swampland below. Torrents of viscous mud periodically descended the water courses in almost complete silence, apart from the rumbling impact of large boulders. They were supplied by the great volume of unconsolidated material on the upper slopes, and carried an astonishing amount of large fragments (Taylor, 1958).

Ambryn and Manam (Melanesia) - After the large eruptions of Manam in 1968, thick layers of scoriaceous lapilli and blocks that had been scattered around acted as a huge sponge and prevented runoff for several weeks. Eventually the saturation point was reached and destructive streams of mud and stone descended onto the flat land, cutting en route gorges 9 m deep overnight (G.A.M. Taylor, pers. comm.). A mudflow at Ambryn on 6 September 1950 (Fisher, 1957, p. 92) was probably similar in origin to those on Manam.

Mayon (Phillipines) - Mudflows were recorded in 1766, 1873, 1879 and 1915. On 23 April 1968, nuées ardentes were emitted from the summit, continuing until 4 May. The larger nuées ardentes generated torrential rainstorms which eroded the loose ash and caused destructive mudflows on the lower flanks (Moore and Melson, 1969).

Fuego (Guatemala) - In September 1963, ash and lapilli exploded from the summit. During 29 September, masses of ash and lapilli accumulated on the steep north-eastern slope of the cone and upon saturation by heavy rains formed a lahar that descended the upper Barranca Honda at great speed. At its lower end the lahar divided into two tongues in north-easterly and southerly directions. Renewed ash fall during the next day (30 September) probably triggered a second lahar in which 7 persons perished (Bohnenberger, et.al., 1971).

Irazú (Costa Rica) - Irazú erupted ash almost continuously from March 1963 to February 1965. Much damage was caused by debris flows originating from the upper slopes of the volcano. Small flows occurred soon after the eruption in March 1963, but the most disastrous debris flow was in December, at the end of the 1963 rainy season. More than 90 debris flows occurred in 1964. A large block transported by one of the flows measured 7.5 x 5.5 x 3 m and was estimated to weigh at least 200 tons (Waldron, 1967, fig. 13). Speeds in excess of 15 - 20 m per sec were attained by some of the larger flows.

Mt. Pelée (Martinique) - Heavy rains accompanied the eruption during the night 7 - 8 May 1902. Torrential rain caused mudflows which ruined parts of the settlements of Grand Rivière, Macouba, Basse Pointe and Prêcheur (Robson and Tomblin, 1966).

TYPE 1(d): LAHARS INITIATED BY COLLAPSE OF CRATER LAKES BY NON-ERUPTIVE MECHANISMS

Lahars resulting from collapse of a crater lake other than by volcanic action are differentiated although the deposits may be similar to those of type 1(a). Such bodies of water at high altitudes are peculiar to volcanic craters. This lahar type is not common, but one New Zealand example is well documented.

Agua (Guatemala) - In 1541 the crater lake rim collapsed and a mudflow occurred, but no eruption was recorded (Mooser, et.al., 1958).

Hood (USA) - Radiocarbon dating showed that about 288 A.D. a "waterburst" flowed out across the south-west flank of Mt. Hood. Lawrence and Lawrence (1959) believed the water had originated from a crater lake that was about 500 m across and 240 m deep. Uncharred wood preserved within the deposits was taken to indicate transport as a cold lahar.

Ruapehu (New Zealand) - During the evening of 24 December, 1953, crevassing movements in a glacier on Mt. Ruapehu probably weakened a low ash barrier retaining the lake, allowing the lake level to drop 6 m in 150 minutes. Calculations showed that the maximum discharge at the Whangaehu River bridge, 19 km to the south, reached 850 m^3 per sec. as the flood wave crest travelled downstream at about 16 km per hour (267 metres per sec.). As an express train was crossing the bridge at the height of the flood, the bridge collapsed and the train plunged into the river, resulting in the deaths of 151 people. The capacity of the lahar to carry debris was demonstrated by the base portion of one of the piers weighing 126 tons being carried 63 m downstream. Two 5 ton concrete blocks from one of the piers were seen about 54 m downstream with boulders of at least the same weight resting on top of them; and one of the railway carriage frames was carried about 2.6 km downstream (Stilwell, et.al., 1954).

Similar lahars have travelled down this river from the crater lake in 1861, 1889, 1895 and 1925. Those of 1861, 1925 and 1953 appear to have been cold lahars due to release of lake water below the glacier. Those of 1889 and 1895 resulted from eruptions in the crater lake (Healy, 1954) and were of type 1(a).

TYPE 1(e): LAHARS INITIATED BY RELEASE OF PONDED WATER FROM BENEATH AN ICE COVER (JÖKULHLAUPS)

The jökulhlaups or "glacier runs" of Iceland are notorious mudflows which have frequently accompanied historic eruptions of Katla and other volcanoes buried beneath the ice of the Vatna Jökull (Rittman, 1962). Recorded 'jökulhlaups' (or 'hlaups' for short) often last about one week, and as much as 7 km^3 (1.5 ml^3) of water have plunged out from beneath glaciers and into the sea, briefly carrying as much water as the Amazon River (Thorarinsson, 1957). Thorarinsson considers a/ that the water is partly magm~~e~~tic, partly ground water, and mostly melt-water stored beneath the glacier ice prior to an eruption.

Katla (Iceland) - In historical times Katla has erupted 13 times and every eruption has been accompanied by "hlaups" (equivalent term for lahar). One hlaup in 1918 had an estimated maximum volume of 3-400,000 m^3. In 1955, the maximum discharge rate of a hlaup reached 3,000 m^3 within an hour after its visible start from a glacier front (Thorarinsson, 1957, fig. 1).

Grímsvötn (Iceland) - Grímsvötn, beneath the middle of the Vatna Jökull of Iceland, is a depression more than 35 km in area and more than 500 m deep, more or less filled with melt-water. About every tenth year the water escapes from beneath the ice, issuing from many tunnels in the glacier front (Thorarinsson, 1956). In July 1954, a maximum discharge of 10,500 m^3/sec was recorded in a hlaup which totalled 3.5 km^3 water discharge. An hlaup in the same area during March 1934 was estimated to have a maximum discharge of 45,000 m^3/sec with a total release of 7 km^3 water (Thorarinsson, 1957).

Hekla (Iceland) - During eruption in 1947, extensive hlaups descended the northern side of Hekla, with flood wave crests travelling at an average velocity of between 5.4 and 8.3 km an hour. The measured volume of water in the hlaups was much greater than the estimated amount of snow and ice available to be melted, indicating that magmatic water contributed significantly to the hlaup, or that a subglacial reservoir existed in the crater. Lava was reported to melt snow only slowly when it flowed over it during the later stages of the eruption (Kjartansson, 1951).

Lassen Peak (USA) - On 19 May 1915, a mudflow descended the north-east side of the peak into Hat and Lost Creeks. Suggested causes include water pouring out from within the mountain (Loomis, 1926), and melting of snow by a downward blast of hot steam, by rain or by hot ashes. Finch (1929, 1930) concluded and Williams (1932 p. 324-9) confirmed that it had formed by lava flows melting snow. If Loomis is correct, then the 1915 lahar should be included in type 1(e), but if Finch and Williams are correct it should be included within type 1(f). Immediately after the mudflow Loomis observed that the lahar varied between 0.8 km and 200 m in width and was about 5 m thick. Rocks up to 6 m diameter were carried 6 km from the mountain and some were still hot for days after the eruption. Earlier mudflows from the peak are also recorded, including one 500 years ago. Williams (1932, p.320) also notes that deposits of some of the older mudflows on the banks of Hat and Lost Creeks, have formed moraine-like mounds.

Ruiz (Colombia) - In 1595, a violent eruption through a subglacial crater produced lahars (Hantke and Parodi, 1966).

TYPE 1(f): LAHARS INITIATED BY MELTING OF SNOW AND ICE DIRECTLY ACCOMPANYING AN ERUPTION

Lahars initiated by snow and/or ice melting are generally local and do not occur on a massive scale.

Tokachi-dake (Japan) - Between December 1925 and May 1926, hot gases and debris melted snow at the summit, causing a mudflow which destroyed the hotel of Hatekeyama. During a later explosion, the north-west part of the cone collapsed, producing a hot avalanche (about 0.004 km^3). The avalanche melted snow and produced a mudflow (similar to those of type 1(b) which descended with an average velocity of about 50 m per sec, reaching the town of Kami-Hurano, 20 km west of the cone in 26 minutes, and killing 144 persons (Murai, 1960).

Asama (Japan) - A mudflow caused by melting of snow is believed to have occurred during the 1531 eruption (Kuno, 1962).

Shiveluch (Kamchatka) - In 1964 a pyroclastic eruption caused rapid melting of ice and snow and generated lahars (Gorshkov and Dubik, 1970). The lahars would be similar to type 1(b).

Bezymianny (Kamchatka) - Similar lahars to those at Shiveluch, accompanied the 1955 eruption (Gorshkov, 1959).

Lassen Peak (USA) - If Williams (1932) and Finch (1929, 1930) are correct, then the 1919 lahar would fall into this category.

Mt. St. Helens (USA) - Some hot lahars are reported to have occurred on this mountain. Mullineaux and Crandell (1962) attribute their origin to hot material falling on the summit, and flowing downslope, increasing in volume by the melting of snow and ice in their paths.

Cotopaxi (Ecuador) - Mudflows were recorded on 21 occasions between 1532 and 1904 (Hantke and Parodi, 1966). Every mudflow was associated with lava flow extrusion, but the source of the water is in doubt. The 1877 eruption was paroxyamal, accompanied by continuous snowfall on the summit. Lahars streamed down the river beds for more than 100 km. In 1877, 40-50 m deep channels were cut in ice as mudflows (avenidas) descended gulches and spread onto the surrounding plain, forming a great lake of mud (Wolf in Anderson, 1933). Melting of snow by lava flows is considered to be the most probable source of the water (Wolf, in Fenner, 1923).

Villarica (Chile) - The volcano in central Chile produced mudflows during eruptions between 9 October 1948 and 3 February 1949. On March 1964 a further mudflow caused by rapid melting of snow and ice at the summit following an eruption, flowed down the northern and southern slopes of the volcano, killing 25 persons (Karsui, 1967).

Calbuco (Chile) - On February 1st, 1961, a lahar descended the northern flank of Calbuco and entered Lake Llanquihue. It was caused by the eruption of lava and pyroclastic material which melted ice and snow on the summit. The lahar descended the Rio Colorado at an estimated velocity of 20 km/hr and totalled 3,000m^3 volume. A further two smaller lahars descended the south flank to Lake Chago and the north-east flank to the Rio Petrohué (Klohn, 1963).

TYPE 1(g): LAHARS INITIATED BY PHREATIC EXPLOSIONS OR DIRECTED BLASTS

All lahar types 1(a)-(f) inclusive involve proportionately large amount of water relative to the amounts of blocks, sand and ash involved in the flow. Some lahars have been reported to contain little water and approach the "directed blasts" described by Gorshkov (1959), yet distinct from the true directed blasts recorded on Mt. Bezymianny.

Sorikmarapi (Sumatra) - A phreatic explosion on 21 May 1892 produced a mudflow (van Padang, 1951).

Tangkuban Prahu (Java) - On 27 May 1846 explosions produced destructive mudflows (van Padang, 1951).

Tjerimai (Java) - Similar mudflows were observed in 1698 (van Padang, 1951).

Bandai-san (Japan) - Mudflows were produced by steam eruptions near the summit of the cone in 806?, 1808 and 1888; and by collapse of solfataric decayed rocks in 1954 (Kuno, 1962). The well-known catastrophic explosions of 1888 were preceded by several weak tremors and one strong one. The major part of the eruption consisted of 15-20 explosions which destroyed most of the peak Kobandai; the fragments pouring down the northern slope of the mountain as a mudflow. More than 460 people were killed by about .25km^3 of rocky debris. Cotton (1944) showed a reconstruction of the cone and stated that the material dislodged from it was thoroughly saturated with water, and was rapidly brecciated. Grange (1931) illustrated the lahar deposit with a drawing and Jaggar (1930) mentions that the material forming the deposit sank away from its highest level, corresponding to the tops of mounds.

Kurikana (Japan) - In 1946 an explosion produced mudflows which flowed rapidly to the north-east causing acidity of the river water (Kuno, 1962).

Yake-dake (Japan) - An explosion in 1585 produced a mudflow which descended a valley, buried the village of Nakao, and finally reached a point 4.5 km north-west of the summit (Kuno, 1962).

Usu (Japan) - Three major mudflows have formed extensive deposits around the base. The earliest was the Minami-Byobu-Yama mud stream on the southern side of the mountain for which no eruption is recorded. The second was the Bunsei mud stream, on the south-western side, which accompanied an explosive eruption at the foot of the Ko-Usu dome in 1822. The third was the Tateiwa mud stream, on the eastern side, which resulted from collapse of the eastern part of O-Usu dome after a series of explosions in 1853. From 23 June to 1 July 1944 small scale mud eruptions commenced inside newly opened craters. A mud stream overflowed from one crater and poured into a depression nearby forming a pond of mud and hot water (Minakami, et.al., 1951).

Shiveluch (Kamchatka) - In 1964, a directed blast from Shiveluch Volcano ejected explosion breccia to a distance of 10 km from the crater. The deposit covered 98 km^2 and its boundaries were sharply delineated by adjacent undisturbed forest. The breccia attained a maximum thickness of 50 m and was cold and inert containing blocks of ice. The origin was not laharic, but the interesting feature warranting its mention here, is the resultant surface topography which appears identical to that of some known lahar deposits. To differentiate directed blast deposits from lahar deposits may be very difficult.

Mt. St. Helens (USA) - The similarity of all the Silver Lake debris flows indicates a common origin. They are thought to have been produced by mild explosive eruptions or by collapse of spines or domes (Mullineaux and Crandell, 1967).

Rainier (USA) - In December 1963, rock debris collapsed from Little Tahoma Peak onto a nearby glacier, and then was avalanched 5 km down valley. Calculations based on the height to which the avalanches rose on the valley walls suggest their velocity reached at least 130-145 km per hour. The resultant deposit showed low mounds with large boulders beneath. The cause of the rock falls was not an earthquake and may have been either surficial freeze action or a steam explosion (Crandell and Fahnestock, 1965).

The Paradise debris flow on the south side of Mt. Rainier (Crandell, 1963) and the Osceola mudflow on the north-west side (Crandell and Waldron, 1956) total at least 13×10^9 m^3. Crandell (1963) has proposed that they originated as avalanches resulting from the destruction of the former summit of Mt. Rainier. The cause may have been phreatic explosions or earthquakes. The missing summit would have been in the order of 2,000 m basal diameter and 450 m high. A similar explanation is offered for younger mudflows on the west side of Rainier, one dated at less than 3,500 years B.P. and the other - the Electron Mudflow - extending 65 km down valley - dated at 500 years B.P. (Crandell and Mullineaux, 1967).

TYPE 2(a): LAHARS INITIATED BY HEAVY RAINS

Rainier (USA) - Debris flows are very common on Mt. Rainier. The largest was probably caused by volcanic explosions, others by heavy rainfall or rapid snowmelt. In October 1947, an estimated 50 million m^3 of rock debris was carried by debris flows from the peak down Kautz Creek Valley during a period of heavy rainfall. Postglacial lahars from Mt. Rainier are summarised by Crandell (1971).

Mt. St. Helens (USA) - Debris flows are frequent on the north side of the volcano (Verhoogen, 1937). Recent flows extend for more than 40 miles down valleys west of the volcano, forming 4.5 - 6 m thick deposits composed mainly of non-vesicular fragments. Their length of travel is attributed to high mobility imbued by water. Wood from one of the western flows gave a radiocarbon age of about 2,000 years B.P. (Mullineaux and Crandell, 1962).

Costa Rica - During the rainy season in Costa Rica, torrents are recorded of mud having flowed off volcanoes into canyons below (Williams, 1952).

Egmont (New Zealand) - Numerous debris flow deposits can be recognised on Mt. Egmont, and many of the fresher ones are known to have occurred within the last 400 years. The rainfall is between 1-1.5 x 10^3 mm per annum. The loose jointed lava flows and interbedded loose breccias of the Egmont composite cone are susceptible to erosion under the prevailing conditions of saturation and high runoff. On 21 February 1935, in torrential rain, part of an hotel's hydro-electric plant was swept away by a debris flow (Scanlan, 1961). Tree-ring dating has been used to determine the ages of a number of historical debris flows (Druce, 1964).

TYPE 2(b): LAHARS INITIATED BY EARTHQUAKE TRIGGERED COLLAPSES

Few lahars are caused solely by earthquakes or surficial geological conditions. However earthquakes may be the major cause in triggering a lahar in association with other events e.g. the 1889 Bandai-san collapse.

Fuego (Guatemala) - In 1917, landslides were initiated by earthquakes (Mooser, et.al., 1958).

White Island (New Zealand) - Situated on the north-east side of New Zealand is White Island volcano, a cone with a horse-shoe shaped crater with its central floor just above sea level. In 1914, part of the crater rim collapsed along a ring fault and fell to the crater floor. Although uncertain, the immediate cause of the landslide may have been an earthquake because moderately severe earthquakes were reported on the island two weeks before the event. Great detonations from the island were heard 40 km away on the mainland, and are attributed to an explosive eruption following blockage of the vents of the main fumarole by debris (Bartrum, 1926). Ward (1922) believed that the eruption caused further rockfalls from the crater walls. The slipped debris was probably lubricated by water from pools in the crater floor and by steam from the main vents, and became mobilised as a lahar which flowed 600 m out of the crater to the eastern coastline, leaving remnant mounds on the crater floor.

Tongariro (New Zealand) - A mudflow has originated in historical times from Ketetahi Springs, on the northern side of Mt. Tongariro (Matthews, 1967). No heavy rain was falling at the time and the mudflow is thought to have been initiated by earthquakes associated with an eruption in the lower Te Mari crater, about 1.5 km to the east (W.W. Topping, pers. comm.).

OTHERS

Lahars for which the origin has not been interpreted, due to insufficient information, are listed according to regions.

Indonesia: Eruptions on Butak Petarangan occurred on 13 May 1928 and on 13 October 1939 producing lahars (van Padang, 1951).

Oceania: Few mudflows have been recorded in Oceania. The island of Niuafo'ou (Tin Can Island) erupted in 1886, and on 13 August, mudflows occurred on the north-east side (Richards, 1962).

Phillipines: Mudflows occurred on the volcano Catamaran in 1827, 1862, 1897, 1902 and between 1 September 1948 and January 1952, and on the volcano Banahao in 1730, 1843 and 1909, the 1843 mudflows being caused by landslides (van Padang, 1953).

Chile: Mudflows are recorded from Petaroa in 1837, Nevados de Chillan between 1861-2 and Llaima in 1876 (Casertano, 1963).

Tanzania: Ol Doinyo Lengai in the African Rift Valley, south of Lake Natron, produced mudflows during eruptions in 1921 and between August 1940 and February 1941 (Richard and van Padang, 1957).

Colombia: Three volcanoes produced mudflows in historical time - Doña Juana between 1897-1906, Puracé in 1869 and Ruiz in 1595 and 1845 (Hantke and Parodi, 1966).

West Indies: Two sets of mudflows are recorded on La

Soufrière, Guadeloupe, on 29 September and 2 October 1797, and on 12 February 1838 (Robson and Tomblin, 1966).

Costa Rica: The volcano Cerro Negro, born during April and May of 1850, produced a mudflow in 1914 (Mooser, et.al., 1958).

Japan: Between July and October 1910, four or five small craters formed along a line at the northern foot of the cone Usa. From these craters, mudflows were discharged several times. Other less well documented mudflows occurred on Kutieraba-Zima between 1931-35; on Kirisima on 20 January 1882; on Hakone in March 1786 and in July 1953; on Iwate in 1686 and on Iwaki in 1597 (Kuno, 1962).

QUATERNARY LAHARS

Old lahar fields are recognised in many parts of the world, the largest being in Indonesia, Japan, United States, Iceland and New Zealand. In 1925 Escher's report on the "Ten Thousand Hills of Tasikmalaja" at the base of Galounggoung in Indonesia, aroused immediate controversy. One critic, Dr. F.X. Schafer, considered that the many hills were man made (Palmer, 1931). Escher (1925) calculated that the aggregate volume of all the 3,648 hills to be a portion of the volume of the huge semicircular gulf at the summit of the mountain. Jagger (1931) supported Escher's theory as to the origin and cited similar deposits on the slopes of Pavlof volcano, in the Aleutian arc.

The Osceloa Mudflow in Puget Sound, Washington, USA, once regarded as a till, was convincingly shown by Crandell and Waldron (1956) to be a late Quaternary mudflow of exceptional dimensions. The deposit varies from about 1 m to 105 m thick, the margins of the flow being digitate and the surface having a slope of 5 m per km. The mudflow overlies a brown podzolic soil, dated at 4,800 years B.P. by 14C dating of contained wood.

Volcanic debris in the Wrangell Mountains, Alaska, shows a distribution and character similar to a volcanic mudflow. The deposit, dated as pre-Wisconsin age, extends 104 km down the present Copper River, and Ferrians, et.al. (1958) have suggested it was probably initiated by melting of snow and ice.

Old lahar fields surround many active, dormant and extinct volcanoes in Indonesia. Large fossil mudstream deposits cover the southern foot of Tandikat volcano. On the north-east side of Blerang Beriti, is a 1,200 m wide crescentic crater of which the north-east side is missing. From this breach stretches a lahar deposit 3 km long, and 1,300 m across at the widest point. Lahar deposits up to 20 km long occur on the north-east slopes of Patuha. Hundreds of hills on the north-east foot of Sundoro, represent the erosion remnants of another vast prehistoric lahar (van Padang, 1951).

A large late Quaternary lahar deposit flowed through the 300 m defile of the Rio Laja, 445 km south of Santiago, Chile (MacPhail, 1966). It extends 40 km from the apex at the defile, and its source locality, Volcan Antuco is located another 56 km east of the apex. The surficial "Clay with Boulders" Formation covering much of the Meseta Central of Costa Rica (Williams, 1952, p. 165), contains boulders more than 3 m across, and a rudimentary horizontal layering. Williams concluded that it was laid down by "torrents of mud forceful enough to transport huge boulders for long distances". Williams (1933, p. 40) also described breccias 75 m thick on the western flank of Tahiti, as lahar deposits.

In New Zealand, studies on Quaternary lahars began in the 1920s. At that time considerable disagreement existed as to the origin of the many thousands of "conical hills" on the western side of Mt. Egmont and Mt. Ruapehu. E. de C. Clarke (1912) and Morgan and Gibson (1927) considered them to have formed over numerous independent volcanic vents. Bossard (1928) suggested that the hills formed at points where volatiles were concentrated in lava flows and had built up sufficient pressure to blow out fragmental material at the top. Grange (1931) quickly recognised that the hills were composed of fragments of andesite set within a fine clastic matrix and that they were not parts of lava flows. He compared them with the mudflow deposits which had recently been described from Indonesia and Japan, and with features of known mudflows on Mt. Ruapehu and at White Island, New Zealand. Te Punga (1952) described the Hautapu Valley Agglomerate in the Rangitikei Valley, New Zealand, and from the distribution and lithology of the formation, he concluded that it had been deposited by lahars derived from Mt. Ruapehu. Single blocks of andesite within the deposit are estimated to weigh up to 300 tons.

PRE-QUATERNARY LAHAR DEPOSITS

By applying criteria for recognising modern lahar deposits in the southern Cascade Mountains, USA, Fisher (1960) concluded that a number of Eocene-Oligocene volcanic breccias near Mt. Rainier are also lahar deposits. Schminke (1967) described about 15 inversely graded lahar deposits in the type sections of the Ellensburg Formation (Pliocene-Pliocene age) in Washington State. He considered the origin to be an ancient Cascade chain of volcanoes 60 km to the west, and he explained the inverse grading as a result of inertial flow.

The nature of the lahars of the Tuscan Formation, California, is very well documented. The breccias within this formation cover over 5,000 km^2, attain a maximum thickness of 500 m and a volume of 1,250 km^3. Anderson (1933) first critically reviewed the possible origins of the formation and tended to favour melting of ice and snow to produce sufficient water. However, Lydon (1968) considers autobrecciation took place in the source area of the lahars and sufficient magmatic and meteoric water was available for their mobility without invoking additional sources, i.e. crater lakes or melting of snow and ice. Apparently emplaced over a period of about a million years, during the late Pliocene, the lahars originated by autobrecciation in dykes and conduits at temperatures probably in the range 340°C to 280°C (Lydon, 1968).

Brief mention should also be made of the literature surveys on volcanic breccias by Parsons (1969). Much of his work arose from observations in the Absaroka Volcanic Field (e.g. Hay, 1964, Parsons, 1958). There, large thicknesses of breccias have no topographically elevated source areas and are believed to have originated by underground brecciation of magma.

"CONICAL HILL" SURFACE TOPOGRAPHY

Lahar mounds or "conical hills" have frequently been described as the diagnostic surface features of lahar deposits, although little research has been made as to their origin.

The Nirasaki mudflow in Japan, which extends for a distance of 23 km from the volcanic Yatsuga-dake is comprehensively described by Mason and Foster (1956). It has a topography of conical mounds like that characteristic of New Zealand and Indonesian lahar deposits. The same topography has been remarked on deposits from the Bandai-san eruption of 1888, the 1919 lahar from Lassen Peak, and the deposits on the flanks of Pavlof in the Aleutians. Mason and Foster concluded that the Nirasaki mounds were formed by hydrostatic pressure when low viscosity material was extruded from the interior of the mudflow through fractures in the drying, hardening crust. The majority of New Zealand lahar mounds show cores of large boulders, suggesting clustering of coarse material and then immobilising of the clusters before predominantly finer and more fluid material had ceased flowing in the intervening areas.

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REFERENCES

* Denotes a description of resultant lahar deposit

o Denotes photograph or map of lahar source and/or deposit.

# Denotes whether mode of origin of lahar stated.

* # A.G.I. Glossary, 1960. "Glossary of geology and related sciences" (2nd edition) 325 pp. + supplement 72 pp. American Geological Institute, Washington, D.C.

o Anon, 1919. A volcanic cataclysm in Java (photo) "Illustration" Aug. 9, No. 3988: 116-7.

* # Anderson, C.A., 1933. The Tuscan Formation in northern California with a discussion concerning the origin of breccias. University of California Publications; Bulletin of the Department of Geological Sciences, 23(7): 215-76.

o# Anderson, T., 1903. Recent volcanic eruptions in the West Indies. The Geographical Journal - March: 265-81.

Bohnenberger, O.H., Bengoechea, A.J., Dondoli, C., and Castro, A.M., 1971. Report on Active Volcanoes in Central America during 1957-1965. Bulletin of Volcanic Eruptions 9-1: 19 pp. in Bulletin Volcanologique 34(2).

*o# Borns, H.W., Hall, B.A., 1969. Mawson "Tillite" in Antarctica: Preliminary report of a volcanic deposit of Jurassic age. Science 166: 870-2.

*o# Bossard, L., 1928. Origin of the conical hills in the neighbourhood of Mount Egmont. N.Z. Journal of Science & Technology 10: 119-25.

*o# Bullard, F.M., 1962. Volcanoes, in history, in theory, in eruption. Univ. of Texas Press, Austin: 441 pp.

\# Casertano, L., 1963. Catalogue of the active volcanoes of the world including solfatara fields. Part XV - Chilean Continent: 55 pp.

\# Clarke, E. de C., 1912. The Geology of the New Plymouth Subdivision, N.Z. Geological Survey Bulletin n.s. 14: 58 pp.

\# Coombs, H.A. and Howard, A.D., 1960. Catalogue of the active volcanoes of the world including solfatara fields. Part IX - United States of America: 68 pp.

*o# Cotton, C.A., 1944. Volcanoes as landscape forms. Christchurch, N.Z. Whitcombe & Tombs: 416 pp.

* Crandell, D.R., 1957. Some features of mudflow deposits. Bulletin of the Geological Society of America 68(2): p.1821.

*o# Crandell, D.R., 1963. Paradise debris flow at Mount Rainier, Washington. U.S. Geological Survey Professional Paper 475-B, pp. B 135-39.

*o# Crandell, D.R., 1971. Postglacial lahars from Mount Ranier Volcano, Washington. U.S. Geological Survey Professional Paper 677: 75 pp.

*o# Crandell, D.R., and Fahnestock, R.K., 1965. Rockfalls and avalanches from Little Tahoma Peak on Mount Rainier, Washington. U.S. Geological Survey Bulletin 1221-A, pp. A1-A30.

*o# Crandell, D.R., and Mullineaux, D.R., 1967. Volcanic hazards at Mount Rainier, Washington. U.S. Geological Survey Bulletin 1238, 26 pp.

*o# Crandell, D.R., and Waldron, H.H., 1956. A recent volcanic mudflow of exceptional dimensions from Mt. Rainier, Washington. American Journal of Science, 254, 349-62.

Druce, A.P., 1970. The vegetation pp. 45-59 in Egmont National Park Handbook Ed. A.B. Scanlan. Egmont National Park Board, New Plymouth, N.Z.

Escher, B.G., 1922. On the hot "lahar" (mud flow) of the Valley of Ten Thousand Smokes (Alaska). Proceedings Koninklijke Akademie van Wetenschappen, Amsterdam, Vol. 24, 282-93.

*o# Escher, B.G., 1925. L'Eboulement prehistorique de Tasikmalaja et le Volcan Gal$\overset{u}{o}$nggoung, Java. Leidsche Geologische Mededeelingen, Dec 17, Aflevering 1, XI, 8-21.

Fenner, C.N., 1923. The origin and mode of emplacement of the great tuff deposit in the valley of ten thousand smokes. National Geographic Society - Katmai Series No. 1, 74 pp.

* # Ferrians, O.J., Nichols, D.R., and Schmoll, H.R., 1958. Pleistocene volcanic mudflow in the Copper River Basin, Alaska. Bulletin of the Geological Society of America v.69(12): p.1563.

Finch, R.H., 1929. The origin of Lassen Mud Flows. Volcano Letter No. 224, April 11.

Finch, R.H., 1930. Mudflow eruption of Lassen Volcano. Volcano Letter No.266, Jan. 30.

Fisher, N.H. 1957. Catalogue of the active volcanoes of the world including solfatara fields. Part V - Melanesia; 105 pp.

*o# Fisher, R.V., 1958. Definition of volcanic breccia. Bulletin of the Geological Society of America 69: 1071-3.

*o# Fisher, R.V., 1960. Criteria for recognition of laharic breccias, southern Cascade Mountains, Washington. Bulletin of the Geological Society of America 71: 127-32.

* Fisher, R.V., 1961. Proposed classification of volcaniclastic sediments and rocks. Geological Society of America Bulletin 72: 1409-14.

*o# Gibson, W. and Morgan, P.G., 1927. The Geology of the Egmont Subdivision, N.Z. Geological Survey Bulletin, n.s. 29: 99 pp.

*o# Gorshkov, G.S., 1959. Gigantic eruption of the volcano Bezymianny (Kamchatka). Bulletin Volcanologique, vol. 20: 77-109.

Gorshkov, G.S., 1963. Directed volcanic blasts. Bulletin Volcanologique 26: 83-8.

Gorshkov, G.S., and Dubik, Y.M., 1970. Gigantic directed blast at Shiveluch Volcano (Kamchatka). Bulletin Volcanologique 34(1): 261-288.

*o# Grange, L.I., 1931. Conical hills on Egmont and Ruapehu Volcanoes. N.Z. Journal of Science and Technology 12(6): 376-84.

*o# Grant-Taylor, T.L. 1970. Geology of Egmont National Park: 69-82 in "Egmont National Park", ed. A.B. Scanlan, Egmont National Park Board, New Plymouth: 86 pp.

Hadikusumo, D., 1967. Description of Volcanic Eruptions - Indonesia. Bulletin of Volcanic Eruptions No.6. in Bulletin Volcanologique 31: 8 pp.

Hantke, G., and Parodi, I.A., 1966. Catalogue of the active volcanoes of the world including solfatara fields. Part XIX - Columbia, Ecuador and Peru: 73 pp.

*o# Hay, R.L., 1954. Structural relationships of tuff-breccia in Absaroka Range, Wyoming. Bulletin of the Geological Society of America, Vol. 65: 605-620.

Healy, J., 1954. Origin of flood and Ruapehu Lahars in Tangiwai Railway Disaster. Report of Board of Inquiry, pp. 6-8, 28-31. Government Printer, Wellington, N.Z.

*o# Jaggar, T.A., 1930. Some analogous boulder hillocks. The Volcano Letter. June 19, No. 286: p.3.

Katsui, Y., 1967. Description of Volcanic Eruptions - Chile. Bulletin of Volcanic Eruptions No. 6: 8 pp. Bulletin Volcanologique 31.

*o# Kjartansson, G., 1951. The eruption of Hekla 1947-1948 II(4). Water and mudflows: Vísindafélag Íslendinga, Reykjavík, Iceland: 51 pp.

*o# Klohn, E., 1963. The February 1961 eruption of Calbuco Volcano. Seismological Society of America Bulletin 53: 1435-36.

o# Kuno, H., 1962. Catalogue of the active volcanoes of the world including solfatara fields. Part XI - Japan, Taiwan and Marianas: 332 pp.

o# Lawrence, D.B., and Lawrence, E.G., 1959. Radiocarbon dating of some events on Mount Hood and Mount St. Helens. Mazama vol. 41(13): 10-18.

* Lindsay, J.F., 1968. The development of clast fabric in mudflows. Journal of Sedimentary Petrology 38(4): 1242-1253.

* Lindsay, J.F., Summerson, C.H., Barrett, P.J., 1970. A long-axis clast fabric comparison of the Squantum "Tillite" Massachusetts and the Gowganda Formation, Ontario. Journal of Sedimentary Petrology 40(1): 475-79.

*o# Loomis, B.F., 1926. Eruptions of Lassen Peak. Loomis Museum Association, Mineral, California: 100 pp.

*o# Lydon, P.A., 1968. Geology and Lahars of the Tuscan Formation, northern California: 441-75. in Studies in Volcanology. Eds. Coats, Hay, Anderson. Geological Society of America Memoir 116.

* # Lyell, C., 1867. Principles of geology, Vol.2. Murray, London: 659 pp.

o Macdonald, G.A., and Alcaraz, A., 1956. Nuées ardentes of the 1948-1953 eruption of Hibok-Hibok. Bulletin Volcanologique 18: 169-178.

* MacPhail, D.D., 1966. An extensive lahar in central Chile. Geological Society of America Special Paper, No. 87. Abstracts for 1965.

*o# Mason, A.C., and Foster, A.L., 1956. Extruded mudflow hills of Nirasaki, Japan. Journal of Geology 64: 74-83.

Mathews, W.H., 1952. Ice-damned lavas from Clinker Mountain, southwestern British Columbia. American Journal of Science 250: 553-65.

o Mathews, W.H., 1967. A contribution to the geology of the Mount Tongariro Massif, North Island, New Zealand. N.Z. Journal of Geology and Geophysics 10: 1027-38.

(not seen)

Meyer-Abich, H., 1956. Los volcanes activos de Guatemala y El Salvador. Anales Servicio Geologico Nacional de El Salvador, Bol. 3, San Salvador 1956.

o Minakami, T., Ishikawa, T., and Yagi, K., 1951. The 1944 eruption of volcano Usu in Hokkaido, Japan. Bulletin Volcanologique 11: 45-157.

Moore, J.G. and Melson, W.G., 1969. Nuées ardentes of the 1968 eruption of Mayon Volcano, Philippines. Bulletin Volcanologique 33(2): 600-620.

Mooser, F., Meyer-Abich, H., and McBirney, A.R., 1958. Catalogue of the active volcanoes of the world including solfatara fields. Part VI - Central America: 146 pp.

*o# Mullineaux, D.R., and Crandell, D.R., 1962. Recent lahars from Mount St. Helens, Washington. Geological Society of America Bulletin 73: 855-70.

*o# Murai, I., 1960. 5. On the mud-flows of the 1926 eruption of volcano Tokachi-dake, Central Hokkaido, Japan. Bulletin of the Earthquake Research Institute 38: 55-70.

*o# Palmer, H.S., 1929. Volcanic mud flow in Java. The Volcano Letter, Oct. 31, No. 253 p.1.

Palmer, H.S., 1930. The bowldery hills of Galounggoung. The Volcano Letter, June 19, No. 286: 2-3.

(not seen)

Parsons, W.H., 1958. Origin, age, and tectonic relationships of the volcanic rocks in the Absaroka-Yellowstone-Beatooth region, Wyoming-Montana. Billings Geological Society Guidebook, 9th Ann. Field Conf., p. 36-43.

*o# Parsons, W.H., 1969. Criteria for the recognition of volcanic breccias: review: 263-304. in Igneous and Metamorphic Geology. Leonard Larsen, Ed Prinz and Manson, Co-eds. Geological Society of America Memoir 115.

*o# Perret, F.A., 1924. The Vesuvius eruption of 1906 - study of a volcanic cycle. Washington, Carnegie Institution of Washington: 151 pp.

Richard, J.J., 1962. Catalogue of the active volcanoes of the world including solfatara fields. Part XIII - Kermadec, Tonga and Samoa: 38 pp.

Richard, J.J. and Van Padang, N., 1957. Catalogue of the active volcanoes of the world including solfatara fields. Part IV - Africa and the Red Sea: 124 pp.

Rittman, A., 1962 (transl. by Vincent, E.A.). Volcanoes and their activity. John Wiley & Sons, New York: 305 pp.

Robinson, G.D., 1948. Exploring Aleutian Volcanoes. National Geographic Magazine 94: 509-28.

o# Robson, G.R. and Tomblin, J.F., 1966. Catalogue of the active volcanoes of the world including solfatara fields. Part XX - West Indies: 56 pp.

Scanlan, A.B., 1961. Egmont: The Story of a mountain. A.H. and A.W. Reed, Wellington. 200 pp.

*o# Schmincke, H-U., 1967. Graded lahars in the type sections of the Ellensburg Formation, south-central Washington. Journal of Sedimentary Petrology 37(2): 438-48.

* # Scrivenor, J.B., 1929. The mudstreams ("lahars") of Gunong Keloet in Java. The Geological Magazine, vol. 66 - Oct: 433-4.

Sharpe, C.F.S., 1938. Landslides and related phenomena. Columbia University Press, New York. 137 pp.

Sharp, R.P., and Nobles, L.H., 1953. Mudflow of 1941 at Wrightwood, southern California. Bulletin of the Geological Society of America 64: 547-60.

Stilwell, W.F., Hopkins, H.J., Appleton, W., 1954. Tangiwai Railway Disaster. Report of Board of Inquiry, Government Printer, Wellington, N.Z.: 31 pp.

*o# Taylor, G.A., 1958. The 1951 eruption of Mount Lamington, Papua. Australian Bureau of Mineral Resources - Geology and Geophysics Bulletin 38: 117 pp.

*o# Te Punga, M.T., 1952. The geology of the Rangitikei Valley. N.Z. Geological Survey Memoir 8: 46 pp.

o# Thorarinsson, S., 1957. The jökulhlaup from the Katla area in 1955 compared with other jökulhlaups in Iceland. Museum of Natural History - Department of Geology and Geography, Reykjavík. Miscellaneous Papers No. 18.

*o# Van Bemmelen, R.W., 1949. Geology of Indonesia, Vol.1. The Hague Government Printing Office.

o# Van Padang, M.N., 1951. Catalogue of the active volcanoes of the world including solfatara fields. Part I - Indonesia: 271 pp.

Van Padang, M.N., 1953. Catalogue of the active volcanoes of the world including solfatara fields. Part II - Philippine Islands and Cochin China: 49 pp.

o# Van Padang, M.N., 1960. Measures taken by the authorities of the vulcanological survey to safeguard the population from the consequences of volcanic outbursts. Bulletin Volcanologique 23: 181-92.

Varnes, D.J., 1958. Chaptr. 3 - Landslide types and processes in Ed. Eckel Landslides and engineering practice - Committee on Landslide investigations. Highway Research Board, Washington, D.C. Special Report 29.

* Verhoogen, J., 1937. Mount St. Helens - a Recent Cascade volcano. Bulletin of the Department of Geological Sciences, University of California 24(9): 263-302.

Vlodavetz, V.I. and Piip, B.I., 1959. Catalogue of the active volcanoes of the world including solfatara fields. Part VIII - Kamchatka and continental areas of Asia: 110 pp.

*o# Waldron, H.H., 1967. Debris flow and erosion control problems caused by the ash eruptions of Irazú Volcano, Costa Rica. U.S. Geological Survey Bulletin 1241 - I: 37 pp.

*o# Williams, H., 1932. Geology of the Lassen Volcanic National Park, California. University of California Publication from the Department of Geological Sciences Bulletin, 21(8): 195-385.

* # Williams, H., 1952. Volcanic history of the Meseta Central Occidental, Costa Rica. University of California Publications in Geological Sciences, 29(4): 145-80.

* Williams, H., 1953. Geology of Tahiti, Moorea, and Maiao. Bernice P. Bishop Museum Bulletin 105 - published by the Museum, Honolulu, Hawaii: 89 pp.

Wing Easton, N., and Kemmerling, G.L.L., 1923. The history and present state of scientific research in the Dutch East Indies - Volcanology. Internationale Circumpacifische Onderzoek Commissie, Koninklijke Akademie van Wetenschappen. J.H. de Bussy (Amsterdam).

o# Zen, M.T., and Hadikusumo, D., 1964. Preliminary report on the 1963 eruption of Mt. Agung in Bali (Indonesia). Bulletin Volcanologique 27: 269-99.

o# Zen, M.T., and Hadikusumo, D., 1965. The future danger of Mt. Kelut (Eastern Java - Indonesia). Bulletin Volcanologique 28: 275-82.

CHAPTER 5

LATE QUATERNARY LAHARS IN WESTERN TARANAKI

INTRODUCTION

The largest known concentrations of lahar mounds in the world are on the flanks of Mt. Egmont, New Zealand and Mts. Raung, Keloet, Galounggoung and Merapi, Indonesia. Numerous mounds to the west of Mt. Egmont were first described by Clarke (1912). They were considered to have formed as independent volcanic vents (Clarke 1912; Gibson and Morgan 1927); but later Bossard (1928) suggested they were blisters on lava flows and Grange (1931) showed they were remnants of a huge lahar flow. The present study investigated their age, whether all the hills constitute one deposit and the conditions of their formation. It was concerned only with the lahar deposits to the west and southwest of Mt. Egmont and does not include a few small lahars that travelled to the east and north-east.

GEOLOGICAL SETTING

Mt. Egmont is a composite volcanic cone of hornblende- and pyroxene-andesite, 2,478m high, situated about half way along the western coastline of the North Island of New Zealand. Lahar deposits crop out from near Mt. Egmont summit to the western coastline, a distance of 30 km (Fig.1). They form the western part of the Egmont ringplain (Hay 1967) which is bounded to the north by a thickly ash mantled ringplain graded to an older volcano - Pouakai. Beneath the surficial lahar deposits described here are older lahar deposits exposed in the coastal cliffs from Opunake south-eastwards to Manaia.

Various thicknesses of volcanic ash have accumulated on the upper surfaces of the surficial deposits, and with little erosion since deposition, much of the original topography is well preserved.

The many thousands of lahar mounds in western Taranaki (Fig.16) were first grouped into the "Opunake stage" by Grant-Taylor (1964), but later mapped as "Opunake Lahars" by Hay (1967) and referred to by Grant-Taylor and Kear (1970) as "Opunake Formation", but no definition or type locality is given. Here "Opunake Lahars" is used in the sense of a sub-group which allows it to be regarded as a subdivision of the Pouakai Group of Fleming (1953) and at the same time to be subdivided, as in this text, into various formations. It is not defined because as the various component formations become more widely used, the unit is likely to become redundant.

Within "Opunake Sub-group" are three widespread lahar formations which crop out between Okato and Awatuna, - the Opua, Warea and Pungarehu formations. The oldest and youngest, the Pungarehu and Opua, show most of the "conical hill" topography. In Waimate West County fluvial gravels and sandstones at least 20 m thick (described by Grant-Taylor and Kear as part of the "Opunake Formation") are considered possible lateral facies equivalents of the Pungarehu Formation.

Above 300m altitude on Mt. Egmont younger debris flow deposits grouped into the Kahui Formation and Maero Debris Flows, completely cover the Pungarehu and Warea formations. Most reflect Holocene collapses of the upper Egmont cone caused mainly by heavy rains. They are generally fan-shaped except where their flow has been controlled by river channels; they

FIGURE 16 - Oblique aerial photograph of western Taranaki lahar mounds (composed of Pungarehu Formation), looking towards the south-east. Lower slopes of Mt. Egmont visible on skyline at left.

FIGURE 17 - Section in road cutting at N118/487628 (1965), on Parihaka Road. Largest boulder is 2m across, preserved within the Warea Formation. Lower breccia is Pungarehu Formation. Details of section in Chapter 5 "Pungarehu Formation - Definition".

show weak graded bedding; each is generally less than 3 m thick except very close to source, and few exceed 10 km in length.

LITHOSTRATIGRAPHY

PUNGAREHU FORMATION (pf)

DEFINITION

The formation named after Pungarehu township, 32 km south-west of New Plymouth, comprises the principal surface rock type on the map NZMS 2,N118/2. South and east of this area the formation is often overlain by younger lahar deposits.

The type locality is the area within 0.5 km of Parihaka and Wiremu (Okahu) road junction, where several good exposures exist, the foremost of which is the Egmont County Council Quarry, N118/494627 (1965). Here a 30 m vertical cliff exposes breccia of the formation. About 0.5 km west of the junction, on Parihaka Road, are exceptionally well exposed contacts with the overlying formations (Fig. 17). As the Pungarehu Formation is the lowermost lahar unit exposed at ground surface in western Taranaki, the base is ill defined. The exposures in the type area show

115-120 cm Oakura Tephra
50 cm Warea Formation conglomerate
60 cm Okato Tephra
25 (max.) cm Saunders Ash
15 cm uppermost ash of Carrington Tephras
sharp, straight contact
1.5 m+ Pungarehu Formation breccia
Base not seen.

For mapping purposes the formation was defined as the laharic breccia and conglomerate beneath the Saunders Ash.

DISTRIBUTION

The Pungarehu Formation extends 16.5 km inland from Cape Egmont before it is overlain by younger debris flow deposits of Mt. Egmont. It is bounded to the north by the Pouakai ring-plain, the boundary closely following the channel of Stony River, whilst to the south (Appendix B2) it is progressively overlapped by the Warea and Opua formations. Many of the hills in the upper portion of the Opua Formation may represent modified mounds of the underlying Pungarehu Formation.

The formation is well exposed along 20 km of the western Taranaki coastline (Appendices B1 and B2). At the most northerly coastal exposure, between Stony River and Kaihihi Stream, it is thin and consists of large rounded andesite boulders surrounded by a friable yellowish brown, allophanic matrix of volcanic ash. Southwards along the coast the formation becomes a breccia-conglomerate and is clearly exposed at sea level in low cliffs as far south as Cape Egmont.

The westwards extent of the formation offshore is unknown, but a sediment chart (McDougall and Gibb 1970) shows a zone of boulders, pebbles and cobbles extending for 8 km west of Cape Egmont before sand and granules become the dominant sediment. This suggests the coarse sediments may represent the western extent of the formation prior to the Post-glacial rise in sea level. Detailed bathymetric maps south-west of Cape Egmont show the presence of conical hills on the sea bottom to a depth of 40 m.

South-east from Kaihihi Stream mouth the formation becomes buried by <400 year old river alluvium along Oxford and Saunders roads.

Its eastern boundary at the 300m contour is marked by irregularly clustered high hillocks which protrude between younger debris flow deposits extending from Oxford Road to Kahui Road (e.g. Raven Trig, N118/503656). Further south the formation is exposed only in deep road cuttings.

GEOMORPHOLOGY

The majority of lahar mounds in western Taranaki belong to the Pungarehu Formation. About 3,000 hills appear on NZMS1,N118; their average height is about 5 m near the coast ranging to 30 m near the 300m contour. The largest hill observed is multiple (Raven Trig, 312m altitude,), and close to the source area; it measures 500 m basal diameter and rises 50 m above the surrounding surfaces.

Previously described as "conical hills", few of the mounds approach a true conical shape and the great majority show a broad basal diameter in relation to height, somewhat like flattened hemispheres. Near the coast the mounds are separated by large areas of flat ground, here termed "inter-areas" but near the 100 m contour they become larger and are compounded (Fig.18) with few inter-areas. Along the entire length of the lahar deposit the great proportion of mounds are circular and discrete, but to the east the larger mounds form irregular clusters. At the north-eastern ends of Ngariki and Arawhata Roads, mounds are sometimes elongate and linear and are oriented radial to Egmont with apparent channels between but there are no drumlin-like or crescentic shaped mounds. Most show rounded summits, often marked by one or a number of large boulders, but a few show planar upper surfaces.

FIGURE 18 - Oblique aerial photograph of Pungarehu Formation mounds. Shadows extend eastwards towards Mt. Egmont, photograph taken at sunset.

Maximum basal diameters of lahar mounds in NZMS2,N118/2 were constructed from aerial mosaic photographs on a scale of 1:25,000 and plotted on a scale of 1:63,360 (Fig.19) and these have been contoured (Fig.20) to include areas not yet mapped at 1:25,000. Contours at 50 m intervals show a concentration of the largest hills in a west-east zone from Pungarehu inland to the 250 m contour. Mound heights were contoured on the single published 1:25,000 map NZMS2,N118/2 of the area and show similar shaped contours to the mound maximum basal diameter contour map indicating that although the heights of mounds are less than basal diameters there is a direct ratio between them.

Many hills have accordant summits which reflect the initial dip of a once continuous upper surface of the lahar, consistent with the present overall topographical contours. Planar summits of mounds along Puniho Road are remnants of this gently seaward dipping surface (Fig. 21). Structural contours which eliminate the effects of stream erosion on the surface, indicate that near upper Parihaka Road the gradient is 1 in 20 and gradually as the formation spreads in a fan-shape towards the coast it flattens to 1 in 66.

To show the change in density and size of Pungarehu Formation mounds from the coast inland, tracings were made from aerial mosaic photograph NZMS3,N118/2 (1:25,000) of a series of grid squares (see Appendix B4) between 350 and 500 eastings taken mostly between the 630-620 northings except where extensive bush cover obscured mound shapes, and the 620-610 northings were used. The squares approximate to 900 m square and thus cover 0.81 km^2. This west-east line corresponds to the longest axis of mounds. Traces of all mounds in the chosen squares were made and the maximum diameters measured. Analyses of the results are

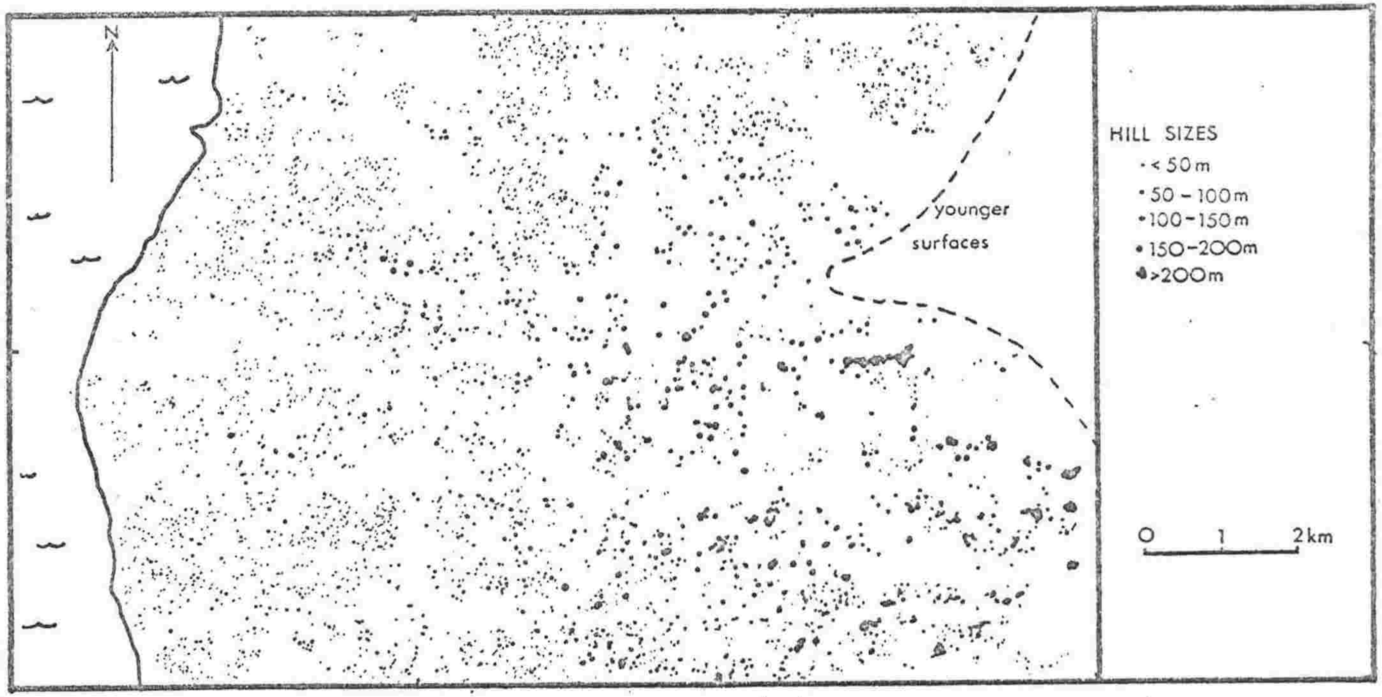


FIGURE 19 - Maximum basal diameters of Pungarehu Formation lahar mounds in NZMS2, N118/2.

FIGURE 21 - Planar summits of lahar mounds within the Pungarehu Formation, on Puniho Road, at N118/474698 (1965).

presented in Figs. 22 and 23. Bar histograms (Fig.22) show the predominance of mounds 10- 30m maximum diameter near the coast, but towards source there is a much wider range in these diameters with a lack of predominance of one mound size.

Plotted means of the maximum basal diameters (Fig. 23a) in all squares increase up to the 120 m contour but have no consistency beyond this altitude, although none of the latter values fall below those near the coast. Most mounds (Fig. 23b) lie below the 90 m contour because with increase in size of mounds there is a corresponding decrease in their number per unit area. By pointcounting 200 points to each square, an estimate was made of the percentage mound cover (Fig. 23c); the degree of confidence is least in squares 9, 10 and 11 due to bush cover. There is a step-like form to the graph which shows an increase from less than 10% cover at sea level near Cape Egmont to a little over 50% at the 240 m contour.

There are two areas where the original Pungarehu Formation surface has been modified either by burial and/or stripping by younger lahars.

(1) Mainly between Warea and Stony rivers, a flood of Warea Formation grit has filled much of the inter-area between Pungarehu mounds. This has resulted in a subdued landscape with many Pungarehu mounds protruding as gentle domes from a planar surface of more recent infill.

(2) South-east of Arawhata Road, cover beds on the formation have been partially stripped or buried by the Opua Formation. Protruding through the Opua Formation, between the 120 m and 250 m contours, are larger sized mounds with steeper margins which are characteristic of Pungarehu Formation mounds.

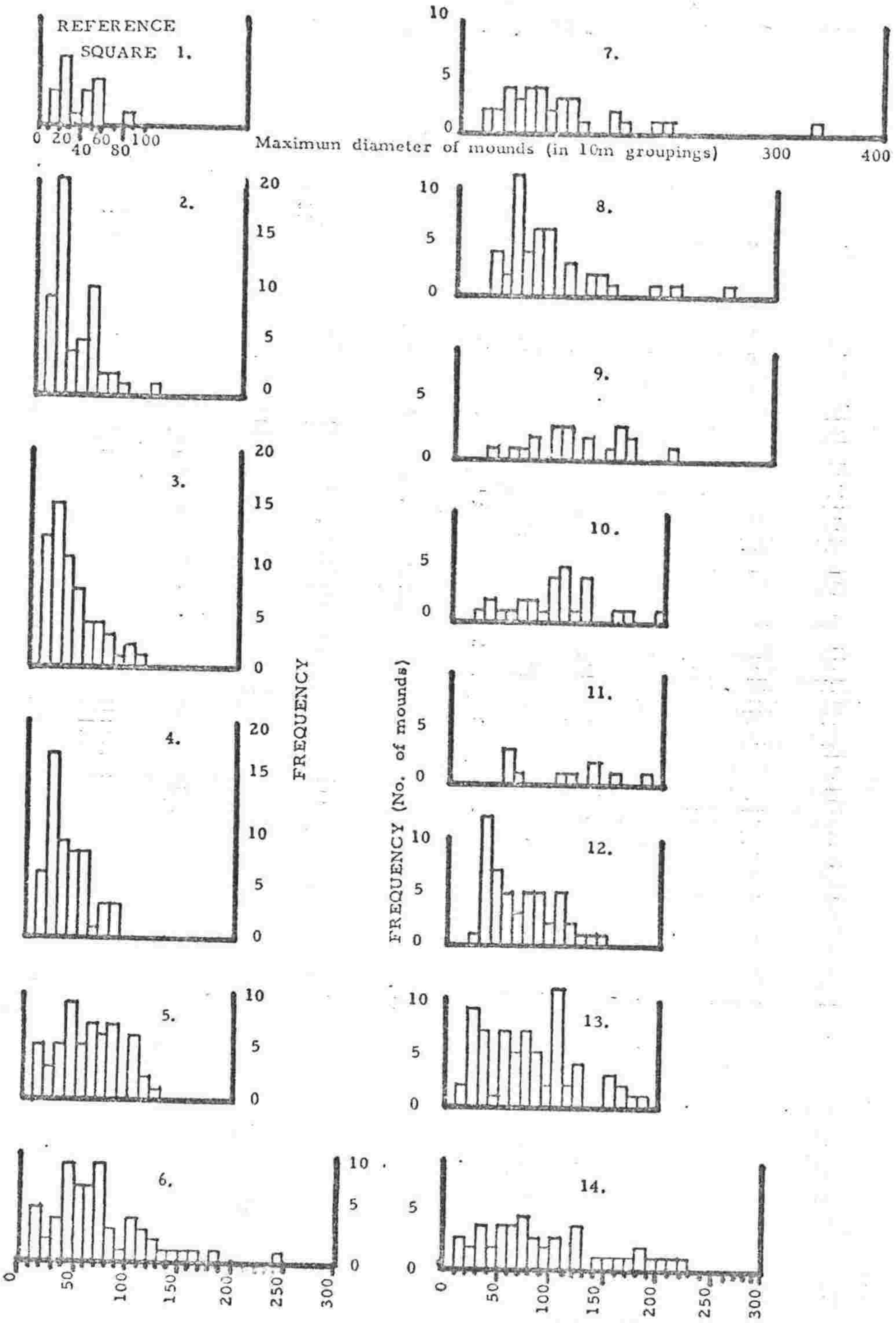


FIGURE 22 - Bar histograms of maximum basal diameters of Pungarehu Formation lahar mounds with distance from source. For full details of method see text. Reference squares 1-14 refer to transect line squares outlined in Appendix B4, each square is 0.81km^2 area. Square 1 is at the coast, square 14 is nearest the source area - Mt. Egmont. Note: maximum diameters are in 10 m groupings in each histogram.

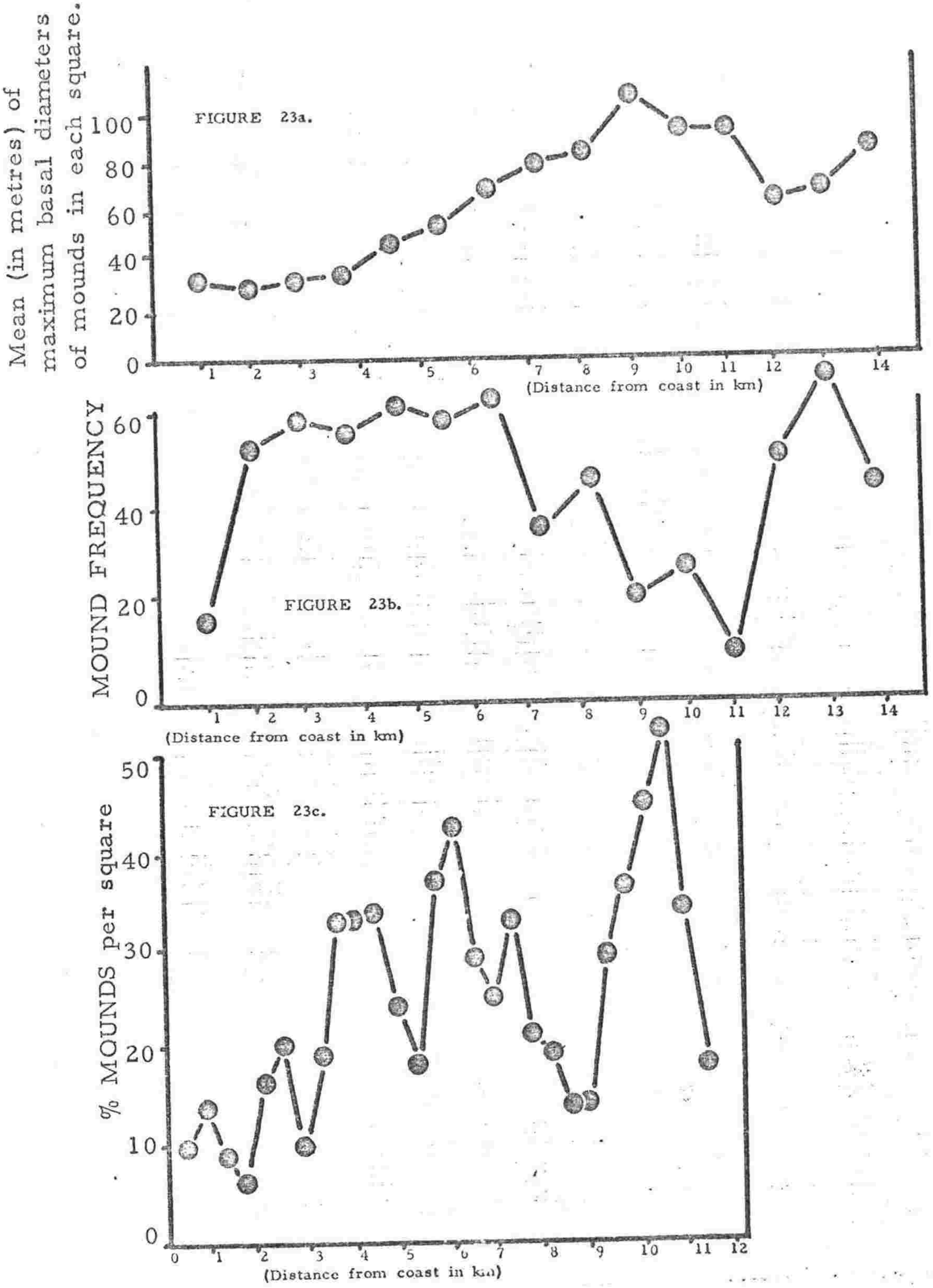


FIGURE 23 - a. Means of maximum diameters of mounds (in metres) in each reference square (1-14 in Fig. 22,

b. -frequency of mounds to each reference square,

c. - % mounds in 400m square units with distance from coast.

Note: For ease of counting % mound cover by dot grid methods, squares in Fig. 23c are 400m square, compared to squares in Fig. 22 and Fig. 23a & b which are 900m square.

DRAINAGE

The characteristic radial drainage from Mt. Egmont is superimposed on the Pungarehu Formation. Poor drainage from the main mound field at Pungarehu is shown by swampy sedge areas with accompanying iron stained soils. No streams are deeply incised into the formation and most have cut only 3 to 15 m deep, beneath thin cover beds, indicating average downcutting rates of between 0.12 m and 0.6 m per 1,000 years. Along the margins of the formation where younger lahars have been deposited upon Pungarehu mounds, there is evidence of more active downcutting and better drainage, probably due to the unconsolidated nature of the younger debris.

LITHOLOGY

Fragments

The deposit is typically unsorted and no bedding has been observed within it. Lithic fragments are very dark grey (5 YR 3/1), drying to light grey (2.5 YR N7/). They are frequently porphyritic pyroxene- and hornblende-andesites supported by the matrix, although the larger boulders up to 4 m across and averaging 2 m diameter, touch. Pumice is absent, although scoriaceous fragments with sulphur stained vesicles occur. A number of xenoliths found within the lithic fragments include with decreasing abundance, diorites, schists, thermally altered Tertiary sandstones and granodiorites.

Near to source at 300 m altitude, most fragments are highly shattered dense andesite and there is little or no clay matrix and a minimum of coarse sand particles between. Along Wiremu Road, between Parihaka and Arawhata roads, the andesite appears massive, although so broken that loose fragments can be prized from exposures with ease. The individual pieces all fit together, and appear to have been contiguous yet were broken in situ. The texture of this material approaches that of an autoclastic flow breccia suggesting that close to source it may have been a viscous brecciating flow. Such flows are known to accompany and have resulted in production of lahars (Fisher 1960, p.976). Away from source, as the % matrix increases the fragments grade from angular to subangular to even subrounded at the coast. Boulders mixed within unidentified ash on the northern fringe of the formation show good rounding.

An exceptionally large and puzzling inclusion within the formation was exposed during August 1971 at the road-metal quarry on Wiremu Road, 0.5 km north of the junction with Arawhata Road at N118/507548. The top of the inclusion is irregular consisting mostly of white friable quartz sand, exposed over $100m^2$. On light pressure the material broke to 90%+ subangular quartz crystals and a few angular glass shards. Towards the outside of the deposit, cream, orange and crimson streaks were present. The unconsolidated nature of the inclusion and the presence of glass and subangular quartz suggests that it was primarily associated with a volcanic source and not derived from Tertiary quartzites beneath the Egmont volcanics. The absence of altered margins precludes an in situ hot spring deposit.

From the appearance of the fresh glass it is possible that it represents the residual components of a Central North Island rhyolitic tephra previously concentrated in Egmont crater. However, no firm conclusions about its origin have been established.

Two very unusual lithic fragments were found which are considered important in ascertaining conditions within the lahar flow. The first just north of Pungarehu, on the east side of the road at N118/403646, has been severely contorted (Fig.24). The fragment is normal dark grey andesite, 1.5 m across, and each "limb" is split by many fractures.

The second fragment is exposed on Wiremu Road, a short distance north of Kina Road junction at N118/499562. Here a large block 4 m high and 1.5 m across, with base unexposed is highly fractured. The individual pieces are covered with purple red, and black coatings, mainly of manganese, sometimes occurring as 5 mm long lenticles which are oriented in circular patterns. Such unusual bright colours associated with alteration of the surrounding material indicate the boulder was hot when the lahar came to rest. Substantial quantities of a dull red material exposed at the Egmont County Council Quarry are similar to material at the above locality and were identified as cristobalite.

Matrix

The matrix consists of fine and coarse sand and clay. Towards the upper surface of most mounds there is often a yellow-brown cemented laminated layer up to 2 m thick, locally referred to as a "shell". Shells only mantle mounds, and are frequently absent from mound tops. They show a high percentage of clay which cements the boulders together forming a hard crust which is difficult to break, even with machinery. This is in marked contrast to the loosely compacted boulders beneath. Frequently the "shells" are brightly coloured (yellowish- to reddish-brown)

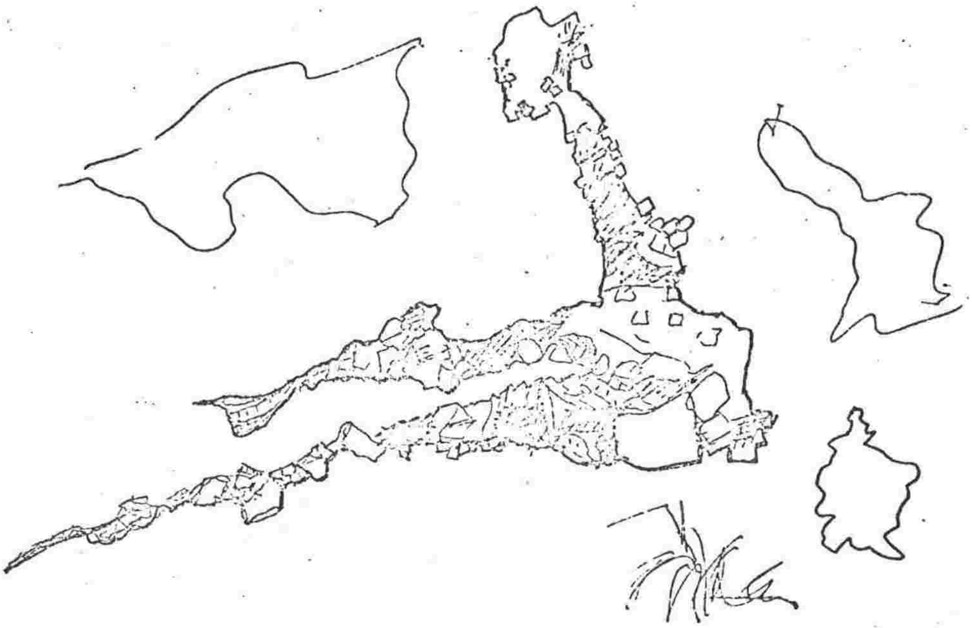


FIGURE 24 - Clast preserved within Pungarehu Formation on Highway 45, north of Pungarehu, at N118/403646. Fragment is 1.5m across and 1m high.

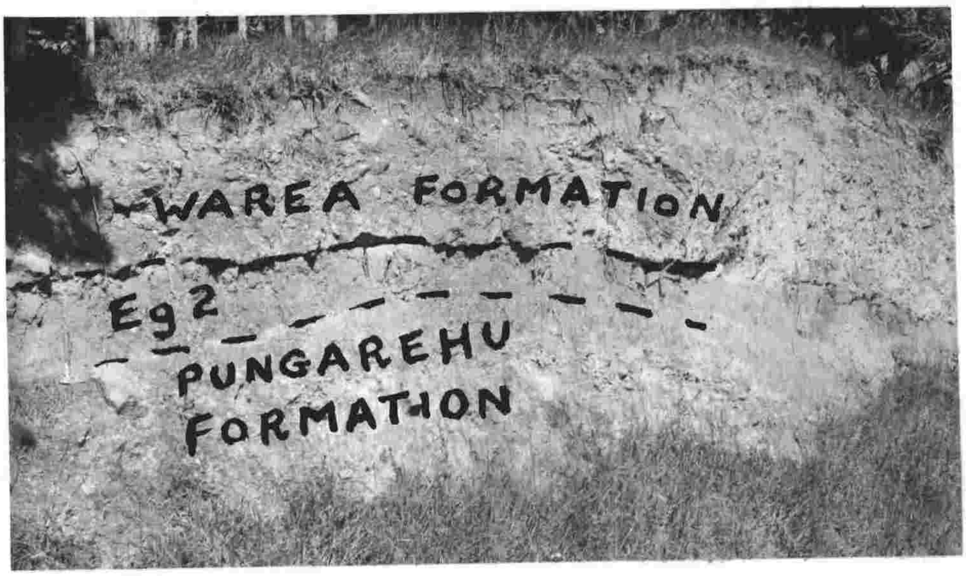


FIGURE 29 - Section on Wiremu Road, immediately south of Kina Road junction, at N118/501557. Section shows Warea Formation overlying Okato Tephra which overlies the Pungarehu Formation.

and show weak layering concordant with the present ground surface, suggesting they are post-depositional features.

The sandy matrix is generally loose and highly porous, but few large vesicles are present. Where cavities are exposed (about 5 cuttings have been found which show cavities greater than 15 cm across), they are always located in interstices between large boulders. Because the cavities occur in newly exposed road cuttings they are clearly not secondary leaching effects due to exposure, and were probably initially filled with air or water at the time of deposition. An infra-red analysis of a sample of matrix showed 34% andesine feldspar, 5-8% halloysitic clay and the remainder a mixture of pyroxene, magnetite and glassy mesostasis.

THICKNESS AND VOLUME

The height of the quarry face in the type area together with drillhole evidence supplied by the Egmont County Engineer indicates that the formation is at least 30 m thick at this point.

The base of the Pungarehu Formation has not been sighted, except where it is very thin along the northern margin, but the increase in relief with proximity to source suggests the formation is thickest near the type area.

Only one drillhole log is available in the entire region which gives an indication of the maximum thickness of the formation (Fig.25). The drillhole is from near Pungarehu in the axial part of the formation and indicates a maximum possible thickness of 60 m. On Hampton Road along the northern boundary it is 2 m thick overlying Carrington Tephras and the Koru lapilli.

FIGURE 25

Description of Hole 2 on K.M. Flemming's property, Pungarehu.

(Information received from Clancey and Associated Drillers Ltd., Waverley)

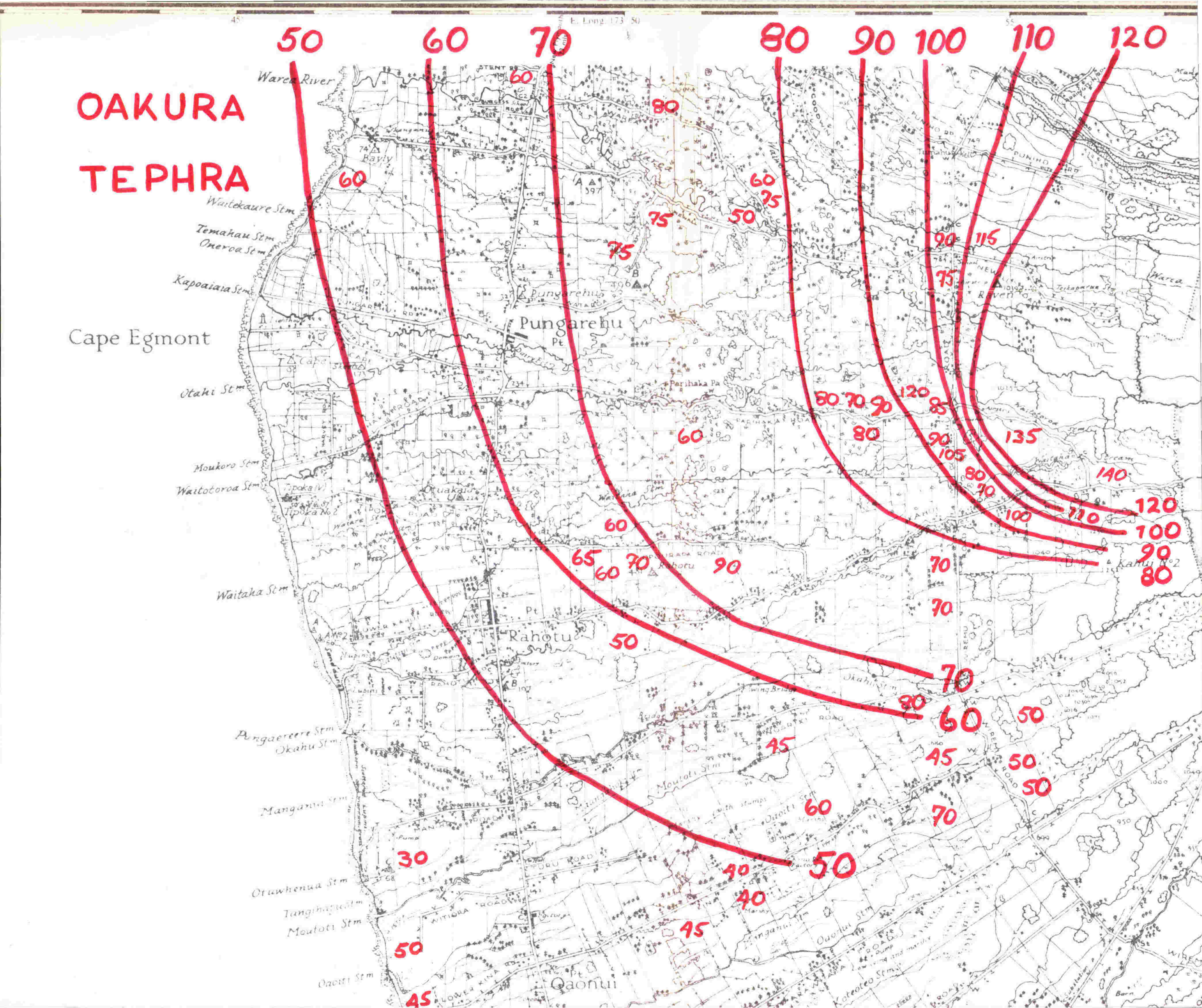
DEPTH (in metres)	DRILLER'S LOG	AUTHOR'S GEOLOGICAL INTERPRETATION	
0 - 1.8	Clay	Oakura & Okato Tephras	
1.8- 10.8	Stones and shingle		PUNGAREHU FORMATION
10.8- 11.4	Solid stone	large boulder	
11.4- 12.0	Stones and shingle		
12.0- 12.3	Solid stone	large boulder	
12.3- 16.5	Stones and shingle		
16.5- 21.0	Coarse dark grey sand with occasional stones		
21.0- 22.2	Stones		
22.2- 26.4	Coarse dark grey sand with occasional stones		
26.4- 32.4	Stones and shingle		
32.4- 33.0	Coarse dark grey sand with occasional stones		
33.0- 35.4	Stones, shingle and sand	? base of formation	
35.4- 39.3	Dark grey sand with odd stones	fluvial	
39.3- 54.0	Sand and stones	andesitic sands	
54.0- 59.4	Sand with odd stones		
59.4- 60.3	Sand dark grey		
60.3- 75.3	Papa	Tertiary mudstone	
75.3- 78.6	Very fine grey sand with shell and silica		

The formation covers 200 km^2 which could be extended a further 50 km^2 if the steep hills in the upper portion of the Opua Formation are interpreted as Pungarehu Formation mounds. If the formation is assumed to have an average thickness of 30 m, then the total volume is between 6km^3 (measured area) and 7.5 km^3 (interpreted extension beneath Opua Formation). These figures would be doubled if the formation is 60m average thickness.

AGE

No radiocarbon datable material has been collected from the formation so the age is best extrapolated from tephrochronology. Tephra control in the area is good (Neall 1972). Two principal ash formations, the Oakura and Okato tephras, mantle the formation indicating that the Pungarehu Formation is pre-Holocene. Isopach maps for these tephras are presented in Figs. 26 and 27, because of their importance in dating several lahars. In the vicinity of upper Parihaka Road, the Saunders Ash and the uppermost Carrington Tephra are preserved ontop the Pungarehu Formation. The Saunders Ash is of restricted distribution (Fig. 28) and along Carrington Road contains charcoal dated (NZ942) at 16,100 ± 220 yr B.P.

In a coastal section at Mangahume Stream mouth, N118/463416, to the south-east of Opunake, is a peat layer with wood fragments, exposed between the base of the Warea Formation and underlying gravels and sandstones, which may be lateral facies of the Pungarehu Formation. A wood sample of Dacrydium biforme from this locality has been radiocarbon dated (NZ1257) at 23,000 ± 300 yr B.P. If the gravels and sandstones are proven to be correlatives of the Pungarehu Formation, then a minimum age of


OAKURA
TEPHRA
50
60
70
80
90
100
110
120
Cape Egmont
Pungarehu
Rahotu
Oaonui
Warea River
Waitekaure Stm
Temahau Stm
Oneroa Stm
Kapoaiaia Stm
Otahi Stm
Moukoro Stm
Waitotoroa Stm
Waitaha Stm
Pungaereere Stm
Okahu Stm
Manganui Stm
Otuwhenua Stm
Tangihaere Stm
Moutoti Stm
Oaoiti Stm
Parihaka Pa
Kahui No 2
E. Long. 173 50
60
60
80
75
75
75
60
75
50
90
115
75
120
80
70
90
85
80
90
105
135
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45
50
45

FIGURE 26 - **Oakura Tephra isopach map.**

Isopach thicknesses in cm.

Base map is on a scale of 1:63,360 and comprises the north-western part of NZMS1,N118.

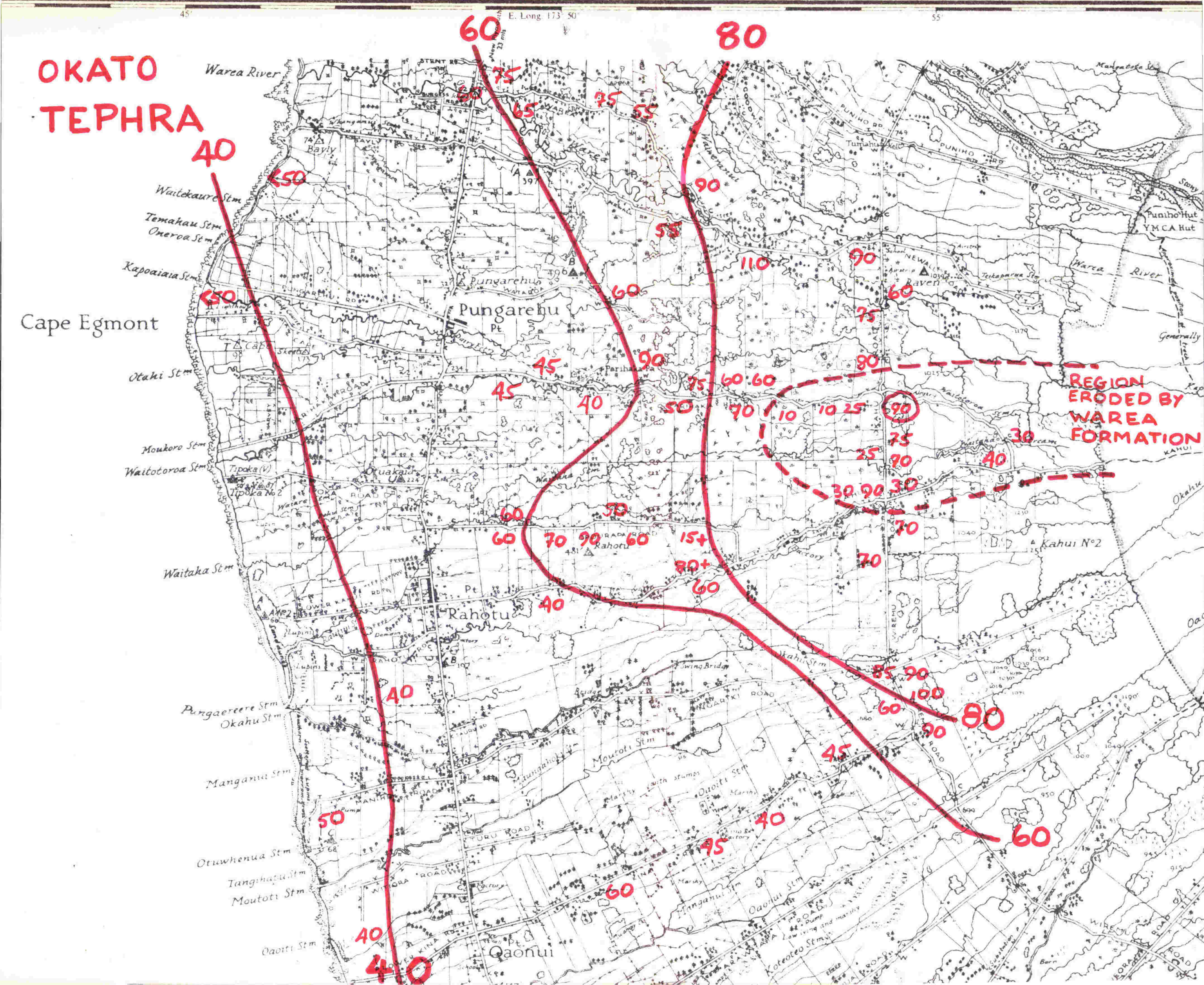
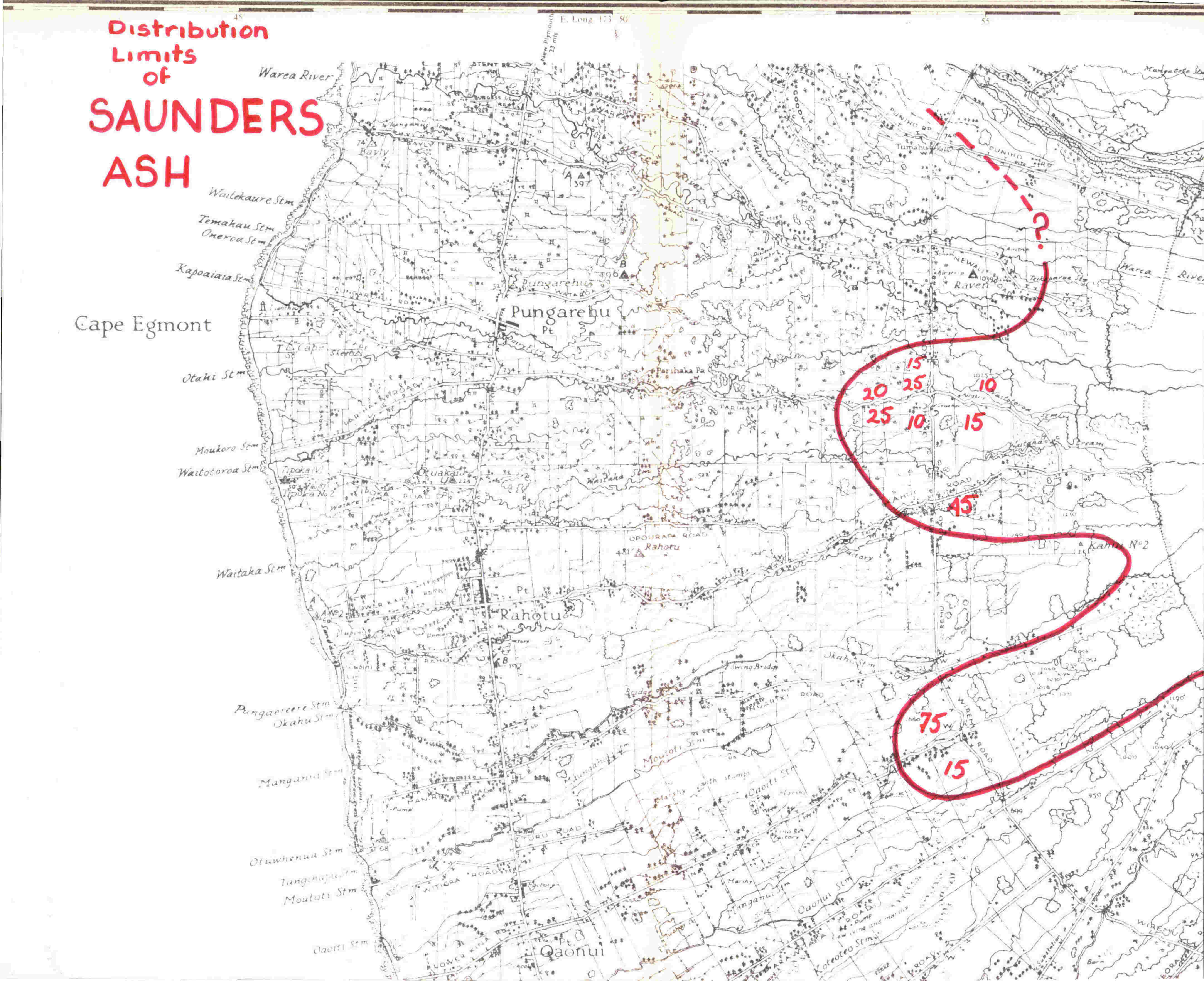

OKATO
TEPHRA
40
60
80
REGION
ERODED BY
WAREA
FORMATION
Cape Egmont
Pungarehu
Rahotu
Oaonui
Kahui No 2
Warea River
Waitekaure Stm
Temahau Stm
Oneroa Stm
Kapoaiaia Stm
Otahi Stm
Moukoro Stm
Waitotoroa Stm
Waitaha Stm
Pungaereere Stm
Okahu Stm
Manganui Stm
Otuwhenua Stm
Tangihapu Stm
Moutoti Stm
Oaoiti Stm
Puniho Hut
YMCA Hut
E. Long. 173° 50'
45'
55'

FIGURE 27 - Okato Tephra isopach map. Isopach thicknesses in cm.

Base map is on a scale of 1:63,360 and comprises the north-western part of NZMS1,N118.



Distribution Limits of SAUNDERS ASH

FIGURE 28 - Distribution limits of Saunders Ash. Thicknesses in cm.

Base map is on a scale of 1:63,360 and comprises the north-western part of NZMS1,N118.

the formation is established at 23,000 yr B.P. Dacrydium biforme no longer lives on Mt Egmont, and its lower altitudinal limit in the northern Tararuas today is 690 m (2,300 ft.), (Mr A.P. Druce, pers.com.), indicating that cooler conditions existed in Taranaki at the time of the peat formation.

ORIGIN OF THE PUNGAREHU FORMATION

The large volume of autogenous breccia in the lahar suggests it was derived from a pre-existing andesite cone by some free fall mechanism. The present Egmont cone consists of loose columnar jointed lava flows with deep seated bedding planes, in places resting upon unconsolidated gravels. A previous Egmont cone would probably be similar in structure. The well preserved source area of the Opua Formation (described in detail later) on the present cone gives an indication of the type of collapse which has occurred in the recent past, and similar collapses are likely to have occurred on a previous Egmont cone.

The directional nature of the Pungarehu deposit indicates collapse occurred to the seaward side of a previous cone and little slippage took place in the east. The confined distribution of the formation towards source indicates a narrow zone from which the lahar flow (s?) emanated and below the 250 m contour it (they?) rapidly spread outwards in a fan shape. Certain features within it (described under "Fragments") indicate parts of it were warm when deposited, implying that the collapse may have been initiated by an eruption, but no distinctive or widespread airfall deposits were erupted at this time to indicate a catastrophic eruption. The absence of pumice fragments and fresh glass shards in the lahar preclude a nuée ardente type of eruption and there is no evidence of widespread dyke intrusion, a mechanism which is thought to have initiated lahars of the Tuscan Formation (Lydon 1968).

The massive character of the formation and an absence of bedding, buried soils or fossil wood indicates the bulk of the formation was deposited as a single event or as a number of closely spaced lahars. Between Opunake and Manaia, gravel and sandstone units are exposed which are possible correlatives of the Pungarehu Formation. Each unit is well sorted, graded, and has been deposited with little erosion of the previous unit. Absence of tephra layers and soil development between the units indicate they accumulated fairly rapidly. There is insufficient evidence at present to link the succession of events in this area to the deposition of the Pungarehu Formation, but if correlation were established then a succession of lahar flows can be recognised which deposited the formation in a pulse-like fashion. Because the Opunake area was located on the southern margin of the main Pungarehu lahar flow, the better sorted and graded units may indicate lahars at this distance were becoming increasingly water dominated and began to grade into a river-type flow.

The unusually shaped block of andesite (Fig. 24), north of Pungarehu, could not have been deformed in situ and must therefore have been deformed nearer source where it became enveloped in clay so that the flanges of the boulder were protected from abrasion. This boulder together with the large block of friable quartz sand indicates the "dispersed phase" was not thoroughly mixed with the "continuous phase" (of Fisher 1971).

Outcrops nearest to source (along Wiremu Road) show highly shattered andesite clasts (averaging 10-20mm) contiguous for many metres. Their identical lithologies suggest they were originally a single large lava block. The original fragments could not have been transported far from source because of their immense size and may have been produced during the volcanic explosions which initiated the lahar.

Alternatively the lava could have been extruded prior to the lahar and was shattered in situ or was dragged a short distance along the base of the flow.

SOURCE AREA

The eastern boundary of the Pungarehu Formation follows a broad V-shape with the apex near the eastern end of Kahui Road. This limits the source area to due east of this point and from projections of Pungarehu Formation surface contours eastwards, the source area may have been slightly west of the present Mt. Egmont summit.

A rough estimate can be made of the size of andesite cone above the 300m contour required to produce a lahar with this volume, assuming that the cone had an average slop of 27°, where r the radius = 2h (h = height), then the volume is calculated by the formula ($V = {}^{1}/3r^{2}h$). If the formation is 30m average thickness, then the cone would have been 1,950m (6,500 ft.) above sea level from the measured extent of the formation, or 2,080m(6,930 ft.) high allowing for the interpreted distribution. Assuming the formation to be 60 m average thickness indicates a cone 2,380m(7,930 ft.) high, or 2,540m(8,470 ft.) high from its interpreted distribution. The last figure is a likely estimate of the size of a source cone because it is unlikely that all the cone collapsed in the one direction to constitute the lahar.

The calculation of $6 km^3$ minimum volume for the formation allows a comparison to be made with historic eruptions which involved large scale collapse. The volume of the directed blast deposits from the 1964 eruption of Shiveluch volcano totalled $1.5\ km^3$ (Gorshkov and Dubik 1970) and for the 1955 Bezymianny eruption $1.8\ km^3$. The release of energy in the Bezymianny eruption (Gorshkov 1959) would probably constitute a similar threshold value required to initiate large scale collapse of a previous Egmont cone.

WAREA FORMATION (wf)

DEFINITION

The formation is named after the settlement of Warea, 29 km south-west of New Plymouth. The type locality is designated in the road cutting immediately south of Warea (N108/412703), and is bounded to the west by a hill (Trig P), altitude 77.7 m, with an old Maori pa site on top. It shows a section almost tangential to the hill which is composed of Pungarehu Formation breccia with wedges of Warea Formation that lap onto both sides. In section, 60 cm Oakura Tephra overly the Warea Formation, which is principally of cobblestone lithology, in places passing to a grit. It fills depressions between Trig P and other surrounding hills and at the north and south ends of the cutting is 2 m thick. It rests on 60 - 90 cm Okato Tephra

on 2m+ Pungarehu Formation breccia to base.

Because the formation shows a wide lateral facies variation, a second (or reference) locality is designated in the road cutting 0.5 km west of the junction between Parihaka and Wiremu Roads (N118/487628), in the type area of the Pungarehu Formation (Fig.17). Here the Warea Formation is a conglomerate with a large 2 m rounded andesite boulder preserved within the deposit.

The formation is distinctive as the principal deposit between the Oakura and Okato tephras. Upper and lower contacts are sharp and well defined. Inland from Wiremu Road, a sequence of debris flow deposits bury the Warea Formation but not the overlying Oakura Tephra.

DISTRIBUTION

The Warea Formation has an unusual distribution (Appendices B1, B2 and B3), consisting of 3 principal lobes here named the north-western, western and southern lobes. Whereas most of the other western Taranaki flows resulted in thick fan-shaped deposits of a single lithology, the Warea Formation is of varying thickness, trilobate and ranges from grit to cobblestone and breccia. The north-western lobe extends from the mouth of the Kaihihi Stream along the coast to Warea River and extends inland to near the junction of Puniho and Wiremu roads. The lobe is roughly triangular, the apex having been overlain by later debris flows. It is composed almost entirely of cobblestones and grit lithologies and rarely contains large enough fragments to be termed breccia or conglomerate.

The western lobe extends from south of Cape Egmont, inland to Kahui No.2 Trig, about 11.5 km east of Rahotu. It is split at the eastern end of Kahui Road into northern, central and southern portions. The northern portion extends along Waitotoroa Stream to near Parihaka Pa. The central portion extends down Waitaha Stream from the 360m to 120m contours and then swings south-westwards across Opourapa Road to Rahotu. At Rahotu it spreads laterally to join the appreciably thicker southern portion which extends from Okahu Stream south to Koteoteo Stream. On Wiremu Road, near Kina Road junction (N118/501557), the formation is 2 m thick (Fig. 29). The southern boundary of the western lobe is overlain by the Opua Formation but in the coastal cliffs to the south the formation is seen to thicken. A U-shaped residual "high" area preserved along Arawhata Road from Highway 45 to the coast represents the main axis of the formation. The "high" is now bordered on both sides by channels along which the Opua lahar flowed.

The southern lobe does not extend to the coast and near the 200m contour bifurcates. Above the bifurcation, the formation is 1.5 km wide and extends between the Punehu and Ouri streams but below the 350 m contour it widens and along Eltham Road is 5 km wide. Below the 200 m contour the formation is thin and terminates in two lobes, one along Oeo Stream down to the 120m contour, the other down Otakeho Stream to the 200m contour.

GEOMORPHOLOGY

In the north-western lobe Warea grits and cobblestones have filled depressions between pre-existing Pungarehu Formation mounds. On aerial photographs the surface is diagnostic, consisting of large flat inter-areas totalling 90-95% surface area with scattered small mounds. The Warea Formation averages 4m thick in this lobe so that many small Pungarehu mounds and their inter-areas have been buried. The formation is in excess of 5m thick at Werekino Stream, and thins to barely cover a Pungarehu mound near Puniho Road, 500m away along Highway 45 (Fig.30).

Along the northern part of the western lobe the formation averages 1-2m and has not modified the physiography. The southern part is thicker and at the Arawhata Road coastal sections totals 5-6m and has buried earlier surfaces.

The southern lobe shows mounds <5m high, between the 450m and 250m contours. They are best exposed near the intersection of Opunake and Oeo roads and gradually become smaller south-westwards along the axis of the western bifurcation. They are absent below the junction of Eltham and Oeo roads where the deposit is thinly spread as a uniform layer about 2m thick.

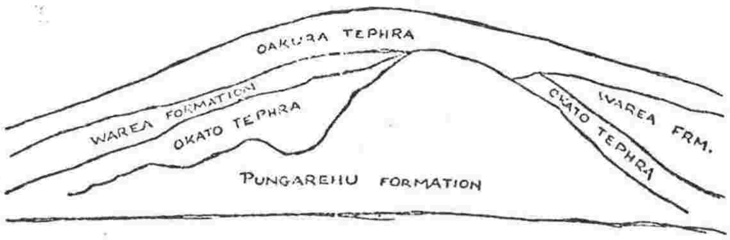
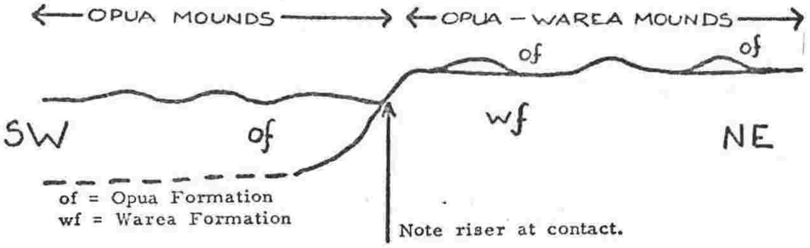


FIGURE 30 - Cross-section of exposure on Main South Road (Highway 45), north of Puniho Road junction, N108/423743. Exposure is 50m long and 4m high.



of = Opua Formation
wf = Warea Formation

Note riser at contact.

FIGURE 32 - Diagrammatic cross-section of Opua Formation mounds and older surface of Opua-Warea"formation" mounds exposed on Waiteika Road, N118/544477. SW=south-west: NE=north-east.

Good exposures of this deposit occur on Eltham Road, immediately east of Awatuna.

Warea Formation deposits are not extensive and thick enough for streams to be confined to them and show no diagnostic features in the present drainage pattern.

LITHOLOGY

The north-western lobe is composed almost entirely of cobblestone and grit showing weak bedding indicative of fluvial origin. At Warea, the cobblestone consists of dark grey (5Y 4/1), black (7.5YR N2) and very dusky red (10R 2/2) andesite fragments which average 3-4cm, set in a dark grey (5Y 4/1) sandy matrix. The material is all lithic andesite and no glassy fragments or vesicles have been noted. The deposit is well lithified and forms an extensive "pan" beneath the topsoil, although the Pungarehu Formation is a higher grade of lithification. Between Stony River and Puniho Road, where the deposit is well exposed, a section at Werekino Stream shows exceptionally good sorting.

The northern portion of the western lobe is considerably coarser and contains well rounded bounders up to 2m across within relatively thin conglomerates averaging 1-2m thick. In the southern portion the fragments become increasingly angular, indicating proximity to the axis of main flow.

At Arawhata Road, the breccia fragments are subangular, average 15 cm across but range up to 80 cm. Most are grey in colour with orange, red and white staining. The sandy clay matrix is dark greyish brown to very dark greyish brown (2.5YR 4/2-3/2) but towards the top becomes increasingly "ashy" (i.e.

containing redeposited tephra) brightening to yellowish-brown (10YR 5/6) colours. Very subtle weak bedding is distinguishable in the matrix as 5mm thick bands which tend to be etched in weathered faces. The formation is less consolidated here compared to most other localities and in contrast to the very well lithified underlying Pungarehu Formation, enabling the otherwise very similar deposits to be separated. Because of the lack of consolidation here, the coastal cliffs formed of the formation are very susceptible to marine erosion and collapses of the cliff face are often evident after stormy seas. Three wood fragments up to 30cm length were also found at this locality, and are the only fragments yet found within the three extensive western Taranaki lahar deposits. Another rare component here is a large boulder 3.5m long, of well laminated fluvial sandstone beds, which dips 45° towards the coast. A second similar boulder is exposed in Heimama Stream, about 100m upstream from the coast. The latter is 10m length and 4m height and represents the largest boulder found in this lahar study, although it was probably not transported far. It is rafted within the lahar deposit and exhibits sandstone beds which have been deformed into an S-shape indicating the boulder was dragged and deformed along the base of the flow.

The southern lobe of the formation contains principally angular grey andesite fragments and is identical to the Pungarehu Formation lithology. Towards its margins the deposit shows a large increase of yellowish brown ash in the matrix particularly about 200m west of Mangawhero-Opunake road junction, and east of Awatuna the deposit is an "ashy" conglomerate showing a ratio of 2:1 matrix to boulders.

THICKNESS AND VOLUME

The isopachs for the Warea Formation (Fig. 31) can be plotted where the deposit is thin, but towards the axial portions the base is unexposed except on the coast, and isopachs are not interpolated. After the deposition of the Pungarehu Formation, the western Taranaki landscape between Warea and Rahotu comprised a "high" area (see Appendix B2). The Warea lahars were strongly topographically controlled so that as they flowed from Egmont they were channelled around the "high" to the north- and south-west.

The northern and central portions of the western lobe are thin and were channelled along valleys bounded by high Pungarehu surfaces. The southern portion of the lobe was deflected to the south of the Pungarehu "high" and south of Kina Road the resultant deposit is thickest with its base below sea level at the coast. South of Arawhata Road the base reappears above sea level as the formation thins towards Mangahume Stream mouth, and at Pihama it is absent. The base of the southern lobe is not exposed in its axial portion but along its margins the deposit averages 2-3m thick. It seems likely that the western and southern lobes are joined between Awatuna and Opunake, but because of insufficient deep exposures and the younger Opua Formation cover, the distribution here is obscure.

The north-west lobe attains a maximum thickness of about 5m and totals about 0.25 km^3. Assuming an average formational thickness of 5m from Rahotu to Awatuna, the total volume of the western and southern lobes is about 1 km^3.

AGE

The age of wood collected from within the formation has not been determined at the time of writing. The formation is underlain by the Okato Tephra which is known to have been erupted between 7 and 16,000 years ago and is most likely between 12 and 16,000 yr B.P. (Neall 1972). The Oakura Tephra dated at <7,000 yr B.P. overlies the formation. An age of about 12-14,000 yr B.P. is likely for the Warea Formation.

SOURCE AREA

The isopach map of the formation shows an origin from Mt. Egmont and not from Fanthams Peak. The deposit thins and laps onto slopes that grade to Fanthams Peak and tends to be channelled away from them. Whether the lahar was derived from the present Mt. Egmont upper cone or a prior cone is difficult to interpret and two alternative hypotheses can be considered.

(1) If the main axis of thickening of the deposit is projected towards Mt. Egmont, it strikes the upper cone in the West Ridge-Oaonui Stream region where the contours show no likely source area. The West Ridge and Oaonui Stream lava flows and associated surfaces represent some of the oldest surfaces on Mt. Egmont. Thus, if the lahar was derived from this region, it must have occurred prior to the extrusion of the West Ridge and Oaonui Stream lava flows. Mt. Egmont's upper cone is generally regarded as having been constructed in Holocene times because of the lack of glaciated features, youthfulness of the cone and a K/Ar date of 21,000 ± 3,000 yrs B.P. obtained from lava flows at Dawson Falls (J.J. Stipp, pers.com.). Thus this

hypothesis infers the extrusion of the above lava flows about 12,000 yr B.P., following the Warea lahar flow.

(2) Alternatively, the main deposit may have been initiated from the Bobs Bluff-Fanthams Peak "amphitheatre". If this is correct the main flow of the lahar changed direction from towards Te Kiri to an area north of Opunake. The presence of the other lobes to the west and north-west requires smaller associated collapses elsewhere on the cone.

In both hypotheses a surplus of water was required for the north-west lobe. Volume calculations of the Bobs Bluff-Fanthams Peak "amphitheatre" show the Opua lahar deposit which grades to it is of a similar volume, indicating that the Warea Formation could not also have been derived from it. The first hypothesis is simpler and involves a lahar derived from a single source area which split and became strongly topographically controlled in contrast to the second hypothesis where at least 2 lahars originate from Egmont above an altitude of about 120m, and which substantially alter direction from a straight radial course. The first hypothesis is thus considered more likely.

NATURE OF FLOWS

The main axis of the isopachs lies in a SW-NE direction, intersecting the coastline between Arawhata and Heimama streams. In this region, the base of the deposit is slightly below sea level, and occupies a former valley that extended in width from a point 2km south of Rahotu to Opunake. The coincidence of the axis of maximum thickness with a breccia lithology suggests the deposit represents a gravity controlled lahar channelled by pre-existing relief.

Some laharic material also flowed south to Awatuna, but the failure of this flow to reach the coastline indicates it was marginal to the main flow.

Where the formation is thin the Okato Tephra is frequently preserved beneath, indicating little erosion at the flow's base. Even where the axis of thickening strikes the coast at Arawhata Stream and also at the Taungatara Stream north, cliff exposures show a thin tephra layer preserved beneath. Above the 200m contour however Okato Tephra isopachs thin, probably reflecting erosion by the overlying lahar on the steeper slopes near source. The tephra however has been completely removed along Wiremu Road between Arawhata and Oeo roads. The "fluvial-like" cobblestones and grits to the north-west suggest a large proportion of water compared to debris was channelled to the north of the Pungarehu "high", and was deposited as a large flood. Other evidence of surplus water is in the western lobe near to source, where the formation is 1m thick, yet is spread over some of the highest Pungarehu mounds. Between the top of the Pungarehu "high", at the Egmont County Council Quarry face and a "low" to the north of Okahu-Parihaka road junction, there is a height threshold of 22.5m. This suggests a flow with a water surplus, at least 25m deep was required to deposit the material over such diverse topography. Further south along Wiremu Road, there is a similar height difference.

In contrast to this, the southern lobe did not contain an excess of water compared to debris, and much of the flow came to rest north of Awatuna. There is no evidence here of finer sands and silts being transported by excess water beyond the distal margin of the coarser debris.

Because the deposit contains uncharred wood, the flow is presumed to have been cold. The two most likely sources of surplus water are considered to be:

(a) from heavy rains, or

(b) by collapse of a water storage reservoir (crater lake or underground water saturated horizons) by a non-eruptive mechanism.

OPUA FORMATION (of)

DEFINITION

The Opua Formation is here named after Opua Road which joins Highway 45 to Wiremu Road, i.e. between points N118/424465 and N118/519529. The type locality is at Opunake (northern) beach N118/445433 where a section has been exposed by a road that descends the cliffs to fishermens' boatsheds. In the upper part there is exposed beneath present day topsoil

4 m Opua Formation with no overlying tephra cover, sharp contact
50 cm Oakura Tephra, sharp, straight contact
35 cm Warea Formation sandstone, sharp contact
30 cm Okato Ash, sharp contact
4 m ?Pungarehu Formation, fluvial gravels and sandstones, sharp, straight contact
5 cm putty coloured ash
further gravels and sandstones to base.

A reference locality is also described at Mangahume Stream mouth, N118/463415, which can be reached by a private road off Highway 45. The private road branches near the coast and the section is best observed where the northern branch descends the cliffs to a bay, north of Mangahume Stream. Here exposed in the upper part is

5 m volcanic breccia-conglomerate
80 cm ash with stones

both comprise the Opua Formation, the latter representing the "ashy" base of the deposit.

70 cm Oakura Tephra

2 m laminated grits of Warea Formation (which thicken to 4m on the headland to the south and where the lithology becomes a volcanic conglomerate)

45 cm Okato Tephra

45 cm peat

2 m cobblestone.

Wood collected from the base of the peat has been dated (NZ 1257) at 23,000 ± 300 years B.P. (see Pungarehu Formation "Age").

The Opua Formation is a laharic breccia/conglomerate which forms the present ground surface in Opunake and Te Kiri districts. There is no tephra cover on this area. The lower contact of the formation is sharp and diagnostic in the coastal cliffs and is underlain by the Oakura Tephra. Good exposures occur on Highway 45 between Waiaua River and Eltham Road (N118/463427), immediately north of Otahi Stream (N118/442442), and immediately north of Heimama Stream (N118/433449).

DISTRIBUTION

The Opua Formation is of a broad delta-like form (see Appendices B2 and B3). Near source, in the dense bush country of Egmont National Park, the extent of the formation is obscure. At the 750 m contour, the formation is 4 km wide extending from Waiaua River to Punehu Stream. At the 400 m contour it attains 9 km width and then spreads outwards to intersect the present coastline over a distance of 22 km. For about 6 km inland from the present coastline the flow was channelled along previous river valleys and between three slightly elevated "highs". The "highs" are triangular in plan; one occurs near the northern boundary and two near the southern boundary (see Appendices B2 and B3). The northern "high" extends along Arawhata Road, as far inland as Arawhata Trig, 91.2 m altitude (N118/455502). The two southern "highs" are centred on Pihama; the first extends inland from Trig E No.2, 46.2 m altitude (N128/507364) to a point N128/535400, near the intersection of Patiki and Skeet roads; the second extends from a point N128/530347, midway between Ouri and Oeo streams, inland along Nopera Road to a point N128/547388. Thus in this region the formation is digitate and restricted to the narrow Ouri and Oeo stream channels.

GEOMORPHOLOGY

The wide range in size of the Opua Formation mounds, together with geomorphological relationships of surfaces indicate mounds are of primary and secondary origins. This relationship has not been proven by tephra correlation because of paucity of deep sections and absence of recent eruptives in this region. In the Opunake area the mounds undoubtedly originated during deposition of the formation; they are discrete and are frequently small in diameter and height. However inland, elongate areas of larger mounds extend radially towards the coast as "interfluves", separated by areas of smaller mounds along existing river channels. The larger mounds appear to be older and to have been completely stripped of their overlying tephra with younger Opua material partially covering them and completely filling valleys between the "interfluves".

On Feaver Road, a road cutting at right angles to the direction of flow, shows younger Opua breccia comprising the upper part and older breccia the lower part of the mound. This mound exposure proves a multiple origin. Between Kaweora and

Waiteika roads, at the 300m contour, 30m high mounds emerge above the pre-Opua lahar deposit, and represent an earlier lahar deposit. Two older lahar surfaces, both of which have been overrun and now protrude from beneath the Opua Formation, are likely correlatives of the Pungarehu and Warea formations. They are accordingly named Opua-Pungarehu (of-pf) and Opua-Warea (of-wf) mounds. The largest Opua-Pungarehu mound is Clement Trig (N118/546497), altitude 230m. It is 200 m in diameter and is the most seaward of the only line of Opua-Pungarehu mounds observed. Opua-Warea mounds are in contrast abundant, particularly above the 100m contour (Appendix B2). The largest is about 80m basal diameter. Along Waiteika Road, near N118/554477, is a riser which is considered to most clearly represent the boundary of the Opua and Opua-Warea surfaces (Fig. 32). Because of the difficulty in separating Opua and Opua-Warea mounds, both types are considered to belong to the Opua Formation in this study.

Most Opua mounds are circular in outline although a few show slight elongation in the direction of flow. Most are irregularly distributed but one distinct line of mounds extends for over 1 km along Waitekia Road, between Eltham and Wiremu Roads. There is no gradation in size between them and they are nearly all connected by low shoulders.

A series of grid squares was chosen radially along a zone of Opua and Opua-Warea mounds to compare their relative size and abundance with Pungarehu mounds.

Tracings were made from N.Z. Lands and Survey aerial mosaic photographs NZMS 3, N118/8 and /9. The method of reference square counting as explained for the Pungarehu mounds was adopted except that because the mounds cross the photograph diagonally in a NE/SW direction, the reference squares were chosen in a diagonal pattern. The series of squares extends from the coastline (between 400 and 410 northings and 470 to 480 eastings), inland to the reference square bounded by the 470 and 480 northings and 540 to 550 eastings. The bar histograms (Fig. 33) show the predominance of 10-20m diameter mounds at the coast but between 4 and 6 km inland, 20 to 30 m diameter mounds are most frequent. Between 6 and 10 km the 10-20m mounds again predominate and in the last reference square 20-30m mounds again form the mode. Plotted means of maximum diameters (Fig.34a) in each of the squares and maximum diameter contours (Fig.20) show a gradual increase inland with a sharp increase near source but nowhere do they approach the size of the largest Pungarehu mounds. Towards the distal margin mounds are smaller and fewer in number than further inland. Between the 80 and 110m contours there is a sharp increase in mound frequency (Fig. 34b), from 70 to over 280 mounds per 0.81 km^2 area. As with the Pungarehu Formation mounds an estimate of the percentage cover of mounds to each square was determined by pointcounting (Fig. 34c). Although the pattern is somewhat cyclic there is a distinct increase in cover from 0 to between 20-30% mounds. This is considerably less than that determined for the Pungarehu mounds which are larger in size and cover a relatively greater area.

As the Opua Formation forms present ground surface in the Opunake-Te Kiri region, the gradient of ground surface represents the gradient over which the lahar flowed. At the 900m contour the gradient is 1 in 6, but this quickly grades to about 1 in 25 near the 350 m contour and to 1 in 77 near the coast.

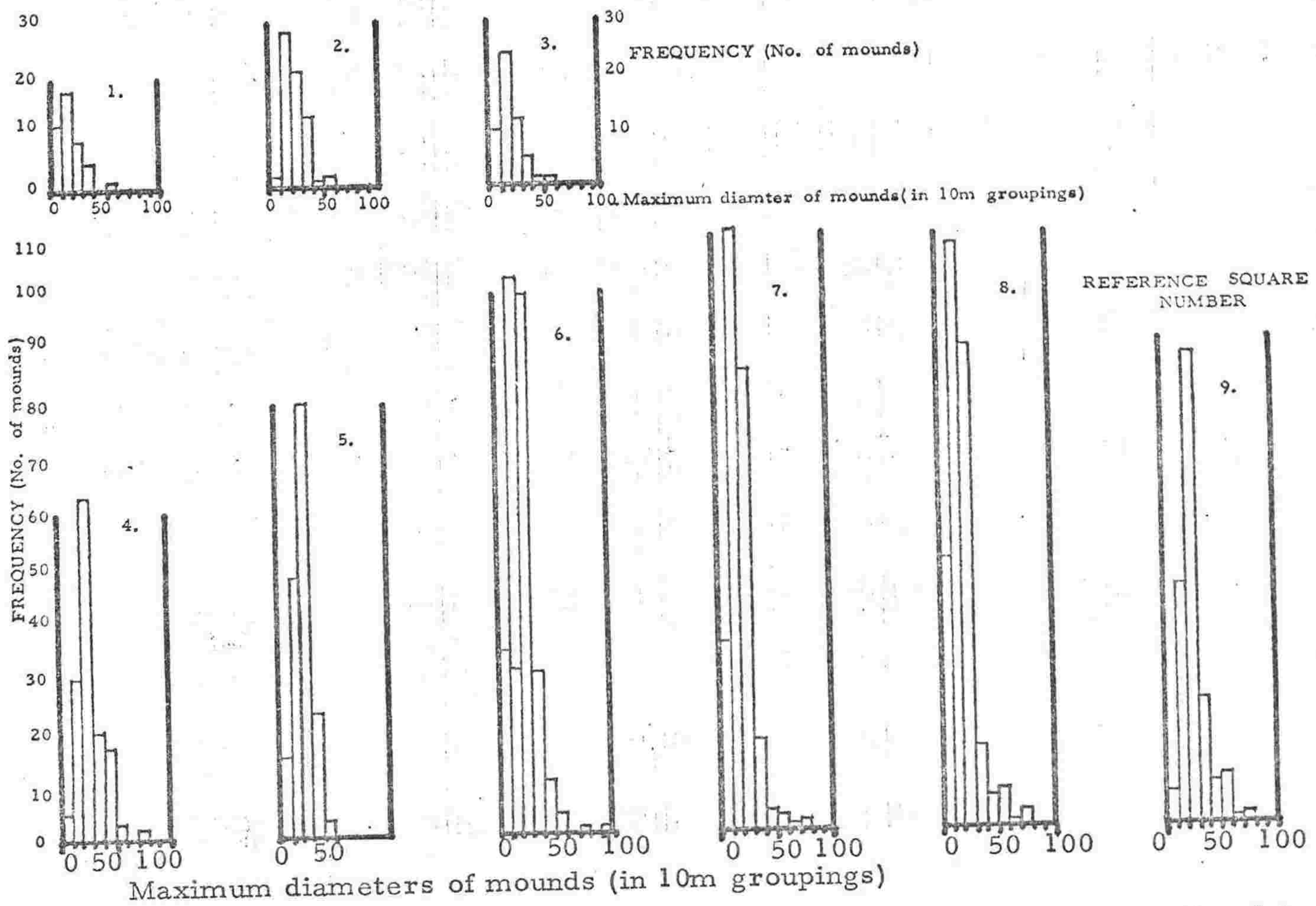


FIGURE 33 - Bar histograms of maximum basal diameters of Opua Formation lahar mounds with distance from source. For full details of method see text. Reference squares 1-9 refer to diagnonal set of grid reference squares in a transect from the coast inland, across NZMS2, N118/8 & /9. Each square is 0.81 km^2 area. Square 1 is at the coast, square 9 is nearest to source - Mt. Egmont.

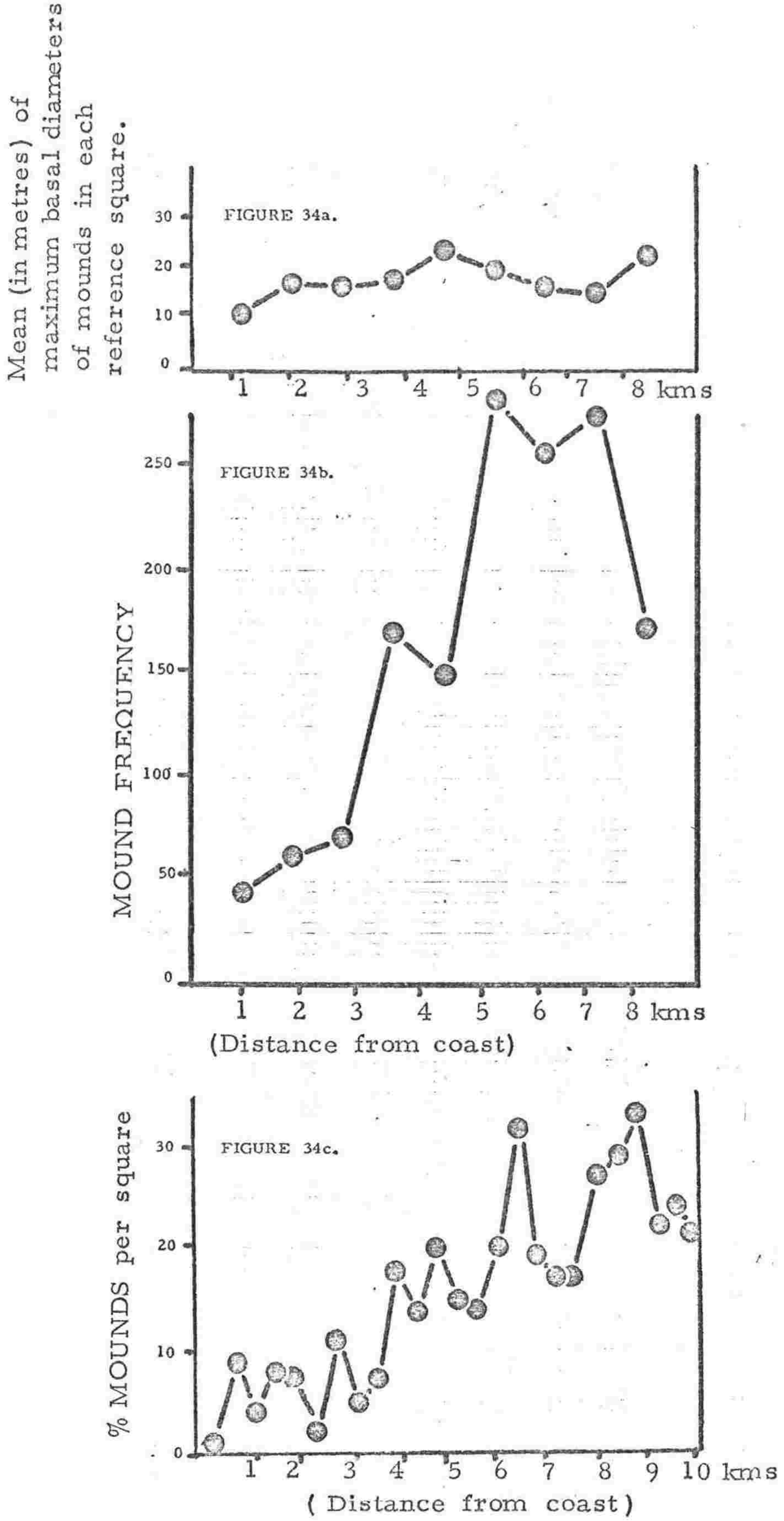


FIGURE 34 - a. Means of maximum diameters of mounds (in metres) in each reference square (1-9 in Fig. 33), b. -frequency of mounds to each reference square, c. - % mounds in 400m square units with distance from coast. Note: For ease of counting, squares in Fig. 34c are 400m square, compared to squares in Fig. 33 and Fig. 34a & b which are 900m square.

DRAINAGE

Streams which flow at present through the Opua Formation drain radially to the coast. In their upper reaches the streams emerge from 30 m deep gorges on the upper south-west flanks of Egmont, but downstream at the 350 m contour the river courses occupy shallow, narrow near straight channels. On nearing the coast, the channels widen and are incised about 12 m below the Opua Formation's upper surface.

The Waiaua River is the largest such river course and near the coast occupies a 0.3 km wide channel. Upstream at the Wiremu Road bridge, a core drilled below river level by Egmont County Council records in excess of 15 m of sand, suggesting that at this altitude the deeply incised river channel is choked with debris which it is unable to carry except during occasional floods. Streams such as this incised through or into the formation show rates of downcutting in excess of 2 - 2.5 m per 1,000 years. This is substantially greater than that calculated for the Pungarehu Formation and indicates a more rapid erosion into the loose unconsolidated Opua Formation debris.

LITHOLOGY

In Heimama Stream, towards the formation's northern boundary, the lithology consists of subangular andesite fragments loosely cemented in a grey sandy grit. Most fragments are less than 1m across, a few are slightly vesicular and they range in colour from 7.5YR N5/ to N/ (grey to dark grey). The matrix is 10YR 4/2 (dark greyish brown) with irregular pockets of "ashy" material 10HR 6/8 (brownish yellow) clearly incorporated within the formation. The deposit is poorly sorted and contains a large percentage of matrix to boulders. Weak bedding is more common than in the Warea and Pungarehu Formations.

At the type section, near the axis of the deposit, the majority of fragments are a grey colour as above, with rarer 10R 4/3 (weak red) and 5YR 4/8 (yellowish red) coloured fragments. The matrix is 10YR 5/2 (greyish brown) with irregular anastomosing networks of 7.5YR 5/6 (strong brown) stains and towards the base the matrix is 5Y 4/2 (olive grey). Boulders are generally less than 1 m across and subrounded, whilst smaller fragments, generally less than about 10 cm across, are angular-subangular. Nearer source, boulders up to 2m across crop out on the surface of the deposit.

THICKNESS, VOLUME AND SOURCE AREA

The base of the Opua Formation can only be recognised with certainty within 1 km of the present coastline, because of the erosive effect of lahar movement upon the underlying tephras nearer source. The formation averages 4 m thickness at the coast although where the flow was largely confined to channels it reaches up to 6 m thick, e.g. along Taungatara Stream. Inland the formation is considered to be of similar thickness because older lahar mounds protrude from beneath. The extent to which older lahar deposits have been stripped and overlain by younger material is variable and accurate volume calculations are not possible. However, assuming an average thickness throughout the entire area of 3 m, the total volume is in the order of 0.35 km^3.

The deltaic form of the deposit, allows easy extrapolation onto the bush covered slopes of Mt. Egmont to a source area between Bobs Bluff and Fanthams Peak, here termed the "amphitheatre" (see Frontispiece). Here, a large sector of the older lavas of Egmont cone (still represented by the West Ridge and Bobs Bluff lava flows), is missing and younger lavas from the present crater have since spread into the missing sector e.g. the Skeet's Ridge lava flows (see NZMS 169). Because the "amphitheatre" is partially filled with younger lavas, the missing sector would have been larger than is at present apparent, and assuming the sector was about 100 m thick, approximately 0.3 km^3 of material would have occupied it. This volume is similar to that computed for the Opua Formation lahar and supports evidence from the distribution pattern, that the Opua Formation represents the collapsed south-western sector of Mt. Egmont.

AGE

No known tephras overlie the Opua Formation below the 350m contour. The Oakura Tephra is preserved beneath the lahar on interfluves at the coast, whilst in some river channels it is incorporated within the lahar to form an "ashy" basal horizon. A radiocarbon date (NZ1141) of 6,970 ± 76 yr B.P. has been obtained from a tree underlying the Oakura Tephra, establishing a maximum age of 7,000 years. Recent correlation of the Oakura Tephra to Section 53 in Wellman (1962) indicates it is <6,300 yr B.P.

NATURE OF FLOW

It is likely that the Opua lahar originated by gravity collapse of material from the "amphitheatre" on the south-west side of Mt. Egmont. Near the 350m contour the lahar must have been strongly erosive because it stripped tephras from underlying surfaces. Further towards the coast, distinct elongate older surfaces radial to Mt. Egmont, show that the lahar was guided by pre-existing river channels, and near the northern and southern margins of the deposit, interfluves protruded above the flow. The strong topographical control of the flow together with increasingly greater evidence of sorting away from source indicate a large proportion of the flow was water saturated. Furthermore, on the eastern margin of the deposit is an extensive but thin deposit of mixed andesite bounders and ash which suggests a slurry flowed laterally onto older surfaces.By the time the flow reached the present coastline it was starting to ramify and channel almost completely into pre-existing river courses, with little erosion of the interfluves where more complete ash sequences are still preserved beneath. The non-erosive nature of the lahar at this distance suggests the lahar was nearly at rest.

ORIGIN OF LAHAR

Most of the lavas adjacent to the source area of the Opua Formation are still preserved and it is clear that neither widespread dyke intrusion nor large scale explosive eruption precipitated the collapse of the now missing segment. The strong topographical control of the lahar indicates that gravity flow may be the simple mechanism whereby material was loosened and travelled at least 22 km to the present coastline. The sharply defined source area, to the side of the main cone, strongly suggests movement on one or more deep seated bedding planes.

In most sections on the present Mt. Egmont, the periphery of the upper lava cone rests upon loose volcanic conglomerate and it is likely that slippage has often occurred along such prominent lithological discontinuities. There is no indication in the tephra column of a large coeval eruption which could have triggered the flow. The role of water established from the distribution and lithology of the deposit, necessitate that water storage within or upon the volcano must be considered as triggering the flow. Water may have been stored in a crater lake or in deep seated aquifers within the volcanic pile, which enabled slippage to occur possibly in association with earthquakes or heavy rains.

Heavy rains alone cannot be discounted because of the unusually large amounts of rainfall which have been recorded during historic storms on Mt. Egmont.

KAHUI FORMATION

DEFINITION

The Kahui Formation is named after Kahui Hill, 850 m altitude, N118/594630, about 500 m west of Kahui Hut. It is defined as the series of debris flow deposits which originated from Egmont and Fanthams Peak cones between the Saunders Ash (dated at 16,100 ± 220 yrs B.P.; NZ 942) and the Oakura Tephra (dated at <6,970 ± 76 yrs B.P.; NZ 1144), and which extend within a 20 km radius of the present summit of Mt. Egmont. The formation is intended to include all the small debris flow units which were deposited around the base of Egmont cone at this time, which are difficult to map separately, but which are distinguishable from larger mudflow deposits of the Warea Formation which extend to the present coastline. The grouping includes at least 8 units in the upper Newall and Puniho road region, and similar aged flows are recorded along the Waiwakaiho River on eastern Mt. Egmont.

The type section is designated in the northern bank of Waiweranui Stream, N118/527665, (Fig. 35a) 1.45 km due north of the eastern end of Newall Road. Here there is exposed

	60 cm	Oakura Tephra
	60 cm	ash with sandy blocks
Debris Flow Unit	165 cm	grey, well bedded andesitic sand
	1 cm	grey ash, upper Stent Ash (Wellman 1962)
	3 cm	dark brown buried soil
Debris Flow Unit	50 cm	grey sand with stones
	100 cm	gravel, with boulders up to 50 cm across
	40 cm	white- greyish sandy ash, Stent Ash (Wellman 1962), with black organic

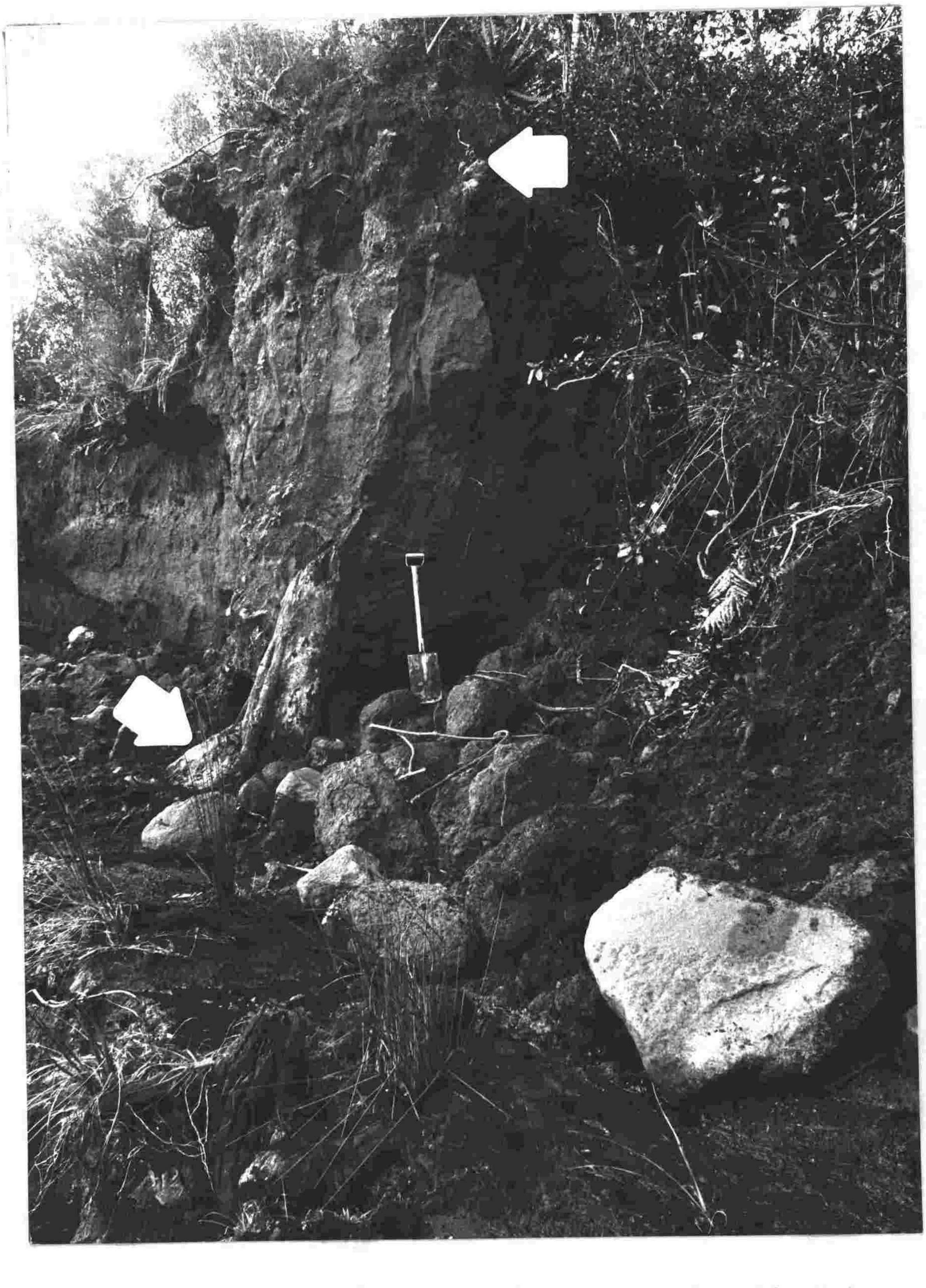


FIGURE 35A - Type locality of Kahui Formation, alongside Waiweranui Stream, at N118/526665. Upper arrow represents base of Oakura Tephra resting upon debris flow deposit. Upper Stent Ash (Wellman, 1962) is preserved at level of spade handle. Lower arrow points to middle Stent Ash which rests upon base of tree trunk dated (NZ1144) at 6,970 ± 76 yr B.P. Note widespread platform at this level, which represents a buried forest floor with small tree base in foreground. Boulders in right foreground are from debris flow deposit which buried tree to left of spade.

		mottles overlying a buried forest of tree trunks which are broken about 160 cm above their basis
(NZ 1144-6,970 ± 76 yr B.P.)		
	160 cm	black buried soil of forest floor, with many twigs and roots
Debris Flow Unit	50 cm	andesitic sand
	7 cm	black buried soil, mainly litter material
Debris Flow Unit		sand to base of section at river level.

A reference locality (N118/512658) is also designated on the north-eastern bank of Teikapurua Stream, opposite Mr W.A. Williams' home, on Newall Road. Here, erosion in 1968-69 exposed an excellent section of the Kahui Formation, but the section was not chosen as a type because it is now overgrown. The section at this locality is presented in Fig. 35B, together with radiocarbon dates (NZ 1142,1143 and 1255) obtained there.

For mapping purposes, the Kahui Formation represents all the Post-glacial debris flows beneath the Oakura Tephra, but excluding the Warea Formation.

DISTRIBUTION

The Kahui Formation constitutes much of the area between Parihaka and Puniho Roads, to the east of Wiremu Road. The flow deposits have filled depressions between higher ridges of the Pungarehu Formation, principally along the Kopoaiaia Stream, Warea River and Waiweranui Stream (see Appendix B2), and have flooded along channels as far west as Goodwin Road. The northern boundary of the formation is buried by younger volcanic derived alluvium deposited from Stony River. Eastwards it is buried by younger

FIGURE 35B- Section exposed opposite Williams' Homestead, Newall Road. N118/512658.

	15 cm	Topsoil, dry grey colour
	12 cm	max. of andesitic sand (Newall Lapilli) 404 ± 44 yrs (NZ 941) obtained from N118/520688
	45 cm	friable yellowish brown ash (Oakura Tephra)
Debris Flow Unit	18 cm	of 3 - 4 cm pebbles, heavily iron stained
Debris Flow Unit	5 cm	grey andesitic sand
	1 cm	light grey-brown to light pink ash
	1 cm	grey andesitic sand
	2 cm	soft light grey-brown ash with putty-like clay, upper Stent Ash (Wellman, 1962)
	4 cm	grey andesitic sand
BS		trace of carbonaceous matter, representing buried soil
	10 cm	yellowish brown soft ash
Debris Flow Unit	105 cm	light greyish andesitic sand with a few pebbles up to 2.5 cm across
BS	4 cm	buried soil
	13 cm	grey clay
Debris Flow Unit	50 cm	of boulders up to 45 cm across around tree stumps projecting upwards, buried soil,
	2.5 - 7 cm	grey to light pinkish brown ash, middle Stent Ash (Wellman 1962)
BS 7,160±80 yrs (NZ 1142)	2.5 - 5 cm	buried soil, black, from which base of tree projects

Debris Flow Unit	15 - 25 cm	fine grey andesitic sand
	4 cm	light pinkish brown ash, lower Stent Ash (Wellman 1962)
BS & Pollen Sample No.1	2.5 - 5 cm	black buried soil
Debris Flow Unit	15 cm	lens of fine andesitic sand
	8 - 18 cm	lapilli
BS Debris Flow Unit	60 cm	chaotic mass of buried trees, averaging 30 cm across, includes branches and logs with black humic layer
	68 cm	grey andesitic sand
Pollen Sample No.2	4 cm	buried soil
11,300 ± 210 (NZ 1255) 12,550 ± 150 (NZ 1143)	3.6 m	andesitic sand, partially grassed over to buried soil at river level, sequence not bottomed.

Maero debris flow deposits (some <100 years old), except for a narrow ridge which extends up the western flanks of Mt. Egmont to Puniho and Kahui Hills. (On the "round-the-mountain" track, at the 900m contour, between the Puniho Track junction and Kahui Hut, river sections indicate the area has not been covered by Maero Debris Flows). South of Kopaiaia Stream, the Kahui Formation has been buried beneath Maero debris flows. Surveys in the Okahu Gorge, West Ridge, Oaonui Fork Stream and Oaonui Hut area indicate the formation reappears as far south as the Waiaua River.

From reconnaissance work on the north-eastern slopes of Mt. Egmont, tentative correlation of the formation is also made to debris flow surfaces between Kaiauai Stream and Waiwakaiho River. Surfaces on the southern flank of Fanthams Peak, between the 750 m and 450 m contours, are also mapped as Kahui Formation.

GEOMORPHOLOGY AND DRAINAGE

There are no diagnostic geomorphological features on the Kahui Formation. The surface contours are quite regular as the gradient drops from 1 in 4 near Puniho Hill to 1 in 40 near the junction of Wiremu and Puniho roads. There is a high likelihood of some straight river courses in the formation, particularly along Waiweranui and Teikapurua streams being controlled by radial faults to Mt. Egmont.

LITHOLOGY

The larger debris flow units within the formation contain boulders up to 50cm across which have snapped trunks of trees leaving the bases in situ. Some deposits are graded with the coarse gravel at the base and sandy lithologies above. Most units show little erosion at the base of the flows and the sequences are well preserved. Thus it seems only material above ground level and in the path of flows i.e. mainly trees, was transported any distance. At the reference section there is a chaotic accumulation of tree trunks and branches in one flow deposit which illustrates this. Smaller debris flows were deposited as fine sands across much of the landscape in a similar manner to floods observed in historic times.

There is no trace of inverse graded bedding in these deposits as is reported from lahars of the Ellensburg Formation by Schmincke (1967). Within the deposits negligible erosion at the base indicates that the flows probably travelled in a laminar fashion.

THICKNESS AND VOLUME

Contacts of debris flow deposits are well exposed and definitive, allowing tephrochronology to be useful for dating. However the base of the Kahui Formation is not exposed in the region of the type locality as it is always below river level. At the 300 m contour the debris flow deposits minimum thickness is 8.5m. The proven extent of the deposits from Puniho and Newall roads to Puniho Hill covers about 32 km^2, so that a minimum volume for the deposits is 0.3 km^3. If correlation with the other areas mentioned is established, and similar thicknesses exist there, then the Kahui Formation totals about 0.5km^3. It was deposited over a period of about 6,000 years.

AGE

The buried forest at the type locality has been radiocarbon dated (NZ1144) at 6,970 ± 76 yr B.P. This sample correlates well with the tree stumps above NZ1142 (7,160 ± 80 yr B.P.) at the reference section. The dates obtained from these two sections indicate the continual aggradation of debris flows between 7 and 12,000 yr B.P., at a rate of about 1 per 1,000 years.

Two pollen analyses by Mr M. McGlone (Botany Dept., V.U.W.) indicate a forest cover at this time, near the 300m contour. Sample 1, from immediately below the 7,160 year horizon is mainly tree ferns, *Ascarina*, and rimu (*Dacrydium cupressinum*), suggesting the sample was on the edge of or under a rimu forest. Sample 2 (Fig. 36) collected from the 11,300 year horizon shows a pollen count indicating regenerating forest.

ORIGIN

Thin pale grey ashes (referred to as upper, middle and lower Stent Ash by Wellman 1962) rest upon tree trunks and buried soils which have been overwhelmed by Kahui Formation debris flows, indicating volcanic eruptions preceded three of the flows. No organic material separates the ashes from the debris flow deposits, indicating a short time interval separated the two events. It is highly likely the eruptions (possibly with associated heavy rains) triggered some of the debris flows.

It is perhaps more than coincidental that the Kahui Formation is a natural grouping of similar sized deposits which accumulated at regular intervals during the period of

FIGURE 36 - Pollen grain count by Mr M. McGlone, Botany Dept., V.U.W. of peat sample collected from horizon dated at 11,300 ± 210 yrs, at reference locality for Kahui Formation.

Kahikitea	1
Rimu	43
Podocarpus	22
Sedge	40
Kanuka	120
Fern	8
Restinaceae	20
Coprosma	7
Gunnera	2
Liliaceae	6
Treefern	7
Haloragis	6
Oleaceae	1
Myrtaceae	3
Beech	1
Neopanax	7
Grass	2
Grissilinia	5
Rubus	1
Malvaceae	1
Dracophyllum	1
Alsetia	1
Polypodium	1

Conclusion: The assemblage is characteristic of a regenerating forest.

amelioration in climate following the last stadial (Wellman 1969; Emiliani 1966), until 6,500 yr B.P. This is in marked contrast to the absence of debris flow deposits in the preceding stadial. It suggests that during the warming climate, more water was stored within the upper levels of the cone (in the stadial before, it may have been frozen), and when slippage occurred sufficient water within the debris allowed flowage to occur. There is no indication of excess water being available in these debris flows, unlike the Opua, Warea and Pungarehu formations, so that much of the water was probably derived from within the original material that collapsed.

The source area of the flows was clearly east of Puniho Hill. However volume calculations show that portions of the present summit's upper cone are unlikely to have contributed enough material to these flows, indicating the deposits are older than the cone above 1,200m altitude, i.e. much of the upper cone is <7,000 years old.

MAERO DEBRIS FLOWS

DEFINITION

Maero debris flows are an informal grouping of at least 14 debris units deposited above the Oakura Tephra. A reference section is here designated in cliffs of Maero Stream adjacent to the Puniho Track (Egmont National Park). It is well exposed (Fig. 37) in the south bank of the stream, at N118/586656, altitude 690 m, where the channel winds in an S-shape, and shows the following

90 cm Debris flow unit 1, grey sand 90%, with pebbles up to 30 cm across (averaging 16 cm across),
weak irregular contact

1 m Debris flow unit 1A, gravel with grey boulders averaging 30 cm across and 15-20% sandy matrix grading to

1.25m coarser gravel base with large boulders, very loose with little matrix
sharp, straight contact

85 cm Debris flow unit 2, 50% sandy matrix, and pebbles, and boulders 50% averaging 30 cm across on

65 cm pebbles and coarse sand to sharp contact with

60 cm Debris flow unit 3, 70-80% sand with many angular cream coloured hydrothermally altered and grey unaltered andesite fragments

90 cm Debris flow unit 4, about 80% sandy matrix with angular pebbles and cobbles with dominantly subrounded-subangular boulders
sharp, straight contact

FIGURE 37A - Photograph of Maero Stream reference section, at N118/586656 (see Chapter 5, "Maero Debris Flows - Definition". Interpretation of units present is shown in Fig. 37B. Section is 10 m high.

FIGURE 38 - View across 80 year old debris flow deposit, looking towards Little and Big Pyramids (in centre); Mt. Egmont summit to upper right. Cross marks site of ecosystem study described in Chapter 8.

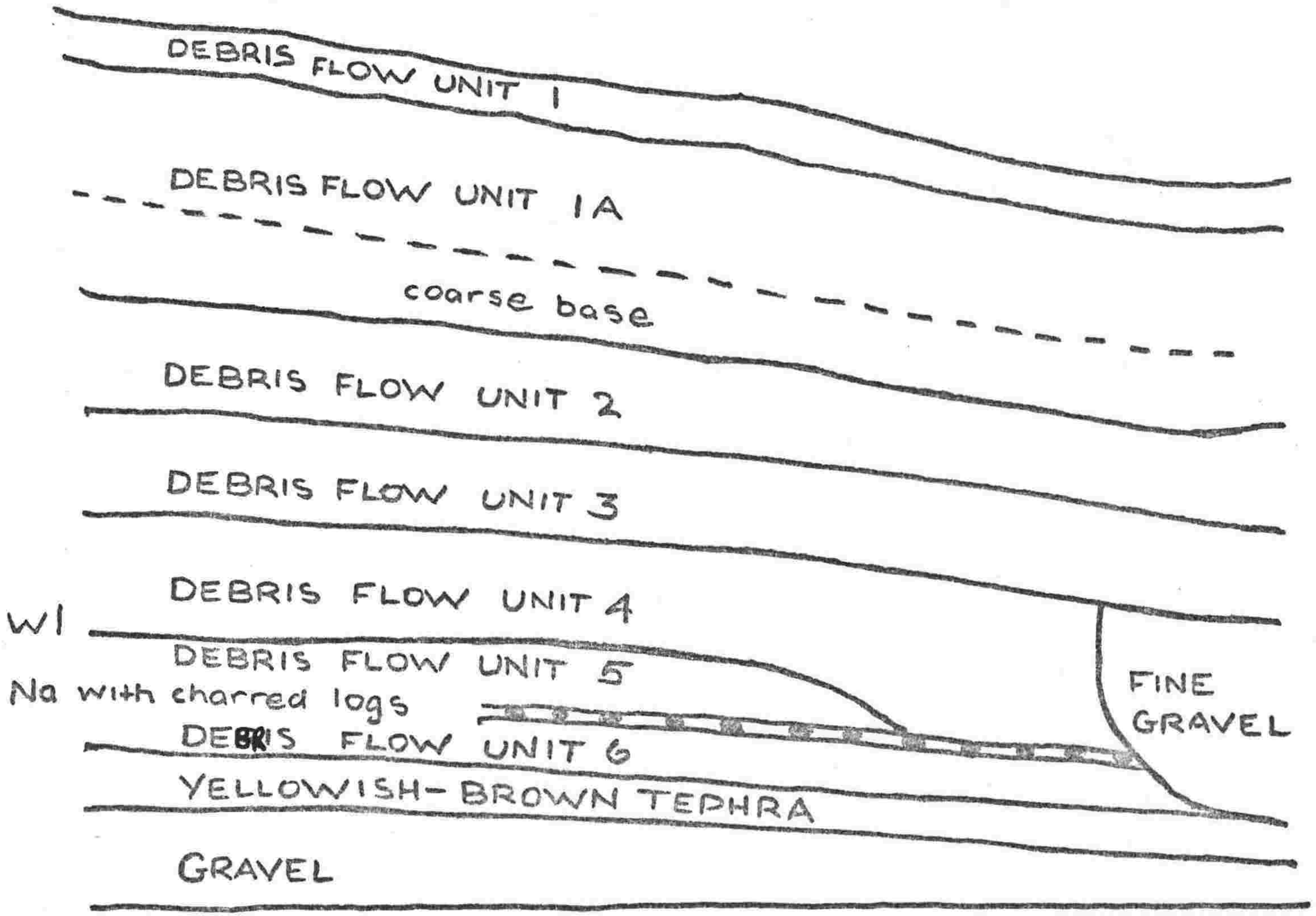


FIGURE 37B - Interpreted units at Maero Stream reference section, N118/586656 (see Chapter 5, "Maero Debris Flows - Definition" and photograph Fig. 37A). Section is 10 m high.

7 cm	buried soil on pale grey medium sand with carbonised twigs (Waiweranui Lapilli)
	sharp, straight contact
1.25m	Debris flow unit 5, about 60% matrix with subangular grey andesite pebbles 3-5 cm across (one carbonised log noted within this unit) on
	sharp, wavy contact
50 cm	medium sand with no pebbles (Newall Lapilli) and large number of carbonised logs 10-20 cm diameter on
	sharp, straight contact
45 cm	Debris flow unit 6, 80-90% sand, with many 1.5 cm pebbles on
	sharp, straight contact
10 cm	laminated sands on
6 cm	grey sand on
6 cm	pinky-cream coloured ash on
5 cm	peat layer with wood fragments (wood sampled for NZ 1145, 1,975± 50 yrs B.P.)
1.6 m	massive yellowish brown tephra, predominantly greasy ash (?Oakura Tephra- near source deposit), with minor lapilli horizons frequently water saturated with much iron staining on
67+cm	?Debris flow unit 7, gravel with subangular andesite fragments up to 7 cm across, 50% sandy matrix to base.

Two similar sections are exposed up and downstream from this locality and are here designated secondary reference sections, (N118/585657, N118/587655).

At least 12 flow deposits within the grouping have originated from the upper Mt. Egmont cone over the last 500 years. In Maero Stream the flows overlie the Oakura Tephra dated at <6,970 ± 76 yr B.P. Debris flow deposits not mantled by the Oakura Tephra are thus mapped as Maero Debris flows.

AGE

The oldest known Maero debris flow deposit is likely to be about 3,000 yr B.P. because it is overlain by the Inglewood Tephra. It crops out at two localities near the 300m contour, on the north-eastern slopes of Mt. Egmont. At the first locality the deposit covers about 1 hectare on the south-eastern side of German Hill and is well exposed on Hill Road at N109/698766 (1965). The second locality is along the western branch of Waionganaiti Stream where the deposit is aligned NE-SW and covers about 1 km^2. It is well exposed on Bedford Road, about 0.5 km north of the Dudley Road junction.

Maero debris flow deposits of pre-Newall age are exposed in cliffs along Stony River and are probably of similar age to those exposed to the north-east of Egmont.

A peat sample collected from 0.7 m below the lower contact of Newall Ash in Maero Stream has been dated (NZ1145) at 1,975 ± 50 yr B.P., indicating a period of 1,500 years stability prior to the Newall eruptions. A single 0.5 m thick debris flow deposit is preserved at the Maero debris flow reference section between NZ1145 and the Newall Ash and Lapilli. The lack of soil development between the flow deposit and the Newall eruptives indicates the debris flow originated at the beginning of the Newall eruptions.

At the Maero Stream section a debris flow deposit occurs between the Waiweranui Lapilli and the Newall Lapilli. Because of the absence of soil development, peat or plant remains between these two members, conformable elsewhere on Egmont, the flow is considered to have been deposited within a very short time after the Newall Lapilli.

All debris flows following the Newall Formation destroyed large areas of vegetation and are therefore capable of being tree-ring dated. Tree-ring dates of kamahi trees which regenerated after having been levelled, on the north-western slopes, all post-date the 1880's, and kanukas (a tree of the first seral stage established following destruction of the forest) show similar ages.

H.M. Skeet, an early surveyor, took a photograph about 1889 A.D. which shows debris flow unit 1 almost devoid of vegetation indicating the short time interval since it had been deposited. Another photograph taken by Skeet, of the northern slopes of Egmont shows a fan of debris in the Ahukawakawa Swamp graded to Minarapa Stream (see Appendix C1). It is almost devoid of vegetation, strongly suggesting it was less than 20 years old at the time. A Mr Casey, now deceased, communicated to the author that when he first resided on upper Newall Road, about 1910 A.D., local residents were aware that parts of the forest nearby had been levelled about 20 years previously, the damage being attributed to high winds from the south-east, (later evidence shows the trees were levelled by a debris flow).

An historic debris flow in the Oaonui valley is dated at 1922 A.D. by Druce (1970). Similar flows have crossed from Mangahume Stream to Waiaua River in 1935 and from Oaonui Stream to Otahi Stream in 1936 (see "Origins").

If the latest debris flows are less than 100 years old then the source area on the upper Egmont cone should have been present prior to about 1880 A.D. Most paintings of Mt. Egmont prior to that date are greatly exaggerated. No paintings or photographs from the west, examined in the Alexander Turnbull Library, Wellington or the New Plymouth Museum, are in sufficient detail to allow interpretation of any major summit changes. A single etching by Barraud and dated circa 1856 shows a distinctive ridge to the western edge of Egmont crater - inconclusive evidence of a former western crater rim. Early information on Egmont's summit was supplied to Hochstetter by Messrs Wellington Carrington, Provincial Surveyor of Taranaki, and Turner and A.S. Atkinson of New Plymouth. Hochstetter writes "Another astonishing error for such an excellent observer as Dieffenbach (the first European to ascend Mt. Egmont, in 1839), says Mr. Atkinson, concerns the surface area of the summit, which Dieffenbach declares to be a square mile. Atkinson thinks that the area amounts to only about a sixteenth part of a square mile i.e. a quarter mile square" (40 acres), (Fleming 1959 p.176). H.M. Skeet measured the area 60 years later (circa 1899A.D.) as 15 acres (Scanlan 1961), which is similar to that today. It is conceivable that some of the debris flow units 1 - 5 at the Maero Stream section, originated over the period between Dieffenbach's and Skeet's visits and that the very large differences in estimates were due to parts of the western crater rim which have since collapsed to the north-west. If Dieffenbach's estimate was accurate then the summit area has decreased from about 300 - 600 acres in 1839, to 40 acres circa

1864 to 15 acres circa 1899, resulting in deposition of the younger Maero debris flows.

TOPOGRAPHY AND DISTRIBUTION

Most Maero debris flows have been directed along river courses, scouring them out at high altitudes. Below the 300 m contour, flows form aggradational terraces but to the north and north-west where much larger quantities of debris slid from Egmont crater deposits are similar to "shingle-fans". Only the latest flow surfaces are preserved but observations of older flow units indicate they were all very similar.

Most river channels draining Mt. Egmont show vegetational evidence of debris flows during the last 100 years and to the north and north-west the bush-line has been depressed to at least 300m below its present level elsewhere on Egmont. Flows to the north-west spread downhill between the Pyramids and Puniho Hill (Appendix B2 and Fig.38) to an altitude of 300m, i.e. the eastern end of Puniho Road. The latest flow deposit shows a low hummocky relief, indicative of irregular compaction around large boulders. A boulder train present along the axis of this deposit contains boulders up to 5 m across (Fig. 38) which appear to have floated on the upper surface and probably reflect the flow's high viscosity. Debris also flowed between the Pyramids, Skinner Hill and Peters Stream, and show similar surface features. On the northern slopes, debris flows extend from Minarapa Stream into Ahukawakawa Swamp.

Flows were also directed through Okahu Gorge and emerged at the 600 m contour devastating native bush down to the 360 m contour. Resultant vegetational patterns are clearly visible on aerial photographs (<u>see</u> Frontispiece). Similar devastations have been identified along Oaonui Stream to the 300 m contour, and down Mangahume Stream and Waiwakaiho River to the 210 m contour. In the latter river, gravels have spread over a 1.5 km wide zone between German Hill and Kaimiro. Other less well documented debris flows originated in Manganui, Maketawa, Punehu and Kapuni streams.

PUNIHO HOLES

About 1 km east of Puniho Hut the latest debris flow surface (<80 years old) is marked by at least six cylindrical holes (here referred to as the "Puniho holes"), some of which extend to 4 m depth. The largest holes reach 2 m diameter and clearly represent the site of former trees. Two similar holes occur within "Okahu agglomerate" (Grant-Taylor 1970, p.78) on Kahui Track near the 750 m contour, and charcoal from them has been dated (NZ567) at 537 ± 55 yr B.P. Grant-Taylor (in Grant-Taylor and Rafter 1971, p.398) considers that trees were "engulfed" by an eruption, partially carbonised and the uncarbonised wood then rotted away to leave cylindrical cavities (the "Kahui holes"). However the existence of carbonised wood does not necessarily indicate that the Okahu agglomerate surrounding the trees carbonised them. The author has observed that since a 1-2m thick post-Newall debris flow overtopped the site of the Puniho holes without filling them, then they must have originated after the latter event. A more complex origin of the Puniho and Kahui holes is indicated. (Fig. 39).

Charcoal collected from within the Newall eruptives give a range of radiocarbon dates. Complete tree specimens give

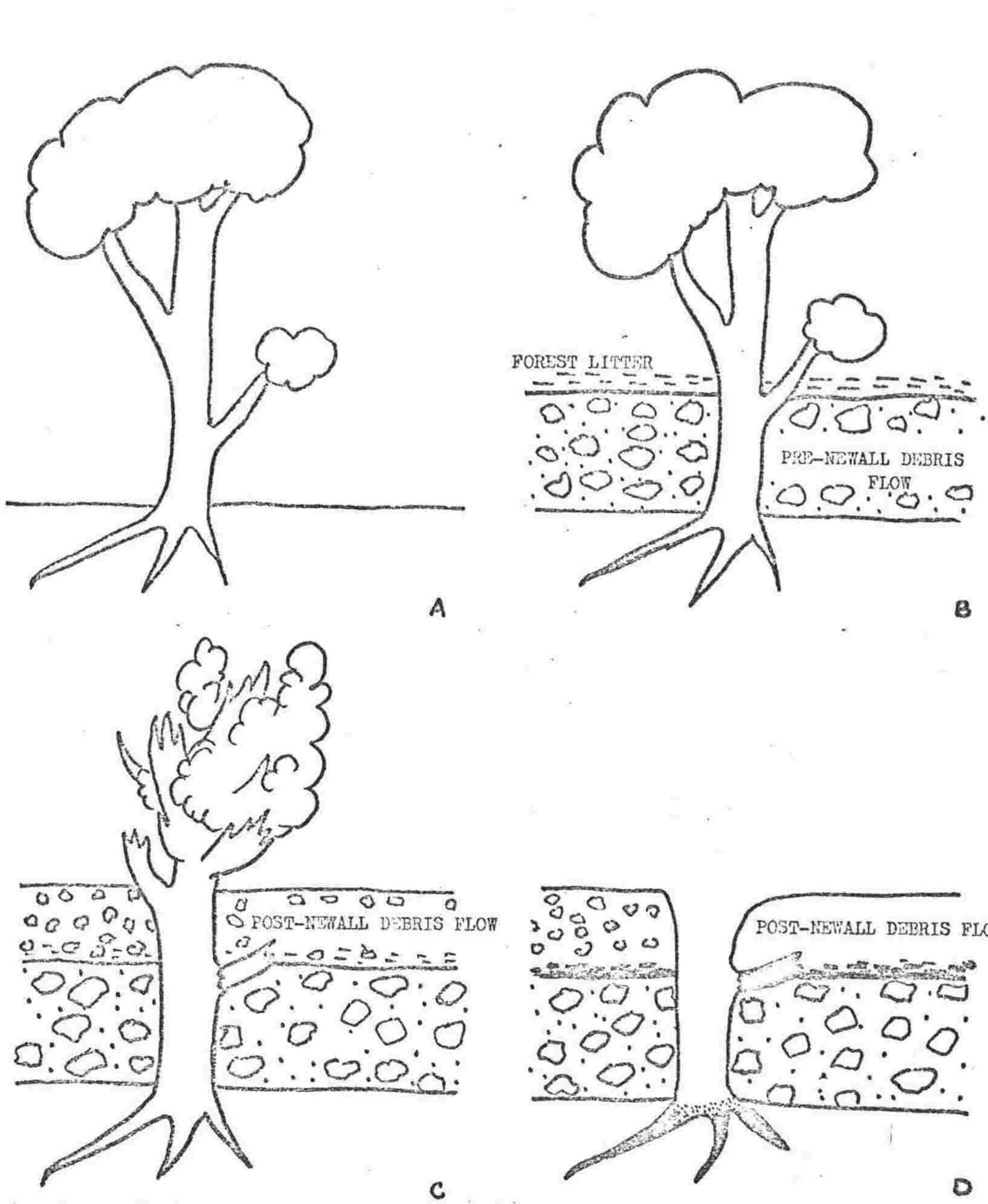


FIGURE 39 - Interpreted series of events which led to formation of the "Puniho and Kahui holes". A = tree growing on original surface, with base of trunk above ground level. B = Pre-Newall debris flow buries base of trunk but tree is not severely damaged and continues to grow. C = Hot nuées ardentes of Newall eruptions begin to burn tree, followed immediately by a post-Newall debris flow. Parts of tree exposed above post-Newall debris flow continue to burn. Wood immediately buried by debris flow after nuées ardentes, is converted to charcoal. D = Hole in debris flow deposits where tree has "burnt out". Fragments of charcoal in base of hole and along contact between pre- and post-Newall debris flow deposits, represent heated wood buried quickly by debris which prevented combustion and enabled slow baking to produce charcoal.

ages of 447 ± 40 yr B.P. (NZ1141) collected from the type locality, and 620 ± 74 yr B.P. (NZ1256) collected from Maero Stream. The five outermost rings of a complete carbonised miro tree (Podocarpus ferrugineus) killed by the Newall eruptions gave a date of 404 ± 44 yr B.P. (NZ941), the most likely age for the Newall eruptions. At the Puniho holes, a carbonised forest litter about 1 m below present ground surface has been dated (NZ720) at 439 ± 55 yr B.P. Thus radiocarbon dates obtained from the Kahui and Puniho holes fall within the range of dates obtained from charcoal within the Newall eruptives.

It is suggested that the trees which once occupied the Puniho and Kahui holes may have been surrounded by a cold debris flow but were not killed and continued to grow with their bole bases covered by debris. At the time of the Newall Ash and Lapilli eruptions, hot nuee ardente avalanches swept down the north-western Egmont slopes and charred or burnt the vegetation only to be rapidly followed by another debris flow (post-Newall Lapilli debris flow). The effect of immediate burial of the forest litter, fallen branches and tree stumps would be to retain heat within the charred vegetation layer leading to slow baking and production of charcoal. Those portions of larger trees which protruded above the surface of the post-Newall Lapilli debris flow deposit may have continued to burn and were completely combusted. Some roots and basal branches may have been buried by falling debris from the sides of the holes, resulting in small carbonised fragments preserved in the flow deposit (Fig. 39) such as the fragments radiocarbon dated (NZ567) in the Kahui holes. This origin is considered likely because

(a) the Newall and Waiweranui lapillis are conformable at most localities on Mt. Egmont and little time separates them. Thus the debris flow deposit separating the two lapillis in Maero Stream probably followed immediately after the Newall Lapilli eruption. This would aid retention of heat in the underlying layers aiding charcoal formation. If the holes had formed prior to this stage then they would have been filled by the flow deposit.

(b) if the pre-Newall Ash debris flow had partially carbonised the trees either

  (i) some decomposition would have preceded the post-Newall Lapilli debris flow. This is unlikely because the debris flow would then have partially or totally filled the holes, or

  (ii) all the wood and charcoal has decomposed during the last 400 years.

The known stability of charcoal in older ash deposits in both Taranaki and the Central North Island, makes the latter alternative unlikely.

LITHOLOGY

At the type section, most debris flow deposits show weak graded bedding indicative of laminar flow. The fragments in all the deposits are supported by the matrix. All the post-Newall debris flow deposits show sharp upper and lower contacts, but the absence of soil or plant material on these contacts suggests any material that was present has been carried away by the flow above. In debris flow unit 1 the bedded units within the flow suggest that the coarser base was deposited a short time before the finer more sandy upper portion and that the flow originated as a series of pulses, such as have been reported in North American mudflows (Broscoe and Thomson 1969; Blackwelder 1928; Sharp and Nobles 1953; Curry 1966).

None of the units are lithologically distinctive except debris flow unit 3, which contains many fragments of hydrothermally altered andesite. These fragments, showing white coatings of mainly cristobalite, are very similar to rocks comprising the eastern wall of Egmont crater, unlike the vesicular andesite of the summit tholoid, suggesting that this flow originated by collapse of the western crater rim. One of the Maero debris flows has been referred to as Okahu agglomerate (Grant-Taylor 1970, p.78) but the material is not welded and is better considered a volcanic breccia.

NATURE OF FLOW

The majority of historic debris flows on Egmont have been associated with heavy rains. Flows have been strongly controlled within existing river channels but where channels meander irregularly, flows have departed from them to cut swathes through the bush. This has often occurred where flows emerge from gorges near the 500 m contour. Debris flows have also crossed interfluves into other catchments, particularly between Okahu and Kopoaiaia streams, Oaonui Stream and Waiaua River, and Maketawa and Little Maketawa Streams. In each case the flows appear to have travelled as turbulent watery suspensions, and with reduction in velocity on lower gradients, gravel was deposited en masse.

In the region between Maero Stream reference section and Ahukawakawa Swamp, much coarse debris slumped downhill from

Egmont summit and flowed up to 5 km. In the latest debris flow (unit 1) the bulk of this debris has spread in a broad fan downhill to the 600 m contour. Most of it appears to have "frozen" as the velocity of the flow decreased, as is typical of laminar flow (Fisher 1971), without settling of larger solids. Large andesite lava blocks on the deposit's surface indicate the high yield strength of the debris which retarded their sinking and kept them suspended during flowage. The unsupported framework of the clast fabric (Fisher 1971) also confirms the high density and high strength of the material.

Below the 600 m contour, debris flow unit 1 becomes thin and difficult to trace but much of the bush below this contour has been devastated to ground level. The present kamahi (Weinmannia racemosa) forest here shows many trees joined laterally at their bases (Figs. 40 and 41) which have grown from fallen logs. Present-day "aerial" roots extend down to the soil surface. Many of the present-day trees are joined by living wood, originally fallen boles, whilst others show hollow cylindrical root networks which grew around fallen boles now rotting away. At the uphill margins of many fallen trees are vertical disc-shaped masses of roots indicating the trees were levelled from an uphill direction. The orientations of 103 fallen logs have been measured (Fig. 42 and 43) and clearly show a strong north-westerly orientation indicating the trees were levelled by a component from the south-east.

Since the trees are dated as having regenerated in the 1880-1890's it is unlikely that any directed volcanic blast occurred without it being recorded by residents in western Taranaki at the time. In addition the forest was not devastated in some areas of high relief close to source. The large scale devastation of the

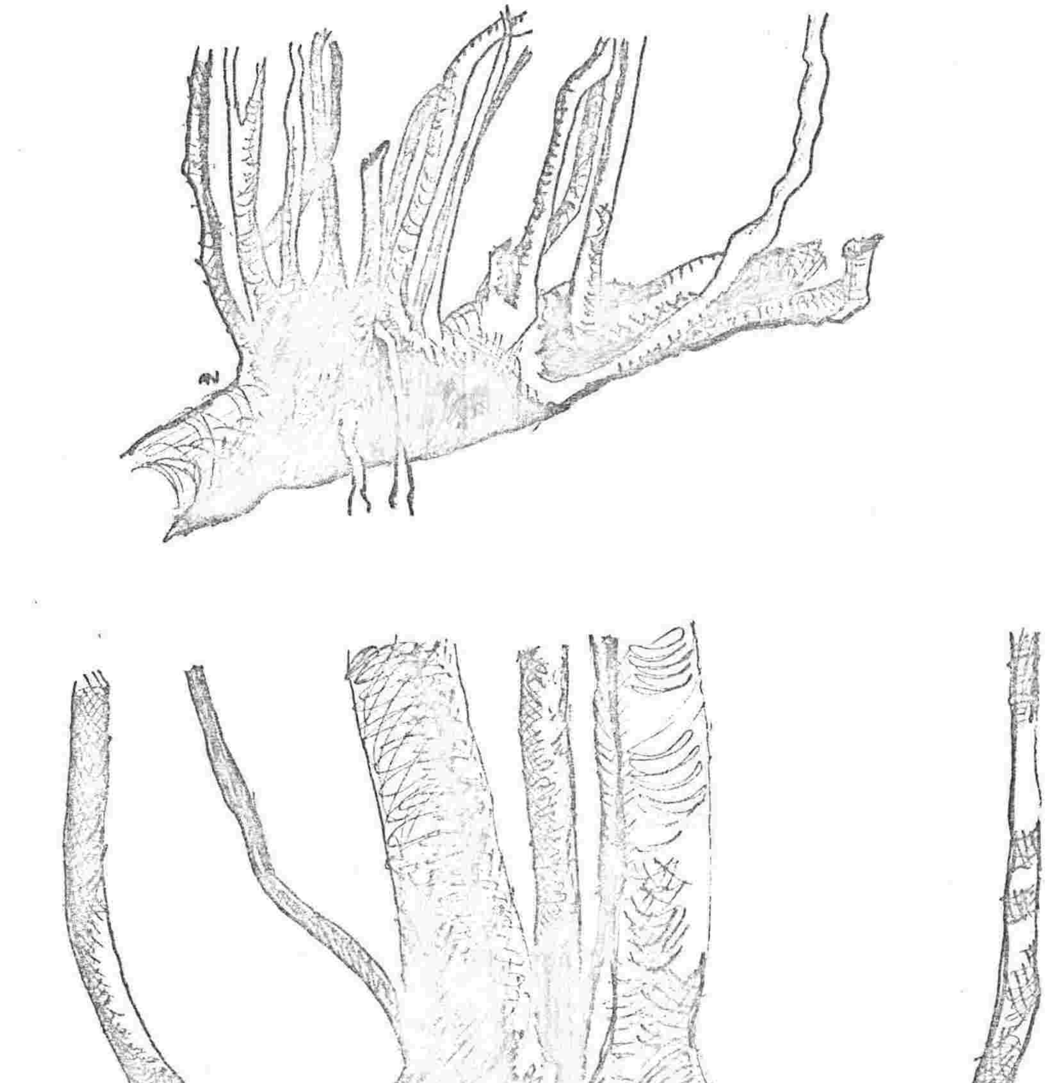


FIGURE 40 - Bases of living kamahi (Weinmannia racemosa) trees along Puniho Track, near N118/553669. Present day boles have grown from branches of fallen trunks.

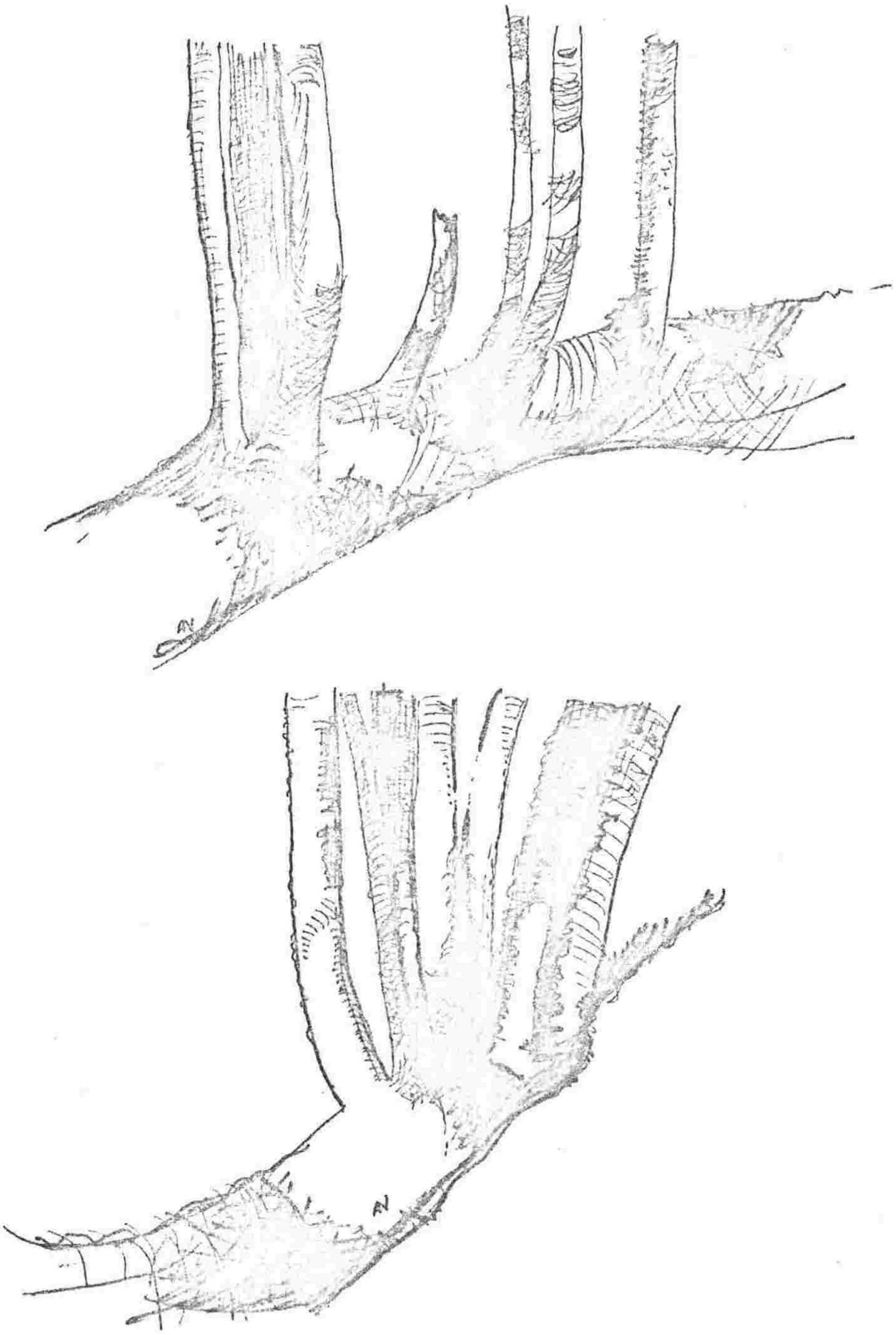


FIGURE 41 - Bases of living kamahi (Weinmannia racemosa) trees along Puniho Track, near N118/553669. Lower sketch shows fallen trunk, with seven boles now growing from point of fracture.

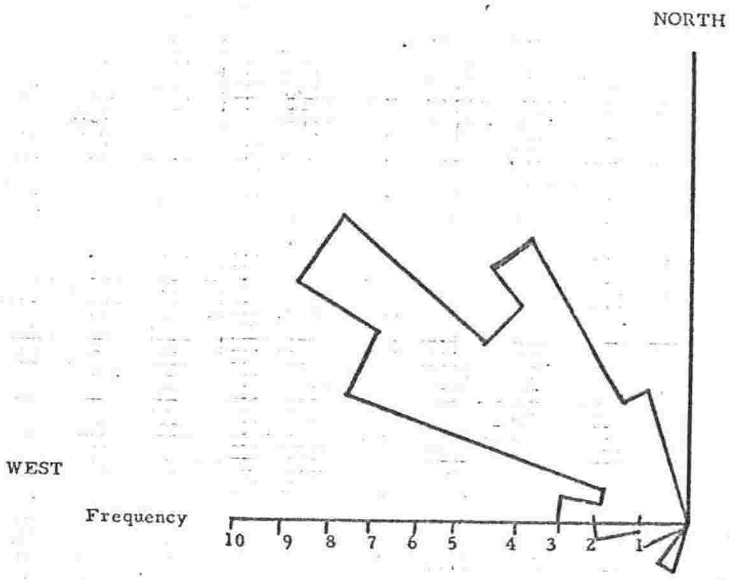


FIGURE 42 - Orientation of fallen kamahi tree trunks (*Weinmannia racemosa*) on Puniho Track, Egmont National Park, between 400 and 435m contours.
Number of trees measured 45.

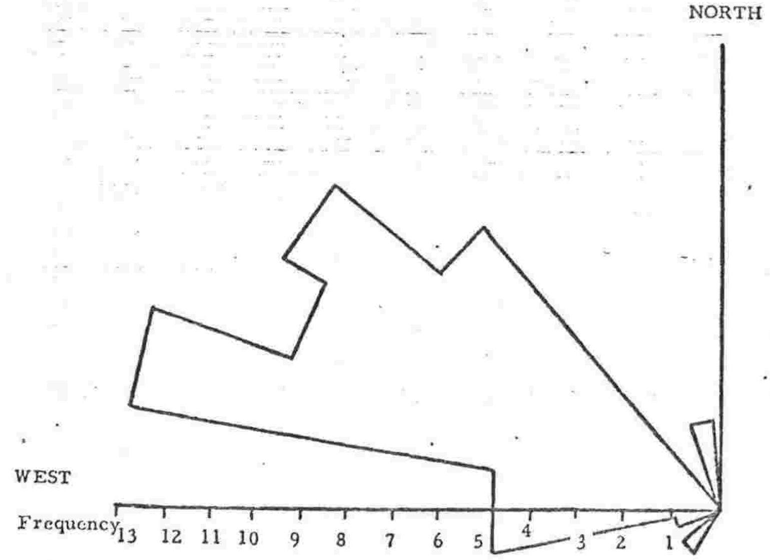


FIGURE 43 - Orientation of fallen kamahi tree trunks (*Weinmannia racemosa*) on Puniho Track, Egmont National Park, between 435 and 480m contours. Number of trees measured 58.

forest by south-east source winds is unlikely because there is no record of damage on the slopes most exposed to the south-east at this time.

The orientation of the fallen trees follows the general drainage in the region and in particular the north-west drainage of the upper Waiweranui Stream channel. At the 450-550m contour fallen trees are oriented parallel with a number of dry channels linked with Waiweranui Stream which here alters course and flows in a westerly direction. Traces of sand on trunk bases and in the forks of surviving trees (Druce 1970) are further evidence that the trees were probably flattened by a wave of sandy water which flowed downslope from the terminal margin of the coarse debris in debris flow unit 1. Additional evidence for this origin is a communication by Skeet to J. Strauchan, Chief Surveyor, New Plymouth, dated 20th April 1901 which reads "On the west side of Mountain between Beehives and the Pouakai ranges, the beds of some of the streams are washed out wide, huge stones are to be seen in the forks of trees, in the bush there are patches of fallen timber. These seem to show that extraordinary downfalls of rain have occurred more like the action of a waterspout than ordinary storms".

Clearly a wave of water was large enough to knock down young kamahi trees so that branches on their upper sides have regenerated and grown into the present forest. Terrestrial ratas (Metrosideros robusta) were sufficiently large, with boles up to 4 m across, to resist being knocked over by the flow. By the time the flow reached the 300m contour it had left the channel of Waiweranui Stream because of its incapacity to negotiate changes in the drainage pattern and flowed north-westwards through the bush into Stony River, producing widespread scour channels. Flows also spread northwards from Minarapa Stream into Ahukawakawa Swamp and down Okahu Gorge at this time.

The gradients of the latest debris flow deposit indicate that between the Pyramids and Puniho Hill the debris started to rise alongside a WNW trending ridge below and west of Puniho Hill. Without surmounting it the flow was guided by the relief and changed direction to flow downhill almost parallel to the ridge. Material diverted to the other side of the ridge passed down Okahu Gorge and overflowed northwards into Kopoaiaia Stream near the 600 m contour. Thus a WNW trending ridge between Waiweranui and Kopoaiaia streams escaped the latest debris flow and now supports an older forest cover of rata (Metrosideros robusta) and rimu (Dacrydium cupressinum). Similar aged forest along low river terraces on the south side of Stony River, above the 450m contour, were probably unaffected because they were situated on the northern margin of most post-Newall debris flow deposits. Below the 450 m contour the older forest along Stony River was levelled because the 80 year old flow left Waiweranui Stream and passed north-westwards into Stony River.

ORIGINS

All the Maero debris flow deposits show distributions, surfaces and lithologies which indicate they were water based. The post-Burrell flow deposits on the north-western Egmont slopes all have characteristics similar to the youngest flow deposit (debris flow unit 1). Thus if the cause of the latest flow deposit could be determined it is likely that similar causes initiated previous flows. From all the available evidence the latest large-scale flow from Egmont summit is thought to have originated about 1880-1900 A.D. with four previous flows originating between 1600-1888 A.D. No eruptions are known to have occurred at this time and only 3 origins for the flow deposits can be considered likely; collapse by

(a) an earthquake

(b) heavy rains, or

(c) a combination of both.

Five major earthquakes were recorded in Taranaki between Dieffenbach's visit and 1900 A.D. Of these, three were between magnitudes 6 and 7.5 and are documented by Eiby (1968) as follows:

> 1853 Jan 1, New Plymouth, felt on both sides of Cook Strait and on a ship near Cape Farewell. Intensity MM8 in New Plymouth. Aftershocks.
>
> 1868 Aug. 16, Taranaki ?Magnitude 6-7.5, felt over the southern half of the North Island and northern half of the South Island. Intensity about MM8 in parts of Taranaki.
>
> 1881 Jun 26, Taranaki, felt throughout both islands. About MM6 in New Plymouth. Possibly deep.

If earthquakes were the primary cause of the youngest Maero debris flows, then summit changes would have been observed between the above dates. The only source of water for such flows would be that stored within the volcanic cone.

Data on some unusual rumblings which are well documented in the "Opunake Times" were kindly brought to my attention by Mr J. Stronge of Arawhata Road. This data is summarised in Fig. 44 together with rainfall data at that time, supplied to me by Mr J. Finkelstein, N.Z. Meteorological Service. The rumblings show an association with periods of rainfall and I consider it

FIGURE 44

Rumblings and Associated Rainfall Data Recorded in Taranaki, during 1890's.

	Rumblings reported by Postmaster at Opunake	Rainfall -Kaponga (in mm)	Rainfall -Riversdale near Inglewood (in mm)
September 1895			
22		5.1	18.2
23		17.2	21.1
24	2 rumblings	48.4	54.1
25	1 rumbling	5.1	44.2
26		0	0.8
27	1 rumbling	4.6	0
28	4 rumblings (also earthquake shock at 1.28 pm recorded on rainfall chart at Riversdale)	25.4	34.5
29	4 rumblings	19.0	66.8
30	1 rumbling	0	5.3
October 1895			
1	2 rumblings	0	0.5
	In October, a continual series of earthquakes were recorded in the Okato district		
August 1897			
14	10.34 pm, sharp shock of E - W duration, 10 secs., with loud rumble with tremor lasting 10 mins.		
15	3.39 am, sharp shock 3 secs with slight tremor and rumbling.		
16	1.25 am, slight shock, rumble and tremor.		

highly likely that the rumblings represent debris flows, the one on September 28 being so large as to produce a local earthquake.

Only one accurate map of Egmont summit area was compiled prior to this date and due to the draughting technique then adopted it is difficult to interpret structures within the crater area which may have provided a source area for the flows. If they were derived from the summit area since the map was compiled in 1885, it must be assumed that they were derived from the area marked West Peak (see Appendix C2) a structure similar in appearance to the Turtle.

Later debris flows along river channels were very much like floods and spread large quantities of coarse debris over extensive areas outside the present National Park. During the flood of 21-22 February 1935, 480 mm rain fell at Dawson Falls in 24 hours (Soil Conservation and Rivers Control Council 1957) and Mr Stronge reports that Mangahume Stream altered its course and flooded into the Waiua River near the 360m contour. Along the Kapuni Stream the hydro-electric generator was swept away (Mr J.L. Wells, pers.com.) at this time. On 1 and 2 February 1936 the worst storm in living memory, a cyclonic storm, struck Taranaki (S.C.R.C.C. 1957).

Oaonui Stream left its banks at the 390 m contour and flowed down Otahi Stream; depositing over 4 km^2 of gravels. (see Appendix B2). Flows also took away portions of Oaonui Gorge, the Okahu River bridge on the main road collapsed, and Mangahume and Taungatara Streams were "washed out".

HOLOCENE COASTAL SECTIONS IN WESTERN TARANAKI

Wellman (1962) described five Holocene coastal sections in Taranaki two of which (Sections 53 and 54) are within the present study area. Section 53 is the more complete stratigraphic section and is here reinterpreted. The section is incorrectly located by Wellman, and should read

> "Stent Road, north end (N108/373710)" which is a locality 7km (4½ miles) north of Cape Egmont.

Wellman's description is presented with my interpretation of the newly named units in the section, (Fig. 45). The first appearance of sands in the Holocene at this section is interpreted as the 6,300 yr B.P. maximum Post-glacial sea level height. The sands overlie the middle member of the Stent Ash, which is dated at 6,970 ± 76 yr B.P. (Neall 1972) and underlie the Oakura Tephra wrongly interpreted by Wellman as the "Stratford Shower". The section establishes a maximum age for the Oakura Tephra of 6,300 yr B.P. and confirms the identification of the middle member of the Stent Ash overlying a forest dated about 7,000 yr B.P.

FIGURE 45 - Holocene coastal section at the end of Stent Road, (N108/373710).

Wellman (1962) - Section 53	Neall (this paper)
150 mm Black sandy soil	Present topsoil
30 mm Trace andesitic ash	? andesitic tephra
30 mm Black sandy soil	Buried soil
60 mm Traces of several minor ash showers	? unidentified tephras
90 mm Rusty black sand with Taupo Pumice and andesite boulders	Taupo Pumice, first occurrence
450 mm Reworked ash and andesite pebbles	Reworked ash and pebbles
150 mm Andesitic coarse-sand-grade ash (Stratford)	Oakura Tephra
300 mm Soil with iron nodules	Buried soil
180 mm Cross-bedded andesitic coarse sand and pebbles	6,300 yr maximum sea level
90 mm Laminated silt-grade putty-coloured ash (Stent Ash middle member)	Stent Ash (middle member) 6,970 ± 76 yr B.P. (NZ1144)
900 mm Soft andesite agglomerate	Warea Formation
	Okato Tephra (preserved in pockets, elsewhere eroded by overlying lahar).
900 mm Peat at about M.H.W.M.	Peat dated (NZ1361) at 18,350 ± 380 yr B.P.
Hard old agglomerate	Pungarehu Formation

COMPOSITIONAL DIFFERENCES BETWEEN MOUNDS AND INTER-AREAS

From preliminary investigations of many hundreds of mounds in Taranaki it was clear that certain relationships existed between the volume of matrix to boulders in mounds and inter-areas. In order to show this, photographs were taken of selected representative sections, cleaned (fretted) to the same degree, and point counting of the components was carried out with an underlay of graph paper. In an attempt to keep the method consistent, photographs record a similar field of view except where lithologies were relatively fine, when photos were taken closer to the outcrop to discern pebble edges. Apart from one photograph of an unusual section where only 432 points could be counted, 23 photographs were examined with between 763 and 1022 points counted on each. Photographs included:

(a) interiors of mounds

(b) the mantling or "shell" material on the mound, which is exceedingly hard, and

(c) the inter-areas

The analyses were grouped into four divisions:

(a) less than 4 mm, or matrix,

(b) 4-64 mm, cobbles,

(c) 64-256 mm, pebbles, and

(d) >256 mm boulders,

and are presented in Fig. 46.

In the Pungarehu Formation near source the matrix ranges from 9.3 to 28.7% and in the centre of a mound near Pungarehu there was only 6.6% matrix. From additional visual observations most mounds inland from Pungarehu are likely to show matrix values which would fall within this range. Between Highway 45 and the coastline, matrix values of 15.6% at Stent Road, 28.6% at the

FIGURE 46 - Grain size analysis of western Taranaki lahar deposits. Pungarehu Formation data is separated into interiors of mounds, "shells" of mounds, and "inter-areas". For method of analysis see text (in "Compositional differences between mounds and inter-areas")

Formation		Sample Locality	Grid Reference	Reference Number	(a) Matrix <4mm	(b) 4-64mm	(c) 64-256mm	(d) >256mm
PUNGAREHU FORMATION		Parihaka Rd.	N118/487628	A1	28.7	24.3	20.0	26.9
	Mounds	Quarry, Wiremu Rd.	N118/506548	A2	9.3	72.6	13.0	4.9
		Highway 45	N118/404653	A3	42.9	48.3	8.6	
		Pungarehu Rd.	N118/359652	A4	48.1	31.1	20.6	
		Coast, Bayly Rd.	N118/367677	A5	28.6	39.9	23.9	7.4
		Highway 45	N118/403650	A6	6.6	45.8	47.6	
		Jtn. Highway 45-Tipoka Rd.	N118/398602	A7	37.6	58.9	3.3	
	(see Fig.47)	Stent Rd.	N108/373710	A8	15.6	31.7	37.2	15.3
		Oxford Rd., Okato	N108/474745	A9	78.4	8.7	8.7	3.9
	"Shells"	Highway 45	N118/403650	A10	72.7	21.7	5.4	
		Highway 45	N118/403650	A11	50.8	36.8	7.2	5.0
		Coast, Bayly Rd.	N118/367677	A12	33.3	40.4	18.9	7.2
		Highway 45, nr.Rahotu	N118/398605	A13	64.0	26.9	9.0	
	"Interareas"	Stent Rd.	N108/373711	A14	57.8	28.0	10.3	3.8
		Bayly Rd.	N118/370685	A15	52.9	33.8	13.1	
		Bayly Rd.	N118/370685	A16	56.1	42.2	1.6	
WAREA FORMATION		Oeo-Opunake Rd.Jtn.	N118/610483	B1	24.7	63.1	12.1	
		Arawhata Rd.Coast	N118/403473	B2	58.5	28.9	12.6	
		Highway 45	N108/431745	B3	92.0	7.9		
OPUA FORMATION		Feaver Rd.	N118/484497	C1	33.4	57.5	9.0	
		Kaweora Rd.	N118/526484	C2	7.2	78.2	14.4	
		Heimama Stream	N118/433449	C3	57.1	34.5	8.2	
	(see Fig.48)	Opunake Beach	N118/445434	C4	66.9	26.1	6.8	
		Opua Road	N118/515525	C5	73.4	24.8	1.8	

FIGURE 47 - Photograph of section A8 of Fig. 46, showing interior of Pungarehu Formation lahar mound, at N118/445434. Scale is 30 cm long.

FIGURE 48 - Photograph of section C4 of Fig. 46, at N108/373710, from "inter-area" of Opua Formation. Scale is 30 cm long.

coastal end of Bayly Road, 37.6% near Tipoka Road, 42.9% near Pungarehu and 48.1% on Pungarehu Road, were obtained. "Shells" photographed on the tops and sides of mounds showed values of 64%, 51%, 73% and 33% and even in the latter case which is noticeably lower than the others, it was a higher matrix value than the interior of the mound. Matrices measured between mounds (inter-areas) showed values of 58%, 53% and 56% even though they do contain some large fragments.

In the Warea Formation, a 24.7% matrix value was measured in mounds near source. A value of 59% was obtained from the coastal end of Arawhata Road where there are no mounds, and in the northern lobe where there has been extensive water sorting the matrix totals 92%.

In the Opua Formation, matrix values inside mounds were 33%, and 7%, both measured about 17 km from source. Inter-area matrix values were 57% and 67% on the coast. A thin veneer of the formation at its northern margin showed 73% matrix.

From the above data it is apparent that no mound interior showed a % matrix in excess of 48.1% and that no inter-area showed a % matrix less than 52.9%. In addition all measurements of mound "shells" showed an increased % matrix compared to the interior of the mound. Thus although the large boulders within and between mounds are common it is the relative abundance of boulders within mounds which characterise them from adjoining inter-areas.

THE FORMATION OF "CONICAL HILLS" OR LAHAR MOUNDS

The origin of "conical hills" that surround many of the circum-Pacific andesite volcanoes has received spasmodic interest. Controversy in the 1920's on the origin of the Taranaki hills has already been mentioned. The mounds of the Pungarehu, Warea and Opua formations could conceivably be:

(1) Primary Volcanic
(2) Tectonic
(3) Geomorphic
(4) Archaeological
(5) Glacial, or
(6) Laharic in origin.

Taking these in turn:

(1) The layered nature of the flow units and absence of vertical connections precludes the hills being small volcanoes, (Clarke 1912; Gibson and Morgan 1927). None of the flow units show lava flows beneath mounds (Bossard 1928).

(2) The hills are not related to fault lines and are too numerous to represent compressional swells.

(3) None of the hills show a differing rock type to the inter-areas that would indicate they are long term erosional features. Both hills and surrounding flat land are continuous and widespread yet relatively thin.

(4) The mounds were formed prior to the human occupation of New Zealand, although many have since been used as Maori pa sites (Dr. F.X. Schaffer in Palmer 1930, on Indonesian mounds).

(5) There is no evidence of definite glacial deposits on Mt. Egmont and the altitude of the mounds is inconsistent with

levels of glaciation elsewhere in New Zealand at this time.

(6) The formation of mounds by lahars in Indonesia and New Zealand has been witnessed on a number of occasions (Grange 1931). The mounds in Taranaki closely resemble the products of historic lahars and are accepted as having been deposited by them.

The formation of "conical hills" by lahars is a widespread phenomenon but little attention has been paid to the processes that lead to their formation. Mounds are known to have formed relatively rapidly because in 1914 on White Island, N.Z., lahar mounds formed over a period of less than two days. In addition, the resultant mounds show accordant summit heights which are considered remnants of a planar upper surface of the lahar. Following the collapse of Bandaisan cone in 1888, Jaggar (1930) reported that the resultant lahar deposit began to sink below its maximum level. This was attributed to consolidation and it was noted that the tops of the remaining hills corresponded with remnants of the upper level of the lahar deposit.

The reason why parts of a lahar flow continue to be mobile whilst other areas are immobile has never been fully explained. Settling of material in the lee of a single large boulder has been suggested as an origin for each hill (J.B. Bradley, pers. com.) but many hills do not contain single large boulders, and many of the largest boulders observed in this study do not occur beneath mounds. Settling of material around slowly melting blocks of ice can also be discounted because lahar mounds have formed in many areas where snow and ice are absent e.g. 1914 White Island lahar, and lahars in Indonesia produced by collapse of crater lakes. Mason and Foster (1956) consider some mounds at Nirasaki, Japan, have formed by extrusion of materials through a hardened crust of a lahar flow. It seems likely that one of two processes leads to this differentiation of the flow. Either

(1) the components of the dispersed phase are never properly mixed in the flow and "clots" of these materials separate out as the more mobile components drain seawards, or

(2) the dispersed phase becomes completely admixed with the continuous phase, and mound formation is related to a settling phenomenon.

The unusual inclusions within the Pungarehu Formation (described under "Fragments") are considered evidence that complete mixing of all components did not take place and that alternative (1) is most likely.

PUNGAREHU FORMATION MOUNDS

Since the bulk of the Taranaki lahar mounds belong to the Pungarehu Formation, the following discussion relates to this formation only. The flat-topped nature of mounds on Puniho Road, and the general accordant hill heights suggest the Pungarehu lahar flow possessed a near planar upper surface. In cross-section the flow would have been a broad sheet slightly domed towards the centre corresponding to the highest "conical hills". Towards the margins of the deposit the mounds decrease in size and merge into an even surface. At Okato, below the even surface, the deposit shows the highest matrix value obtained in this study of the Pungarehu Formation (78.4%). This is probably due to a high proportion of water at the flow margin which mixed boulders with copious quantities of ash mantling the older Pouakai ringplain.

Once the flow was initiated the velocity generated by the steep gradient and gravitational acceleration combined with a high density of component materials in suspension (the continuous phase of Fisher 1972), allowed boulders 3-4 m across to be carried. On the lower slopes of the volcano, substantial portions of the flow would have lost velocity and competence to carry larger fragments of the dispersed phase, which were not admixed with the continuous phase, and they would have begun to settle towards the base. The relative increase in friction at the base of the flow would also aid further settling. Coarse material accumulated until it exceeded a critical dimension as finer mobile material was directed to both sides. Less mobile material settled and built up in linear ridges behind the initial accumulations. However, along the main axis of the flow there is a substantial unchannelled deposit which corresponds to the area of largest mounds (Fig.20), probably representing the main axis of deposition. The lack of distinct drainage channels in the axial part of the flow suggests a large porportion of the coarsest material had come to rest a short distance from source and was incapable of flowing further. This prevented finer materials draining into channels. In contrast the distal and lateral margins show distinctive channelling indicative of more protracted flow.

As the surface of the lahar flow began to subside, near source hills began to protrude above the surrounding lowering level of finer material which continued to drain seawards. As larger fragments in the zones of accumulation became immobile they began to collapse together and finer material within interstices seeped laterally outwards subtracting matrix from the mounds. Many fragments would reach stability upon piles of boulders beneath, whilst those which became unstable on removal of the fines would have slid from ridges or mounds of coarse material. In this way the tops of the present hills represent remnants of an upper surface of the flow and their slopes most nearly represent the natural angle of rest of the exposed component breccia or conglomerate. It is apparent that the 30m high mounds inland imply a greater relative drop in the level of the flow compared to the 10 m high mounds near the coast. The gradual decrease in size and number of mounds seawards corresponds to where finer material continued to flow further towards the distal margin as the proportion of coarser material decreased.

The reason for the hill formation is therefore attributed to accumulation of largely unmixed portions of the flow where there is an obvious change in gradient from the steep upper Egmont slopes above 300m (about 1 in 6) to the gentle lower slopes (about 1 in 66). There is a very strong correlation between the mound distribution and slope.

In near source deposits the chaotic nature of the fragments, their large size, and intense shattering strongly suggest the flow was turbulent. However ?distal units between Opunake and Manaia appear to have been deposited by laminar flow, possibly due to excess water draining seawards after the main load was deposited. It is probable that the vesicles described earlier, which are present in the matrix, contained pockets of entrapped air which probably result from fluidisation in the flow, which enabled the flows to travel such large distances.

The presence of a "shell" of finer material around most mounds can be explained either as

(1) the fine material that seeped from the interstices of the boulders within the mounds to the exterior or

(2) as a thin veneer of material which had been continuous over the mounds and inter-areas but which had adhered to and hardened on the upper portions of the mounds to form a crust.

Because they most frequently occur on the sides of mounds only and not on the inter-areas, the first origin is considered most likely.

WATER REQUIREMENTS

Almost all Taranaki mudflows and debris flows have been water based, but debris flows are many times smaller than the huge mudflows which travelled beyond the present coastline. In the Maero debris flows and the Kahui Formation most of the component materials came to rest about 5-10 km from source, as water continued to flow from the terminal margin of the deposit similar to a huge flood. In contrast the mudflows of the Pungarehu, Warea and Opua Formations appear to have contained vast quantities of water which transported debris 20-30 km to the coast. The most likely sources of such large quantities of water are

(1) from very heavy rains
(2) melting of snow and ice
(3) stored water in or on a volcano e.g. a crater lake, and
(4) eruption of juvenile water.

Taking these in turn:

(1) Heavy rains have been known to have produced lahars but are not known to produce strongly directional deposits of such large size as the Pungarehu Formation.

(2) Grant-Taylor (1970) considered that many of the older lahar deposits in Taranaki "developed by eruptions under much thicker ice during the glaciations". In such times "eruptions melting the ice and snow would much increase the bulk of water thrown out during an eruption". Cold climate pollens extracted from peats interbedded with lahar deposits older than 30,000 yr B.P. support this idea. However some authors have shown that large quantities of water are not produced from melting of snow

and ice during eruptions, probably because of the large amount of heat required almost instantaneously. Kjartansson's (1951) calculations on the amounts of water released from the 1949 Hekla eruption show that the bulk of water could not have been derived from the melting of snow and ice and he suggests it was water released from within the volcanic crater, probably as juvenile water. Mathews (1952) has described lavas that were dammed by a Pleistocene ice sheet in British Columbia, Canada. Also Robinson (1948, p.525) illustrated a photograph of a steaming lava dome protruding from an ice filled crater on Great Sitkin Island in the Aleutians, which shows no surface water or meltwater streams and most ice is simply cracked.

It would be very difficult to determine origin (3) and (4) when dealing with pre-historic lahar deposits. The cliff section exposed at Opunake is correlated with the type section of the Kahui Formation (Fig. 49). Two radiocarbon dates (NZ1257 and NZ1361) collected from Mangahume Stream 1.5 km to the south-east of Opunake, and from Stent Road 20.5 km to the NNW, have also been correlated to the Opunake section. The combined sequence shows up to 13m of lahar deposits accumulated between about 33,000 and 23,000 yr B.P. A period of peat accumulation occurred between 23,000 and 16,000 yr B.P., with a further period of lahar accumulation from 14,000 yr B.P. to the present. The period 33,000 to 23,000 yr B.P. is recorded (Emiliani 1966) as having been of temperate climate compared to the cooler period which followed between 22,000 and 15,000 yr B.P. In addition during the amelioration of climate following the last stadial 12-6,000 yr B.P., the Kahui Formation was deposited nearer source. My

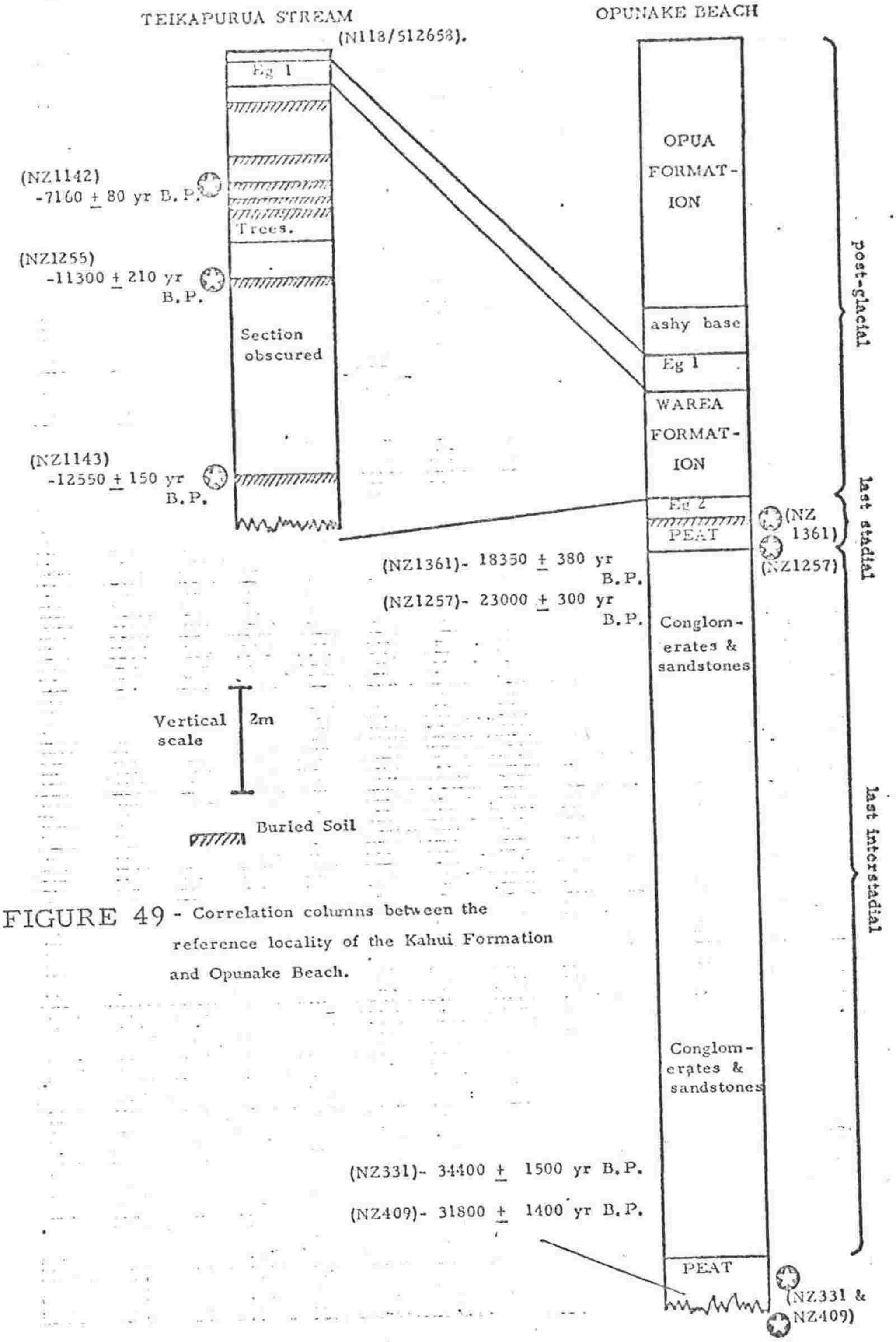


FIGURE 49 - Correlation columns between the reference locality of the Kahui Formation and Opunake Beach.

interpretation of this sequence is that during the last stadial widespread peat accumulation occurred at the present coastline and during the interstadial and post-glacial periods there was a high frequency of lahars consequent on increased rainfall and greater water storage at high levels within the volcano. In one of the largest historic lahars known, from Mt. Keloet, Indonesia, an estimated 30-40 million m^3 of water released from its crater lake transported debris up to 30 km from source. This indicates the large amount of water which can be stored in a volcanic crater, not always by a lake of large areal extent but by one which is relatively deep. The jokulhlaups of Iceland are examples of water being stored in volcanic craters subglacially. Thorarinsson (1957) considers that little ice is melted directly when jokulhlaups are initiated, but that most water is stored meltwater mixed with some juvenile water.

The summit of Mt. Egmont is a likely area for water to have been stored in the past. The region has an unusually high rainfall at present (between $10 - 15 \times 10^3$mm per annum) and the area is likely to have had a high rainfall, relative to most other areas of New Zealand, during the late Quaternary. The source of water available for transportation of the vast quantities of debris present in the Opua, Warea and Pungarehu Formations is thus considered most likely to have originated from water storage on the volcano, probably in the form of a crater lake.

The widespread uniform thickness of older lahar deposits on interfluves along the southern Taranaki coastline may be interpreted three ways:

(1) Rivers would aggrade during glacial periods so that lahars would spread over a wide area. During interglacial periods there were no large lahars. This proposal as an absolute generalisation is unlikely because of the occurence of interstadial and post-glacial lahars in western Taranaki.

(2) As above, but during interglacials, lahars were channelled along deeply incised gullies. It is however unlikely that a large lahar would be confined to a single river channel as it would tend to spread laterally outwards in a lobate form. The latest large-scale collapse from Egmont formed the Opua lahar, 20 km in width at the present coastline and spanning 13 major stream and river channels.

(3) There has not been a major difference in the preservation of lahars in glacial and interglacial periods, so that a lahar is likely to quickly fill any river gullies (most of which are small at present) and spread laterally, irrespective of the climatic regime. This alternative is consistent with the observed data obtained at present on lahar deposits in Taranaki.

CONCLUSION

The lahars which deposited the formations described in this paper are considered to have formed by gravity collapse of Egmont cone with accompanying release of substantial quantities of water probably from a crater lake during periods of temperate climate about 25,000 yr B.P. and between 14,000 yr B.P. and the present day.

REFERENCES

Blackwelder, Eliot, 1928: Mudflow as a geologic agent in semi-arid mountains. Geological Society of America Bulletin 39: 465-80.

Bossard, L. 1928: Origin of the conical hills in the neighbourhood of Mount Egmont. N.Z. Journal of Science and Technology 10(2): 119-124.

Broscoe, A.J.; Thomson, S., 1969: Observations on an alpine mudflow, Steele Creek, Yukon. Canadian Journal of Earth Sciences 6(2): 219-29.

Clarke, E. de C., 1912: The Geology of the New Plymouth Subdivision. N.Z. Geological Survey Bulletin n.s.14. 58 pp.

Curry, R.R., 1966: Observation of alpine mudflows in the Tenmile Range, Central Colorado. Geological Society of America Bulletin 77: 771-6.

Druce, A.P., 1970: The Vegetation pp.45-59 in Scanlan, A.B. (Ed.), Egmont National Park Handbook. Egmont National Park Board, New Plymouth.

Eiby, G.A., 1968: An annotated list of New Zealand Earthquakes, 1460-1965. N.Z. Journal of Geology and Geophysics 11: 630-47.

Emiliani, C., 1966: Paleotemperature analysis of Caribbean cores P6304-8 and P6304-9 and a generalised temperature curve for the past 425,000 years. Journal of Geology 74: 109-126.

Fisher, R.V., 1971: Features of coarse-grained, high-concentration fluids and their deposits. Journal of Sedimentary Petrology 41(4): 916-27.

Fleming, C.A., 1953: The Geology of Wanganui Subdivision. N.Z. Geological Survey Bulletin n.s.52: 362pp.

Fleming, C.A., 1959: Ferdinand von Hochstetter, Geology of New Zealand. Government Printer, Wellington, 320pp.

Gibson, W.; Morgan, P.G., 1927: The Geology of the Egmont Subdivision. N.Z. Geological Survey Bulletin n.s. 29: 99pp.

Gorshkov, G.S., 1959: Gigantic eruption of the Volcano Bezymianny. Bulletin Volcanologique, 20: 77-109.

Gorshkov, G.S.; Dubik, Y.M., 1970: Gigantic directed blast at Shiveluch Volcano (Kamchatka). Bulletin Volcanologique 24(1): 261-88.

Grange, L.I., 1931: Conical Hills on Egmont and Ruapehu Volcanoes. N.Z. Journal of Science and Technology 12(6): 376-84.

Grant-Taylor, T.L., 1964: Geology of Egmont National Park. Pp.13-26 in Scanlan, A.B. (Ed.): Egmont National Park. Egmont National Park Board, New Plymouth. 87pp.

Grant-Taylor, T.L., 1970: Geology of Egmont National Park. Pp. 69-82 in Scanlan, A.B. (Ed.): Egmont National Park. Egmont National Park Board, New Plymouth. 86 pp. (Revised ed.)

Grant-Taylor, T.L.,; Kear, D., 1970: Geology pp.20-23 in Waimate West County, N.Z. Land Inventory Survey - County Series. Department of Lands and Survey. Government Printer, Wellington. 60 pp.

Grant-Taylor, T.L.; Rafter, T.A. 1971: New Zealand Radiocarbon Age Measurements - 6. N.Z. Journal of Geology and Geophysics 14(2): 364-402.

Hay, R.F., 1967: Sheet 7 Taranaki (1st ed.) "Geological Map of New Zealand 1:250,000". Department of Scientific and Industrial Research, Wellington.

Jagger, T.A., 1930: Some analagous bowlder hillocks. The Volcano Letter 286. p.3

Kjartansson, G., 1951: Water Flood and Mud Flows. II,4 of The Eruption of Hekla 1947-1948. Vísindafélag Íslendinga (Societas Scientiarum Islandica) & Museum of Natural History, Reykjavík. 51 pp.

Mason, A.C.; Foster, H.L., 1956: Extruded mudflow hills of Nirasaki, Japan. Journal of Geology 27(1): 74-83.

Mathews, W.H., 1952: Ice-damned lavas from Clinker Mountain, Southwestern British Columbia. American Journal of Science 250: 553-65.

McDougall, J.C.; Gibb, J.G., 1970: Patea sediments. N.Z. Oceanographic Institute Chart, Coastal Series, 1:200,000.

Neall, V.E., 1972: Tephrochronology and tephrostratigraphy of western Taranaki (N108-109). N.Z. Journal of Geology and Geophysics 15(4): 507-57.

Palmer, H.S., 1930: The Bowldery Hills of Galounggoung. The Volcano Letter 286: 2-3.

Robinson, G.D., 1948: Exploring Aleutian Volcanoes. National Geographic Magazine 94: 509-28.

Schmincke, H-U., 1967: Graded lahars in the type sections of the Ellensburg Formation, South-Central Washington. Journal of Sedimentary Petrology 37(2): 438-48.

Sharp, R.P.; Nobles, L.H., 1953: Mudflow of 1941 at Wrightwood, Southern California. Geological Society of America Bulletin 64: 547-60.

Soil Conservation and Rivers Control Council, 1957: Floods in New Zealand, 1920-53, with notes on some earlier floods. Government Printer, Wellington. 239pp.

Thorarinsson, S., 1957: The Jökulhlaup from the Katla Area in 1955 compared with other Jökulhlaups in Iceland. Jökull, 7.ar, Reykjavík: 21-5.

Wellman, H.W., 1962: Holocene of the North Island of New Zealand: a Coastal Reconnaissance. Transactions of the Royal Society of New Zealand (Geology) 1(5): 29-99.

CHAPTER 6

STRUCTURE OF EGMONT CONE

The boundary of Egmont National Park, defined as a 6 mile radius (9.5 km) from Egmont summit, is at 450m (1,500ft) altitude to the east and 390m (1,300 ft) to the west indicating Egmont cone is not perfectly symmetrical from east to west. This slight asymmetry is due to large scale collapses from the west side of the cone which have resulted in slightly steeper gradients. In a north-south cross-section the Egmont cone is broken to the south by Fanthams Peak, frequently referred to as a parasitic cone to Egmont. The southern cone has been in existence for at least 35,000 years and may have formed prior to the Egmont cone in which case "Egmont" has become parasitic upon "Fanthams Peak" and then grown larger.

Above the 450m contour the ringplain surfaces, which extend to the western Taranaki coastline, abut against the upper Egmont cone. Frequently the contact is obscured by scree covered lava flows which terminate near the 1,200m contour. The oldest parts of the upper cone are preserved in the west between West Ridge and Bobs Bluff, and in the north and east between Carrington and Curtis ridges. Many remnants of the old lavas are preserved as flows capping ridges which have been severely dissected by lateral stream channel erosion. Many of the gullies incised within the old lava flows have since been filled by more recent flows which include Minarapa Stream lava flow, (see Frontispiece), Sharks Tooth, Dray Track and Skeets Ridge flows, the latter in the amphitheatre between Bobs Bluff and Fanthams Peak. The old lavas are likely to be less than 16,000 years old because they could not have been extruded until after the dated Warea Formation originated from the cone. The younger flows to the north and south in contrast postdate the <7,000 year old Opua Formation. Some of these flows have followed the present day stream channels and have also been diverted away from Fanthams Peak. Thus most of the upper Egmont cone appears to have been constructed during the Holocene.

On the eastern side of Egmont cone is a flattening of slope near the 1,200m contour which Grant-Taylor (1964) referred to as a somma-ring, formed by subsidence of the upper parts of the mountain, and that Egmont has grown in a caldera. Somma-ring is defined as "a high, circular or crescent-shaped ridge, with steep inner walls, surrounding a central volcanic cone" (A.G.I. Dictionary 1960). None of these features are present on the east side of Egmont and the plateau referred to by Grant-Taylor is where the volcaniclastics abut against the lavas of the upper Egmont cone. In certain areas lavas have flowed onto the volcaniclastics e.g. West Ridge.

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VOLCANIC DOMES AND LINEATIONS IN EGMONT NATIONAL PARK

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ABSTRACT

Three zones of radial lineations interpreted as faults are described on the lower slopes of Mt Egmont. Magma is considered to have ascended along three of the faults to form four cumulodomes—The Dome, Skinner Hill, and the two Beehives. Jointing patterns, concentric to the margins, suggest that the cumulodomes formed largely by internal growth.

INTRODUCTION

Mt Egmont is a volcanic cone 8,260 ft in elevation, on the west coast of the North Island of New Zealand, 140 miles north-west of Wellington. Its simple conical shape is broken only by Fanthams Peak, a smaller cone to the south. The steep non-vegetated scree-covered slopes of the upper cone pass downwards to the more gently dipping forest-covered lower slopes below 4,000 ft. The mountain lies largely within Egmont National Park, the Park boundary being a circle of 6 mile radius from the summit, except to the north where it extends to include the Pouakai and Kaitake Ranges. Four dome-shaped hills, covered by heavy forest, protrude from the lower slopes of the mountain. The names of the domes are those used on sheets N108, N109, N118, and N119 of the 1 : 63,360 topographical map series (NZMS 1), except for the two Beehives which, to avoid confusion, are independently referred to as Northern Beehive* and Southern Beehive*. The two Beehives are 4 km and 5 km respectively to the south of the summit. The Dome is at the foot of the northern slope of Mt Egmont, adjacent to the southern slopes of the Pouakai Range, and Skinner Hill, 4,300 ft, lies half way up the northern flank of Egmont, almost due south of The Dome. Skinner Hill is partially covered by debris flow material from the upper cone of Mt Egmont.

PREVIOUS WORK

Gibson and Morgan (1927), in a survey of the Egmont Subdivision, regarded the Beehives as probably being small volcanic cones, parasitic to Mt Egmont. Arnold (1959) suggested that they are "very viscous lava . . . extrusions". Numerous "conical hills" in Taranaki are considered to be laharic in origin (Grange, 1931). Grant-Taylor (1964) regarded the two Beehives as probably being unusually large "conical hills" perhaps "formed around exceptionally large blocks of andesite lava stranded at the bottom of the steep mountain slope".

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*These are not approved Geographic Board names.

N.Z. Journal of Geology and Geophysics 14 (1): 71–81

TERMINOLOGY

The terminology of volcanic domes is confused and unsatisfactory since domes formed by identical processes are divided only on the basis of whether or not they are extruded within a pre-existing crater.

The term "tholoid"—anglicised from "tholoiden" by Escher in 1920—is a convenient term for domes extruded within craters, with the dome on Galunggung (Java) being the type example. The term "cumulodome" as used by Holmes (1965) is "an isolated volcanic dome which shows no sign of a crater or orifice". (The term as originally used by Fouque (1879) is "cumulovolcans".) Indicative of the confusion of the literature the term "tholoiden" was first applied to the Grand Puy de Sarcoui in the Auvergne, which is now regarded by Holmes as a "cumulodome".

The term "volcanic dome" can be used for both cumulodome and tholoid, and was defined by Williams (1932) as a "steep-sided, viscous protrusion of lava forming a more or less dome-shaped mass around its vent". It is suggested that Williams' phrase "around its vent" would be better expressed as "above and within its vent". In general, a volcanic dome is developed by internal and external accumulation of highly viscous lava over a hidden vent.

STRUCTURE OF THE DOMES

Hay (1967) identified Mt Egmont (including the four domes described) and the Pouakai Range as hornblende-andesites. I have examined thin-sections from all of the domes and a few lavas from the main cone of Mt Egmont, and they are predominantly pyroxene-andesite and plagioclase-pyroxene andesite. The Southern Beehive and Skinner Hill are composed of hornblende-andesite. (The andesite terminology is that used by Clark, 1960.)

The Dome (N118/624668*) shown in Figs. 1, 2, and 3, is 3,439 ft in elevation, and rises as a steeply sided, dome-shaped structure 400 ft above the surrounding debris flow surfaces. It presents a smooth hemispherical outline from all directions. The Dome has steep slopes with a gently undulating relatively wide upper surface of about $4{\cdot}5 \times 10^4$ m^2. The estimated volume is $2{\cdot}57 \times 10^7$ m^3. It is elliptical in plan, being 0·8 km long in an east–west direction and 0·5 km in a north–south direction. An arcuate furrow, concave to the west, runs across the undulating top of the dome. According to Mr A. R. Duncan (pers. comm.) a volcanic dome on the flank of Mt Edgecumbe shows a similar arcuate furrow. The northern part of The Dome has been eroded through by Stony River forming a 300 ft andesite lava section showing vertical columnar joints up to 200 ft high in the basal part. The base of the dome is exposed behind the foot of Bells Falls and rests on volcanic conglomerate. The basal contact dips to the south at about 25°.

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*Grid reference based on the sheet district of the 1 : 63,360 topographical map series (NZMS 1) and the national thousand-yard grid shown on that series.

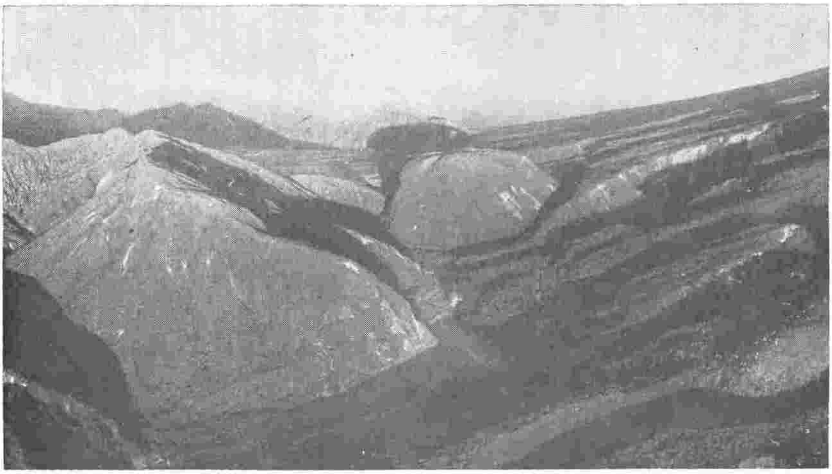
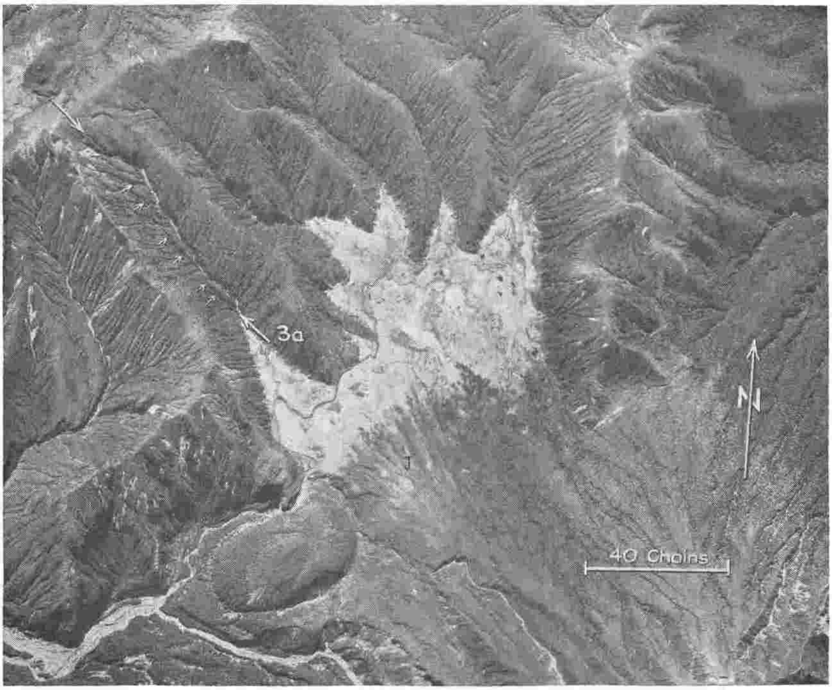


FIG. 1—The Dome (centre) viewed from the west, at sunset, with its shadow cast on to ridge of Pouakai Range (middle background). Debris flow surfaces derived from Mt Egmont (right) with the Pouakai Range (to left).



By courtesy of Department of Lands and Survey

FIG. 2—Vertical aerial photograph of The Dome (lower left) and Ahukawakawa Swamp (centre). Arrows indicate lineation 3a. Recent debris flows derived from Mt Egmont extend into Ahukawakawa Swamp from the south (point J). Measured line (40 chains) = 800 metres.

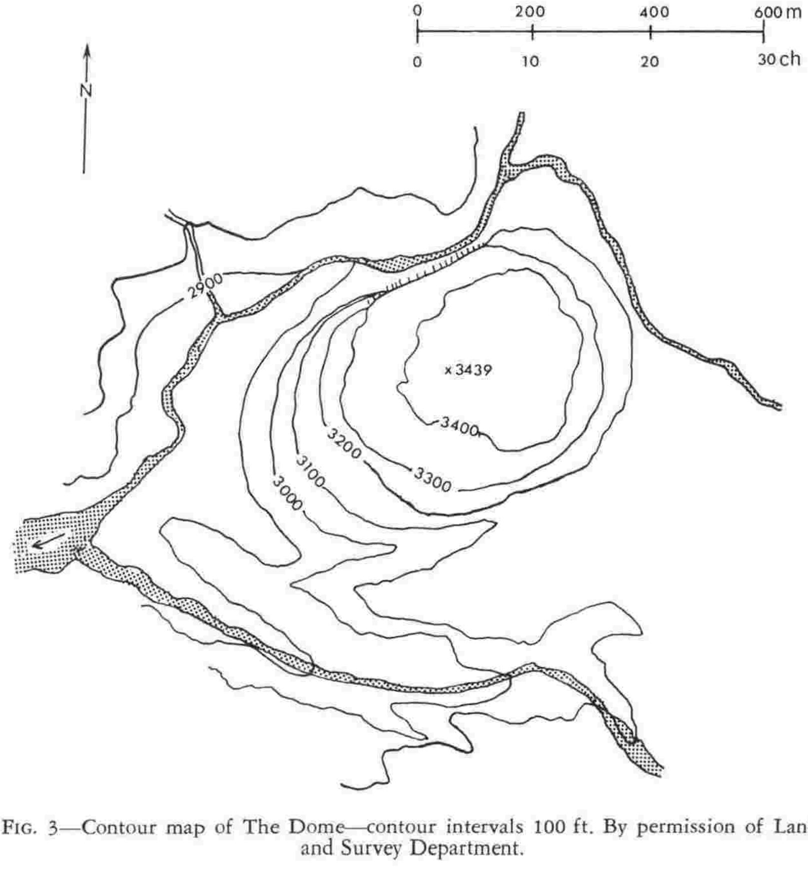


FIG. 3—Contour map of The Dome—contour intervals 100 ft. By permission of Lands and Survey Department.

FIG. 4—View of Skinner Hill from the north-west, Mt Egmont in background to the left.

Skinner Hill (N118/625648) has an elevation of 4,300 ft (*see* Fig. 4). It shows a domed form only from the north, since the southern part has been buried beneath debris flow material from the upper cone of Mt Egmont. The dome is 0·5 km wide in an east–west direction and 400 ft high. The volume is estimated to be about $5{\cdot}74 \times 10^6$ m^3. The exposed part of the upper surface is nearly horizontal. Upsom Stream has cut through the northern part of the dome to expose weak columnar jointing overlain by jointing concentric to the surface of the dome. A slip scar 50 m north-west shows the same concentric joint pattern. A rock sample from the slipface is a vesicular hornblende-andesite strongly stained by limonite.

The lack of outcrops to the south-east side of Skinner Hill does not allow a complete investigation of the structure, and the hill could also be interpreted as a coulée. From the observed jointing and the proximity of the other circular cumulodomes, Skinner Hill is included with them.

The Northern Beehive (N118/641577), 3,121 ft in elevation (shown in Figs. 5 and 6), lies on the gently seaward-dipping southern slopes of Fanthams Peak. Not as steep-sided as the other domes, it rises 200 ft from a circular base to a nearly flat summit $1{\cdot}1 \times 10^4$ m^2 in area. Its basal diameter is 0·5 km and its volume is estimated to be $7{\cdot}2 \times 10^6$ m^3. Its base is buried by debris flow material derived from the north. The only outcrop found on the dome is in a small stream that drains Lake Dive, half a mile from the outlet. The rock is pyroxene-andesite with minor olivine. Vertical joints concentric to the centre of the dome cross the stream obliquely, forming small ponds and waterfalls.

The Southern Beehive (N118/640570) shown in Figs. 5 and 6, the smallest of the four domes, rises almost 300 ft above the surrounding slopes as a perfect hemisphere. Its elevation is 2,775 ft, its basal diameter is 0·4 km, and its estimated volume $2{\cdot}5 \times 10^6$ m^3. Like the Northern Beehive, its perfectly circular basal outline has been obscured by debris flow material derived principally from the north-north-east. No clear rock exposures are visible, but a 2 m deep pit, excavated through tephra on top of the dome, exposed a highly irregular surface of vesicular lava. The lava is a hornblende-andesite with marked trachytic texture.

TABLE 1—Dimensions of the Three Prominent Domes

	Diameter (metres)	Height (metres)	Height (feet)
The Dome	max. 700, min. 400	162	540
Northern Beehive	400	120	400
Southern Beehive	300	83	275

By courtesy of Department of Lands and Survey

FIG. 5—Vertical aerial photograph of Northern Beehive and Southern Beehive (lower left). Arrows indicate lineations 3d and 3e. Cross marks bog-iron deposit. Measured line (40 chains) = 800 metres.

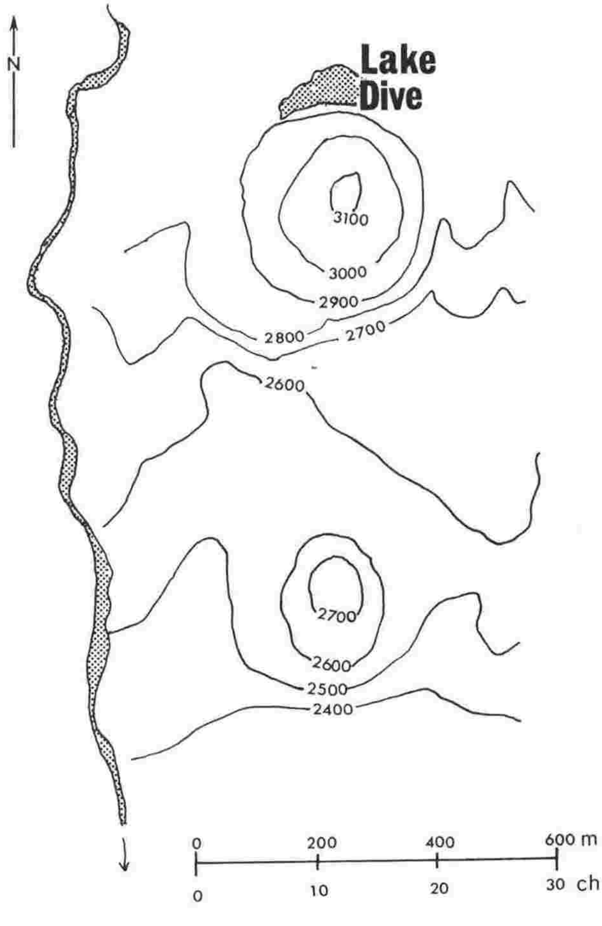


FIG. 6—Contour map of the Beehives, contour interval 100 ft. By permission of Department of Lands and Survey.

DOME INTERPRETATION

Williams (1932) in his general survey of volcanic domes of the world stated that lava of high viscosity is a prerequisite to their formation. Domes are thus composed of lavas of acid and intermediate composition and not of the more fluid basic lavas. He recognised nine types of lava associated with volcanic domes, pyroxene-andesite—the rock of which two domes are largely composed—being the most abundant.

No cumulodomes have been observed on the upper cone of Mt Egmont. All four cumulodomes described are located between the altitudes of 2,000 ft and 5,000 ft on the lower slopes of the volcano, which has an average slope of 12°. Lava extruded from the summit crater of Mt Egmont has flowed on slopes averaging 28°, from the top of the mountain at 8,000 ft altitude down to about 4,000 ft. The same viscosity lava extruded on slopes of 12° could well form domes instead of flowing downhill.

LINEATIONS

Because of its conical form, the drainage pattern of Mt Egmont is radial and fairly regular. Examination of aerial photographs showed a number of radial streams to have unusually straight reaches sometimes flanked on one side by high lava cliffs. Other evidence includes 30 offset streams, a bog-iron deposit, and straight reaches in a number of streams being strongly collinear. The linear reaches and the high straight cliffs are considered to have been caused by faulting. Most other streams on Mt Egmont are not linear and follow irregular, winding courses. Descriptions of the lineations are listed below; letters in brackets after the names of geographical features refer to their locations as shown on Fig. 7.

1a—Straight reach in Cold Creek (A); collinear with straight reach in unnamed creek and straight stretch in Mangahume Stream (B). In upper Mangahume Stream lineation flanked to north-west by high lava cliffs of Bobs Ridge (C).

1b—From Dieffenbach Cliffs (D), linear reach along main headwater stream of Waiwakaiho River; flanked to north-west by line of south-east facing cliffs in middle reaches of river down to 2,000 ft contour.

2a—Straight reach in a tributary of Okahu Stream, to south of the hill Maru; lineation extends approximately eastwards along cliffs forming upper part of Skeets Slide (E), to upper Okahu Gorge; lineation flanked by linear cliff of northerly facing columnar jointed andesite, to south of Okahu Gorge, adjacent to West Ridge (F).

2b—Lineation begins south of Warwick Castle (G) and continues eastwards along a tributary of Manganui River to north-east of Curtis Falls (H); lineation continues eastwards for over 2 miles along main channel of Manganui River to beneath the 2,000 ft contour.

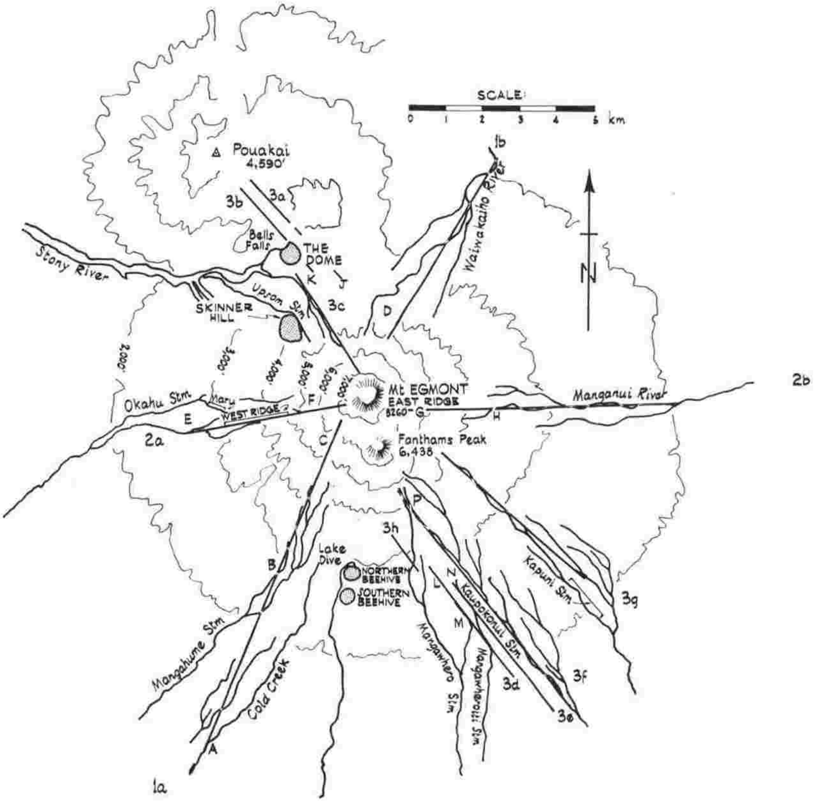


FIG. 7—Lineation pattern constructed from aerial photographs and ground observations. Contour interval, 1,000 ft. For symbols used see text.

The third and most dominant set of lineations (Lineations 3a–3g) occupies a 1½ km zone trending in a north-west–south-east direction.

3a—Marked by a lineation which strikes parallel to and just to south of small stream to north of Bells Falls; recent debris flows in order of a few hundred years old are considered to have covered the trace to the south (J): the lineation corresponds to a line of disturbed drainage in 11 stream courses, interpreted as due to faulting.

3b—Parallel to lineation 3a, and striking along south side of the ridge from lineation 3a; consists of knick points in 20 small parallel streams; lineation stops abruptly at Bells Falls, and is thought to reappear in a tributary of Stony River Mountain Branch (K).

3c—Recognised in straight course of Stony River Mountain Branch, from The Dome south-eastwards almost to summit of Mt Egmont.

3d—Extends from linear reach in Mangawhero Stream (L), south-eastwards along collinear reach of Mangawheroiti Stream, down to beneath the 2,000 ft contour; large spring depositing bog iron observed along this lineation (M), (Mr A. P. Druce, pers. comm.).

3e—Linear trace along upper reaches of Mangawheroiti Stream, parallel to lineation 3d, extending down to the 1,500 ft contour.

3f—Linear course of main branch of Kaupokonui Stream from about 4,500 ft on the slopes of Fanthams Peak (N) down to beneath the 2,000 ft contour.

3g—Collinear trace of two tributaries, in upper reaches of Kapuni Stream, from the 4,000 ft to the 2,000 ft contour.

3h—Short lineation cutting obliquely across drainage pattern of Mangawhero Stream.

All the lineations are grouped into three principal directions. Lineations 1a and 1b may represent a single lineation that strikes at 20°–30°. Lineations 2a and 2b are considered to represent a further single lineation striking between 80° and 90°. The third set of lineations, 3a–3g, is a zone of collinear features up to 1½ km wide, striking 130°–145°. Lineations 1 and 2 intersect near the summit, but do not show on the upper and younger part of the cone (above 5,000 ft) due to extensive screes and recent lava extrusions. The centre of the third zone passes close to the intersection point of lineations 1 and 2.

CONCLUSIONS

The third lineation zone is interpreted as a fault zone; lineation 3b is considered to be a fault upthrown to the north-east. A suggested origin for the domes is that they were formed by rising viscous lava along vertical radial faults around the base of Mt Egmont. With little dislocation of the surrounding strata, the domes probably grew endogenously (internally) over their vents. Prominent polygonal jointing in the centre of The Dome suggests that a thick crust developed on the external surface and internal cooling occurred comparatively slowly. Skinner Hill is not radially linear with The Dome and is not sited on an observed lineation. However, it probably originated by lava rising along a radial fault which reached the surface a short distance from the fault trace.

Both of the Beehives lie on a straight line, which extends radially from the summit of Mt Egmont, and are therefore also considered to have reached the surface along a radial fault plane. However, from observations made from aerial photographs, an anticline is considered to exist along the axis of the two domes, which if projected northwards extends to the summit of Fanthams Peak. Rock outcrops along this projected line suggest dike intrusion, and towards Fanthams Peak lavas have diverged and flowed off the axis of the anticline. Furthermore, recent debris material which has flowed down the anticlinal axis has tended to slide off the axis to one side, and in so doing has built an apron of volcanic conglomerate on both sides of the Beehives. This has led to an area of non-deposition along the upper base of the Northern Beehive, thus altering the present drainage pattern and forming Lake Dive (*see* Fig. 4).

ACKNOWLEDGMENTS

I wish to thank Professors H. W. Wellman and P. P. Vella, Dr J. Cole, and Mr A. R. Duncan for their criticism of preliminary drafts of this paper; Messrs A. P. Druce, W. W. Topping and P. A. Williams for their assistance in the field; and Mr W. F. Cree, Department of Lands and Survey, for preparing the contour maps.

REFERENCES

ARNOLD, H. C. 1959: The Sugar Loaf intrusions near New Plymouth. *N.Z. Jl Geol. Geophys. 2*: 735–45.

CLARK, R. H. 1960: Petrology of the volcanic rocks of Tongariro Subdivision: 107–23 *in* Gregg, D. R. The Geology of Tongariro Subdivsion. *Bull. N.Z. geol. Surv. n.s. 40.*

DRUCE, A. P. 1966: Tree-ring dating of Recent volcanic ash and lapilli, Mt Egmont. *N.Z. Jl Bot. 4*: 3–41.

ESCHER, B. G. 1920: L'éruption du Gounoung Galounggoung en juillei 1918. *Natuurk. Tijdschr. Ned.-Indië 80*: 259–63.

FOUQUE, F. 1879: "Santorin et ses Éruptions", Corbeil, Paris.

GIBSON, W.; MORGAN, P. G. 1927: The geology of the Egmont Subdivision, Taranaki, N.Z. *Bull. N.Z. geol. Surv. n.s. 29.*

GRANGE, L. I. 1931: Conical hills on Egmont and Ruapehu Volcanoes. *N.Z. Jl Sci. Technol. 12 (6)*: 376–84.

GRANT-TAYLOR, T. L. 1964: Geology of Egmont National Park *in* "Egmont National Park Handbook". Egmont National Park Board, New Plymouth.

HAY, R. F. 1967: Sheet 7 Taranaki (1st ed.) "Geological Map of New Zealand 1 : 250,000". Department of Scientific and Industrial Research, Wellington.

HOLMES, A. 1965: "Principles of Physical Geology". Nelson, London.

WILLIAMS, H. 1932: The history and character of volcanic domes. *Univ. Calif. Publs geol. Sci. 21 (5)*: 51–146.

A.G.I. Dictionary, 1960. "Glossary of geology and related sciences" (2nd edition) 325 pp. + supplement 72pp. American Geological Institute, Washington, D.C.

VOLCANIC DOMES AND LINEATIONS IN EGMONT NATIONAL PARK

The following article has been submitted for publication in N.Z. Soil News.

CHAPTER 7

AGE RELATIONSHIPS OF WESTERN TARANAKI SOILS

SUMMARY

The age relationships of the soil types described by Grange and Taylor (1933) and mapped on a scale of 4 ml to 1 inch in Sheets NZMS1-N108, N118 and N128 are examined in context of both geomorphic surfaces and the succession of dated andesitic tephras and lahar deposits. Of two principal "sets" of ringplain surfaces, the older set (a) grades to the Pouakai Range and is mantled by about 10 m thickness of tephras. On the higher slopes of the Pouakai Range, Holocene tephras (formally named Oakura and Okato Tephras) total about 2 m of this tephra mantle and form the parent material to soil mapped as Patua sandy loam. However, below the 200 m contour the Holocene tephras thin to less than 30 cm and rest upon an halloysite rich subsoil (Gradwell and Birrell 1954) extending back at least 50,000 years or more in age. The soils developed on these latter parent materials are mapped as New Plymouth black and brown loams.

The younger set of ringplain surfaces (b) grades to Mt. Egmont and comprises at least 3 lahar units in western Taranaki. The oldest lahar unit is about 25,000 years old and is mantled by the Holocene ashes Oakura and Okato tephras. The middle lahar unit is between 12 and 16,000 years old and is mantled

by Oakura Tephra. The youngest lahar unit is less than 7,000 years old with no tephra mantle. Warea soils are developed upon the Oakura and Okato tephras which overly andesitic breccia of the oldest lahar unit. Warea soils are similar in age to Patua soils, but the latter soils occur at greater elevation and under higher rainfall on the Pouakai ringplain and because they are nearer the tephra source - Mt. Egmont, contain numerous pumice fragments. Rahotu and Glenn loams are developed upon the Oakura Tephra overlying the middle lahar unit and Glenn and Awatuna loams are developed directly upon the youngest lahar unit. Newall bouldery sands (developed on 7 - 12,000 years old debris flow deposits), Inglewood coarse sandy loam (on a pumice shower dated about 3,000 years old) and Hangatahua soils (on less than 500 year old gravels and sands) are of restricted distribution and are each related to special parent materials.

INTRODUCTION

The recent volcanic history of Taranaki is dominated by the activity of two volcanoes - Egmont and Pouakai, which have constructed extensive ringplains of detrital volcaniclastics graded to each centre. Tephras erupted from the older Pouakai volcano are preserved only on the Pouakai ringplain. Tephras erupted from Egmont centre have been deposited on both the older Pouakai ringplain (a) and the younger Egmont ringplain (b) and recent lahars from Mt. Egmont have destroyed all but the youngest Egmont source tephras on the Egmont ringplain.

The tephrochronology and tephrostratigraphy of these deposits has been discussed separately.

PARENT MATERIALS

Recent eruptions from Mt. Egmont have spread andesitic tephra over a 50 km radius of Egmont summit so that most of the tephras on the Pouakai ringplain surfaces (a) are now mantled with a layer of Holocene tephra. The most widespread of these tephras have been named Oakura and Okato tephras (Neall 1972) and correspond approximately to the "Egmont Shower" of Grange and Taylor (1933). The Okato Tephra rests upon an ash dated (NZ 942) at 16,100 ± 220 yr B.P.) and the Oakura Tephra rests upon a buried forest dated (NZ1144) at 6,970 ± 76 yr B.P. At New Plymouth, the Oakura and Okato tephras total less than 30 cm thick and the considerably older New Plymouth Ashes occur at 2-3 m depth. The latter material is considered older than 50,000 yr B.P. and contains halloysite horizons (Gradwell and Birrell 1954; Birrell, Fieldes and Williamson 1955) which alternate with dominantly allophanic layers (Dr K.S. Birrell, pers.com.). Detailed investigations show their relationship to each tephra unit; the upper part (paleosol) contains both allophane and halloysite, the lower part (parent tephra) contains only allophane. Above the New Plymouth Ashes, intermittent weak soil development with no halloysite suggests small time intervals between eruptives which were insufficient for allophane-halloysite transformation to occur. It is suggested that halloysite forms as a result of prolonged weathering with little amounts of ash deposited, rather than as a function of differences in initial parent material composition or increasing age.

The bulk of the soils on the younger Egmont ringplain surfaces (b) are developed on three formations of widespread lahar deposits and within their respective tephra covers (<25,000 years old) where present. The oldest deposit occurs to the west of Egmont summit and extends from Okato in the north to Rahotu in the south. It is about 25,000 years old and is mantled only by the Oakura and Okato tephras. The middle deposit is trilobate and extends north-west to Okato, west to Rahotu and south to Awatuna. It is mantled by the Oakura Tephra and is dated between 12 and 16,000 years ago. The youngest deposit derived from an amphitheatre between Bobs Bluff and Fanthams Peak, on the south-west side of Mt. Egmont, is spread south-westwards to the coast at Opunake. There is no tephra on this lahar deposit and in the coastal cliffs both Oakura and Okato tephras are exposed beneath it, indicating an age considerably less than 7,000 years B.P. Between the above 3 lahar deposits on the coastal lowlands and Egmont summit, there is a zone of debris flow deposits which do not extend far beyond the present Egmont National Park boundary. At least 6 of these deposits are mantled by the Oakura Tephra and have been dated between 7 and 12,000 years B.P., and at least a further 5 have no tephra cover, being deposited during the last 500 years.

SOIL TYPES DEVELOPED ON ANDESITIC TEPHRAS

New Plymouth black and brown loams (3 & 3A) Fig. 50 are restricted to the Pouakai ringplain surfaces (a) and frequently comprise a young allophanic topsoil of Egmont derived tephras with a subsoil of older allophanic or halloysitic tephras. Halloysite occurs at higher levels in the profile where the Oakura and Okato tephras are relatively thin e.g. in the coastal region between Okato and New Plymouth. New Plymouth black and brown loams grade into Patua sandy loam (6) with increasing elevation and increasing rainfall, and near the 300 m contour the Oakura and Okato Tephras thicken to greater than 2 m thick containing numerous pumiceous lapilli which impart a sandy texture.

Warea black and brown loams (2 and 2A) occur below the 120 m contour upon all three lahar deposits but mostly upon the oldest lahar deposit with its corresponding Oakura and Okato tephra cover. On the youngest formation, north-east of Opunake these soils occur on parent materials between about 3,000 - 14,000 yr B.P. The most likely factors influencing the mapping of these soils were clearly climate and conical hill topography rather than the variable thickness of tephra cover. More detailed surveys in the future may find it necessary to restrict the "Warea soils" to those developed only upon the oldest lahar deposit and its corresponding Holocene tephra cover.

New Plymouth bouldery loam (3B) soils occur upon identical geomorphic surfaces as Warea soils, but at a higher altitude, from 120 to 420 m altitude. The great similarity between

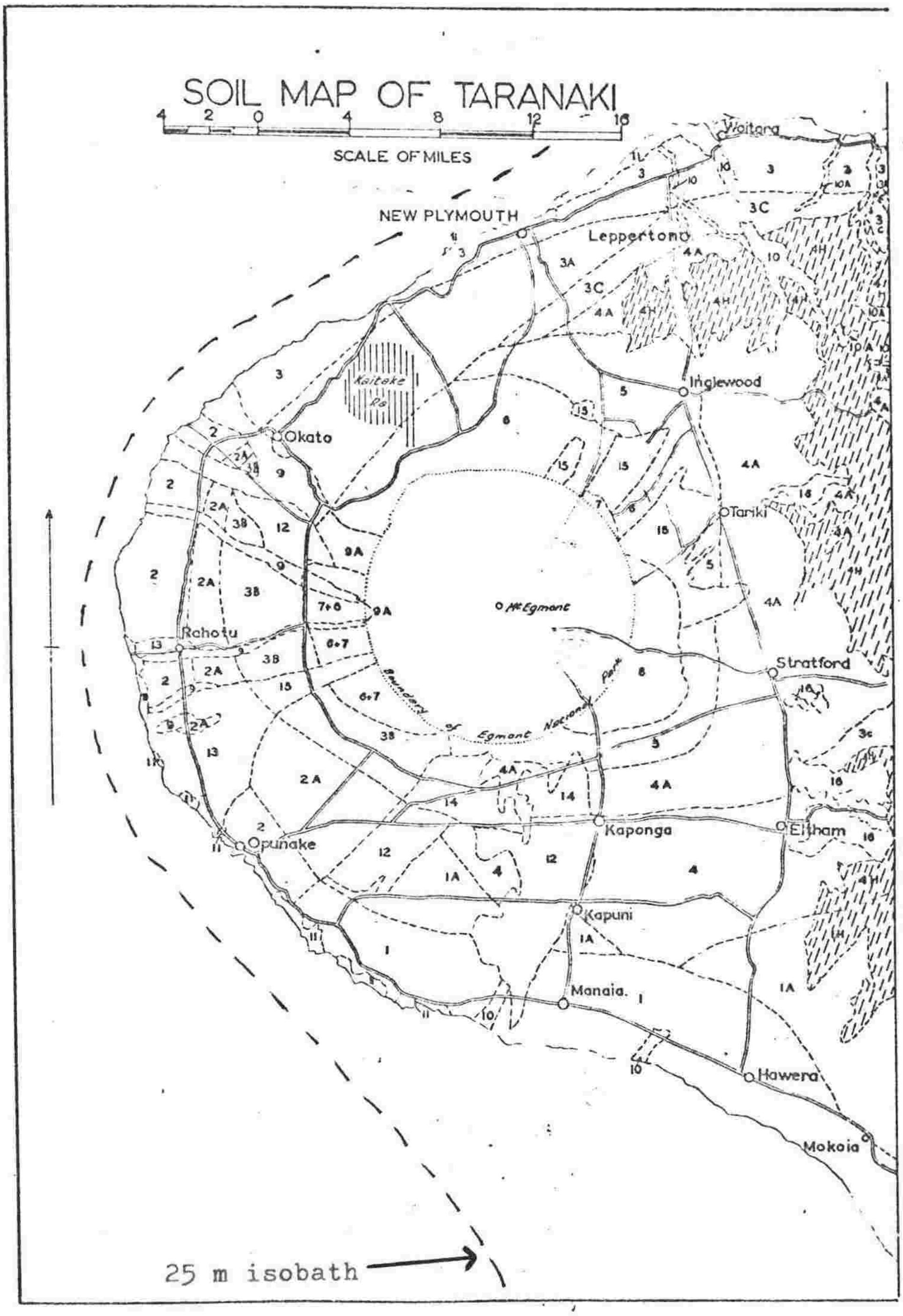


FIGURE 50 - Soil map of Taranaki compiled by H.S. Gibbs.

LEGEND FOR FIGURE 50

YELLOW-BROWN LOAMS	
Egmont black loam	1
Egmont brown loam	1A
Egmont hill soils	1H
Warea black loam	2
Warea brown loam	2A
New Plymouth black loam	3
New Plymouth brown loam	3A
New Plymouth bouldery loam	3B
New Plymouth sandy loam	3C
Stratford sandy loam	4
Stratford sand	4A
Stratford hill soils	4H
Inglewood coarse sandy loam	5
Patua sandy loam	6
Newall bouldery sand	7
Burrell gravelly sand	8
RECENT SOILS	
Hangatahua sand & gravelly sand	9
Hangatahua mottled sands	9A
Waitara sandy loam	10
Waitara silt loam	10A
Patea sands	11
GLEY SOILS	
Glenn loam	12
Rahotu loam	13
Awatuna loam	14
Norfolk sandy loam	15
ORGANIC SOILS	
Eltham peaty loam	16

Map Compiled by H.S. Gibbs
from soil surveys by L.I. Grange,
N.H. Taylor & H.S. Gibbs, 1951.

Grid Reference:
N 108,109,118,119,128,129.

these soils and Warea loams in climatic regime, parent materials, soil morphology and age leads me to recommend that New Plymouth bouldery loam be changed to Warea bouldery loam.

Rahotu loam (13) soils occur almost entirely upon the middle lahar deposit with its accompanying Oakura Tephra cover, between Rahotu and Opunake. The gentle surface topography of the distal portion of this lahar deposit has resulted in poor drainage and the development of a prominent iron pan of Rahotu soils.

Glenn loam (12) is of similar age to Rahotu loam but is developed on debris flow deposits above the 100 m contour. In the Awatuna district it is also formed upon a thin marginal ash-rich lithology of the youngest lahar deposit. The loam parent material consists of stones carried by the lahar admixed with Oakura Tephra and overlies the middle lahar deposit. It differs from Hangatahua soils in that the parent material is older and consists of Oakura Tephra resting on andesitic debris about 7,000 years old. The soil is poorly drained and often supports swamp vegetation. The Awatuna loam (14) is of similar age and clearly indicates a climatic basis for separating equivalents of Glenn soils above the 200 m contour.

A complex of Newall bouldery sands (7) and Patua sandy loam (6) mapped along the western boundary of Egmont National Park, occur respectively on (a) debris flow surfaces of 7,000 years B.P. age with their Oakura Tephra cover and (b) the Oakura and Okato tephra mantled older surfaces which protrude between them.

In the Inglewood district, two tephras (Inglewood Tephra and Korito Tephra) about 3,000 years old, mantle the topsoil. They have been dated according to the degree of pumice weathering in relation to known dated pumices. The distribution of these tephras shows strong coincidence with that of the Inglewood coarse sandy loam (5) in the north-eastern sector, and is likely to have strongly influenced soil development.

Hangatahua Series soils extend over 40 km^2 between Okato and Warea (see Appendix C) and are considered to have been deposited by a large flood which followed the Newall eruptions (Druce 1966) on Mt. Egmont. Debris flows probably triggered by heavy rains transported large quantities of gravel and sand down Stony River to flood onto the surrounding lowlands, consequent to the eruptions. Okato means in Maori "place of the great tidal wave" and since it is 90 m above sea level and 5 km from the coast, the name probably refers to this flood. Hangatahua sand, gravelly sand and mottled sand (9 & 9A) are soils developed upon these andesitic gravels and sands, which because they contain charcoal from the Newall eruptions, are dated at less than 450 years B.P. Norfolk sandy loam (15) soils in the vicinity of the Waiwakaiho River are of similar age.

SOIL TYPES DEVELOPED ON TEPHRIC LOESS

In southern Taranaki Egmont black and brown loams (1 & 1A) occur on the Egmont ringplain surfaces to the west of Manaia, but to the east they occur on the uplifted marine bench termed the Rapanui Formation (Fleming 1953). The parent material of the Egmont soils in the Manaia district is principally Holocene volcanic ash (Oakura and Okato tephras) resting upon andesitic conglomerates and sandstones. South-eastwards of Manaia the parent material of these soils changes, the Holocene tephras thin rapidly and appear to rest upon a volcanic derived (or tephric) loess. Preliminary investigations of the loess sand grain mineralogy between Pihama and Nukumaru indicate that besides the large proportion of andesitic material present, there is a gradual increase in "foreign" grains, such as quartz, alkali feldspar and metamorphic grains, south-east away from Taranaki (G. Watt, pers.com.). Attendant soil profile studies indicate the loess and overlying ash are readily separable on the basis of colour, consistency and structure.

DISCUSSION

The apparent absence of loess in western Taranaki may be explained in part by the relatively young volcanic surfaces in the region. However, even in the older soils on the Pouakai ringplain there is an absence of loess. This is attributed to an absence of a source area where loess could be derived. In southern Taranaki the major probable source was the present day continental shelf which has been exposed during stadial periods to the south and west. Because there is a very narrow continental shelf zone around the western Taranaki coastline such a source may not have existed during these periods.

The age relationships between the western Taranaki soil types are summarised in Fig. 51. Of the three principal intrazonal soil types in the region, New Plymouth loams predate Egmont loams which predate Warea loams (Fig. 52). The subsoils upon which all of them rest vary from older tephras in the north-west (New Plymouth), to laharic breccias in the west (Warea) to tephric loess in the south-east (Egmont).

Recommendations from the present work include the following:

1. New Plymouth bouldery loam is considered undesirable nomenclature because the soil is more closely allied to the Warea loams and was initially referred to as Warea stony loam (Grange and Taylor 1933). Warea bouldery loam is considered preferable.
2. The strikingly similar lithology and age of the Rahotu, Glenn and Awatuna loams suggests that all are monogenetic and there is some justification for seeing if amalgamation of these terms is needed.
3. The parent materials of Hangatahua soils and Norfolk sandy loam are more similar in lithology and age, than appears previously recognised.
4. The designation of reference or type localities for all the Taranaki soil types, and more particularly the New Plymouth and Warea loams is considered most desirable.

GEOLOGY	AGE (in yrs B.P.)	LITHOLOGY OF PARENT MATERIALS	SOIL TYPES → incre increased rainfall and in	
Hangatahua Gravels and Sands	450	Andesitic gravel & sand	Hangatahua sand & gravelly sand	
Inglewood and Korito tephras	3,000	Pumiceous lapilli on coarse ash	Inglewood coarse sandy	
Opua Formation	7,000	Andesitic breccia	Glenn loam	
Warea Formation	12,000	Oakura Tephra (allophanic ash) on andesitic grits & breccias	Rahotu loam (poor drainage)	Warea black loam
Pungarehu Formation		Oakura and Okato Tephras (allophanic ashes) on andesitic breccia		
Fluvial sandstones, grits and conglomerates	30,000	Oakura and Okato Tephras (allophanic ashes) on appropriate lithology	Egmont black loam	
Pouakai ringplain (New Plymouth Ashes on Lower Pouakai Agglomerate)	50,000	Oakura and Okato Tephras overlying allophanic tephras which mantle halloysitic bearing tephras	New Plymouth black loam	

FIGURE 51 - Age relationships of parent materials and soils in western Taranaki.

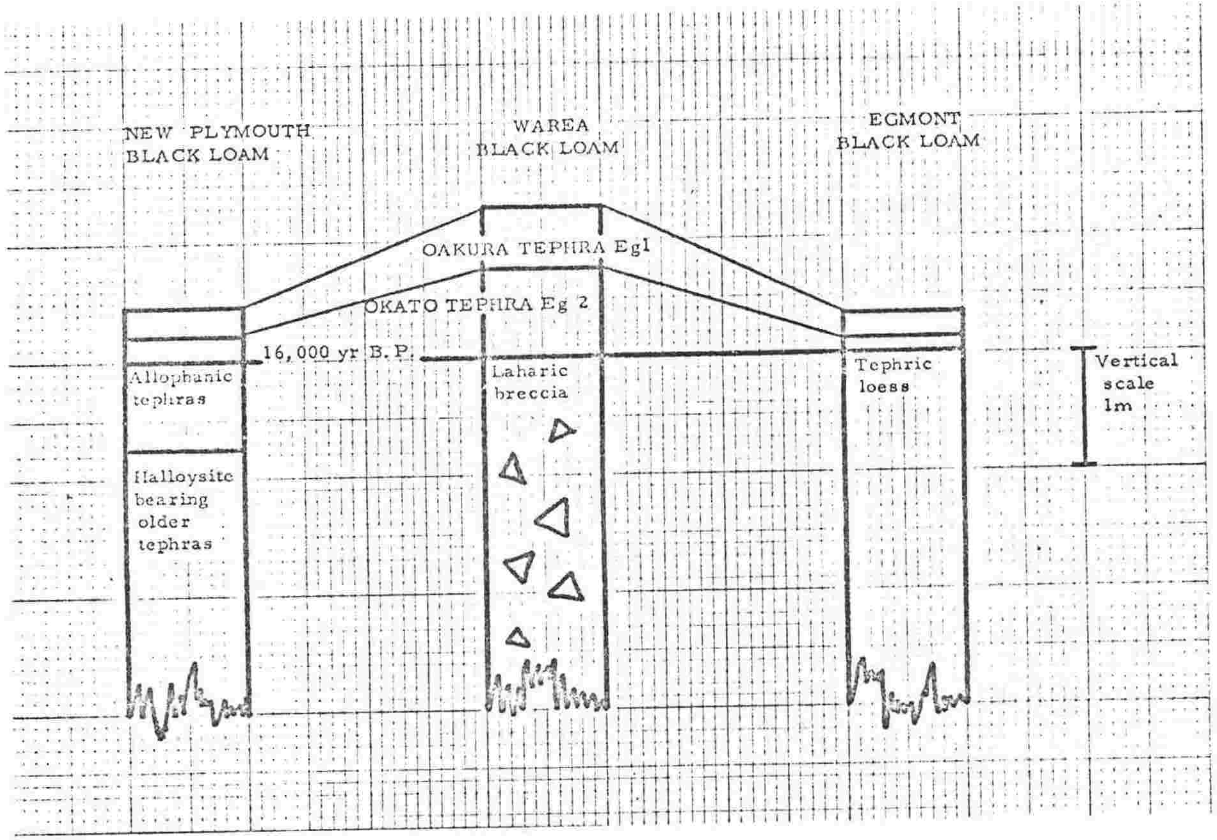


FIGURE 52 - Stratigraphic correlation columns of parent materials forming New Plymouth black loam, Warea black loam, and Egmont black loam.

INFRA-RED, X-RAY DIFFRACTION & DIFFERENTIAL THERMAL ANALYSIS OF SOIL PARENT MATERIALS

In a study of allophanes separated from the Patua, Stratford and Egmont profiles, Fieldes and Furkert (1966) studied DTA and IR patterns from coarse and fine clay separates and compared them to soils developed on Central North Island eruptives. In this report the soil sequence Egmont, Stratford, Patua of increasing age and maturity was misrepresented. From detailed tephrostratigraphy it has been shown that Patua soils are slightly younger than Stratford soils which are much younger than Egmont soils. If this factor is taken into account with their presented data, the trends in the observations are made substantially clearer and meaningful.

The coarse clays from the 3 Taranaki and 3 Central North Island soils show IR absorption at 800 cm^{-1}, which becomes increasingly stronger in the younger samples (Fig. 1, Fieldes and Furkert 1966, p.611) i.e. absorption in the Patua sample does not represent a cyclic endpoint to patterns presented, but rather a position in the weathering sequence between the Taupo and Tirau profiles. Similarly average values of peak heights from the man X-ray powder diffraction maxima of cristobalite and feldspar show distinctively higher values in the younger samples. The amounts of organic matter on IR patterns of fine clay separates (below 0.2μ) can also be correlated with the relative age of the selected samples.

Clay fractions of all the principal Taranaki tephras were analysed by X-ray diffraction (XRD) and differential thermal analysis (DTA) techniques. The large clay content in the samples made it possible to separate off the clay by addition of sodium hexa-metaphosphate and ultrasonic treatment accompanied by active stirring.

XRD traces show allophane is the only clay constituent in all the samples above the New Plymouth Ashes. Halloysite first appears in the upper part of the uppermost tephra bed of the New Plymouth Ashes but is not present in the lower part of the bed.

DTA traces were prepared using Al_2O_3 as standard with a temperature increase of 12°C per minute (Fig. 53). A comparison of H_2O_2 and non-H_2O_2 treated samples showed a decrease in size of the exothermic peak between 550-750°C with treatment.

All the DTA traces except that for the New Plymouth Ash show a low temperature allophane endothermic peak occurring between 195° and 215°C, which represents the removal of absorbed water. This value is slightly higher than for many New Zealand allophanes but is probably due to the slightly higher rate of temperature increase. The allophane high temperature exothermic peak attributed to mullite or gamma-alumina formation (Insley and Ewell 1935), ranges mostly between 860° and 920°C. Small endothermic peaks between 285° and 305°C, and occasionally at 375°, 415° and between 420° and 470°C are attributed to organic-alumina complexes and iron oxides (Fieldes 1957), and van der Marel (1966) includes jthem as a common thermal reaction of allophane up to 550°C. In addition to this, samples not treated with H_2O_2 show a strong exothermic peak (Fig. 53) which decreases in temperature value with increase in age, from near 750° to 560°C, and in the

FIGURE 53 - DTA traces of clay fractions separated from selected Taranaki tephras. Traces are arranged in stratigraphic order, youngest at the top. Only the uppermost sample was treated with H_2O_2. Sample localities refer to sections and a best locality in Neall (1972). Traces 1A (H_2O_2 treated) and 1B (non-H_2O_2 treated) samples of Okato Tephra from Section 1; trace 2 - Koru lapilli from section 6; trace 3 -Weld ash from section 6; trace 4 - Weld ash from section 1; trace 5 - Weld tuff from its best locality; trace 6 - unnamed ash from section 6; trace 7 -unnamed ash from best locality of Weld tuff; trace 8 - uppermost New Plymouth Ash (upper part) from section 1.

oldest two samples the sharp peak is lost. This is attributed to organic matter. In addition, the peak is present in the H_2O_2 treated sample, and is due to organic matter retained by the clay despite treatment, being burnt off (Fieldes 1955, p.342).

The DTA trace of the upper part of the uppermost New Plymouth Ash and to a much lesser extent the unnamed ash above, show the presence of halloysite with an endothermic peak between 500° and 528°C, due to the loss of a structural hydroxyl. The temperature value of the peak is often substantially lowered if halloysite is present in only small quantities and this explains trace 8, which is consistent with New Zealand and overseas data (Fieldes 1957; van der Marel 1966). The additional high temperature exothermic peak between 930° and 950°C is also attributed to halloysite. However, it is apparent that allophane continues to dominate over halloysite in abundance.

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REFERENCES

Birrell, K.S.; Fieldes, M.: Williamson, K.I., 1955, Unusual forms of halloysite. American Mineralogist 40: 122-4.

Druce, A.P., 1966, Tree-ring dating of Recent volcanic ash and lapilli, Mt. Egmont. N.Z. Journal of Botany 4: 3-41

Fieldes, M., 1955, Clay mineralogy of New Zealand Soils, Part 2. Allophane and related mineral colloids. N.Z. Journal of Science Technology B37: 336-50

Fieldes, M., 1957, Clay mineralogy of New Zealand Soils, Part 4. Differential Thermal Analysis. N.Z. Journal of Science and Technology B38: 533-70

Fieldes, M.; Furkert, R.J., 1966, The Nature of allophane in soils. Part 2. Differences in composition. N.Z. Journal of Science 9(3): 608-22

Fleming, C.A., 1953, The geology of Wanganui Subdivision. N.Z. Geological Survey Bulletin, n.s. 52: 362 pp

Gradwell, M.; Birrell, K.S., 1954, Physical properties of certain volcanic clays N.Z. Journal of Science and Technology B36: 108-22

Grange, L.I.; Taylor, N.L., 1933, Report on soil surveys for 1932-33. in N.Z. Department of Scientific and Industrial Research Annual Report 1932-33: 3pp

Insley, H.; Ewell, R.H., 1935, Thermal behaviour of Kaolin minerals. Journal of Research of National Bureau of Standards., 14: 615-27

Neall, V.E., 1972, Tephrochronology and tephrostratigraphy of western Taranaki (N108-109), New Zealand. N.Z. Journal of Geology and Geophysics 15(4): 507-57.

Van der Marel, H.W., 1966, Quantitative analysis of clay minerals and their admixtures. Contributions to mineralogy and petrology 12: 96-138.

CHAPTER 8

AN INVESTIGATION OF MOSSFIELD AND SHRUB ECOSYSTEMS ON MOUNT EGMONT, TARANAKI, NEW ZEALAND.

INTRODUCTION

A large proportion of the published information on organic matter production, turnover and nutrient cycling in terrestrial ecosystems is concerned with tree ecosystems, but prior to 1966 few attempts had been made to assess similar features of shrub ecosystems (Egunjobi 1967). In New Zealand, detailed studies have been carried out into primary production and nutrient cycling of hard beech (Nothofagus truncata (Col.) Ckn.) in western Hutt Valley (Miller 1963a,b,c), of Pinus radiata forests in the Central North Island (Will 1959, 1964, 1966) and of gorse and pasture ecosystems in eastern Hutt Valley (Egunjobi 1967, 1969a,b). Little work in New Zealand has been concerned with subalpine scrub and herbfield production and nutrient cycling, probably due to lesser economic importance. Overseas studies into primary productivity of subalpine and alpine ecosystems include those into alpine microenvironments at Mt. Washington, New Hampshire, U.S.A. (Bliss 1966), heath and grass balds and other shrub communities in California (Whittaker 1961, 1962, 1963, 1966) and of prairies and savannah land in Minnesota (Ovington, et.al. 1963).

The following paper reports a study of primary production and nutrient cycling within mossfield and shrub ecosystems at 1170m (3,9000 ft) altitude on Mt. Egmont, Taranaki, New Zealand. The study site was chosen because the ground surface (and soil) is known to have originated as a debris flow 80 years ago (see Chapter 5, "Maero Debris Flows"), allowing calculations to be made on rates of organic matter accumulation and soil development. The mossfield ecosystem is principally composed of a greyish white moss (*Rhacomitrium lanuginosum* var. *pruinosum*) up to 15 cm thick, whilst the shrub ecosystem contains the nodulated non-leguminous mountain tutu (*Coriaria plumosa*, W.R.B. Oliver) leatherwood (*Senecio elaeagnifolius* Hook.f.) and tussock grass (*Chionochloa rubra* Zotov unnamed var,) all less than 2m high. The relationship between recent soils developed in these ecosystems after 80 years is then compared to soils developed on older debris flow deposits preserved at lower elevation, to show the evolutionary development of a yellow-brown loam soil.

TERMINOLOGY

A comprehensive review of primary productivity and nutrient cycling in terrestrial ecosystems with particular reference to New Zealand is presented by Egunjobi (1969). Due to the lack of generally accepted terminology in this field, definitions of concepts and terms as used in this paper are those of Egunjobi (1969) and Atkinson, *et.al.* (1968). In particular, *biomass* is used as the total weight of organic matter (above and below ground level) both living and dead, per unit area, and *net primary productivity* is used as the rate of organic matter fixed in an ecosystem per unit area over a unit period of time.

STUDY SITE

On the north-western slopes of Mt. Egmont, 2,478m (8,260ft) altitude, a succession of at least 11 debris flow deposits has originated from Egmont summit area during the Holocene. The latest flow deposit is widespread and extends from 1,2000m to 200m altitude some 10 km from source. It covers 2.5 km^2 to a depth of at least 3 m, and trees were destroyed beyond the terminal margin of the flow deposit for a further 5 km^2. Tree-ring dating of regenerating kamahi (*Weinmannia racemosa* Linn.f. forest) knocked over but not killed at the terminal margin indicate that the flow originated in the 1880's (Druce 1970). Early photographs of the deposit taken about 1900 A.D. by the surveyor H.M. Skeet, suggest a recent age for the flow and confirm a date of origin between about 1880-1890 A.D. Skeet's photographs show no fallen logs or other debris exposed on the upper surface and preclude previous organic matter accumulations on the flow deposit. Thus all the organic matter now present on the debris flow deposit has accumulated since about 1885 A.D.

A study site was chosen to examine in detail a mossfield ecosystem at the 1,200 m contour and the influence of *Coriaria* as a key seral stage in the establishment of full shrubland cover at this altitude. Unpublished detailed studies on glacial outwash gravels at Franz Joseph, Westland by Stevens and on Canterbury river terraces by Silvester, indicate that *Coriaria* species play a vital role in the rapid buildup of soil nitrogen which leads to increased vegetative growth.

Nutrient cycling within the mossfield ecosystem and a shrub ecosystem was investigated over an 18 month period between December 1968 and May 1970, on the 80 year debris flow deposit, at a site which met a number of critical conditions;

(a) dominantly *Coriaria* and *Rhacomitrium* ecosystems were essential

(b) a shrub community should contain a single Coriaria species e.g. C. plumosa. At lower altitudes on the deposit, two other species C. arborea Lindsay and C. pteridoides W.R.B. Oliver are common and hybridisation also occurs between them (A.P. Druce, pers.com.).

(c) a locality was required for the installation of valuable equipment away from tracks and the possibility of vandalism, but easily located during unfavourable weather conditions. The site eventually chosen was marked by a large 6 m high boulder which enabled ready location in misty conditions.

(d) A site sufficiently accessible for samples to be collected within a one day visit from the nearest road.

The final site was chosen near Little Pyramid, at 1,170m (3,900 ft) altitude, grid reference N118/615638 (1965), see Figs. 1 & 38. The site is reached by climbing the Puniho Track to the 660 m contour and then travelling eastwards along the "round-the-mountain track" towards Pyramid Stream. The site is 2.8 km WNW of Mt. Egmont summit, and 7 km from the Egmont National Park boundary and nearest road access. The average angle of slope is 14° and the aspect north-westerly.

HISTORICAL GEOLOGY

A large number of "natural disasters" have severely modified the vegetation pattern in the study area during the last 500 years. About 1500 A.D. the Newall Ash and Newall Lapilli, products of two nuée ardente eruptions from Mt. Egmont, carbonised most of the forest on the north-western Egmont slopes. Fires also spread 3 km northwards across the western flanks of the Pouakai Range (Druce 1970). Following these eruptions the western rim of Egmont crater collapsed on five occasions producing debris flows which deposited gravel units averaging 2.5 m thick. All were similar in size to the latest and best preserved deposit, which is composed entirely of fresh andesite boulders, cobbles and pebbles with coarse sand. In all stream exposures of this deposit there is weak grading of coarser boulders to the base, although near the study area, a boulder train is preserved at ground surface along the axis of the deposit. The lateral boundaries of the deposit appear very sharp on Skeet's photograph. However, at the distal margin of the deposit, large quantities of water reduced trees to ground level without depositing a substantial quantity of debris.

Another photograph taken by Skeet in 1899 A.D., of the northern Egmont slopes, shows a similar bouldery fan of debris which appears to grade to Minarapa Stream. From the photographic evidence of two fans of debris to the north and north-west of Egmont summit deposited about this time, together with apparent water damage to trees at the distal margin of one flow deposit, it is considered likely that exceptionally heavy rain storms were the triggering mechanisms for the flows.

CLIMATE

The climate of Taranaki Province is strongly controlled by the orographic effect of Mt. Egmont which together with a maritime influence produces regular rainfall distributed evenly throughout the year, interspersed with substantial periods of bright sunshine. Scanlan (1961) quotes data that the mean range between hot and cold extremes is smaller in New Plymouth than anywhere in New Zealand. Although two permanent climate stations are situated on the eastern slopes of Mt. Egmont, no climatic records on the west side of Egmont were available at the beginning of this study. Since the study started a raingauge has been installed by Hydrology Division, Ministry of Works, in the Mangahume Stream catchment, grid reference N118/628600. Rainfall data recorded at the study site, Mangahume station, Dawson Falls and Stratford Mountain House for the period December 1968 to May 1970, are presented in Table 8. The data have been averaged to provide estimated annual rainfall, by the formula T x 12/n= R, where T is the total rainfall for 18 months, n is the number of months readings and R is the annual rainfall. In addition Scanlan (1961) mentions that P. Marshall in "Geography of New Zealand" recorded an annual rainfall of 7,290mm in 1910 at an elevation of 942m on the northern Egmont slopes. These figures indicate that the western sector of Mt. Egmont is drier than the eastern sector and the south-west sector appears driest. The high rainfall effect to the north-east of Egmont at low altitudes is also prevalent at 1,200 m altitude.

During the study period light integrators were operated at the study site to record solar radiation. Details of these records with comparative data from Ohakea, Auckland and Wellington are presented under "Light Utilisation". The relationship between monthly rainfall and monthly isolation is shown in Appendix D1. Of the 10 months with lowest measured solar radiation, seven recorded the highest monthly rainfalls.

Maximum and minimum temperature readings have been regularly recorded at Stratford Mountain House since 1965. The temperature readings indicate the mean annual minimum temperature is 4.5°C, mean annual maximum temperature is 12.5°C and mean temperature

TABLE 8 - Monthly rainfall (in mm) recorded at

(a) Study site near Little Pyramid N118/615638(1965)

(b) Mangahume Stream* N118/628600

(c) Dawson Falls N119/683595(1957), and

(d) Stratford Mountain House N119/701615

		(a)	(b)	(c)	(d)
December	1968	463.6	---	437.9	477.5
January	1969	438.2	572.0	658.1	631.7
February	1969	289.6	230.1	400.8	476.8
March	1969	241.3	126.5	607.0	74.4
April	1969	520.7	385.1	579.9	547.6
May	1969	571.1	515.1	636.5	665.0
June	1969	304.8	462.8	494.3	472.7
July	1969	304.8	186.7	246.6	253.5
August	1969	990.6+	417.3	444.2	522.0
September	1969		557.0	664.0	625.3
October	1969	330.2	306.6	250.7	241.8
November	1969	209.6	226.8	226.3	192.5
December	1969	419.1	332.0	460.2	484.6
January	1970	209.6	226.3	201.9	232.9
February	1970	146.1	127.0	189.0	177.0
March	1970	495.3	475.2	571.5	646.4
April	1970	596.9	162.1	359.9	366.0
May	1970	584.2	641.1	708.2	679.2
TOTAL		7,116.1	5,949.7*	7,590.8	7,766.9
Averaged annual rainfall from 18 months readings		4,744	4,200	5,061	5,178

* 17 months total. Data from Hydrology Section, Ministry of Works, Wanganui. Monthly figures assessed on Auroa Road automatic raingauge.

is 8.5°C. The study site is 340 m higher than this station and on the west side of Mt. Egmont (Fig.1). The lack of bush cover at the study site compared to forested Stratford Mountain House would indicate a more exposed situation in which slightly lower temperature means could be expected.

The study site is 1,200 m below the permanent snowline but on two occasions during the 18 months observations, snow was encountered there. In June 1969, an estimated 660 mm of snow fell, and lighter falls were evident down to 1,800 m altitude. The snow had formed drifts and all but the Senecio and Cassinia shrubs were buried. On the July 1969 visit, much of the snow had disappeared but numerous remnant patches were preserved on slopes with a southerly aspect. During the months June to August, severe frosts were common at the study site.

Hourly wind speed and wind direction readings are recorded during daylight hours at New Plymouth Airport. From over 15,000 readings from February 1962 to January 1969, a number of generalisations can be made concerning seasonal wind directions. During the autumn and winter months south-easterly winds predominate and are the only winds to attain speeds greater than 37 knots. South-west to north-west winds are next most frequent. In spring and summer months south-east and west winds dominate.

The intensity of thunderstorms around Mt. Egmont was noted by Kidson and Thomson (1931). Early readings at Riversdale, near Inglewood, indicated the maximum intensity of thunderstorms occurs in the evening, with a secondary maximum in the early morning, the frequency remaining high throughout the night. The cause of such thunderstorms was attributed to the presence and the height of Mt. Egmont nearby.

VEGETATION

The vegetation pattern on Mt. Egmont has been described as a perfect altitudinal zonation (Mason 1951), but more detailed botanical studies by Druce (1970) indicate that the zonation is not continuous around Mt. Egmont. Climatic effects, eruptions and debris flows have strongly influenced the vegetation pattern especially on the western slopes and more particularly at the study site. For example, the study site vegetation consists of a mixed subalpine shrubland and herbfield (Fig. 38) situated at an altitude which elsewhere on Egmont consists of dense *Senecio* shrubland.

In Skeet's early photographs (c.1900 A.D.) of the most recent debris flow deposit, near the Pyramids, the upper surface is sparsely covered with short vegetation, and has the appearance of an almost bare scree with boulders up to 2 m across resting on it. Observations in the 1930's of the anomalous moss pattern in this area led to the area being named "Moss Slopes" (D.H. Rawson, pers.com.). Since this date a more complete vegetative cover has established. Tree-ring counts of *Senecio* shrubs indicate they originated about 1940-1945 A.D. Growth on the flow deposit has been more rapid at lower altitudes than the study site, so that hereon the vegetation succession refers only to the study area at 1170 m altitude.

The mossfield ecosystem is dominated by a moss cushion of *Rhacomitrium lanuginosum* var. *pruinosum*, about 15 cm thick, with a variety of small vascular plants immersed within the moss. However in certain sites, generally with a northerly aspect, the succession has developed a stage further. Often this is due to less severe climatic conditions. Here shrub ecosystems are developed consisting of circular patches of mountain tutu (*Coriaria plumosa*), frequently accompanied by leatherwood (*Senecio elaeagnifolius* unnamed var.), koromiko (*Hebe stricta* var. *egmontiana* L.B. Moore), tussock (*Chionochloa rubra* unnamed var.), and inaka (*Dracophyllum filifolium* Hook.f.). The latter four species show enhanced growth compared to scattered counterparts not associated with *Coriaria plumosa*. The smaller circular areas are dominated by *Coriaria* in the centre but larger areas tend to be dominated by *Senecio*, *Chionochloa* and *Dracophyllum*. As pointcounted from vertical aerial photographs, the proportional area of circular *Coriaria* patches to surrounding herbfield is about 3:5 at the study site, but at higher altitudes it is only about 1:20 and at lower altitudes is nearly 1:1.

Coriaria arborea is known to contain root nodules which actively fix nitrogen (Bond 1958, Harris and Morrison 1958) and Druce (*in* Morrison and Harris, 1959) recognised field evidence in the tussock grassland on Mt. Egmont that *C.plumosa* and *C.pteridoides* produced a vigorous response in growth of *Chionochloa rubra* (1959). Burke (1963) established that all recognised species of *Coriaria* possess nodulated root systems. Samples of *C.plumosa* from Mt. Egmont contain nodules similar to that in *C. sarmentosa* Forst. f. figured by Burke (1963, Fig.2). This indicates that *C.plumosa* is likely to be an active nitrogen fixer. From field evidence at the study site it is apparent that once the *Coriaria* has increased soil nutrients to a particular threshold value it is replaced by *Senecio* and other vascular plants of the next seral stage. *C. plumosa* is hereafter referred to in the text as *Coriaria*.

SOIL

The soil is less than 90 years old and consists of loose andesite boulders often angular, with cobbles, pebbles and abundant coarse sand. The parent material is 100% andesite. There is no distinctive soil profile beneath the vegetation cover and horizon differentiation can only be interpreted from weak colour differences and chemical analyses. The soil is referred to as an eldeclini-volic soil of the N.Z. genetic classification of Taylor and Pohlen (1962) by Tonkin (1970).

Beneath the shrub ecosystem is a 5 cm layer of coarse sand, here termed A horizon, passing into coarse boulders (C horizon). Beneath the mossfield is a mat of slowly decomposing brown moss litter which provides a rooting medium for higher plants. It is here referred to as an O horizon, it varies in thickness from 0 to 10 cm and has been considered to average 5 cm thick for quantity calculations. It rests directly on mineral soil of similar nutrient status to the shrub system.

METHODS OF STUDY

INSTRUMENTATION - Lysimeter equipment and collection of water samples

Two 2m^2 lysimeter plots, one principally *Coriaria* the other mainly moss, were staked out and a trench was excavated around them, to at least 30 cm depth. Thick colourless plastic sheeting was then laid in an upright position around the upper and two lateral "faces" of the plots. The trenches were then refilled almost to ground level, but sufficiently depressed to allow surface water from upslope to flow around either side of the plot. On the downhill side of each plot, a fabricated stainless steel tray was hammered into the soil at a depth of about 20 cm in a sub-horizontal position. The tray was fabricated from an AISI type 304/2B finish 14 gauge (austenitic) stainless steel sheet. The tray measuring 1 m across had a 2 cm high flange to each side with a f~~r~~abricated trough on the downslope side. One end of the trough was sealed, the other led to a clamped polythene filter funnel containing nylon cloth to sieve leaves and other extraneous matter. After the initial 2 summer months operation, little material had collected in the boulting, except for insects. The polythene funnel was connected underground (to prevent freezing of the conduit) by a polythene hose to a 45 litre bulk plastic container. During the winter months, the container was insulated by covering it with large amounts of moss. Only the upper 1-5 mm of water in the container then froze. Each month, samples from the bulk container were collected and the remaining volume measured and removed for the following months observations. To prevent direct rainfall accession onto the stainless steel tray and also to protect it from browsing animals, a one metre high wooden support frame was installed. It was covered by two layers of clear polythene sheeting firmly anchored by no. 8 gauge fencing wire to pegs and large boulders. After about 8 months, the polythene had to be replaced.

- Rainfall

Two raingauges were installed, one a "frost-proof" fibreglass open-ended type, the other was a type specially designed to collect rainwater without contamination, rather than as a direct measure. However, the "frost-proof" type, loaned by Hydrology Division, Ministry of Works, was unable to withstand the Egmont conditions. The "specially designed raingauge" was thus used for both water analysis collection and rainfall measurement, although for accurate measurement it has some disadvantages. It was prepared from a 15 cm diameter carbon black polythene tube, to prevent penetration of sunlight and thus prevent micro-organisms growing in the water between collection dates. The container was anchored firmly to a steel pole cemented in the debris flow deposit. A stainless steel collector (see Appendix D2) was fabricated for the raingauge to the following specifications:

(a) the collector contained a sieve-plate joined to a 13mm diameter tube which led to the container. This minimises evaporation and prevents leaves and insects entering the container

(b) a prevalent problem with many raingauges designed for rainwater analysis is the accession of materials from birds perched on the perimeter. Various methods have been employed to prevent this, including metal plates which rattle in the wind on a ring of much larger diameter around the collector. This method was not practical in the severe Egmont climatic conditions, instead stainless steel mounting (entomological) pins were cemented with araldite to the outside 7.5 mm high rim of the collector. Occasional bent pins testified to their effectiveness and were replaced when rendered ineffective.

(c) the collector was constructed so that it slid on top of the outside diameter of the container. The inside diamater of the collector was the same as the inside diameter of the container. This enabled simple conversion of the container water depth to mm rainfall. After each visit the collector was held in position by a jubilee clip and wire attachment to a support pole.

One disadvantage of the collector was that in hailstorms, hailstones tended to bounce out of the shallow dish but this is not likely to have influenced the total fall significantly. The maximum capacity of the container was 990mm of rainfall, which was exceeded only when it was not possible to collect the August 1969 sample. The combined figure of August-September 1969 does not however differ greatly from rainfall recorded at the Mangahume station over this period.

BIOMASS AND PRODUCTIVITY DETERMINATIONS

Numerous methods have been proposed for the accurate assessment of biomass but none has been any more successful than the direct harvesting method (as summarised by Egunjobi 1969).

Four biomass determinations were carried out at the study site in December 1968, January and February 1970 and February 1971. Each sample was collected from a one square metre quadrat. All plant materials above ground, both living and dead, were cut with secateurs and separated into Rhacomitrium, Coriaria, Senecio, Chionochloa, Cassinia and "others". The "others" consisted principally of snowberry (Gaultheria depressa (Hook.f.) var. novae-zelandiae), everlasting daisy (Helichrysum prostratum Hook.f. unnamed var.) and Forstera bidwilli var. densifolia Mild. Minor components in "others" consisted of Anisotome aromatica Hook.f., Wahlenbergia pygmaea, Col. & Lycopodium fastigiatum R.Br. Living and dead components were separated where possible and comprised mainly dead moss and litter. Litter biomass was greatest in the February 1970 sample and comprised leatherwood leaves, twigs and exfoliated bark.

All samples were harvested into plastic bags, transported back to Wellington and weighed immediately, except for larger volumes of vegetation which were subsampled at the study site. Samples were dried at 110°C for 24 hours and then reweighed and sealed in plastic bags. Little difficulty was encountered separating roots because most were growing to the moss litter and few penetrated the mineral soil beneath. On two occasions (February 1970 and February 1971), Chionochloa and Cassinia roots were considered to be of negligible biomass and were incorporated into "others" roots. In four of the calorific determinations of plant material, lower values with increased ash contents indicate some mineral soil contamination.

One problem encountered was the definition of ground level, because the moss litter supports most roots of the higher vascular plants. Ground level was thus defined for this study as the boundary between the living greyish white moss and the mat of decomposing brown moss, the latter being considered a litter horizon of the soil profile.

METHODS OF CHEMICAL ANALYSIS

PLANT MATERIALS

All material for chemical analysis was ground to 2mm by a C & N Junior Laboratory Mill. Senecio stem and root samples were reduced to 1-2 cm chip size before milling. Samples of plant materials from the principal components of the first three periods (December 1968, January 1970, February 1970) were prepared in duplicate. Samples were run in triplicate and averaged, if values differed by greater than 15%. An 0.1 gram sample was rolled in ash-free filter paper and bound tightly by platinum wire. The wire was suspended from a hook in the top of a 2 litre oxygen flask. The sample was then ignited and plunged into the oxygen filled flask until combustion was complete. The wire was then shaken off the hook and any residue remaining on the wire was dissolved with a 0.05N solution of nitric acid in the base of the flask. A few very small particles in some moss samples which did not dissolve were considered to be silica beads produced from plant opal. The fumes within the flask settle within 30 minutes and are rapidly absorbed by the nitric acid. Solutions were made up to 250 ml with deionised water and lanthanum solution to make the lanthanum concentration about 2,000 mg/l in the final sample. Variations in the weight of sample and dilution of nitric acid were carried out, but the above procedure proved most satisfactory.

Na, K, Mg and Ca determinations were made on an AA4 atomic absorption spectrophotometer. Phosphorus determinations were assessed using the nitrovanodomolybdic yellow method (Metson 1956) Nitrogen determinations were made using the Kjeldahl micro method and Parnas-Wagner apparatus (Metson 1956) using 0.1 gm samples.

SOIL ANALYSES

Cation exchange capacities (CEC) and total exchangeable bases (TEB) were determined by the modified NaCl method (Metson and Blakemore 1964). Total organic carbon and nitrogen were analysed by methods of Metson (1956). Separate Na, K, Mg and Ca analyses were determined from base saturation leachates using atomic absorption methods. Nitrogen and phosphorus methods were identical to those used for plant analysis, except that the soil samples weighed 0.5 gram.

WATER ANALYSES

Na, K, Mg and Ca of rainwater and lysimetric water samples were determined using a Perkin-Elmer atomic absorption unit. Phosphorus was analysed by the molybdenum blue method where ascorbic acid is used as a reducing agent (Fogg and Wilinson 1958). Sulphate analyses were determined by boiling down the sample solution and taking the sulphate up with excess BaCl, the excess BaCl then being taken up by EDTA. This method is used by the World Health Organisation, but more recent work on this method suggests it is unreliable, and little significance can now be attached to the sulphate values in this paper. Ammoniacal nitrogen and chloride were determined by standard methods of the American Public Health Association and American Water Works Association (1965). Albuminoid nitrogen and the permanganate method for amount of oxygen absorbed in 4 hours at 20°C, were determined by methods outlined by Taylor (1958).

RESULTS

BIOMASS AND PRODUCTIVITY

Dry weight biomass determinations for four $1m^2$ sample quadrats together with an average value are presented in Table 9 and Fig. 54. The net primary productions from the four sampled quadrats are considered reasonably consistent and a good estimate of the biomass at the study site. A very considerable increase in labour would have been required to obtain larger biomass samples from the site.

The highest production was observed in the "simplest" of the communities, due to the dominance of moss. The average production figure of 86,300 ± 9,426 kg/ha* is considered a reliable estimate of production on the 80 year old surface. Water contained in the living biomass was 176×10^3 kg/ha or 67% of the sampled weight. This comprised 57% living material. The dead material was mainly moss. This water content is an average value expected for temperate forests, of between $100\text{-}200 \times 10^3$ kg/ha (Ovington 1962), but considerably larger than that obtained from Australian brigalow of 33×10^3kg/ha (Moore, et.al.1967).

Mean annual primary productivity was estimated by averaging the net production over the age of the ecosystem (80 years) and the average value obtained is 1,080 kg/ha/yr. The reliability of this figure is subject to a number of variations pointed out by previous workers (e.g. Egunjobi 1969b). These variations include respiratory losses and initial slow accumulation or organic matter, succeeded by greatest production at a climax followed by a decline. Elsewhere on Mt. Egmont, at similar altitudes adjacent to the study site and not influenced by recent debris flows, the vegetation is principally dense Senecio

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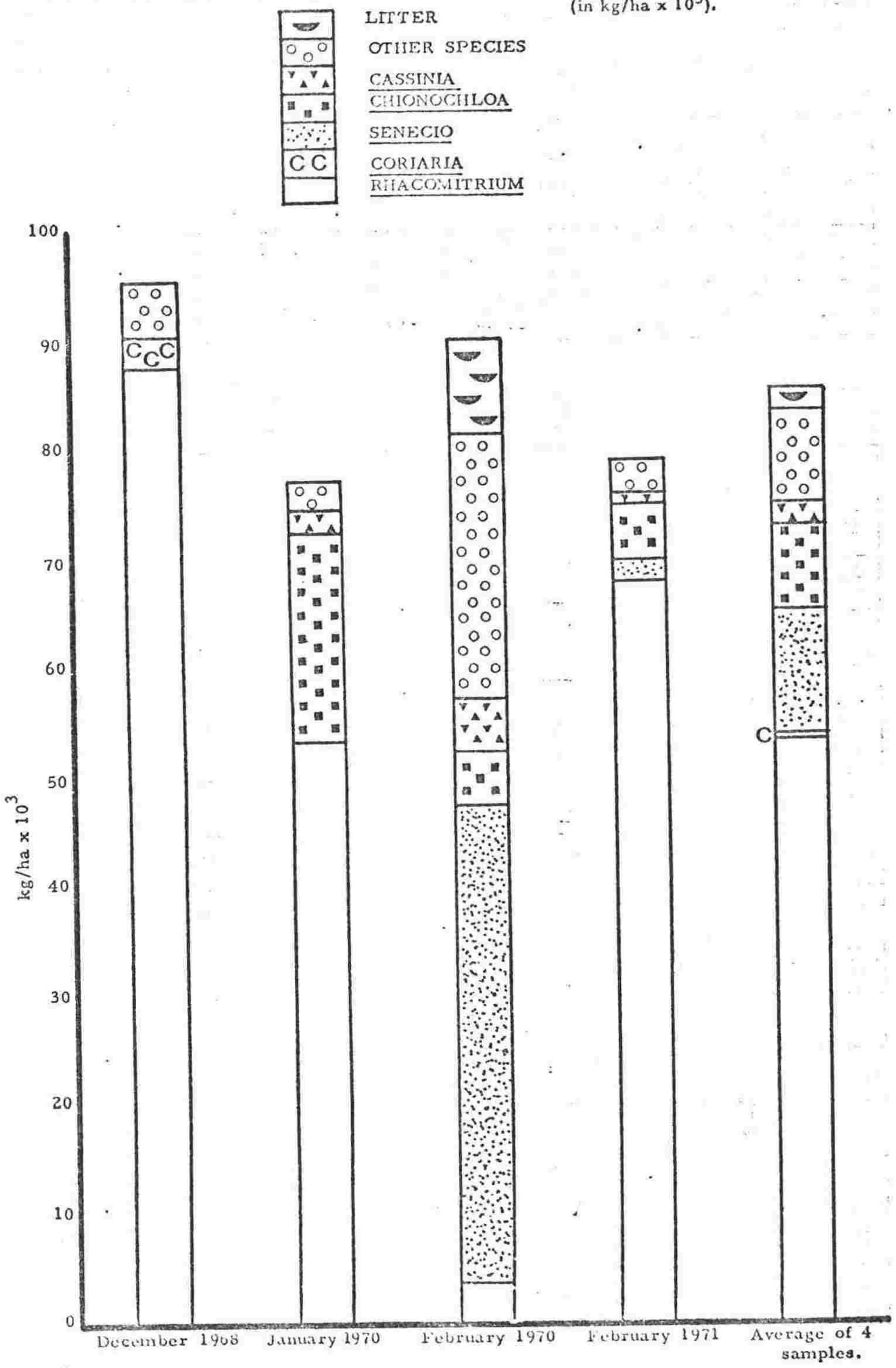
* Footnote: One standard deviation at the 66% confidence level.

FIGURE 54 - Oven dry weights of four sampled quadrats and an average value (in kg/ha x 10^3).



		Dec.68	Jan.70	Feb.70	Feb.71	Average	
Rhacomitrium	A.G.	18,720	35,162	3,991	25,207		
	B.G. (litter)	69,040	18,709	2,989	42,864		
	Total	87,760	53,871	6,980	68,071	54,170	
Coriaria	A.G.	330	-	-	-		
	B.G.	2,620	-	-	-		
	Total	2,950	-	-	-	738	
Senecio	A.G. leaves	-	-	12,178	1,933		
	A.G. stems	-	-	15,550			
	B.G.	-	-	15,824	-		
	Total	-	-	43,552	1,933	11,371	
Chionochloa	A.G.	-	14,208	4,931	5,065		
	B.G.	-	4,662	*	*		
	Total		18,870	4,931	5,065	7,217	
Cassinia	A.G.	-	1,507	5,044	1,067		
	B.G.	-	247	*	*		
	Total	-	1,754	5,044	1,067	1,966	
Gaultheria	A.G.	-	576	-	-		
Hymenophyllum	A.G.	-	49	3,456	-		
"Others"	A.G.	519	565	599	499		
Gaultheria, Hymenophyllum & Others B.G.		4,200	1,528	20,334	2,544		
Total		4,710	2,718	24,389	3,043	8,715	
Litter		-	-	8,480	-	2,120	
Production		95,420	77,213	93,376	79,179	86,297	
Mean Annual Productivity (Production/age of stand) in kg/ha/yr		1,193	965	1,170	990	1,080	Age of stand = 80 years
Mean annual productivity of Senecio				1,613	-		Age of stand = 27 years.

TABLE 9 - Oven dry weights (in kg/ha) and mean annual productivity (in kg/ha/yr) of biomass.
* denotes low biomass value incorporated into "others" B.G.
A.G. = above ground; B.G. = below ground.

shrubland. Full utilisation at the study site has therefore not been reached and the community represents an intermediate seral stage. The slow accumulation of organic matter is attributed to the climatic conditions and poor soil materials.

The moss has existed at the site for a much longer period than the other species. Thus it should be taken into account that if the annual litter fall of the above ground parts of Coriaria are included in the mean annual productivity, a current annual productivity of about 1,160 kg/ha/yr is estimated. Senecio productivity, derived on the basis of 27 years age, in sample 3 (February 1970), has been 1,613 kg/ha/yr and represents the incoming of faster organic matter production.

This type of productivity determination has been used extensively elsewhere and does allow some comparison to be made with other herbaceous and forest stands. The value is much lower than productivity values obtained from lower altitudes elsewhere in New Zealand, and represents about one tenth that obtained from a six year old gorse (Ulex europaeus L.) stand in the eastern Hutt Valley (Egunjobi 1967).

The productivity is not substantially lower than mean annual productivity of 2,500 hg/ha/yr estimated for hard beech (N. truncata) in the western Hutt Valley (Miller 1963c). However it does compare well with annual shoot productivity on Mt. Washington, New Hampshire, U.S.A. which ranges from 670 kg/ha/yr in cushion plant communities and 1,760 kg/ha/yr in sedge meadows to 2,830 kg/ha/yr in heath shrubs (Bliss, 1966).

Table 10 shows the relative proportions of the biomass components. In sample 1 (December 1968) nearly 80% of the total dry weight was dead Rhacomitrium. In the other samples the

TABLE 10 - Relative proportions of biomass components in four biomass samples and percentage values

(a) living or dead

(b) above or below ground level

(c) individual plant components, in principal generic classes.

		Dec. 68	Jan. 70	Feb. 70	Feb. 71	Average
TOTAL kg/ha		95,420	77,213	93,376	79,179	86,297
(a)	% living	27.6	75.8	82.4	45.0	57.2
	% dead	72.4	24.2	17.6	55.0	42.8
(b)	% above ground	20.5	67.4	58.1	42.7	46.2
	% below ground	79.5	32.6	41.9	57.3	53.8
(c)	% *Rhacomitrium*	92.0	69.8	7.5	86.0	62.8
	% *Coriaria*	3.1	0	0	0	0.9
	% *Senecio*	0	0	46.6	2.4	13.2
	% *Chionochloa*	0	24.4	5.3	6.4	8.4
	% *Cassinia*	0	2.3	5.4	1.3	2.3
	% "Others"	4.9	3.5	26.1	3.8	10.1
	% Litter	0	0	9.1	0	2.5

appearance of new species to the ecosystem has led to increased living weight above ground. It should be noted that because assessment of ground level was taken from the top of the dead moss layer, there is a high percentage of below "ground level" biomass in sample 1, because of the predominance of dead moss. *Rhacomitrium* totals nearly 63% of the biomass and is the dominant component except in sample 3 where *Senecio* dominates. *Senecio*, *Chionochloa* and *Cassinia* total about one quarter of the total biomass sampled. "Others" plus *Coriaria* total 11%.

A primary productivity of about 1,000-1,200 kg/ha/yr is thus established for the study site, and as conditions favour the establishment of higher vascular plants, there is a consequent increase in productivity, which is probably doubled with the presence of *Senecio*.

CHEMICAL ELEMENTS IN THE ECOSYSTEM

In this study two ecosystems are recognised

(a) a mossfield ecosystem dominated by *Rhacomitrium*, and
(b) a shrubland (*Coriaria*, *Senecio*, *Cassinia*, *Chionochloa*) ecosystem.

In the mossfield ecosystem the moss litter was regarded as part of the vegetation system for elemental calculations although it is defined as "below ground surface". Because many sand particles become trapped by the moss, total exchangeable bases determined for the moss litter were included in elemental quantity calculations of "elements in the *Rhacomitrium* soil", (i.e. total element values of *Rhacomitrium* material were also included within the plant system estimates).

Chemical elements in the ecosystem include those contained in the plant materials together with those in the soil. However because the total elements in the soil do not represent those which are available for organisms, only the exchangeable elements were determined.

Additions of elements into the ecosystem include those being weathered from the parent materials and those being added from the atmosphere; losses of elements occur principally by leaching of waters through litter and soil horizons. Once the net gains and losses of elements to the ecosystem are quantified over a given period, and the element content capital of the plant components and soil is known, rates of nutrient cycling in the ecosystem can be estimated. For this general scheme see Fig. 55.

EXCHANGEABLE ELEMENTS IN THE SOIL

The subalpine mountain soil has low levels of exchangeable cations. Chemical analyses of the upper and lower portions of the A horizon on an oven dry weight basis (Table 11a) show a marked decrease in the already low CEC and TEB values below 5cm depth. No roots penetrate beyond 10 cm depth and most form an intricate mat in the Rhacomitrium litter, so that values below 5 cm depth are unlikely to be important. The A horizon developed beneath the shrubland ecosystem shows the physical character of an A1 horizon because of its dark stained, slightly weathered appearance compared to the mossfield soil. Exchangeable cation concentrations under shrubland show slightly lower values than under Rhacomitrium, because large amounts of low bulk density moss are needed for CEC and TEB determinations i.e. it is

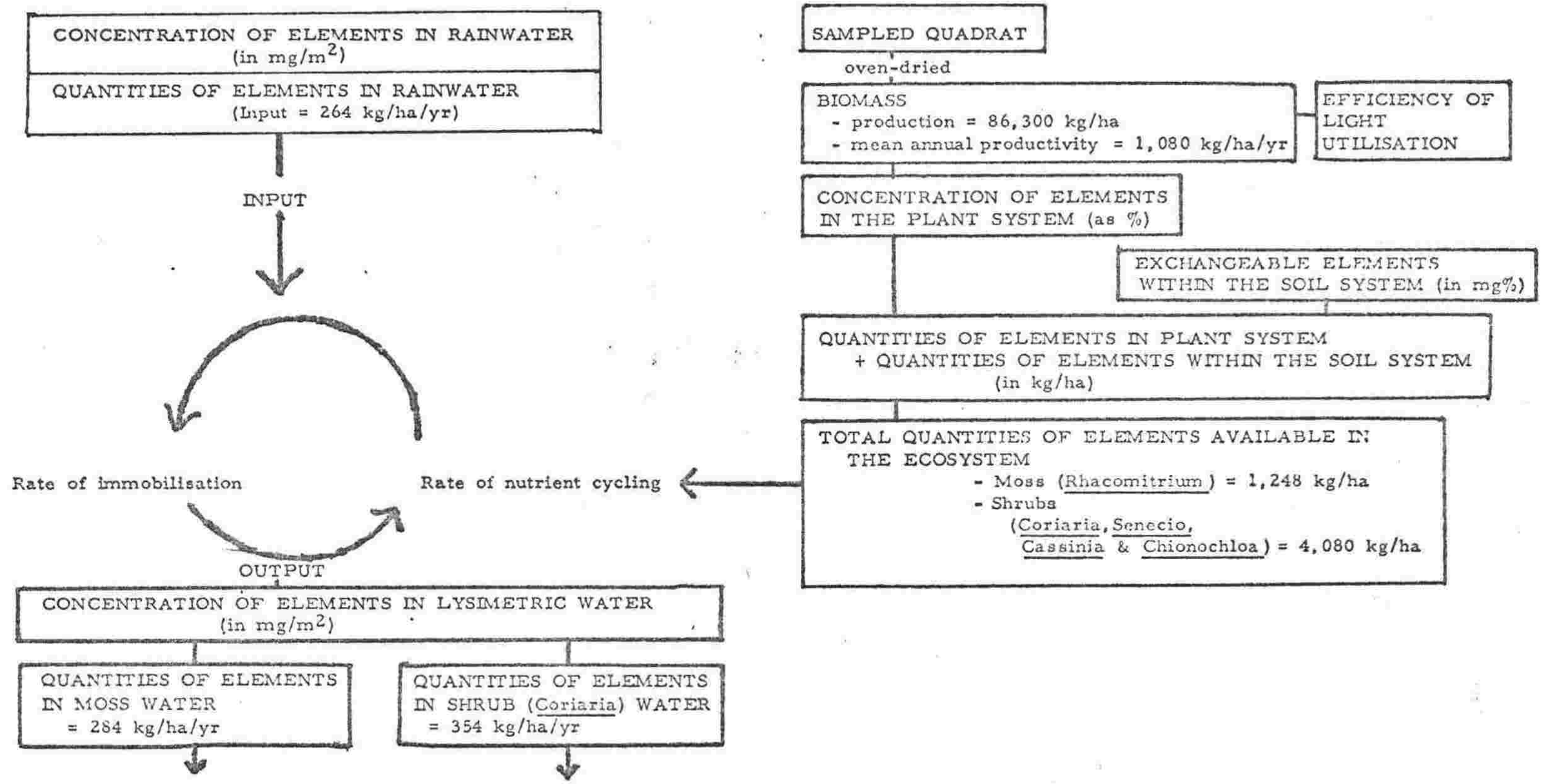


FIGURE 55 - Diagrammatic representation of steps undertaken in ecosystem study.

TABLE 11 - (a) Analysis of soil sampled from beneath shrubland and mossfield ecosystems. Quantities of elements in soil sampled beneath shrub and mossfield ecosystems

(b) to 5 cm depth, and

(c) nitrogen to 10 cm depth.

(a)

	Horizon	CEC me%	TEB me%	BS%	%Org.C	%N	C/N	Na mg%	K mg%	Mg mg%	Ca mg%	P mg%
Shrubland	Al	13.4	2.2	16	24.3	0.33	73	1.5	1.0	2.0	3.0	1.5
Shrubland	C	3.6	1.7	47	3.8	0.11	34	-	-	-	-	-
Mossfield	O	44.8	14.3	31	51.0	0.62	82	3.0	2.5	4.0	3.0	nd
Mossfield	C	5.4	0.8	14	5.6	0.02	280	-	-	-	-	-
Otanomomo Peat (*Sphagnum* moss)	O	92.0	27.8	30	48.4	1.43	34	2.5	1.07	14.8	9.2	4

N.Z. Soil Bureau 1968.

(b)

In kg/ha, to 5 cm depth		Na	K	Mg	Ca	N	P
Shrubland	A	1.2	0.8	1.6	2.3	730	2.21
Mossfield	O	0.2	0.2	0.2	0.3	124	trace

(c) Nitrogen to depth of 10 cm in kg/ha.

Shrubland	A	730	
Shrubland	C	+245	=975
Mossfield	O	124	
Mossfield	C	+ 43	=167

based on a weight measure. In both ecosystem soils, element concentrations are in the order Ca>Mg>K>Na. Levels for phosphorus in mg% are low within the shrubland soil but are negligible for both living and dead Rhacomitrium. The high organic C% and total N values in the mossfield soil compared with the shrubland soil are due to the slowly decomposing moss litter. CEC and TEB values of the Rhacomitrium litter are of similar order to values obtained from Sphagnum moss in the Otanomomo Peat from Southland (N.Z. Soil Bureau 1968, p.109).

Levels of exchangeable cations in the soil to a depth of 5 cm on a volume basis, are presented in Table 11b. In calculating these values an average density of 0.65 g/cc was assumed for the shrubland A and C and mossfield C horizons, and 0.04 g/cc for the dead moss 0 layer. These values were obtained by comparison with similar soil materials reported from elsewhere in New Zealand by N.Z. Soil Bureau (1968). For the stony soil, a correction was made for the 32% stones sieved from the samples. The volumes of exchangeable cations in both soils show a similar ordering as their concentrations, but the volume of exchangeable cations in the mossfield soil are negligible compared to the shrubland soil. No P was detected in the mossfield soil. The quantities of N in the Rhacomitrium litter are small and probably become available only by slow decomposition, compared to the much larger amounts readily available under the shrubs. Because of the large differences in N values in the A horizons, quantities in the C horizons were also calculated. Table 11c shows that to a depth of 10 cm, there was 5 times as much nitrogen in the shrubland soil compared to soil under the mossfield. The high N values in the shrubland soil have probably contributed to the lower C values i.e. low C/N ratio, compared to the mossfield soil with a C/N ratio of 280.

CHEMICAL ELEMENTS IN THE PLANT SYSTEM

Mean percentage compositions of plant components were determined from 28 analyses in duplicate on plant material collected from the first three sample periods. The values as percentages by weight were corrected by a moisture factor to give values for oven dried materials (Table 12).

Element concentrations are higher in material above ground than below ground. The highest Na values (0.35%) were in Cassinia, both above and below ground level. The values are 10 times greater than concentrations in the Rhacomitrium and double the Na% in Nothofagus truncata leaves (Miller 1963a). Senecio leaves contain the highest K concentration (1%), a feature consistent with previous observations that leaves contain the highest K% of most plant components e.g. N. truncata leaves are 0.5%K (Miller 1963c), and Acacia harpophylla F. Muell leaves and twigs are 0.7% (Moore, et.al. 1967). The other "high" K values of about 0.6% occur in Cassinia, Coriaria and "others" species all above ground. However all these values are low in comparison with herbaceous crops growing adjacent to the A. harpophylla analysed above, such as grass, lucerne and weeds which contained 2-4%K (Moore, et.al. 1967). The Mg values (1.1-1.4%) in the Coriaria leaves and stems, and Senecio leaves are about double the values of other plant materials analysed on the Egmont andesite in this study and are almost 10 times as high as N.truncata leaves on greywacke (Miller 1963c). On the other hand Senecio stems and Chionochloa above ground have low Mg values. Ca is

<u>TABLE 12</u> - Mean percentage element composition of plant components
(to convert to mg/gm x 10) tr = trace

		Na%	K%	Mg%	Ca%	N%	P%
<u>Rhacomitrium</u>	A.G.	.04	.07	.21	.16	0.62	tr.
	B.G.	<.03	.02	.13	<.17	0.62	tr.
<u>Coriaria</u>	A.G.	.22	.70	1.46	1.03	3.64	0.28
	B.G.	.26	.27	.27	.20	0.84	0.17
<u>Senecio</u>	A.G. leaves	.33	1.05	1.14	.85	0.94	0.09
	A.G. stems	.09	.28	.09	.27	0.34	tr.
	B.G.	.22	.23	.27	.61	0.40	tr.
<u>Chionochloa</u>	A.G.	.03	.12	.08	.14	0.58	tr.
	B.G.	.08	.08	.21	.22	n.d.	n.d.
<u>Cassinia</u>	A.G.	.38	.62	.32	.44	0.75	tr.
	B.G.	.36	.67	.19	.27	n.d.	n.d.
"Others"	A.G.	.12	.57	.53	.72	0.89	.06
	B.G.	.12	.19	.34	.35	0.66	tr.
Litter		.08	.19	.65	1.06	1.29	n.d.

n.d. - not determined

high in the litter samples, probably due to the loss of more mobile elements e.g. Na which is very low, Relative Ca increase with time is a common feature in little samples, probably related to Ca-forming compounds in cell walls. Increase in Si accompanies Ca increase, as Na and K decrease with time. This feature is best expressed by the Ca/K ratio which in the above litter is 5.7, in *Coriaria* stems and leaves is 1.5 and in *Senecio* leaves 0.8. Of the plant materials analysed, the highest Ca concentration is in the *Coriaria* whereas the lowest Ca, Na and K figures occur in *Rhacomitrium* and *Chionochloa*.

The *Coriaria* leaves and stems contain more nitrogen than the *Coriaria* roots and contain higher levels than gorse, an active nitrogen fixing legume (Egunjobi 1967). It appears that substantial amounts of nitrogen made available by the *Coriaria* nodules are rapidly translocated to the *Coriaria* stems and leaves eventually to be returned to the soil (and thus to other species) in the annual autumn leaf fall. The other N values are comparable with species such as *N. truncata*. The *Coriaria* also shows the highest P concentration and only the above ground "others" and *Senecio* leaves contain determinable amounts of P. This is probably an expression of the minute amounts of P available in the soil.

QUANTITIES OF ELEMENTS

The relative abundance of the elements Na, K, Mg, Ca, N & P in the plant materials of the four samplings is presented in Appendices D3 and D4 and these have been averaged (Table 13) and expressed in bar histogram form (Fig.56.). The tables were compiled from analysed samples (oven dry weight) together with

<u>TABLE 13</u> - Average quantities of elements in combined mossfield and shrubland systems (Kg/ha)

		Na	K	Mg	Ca	N	P
<u>Rhacomitrium</u>	A.G.	5.85	10.78	38.21	31.54	128.77	tr
	B.G.	6.69	5.86	22.09	39.98	207.08	tr
	Total	12.54	16.64	60.30	71.52	335.85	tr
<u>Coriaria</u>	A.G.	0.19	0.93	0.96	0.75	3.84	0.23
	B.G.	1.69	1.78	1.78	1.33	5.50	1.08
	Total	1.88	2.71	2.74	2.08	9.34	1.31
<u>Senecio</u>	A.G.	14.45	55.11	42.45	41.48	45.87	2.83
	B.G.	12.35	13.42	7.76	18.62	15.82	tr
	Total	26.80	68.53	50.21	60.10	61.69	2.83
<u>Chionochloa</u>	A.G.	2.46	10.66	3.17	7.32	28.85	tr
	B.G.	0.89	0.95	2.43	2.53	6.76	tr
	Total	3.35	11.61	5.60	9.85	35.61	tr
<u>Cassinia</u>	A.G.	6.66	10.59	5.77	8.33	14.28	tr
	B.G.	0.22	0.41	0.12	0.17	0.46	tr
	Total	6.88	11.00	5.89	8.50	14.74	tr
"Others"	A.G.	2.54	9.08	9.61	8.88	13.92	0.86
	B.G.	6.62	8.17	25.80	21.02	47.20	tr
	Total	9.16	17.25	35.41	29.90	61.12	0.86
Litter		1.73	3.92	13.84	22.49	27.35	n.d.
Total Quantities of Elements in Systems		62.32	131.66	173.99	204.43	545.70	5.00

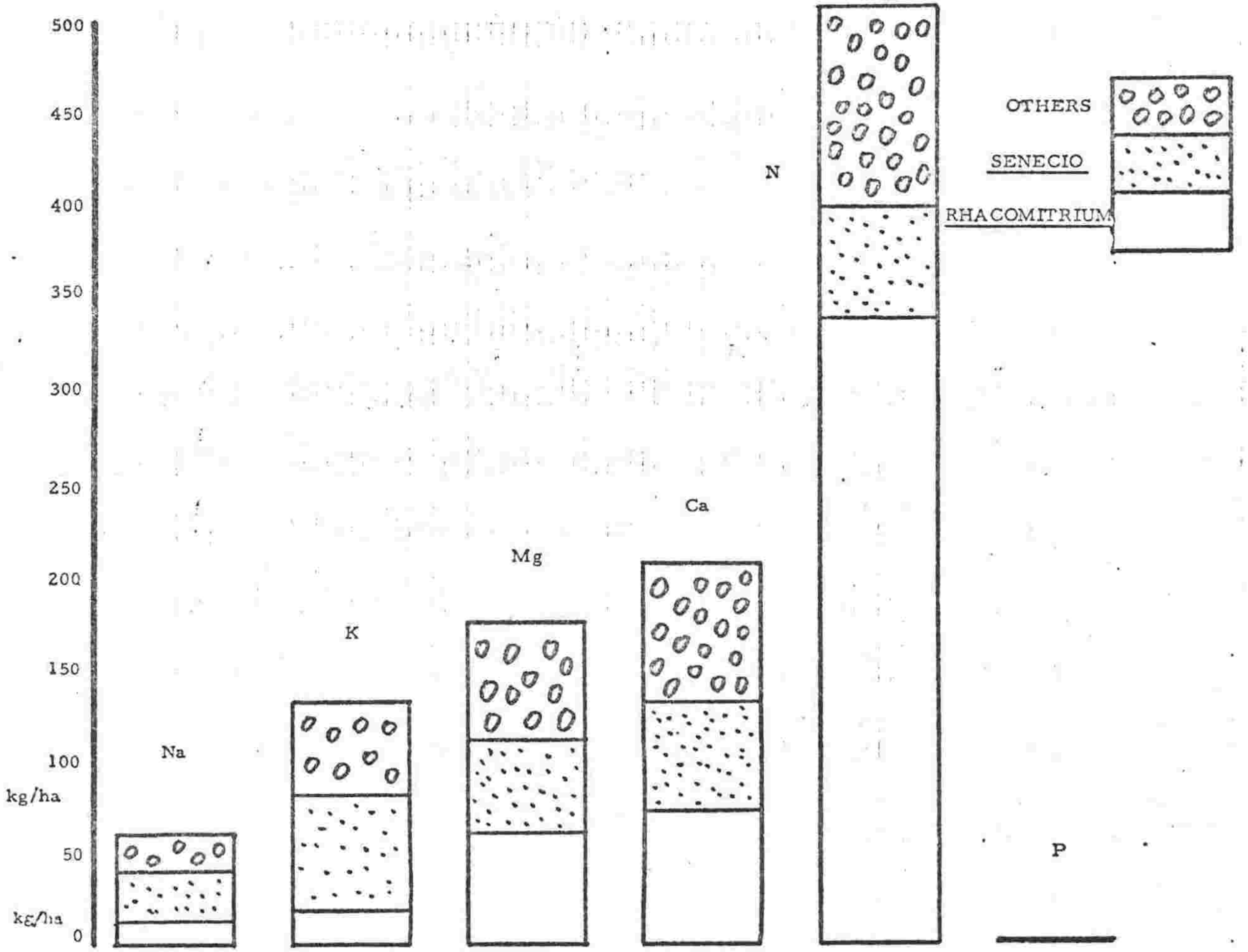


FIGURE 56 - Average elemental abundances in plant components of the combined mossfield-shrubland ecosystems, (in kg/ha).

assumed values for most of the February 1971 samples, for which the average values from similar plant materials were applied. Because of the minor importance of Chionochloa and Cassinia roots, the above ground N & P values were applied to them, and thus N & P abundances in the roots are likely to be maximal values.

Although Rhacomitrium comprises the largest percentage of the biomass the Senecio contains nearly 50% of the Na and K. Rhacomitrium, Senecio and "others" species contain near equal proportions of Mg and Ca. The large leaf biomass for Senecio accounts for the high amounts of Na and K. Most of the Mg and Ca is contained in Senecio, alive and dead Rhacomitrium and "others" roots, although the high values in the roots may be due to some soil contamination. There is a marked order of elemental abundances in the litter from Ca>Mg>K>Na, which confirms the rapid mineralisation of K and Na, with apparent concentration of Ca which is slow to cycle. The highest N values per hectare are in dead Rhacomitrium, although much of this is probably in a form unavailable for use by other organisms. It is noticeable that quantities of N in Coriaria per hectare, are low, compared to other species, but these values do not take into account, the rate at which N is being cycled. P occurs in detectable quantities in Coriaria and Senecio whereas it was not detected in Rhacomitrium, Cassinia and Chioncohloa (Table 6). Johnston (1959) has shown the ability of citric, oxalic, tartaric and malic acids to extract phosphate and it is possible that similar acids are released by Coriaria which enable it to extract P from the andesite.

In comparison with other vegetation systems the total quantities of elements in the combined mossfield and shrubland systems are surprisingly high considering the low productivity and youthfulness of the ecosystems (Table 14). The plant components of the ecosystems contain substantially higher amounts of Na and Mg than the N. truncata stand examined by Miller (1963) and the natural Ulex ecropaeus L. ecosystem (unfertilised) studied by Egunjobi (1967). Total K is low and appears limiting. Most of it appears met from rainwater. The Mg content is similar to a brigalow (Acacia harpophylla) of about three times the biomass (Moore, et.al. 1967) whilst Ca values approach those obtained from U. europaeus (Egunjobi 1967) and Pinus radiata communities (Will 1966). Quantities of total nitrogen are in excess of those in P. radiata, probably due to the absence of nitrogen fixing plants in the latter community. On the other hand P is almost negligible in the mossfield and is low in the shrubland systems. The most abundant elements are thus N, Ca and Mg.

TOTAL AVAILABLE ELEMENTS IN THE ECOSYSTEMS

Total available elements in the mossfield and shrubland ecosystems (total plant and exchangeable soil) are presented in Table 15, calculated to a depth of 5 cm. The plant quantities have been averaged from the four sample periods, but quantities of elements available in the soil are those obtained from beneath the separate mossfield and shrubland vegetation systems. Percentages of nutrients in the plant and soil systems are also included.

Little or no exchangeable Na, K, Mg and Ca is present within the soil of the mossfield ecosystem and only slightly

TABLE 14 - Quantities of elements in kg/ha contained in various vegetation systems

Dominant Plant Species	Age (yrs) of vegetation system	Dry Matter kg/ha	Na	K	Mg	Ca	N	P
Mossfield-shrubland (*Rhacomitrium*, *Coriaria*, *Senecio*) (this account)	80	86,300	62	132	174	204	546	5
Gorse (*Ulex europaeus*) (Egunjobi, 1967)	8	Fertilised 97,900	76	349	114	226	884	37
		Control 87,300	45	256	102	197	755	20
Brigalow (*Acacia harpophylla*) (Moore, *et.al.* 1967)	-	293,000	100	300	180	2,230	1,600	38
Beech (*N. truncata*) (Miller, 1963b)	110	313,600	30	465	149	1,340	530	86
Pinus radiata (A.G.) (Will, 1966)	35	304,600	-	324	-	187	319	40

TABLE 15 - Total (Kg/ha) and Breakdown in Plants and Soil (Exchangeable) of elements in Mossfield and Shrub Ecosystems, to soil depth of 5 cm.

		Na	K	Mg	Ca	N	P
Mossfield	Plants %	99.7	99.9	99.9	99.9	81.5	100
Ecosystem	Soil %	0.3	0.1	0.1	0.1	18.5	trace
	Total kg/ha	62.5	131.8	174.2	204.7	670.0	5.00
Shrubland	Plants %	98.1	99.4	99.1	98.9	42.8	69.3
Ecosystem	Soil %	1.9	0.6	0.9	1.1	57.2	30.7
	Total kg/ha	63.2	132.8	175.6	206.3	127.6	7.21

larger percentages under the shrubland. For nitrogen the proportion~~s~~ (in soils and plants) varies greatly; there is only 18% of the total N of the mossfield ecosystem in the soil but 57% of the N in the shrubland ecosystem is in the soil. Thus because the total N in the shrubland ecosystem is considerably higher than the mossfield there are significant quantities of the element in various forms available in the soil beneath the shrubs for utilisation by other species. Available soil phosphorus was detected only in the soil beneath the shrubs and indicates that <u>Coriaria plumosa</u> is probably capable of extracting and making P available in addition to N, because it is the first seral species of the shrubland ecosystem.

QUANTITIES OF ELEMENTS IN RAINWATER (INPUT OF ELEMENTS INTO THE ECOSYSTEM).

Published rainwater analyses in New Zealand come from sample sites at Lincoln (Gray 1888, 1910), the southern part of the North Island (Blakemore 1953, Miller 1961) and in the Rotorua district (Will 1959). The relative quantities of elements measured in these rainwaters show strong correlation with distance from the coast. Accordingly high values of elements in rainwater might be expected for samples collected from Mt. Egmont because the collection site is only 24 km from the Tasman Sea and is at 1170m (3,900 ft) altitude.

The chemical composition of monthly rainwater samples collected from the site is presented in Table 16. No sample was obtained for August 1969 and thus the September value is for a two month period. Of the total analysed elements added in the rainwater per annum, Na and Cl total 83.1%, K 6%, Ca 4.8%,

TABLE 16 - The Chemical composition of rainwater, Little Pyramid, Mt. Egmont 1968-70. Altitude of site 1,170m (3,900 ft). In mg/m^2

Month	Sample date	Days in Period	Rainfall (mm)	Na	K	Mg	Ca	Cl	P	Nitrate	Nitrite	Ammon-iacal Nitrogen
Dec.	31/12/68	31	464	209	n.d.	23	32	927	-	-	-	-
Jan.	31/ 1/69	31	438	394	n.d.	44	22	876	-	-	-	-
Feb.	28/ 2/69	28	290	232	29	17	58	-	57.9	-	-	-
Mar.	30/ 3/69	30	241	483	48	17	17	483	9.7	-	-	-
Apr.	1/ 5/69	32	521	1,302	104	156	104	2,083	-	-	-	-
May	31/ 5/69	30	572	857	57	114	114	572	-	-	5.7	-
Jun.	28/ 6/69	28	305	1,006	30	152	76	2,134	-	-	-	-
Jul.	2/ 8/69	35	305	457	30	61	61	1,524	-	-	-	-
Aug.)												
Sep.)	27/ 9/69	56	991	991	99	99	99	991	-	-	-	-
Oct.	1/11/69	35	330	991	66	132	198	1,651	-	-	-	-
Nov.	29/11/69	28	210	231	21	10	105	419	-	-	-	-
Dec.	29/12/69	30	419	629	84	42	210	1,048	-	-	-	-
Jan.	31/ 1/70	33	210	356	21	21	105	419	-	-	-	10.5
Feb.	28/ 2/70	28	146	263	131	73	58	1,169	-	-	-	21.9
Mar.	27/ 3/70	27	495	792	347	99	149	1,486	-	-	-	-
Apr.	2/ 5/70	36	597	955	478	179	119	2,388	-	-	-	-
May	30/ 5/70	28	584	993	584	292	409	3,505	-	-	-	-

n.d. = not determined

\- = not detected

Mg 3.8%, S 1.5%, P 0.17% and N 0.09%.

The six high Na sample periods correspond to the high Cl periods, five of the six high Mg periods and two of the three high K periods; all being recorded between the months of April and October. The lowest K values (less than 30 mg/m^2) were between November and February. Highest Mg values were recorded in the months of April and May, whilst the low values were between November and March. Phosphorus was measurable only in February and March 1969, when rainfall was minimal. Similar seasonal variations in phosphorus occurrence have been noted in Rotorua rainwater samples and high P has been related to periods when the atmosphere is "dirty and dusty after a dry spell" (Dr. G. Fish, pers.com.). The most neutral waters were also recorded at this time of year, and the five samples nearest pH 7.0 were during the months January to May. Ionic ratios on a chloride basis of Na, K, Mg & Ca were determined for the four low rainfall months, the four peak months and 18 averaged months, but there was not such a clear trend evident as at Taita (Miller 1961).

The observations of the cation concentrations conform to Wilson's (1959, 1960) and Miller's (1961) contention that proportionately more elements are derived from surface seawater during the winter months when winds whip nitrogenous rich surface spray high into the atmosphere. However no nitrate and very little nitrite, ammoniacal and albuminoid nitrogen was detected by the methods employed, to accurately plot N against K as Wilson (1960) did.

Values of oxygen absorbed in four hours at 27°C are accepted as a measure of the amount of organic matter in a water sample. Organic matter content was highest during the months of February and March 1969 and January, March and May 1970, possibly indicating considerable terrestrial dust in the summer-autumn samples. The detectable amounts of sulphur and several forms of nitrogen during these months also suggests some elements including considerable amounts of N may accumulate during the drier months at Egmont. Dust clouds originating from deep gorges nearby, as have been observed during dry summer months, may have introduced fine terrigenous dust during some sample periods. Tonkin (1970) reports that a constant feature of subalpine soils on Egmont is a layer of wind blown sand trapped in the moss mat that covers the soil surface.

The elemental composition of rainwater collected over an 18 month period (December 68 - May 70) has been converted to kg/ha/yr (Table 17). The higher P and K values at Egmont, compared to Taita and Rotorua, probably result from frequent aerial topdressing of superphosphate and potash on the surrounding farmlands. The N and S values are considerably lower than rainwater samples at Taita (Miller 1961) and may be explained as

(1) a real difference because Taita is nearer the coast, if most of the N is from a marine source, or

(2) the true values were below the detection limits of the methods employed.

Alternative (2) is more likely to apply although Na and Cl values are higher than Taita samples and thus N & S could be expected to be higher. Total values have also been included for these latter elements over the 18 month period.

Na and Cl values are higher than at Taita (Miller 1961) indicating the height to which large amounts of salts can be

TABLE 17 - Annual Quantities of Elements in Rainwater (averaged from 18 months data) in kg/ha/yr.

Locality	Rainfall (mm)	Cl	N	P	S	Na	K	Mg	Ca	Sum.
Mt. Egmont (this account)	4270	146	0.25 (*0.38)	0.45 (*0.68)	3.9 (*5.9)	74	16.0	10.2	12.9	264
Taita (Miller, 1961)	1352	116	2.8	0.22	8.4	59	6.6	11.2	7.3	212
Rotorua (Will, 1959)	-	-	-	0.3	-	32.5	5.8	-	3.2	

* Total values for 18 months.

carried to, but they are not as high as the 235 kg/ha/yr recorded on the coast near Wellington (Blakemore 1953).

"Excess potassium ion concentrations" (Wilson 1959) were calculated for the monthly samples (see Appendix D5), and expressed relative to Na. Only in the months of May and July 1969 and January 1970 did the concentrations approach those of sea water. The high ratios of the last four samples were probably associated with an increased K input during a period of high monthly rainfalls.

The higher annual computed inputs of Na, Cl, K and Ca in rainfall at the study site compared to Taita probably reflect both

(1) a stronger maritime influence in Taranaki, and

(2) higher and evenly distributed rainfall throughout the year.

QUANTITIES OF ELEMENTS IN RUNOFF WATERS

Leaching of elements from the soil is strongly dependent upon rainfall, interception at ground level and lateral surface and subsurface flow depending on the angle of slope. Where the hydrology is not fully known instruments for water quality and quantity studies can prove difficult to install. Many workers on nutrient cycling have resorted to data on sampling of stream waters (Miller 1963b), but changes in nutrient values occur in runoff water between the soil profile and the open stream channel. Two lysimeters were installed under Rhacomitrium and Coriaria systems and are described under "Methods of Study". Water analyses of samples collected from the lysimeters and analysed between December 1968 and May 1970 at monthly intervals are presented in Tables 18 and 19.

TABLE 18 - The Chemical Composition of *Rhacomitrium* lysimeter water, Little Pyramid, Mt. Egmont in mg/M^2. 1968-70
Altitude 3,900 ft (1,170m)

Monthly Sample	Sample Date	Na	K	Mg	Ca	Cl	P	Nitrate	Nitrite	Ammonia-cal Nitrogen	Albumin-oid Nitrogen	S	pH	0_2 absorbed in 4 hrs at 27°C	Water discharge in $1/m^2$	PEP value in ug/ml
Jan.	31/ 1/69	163	n.d.	13	n.d.	875	75	-	-	n.d.	n.d.	-	4.9	6.3	125	n.d.
Feb.	28/ 2/69	51	20	10	10	-	20.4	-	-	-	10.2	6.1	6.6	0.58	102	n.d.
Mar.	30/ 3/69	243	68	19	22	485	3.9	-	-	-	-	-	4.9	4.1	97	n.d.
Apr.	1/ 5/69	626	169	209	167	2,085	-	-	-	-	tr	-	4.6	2.7	417	n.d.
May	31/ 5/69	287	306	38	115	573	-	-	-	-	n.d.	-	6.8	3.2	191	0.8
Jun.	28/ 6/69	383	28	28	85	2,130	-	-	-	-	5.7	-	5.3	3.0	142	0.9
Jul.	2/ 8/69	1,067	305	305	457	1,524	-	-	-	-	n.d.	-	5.3	2.2	1,524	n.d.
Aug.) Sep.)	27/ 9/69	356	40	20	20	990	-	-	-	-	n.d.	-	4.7	4.8	198	0.7
Oct.	1/11/69	659	37	110	110	1,647	-	-	-	-	n.d.	-	4.9	3.2	183	n.d.
Nov.	29/11/69	308	28	28	70	420	-	-	-	-	-	-	5.2	5.3	140	n.d.
Dec.	29/12/69	3,039	419	210	629	1,048	-	-	-	-	n.d.	-	5.3	6.2	1,048	n.d.
Jan.	31/ 1/70	123	20	20	25	417	-	-	-	4.9	n.d.	-	4.8	6.4	49	n.d.
Feb.	28/ 2/70	221	169	78	481	1,170	-	-	0.5	-	n.d.	-	5.1	2.8	130	n.d.
Mar.	27/ 3/70	743	356	178	238	1,485	-	23.8	-	-	n.d.	-	5.7	18.0	297	n.d.
Apr.	2/ 5/70	956	430	478	287	2,390	-	-	-	-	n.d.	-	5.0	4.6	478	n.d.
May	30/ 5/70	1,096	745	307	569	3,504	-	65.7	-	-	n.d.	-	5.0	2.0	438	n.d.

n.d. - not determined

\- not detected

TABLE 19 - The Chemical Composition of Coriaria lysimeter water, Little Pyramid, Mt. Egmont. 1968-70
Altitude 3,900 ft (1,170m). In mg/m^2.

Monthly Sample	Sample Date	Na mg/m^2	K	Mg	Ca	Cl	P	Nitrate	Nitrite	Ammonia-cal Nitrogen	Albumin-oid Nitrogen	S	pH	O_2 absorbed in 4 hrs at 27°C	Water discharge in l/m^2	PEP value in ug/ml
Jan.	31/ 1/69	500	n.d.	21	88	875	62.5	18.8	-	-	n.d.	-	5.5	17.3	135	n.d.
Feb.	28/ 2/69	202	269	8	34	-	235.2	-	-	-	16.8	16.8	6.4	>6.85	84	n.d.
Mar.	30/ 3/69	331	166	21	31	483	10.3	-	-	-	13.8	-	5.2	19.5	69	n.d.
Apr.	1/ 5/69	4,164	694	625	347	2,082	-	-	-	-	173.5	-	5.0	7.5	694	n.d.
May	31/ 5/69	630	134	57	57	573	-	-	1.9	-	n.d.	-	6.8	15.6	191	3.65
Jun.	28/ 6/69	838	93	200	166	2,128	-	-	-	-	5.3	-	5.3	9.4	133	3.92
Jul.	2/ 8/69	2,770	831	554	2,770	1,524	-	-	-	-	n.d.	-	5.0	12.7	1,385	n.d.
Aug.) Sep.)	27/ 9/69	297	33	83	17	990	-	-	-	-	n.d.	-	4.9	24.2	165	3.8
Oct.	1/11/69	824	144	185	185	1,648	-	-	-	-	n.d.	-	4.2	13.5	206	n.d.
Nov.	29/11/69	336	126	32	74	420	-	-	-	-	-	-	5.1	18.5	105	n.d.
Dec.	29/12/69	1,100	314	210	472	1,048	-	-	-	-	n.d.	-	5.2	14.8	524	n.d.
Jan.	31/ 1/70	420	84	105	168	420	-	-	-	21.0	n.d.	-	5.1	16.0	210	n.d.
Feb.	28/ 2/70	204	97	466	68	1,164	-	4.9	-	9.7	n.d.	-	5.3	22.6	97	n.d.
Mar.	27/ 3/70	564	267	178	149	1,485	-	-	-	-	n.d.	-	5.2	24.0	297	n.d.
Apr.	2/ 5/70	637	318	199	1,274	2,388	-	-	-	-	n.d.	-	5.3	1.7	398	n.d.
May	30/ 5/70	729	459	324	567	3,510	-	-	-	-	n.d.	-	4.9	14.4	270	n.d.

n.d. - not determined

\- not detected

Water collected from the *Coriaria* lysimeter was frequently discoloured appearing rather like weak tea, compared to little or no discolouring of the *Rhacomitrium* water. When analysed the *Coriaria* water showed a higher elemental composition than the *Rhacomitrium* water (i.e. higher element loss) which appears associated with the discolouration. A good measure of the amount of dissolved organics in the water, which are likely to cause the discolouration, was the value of oxygen absorbed in 4 hours at 27°C. This value was consistently much larger in the *Coriaria* lysimeter water than in the *Rhacomitrium* water except on one occasion. The values indicating organic matter content, peak (Table 19) in the *Rhacomitrium* lysimeter during March 1970 (with a value of 18) and in the *Coriaria* lysimeter during September 1969, February and March 1970 (up to a value of 24). Three samples from each lysimeter were submitted to Dr. K.R. Tate, Soil Bureau, DSIR, Taita, for polyphenol analysis. The values quoted as "PEP" (Tables 18 and 19) are the total polyphenolic compounds in the water determined by using the Folin and Ciocalteu (1927) reagent for colour development. Phloroglucinol was used to construct a calibration curve, and measurements were made on a Beckman DU spectrophotometer. Samples from the *Coriaria* water showed PEP values four times greater than those obtained from the *Rhacomitrium* water. This confirms that the greater absorption of oxygen by the *Coriaria* water is likely to be due to the presence of polyphenols. The high values in the autumn and winter months probably represent the release of a large proportion of organics from the *Coriaria* leaves which generally fall between February and May.

The highest Na values in both sets of runoff waters and the highest K, Mg and Ca concentrations in the Coriaria water coincide with calculated greater discharges during periods of heavy rainfall. The highest K, Mg and Ca values in the Rhacomitrium water do not correspond to the higher calculated discharges although heavy rainfall was recorded in each of these high value months.

Because of the large amount of runoff water, the bulk containers frequently overflowed and only summer flow could be accurately measured when the containers were not completely filled. In order to calculate the volume of water lost from each lysimeter and thus the amount of leaching it was necessary to use an indirect method to calculate water flow. Because Cl is only weakly absorbed by soil, rock and plant materials and since there is little Cl in andesite, it is assumed that the bulk of the Cl added in rainfall is lost from the ecosystem in runoff. Thus if the amounts of chloride are known entering the ecosystem with unit time, it is possible to speculate on the amount of elements leaving the ecosystem by assuming similar total chloride loss, i.e.

Rainwater volume (cc) x chloride concentration = Volume of water discharged x chloride concentration in water discharged.

The water discharges listed in Tables 18 and 19 have been calculated from this equation. It should be noted that on rare occasions the calculated water discharge is greater than the rainfall volume, but this has not been corrected because of the time lag between addition and discharge of chloride cocentrations to and from the ecosystem.

Once the water discharge is known, totals of elements lost in runoff water can be calculated and expressed in kg/ha/yr (Table 20). Quantities of elements from the *Rhacomitrium* lysimeter show values approaching those obtained by Miller (1961), estimating values from Johannesson's data, except for P & S. However, the amounts of elements lost from the *Coriaria* lysimeter were significantly greater than the *Rhacomitrium* lysimeter. There was more than double the amounts of N, P & S and 30% more Na, K, Mg & Ca lost from the *Coriaria* ecosystem than from the *Rhacomitrium* ecosystem. This is best expressed in the sum total of the salts which were lost from the *Rhacomitrium* lysimeter per annum (284) and in the *Coriaria* lysimeter 354 kg/ha/yr.

In order to determine if river waters in the area showed higher or lower amounts of nutrients than the *Coriaria* waters, samples were collected on 4 occasions from the following localities:

(a) near the 600m (2,000 ft) contour in Maero Stream, Grid Reference: N118/584657

(b) near the 270 m (900 ft) contour in Stony River, N118/518687 and

(c) near the 60 m (200 ft) contour, alongside Highway 45 bridge over Stony River, N108/453752.

The concentrations of elements in the Maero Stream waters (Table 21) are lower than in the runoff water from the *Coriaria* ecosystem. However when the Maero Stream joins Stony River there is an apparent four fold increase in the Mg values although other element values remain of a similar order. These Mg values were consistently higher on the four occasions sampled and the most likely source for this anomalous occurrence is either:

<u>TABLE 20</u> - Elements lost to drainage in <u>Rhacomitrium</u> and <u>Coriaria</u> lysimeters on an annual basis, in kg/ha/yr.

	Cl	N	P	S	Na	K	Mg	Ca	Sum.
<u>Rhacomitrium</u> Lysimeter	146	0.89 (1.1)	0.7 (0.99)	0.04 (0.06)	73	24	14	25	284
<u>Coriaria</u> Lysimeter	146	1.88 (2.65)	2.17 (3.08)	0.12 (0.17)	103	30	23	46	354
<u>Nothofagus truncata</u> Ecosystem (Miller 1963c)	143	2	0.13	15	71	15	15	30	291

TABLE 21 - Analyses of selected water samples from (a) the study site lysimeters,
(b) Maero Stream, and
(c) Stony River
in mg/litre

		Na	K	Mg	Ca
STUDY SITE	- *Rhacomitrium* (average value)	2.0	0.7	0.4	0.7
STUDY SITE	- *Coriaria plumosa* (average value)	3.1	1.1	0.8	1.0
MAERO STREAM at N118/584657					
	- March 1970	1.8	0.8	1.5	0.5
	- May 1970	2.7	1.4	1.6	0.6
STONY RIVER at N108/453752					
	- March 1970	2.1	1.1	4.3	1.2
	- April 1970	2.7	1.3	5.5	1.5
	- May 1970	2.5	1.6	5.3	1.6
	- April 1971			5.6	
STONY RIVER at N118/518687					
	- April 1971			5.6	

(1) derivation from a reducing environment in Ahukawakawa Swamp in the headwaters of Stony River, or

(2) rapid release of Mg from the more weathered Pouakai andesites (compared to the Egmont andesites), exposed along the north bank of Stony River.

DISCUSSION

The elemental content of the *Coriaria* plant components is clearly not substantial but most elements in *Coriaria* components are likely to have a much higher rate of return to the soil than other plants. Relatively high N and significant but low P values in the shrubland soil support this view. The high nutrient status of the *Coriaria* components together with high N, Mg and some P in the soil may also explain the increased observed growth of *Senecio* and *Chionochloa* where *Coriaria* is present. The release of these nutrients following an autumn leaf fall is a likely explanation for the higher element values obtained from the *Coriaria* lysimeter. The Mg and K values peaked in the lysimeter water after this fall, between February and July. In addition, during the late summer months numerous *Coriaria* plants are stripped of their leaves by insect activity. The high content of nutrients in the *Coriaria* leaves may be an attractive and important food source for arthropods, and a high proportion of the *Coriaria* nutrients may be returned to the soil indirectly in their dead bodies, faecal pellets and frass.

It appears more than coincidental that quantities of K are lower and Mg are higher than in other ecosystems and that K levels are low and Mg levels are high in the *Coriaria* stems and leaves. Yet, the *Coriaria* forms only a small amount of the biomass. It is suggested that the Coriaria may be controlling the bulk of elemental weathering and organic cycling of elements such as Mg which then become rapidly available to other species for utilisation. Coriaria lysimetric water showed double the amounts of K, Mg and Ca were lost than were being added in rainwater. Where Coriaria and its associated organics are absent, elements are more slowly released by weathering and may limit growth of other plants.

In comparison with other rock types (Table 22) the Mt. Egmont andesites contain low K_2O and high MgO. Release of these elements by organic acid interactions is likely to produce an ecosystem low in K and high in Mg, compared to the rhyolite and greywacke soils of the Central North Island. Only basalts and other andesites show similar elemental abundances. The abundance of major elements in the mossfield-shrubland ecosystems is therefore considered to be largely governed by the andesitic rock composition and the rate at which the components can be weathered. There is no appreciable difference in the texture of soil parent material in the mossfield and shrubland ecosystems suggesting that the higher CEC values under the shrubs are due to humic compounds released from litter. CEC values of carboxyl and phenolic hyrdoxyl radicals are considerably greater than inorganic clay minerals and vary up to 300-700 me% (Comber 1960). Considerably greater polyphenol values in water draining from the Coriaria lysimeter have been measured, and it is likely that they are involved with a large number of the exchangeable reactions in the shrubland soil.

TABLE 22 - Average rock compositions of volcanic and greywacke parent materials, North Island, N.Z. from Ewart and Stipp (1968) together with average composition of Mt. Egmont andesite from Gow (1968).

	1	2	3	4	5	6	7
SiO_2	54.70	74.22	61.2	55.90	51.16	49.52	71.1
Al_2O_3	18.07	13.27	16.9	16.90	17.12	17.32	13.9
Fe_2O_3	3.90	0.88	2.4	2.10	2.40	3.81	tr
FeO	3.75	0.92	4.0	6.30	7.25	7.03	2.7
MgO	3.32	0.28	3.7	5.20	6.12	6.01	1.3
CaO	8.17	1.59	6.9	8.40	11.41	11.41	1.8
Na_2O	3.69	4.24	2.9	2.60	2.28	2.50	3.7
K_2O	1.88	3.18	1.53	1.00	0.54	0.33	2.3
TiO_2	0.85	0.28	0.17	0.76	0.80	1.15	0.50
P_2O_5	-	0.05	0.02	0.10	0.13	0.19	0.10
MnO	0.16	0.05	0.02	0.15	0.18	0.19	0.05
H_2O^+	-	0.80	0.31	tr	0.27	0.25	1.9
H_2O^-	-	0.23	0.22	0.06	0.15	0.26	0.26
CO_2	-	-	-	-	-	-	0.12
	98.49	99.99	100.27	99.47	99.80	99.97	99.73

1. Average composition of Mt. Egmont andesites (Gow 1968)
2. Average composition of rhyolite lavas and domes (average of 25 analyses)
3. Andesite, Mount Edgecumbe (P.29166)
4. Andesite, Ngauruhoe lava of 1954 (Steiner, 1958)
5. Basalt lapilli, Tarawera (Grange 1937)
6. Basalt, K-Trig (Grange 1937)
7. Composite greywacke sample from Wellington (Reed; Table 1, No.1).

ORGANIC TURNOVER AND CHEMICAL CYCLING IN THE ECOSYSTEMS

MINERAL CYCLING

The mean rate at which the principal elements are immobilised in the vegetation is presented in Table 23A together with comparable data from Ulex europaeus and Nothofagus truncata stands. The Egmont figures were obtained by dividing the averaged total element content of the biomass (from the four sample quadrats), by the age of the vegetation (80 years). The element values for Coriaria above ground level were not included in these figures because they are not immobilised but returned to the soil each autumn. Immobilisation and return of the Coriaria leaves and stems are expressed as percentages of the total uptake. Recretion and dry salt return to the soil were not measured in this study and are doubtfully significant because there is only scattered growth of Senecio and Cassinia shrubs within large intervening areas of Chionochloa and Rhacomitrium which would prove difficult to measure.

The estimated annual uptake of elements is very low in comparison to the Ulex europaeus ecosystem examined in New Zealand (Egunjobi 1968). The figures do not greatly differ from figures obtained from N. truncata and show greater Na, Mg and N uptake. K, Ca and P uptake is lower than the N. truncata though K and P in sample quadrat 1, with Coriaria present, do show higher values. These general trends indicate a very large proportion of materials that become available to the vegetation are being directly immobilised with little return in leaf or twig fall (except for Coriaria). Percentage immobilisation is high for all the elements except P, compared to U. europaeus and N. truncata figures (Table 23B). Nearly 80% of the P is returned

TABLE 23 - Annual uptake, immobilisation and return of major elements in kg/ha/yr - (Immobilisation expressed as a % of annual uptake) in A. combined mossfield-shrubland ecosystems,
B. N. truncata, and U.europaeus ecosystems, and
C. the shrubland ecosystem of sample quadrat 1.

A.	Element		Na	K	Mg	Ca	N	P
	Total uptake		0.96	2.57	3.13	3.31	10.61	0.29
	Immobilised		0.78	1.64	2.16	2.56	6.77	0.06
	Returned i.e. Coriaria litter (recretion & dry salt not determined)		0.19	0.93	0.96	0.75	3.84	0.23
	Return as % Uptake		19.1%	35.2%	30.8%	22.6%	36.2%	79.1%
	% Immobilised		80.9%	64.8%	69.2%	77.4%	63.8%	20.9%
B.	N.truncata	% Immobilised	4%	13%	9%	12%	8%	21%
	(Miller 1963c)	Total uptake	0.23	4.5	1.2	10.1	3.4	0.7
	U.europaeus	% Immobilised	36%	37%	25%	27%	31%	43%
	(Egunjobi, 1967)	Total uptake	14	81	36	56.5	229.4	7.03
C.	Shrubland Ecosystem Only (containing Coriaria) (SAMPLE QUADRAT 1)							
	Total uptake		1.07	4.13	4.84	4.41	22.80	0.92
	Immobilised		0.33	0.42	0.99	1.42	7.46	0.01
	Returned		0.74	3.72	3.85	2.99	15.35	0.91
	% Immobilised		30.8%	10.1%	20.4%	32.1%	32.7%	13.1%

in Coriaria leaves and stems. Rates of immobilisation were also calculated for the Coriaria areas only and show the important effect the plant has in recycling most of the nutrients in the site (Table 23C). Immobilisation rates of sample 1 only, show that Na, Mg, Ca and N immobilisations are similar to those of U. europaeus, but that K and P are substantially lower and comparable to those of N. truncata. It should be noted however that the return of nutrients to the soil in sample quadrat 1, will be about four times as high as the overall mossfield-shrubland ecosystems which are considered a more representative estimate of nutrient return over the entire debris flow deposit at this altitude.

CHEMICAL BALANCE SHEET

There was a gain of elements into the mossfield and shrubland ecosystems from the atmosphere and 18 analyses of monthly rainwater samples are considered sufficient to estimate this supply. In addition there is input of nutrients from weathering of the andesitic sand in the soil system. Die back of the Coriaria stems and leaves will return nutrients to the soil and is broadly equivalent to litter fall recorded in higher stands of vegetation. Losses to the soil system will include those elements immobilised in the plant material and loss to drainage will be loss from the ecosystem as a whole. In calculating amounts of elements in runoff water, it should be emphasised that quantities of runoff waters were not observed accurately and were calculated from the chloride concentrations.

From the available data an attempt has been made to produce a chemical balance sheet for the mossfield and shrubland ecosystems. Table 24 shows a simple chemical balance using the same rainfall and average immobilisation data but separate *Rhacomitrium* and *Coriaria* lysimeter values. Net losses from the shrubland ecosystem are substantially higher than from the *N. truncata* values obtained by Miller (1963c) but net loss of P, K and Mg from the mossfield ecosystem is similar to *N. truncata* and there is even a slight gain of Na and S.

To compare the cycling of nutrients in the mossfield and shrubland soils, separate balance sheets (Table 25) were prepared from the sample quadrats 1 (with *Coriaria*) and 2 (without *Coriaria*). It should be noted that without the *Coriaria* growth there is no measurable return of nutrients to the soil from plant materials and only rainwater input, drainage losses and rates of immobilisation can be calculated. The influence of the *Coriaria* is marked and leads to greatly increased losses of Na, Mg, Ca and P. The return in the litter of substantial amounts of nitrogen, presumably in a readily available form, is a net addition to the soil system of 6 kg/ha/yr and is rapidly immobilised. It is noticeable that the net loss of K (10kg/ha/yr) is similar for both mossfield and shrubland ecosystems, but Mg loss from the shrubland is more than double that from the mossfield. The amounts of elements reaching the soil beneath the *Coriaria* from rainfall and from litter return are presented diagrammatically in Appendix D6. Most of the nitrogen is from the *Coriaria* whilst most Na, K, and Ca is from rainfall. About 2½ times as much Mg but only ½ the amount of P is added in rainwater as from *Coriaria* litter fall.

TABLE 24 - Annual chemical element budget for the mossfield and shrubland ecosystems (in kg/ha/yr).

SITE	Cl	N	P	Na	K	Mg	Ca
Increments from atmosphere	146	0.25	0.45	74	16	10.2	12.9
Shrubland ecosystem							
- immobilisation in plants	-	6.5	0.06	0.8	1.6	2.2	2.6
- lost to drainage	146	1.88	2.17	103	30	23	46
Total losses	146	8.38	2.23	103.8	31.6	25.2	48.6
Net losses or gains	-	- 8.13	- 1.78	- 29.8	- 15.6	- 15	- 35.7
Mossfield ecosystem	-	6.5	0.06	0.8	1.6	2.2	2.6
- immobilisation in plants	-	6.5	0.06	0.8	1.6	2.2	2.6
- lost to drainage	146	0.78	0.7	73	24	14	25
Total losses	146	7.28	0.76	73.8	25.6	16.2	27.6
Net losses or gains	-	- 7.0	- 0.3	+ 0.2	- 9.6	- 6.0	- 14.7
Hard beech (*N.truncata*) ecosystem (Miller 1963c). Net losses	-	2	0.3	5	10	4	30

TABLE 25 - An annual chemical budget for *Coriaria* (Sample quadrat 1 - December 1968) and *Rhacomitrium* (Sample quadrat 2 - January 1970) soils, (in kg/ha/yr).

SOIL BENEATH CORIARIA	Cl	N	P	Na	K	Mg	Ca
Input from rainwater	146	0.25	0.45	74	16	10.2	12.9
Coriaria litter	-	15.35	0.91	0.7	3.7	3.9	3.0
Recretion & dry salt (not determined)							
Total increment	146	15.60	1.36	74.7	19.7	14.1	15.9
Output by immobilisation	-	7.46	0.01	0.3	0.4	1.0	1.4
Lost to drainage	146	1.88	2.17	103	30	23	46
Total losses	146	9.34	2.18	103.3	30.4	24.0	47.4
NET LOSSES OR GAINS	-	+ 6.26	- 0.72	- 28.6	- 10.7	- 9.9	-31.5
SOIL BENEATH RHACOMITRIUM							
Input from rainwater	146	0.25	0.45	74	16	10.2	12.9
Output by immobilisation	-	2.49	0.01	1.0	2.4	2.7	3.5
Lost to drainage	146	0.8	0.7	73	24	14	25
Total losses	146	3.27	0.71	74	26.4	16.7	28.5
NET LOSSES OR GAINS	-	- 3.0	- 0.3	0	- 10.4	- 6.5	-15.6

LIGHT UTILISATION BY MOSSFIELD AND SHRUB ECOSYSTEMS

Autotrophs are the primary components in an ecosystem, involved in the fixation and accumulation of energy that is principally derived from solar energy. The efficiency of autotrophs in converting solar energy into chemical energy by photosynthetic processes within the ecosystem is referred to as the photosynthetic efficiency (PE). Generally plants are highly inefficient at utilising available energy except under very low light intensities.

Various methods have been used to assess PE values but unfortunately there is a lack of standardised terminology, ~~and~~ The method here used follows Egunjobi (1967, 1969). Most solarimeters measure total insolation, but only visible light (400-700 mu) is used in photosynthesis. Thus various correction factors can be applied to allow for this effect (Bray 1961).

Without detailed observations at the study site, the visible light fraction referred to as photosynthetically active radiation (PAR), is here assumed as 50% of total insolation. It is likely that this figure is slightly overestimated in which case the calculated PE value will be minimal.

The calculation of energy being fixed within an ecosystem may be determined from net, gross or current primary production figures. In this study the calculated current production figures were used because gross production is difficult to determine (i.e. respiration losses have to be accounted for) and net production does not take into account losses to the system from litter fall and recretion.

Measurement of Solar Radiation

Solar radiation measurements were recorded at the study site from December 1968 to May 1970 using light integrators designed by the Plant Physiology Division, Palmerston North. These instruments consist of a photovacuum cell mounted beneath a special diffusing unit to obtain good response. The spectral response of the integrators has been adjusted so that prime response is to the visible (photosynthetically active) light.

A stand fixed by an adjustable flange to a pole cemented below ground level was used to support the light integrator. When mounted on the stand, the instrument rested on a horizontal surface and no objects obscured the horizon, although Mt. Egmont was 2.8 km directly to the south-east. The equipment was fixed in position by four No.8 fencing wires attached to large boulders, and which proved effective supports in the strongest of winds. Immediately prior to the installation of each instrument, the integrator was calibrated to the Eppley pyranometer at Plant Physiology Division, Palmerston North. Each instrument was changed at two monthly intervals and immediately recalibrated with the Eppley pyranometer again. By adopting this procedure calibration drift can be checked and minimal errors are incurred (Dr. J.P. Kerr, pers.com.). Monthly and at times weekly readings from November 1968 to May 1970 were obtained for the study site. The instruments worked well in the cold conditions experienced on Egmont and no problems were encountered with the electronic gear. New batteries were inserted prior to each installation because of their short life, and in plastic bags to keep water out.

Details of the recordings are tabulated in Table 26 together with comparative data from Ohakea, Auckland and Kelburn. The

TABLE 26 - Solar Radiation at Little Pyramid, Mt. Egmont 1968-70 with comparative data from Ohakea, Kelburn and Auckland. Altitude 3,900 ft (1,170m).
As measured by light integrators loaned by Plant Physiology Division, D.S.I.R., Palmerston North and calibrated with Eppley Pyranometer, at Palmerston North.

Monthly Sample	Sample periods	cals/cm^2	Ohakea	Kelburn	Whenuapai
Dec.68	1/12 - 31/12	10,193	15,084	13,472	14,568
Jan.69	31/12 - 31/ 1	13,292	15,567	11,741	16,723
Feb.69	31/ 1 - 28/ 2	13,067	13,213	10,264	14,570
Mar.69	28/ 2 - 30/ 3	8,954	11,432	11,096	16,649
Apr.69	30/ 3 - 1/ 5	5,653	7,546	6,794	9,753
May 69	1/ 5 - 31/ 5	4,633	4,876	3,699	4,671
Jun.69	31/ 5 - 28/ 6	3,930	3,904	3,967	3,962
Jul.69	28/ 6 - 2/ 8	5,679	4,279	3,873	5,667
Aug.69	2/ 8 -)		5,455	4,986	6,856
Sep.69	27/ 9)	10,995	8,489	7,870	8,293
Oct.69	27/ 9 - 1/11	7,866	12,534	13,439	12,499
Nov.69	1/11 - 29/11	13,991	15,061	15,098	* 15,955
Dec.69	29/11 - 29/12	12,569	15,836	15,885	17,078
Jan.70	29/12 - 31/ 1	16,729	16,600	16,948	19,487
Feb.70	31/ 1 - 28/ 2	12,549	12,995	14,273	15,554
Mar.70	28/ 2 - 27/ 3	7,503	10,519	9,367	12,161
Apr.70	27/ 3 - 2/ 5	7,013	6,981	7,952	8,423
May.70	2/ 5 - 30/ 5	4,640	5,437	5,156	6,393
	18 months total	159,256 cals/cm^2	185,808	175,880	209,262
	Average monthly value 1/12/68 - 30/5/70 =	8,848 cals/cm^2	10,323	9,771	11,626

* instrument moved to Auckland International Airport

average value was 8,847.5 cals/cm^2 per month or 106,176 cals/cm^2 per annum. For comparison, values for the 18 month period from all the recording stations in Table 26 have been converted to annual values by a factor of 0.66. Despite the fact that in some months the site received substantially more solar radiation than Kelburn, it receives about 1,000 cal/cm^2 less per annum. Thus total photosynthetically active radiation (PAR) for the year amounts to about 53,000 cal/cm^2 (or x 10^5 Kcal/ha).

Calorific value of plant materials

The calorific value of selected plant materials corrected to a dry basis are presented in Table 27. *The bulk of the determinations give a range of values (4.3-4.8 Kcal/g) similar to those obtained from black beech (*Nothofagus solandri* var. *solandri* (Hook.f.) Oerst.) litterfall in the Wairarapa (Bagnall

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Footnote

* Methods used were those specified for coal analyses in determining moisture, ash and calorific values. Agreement between duplicate samples was within specified limits except in the case of four calorific values and one ash content. Samples 14/595, 14/596 and 14/601 were analysed five times (and 14/600 four times) to obtain the mean calorific value presented. Sample 14/598 was analysed 10 times to obtain the mean ash content. The inconsistent and high ash content of this sample may contain a larger error than the other materials, so the high dry ash free basis calorific value is also likely to be in error. Other than this, all materials when corrected for ash contents fall within the range 4.6 - 5.3 Kcal/g.

<u>TABLE 27</u> - Calorific value of selected plant materials in cal/gm on a dry basis

		Sample Date	CRA Ref.	Dry Basis Calorific Value cal/gm	Ash % as analysed	Dry ash-free basis calorific value cal/gm
<u>Rhacomitrium</u>	A.G.	Feb.1970	14/587	4350	7.4	4,740
	B.G.	Jan.1970	14/595	3770	19.3	4,790
	B.G.	Feb.1970	14/600	3800	19.8	4,860
<u>Chionochloa</u>	A.G.	Jan.1970	14/588	4560	4.0	4,770
	B.G.	Jan.1970	14/596	2970	36.8	4,910
	dead A.G.	Feb.1970	14/601	3010	34.8	4,800
<u>Coriaria</u>	A.G.	Dec.1968	14/593	4690	1.4	4,770
	B.G.	Dec.1968	14/594	4640	2.7	4,780
<u>Senecio</u>	leaves	Feb.1970	14/591	4750	4.2	4,980
	stems	Feb.1970	14/592	4610	1.4	4,680
	roots	Feb.1970	14/597	4510	3.4	4,690
<u>Cassinia</u>	A.G.	Feb.1970	14/589	5120	2.2	5,230
"Others"	A.G.	Feb.1970	14/590	4610	4.3	4,840
	B.G. roots	Feb.1970	14/598	1870	63.4	5,490
	B.G. roots	Jan.1970	14/599	4530	6.4	4,870
Litter		Feb.1970	14/602	4530	13.0	5,280

CRA = N.Z. Coal Research Association Reference Number

1972). Living Rhacomitrium was about 500 cal/g higher than Rhacomitrium litter. The highest value in the study was 5,120 cal/g for Cassinia leaves and stems which compares with 5,340 cal/g obtained from Spanish heath (Erica lusitanica Rudolphi), the highest value determined by Egunjobi (1968). Expression on a dry ash-free basis eliminates the difference due to soil particles if values are required for organic matter values only. In Senecio and Coriaria there was little difference in values from the various components.

Total energy content in the ecosystems

In order to assess the total energy content of the ecosystems, each of the major plant components sampled on different occasions were assigned calorific values according to the representative samples determined. Calorific values of the materials in each sample period averaged between 4,151 and 4,437 cal/g showing a mean of about 4,300 cal/g. Total energy contents on the four sampling dates amounted to 379; 323; 367 and 323 x 10^6 Kcal/ha (Appendix D7). These values were then averaged in order to obtain a figure for the total energy within the ecosystem.

The annual rate of energy accumulation was determined by multiplying the current annual primary production (1,160 kg.ha) by the averaged calorific value of the plant materials (4.3 Kcal/g).

Efficiency of light utilisation

The photosynetically active radiation (PAR) at the study site totals 53,000 x 10^5 Kcal/ha/yr, which is not substantially different from the value of 55,800 x 10^5 Kcal/ha/yr determined at Taita in 1966 (Egunjobi 1967). The mean annual rate of energy accumulation calculated from averaging the four sample period values is 43.5 x 10^5 Kcal/ha/yr and the energy in the current annual dry matter production totals nearly 50 x 10^5 Kcal/ha/yr. Nearly 18 times this value was obtained for the natural gorse ecosystem at Taita (Egunjobi 1967). Thus the PE value

$$\frac{(\text{energy of net production per annum} \times 100)}{\text{energy in PAR per annum}} = \frac{50 \times 10^5}{53{,}000 \times 10^5} \times 100 = 0.09\%$$

The low value is clearly due to the low utilisation of the energy available, since that solar energy which could be theoretically utilised is of a similar magnitude to that at Taita. This particularly low value is provisionally attributed mainly to the climatic conditions at this altitude which lead to low productivity. However the PE value is a minimal figure because no account is taken of respiratory losses and the decomposed moss.

Because the Senecio components could be accurately dated by tree-ring dating at 27 years old it is possible to make an estimate of Senecio photosynthetic efficiency over this period. In the February 1970 sample, the total energy content of the Senecio totals 72.4 x 10^5 Kcal/ha, which results in a calculated PE value for Senecio of 0.14%. This value is more appropriate to the latest growing period and makes allowance for the initial slow period of establishment of a vegetative cover following the deposition of the new flow deposit.

The calculated PE value for the Senecio components can be expected to increase as productivity within the ecosystem increases coupled with colonisation of higher plants. The nearest comparable low PE value established in New Zealand is 0.4%, obtained from unfertilised mixed pasture in the Hutt Valley (Egunjobi 1967).

SOIL DEVELOPMENT ON DEBRIS FLOW DEPOSITS

Most constructional surfaces below 600 m (2,000 ft) altitude on Mt. Egmont consist of unconsolidated gravels deposited by successive debris flows or floods. Gravels deposited over the last 500 years show little profile differentiation and consist simply of a thin litter horizon overlying coarse sandy material. Pre-500 year old deposits however rarely contain topsoils which have not received additions of tephras because of the intermittent volcanic activity at Mt. Egmont. In an attempt to establish a soil chronosequence on the debris flow deposits it was first necessary to establish the relative ages of various flow deposits and the associated tephra mantle of each deposit. Most tephras erupted from Mt. Egmont have been influenced by dominant southerly and westerly winds in the region, and tend to be distributed to the north and east. Thus because there is less tephra cover to the west of Egmont, it is the most likely area to find a soil chronosequence on debris flow deposits.

Three soil sites were established which show no visible tephras in their topsoils. They are approximately 80, 400 and about 4,000 years old. However, no older surfaces were found which do not contain prominent tephras in the topsoil and two of these have been incorporated in this study because they form an important step in the evolution of a Recent soil into a gley recent (with time) to a yellow-brown loam (with addition of andesitic tephra and further time).

Details of the soil sample sites are as follows. Profiles 1 and 2 are from the Pyramid study site and are included to show the effects of altitude on initial soil development of a similar aged debris flow.

Profile 1 - Pyramid study site; at 1,170 m (3,900 ft) altitude; vegetation *Rhacomitrium lanuginosum*.

Profile 2 - Pyramid study site; as above but developed under *Coriaria plumosa*

Profile 3 - near western end of Puniho Road, grid ref: N118/550670; altitude, 420m (1,400 ft); vegetation kamahi (*Weinmannia racemosa*) forest; soil type Hangatahua mottled sand

Profile 4 - near western end of Saunders Road; grid ref. N118/588507; vegetation kamahi (*Weinmannia racemosa*) forest; soil type, Hangatahua mottled sand

Profile 5 - on Kiri Road at 300m (1,000 ft) contour; grid. ref. N118/588507; vegetation kamahi (*Weinmannia racemosa*) forest with some rimu (*Dacrydium cupressinum* Lamb) and rata (*Metrosideros robusta* A. Cunn). soil type c.f. Warea bouldary loam

Profile 6 - near northern end of Auroa Road; grid ref. N118/635523; alt. 435m (1,450 ft); vegetation *Dacrydium* - *Metrosideros* - *Weinmannia* forest; soil type, Awatuna loam.

Profile 7 - near northern end of Mangawhero Road; grid ref. N118/659524; altitude 450m (1,500 ft); vegetation *Dacrydium* - *Metrosideros* - *Weinmannia* forest; soil type, Stratford sand.

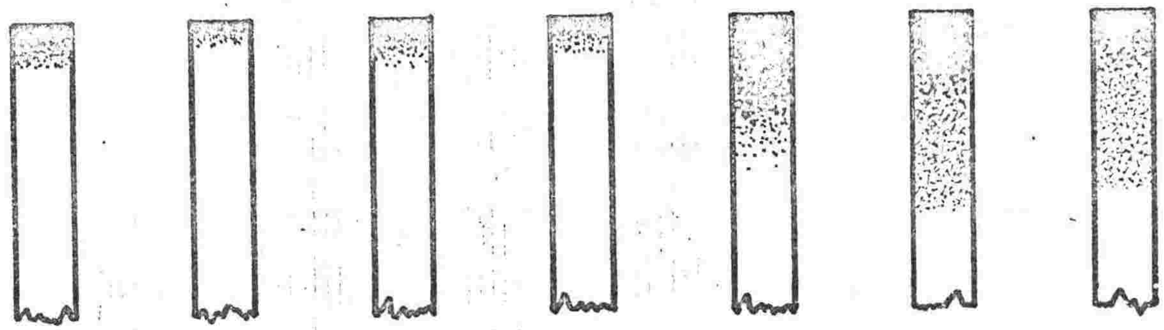
Except for profiles 1 and 2, all the soils occur near the 360m contour and were sampled from beneath *Weinmannia racemosa* trees. All soil samples were collected from the western and southern ringplain graded to Mt. Egmont and 18 km (11 miles) separates the northernmost and southernmost samples indicating fairly similar climatic conditions exist at the sample sites.

SOIL MORPHOLOGY

Parent materials of profiles 1 to 5 consist of Recent sands with or without boulders. Profile 6 is developed upon the richly allophanic Oakura Tephra which overlies the Warea Formation, a lahar deposit. Thus the topsoil is dated at <7,000 years old. Profile 7 consists of both Oakura and Okato tephras overlying a thick sequence of older ashes. This soil therefore has a topsoil dated at <7,000 years resting upon a subsoil of older ashes extending back to at least 50,000 years age.

The soil profiles in the sequence are readily distinguished (Fig.57). The thin A horizons apparent in the youthful sandy (or gravelly) soils become progressively thicker and darker with time, but once tephra is added to the topsoil, the A horizons decrease in prominence and thickness. In profile 7, the A is thin with a mull-like forming litter in contrast to the sticky, black mor-like A horizon in profile 5 where maximum A horizon development occurs. This development of the A horizon is attributed to the poor drainage and high rainfall which together with the vegetation leads to mor-forming conditions. After tephra is incorporated in the topsoil the drainage is greatly modified due to the free draining properties of the newly added materials. There is then an attendant increased rate of breakdown of plant residues and no further gleying.

No discernible B horizon is present in profiles 1 to 5 and an incipient B first appears in profile 6. The (B) horizon is no better developed in profile 7 although it is thicker, and is



Profile number:	1	2	3	4	5	6	7
	PYRAMIDS MOSS	PYRAMIDS CORIARIA	PUNIHO	SAUNDERS	KIRI	AUROA	MANGAWHERO
AGE: (in yrs)	80	80	80	400	c. 4;000	7,000	16,000
ALTITUDE: (in metres)	1170	1170	420	360	300	435	450
PARENT MATERIAL:	Boulders + sand	Boulders + sand	Sand	Sand	Boulders + sand	Oakura Tephra (allophanic ash) on breccia	Oakura + Okato tephras (both allophanic ashes) on older ashes.
VEGETATION:	*Rhacomitrium* moss.	*Coriaria plumosa*	← Kamahi (*Weinmannia racemosa*) →				
SOIL:	Mountain soil	Mountain soil	Recent	Recent	Gley recent	Gley	Yellow-brown loam

FIGURE 57 - Details of soil profiles developed on debris flow deposits in western Taranaki chronosequence.

considered to be a result of additional tephra.

It is of interest that the Rahotu loam is a soil developed on similar parent materials to profile 6 (Awatuna loam), but does not occur above the 150 m contour. In the Rahotu loam the Oakura Tephra is considerably thinner due to greater distance from the source - Mt. Egmont, and the resultant profile represents a further stage of development which can occur if little tephra is added to the topsoil (see Figure 59). The result is a heavily iron stained soil with an iron pan often occurring at the upper contact of the Warea Formation, presumably due to a longer period without substantial changes in the drainage regime.

SOIL CHEMISTRY

Samples for chemical analysis were selected from the upper 3-10 cm of the A horizon unless otherwise stated. CEC, TEB, organic carbon and total nitrogen values are presented for the seven profiles (Table 28) together with data from the $A_{1.1}$ horizons in the Stratford and Egmont reference sites (N.Z.Soil Bureau 1968). The unusually high CEC and TEB values in the upper layers of the Pyramid soils are due to a thin layer of high organic matter resting upon an infertile subsoil. Except for the youngest soil there is fairly good correlation of increasing CEC, TEB and base saturdation percentages with age which is probably a function of increase in colloidal materials. The BS% drop to 16.6% in profile 6 is probably associated with maximum uptake of exchangeable bases in a highly organic profile. Once the tephra cover reaches a threshold thickness as in profile 7, the BS% increases, probably largely due to the addition of fresh minerals in the ash of the topsoil. C/N ratios are very

TABLE 28 _ Chemical analyses of A_1 horizons selected from western Taranaki soils developed on debris flow deposits, with comparative data from the Stratford and Egmont reference sites (N.Z. Soil Bureau 1968).

	Horizon	Profile No.	CEC	TEB	BS%	%C	%N	C/N
Pyramid Study Site	*Rhacomitrium* - 0	1	44.8	14.3	31	51.0	0.62	82
	Rhacomitrium - C	1	2.3	0.1	15	5.6	0.02	280
	Coriaria - A	2	10.3	1.5	16	24.2	0.33	73
	Coriaria - C	2	0.5	1.0	47	3.8	0.11	35
Puniho Road	- A 1	3	6.5	1.5	23	8.8	0.20	44
Saunders Road	- A 1	4	7.7	2.4	29	10.2	0.29	35
Kiri Road	- A 1.1	5	19.8	4.0	20	53.6	1.26	43
	- A 1.2	5	n.d.	n.d.	n.d.	18.6	n.d.	15 *
Auroa Road	- A 1.1	6	25.8	3.8	17	32.0	0.79	41
	- A 1.2	6	n.d.	n.d.	n.d.	19.8	n.d.	24 *
Mangawhero Road	- A 1.1	7	22.3	11.3	47	19.6	0.76	26
Stratford Reference Site -			28.1	11.3	40	10.9	0.80	13
Egmont Reference Site - (N.Z. Soil Bureau 1968)			36.9	18.8	51	12.3	0.93	13

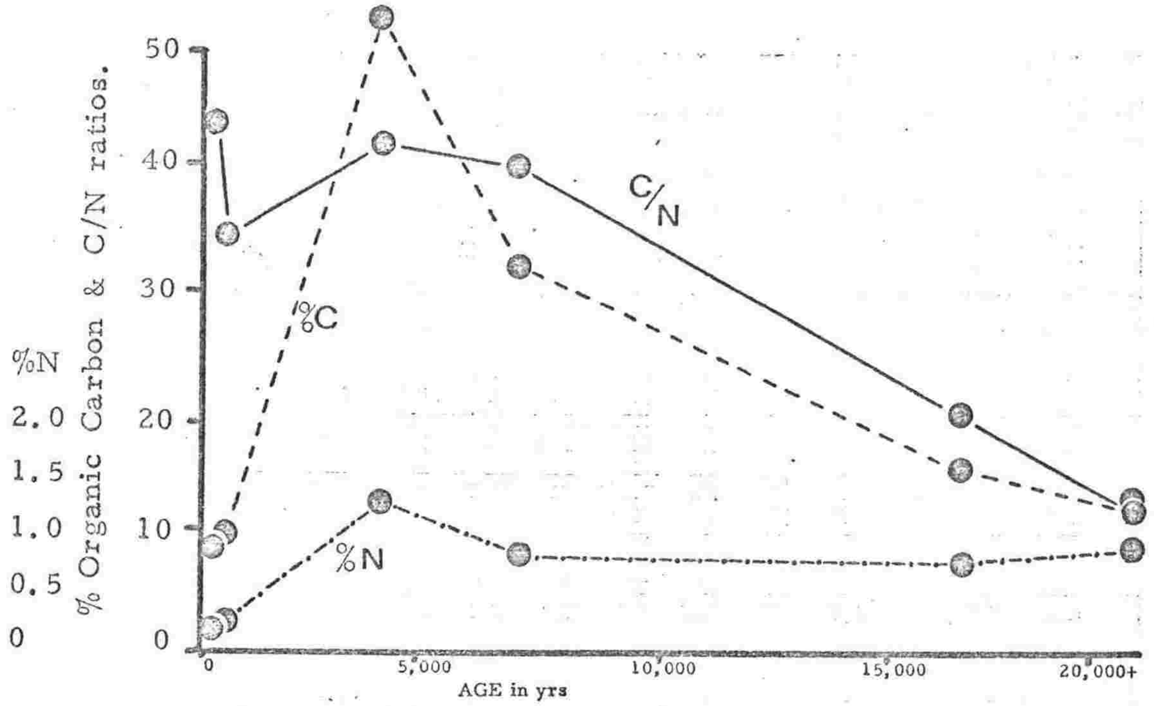
* C/N ratio based on N value for $A_{1.1}$ horizon

high throughout the sequence and only in profile 7 do they drop to a level indicative of more rapid breakdown of plant residues. Samples selected from the lower A horizon in profiles 5 and 6 show considerably reduced C/N ratios.

Comparative data has been included from the Stratford and Egmont reference sites (N.Z. Soil Bureau 1968) because they represent advanced stages in this soil sequence (see Figure 59). They have a much longer history of tephra accumulation and are thus much more free-draining due to their low bulk density and high allophane content, although they have developed at a lower altitude and under a different plant cover. Assuming that the main part of the Egmont profile is at least 20,000 years (or older), the CEC, TEB, %C and %N values can be plotted in the sequence (Figure 58). It shows that carbon and nitrogen attain maximum values in the $A_{1.1}$ horizon of profile 5, corresponding to the maximum A horizon development in the sequence.

DISCUSSION

Very small amounts of exchangeable cations are present in the 80 year old soils. The soils are extremely acid and mantled by very slowly decomposing plant materials. At 400 years, TEB values almost double although little horizon differentiation is visible. In the 4,000 year old soil, CEC and TEB values are considerably higher, with carbon approaching its maximum value in the sequence and strong A horizon development. In the final stages of the sequence, with addition of new tephra showers, the profiles become increasingly well drained, organic breakdown and turnover increases and the soils have increased exchangeable cation levels. A suggested evolution of Taranaki soils from a



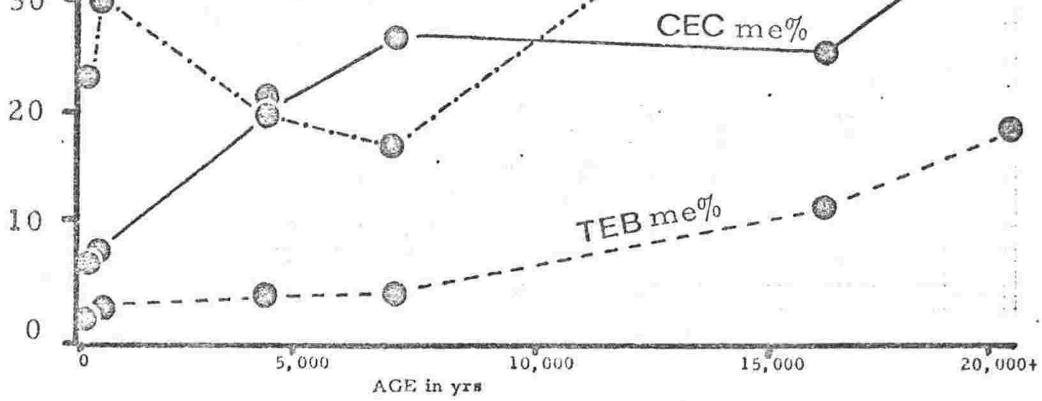


FIGURE 58 - Chemical data of soil suite plotted against age of soil parent materials. **Data for the 16,000 year old soils (Profile 7 & Stratford Reference Site) have been averaged.**

Recent soil derived from andesitic gravels and sands to a yellow-brown loam derived from andesitic tephra is presented in Figure 59.

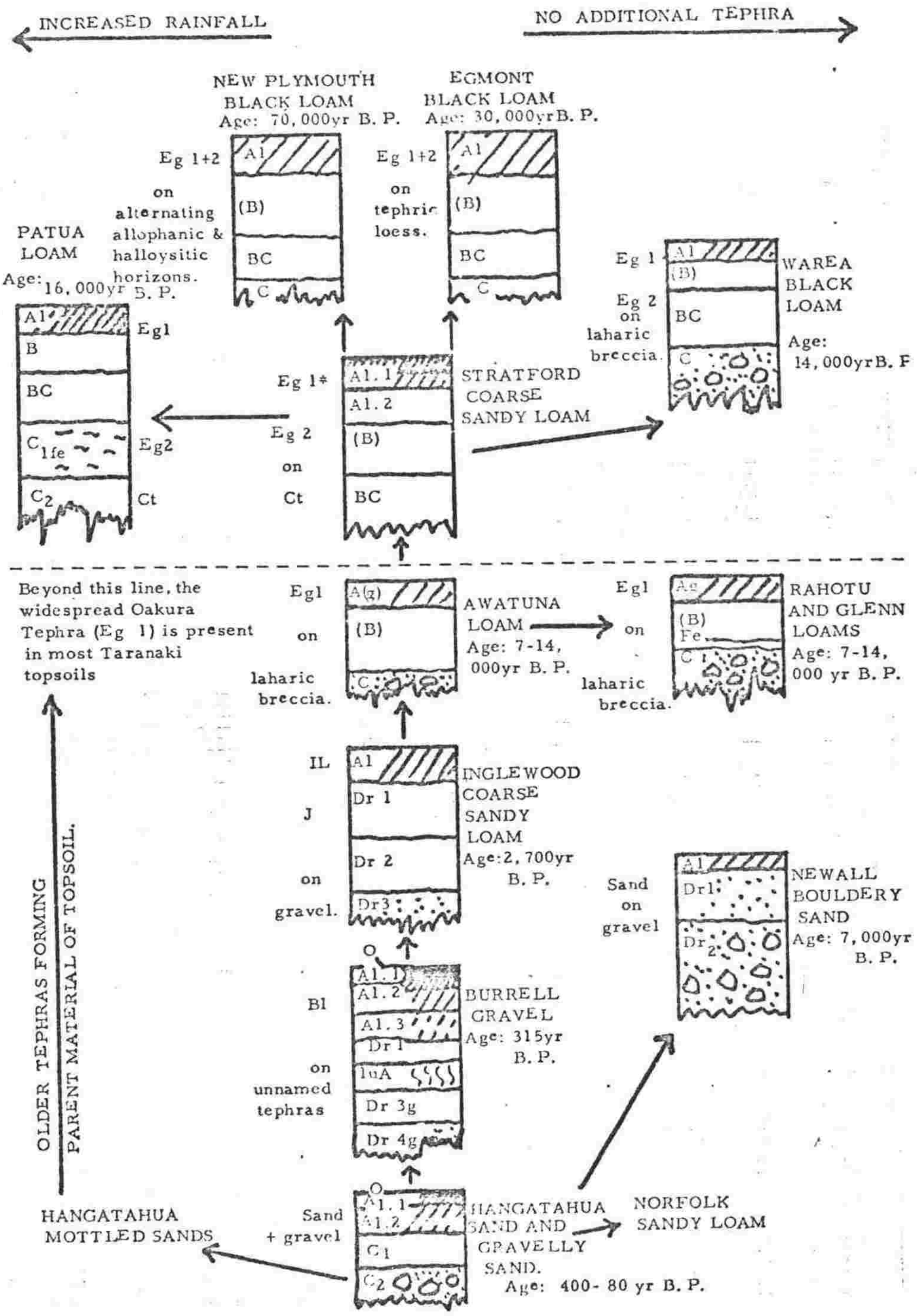


FIGURE 59 - The evolutionary devlopment of western Taranaki soil types interpreted from tephrochronology, lahar stratigraphy and soil morphology.

CONCLUSIONS

1. *Biomass* production at the four sample sites at 1170m altitude on the north-west flank of Mt. Egmont, ranged between 77-95,000 kg/ha and averaged 86,000 kg/ha. The average is considered a reliable estimate of the herbfield-shrubland biomass, despite the small size of the samples. Water contained in the living biomass totalled 176 x 10^3kg/ha. Mean annual productivity at this altitude is 1,000 kg/ha/yr calculated for the 80 years available for establishment. From the known age of *Senecio* trees from ring-counts it was determined that the more recent productivity is up to 1,600 kg/ha/yr. For diagrammatic representation of results *see* Figure 4.

2. *Quantities of exchangeable cations and total N in the soil* show the influence of *Coriaria* is considerable. Where dead *Rhacomitrium* is present it serves as a useful rooting medium for higher plants, but beneath is a sandy subsoil with low exchangeable cation values. With *Coriaria* present a clear, although thin A horizon is developed containing increased amounts of exchangeable cations and much higher values of N and P (although P is still very low). Total N to a depth of 10 cm totals 1,950 kg/ha in the shrub ecosystem but only 294 kg/ha in the mossfield ecosystem.

3. *Chemical elements in the plant system* show higher element concentrations in material from above ground than below ground. The highest concentrations of elements occur in *Coriaria* and *Senecio* components above ground level. Average quantities of elements in the combined mossfield and shrubland totalled (in kg/ha) 62 Na, 132 K, 174 Mg,

204 Ca, 546 N and 5 P. This indicates there is lower K and higher Mg in the vegetation systems than is average for most other New Zealand vegetation systems previously investigated. Although there are only small quantities of elements in the Coriaria plants, the high element concentration in their annual leaf fall is related to the rapid rate of element turnover in the vicinity of Coriaria stands. Elements initially extracted by Coriaria appear to be returned to the soil through the annual leaf-fall and become rapidly available for utilisation by other species.

4. Totals of elements in the ecosystems show that the shrub ecosystem has slightly higher quantities of Na, K, Mg and Ca available than in the mossfield ecosystem, but contains greater proportions of N (3 times) and P (twice as much).

5. Accession of elements into the ecosystem total 264 kg/ha/yr and comprise 146 Cl, 74 Na, 16 K, 10 Mg, 13 Ca and 4 S (in kg/ha/yr). These values tend to be higher than previous estimates of rainwater accessions elsewhere in New Zealand. However the concentration of elements is not significantly different and the increases are probably due to the increase in precipitation.

6. Annual quantities of elements lost to drainage in mossfield and shrub (in brackets) ecosystems, in kg/ha/yr, total 0.78 (1.88) N; 0.7 (2.17)P; 73/103)Na; 24(30)K; 14(23)Mg and 25(46)Ca. Water draining from the shrub lysimeter contained a much higher content of organic acids than water draining from the mossfield. Many of the organic acids are polyphenols which are considered effective at

chelating cations and are responsible for higher element losses. Reconnaissance sampling of water samples in the vicinity of the study site show a ten fold increase in Mg below the junction with Stony River. No clear evidence as to the source of Mg is known but it is suggested that it is due in part to the high Mg content of the andesitic parent materials compared to the lower Mg greywacke and pumice parent materials of soils in previously studied ecosystems.

7. Rates of immobilisation of elements for the combined mossfield and shrubland vegetation systems are 81% Na, 65% K, 69% Mg, 77% Ca, 64% N and 21% P. However if the sample quadrat 1, with Coriaria present, is examined separately the high return of nutrients is evident and immobilisation rates drop to 31% Na, 10% K, 20% Mg, 32% Ca, 33% N and 13% P.

8. An estimate was made of the annual chemical budget for the shrub and mossfield ecosystems. Losses in kg/ha/yr are:

	N	P	Na	K	Mg	Ca
(a) for shrub ecosystem	8	1.8	30	16	15	36
(b) for mossfield ecosystem	7	0.3	0	10	6	15
(c) for Nothofagus truncata ecosystem	2	0.3	5	10	4	30

The mossfield ecosystem shows values very similar to the Nothofagus ecosystem investigated by Miller (1963c), except for N and Ca. However the shrub ecosystem shows greater element losses than from Nothofagus or mossfield ecosystems.

9. Chemical budgets for the soil systems show net losses for both mossfield and shrub systems are similar, except for a 6 kg/ha/yr increase in nitrogen in the shrubland soil.

10. The calorific value of plant materials sampled from the ecosystems are predominantly in the range 4.3 - 4.8 Kcals/gm. Total photosynthetically active radiation per annum at the study site amounts to about 53,000 cals/cm^2. A photosynthetic efficiency was calculated for the ecosystem of 0.09% although if the dominantly Senecio sample quadrat was selected the figure would increase to 0.14%. These figures are substantially lower than most other values obtained from natural ecosystems, but it is to be expected under the severe climatic factors which limit plant growth at the study site.

11. Investigations of older debris flow deposits indicate that organic matter % and A horizon development can be expected to increase rapidly providing the site remains stable, to reach a maximum in about 5,000 years. Poor drainage conditions and consequent iron mottling accompanies this process. Assuming deposition of volcanic ash and lapilli will occur after this time the trend towards gleying conditions and iron mobilisation will be halted and the new low bulk density parent material imparts free draining properties to the soil. This leads to the evolution from a recent or gley recent to a yellow-brown loam.

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I am indebted to the following for their assistance in this project and without whom the project would not have been possible; Mr J. Ure, who as Conservator of Forests, Palmerston North, allowed me to transport equipment by helicopter on contract to the N.Z. Forest Service; Mr & Mrs L.D. Hickford of Okato and Mr & Mrs E.A. Atkinson of Oakura for their kindly assistance and accommodation; Messrs. B.L. Cockburn and P.A. Williams for collecting the November and December 1969 samples whilst I was in Antarctica; Dr. M. Kingsford, Chemistry Division, D.S.I.R., Gracefield, for arranging analysis of the water samples; Dr. J.P. Kerr, Plant Physiology Division, D.S.I.R., Palmerston North, for the loan of light integrators; the Internal Research Committee, Victoria University, for financing the project, and particularly to Messrs. A.P. Druce and C.G. Vucetich for assisting me with initial investigations for the project and their enthusiastic support. I thank Messrs. C.G. Vucetich and H.W. Johnston, Drs. R. McQueen and R.B. Miller for their constructive criticisms of preliminary drafts of this paper. Miss G. Davies, Mr & Mrs R.W. Bruning, Mr & Mrs B. Conway, Messrs. A. & P. Atkinson, A. Cavanagh, R. Chinnock, B.L. Cockburn, C. Douch, M. Kerr, B.P. Kohn, G.N. Park, D.H. Rawson, F. Schaffer, P.M. Scott, W.W. Topping, C.G. Vucetich and P.A. Williams all assisted in transporting samples and equipment from the study site to Puniho Hut and to whom I am most grateful.

REFERENCES

American Public Health Association & American Water Works Association, 1965: Standard Methods for the examination of water and waste water. 12th Ed. New York.

Atkinson, I.A.E., Jenkins, P.F., Druce, A.P., 1968: Definitions and discussion of some concepts and terms relating to terrestrial ecosystems. Tuatara 16(2): 98-110.

Bagnall, R.G., 1972 : The dry weight and calorific value of litter fall in a New Zealand Nothofagus forest. N.Z. Journal of Botany 10(1): 27-36.

Blakemore, L.C., 1953: The chloride content of rainwater collected in the Wellington Province. N.Z. Journal of Science and Technology B.35: 193-7.

Bliss, L.C., 1966: Plant productivity in alpine microenvironments on Mt. Washington, New Hampshire. Ecological Monographs 36(2): 125-55.

Bond, G., 1958: Root nodules of Coriaria. Nature, Lond. 182:474

Bray, J.R. 1961: An estimation of a minimum quantum yield of photosynthesis based on ecological data. Plant Physiology 36: 313-33.

Burke, W.D., 1963: Note on the occurrence of nodules in the New Zealand species of Coriaria. N.Z. Journal of Botany 1(4): 377-80.

Comber, N.M., 1960: An introduction to the scientific study of the soil. Revised by Townsend, W.N. Edward Arnold (Publishers) Ltd. London. 232pp.

Druce, A.P., 1970: The Vegetation in Scanlan, A.B. (Ed.), Egmont National Park Handbook. Egmont National Park Board, New Plymouth.

Egunjobi, J.K., 1967: A comparison of primary productivity and chemical element cycling in gorse (*Ulex* *europaeus*.L.) and pasture ecosystems, Ph.D. Thesis, Victoria University of Wellington.

Egunjobi, J.K., 1969a: Dry matter and nitrogen accumulation in secondary successions involving gorse (*Ulex* *europaeus* L.) and associated shrubs and trees. *N.Z. Journal of Science 12(2)*: 175-93.

Egunjobi, J.K., 1969b: Primary productivity and nutrient cycling in terrestrial ecosystems, a review with particular reference to New Zealand. *Tuatara 17(2)*: 49-66.

Ewart, A.; Stipp, J.J., 1968: Petrogenesis of the volcanic rocks of the Central North Island, New Zealand, as indicated by a study of Sr^{87}/Sr^{86} ratios, and Sr, Rb, K, U and Th abundances. *Geochimica et Cosmochimica Acta 32*: 699-736.

Fogg, D.N.; Wilkinson, N.T., 1958: The colorimetric determination of phosphorous. *The Analyst 83*: 406.

Folin, O.; Ciocalteu, V., 1927: Tyrosine and tryptophon determination in proteins. *Journal of Biological Chemistry 73*: 617.

Gow, A.J., 1968: Petrographic and petrochemical studies of Mt. Egmont andesites. *N.Z. Journal of Geology and Geophysics 11(1)*: 166-90.

Grange, L.I., 1937: The Geology of the Rotorua-Taupo Subdivision. *N.Z. Geological Survey Bulletin n.s. 37*: 138 pp.

Gray, G., 1888: On the dissolved matter contained in the rainwater collected at Lincoln, Canterbury, New Zealand. *Proceedings of the Australian Associated for the Advancement of Science 1*: 138-52

Gray, G., 1910: On the dissolved matter contained in rainwater collected at Lincoln, New Zealand. *Canterbury Agricultural College magazine 24:* 183-95.

Harris, G.P.; Morrison, T.M. 1958: Fixation of Nitrogen-15 by excised nodules of *Coriaria arborea* Lindsay. *Nature, Lond. 182:* 1812.

Johnston, H.W., 1959: The solubilization of "Insoluble" phosphates: V- The action of some organic acids on iron and aluminium phosphates. *N.Z. Journal of Science 2:* 215-8

Kidson, E.; Thomson, A., 1931: The occurrence of thunderstorms in New Zealand. *N.Z. Journal of Science and Technology 12(4):* 193-206.

Mason, G.W., 1951: A note on the vegetation of Mt. Egmont. *Tane 4(1):* 23-5.

Metson, A.J., 1956: Methods of chemical analysis for soil survey samples. *N.Z. Soil Bureau Bulletin 12:*1-208.

Metson, A.J.; Blakemore, L.C., 1964: Determination of cation-exchange capacity of soils by determinations of absorbed ammonium ion. *Soil Bureau reprint 6/1964:* 12 pp.

Miller, R.B., 1961: The chemical composition of rainwater at Taita, New Zealand, 1956-58. *N.Z. Journal of Science 4:* 844-53.

Miller, R.B., 1963a: Plant nutrients in hard beech I. The immobilisation of nutrients. *N.Z. Journal of Science 6:* 365-77.

Miller, R.B., 1963b: Plant nutrients in hard beech II. Seasonal variation in leaf composition. *N.Z. Journal of Science 6:* 378-87.

Miller, R.B., 1963c: Plant nutrients in hard beech III. The cycle of nutrients. N.Z. Journal of Science 6: 388-413.

Moore, A.W.; Russell, J.S.; Coaldrake, J.E., 1967: Dry matter and nutrient content of a subtropical semi-arid forest of Acacia harpophylla F. Muell (Brigalow). Australian Journal of Botany 15: 11-24.

Morris, R.A., 1966: A daylight integrator. The radio and electronic engineer 31(6): 326.

Morrison, T.M.; Harris, G.P., 1959: Root nodules in non-leguminous plants in New Zealand. Proceedings of the New Zealand Ecological Society 6: 23-4.

N.Z. Soil Bureau, 1968: Soils of New Zealand, Part 3. N.Z. Soil Bureau Bulletin 26(3): 127pp.

Ovington, J.D., 1962: Quantitative ecology and the woodland ecosystem concept. Advancements in ecological research 1: 103-92

Ovington, J.D.; Heitkamp, D.; Lawrence, D.B., 1963: Plant biomass and productivity of prairies, savanna, oakwood and maize field ecosystems in central Minnesota. Ecology 44: 52-63.

Reed, J.J., 1957: Petrology of the Lower Mesozoic rocks of the Wellington District. N.Z. Geological Survey Bulletin n.s. 57.

Scanlan, A.B., 1961 "Egmont. The story of a mountain". A.H.&A.W. Reed, Wellington. 200pp.

Steiner, A., 1958: Petrogenetic implications of the 1954 Ngauruhoe lava and its xenoliths. N.Z. Journal of Geology and Geophysics 1: 325-63.

Taylor, E.W.D., 1958: The examination of waters and water supplies (Thresh, Beale and Suckling) 7th Ed. J.A. Churchill, London. 841pp.

Taylor, N.H.; Pohlen, I.J., 1962: Soil Survey Method. N.Z. Soil Bureau Bulletin 25: 242pp.

Tonkin, P.J., 1970: The soils of the southeastern sector of Egmont National Park. Earth Science Journal 4 (1): 36-57.

Whittaker, R.H., 1961: Estimation of net primary production of forest and shrub communities. Ecology 42: 177-80.

Whittaker, R.H., 1962: Net production relations of shrubs in the Great Smoky Mountains. Ecology 43: 357-77.

Whittaker, R.H., 1963: Net production of heath balds and forest heaths in the Great Smoky Mountains. Ecology 44: 176-82.

Whittaker, R.H., 1966: Forest dimensions and production in the Great Smoky Mountains. Ecology 47: 103-21.

Will, G.M., 1959: Nutrient return in litter and rainfall under some exotic conifer stands in New Zealand. N.Z. Journal of Agricultural Research 2: 719-34.

Will, G.M., 1964: Dry matter production and nutrient uptake by Pinus radiata in New Zealand. Commonwealth Forestry Reveiw 43: 57-70.

Will, G.M., 1966: Root growth and dry matter production in a high producing stand of Pinus radiata. N.Z. Forest Research Notes 44: 15pp.

Wilson, A.T., 1959: Surface of the ocean as a source of air-borne nitrogenous material and other plant nutrients. Nature (London)v.184: 99-101.

Wilson, A.T., 1960: Sodium/Potassium ratio in rain-water. Nature (London) v.186 no.4726: 705-6

The following paper has been submitted for publication in the N.Z. Journal of Geology and Geophysics.

Titanomagnetite analyses are by B.P. Kohn;
Mineralogy and stratigraphy are by V.E. Neall.

APPENDIX A1

IDENTIFICATION OF LATE QUATERNARY TEPHRAS FOR DATING TARANAKI LAHAR DEPOSITS.

B.P. KOHN and V.E. NEALL

ABSTRACT

Major and minor elements were analysed from titanomagnetites extracted from 12 Taranaki tephras. The tephras fall into five groups characterised by specific abundances of chromium, vanadium, nickel, cobalt and manganese. The titanomagnetite analyses allow the positive identification of two widespread, but thin tephras at distances >25 km from their source. The preservation and identification of these dated tephras between three extensive lahar deposits in western Taranaki allows age limits to be placed on periods of lahar deposition. The oldest lahar is dated (N.Z.942) at >16,100 yr B.P. The middle lahar deposit is dated (N.Z. 1143 and N.Z. 942) between 12,500 and 16,100 yr B.P. The youngest lahar is dated (N.Z.1144) at <6,970 yr B.P.

Titanomagnetites analyse~~s~~d from Tongariro eruptives are more basic in composition than those from Taranki tephras and this regional difference allows source areas to be determined for soil parent materials in areas between the two volcanic centres.

INTRODUCTION

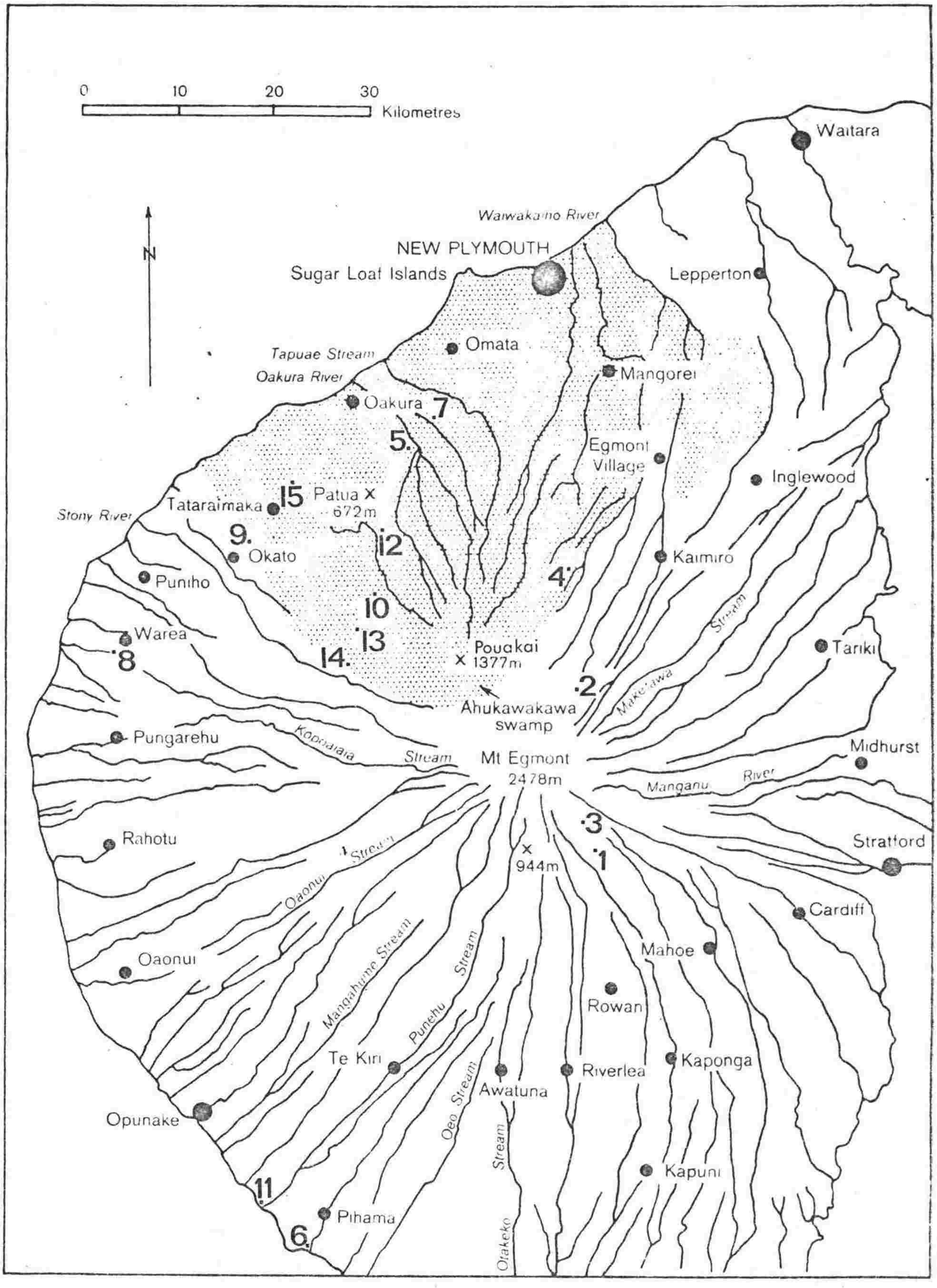
The recent volcanic history of Taranaki is dominated by the activity of Egmont and Pouakai volcanoes (Fig.1). Extensive ringplains of detrital volcaniclastics slope away from each centre. Marker beds from a 30m tephra column on Pouakai ringplain, to the north of Mt. Egmont, have been radiocarbon dated on their content of wood, peat and charcoal (Neall 1972). This allows correlation between late Quaternary sections over 1,000 km^2. To the south, on the younger Egmont ringplain, much of the tephra has been destroyed by volcanic activity or is overlain by later lahar deposits. The positive identification of dated tephra layers on Egmont ringplain thus enables interspersed volcanic events to be accurately dated.

IDENTIFICATION OF TEPHRAS

General

With increasing distance from source tephra marker beds thin out and change in lithology and appearance so that at distances greater than 25 km only tentative correlation can be made. Identification by laboratory methods is therefore critical in tracing Taranaki tephras into peripheral Quaternary sequences, to extend the range of present time control.

Initial investigations by the authors attempted to identify known Taranaki tephra layers by physical and optical methods, but with little success. Most methods for identifying tephras require distinctive properties of volcanic glasses or phenocrysts.



APPENDIX A, FIGURE 1. Locality map of Taranaki, showing sample sites. Numbers refer to localities in Table 2. Dotted area outlines surfaces graded to Pouakai volcano.

Glass and plagioclase weather rapidly to allophane under Taranaki climatic conditions and are only fresh in the youngest eruptives. Allophane is the dominant clay mineral in the younger tephras, and halloysite is restricted to the uppermost New Plymouth Buried Soil and buried soils beneath (Table 1), where it coexists with allophane. The presence of halloysite is therefore of limited use for tephra correlation. Although the age of the allophane-halloysite transition in Taranaki is not accurately dated, extrapolated tephra accumulation rates suggest it is between 70 - 100,000 yrs B.P. This is in marked contrast to the age of the major transition in the Rotorua-Bay of Plenty region which is dated at 20,000 yrs B.P. (Mr C.G. Vucetich, pers. com.).

Ferromagnesian phenocryst assemblages have been used for tephra correlation in the United States, but this technique shows greatest potential with rhyolitic and dacitic tephras and also where tephras are derived from different source areas (Wilcox 1965). Samples of the principal Taranaki tephras were examined for ferromagnesian phenocryst abundances. Abundant augite, titanomagnetite and rare hornblende characterise all the tephra heavy mineral assemblages. Hypersthene is absent from Weld tuff and the uppermost New Plymouth Ashes. Where present, hypersthene commonly forms distinctive acicular or equant crystals averaging 0.02 mm across in contrast to augite which averages 0.25 mm across. Seven samples from the youngest eruptives examined by Tonkin (1970), show similar mineralogy except for the absence of hypersthene in the Burrell Ash. A diagnostic feature of augite crystals within the tephras is that with increasing age they become increasingly etched.

	FORMATIONS	NAMED MEMBERS	UNNAMED ASHES	SYMBOLS	AUTHOR	AGE
	TAHURANGI FORMATION	TAHURANGI ASH		Ta	Druce (1966)	1755 AD
	BURRELL FORMATION	PUNIHO LAPILLI 2		Pl 2	Druce (1966)	1655 AD
		PUNIHO LAPILLI 1		Pl 1		1655 AD
		BURRELL LAPILLI		Bl		1655 AD
		BURRELL ASH		Ba		1655 AD
	NEWALL FORMATION	WAIWERANUI ASH		Wa	Druce (1966)	Revised Age 1500 - 1550 AD
		WAIWERANUI LAPILLI		Wl		
		NEWALL LAPILLI		Nl		
		NEWALL ASH		Na		
			Unnamed Ash Beds			
	INGLEWOOD TEPHRA			Il		
	KORITO TEPHRA			J		
EGMONT SHOWER	OAKURA TEPHRA		Unnamed Ash	Eg 1	Grange and Taylor 1931, 1933	<6,970 ± 76 Yrs. B.P.
		Basal lapilli		Eg 1 lap.		
	STENT ASH				Wellman (1962)	
	OKATO TEPHRA		Unnamed ash Unnamed lapilli Unnamed ash	2A 2B Eg 2	Grange and Taylor 1931, 1933	
		Ahuahu Lapilli		Aa		
	SAUNDERS ASH			Gg		16,100 ± 220 yrs.
	CARRINGTON TEPHRAS			Ct		
	KORU TEPHRA	Koru ash		Ka		
		Koru lapilli		Kp		
	PUKEITI TEPHRA			Pk		
	WELD TEPHRA	Weld ash		Wd		
		Weld tuff		Wt		
			Unnamed Ash Unnamed Lapilli			
	NEW PLYMOUTH ASHES AND BURIED SOILS			NPA NPBS		

APPENDIX A, TABLE 1. Stratigraphic column of Taranaki tephras (Modified after Neall 1972).

In tephras above the New Plymouth Ashes the augites show only weak etching on basal pinacoid faces (Fig. 2A), but below this horizon moderate to severe etching occurs on the basal pinacoid (Fig.2B) and the crystal faces of some pyroxenes are completely destroyed by corrosion.

Bulk chemical analyses are considered unsatisfactory for correlation purposes because of the rapid weathering of glass and varying amounts of phenocrysts within the Taranaki tephra deposits.

Identification by Titanomagnetite Analyses

A method for the identification of tephras involving recognition of chemical variations within titanomagnetite, analysed by optical emission spectroscopy, has been described by Kohn (1970). The method is particularly suitable for use in the Taranaki area where all tephras contain abundant titanomagnetite, a mineral which has been shown by Aomine and Wada (1962) and Ruxton (1968) to be relatively stable during weathering. To assess the potential of the technique for identifying Taranaki tephras mostly derived from a similar source, 31 samples of titanomagnetite from 15 localities (Fig.1) were separated.

Results of analyses from 12 Taranaki tephras are presented in Table 2. The tephras fall into five groups (a - e), based on similarity of elemental abundances.

a) Burrell Lapilli, Waiweranui Ash, Newall Ash, Oakura Tephra, Ahuahu Lapilli member of Okato Tephra, Saunders Ash and Weld tuff.

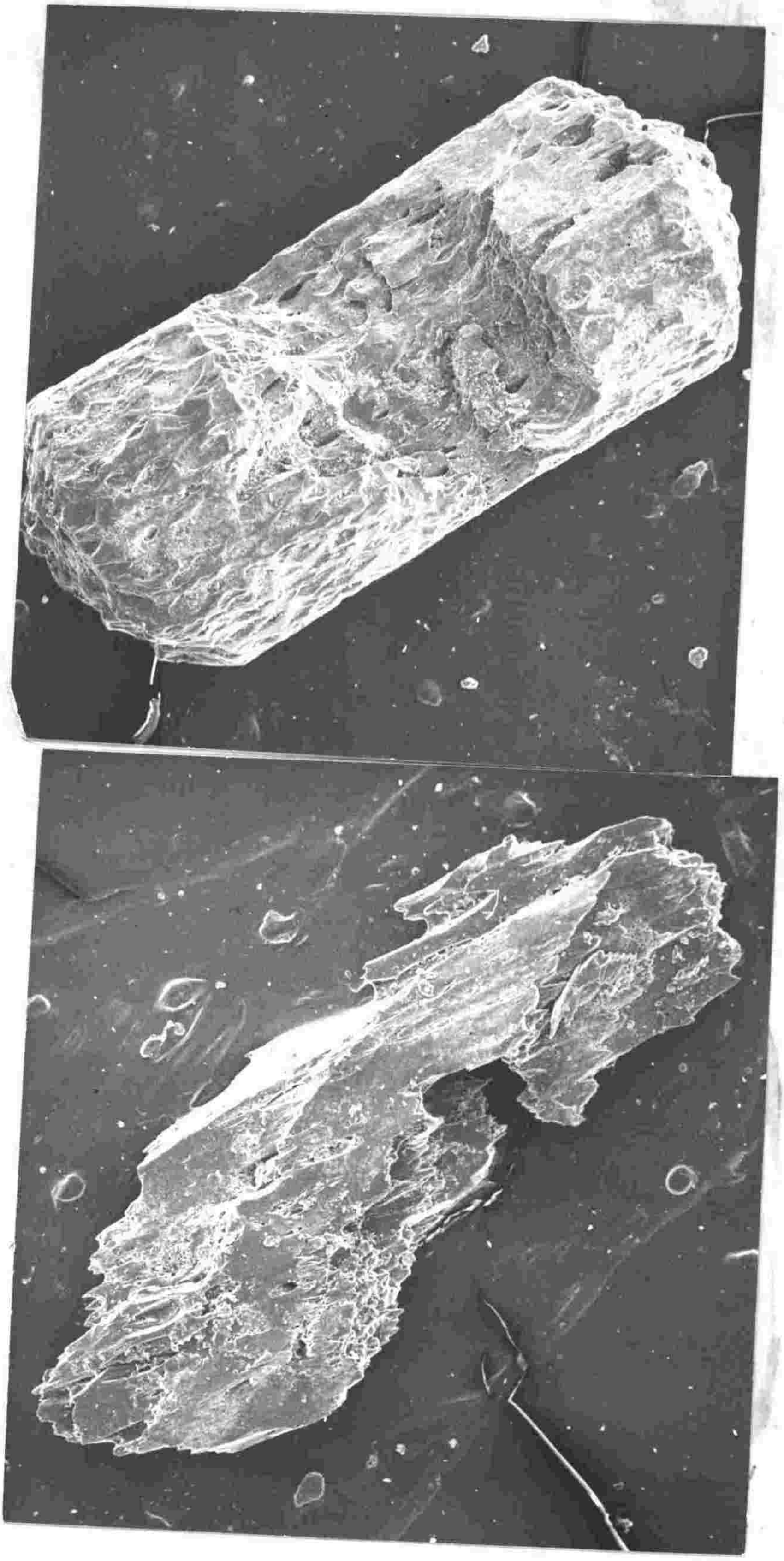


FIGURE 2(B).

APPENDIX A, FIGURE 2 - Scanning electron microscope photographs of (a) weakly etched augite crystal, note cavity on side, previously occupied by magnetite crystal x 180,

(b) moderately to severely etched augite crystal x 200.

APPENDIX A, TABLE 2 (Continued on next page).

Locality No.	Sample	Locality	Grid Reference	Ti%	Mg%	Mn%	Ca%	V	Cr	Co	Ni	Zr	Cu
1	Burrell Lapilli	Dawson Falls	N119/682593	4.16	1.67	0.40	1.03	3662	131	188	159	57	182
1	Burrell Lapilli (lithic fragments)	Dawson Falls	N119/682593	4.84	1.11	0.44	0.76	4075	112	164	171	112	247
2	Burrell Ash	Translator Road	N119/668647	4.88	1.20	0.49	0.48	3528	95	157	134	67	178
2	Waiweranui Ash	Translator Road	N119/668647	5.41	1.22	0.64	0.28	3220	106	147	117	93	146
2	Newall Ash	Translator Road	N119/668647	5.13	1.32	0.51	0.85	3484	71	156	136	103	217
3	Newall Ash (above maori oven)	Mt Egmont	N119/678607	4.78	1.34	0.51	0.80	3387	102	149	118	110	171
2	Unnamed ash (beneath Newall Ash)	Translator Road	N119/668647	5.31	1.21	0.54	0.27	3300	99	147	111	73	135
4	Inglewood Tephra	Maude Road	N109/672751	4.09	1.30	0.74	1.22	3008	164	109	94	57	142
5	Oakura Tephra	Plymouth Road	N108/584818	5.46	1.82	0.49	0.16	4122	94	185	153	85	148
6	Oakura Tephra	Puketapu Road	N128/509357	5.01	1.70	0.59	0.40	3914	110	170	130	85	141
7	Oakura Tephra	Hurford Road	N108/592843	5.85	1.96	0.51	0.16	4521	114	185	156	79	117
8	Oakura Tephra	Warea	N108/410703	5.63	1.91	0.55	0.12	4401	87	180	141	93	201
7	Oakura Tephra (basal lapilli)	Hurford Road	N108/592843	5.07	2.01	0.52	0.47	3857	115	192	139	57	94
9	Oakura Tephra	Okato - Main Road	N108/476758	5.31	1.89	0.60	0.10	3760	93	170	122	87	114
10	Okato Tephra (upper lapilli)	Dover Road/ Carrington Road	N108/552713	4.80	1.55	0.60	0.63	3567	220	158	109	68	88
6	Okato Tephra (ash)	Puketapu Road	N128/509357	5.63	2.11	0.64	0.19	3998	187	207	139	123	116
8	Okato Tephra (ash)	Warea	N108/410703	5.61	2.03	0.62	0.12	4054	254	197	142	109	120
7	Okato Tephra	Hurford Road	N108/592843	5.17	2.09	0.59	0.10	3982	343	181	171	75	121
11	Okato Tephra (ash)	Taungatara River Mouth	N128/478394	5.29	2.06	0.64	0.12	4075	188	190	142	83	117

APPENDIX A, TABLE 2. Chemical analyses of titanomagnetites from Taranaki tephras and Tongariro tephras and a lava (values are in p.p.m. unless otherwise indicated). Analyses presented are the averaged composition of samples which have generally been run in triplicate. Samples were analysed at Chemistry Division, D.S.I.R., Gracefield, using a Hilger-Littrow optical spectrograph. Operating conditions are given by Kohn (1970). The analytical precision, expressed as relative deviation is approximately ± 10 per cent.

APPENDIX A, TABLE 2 (Continued).

Locality No.	Sample	Locality	Grid Reference	Ti%	Mg%	Mn%	Ca%	V	Cr	Co	Ni	Zr	Cu
12	Okato Tephra (Ahuahu Lapilli)	Pukeiti	N108/564742	5.23	1.98	0.55	0.34	3455	73	191	136	64	112
10	Okato Tephra (Ahuahu Lapilli)	Dover Road/ Carrington Road	N108/552713	5.47	1.44	0.58	0.44	3931	83	144	111	75	102
13	Saunders Ash	Carrington Road	N108/533704	5.53	1.53	0.55	0.63	3910	73	154	118	102	181
14	Saunders Ash	Saunders Road	N118/510698	5.91	2.07	0.59	0.66	4193	85	179	142	78	182
7	Koru Lapilli	Hurford Road	N108/592843	6.06	2.27	0.77	0.36	3991	229	158	115	63	81
12	Koru Lapilli	Pukeiti	N108/564742	5.29	1.85	0.63	0.58	3840	293	158	104	79	91
12	Pukeiti Tephra	Pukeiti	N108/564742	4.31	0.96	1.17	0.16	2829	133	93	77	208	83
7	Pukeiti Tephra	Hurford Road	N108/592843	4.55	1.07	1.12	0.18	3252	135	102	79	231	78
9	Weld Tuff	Okato - Main Road	N108/476758	5.32	1.64	0.57	0.34	4678	133	175	123	71	92
15	Weld Tuff	Timaru Road	N108/503785	4.94	1.97	0.66	0.18	4100	133	179	137	57	110
15	New Plymouth Ash	Timaru Road	N108/503785	4.42	1.95	0.58	0.07	4249	501	190	192	50	118
9	New Plymouth Ash	Okato - Main Road	N108/476758	4.43	1.80	0.63	0.07	4189	759	176	197	57	133

ANDESITIC TEPHRAS AND LAVA FROM TONGARIRO-NATIONAL PARK.

Locality No.	Sample	Locality	Grid Reference	Ti%	Mg%	Mn%	Ca%	V	Cr	Co	Ni	Zr	Cu
	Poutu Lapilli	National Park-Taupo Road	N112/239901	5.77	1.15	0.43	0.66	4954	1706	163	322	103	170
	Te Rato Lapilli	Te Ponanga Road	N112/221978	3.64	0.66	0.30	1.17	4337	960	163	284	70	121
	Rotoaira Lapilli	Rotoaira Road	N112/158980	7.41	1.80	0.35	0.27	9870	2472	219	499	108	180
	North Crater - lava	North Crater	N112/136855	8.42	1.07	0.29	0.15	8809	2470	173	280	106	110

b) Okato Tephra (above Ahuahu Lapilli member) and Koru Tephra.

c) Inglewood Tephra.

d) Pukeiti Tephra.

e) New Plymouth Ashes.

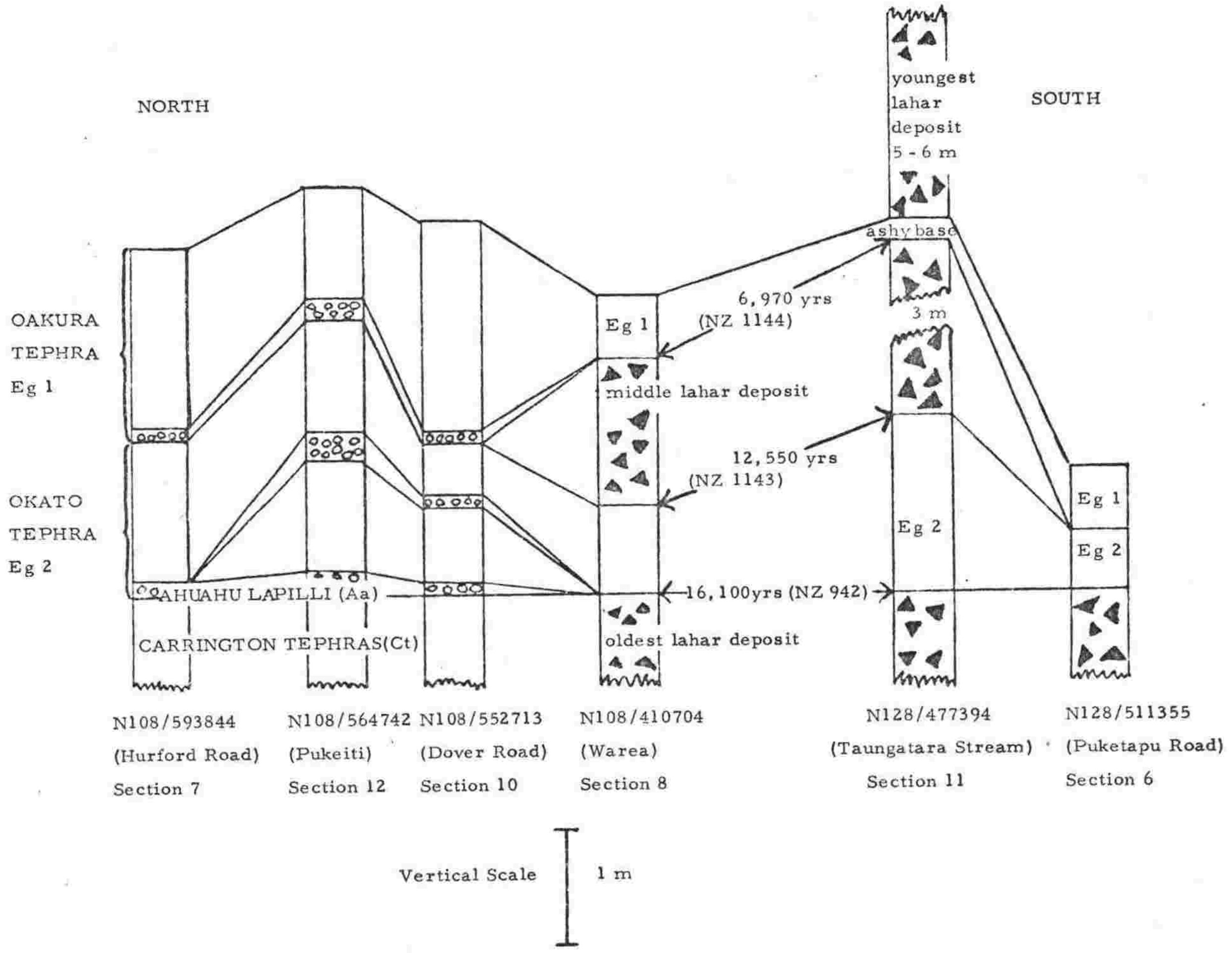
Chromium is the most variable element between these groups, a finding similar to that of Duncan and Taylor (1968) for titanomagnetites from andesitic and dacitic lavas from Bay of Plenty. Vanadium, cobalt and nickel values are generally similar in groups (a), (b) and (e) but are less abundant in Inglewood Tephra and Pukeiti Tephra. Manganese abundances in titanomagnetites from Inglewood Tephra and Pukeiti Tephra are markedly higher than those in other groups. Values obtained from the upper ash and basal lapilli of the Oakura Tephra at Hurford Road (Table 2) show similar composition and thus indicate no differential weathering and suggest deposition during one volcanic event.

There are no systematic differences in titanomagnetite composition with time from tephras above the New Plymouth Ashes. The markedly high chromium and nickel values in the New Plymouth Ashes indicate that these were probably erupted from a magma of different composition from that which gave rise to the younger Mt. Egmont tephras. The New Plymouth Ashes are separated from the younger Egmont tephras by a widespread paraconformity and are only preserved on the older Pouakai ringplain. From this evidence together with the titanomagnetite analyses it is suggested that these tephras were erupted from the older Pouakai Volcano; the magma differing slightly in composition to that from Egmont. Titanomagnetite from tephras and lavas in the Tongariro-National Park region also show increasing chromium and nickel values relative to younger samples indicating a similar change in both regions with time.

Oakura and Okato Tephra Analyses

Particular attention was given to the analysis of titanomagnetite from the Oakura and Okato tephras which form the most widespread and important Holocene tephras in Taranaki and are also preserved between a sequence of three principal lahar units to the west and south-west of Mt. Egmont. Near their source, the strongly erosive lahar flows have destroyed the underlying tephra record, and only minimal age estimates of deposits can be determined from overlying tephras. The Oakura and Okato tephras are best preserved between the formations at the present coastline where the lahars do not incorporate underlying materials at their base and apparently did not erode the earlier deposits. Positive identification of the tephra formations between the lahar units allows both maximum and minimum ages to be obtained for periods of lahar deposition.

Near its source, the Okato Tephra (Eg 2) comprises two lapilli units (Section 7, Fig 3 and Table 1) both overlain by ash. The basal lapilli unit is widespread and has been formally named Ahuahu Lapilli (Aa) member (Neall 1972), but the upper lapilli unit is unnamed and restricted to a few sections near Pukeiti. The two lapilli beds are not separated by weathering or erosional breaks and are therefore considered to be part of the same tephra formation. The upper limit of the formation is defined by a palaeosol at the top of the ash overlying the unnamed upper lapilli unit. Titanomagnetite was analysed from



APPENDIX A, FIGURE 3 - Six correlation columns between principal sample sites in Western Taranaki. Section numbers refer to localities in Appendix A, Fig. 1 and Table 2.

the widespread upper ash and the two lapilli units of Okato Tephra (Table 2). The upper lapilli has higher chromium values than the basal Ahuahu Lapilli (Aa), (usually greater by a factor exceeding two). The Ahuahu Lapilli (Aa) is similar to the basal lapilli of the younger Oakura Tephra (Eg 1 lap.) and thus the basal lapilli of the Okato and Oakura Tephras are chemically indistinguishable.

At Warea, Taungatara Stream and Puketapu (Fig.1), to the west and south-west of Mt. Egmont, the lapilli units (Eg 1 lap, unnamed lapilli and Aa) are absent and only ashes (correlated with the Oakura and Okato tephras) could be sampled for titanomagnetite analysis. The low chromium values of titanomagnetite (Group a) in the uppermost tephra at Warea and at Puketapu (Table 2 and Fig. 3) confirm the identification as Oakura Tephra. The higher chromium values of titanomagnetite (Group b) from tephra sampled beneath the middle lahar unit and above the oldest lahar unit at Warea and at Taungatara Stream (Fig.3) confirm correlation as Okato Tephra. At Puketapu, the higher chromium values (Group b) confirm the Okato Tephra underlies the previously identified Oakura Tephra (see above) and overlies the oldest lahar unit. At Taungatara Stream, the positive identification of the Okato Tephra beneath the middle lahar unit indicates that it must be the Oakura Tephra which forms the ashy base of the youngest lahar unit. The high chromium values of titanomagnetite in the Okato Tephra at all these localities indicates that the lower ash and lapilli of the Okato Tephra are restricted to near source.

CONCLUSION

Age of Lahar Units

The Oakura and Okato Tephras can be correlated from New Plymouth to at least as far south as Puketapu Road. Titanomagnetite analyses from these tephras, preserved between the western Taranaki lahar units at Warea, N108/410704, and at Taungatara Stream, N128/511355, confirm that beyond 25 km radius from Egmont summit:

a) the Okato Tephra overlies the oldest lahar unit and underlies the middle lahar unit,

b) the Oakura Tephra overlies the middle lahar unit and underlies the youngest lahar unit.

Since the age of the tephras has now been established in the northern part of this area (Neall 1972), the three lahar units can now be dated.

The Okato Tephra is dated (NZ1143, Grid Ref; N118/512658 and NZ942, Grid Ref: N108/534704) between 12,550 ± 150 hr B.P. and 16,100 ± 220 yr B.P., indicating a minimum age of about 16,000 years for the age of the oldest lahar unit.

The Oakura Tephra is dated (NZ1144, Grid Ref: N118/526665) at less than 6,970 ± 220 yr B.P. This indicates an age for the middle lahar unit between 7 - 14,000 yr B.P. The apparent absence of this lahar unit within a well preserved debris flow sequence near Mt. Egmont, dating back to 12,550 yr B.P. (NZ1143), suggests the middle lahar originated about 13 - 14,000 yr B.P.

The youngest lahar unit is underlain by Oakura Tephra, indicating an age of less than 6,970 yr B.P. (NZ1144), yet no widespread tephras mantle this lahar unit, so that it is likely to be about 3 - 5,000 yr old.

Comparison of Taranaki and Tongariro titanomagnetites

Titanomagnetite compositions of tephra from Taranaki were compared with three widespread lapilli units and a lava erupted from Tongariro Volcanic Centre (Table 2). The Tongariro eruptives contain titanomagnetite lower in manganese and higher in vanadium, nickel and chromium than the younger Taranaki eruptives. Chromium is at least three times but commonly eight times higher in the Tongariro eruptives, and is therefore the most distinctive and useful element. Thus in areas between Tongariro National Park and Mt. Egmont, where late Pleistocene and Holocene tephras from the two sources may interdigitate, the andesitic tephras can be clearly distinguished on the basis of their titanomagnetite composition. Ready identification of these tephras may prove valuable in future Quaternary tephrochronology and soil genesis studies.

ACKNOWLEDGEMENTS

The photographs in Fig. 2 were made by Dr P.N. Webb, N.Z. Geological Survey, using the scanning electron microscope at Physics and Engineering Laboratories, D.S.I.R., Gracefield. The authors also wish to thank Professor J.B. Bradley, Dr J.W. Cole and Mr C.G. Vucetich for much useful discussion and for critically reading the manuscript. We wish to thank Mr W.W. Topping for supplying samples from localities 1, 2 and 3, and the Tongariro region.

REFERENCES

Aomine, S.; Wada, K. 1962: Differential Weathering of pumice, resulting in formation of hydrated halloysite. American Mineralogist 47 : 1024-48.

Duncan, A.R.; Taylor, S.R. 1968 : Trace element analyses of magnetites from andesitic and dacitic lavas from Bay of Plenty, New Zealand. Contributions to Mineralogy and Petrology 20 : 30-3.

Kohn, B.P. 1970 : Identification of New Zealand tephra-layers by emission spectrographic analysis of their titanomagnetites. Lithos 3 : 361-68.

Neall, V.E. 1972 : Tephrochronology and tephrostratigraphy of western Taranaki. N.Z. Journal of Geology and Geophysics 15(4): 507-57.

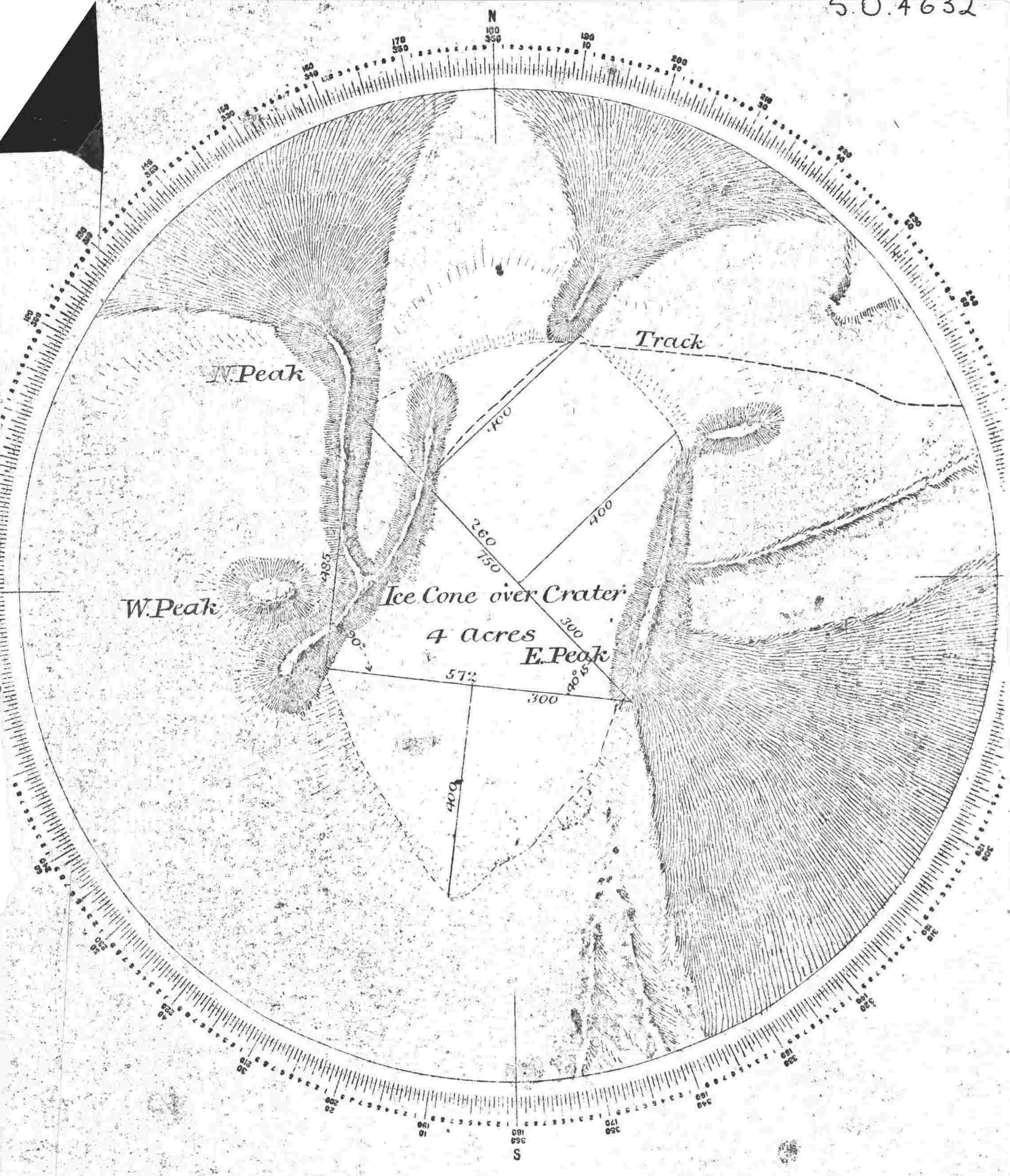
Ruxton, B.P. 1968 : Rates of weathering of Quaternary volcanic ash in north-east Papua. 9th International Congress of Soil Science Transactions, Vol.4, Paper 38 : 367-76.

Tonkin, P.J. 1970 : The soils of the southeastern sector of Egmont National Park. Earth Science Journal 4 (1) : 36-57.

Wilcox, R.E. 1965 : Volcanic-ash chronology. In The Quaternary of the United States (Princeton University Press), 807-16.

APPENDIX C1 - View of Mt. Egmont looking south from the Pouakai Range, circa 1899 A.D. Photograph taken by H.M. Skeet. Note fan of alluvial debris originating from Minarapa Stream.

S.O. 4632



APPENDIX C2.

Plan of the Summit of Mt Egmont
Surveyed by J. W. Davis & F. Carrington 1885
Scale 2½ Chains to an Inch.

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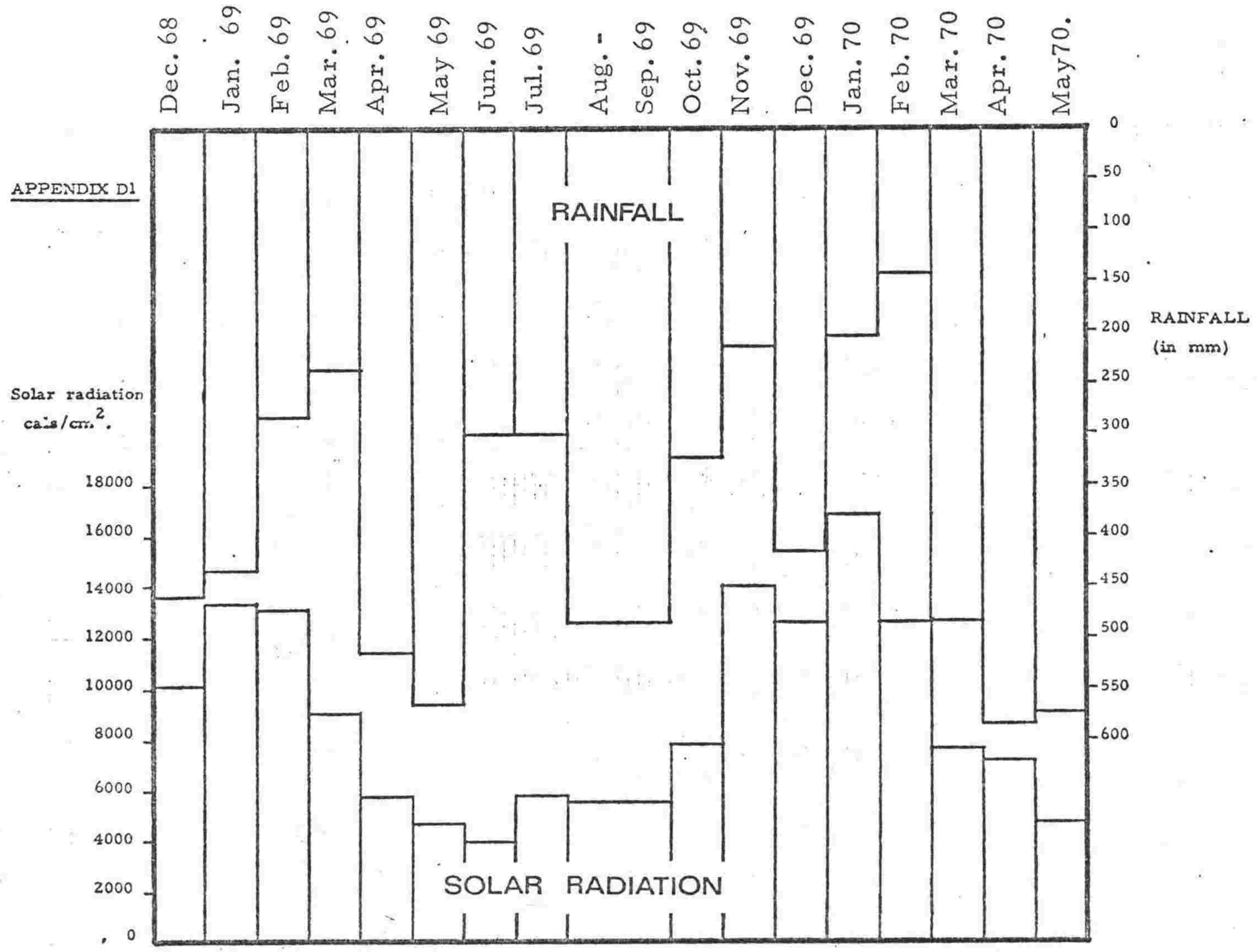
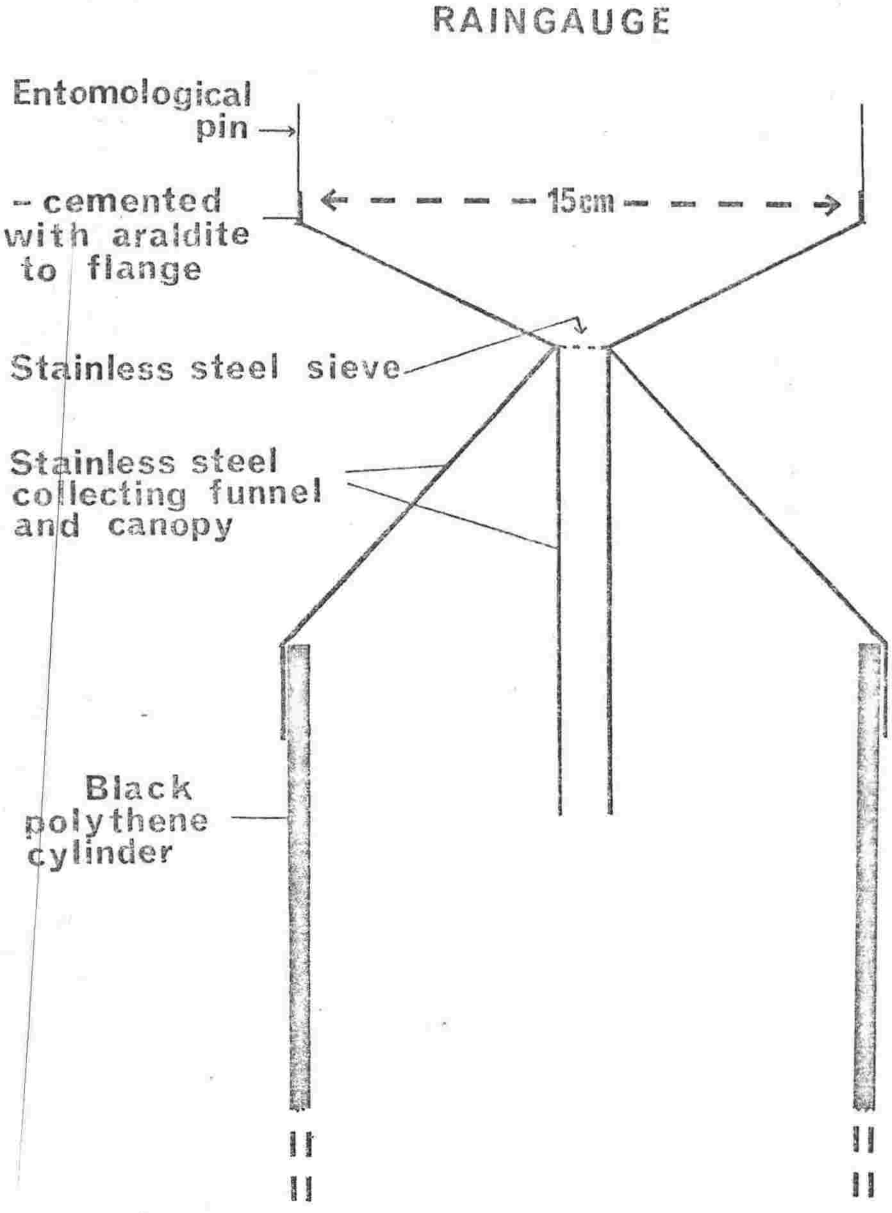
NOTE. Measured lines to be drawn in red, calculated or scaled lines in black, observed bearings in blue, the figures also being in red, black and blue respectively. Draw a red circle round each peg, a double red circle round each trig station. Remarks of Surveyor to be noted on back hereof.

APPENDIX D1



APPENDIX D1 - Relationship between solar radiation (in cal/cm^2) and rainfall during the study period (December 1968 - May 1970) at Little Pyramid, Mt Egmont, altitude 1170m.



APPENDIX D2. Cross-section of raingauge constructed for rainwater sampling. Diameter of black polythene cylinder is the same diamter (15 cm) as the collector.

APPENDIX D3 - Breakdown of quantities of Na, K and Mg in biomass samples collected between December 1968 and February 1971.

		Na (kg/ha)				K (kg/ha)				Mg (kg/ha)			
		Dec.68	Jan.70	Feb.70	Feb.71	Dec.68	Jan.70	Feb.70	Feb.71	Dec.68	Jan.70	Feb.70	Feb.71
Rhacomitrium	A.G.	5.20	5.80	2.79	9.60	9.88	12.59	4.25	16.39	40.08	48.49	11.18	53.09
	B.G.	10.08	2.60	1.74	12.35	10.08	2.60	1.16	9.60	20.09	5.18	9.51	53.58
	Total	15.28	8.40	4.53	21.95	19.96	15.19	5.41	25.99	60.17	53.67	20.69	106.67
Coriaria	A.G.	0.74	-	-	-	3.72	-	-	-	3.85	-	-	-
	B.G.	6.76	-	-	-	7.11	-	-	-	7.11	-	-	-
	Total	7.50				10.83				10.96			
Chionochloa	A.G.	-	6.95	0.66	2.21	-	32.01	0.79	9.83	-	3.86	6.62	2.19
	B.G.	-	3.54	-	-	-	3.79	-	-	-	9.73	-	-
	Total		10.49	0.66	2.21		35.80	0.79	9.83		13.59	6.62	2.19
Senecio	A.G.	-	-	50.58	7.24	-	-	203.65	16.80	-	-	146.58	23.24
	B.G.	-	-	49.38	-	-	-	53.68	-	-	-	31.04	-
	Total			99.96	7.24			257.33	16.80			177.62	23.24
Cassinia	A.G.	-	6.49	16.15	4.00	-	11.35	24.42	6.60	-	4.87	14.93	3.30
	B.G.	-	0.88	-	-	-	1.65	-	-	-	0.47	-	-
	Total		7.37	16.15	4.00		13.00	24.42	6.60		5.34	14.93	3.30
Others	A.G.	1.41	2.28	5.47	1.00	2.54	7.50	23.44	2.84	3.11	5.87	26.79	2.66
	B.G.	3.00	3.28	17.06	3.13	3.60	6.09	18.14	4.86	8.39	6.30	79.99	8.53
	Total	4.41	5.56	22.53	4.13	6.14	13.59	41.58	7.70	11.50	12.17	106.78	11.19
Litter		-	-	6.92	-	-	-	15.69	-	-	-	55.36	-
Grand Total		27.19	31.81	150.75	39.54	36.93	77.58	345.21	66.92	82.63	84.77	382.00	146.58

APPENDIX D4 - Breakdown of quantities of Ca, N and P in biomass samples collected between December 1968 and February 1971.

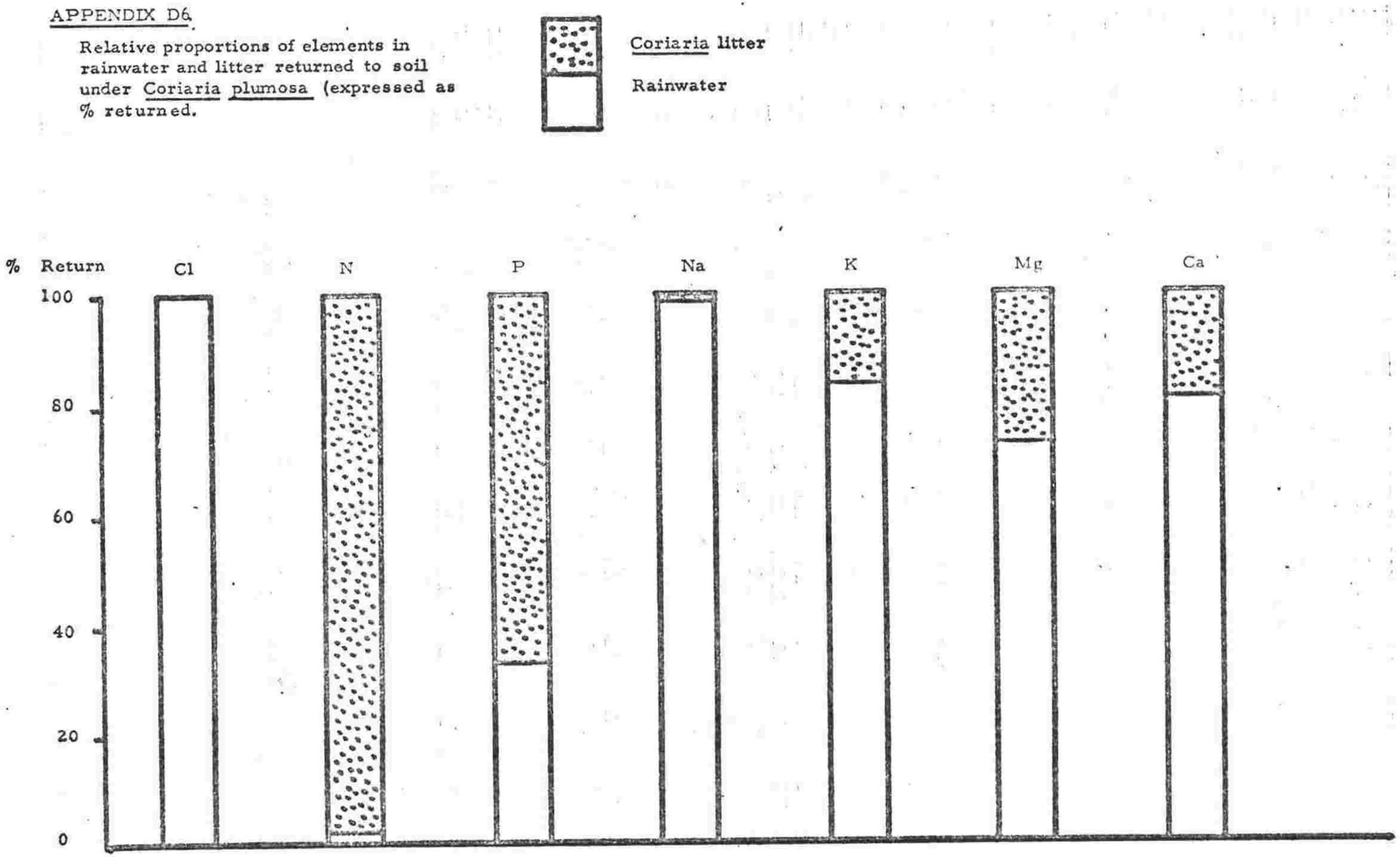
		Ca (kg/ha)				N (kg/ha)				P (kg/ha)			
		Dec.68	Jan.70	Feb.70	Feb.71	Dec.68	Jan.70	Feb.70	Feb.71	Dec.68	Jan.70	Jan.71	Feb.71
Rhacomitrium	A.G.	31.23	48.49	6.71	39.73	116.06	218.00	24.74	156.28	tr	tr	tr	tr
	B.G.	60.27	15.55	10.34	73.77	428.05	116.00	18.53	265.76	tr	tr	tr	tr
	Total	91.50	64.04	17.05	113.50	544.11	334.00	43.27	422.04	tr	tr	tr	tr
Coriaria	A.G.	2.99	-	-	-	15.35	-	-	-	0.91	-	-	-
	B.G.	5.33	-	-	-	22.01	-	-	-	4.32	-	-	-
	Total	8.32				37.36				5.23			
Chionochloa	A.G.	-	15.43	7.94	5.89	-	82.40	28.60	4.37	-	tr	tr	tr
	B.G.	-	10.10	-	-	-	27.04	-	-	-	tr	-	-
	Total		25.53	7.94	5.89		109.44	28.60	4.37		tr	tr	tr
Senecio	A.G.	-	-	148.48	17.43	-	-	164.91	18.55	-	-	11.32	tr
	B.G.	-	-	74.47	-	-	-	63.30	-	-	-	tr	-
	Total			222.95	17.43			228.21	18.55			11.32	tr
Cassinia	A.G.	-	6.89	21.71	4.74	-	11.30	37.83	8.00	-	tr	tr	tr
	B.G.	-	0.68	-	-	-	1.85	-	-	-	tr	-	-
	Total		7.57	21.71	4.74		13.15	37.83	8.00		tr	tr	tr
Others	A.G.	4.99	6.85	20.09	3.59	4.54	10.59	36.09	4.44	0.28	0.66	2.23	0.27
	B.G.	11.38	7.77	56.00	8.94	27.72	10.09	134.20	16.79	-	-	-	-
	Total	16.37	14.62	76.09	12.53	32.26	20.68	170.29	21.23	0.28	0.66	2.23	0.27
Litter		-	-	89.96	-	-	-	109.39	-	-	-	n.d.	-
Grand Total		116.20	111.75	435.70	154.09	613.72	477.28	617.60	474.20	5.51	0.66	13.56	0.27

APPENDIX D5 - "Excess potassium concentrations" (Wilson 1959, 1960) in rainwater samples collected study site

	Na^+ ppm	K^+ ppm	Corrected K^+ $= K^+ - \frac{Na^+}{27}$ ppm	$\frac{K^+ \text{(corrected)}}{Na^+}$
Dec.68	0.45	n.d.	n.d.	
Jan.69	0.9	n.d.	n.d.	
Feb.69	0.8	0.1	0.07	0.09
Mar.69	2.0	0.2	0.13	0.06
Apr.69	2.5	0.2	0.11	0.04
May 69	1.5	0.1	0.05	0.03
Jun.69	3.3	0.1	0.02	0.01
Jul.69	1.5	0.1	0.05	0.03
Aug.69	)			
Sep.69	) 1.0	0.1	0.06	0.06
Oct.69	3.0	0.2	0.09	0.03
Nov.69	1.1	0.1	0.06	0.05
Dec.69	1.5	0.2	0.15	0.10
Jan.70	1.7	0.1	0.04	0.02
Feb.70	1.8	0.9	0.83	0.46
Mar.70	1.6	0.7	0.64	0.40
Apr.70	1.6	0.8	0.74	0.46
May 70	1.7	1.0	0.94	0.55
Seawater	11,000	410	0	0.04

APPENDIX D6.

Relative proportions of elements in rainwater and litter returned to soil under Coriaria plumosa (expressed as % returned.



APPENDIX D7 - Total energy content of combined mossfield and shrubland ecosystems

Sample Date	A.G./B.G.	Material	Total dry matter (oven dry wt.) kg/ha	Dry basis calorific value (cals/gm)	Total calorific value (x10^{3}K cals/ha)	Total (x10^{3}K cals/ha)	Mean annual rate of energy accumulation x10^{3}K cals/ha
Dec.68	A.G.	Rhacomitrium	18,720	4,350	81,432		
		Coriaria	330	4,690	1,547.7		
		Others	510	4,610	2,351.1		
	B.G.	Coriaria	2,620	4,640	12,156.8		
		Rhacomitrium	69,040	3,800	262,352		
		Others	4,200	4,530	19,026	= 378,865	4,735
Jan.70	A.G.	Rhacomitrium	35,162	4,350	152,954.7		
		Chionochloa	14,208	4,560	64,788.5		
		Cassinia	1,507	5,120	7,715.8		
		Others	1,190	4,610	5,485.9		
	B.G.	Rhacomitrium	18,709	3,770	70,532.9		
		Chionochloa	4,662	2,970	13,846.1		
		Others	1,775	4,530	8,040.8	= 323,364	4,042
Feb.70	A.G.	Senecio - leaves	12,178	4,750	57,845.5		
		Senecio - stems	15,550	4,610	71,685.5		
		Cassinia	5,044	5,120	25,825.3		
		Others	4,055	4,610	18,693.6		
		Rhacomitrium	6,980	4,350	30,363		
		Litter	8,480	4,530	38,414.4		
	B.G.	Dead Chionochloa	4,931	3,010	14,842.3		
		Others	20,334	1,870	38,024.6		
		Senecio	15,824	4,510	71,366.2	= 367,060	4,588
Feb.71	A.G.	Rhacomitrium	25,207	4,350	109,650.5		
		Chionochloa	4,311	4,560	19,658.2		
		Senecio	1,933	4,750	9,181.8		
		Cassinia	1,067	5,120	5,463		
		Others	499	4,610	2,300.4		
	B.G.	Dead Chionochloa	754	3,010	2,269.5		
		Rhacomitrium	42,864	3,800	162,883.2		
		Others	2,544	4,530	11,524.3	= 322,930	4,036
Average				4,300		348,055	4,350