GEOLOGY OF THE WESTERN MAMAKU PLATEAU

AND

VARIATIONS IN THE MAMAKU IGNIMBRITE

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ABSTRACT

Pleistocene ignimbrites in the western Mamaku Plateau east of Putaruru consist of the following successively younger formations: (?) Ongatiti Ignimbrite, Ahuroa Ignimbrite, Whakamaru Ignimbrite, Waihou Ignimbrite (new), Waimakariri Ignimbrite (new), Mamaku Ignimbrite. They can be distinguished on the basis of their compositional-, welding-, textural-, and field characteristics. The ignimbrites are separated by unconformities, and intercalated fluvial sedimentary deposits. The three most important units are the Whakamaru, Waimakariri and Mamaku Ignimbrites, which are well exposed and widespread.

The Mamaku Ignimbrite covers a surface area of nearly 4300 km^2 on the Mamaku Plateau. Corresponding vertical changes in lithology, petrography and physical properties near the Rotorua Caldera define two flow members: a lower Sheet 1, and an upper Sheet 2, each of which is about 60 m thick. The ignimbrite constitutes a simple cooling unit which indicates that Sheet 2 was emplaced shortly after Sheet 1. Only one sheet (? Sheet 1) is evident in the western Mamaku Plateau. Welding zonation near-to-source is characterised by a gradual change from a basal glassy lenticulite zone to a nonwelded top. Smith's (1960b) zonal classification ranks the ignimbrite as being partially welded. This condition suggests that total thickness is not necessarily a major factor in the degree of welding of ignimbrites.

The phenocryst assemblage of plagioclase, quartz, pyroxene, opaques, hornblende and biotite, is set in a devitrified fine ash matrix, which is an ubiquitous feature of the ignimbrite. Higher modal phenocryst content at the base of each sheet is attributed to compaction. Overall the phenocrysts are uniformly distributed and there is little vertical variation. Seven bulk chemical analyses reveal only minor vertical variations in composition. The near uniform chemical and mineralogical trends suggest nondifferentiation of the source magma.

Texturally the Mamaku Ignimbrite is a poorly sorted lapilli ash. The grading of fragments like that shown in "the standard ignimbrite flow unit" is absent. However, the presence of a zone of aligned pumice fragments indicates that laminar flow operated during the later stages of deposition.

Two major inferred faults in the western Mamaku Plateau define a western horst, a central graben, and an eastern horst. The eastern horst is postulated to be the southern extension of the axial median horst in the Hauraki Depression and of the Hauraki Rift.

Repeated and extended intervals of erosion followed the emplacement of the ignimbrites. Detritus from the eroding sheets was removed by rivers flowing into the Hauraki Depression. Construction of the Mamaku Plateau has largely taken place since the eruption of the Whakamaru Ignimbrite, *c.*300,000 years ago, and terminated with the eruption of the Mamaku Ignimbrite, *c.*140,000 years ago. Excavation of the long deep valleys in the plateau occurred mainly in the latter 42,000 years.

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CHAPTER ONE

INTRODUCTION

1.1 OBJECTIVES

This study has two major aims. The first is to investigate the vertical and lateral variations of the Mamaku Ignimbrite is the distal and the near-to-source sections with a view to understanding some of the eruption, emplacement, and cooling processes. The second aim is to describe the structure, stratigraphy and characteristics of ignimbrites in the western Mamaku Plateau, and to construct a geological history of the area. These aims stem from a lack of published information about the Mamaku Ignimbrite and the stratigraphy in the western Mamaku Plateau.

1.2 BACKGROUND AND RATIONALE FOR THE STUDY OF THE MAMAKU IGNIMBRITE

The Mamaku Ignimbrite is one of the youngest (*c.* 0.14 m.y.B.P. - Murphy and Seward, 1981) and most voluminous (*c.*300 km^3 = magnitude 6 [Smith, 1960,a]) rhyolitic ignimbrites to have erupted from the Taupo Volcanic Zone. The ignimbrite covers about 4350 km^2 and forms the Mamaku Plateau to the northwest, west and southwest of the Rotorua Caldera (Fig. 1.1). The caldera is probably the source of the Mamaku Ignimbrite (Healy, 1963). Deep drillholes indicate a (maximum) thickness of about 150 m on the northwestern side of Lake Rotorua. At the distal margins the thickness varies from 20 to 50 m.

Geological investigations of the Mamaku Ignimbrite were carried out about 1957/58 when the Lower Kaimai and Kaituna River areas (Fig. 1.1), were surveyed for hydro-electric development. In a geological report in the Kaituna Area, Thompson (1958) found that there was little sign of lateral variation in rock type in outcrops, but vertical variation existed, as revealed by drill-cores. At depth the ignimbrite became progressively harder and the pumice fragments more flattened. Near the base of the ignimbrite the structure is lenticulitic. A petrographical

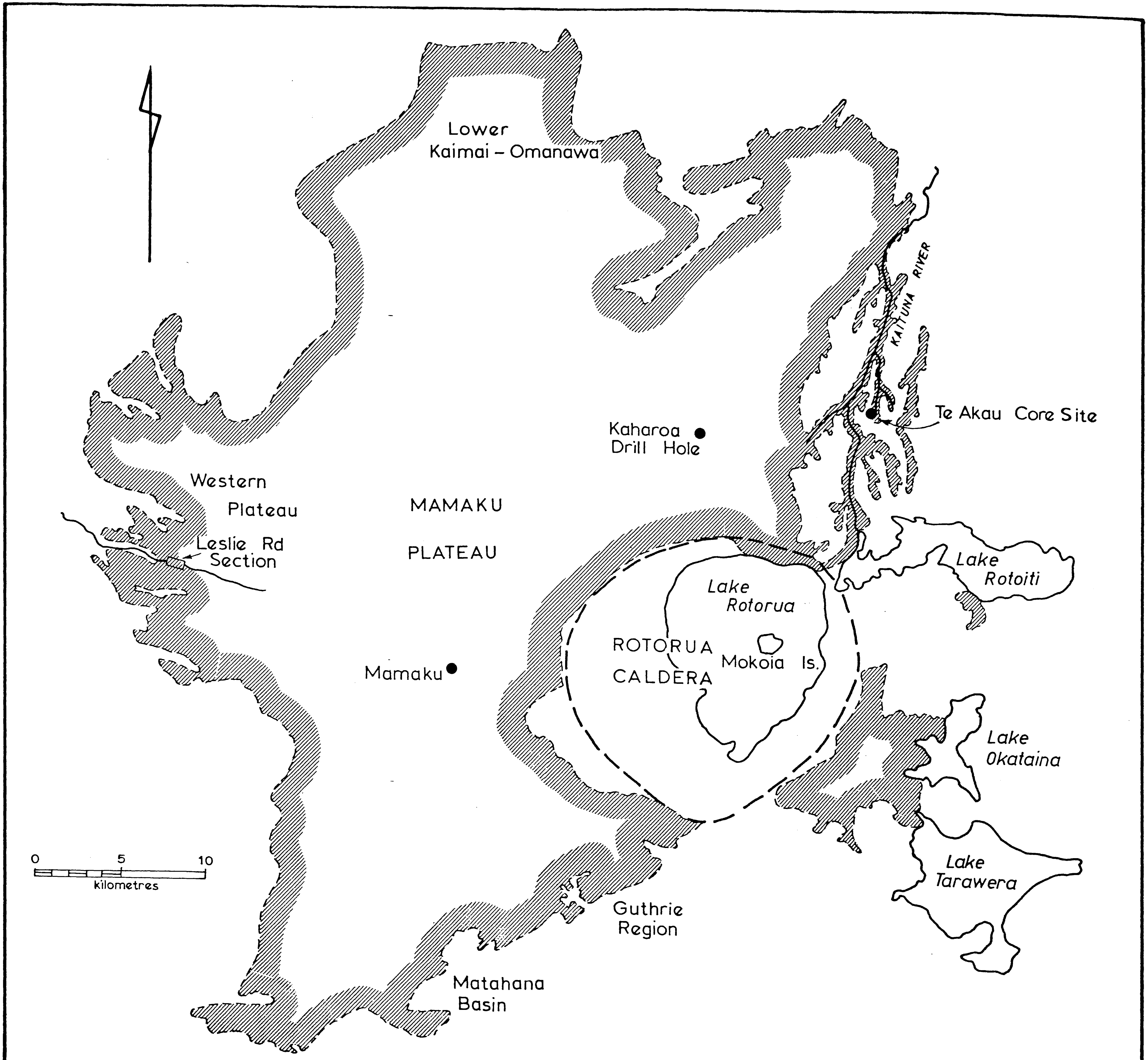


Fig. 1·1. Location map showing the outcrop area of the Mamaku Ignimbrite (from Healy et al, 1964.)

study by Nathan (1975) of the Kaharoa drill-core (Fig. 1.1), revealed a significant enrichment of phenocrysts near the base.

There is uncertainty about the number of flow units that comprise the Mamaku Ignimbrite. Healy and Ewart (1965) report at least three flow units. Thompson (1958) identified only one sheet in drill-cores near Te Akau (Fig. 1.1). However, Murphy (1977) found a number of small flow units separated by airfall tephra in a basal zone of the Mamaku Ignimbrite in the Matahana Basin (Fig. 1.1). He also subdivided the thicker overlying ignimbrite into three units based on the degree of welding.

There has been no detailed volcanological study, of the Mamaku Ignimbrite comparing its vertical or lateral variations found with those of other ignimbrites described from around the world (e.g. the western United States).

Comparison of physical and petrographical characteristics is required at distal and proximal sections of the Ignimbrite. Near-to-source samples were collected from two deep cores, the Te Akau 5 and 17, which were drilled during the 1957/58 geological survey. It is only possible to study the complete sequence of the Mamaku Ignimbrite near to its source from drill cores since the base of the Ignimbrite is not exposed. Another advantage of the core is that good control was obtained on the position of the samples. As hoped the second core provided a "double-check" of observed vertical variations. A distal section was chosen in the western Mamaku Plateau near Putaruru. This section is located on Leslie Road (Fig. 1.1) and field mapping showed it to be the most complete and a typical example of the Mamaku Ignimbrite in this area.

1.3 LOCATION AND PHYSIOGRAPHY

The study area lies east of Putaruru (Fig. 1.2), in which geological mapping was carried out, and is a part of the western portion of the Mamaku

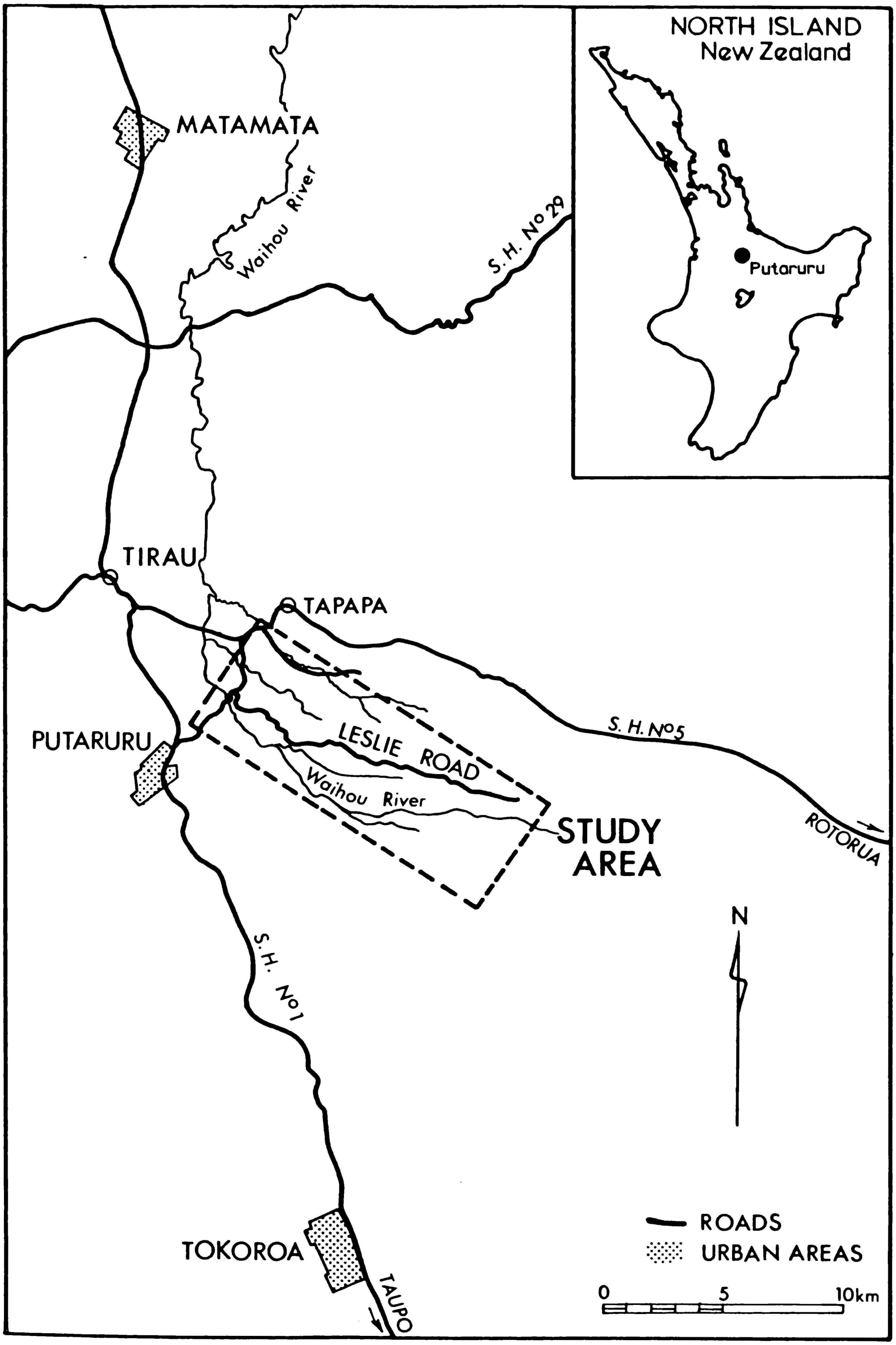


Fig 1·2 Location map of the study area.

Plateau. The edge of the plateau terminates abruptly along the north-western boundary of the study area. The main access routes are State Highways No. 1 and No. 5. Leslie Road bisects the area and it is the most useful service road from which to examine the geology of the plateau.

The southeastern part of the study area is covered mainly by exotic forest and can be entered by a network of private forestry roads. In the northwestern half of the study area, mixed farming is predominant.

The Mamaku Plateau is a broad fan-shaped structure which is gently arched to an elevation of 600 m along a north-south axis near Mamaku (Fig. 1.1). There the highest levels of the plateau are eroded, leaving a landscape dominated by upstanding bodies of rock (tors) on a relatively flat surface. The plateau descends westwards into the study area where valleys are separated by the roughly accordant surfaces of interfluves (Fig. 1.3 and 2.23).

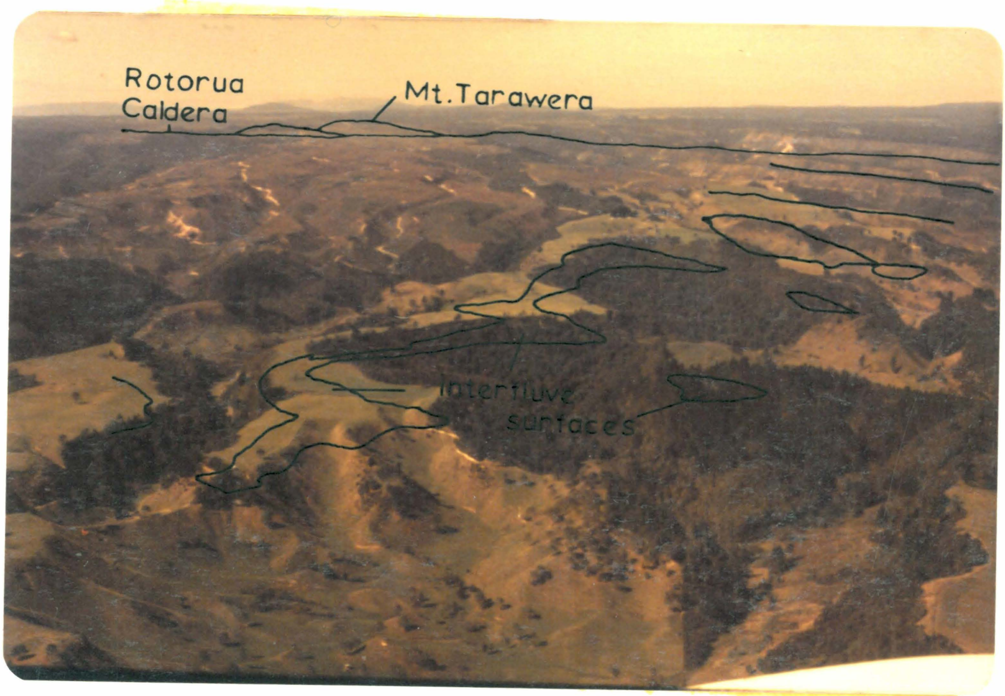


Fig. 1.3 - The western Mamaku Plateau in the study area looking east. On the horizon are seen the rhyolite domes of the Rotorua-Okataina Volcanic Centres. In the foreground are seen remnants of the original plateau surface (valley interfluves - outlined). Photograph by courtesy of J.D. McCraw.

Major waterways draining the area are the Waimakariri and Purere Streams and the Waihou River. These waterways flow in deep (100-150 m) valleys cut into the plateau. Many of the valleys, however, contain underfit streams. The floor of the valleys are usually flat or they have undulating hills which sometimes expose bluffs. The sides of the valleys are steep (40-50°) and are often interrupted by vertical cliffs. The slopes sometimes end sharply at the surface edge of the interfluves.

A panoramic view of the regions major physiographical features are seen from the top of the plateau. Northwards, the Kaimai Range terminates abruptly against the Mamaku Plateau (Fig. 1.4). The western edge of the range has steep fault scarps which overlook a broad (20-30 km) depression of the Hauraki Plains. To the west and southwest lies the older and more dissected Tokoroa Plateau.

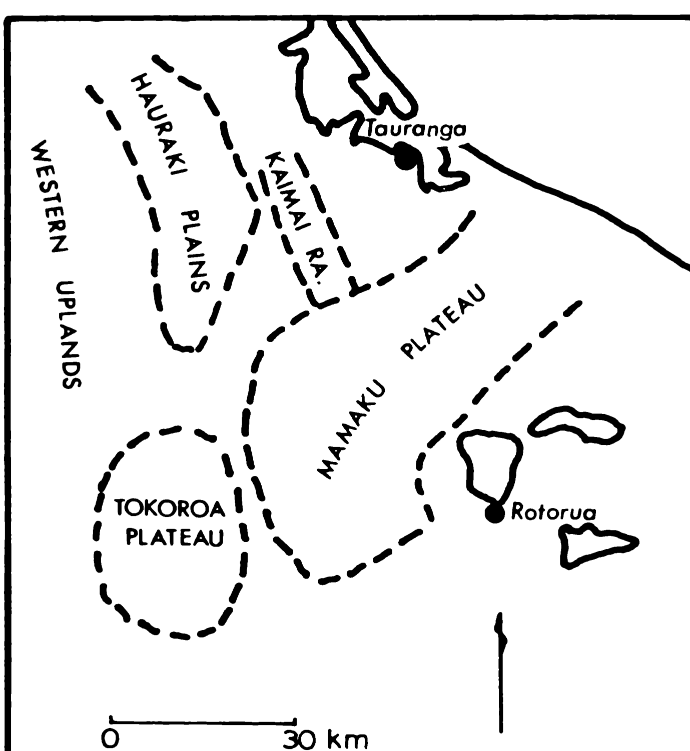


Fig. 1·4 Major physiographical features in the region.

1.4 GEOLOGICAL SETTING

The geology of the study area is the result of tectonism and volcanism which has operated on a regional scale.

The oldest rocks in the region are Mesozoic greywackes of the Manaia Hill Group which are exposed only on the ranges along the western margin of the Hauraki Depression (Fig. 1.4). Gravity surveys carried out by Hochstein and Nixon (1979) across the Hauraki Plains* indicate that the greywacke is downfaulted along faults which bound the eastern and western margins of the depression. The maximum thickness of unconsolidated (Quaternary) sediments which overlie this greywacke 'basement' is between 1000 to 1500 m (Hochstein and Tearney, 1981).

The southern end of the Kaimai Range consists of rhyolite domes. These acid volcanics were active from Upper Miocene to Pliocene times (Rutherford, 1976). Capping the Kaimai Range north of these domes is the Waiteariki Ignimbrite. A part of this ignimbrite lies in the Hauraki Depression.

The Quaternary rocks of the Putaruru region are mainly ignimbrites which were erupted from the Taupo Volcanic Zone in the central North Island. At least eight ignimbrites flowed into the region and formed mainly the Western Uplands, the Tokoroa and the Mamaku Plateaus (Fig. 1.4). Some of these ignimbrites are shown in Fig. 1.5.

The geological setting near the Te Akau core-site is reviewed in Chapter 4 (4.1).

* In this study, the surface of the Hauraki Depression is referred to as the Hauraki Plains. This is flanked to the east and west by ranges. Structurally the depression is a rift feature, i.e. the Hauraki Rift (Hochstein and Nixon, 1979).

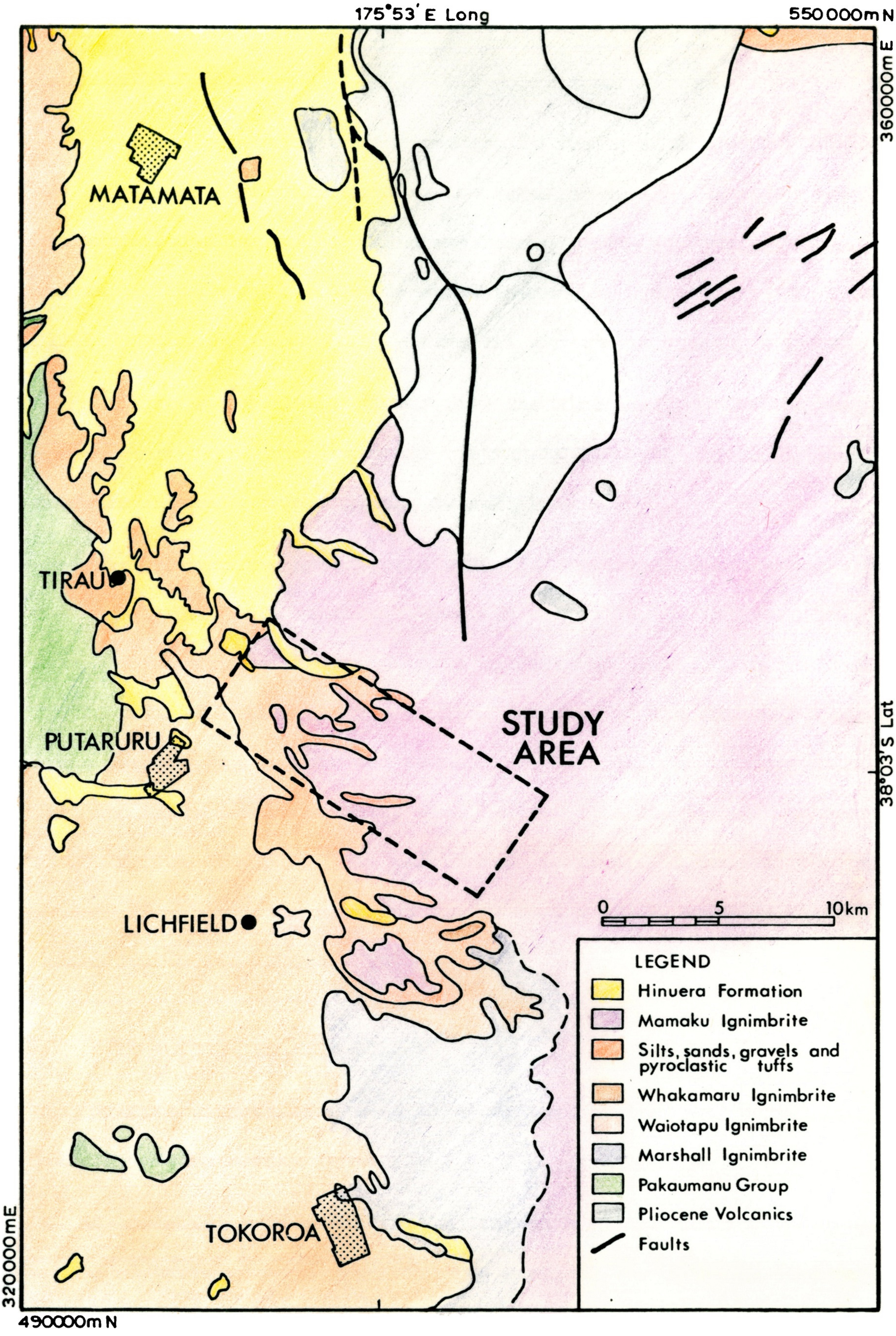


Fig 1.5 Generalised geological map for the region. (after Healy et al. 1964)

1.6 PREVIOUS WORK

Specific reference to the geology in the area defined in this study was first made by Martin (1961). He reported (p.471) that the Mamaku Ignimbrite overlies tuffs which may belong to the Whakamaru Ignimbrites. The map of Healy *et al.* (1964) shows the Mamaku Ignimbrite with intercalated "Puketoka Formation" sediments, and the Whakamaru Ignimbrite.

Cuthbertson (1981) showed that the Hinuera Formation is largely derived from detritus eroded off the Mamaku Plateau. These sediments form the present surface of the Hauraki Plains.

Airfall tephras have proved valuable in stratigraphic correlation and geomorphological studies. Vucetich and Pullar (1969) described the Late Pleistocene ash beds and loess deposits on Leslie Road. McCraw (pers. comm.) is studying the erosion patterns of the Mamaku Plateau using tephrostratigraphic and pedological methods. He has suggested that the early tephra deposits were derived from the aerial components of ignimbrite eruptions. In particular, reference is made to the upper members (H_5-H_7) of the Hamilton Ash Formation which possibly lie on the Mamaku Ignimbrite (McCraw, 1973).

1.7 INTRODUCTION TO METHODOLOGY

Several methods were used to study the physical and petrological features of the Mamaku Ignimbrite.

By counting pumice and lithic fragments at the outcrop using the method of Yamazaki *et al.* (1973), the vertical variation in their abundance in the distal section was determined. The lack of cohesion of the pumice fragments results in their destruction if samples are handled or sieved. The ignimbrite in the cohesive parts resist separation because of a high degree of welding. For the same reasons, phenocryst and mineral abundance were determined by grid-point counting of prepared rock slices mounted on glass. Both distal and near-to-source rock samples were used.

Bulk density, particle density and porosity were analysed to determine the degree of welding. Vertical changes of physical properties and phenocryst abundances in the core samples were compared, to detect the presence of possible flow boundaries.

The flatness ratio of pumice fragments in core samples was determined following Peterson's (1979) method. These measurements show vertical variations in size and abundance. Seven core samples were prepared for bulk chemical analysis by X-ray fluorescence.

1.8 PRINCIPLE RESULTS

Near-to-source the Mamaku Ignimbrite consists of two major eruptive units or sheets. In the distal margin only one of these sheets is thought to be present. The two sheets were emplaced within a short time interval and cooled as a single unit. The base of each sheet is characterised by an enrichment of phenocrysts. Plagioclase dominates the total phenocryst assemblage and throughout the core shows only slight vertical variation. Bulk chemical abundances, in the core show slight vertical variations of SiO_2, Al_2O_3, CaO, Na_2O, K_2O, Rb and Sr.

In the western Mamaku Plateau two new ignimbrites have been found which are separated from the Whakamaru and Mamaku Ignimbrites by erosional unconformities. Two inferred faults (one buried) appear to define a horst and graben structure which is linked to the major north-south structural trend of the Hauraki Rift.

1.9 NOMENCLATURE

Definition of terms used in this study is based on Smith (1960a,b), Blank (1965), Scott (1966) and Schmid (1981).

Pyroclastic deposit

The term pyroclastic deposit is used in a broad sense to mean an "assemblage of pyroclasts" meaning material which is generated by disruption as a direct result of volcanic action. Pyroclastic deposits include subaerial fall, flow and surge deposits.

Tephra

A collective term for pyroclastic deposits that are predominantly unconsolidated.

Ignimbrite

The term "ignimbrite" has been employed to denote both the body and the type of deposit produced by what is inferred to have been a pyroclastic flow. Ignimbrites are commonly recognised by their extensive sheet-like distribution and lithological features. They consist of pumice, crystal, glass shard and rock (lithic) fragments, which are often poorly sorted. The term "ignimbrite" is used regardless of the degree of welding, compaction or secondary crystallisation which may also be diagnostic properties. The term "lenticulite" is used to describe a part of an ignimbrite which is characterised by flattened pumice fragments (lenticles).

Some complementary terms for ignimbrite are ash-flow tuff and welded tuff but are not used here.

Sheet

An unspecified sheet-like unit or group of units which comprise an ignimbrite.

Cooling Unit

A single or multiple pyroclastic flow deposit that can be shown to have undergone continuous cooling is a cooling unit. The cooling history of the unit may have been essentially uniform, but not interrupted to the extent that one part cooled completely before another was emplaced on top of it.

Simple Cooling Unit

Single or multiple pyroclastic flow deposits that have an essentially uninterrupted cooling history. Such units remain either non-welded and non-crystalline during cooling or form a pattern of textural zones.

Deuteric Alteration

Alteration which occurs after emplacement of ignimbrite sheets during the cooling period and results in the ionic transfer and exchange of elements between the hot fluid phase and the unstable volcanic glass. The zones of devitrification, vapour phase crystallisation and fumerolic activity in ignimbrite cooling units are products of deuteric activity.

Grain Size Terms

The definition of grain size terms used to describe the lithology of ignimbrites in this study are based on the recommendations proposed by the International Union of Geological Sciences (Table 1.1).

Table 1.1 Granulometric classification of pyroclasts and of unimodal, well-sorted pyroclastic deposits (after Schmid, 1981).

Clast size (mm)	Pyroclast	Pyroclastic deposit	
		Mainly unconsolidated: Tephra	Mainly consolidated: Pyroclastic rock
	Bomb, block	Agglomerate, bed of blocks or bomb, block tephra	Agglomerate, pyroclastic breccia
64 mm			
	Lapilli	Layer, bed of lapilli or lapilli tephra	Lapilli tuff
2mm			
	Coarse ash grain	Coarse ash	Coarse (ash) tuff
1/16 mm			
	Fine ash (dust grain)	Fine ash (dust)	Fine (ash) tuff (dust tuff)

Poorly sorted pyroclastic deposits such as ignimbrites which contain pyroclasts of more than one dominant size fraction should be named by using an appropriate combination of terms cited in Table 1.1 (Schmid, 1981).

Examples:

ash - lapilli tuff	(lapilli > ash)
lapilli - ash tuff	(ash > lapilli)
lapilli tuff - breccia	(lapilli - blocks)
ash - lapilli tuff - breccia	(lapilli > ash - blocks)

CHAPTER TWO

STRATIGRAPHY OF THE WESTERN MAMAKU PLATEAU

2.1 MAPPING METHOD

Field mapping was carried out from December 1980 to March 1981. Aerial photographs with scales of 1:18,300 and 1:25,000 were used to locate an outcrop. These outcrop sites were then transferred to a 1:25,000 metric base map with a 20m contour interval. The geological map was drawn at a scale of 1:20,000. The map pocket in this thesis contains three maps. Map 1 gives all site localities examined and indicates the coverage given to the mapping exercise. Some localities are referred to in the text. Maps 2 and 3 show relief and geology respectively. The relationship between geological contacts and contour heights show a parallelism typical of ignimbrites and can be appreciated by comparing Maps 2 and 3.

2.2 STRATIGRAPHIC CHANGES AND USAGE

A new stratigraphic column is erected for the ignimbrites and intercalated sediments of the western Mamaku Plateau (Fig. 2.1, in back pocket). Two new ignimbrites were identified and given locality names; the Waihou Ignimbrite and the Waimakariri Ignimbrite. They are separated from each other and from the Whakamaru and Mamaku Ignimbrites by erosional unconformities and therefore may be assigned formation status.

In Fig. 2.2, a comparison is made between the new ignimbrite stratigraphy with that previously established for the Tirau-Putaruru-Tokoroa areas by Healy *et al.* (1964). Their established lithostratigraphic nomenclature is generally adopted in this study although geological mapping has affected some major changes to the stratigraphy and to the spatial distribution of the formation boundaries. In particular, the Puketoka Formation that was mapped in the western Mamaku Plateau by Healy *et al.* (1964) is now redefined. They adopted this formation name from Kear (1960) to define rocks exposed mainly along the western edge of the Hauraki Plains. Kear and Schofield (1965) define the Puketoka Formation as "well sorted

Fig. 2.2 Comparison of stratigraphy

Healy *et al.* (1964)	This study
Hinuera Formation Mamaku Ignimbrite	Hinuera Formation Mamaku Ignimbrite
not recognised	Waimakariri Ignimbrite Waihou Ignimbrite
Puketoka Formation	sediments
Whakamaru Ignimbrite	Whakamaru Ignimbrite
Waiotapu Ignimbrite	not found
Marshall Ignimbrite	not found
Pakaumanu Group (Ahuroa Ignimbrite)	Pakaumanu Group (Ahuroa Ignimbrite and Ongatiti Ignimbrite)

light grey to white pumiceous clays, sands, and breccias and unsorted beds that are probably the distal portions of ignimbrites". The Formation is thickest near the Morrinsville Gap and Healy *et al.* (1964) extended it from there into the Hauraki Depression.

The area that was mapped as "Puketoka Formation" is now recognised to include Whakamaru, Waihou, and Waimakariri Ignimbrites and intercalated fluvial sediments. The Puketoka Formation, as such, is not recognised in the study area.

The major mapping changes effected in this study from the formations mapped by Healy *et al.* (1964), (Fig. 1.5) are:

(1) the Ahuroa and Whakamaru Ignimbrites have a greater outcrop area.

(2) The areal distribution of the Mamaku Ignimbrite has slightly diminished.

The thickness of the rock unit mapped as Waihou Ignimbrite and interbedded sediments is not always accurately expressed on the geological map (Map 3). This is because the unit is usually too thin to be represented. However, the fact that it thickens appreciably in some areas, and crops out frequently, permits the unit to be mapped. The Hinuera Formation represents a thin veneer of sediments and is mapped in the study area as terraces or flood plains adjacent to stream channels. It is not intended in this study to describe this formation in detail.

2.3 STRATIGRAPHY

The Pakaumanu Group consists of the Rangitoto, Ongatiti, Waipari, Ahuroa and Rock Hill Ignimbrites (Blank, 1965). Only the Ongatiti and Ahuroa have been found in the study area.

2.3.1 ONGATITI IGNIMBRITE

Age, source, distribution and correlation

This ignimbrite was named by Martin (1961) who found it to be one of the most widespread formations in the western King Country area. Healy *et al.* (1964) assigned the Ongatiti to the Lower Pleistocene but the Ignimbrite is now considered to be of Middle Pleistocene age on the basis of Kohn's (1973) fission-track date of about 0.75 m.y.B.P.

The source of the Ongatiti Ignimbrite was suggested by Blank (1965) to be southwest of the Rangitoto Range and east to northeast of the Hauhungaroa Range, i.e. approximately 65 km south of the study area.

The Ongatiti flowed west into the King Country region and north into the Karapiro-Arapuni area where it is very thick (about 50 m) and strongly welded (Olissoff, 1981). It also extended into the Hauraki Depression where drill-cores suggest it is widespread not far below the surface (Cuthbertson, 1981).

Only two outcrops of the Ongatiti Ignimbrite occur in the study area, one near the Gun Club (Locality 211), and the other off Leslie Road (Locality 47 and 48). Recognition and correlation of the Ignimbrite across the Tokoroa Plateau are based on the following characteristic features:

(1) it has a similar lithology to the Ongatiti in the Karapiro-Arapuni region.

(2) it has a high (*c*.16%) phenocryst abundance.

(3) it lies stratigraphically below the Ahuroa Ignimbrite.

(4) it has a coarse glass shard texture in thin-section.

(5) the large areal extent and distance travelled to form a welded ignimbrite (i.e. as far as Morrinsville), and the proximity to the Karapiro region indicate that it is likely to be present in the Mamaku Plateau.

A major problem concerning the identity of the Ongatiti Ignimbrite in the study area is the presence of biotite (Table 2.1). In both the Karapiro-Arapuni region and King Country, biotite is absent in modal, abundance (Blank, 1965; Olissoff, 1981). However, Olissoff did find traces of biotite in the third zone (Zone D) of flow in the lower unit of the Ongatiti Ignimbrite in the Karapiro-Arapuni region. The lower unit is not widespread in this area and it is possible that the zone containing biotite represents a different flow of the Ongatiti sequence which extends eastwards beneath the Mamaku and Tokoroa Plateaus (c.f. Smith and Bailey, 1966, p.91).

An alternative correlation could be with the Waiteariki Ignimbrite (*c*.0.84 m.y.B.P.), which forms the Whakamarama Plateau on the Kaimai Range. The lower lenticulite member is densely welded, dark grey and is overlain by an unwelded to weakly welded tuff breccia member (Cuthbertson, 1981). The Waiteariki Ignimbrite is crystal rich and the dominant phenocrysts are plagioclase and quartz, with hypersthene, augite and magnetite occurring throughout. Biotite is absent from the lower part but is present in the upper (Healy, 1967).

Further detailed petrological and field work is necessary of the Waiteariki Ignimbrite. For these reasons and those listed above in the study area the name "Ongatiti Ignimbrite" is preferred as the oldest ignimbrite in the study area.

Lithology

The Ongatiti Ignimbrite near Leslie Road (Map 3) protrudes from the valley floor as small knobs and a larger bluff (about 3 m high) of strongly welded, pinkish to purplish grey ignimbrite. The rock has a block, lapilli-ash texture of white glassy pumice. Block fragments are up to 210 x 190 x 120 mm in size, and the average size of the pumice lapilli is 10 - 20 mm. The pumice fragments are slightly oxidised to yellowish-brown to brown. In handspecimen both the pumice and matrix are phenocryst rich and consist of plagioclase, quartz, dark green hornblende, black hypersthene, magnetite and biotite flakes. Rock fragments are abundant and in particular large cryptocrystalline rhyolite fragments are conspicuous.

Near the Gun Club, a 7 m exposure of weakly welded ignimbrite (below a bluff of Ahuroa Ignimbrite, Fig. 2.3) has a brownish grey matrix with abundant white, pale orange and pink pumice fragments up to 100 mm in diameter. Most fragments average 10 - 20 mm in diameter. Some large pumice fragments have a vesicular swirl and tubular structure. Lithic fragments are scarce here.

Petrography

Specimens from the above localities and from the floor of the Lichfield Quarry have similar shard matrix characteristics, phenocryst abundance and mineral content (Table 2.1). Large (1.5 mm) euhedral crystals of biotite and hornblende look striking in their crystal-rich, yellow and brown vitroclastic matrix. The matrix is generally uncompacted (except for the Leslie Road sample) and comprises fine ash size particles, thick brown glass shards and abundant non-vesicular glass fragments with perlitic fracture.

Axiolitic secondary growth textures, which may occur along the margins of some pumice fragments, indicate incipient devitrification.

Contact relations and thickness

The Ongatiti Ignimbrite is unconformably overlain by the Ahuroa Ignimbrite near the Gun Club (Fig. 2.3; Map 3). Although the actual upper contact is not exposed, approximately 20 m away, the outcrop reveals a bed of indurated, fine sand which underlies the Ahuroa Ignimbrite (Fig. 2.4). Approximately 10 m further southeast, this sediment grades into a cross-bedded gravelly sand, indicating a fluvial deposit.

Table 2.1 Approximate average modal mineralogical abundances of the Ongatiti Ignimbrite. See Appendix 2.2 for detailed calculations

Locality	%	Matrix	Rock Fragments	Total Phenocrysts	Plagioclase	Quartz	Pyroxene	Opaques	Hornblende	Biotite
Leslie Road	W.R.	87	3	10	8	1	tr	tr	1	tr
	P				75	12	1	3	6	3
Waihou River	W.R.	83	1	16	14	tr	1	tr	tr	1
	P				84	2	3	2	3	6
Lichfield Quarry	W.R.	79	4	17	13	1	1	1	1	1
	P				79	3	5	3	6	4

W.R. = of whole rock; P = of total phenocrysts; tr = trace (<0.5%); matrix = pumice + shards; n.d. = not determined.

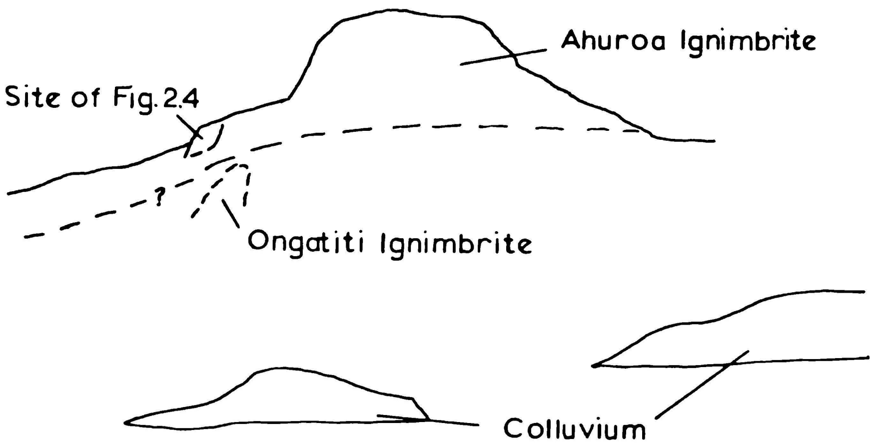


Fig. 2.3 Bluff (approximately 8 m high) of Ahuroa Ignimbrite near the Gun Club. Exposed below bushed area to the left of the bluff is the Ongatiti Ignimbrite (see sketch above).

The Ongatiti Ignimbrite is petrographically distinct from the Ahuroa Ignimbrite as it has a higher crystal abundance (*c*.16% c.f. 4%) and contains quartz and biotite.

The base of the Ongatiti is not exposed in the study area, and although the thickness cannot be determined directly, remnants of strongly welded ignimbrite off Leslie Road suggest a minimum thickness of about 20 m. Only a small remnant of poorly welded ignimbrite is now exposed. This paucity of exposure suggests that much of the Ongatiti Ignimbrite was eroded prior to subsequent ignimbrite emplacement.

Fig. 2.4 Ahuroa Ignimbrite overlying an indurated fine sand layer (contact, seen along hammer head, dips about 20^{o}N). Locality shown in sketch of Fig. 2.3. Height of outcrop = 5 m.

2.3.2 AHUROA IGNIMBRITE

Age, source and distribution

This is the next oldest ignimbrite of the Pakaumanu Group in the study area and is fission-track dated at about 0.65 m.y.B.P. (Kohn, 1973). It was named by Martin (1961) who distinguished two lenticul members. Later, Blank (1965) discerned the lower, middle and upper members of the Ahuroa Ignimbrite in the King Country. Blank describes the middle member as a pumice breccia sheet. Olissoff (1981) refers to this member as the "black sandy basal unit" or the "basal breccia" of the Upper Ahuroa Ignimbrite, in the Karapiro-Arapuni region. The upper member is a lenticulite.

Blank (1965) suggests two separate source areas for the Ahuroa Ignimbrite. The lower member is limited in extent and probably has a source north of the Rangitoto Range, and from there it spreads to the west and south. The middle and upper members probably erupted from a source east of the Maraeroa Plains (about 55 km southwest of the study area). They extend westwards beyond Waitomo and northwards to Arapuni (Olissoff, 1981). Within the Hauraki Lowland, Cuthbertson (1981, fig. 2.6) shows an ignimbrite resembling the Ahuroa as eroded collapsed pinnacles along the Firth of Thames Fault.

The Ahuroa Ignimbrite in the study area is exposed mainly on the western side of the Waihou River. Patchy occurrences in the Purere and Waipare streams suggest that the Ignimbrite was originally more widespread than shown by Healy *et al.* (1964).

Lithology

The exposed surfaces of bluffs in the area have a 1 - 3 mm thick case hardened crust of siliceous cement. The characteristic textural feature of the middle member of the Ahuroa Ignimbrite is the large (e.g. 280 x 40 mm, 100 x 200 mm) platey, orange to yellow pumice. These have a delicate tubular structure. The matrix is a dark grey to blackish fine-vitric ash (glass shards) which comprises up to 70% of the fragmental composition. The other 30% is made up of 15% pumice lapilli and 15% pumice blocks. Crystal and lithic fragments are scarce.

The best outcrops of the Ahuroa Ignimbrite occur near the Gun Club (Fig. 2.3 and 2.4), and Whites Road. At outcrops near the Gun Club the middle "basal breccia" member grades into the upper lenticulite (Fig. 2.5). The upper lenticulite is more strongly welded and the pumice lenticles are wispy and impart a eutaxitic texture. The lenticules are generally inconspicuous due to the uniform pinkish grey rock colour.

Petrography

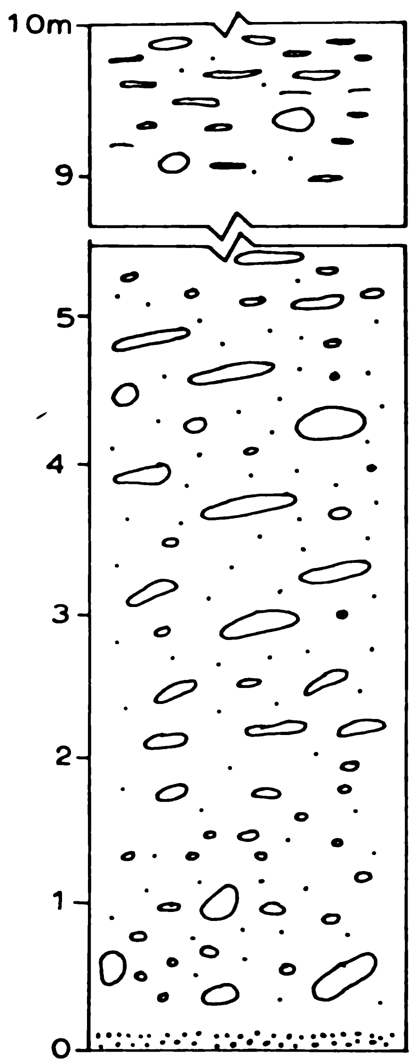
The Ahuroa Ignimbrite is rich in glass shards but poor in crystal and lithic components (Table 2.2). A moderate amount of pumice fragments are present which are of two types:

(1) those that have remnant gas bubble and co-existing large tubular cell structures.

(2) those that have a fine fibrous structure only.

The unbroken glass shards (i.e. those that show remnant gas bubble and cusp-shaped shards) may have thick walls which make up 40 - 50% of the shard matrix. Crystals of plagioclase and hypersthene are conspicuous in glomeroporphyritic clots in the pumice fragments. Hornblende, opaques and zircons are scarce, and quartz and biotite are absent. The rock fragments are small (*c*.5 mm in diameter) weathered fragments of andesite or rhyolite, greywacke (poorly sorted sandstone with anhedral cyrstals), and obsidian.

Vertical variations in fabric are due to compaction and welding. Near the base, the weak to moderately welded ignimbrite has an undeformed,



Upper lenticulite member

Strongly welded pinkish grey to blackened wispy lenticles, 1-3 cm long, 1mm thick. Eutaxitic structure. Undeformed pumice devitrified Platey joints.

Middle "basal" breccia member

Strongly welded, vertical joints

Large platey orange to yellow pumice fragments in blackish matrix showing flow alignment

Moderately welded.

White to yellow moderately abundant pumice (≈ 40 % 1cm Max. size 19x7cm Many block size pumice. Joints absent.

Iron cemented, crystal rich layer 1·5 cm thick.

Fig. 2.5. A generalised description of vertical variation in the Ahuroa Ignimbrite near the Gun Club.

Table 2.2 Approximate average modal mineralogical abundances of the Ahuroa Ignimbrite. See Appendix 2.2 for detailed calculations

%	Matrix	Rock Fragments	Total Phenocrysts	Plagioclase	Quartz	Hypersthene	Opaques	Hornblende	Biotite	Other
W.R.	96	1	4	4	-	tr	tr	tr	-	tr
P				88	-	4	4	n.d.	-	2

Abbreviations defined in Table 2.1

Table 2.3 Approximate average modal mineralogical abundances of the Whakamaru Ignimbrite. See Appendix 2.2 for detailed calculations

%	Matrix	Rock Fragments	Total Phenocrysts	Plagioclase	Quartz	Pyroxene	Opaques	Hornblende	Biotite
W.R.	84	tr	16	12	2	1	1	tr	tr
P				78	13	4	4	1	1

Abbreviations defined in Table 2.1

chaotically stacked shard matrix. The matrix becomes progressively packed with increasing thickness. By 8 - 9 m above the base the shards are deformed and stacked horizontally. However, the large platey pumice still retains a primary tubular cell structure which indicates that compaction was incomplete. The upper lenticulite member has strongly deformed shards and pumice, resulting in a wispy eutaxitic structure.

Field Relationships

The Ahuroa Ignimbrite crops out along a relatively straight NW-SE line along the Waihou River and changes to a N-S direction near the Water Wheel. In the Purere and Waipare Streams the Ignimbrite crops out 10 - 20 m up the valley sides. The paucity of exposures in the study area suggests that the Ignimbrite was severely eroded and possibly faulted before being buried by the Whakamaru Ignimbrite.

2.3.3 WHAKAMARU IGNIMBRITE

Age, source and distribution

The Whakamaru Ignimbrite was named by Martin (1961). Its source is thought to be from the Western Bays of Lake Taupo (Briggs, 1973). From here it flowed more than 90 km northwards into the Hauraki Depression and onto the western upland plateau (Fig. 1.4), which was constructed by the Pakaumanu Group ignimbrites in the Karapiro-Arapuni region. From its source it also flowed west and northwest through the Hauhungaroa Range to the lowlands between Taumarunui and Benneydale. In this area it is several hundred feet thick (Blank, 1965). Kohn (1973) gave a fission-track age of about 0.33 m.y.B.P. Healy (pers. comm. in Olissoff, 1981), suggested a revised date of 0.30 m.y.B.P.

Lithology

The Ignimbrite is typically pale grey to blue-grey, and moderately to strongly welded. It contains from 5% to 20% small (10 - 20 mm), white, vitric pumice fragments and the matrix is generally rich in crystals and lithics. Black biotite crystals are usually conspicuous and are a useful marker mineral of the rock. Occasional lateral variations of the Ignimbrite in the study area include very strongly welded crystal and shard-rich zones, and samples which are poor in pumice, lithics, and biotite.

Vertical variations in hardness, jointing and pumice type (Fig. 2.6) occur in the vicinity of the Water Wheel (Map 3). Near the base of the section, 150 - 200 m upstream, the blocky jointed rock contains relatively undeformed pumice. However, in the vertically jointed bluffs above this zone pumice fragments are scarce, but when present they are severely flattened. A sudden change to a densely welded ignimbrite (a 2 - 3 m thick zone) occurs approximately 20 m above the blocky jointed zone. This change is shown in the bulk density and porosity profiles in Fig. 2.6. The Ignimbrite at the top of this section contains fibrous pumice fragments. Devitrification is indicated by the presence of small granules . (<1 mm in diameter) in some of the pumice fragments.

Petrography

In thin-section the matrix of the Whakamaru Ignimbrite is brown and relatively rich in phenocrysts (*c*.16%) which consist mainly of plagioclase with lesser amounts of quartz, hypersthene, opaques, hornblende and biotite (Table 2.3). The matrix is dominated by fine grained (<0.2 mm) glass shards and flattening of these is a feature in strongly welded specimens. Pumice fragments are scarce and generally small (<7 mm in diameter) whereas the lenticles are up to 20 mm in length.

Vertical variations in the groundmass and texture of the Whakamaru Ignimbrite fall into three main categories. The following description is from the section in the vicinity of the Water Wheel.

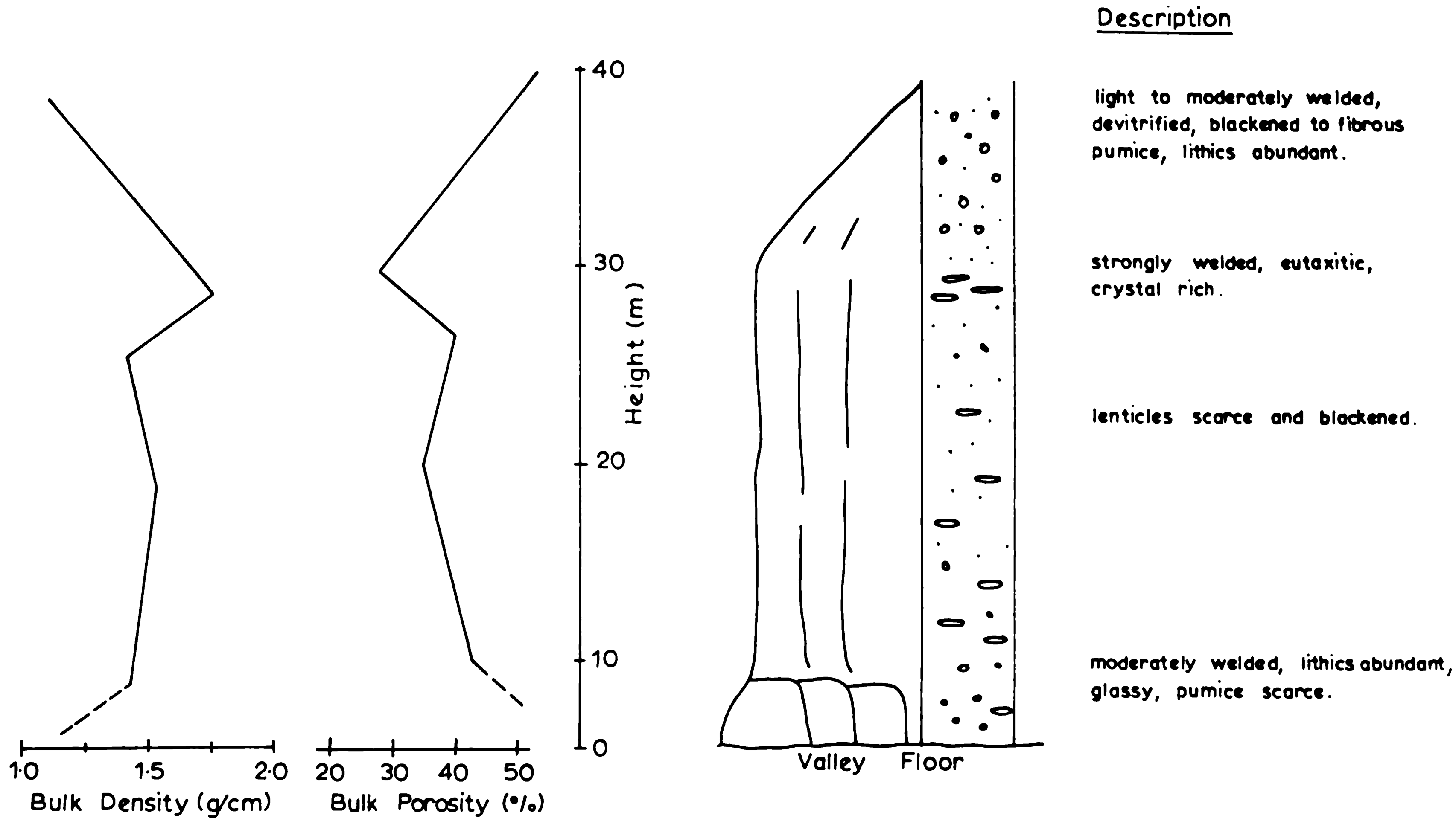


Fig. 2.6. Vertical variations in the Whakamaru Ignimbrite

(1) The rock of the blocky jointed basal zone has an open shard fabric. The glassy pumices have an undeformed cellular structure and fragments comprise 5 - 10% of the area of the thin-section.

(2) The rock of the vertical jointed zone has a low void space and the shard matrix is moderately to strongly compacted. The shard outlines are poorly defined and glassy. The pumice lenticles are scarce but when present, they are devitrified. Their internal structure or textures may be axiolitic, granular and spherulitic.

(3) The Ignimbrite at the top of the section has a void space (*c*.40 - 50%) and the shards are moderately consolidated. Approximately 50% (by area) of the shard matrix is devitrified as exemplified by the axiolitic structure in the shard fragments. Pumice fragments comprise 5 - 10% of the area of the thin-section.

Field Relationships

The Whakamaru Ignimbrite in the study area is usually found at valley floor level or up to 20 m up the valley sides. It is often exposed as hard, jointed bluffs (5 - 15 m high) or as undulating hills (section 1.3), whose shapes tend to reflect the relative hardness of the Ignimbrite.

The Whakamaru Ignimbrite is up to 30 - 40 m thick in the vicinity of the Water Wheel and overlies outcrops of the Ahuroa Ignimbrite. Towards Harris Road the Whakamaru Ignimbrite is widespread and thickens to more than 50 m.

Near the Water Wheel and at a locality 1.6 km upstream, bluff exposures of the Ignimbrite show vertical joints with 1 - 3 m spacing. This feature changes abruptly at the base of the bluff where a blocky, irregular joint pattern occurs (Fig. 2.7). This pattern is thought to be produced by cooling of the Ignimbrite in contact with a cold ground surface. This suggests that the base lies at shallow levels (*c*.5 m) below the valley floor. Contrast in the relative elevation of the blocky joint patterns near and upstream of the Water Wheel suggest that the Whakamaru Ignimbrite covered an eroded landscape.

Fig. 2.7 A typical exposure of the Whakamaru Ignimbrite showing upper vertical and lower blocky joint patterns, and pale grey to blue grey colour. The blackening is a surficial algal growth. Height of face is about 4 m.

2.3.4 FLUVIAL SILTS, SANDS AND GRAVELS

General Description

Fluvial silts, sands and gravels are intercalated in many places between the Whakamaru and Waimakariri Ignimbrites. Only once were they seen between the Waihou and Waimakariri Ignimbrites. These sediments are probably a proximal correlative of the Puketoka Formation and occur over the whole study area varying widely in thickness and lithology (Fig. 2.8). Lateral changes in these lithologies are difficult to assess because of sporadic exposure. Contact relationships with ignimbrites are described in sections 2.3.5 and 2.3.6.

The lithologies have vertical and lateral erosive contacts with each other and do not occur in any regular or predictable stratigraphic pattern. Sedimentary cycles which fine upwards, like those commonly developed in alluvial sequences (Allen, 1965) do not appear to occur in the study area. This random pattern of sedimentation is also a common feature of the well studied Late Pleistocene Hinuera Formation in the South Auckland region (Hume *et al.*, 1975).

Based on bulk texture two broadly defined lithofacies occur:

(1) Scour-and-fill deposits of grey to white cross-bedded sands and gravelly sands. Massive to planar bedded sandy gravels and gravelly sands form the thickest (up to 12 m) lithology and are most common in the northwestern part of the study area (e.g. on Whites Road, Fig. 2.9). Here, large boulders and rhyolitic gravels are evidence of a high bedload and high flow competence.

(2) The main lithofacies consists of massively bedded, sometimes normally graded pumiceous, sandy silts and silty sands. They often form buttresses in the more swampy areas. At some localities the sediments are less indurated and may have thin interbedded layers of clays, silts and fine to medium sands. Lithics and pumice gravels are generally scarce.

Vertical sequences of these sediments are described in detail in Appendix 2.3.

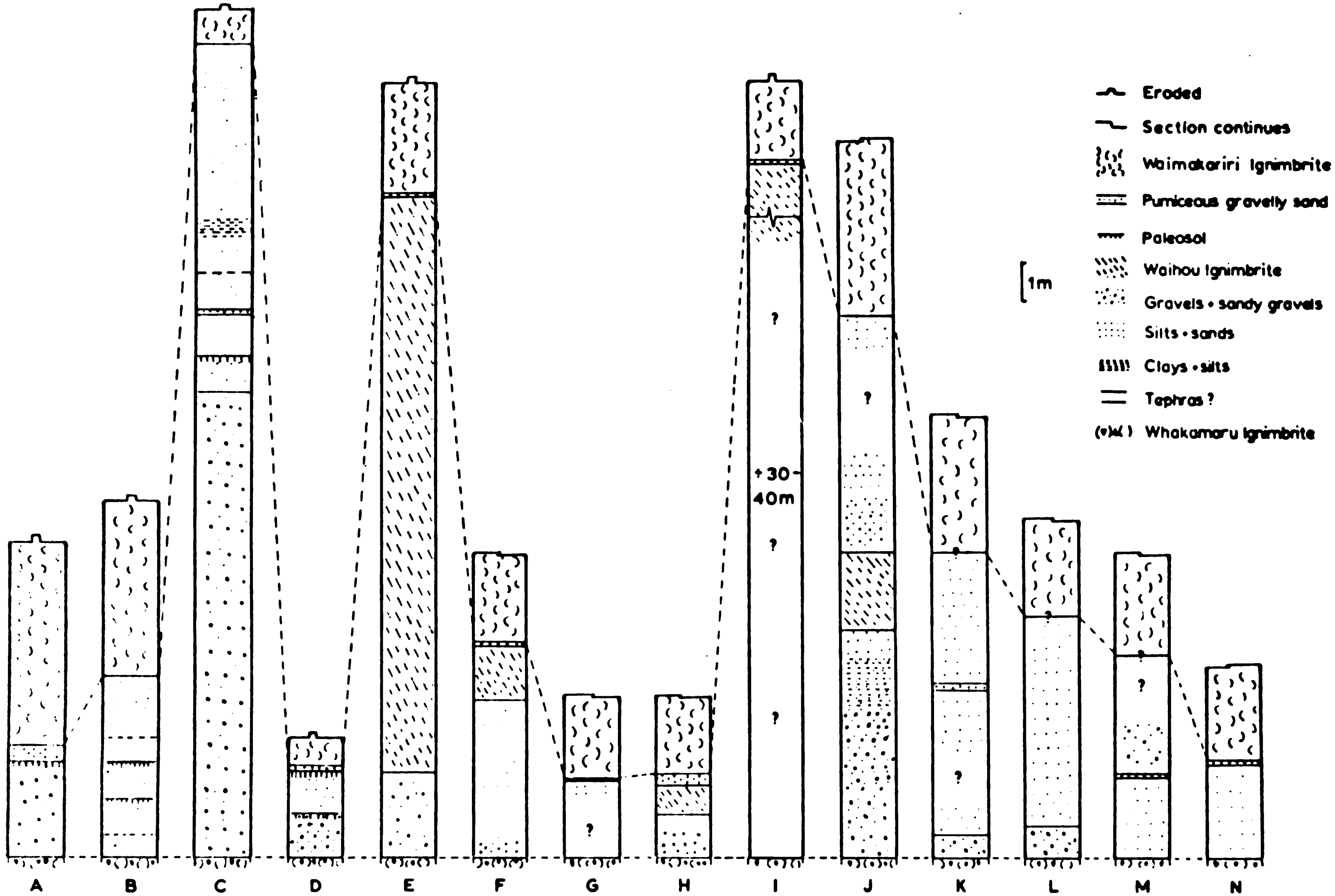
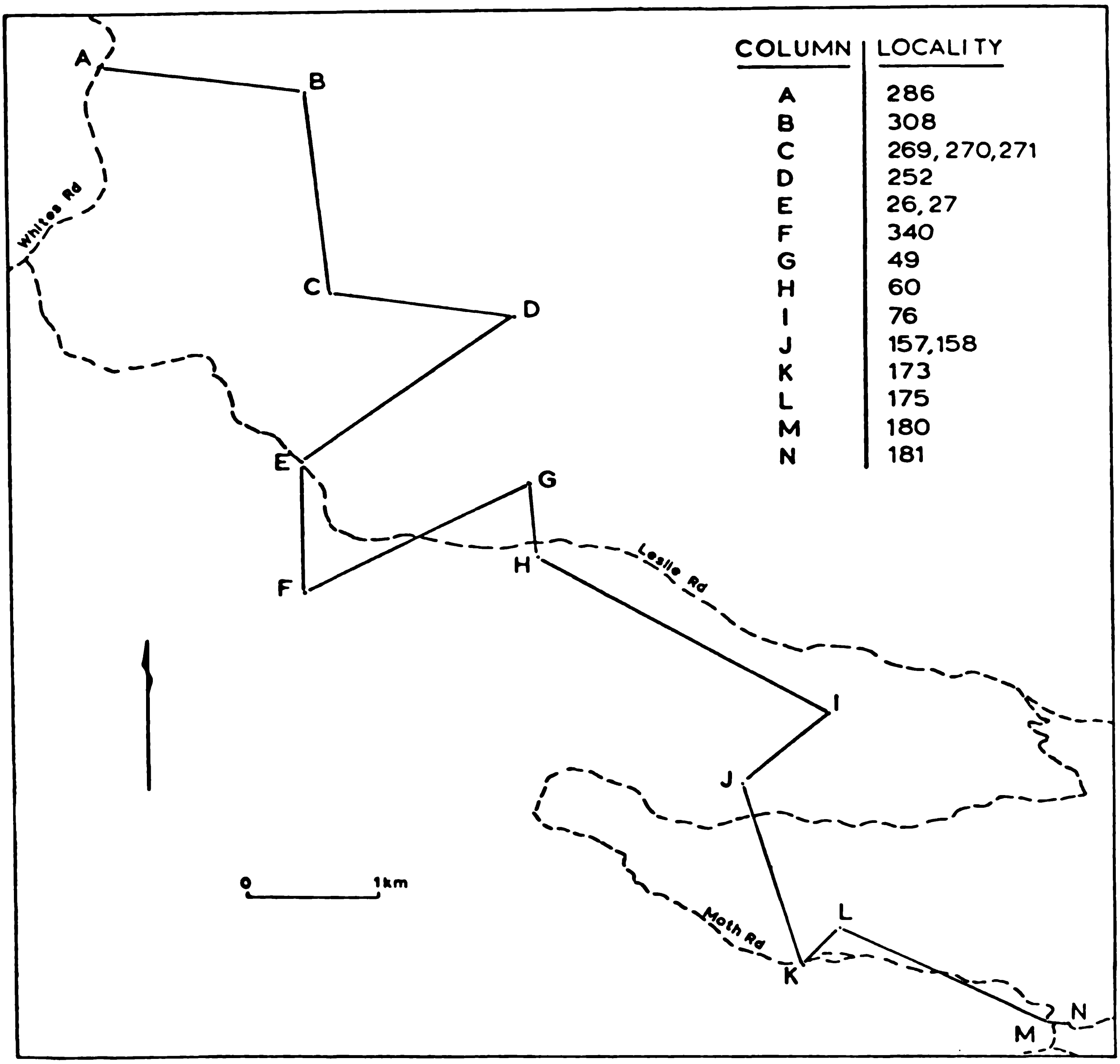


Fig. 2.8. Generalised stratigraphic columns of the sediment / ignimbrite relations in the western Mamaku Plateau. Location map overleaf.



Location map of stratigraphic columns in Fig. 2.8.

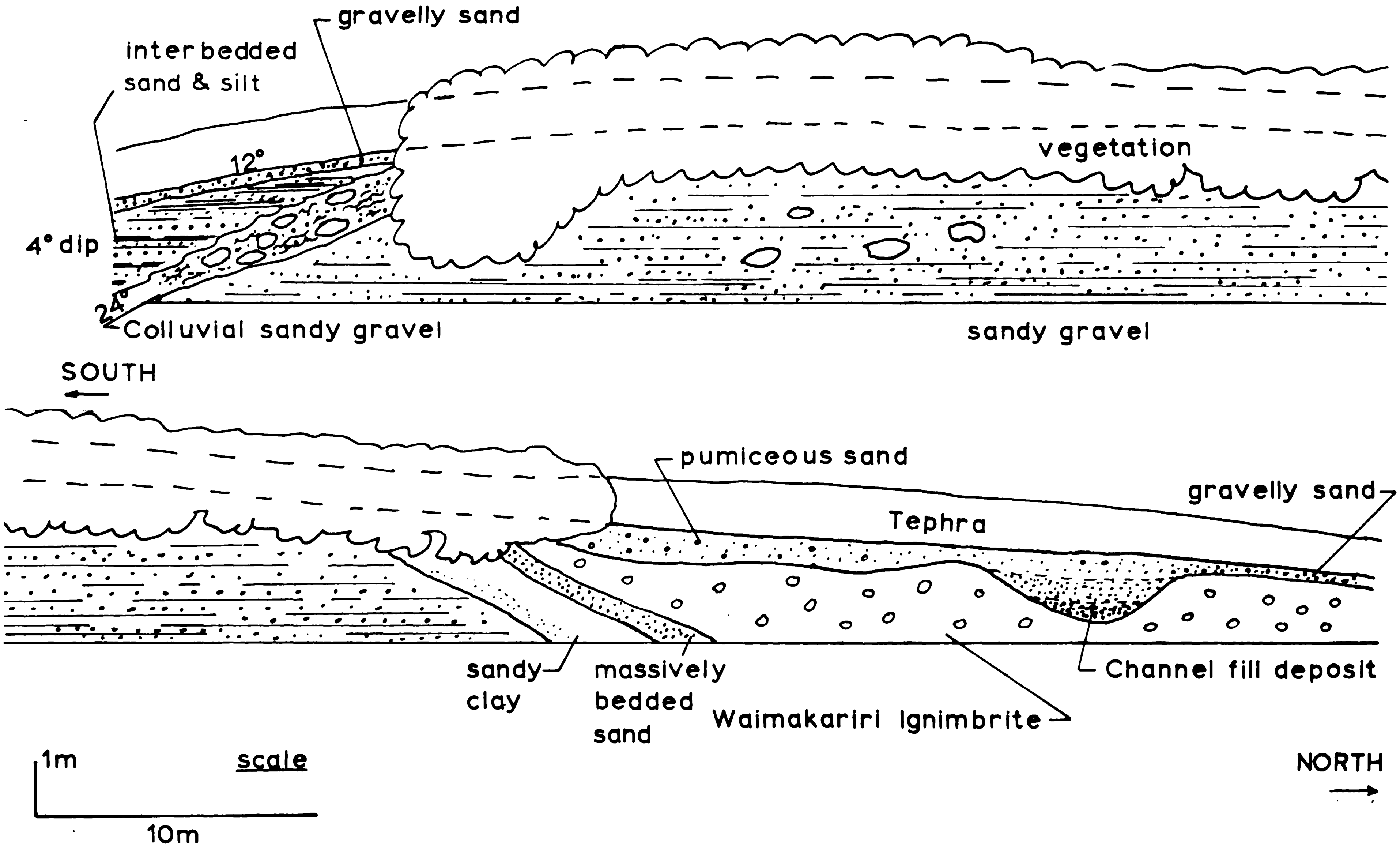


Fig. 2.9. Stratigraphic relation of a coarse grained (sandy gravel) lithofacies with the Waimakariri Ignimbrite at locality 249.

Paleoenvironment

The fine-grained lithofacies are typical of overbank sediments of flood plains. Allen (1965) indicates that interstratification of coarse with fine overbank sediments are found throughout the topstratum of flood-plains lacking clear environmental subdivisions (e.g. an alluvial ridge). The scour-and-fill deposits are characteristics of stream channels and indicate bedload transport.

A paleorelief relief map (Fig. 3.1) shows that the northwestern part of the study area was a basin. The surface of this basin had apparently little change in relief. The valleys of an eastern paleoplateau (Fig. 3.1) probably fed drainage waters to the basin. At times of high rain-fall, accumulating waters flooded the area depositing thin layers of pum-iceous sediment derived from the Whakamaru and Waihou Ignimbrites. Fine grained lithologies were probably deposited from suspension away from the main river channels.

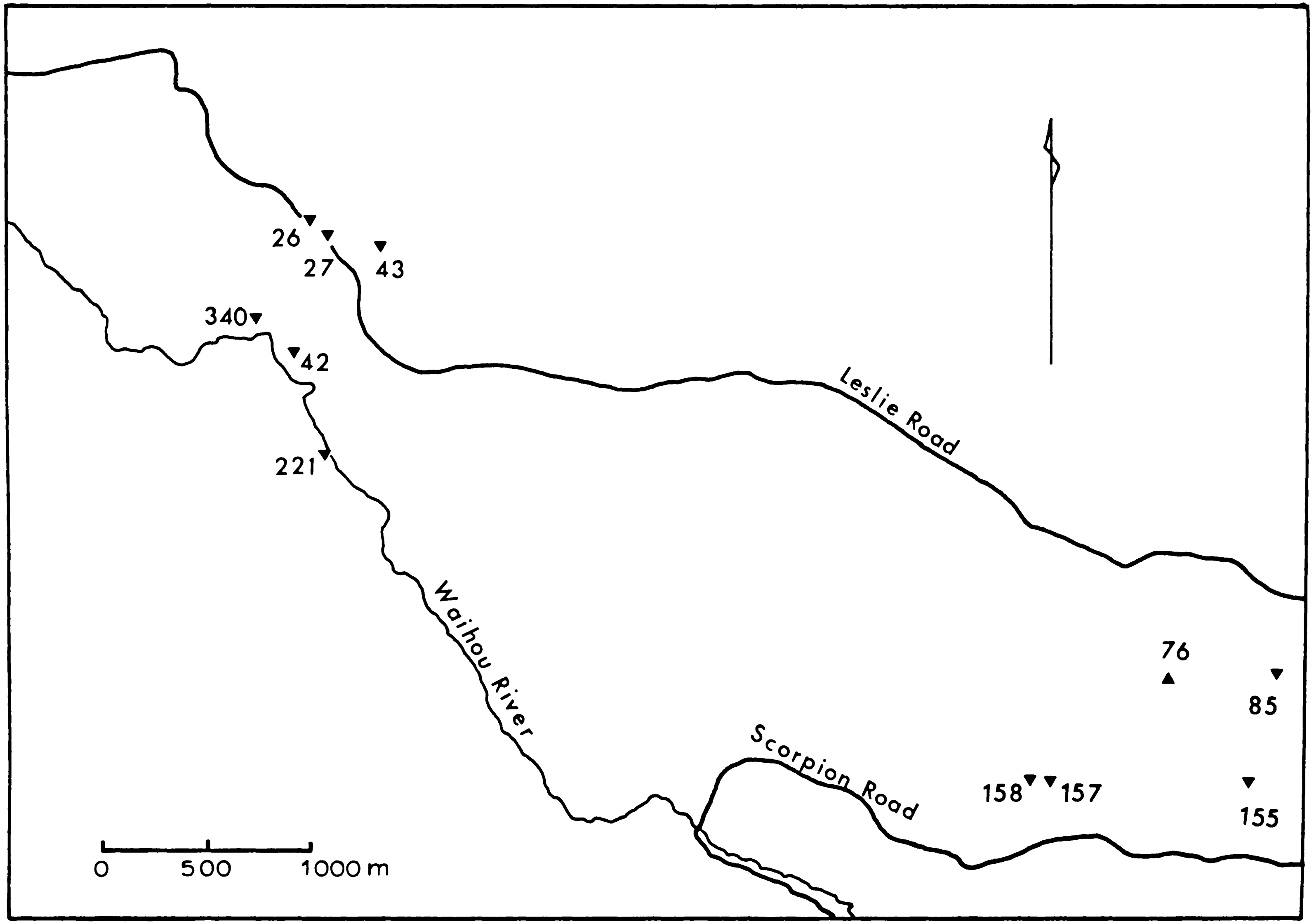
2.3.5 WAIHOU IGNIMBRITE

Age, source and distribution

The Waihou Ignimbrite is recognised as a new formation in the western Mamaku Plateau and it is separated from older and younger ignimbrites by erosional unconformaties and sediments. The Ignimbrite's age is unknown but it was emplaced between 300,000 and 140,000 years ago (Fig. 5.2).

The source of the Waihou Ignimbrite is inferred from field evidence to be from the Rotorua or Okataina Volcanic Centres. Although the Ignim-brite is poorly exposed, small outcrops occur in two areas (Fig. 2.10). Near Scorpion Road the Ignimbrite outcrops at higher elevations (220-250m) than in the Leslie Road area (elevation 140-150 m) situated about 3 km to the northwest. Ignimbrites have a tendency to flow into topographic depressions (Walker *et al.*, 1980a), and it is thought that the Waihou Ignimbrite behaved similarly. The contrast in elevation between the two

Fig.2.10 Site locality map for exposures of the Waihou Ignimbrite.



areas suggests a source to the east or southeast of the study area - probably towards Rotorua. From there it flowed northwestwards over relatively high ground and was funnelled into valleys (Fig. 3.1).

Lithology

The type locality for the Waihou Ignimbrite is at Locality 26 (Fig. 2.10) on Leslie Road. The Waihou Ignimbrite is a poorly welded, friable, creamy-whitish grey vitric ignimbrite bearing white pumice which often has a delicate fibrous structure. The pumice lapilli average 40 - 60 mm in size and give the Ignimbrite its coarse appearance. The matrix is relatively poor in crystals. Plagioclase crystals are predominant and up to 3 mm long. Small (*c*.1 mm), dark, elongated mafic minerals are also conspicuous.

Vertical variations in size and abundance of the pumice fragments occur at Locality 43 (Fig. 2.11). At least two upward coarsening sets are present which suggests that there are two or more flow units present. Reverse grading of pumice clasts in ignimbrites is documented by Sparks *et al.* (1973) and Sparks (1976). They suggest that a coarse pumice zone often marks the top of a pyroclastic flow.

A sudden change in pumice content was seen near the base of the Ignimbrite (Locality 340), (Fig. 2.12). The Ignimbrite consists of a pumice breccia in which the fine ash particles are scarce (<5%). This lithology is similar to the "fines-depleted ignimbrite" described in the Taupo Ignimbrite by Walker *et al.* (1980b).

Petrography

The Waihou Ignimbrite consists of undeformed glass shards which show remnant bubble wall structure. Generally the pumice fragments have a fine wispy fibrous habit, sometimes with distorted swirl structures. Non-vesicular glass fragments also occur. The Ignimbrite is generally crystal,

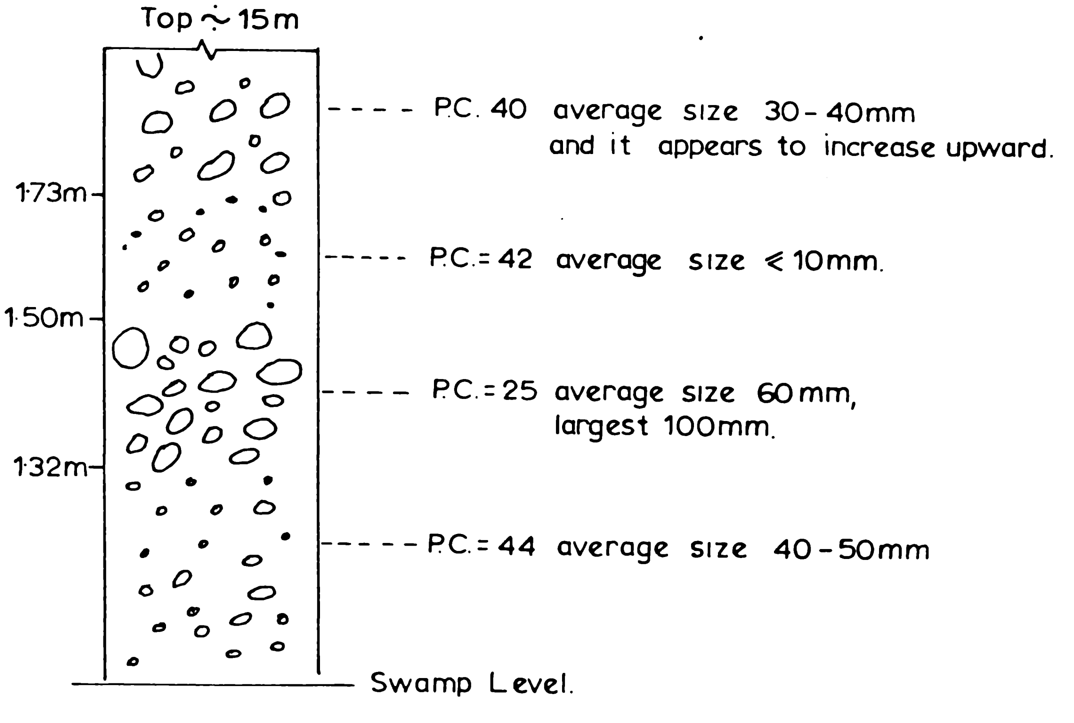
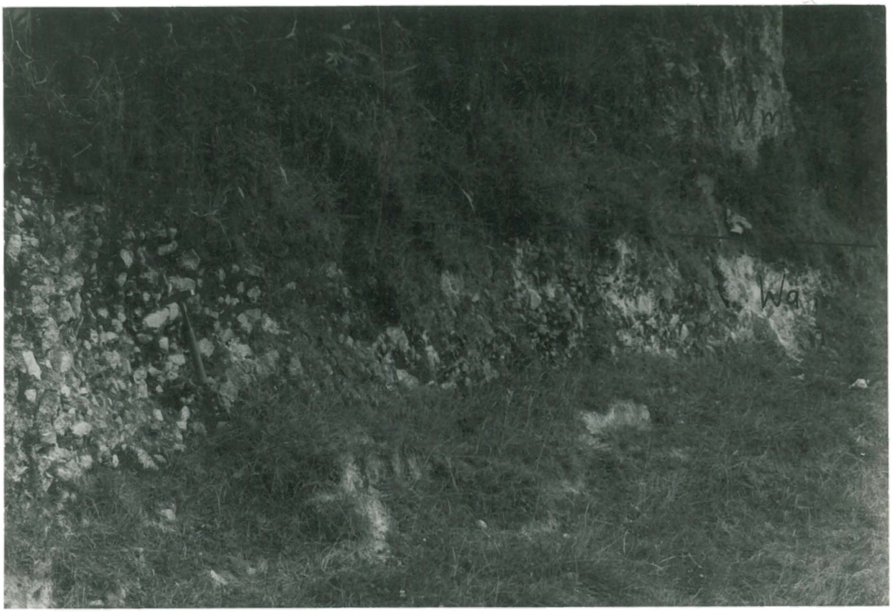


Fig. 2.11. Vertical variation of pumice fragments in the Waihou Ignimbrite. P.C. = Pumice counted in a representative 15 x 50cm area.



A

B

Fig. 2.12 (A) Basal pumice breccia zone (<1 m thick) of the Waihou Ignimbrite. Exposed in cliff face above vegetation is the Waimakariri Ignimbrite.

(B) Detail of the Waihou Ignimbrite - breccia variant. Hammer is 300 mm long.

and lithic-poor (Table 2.4), and consists predominantly of plagioclase, with trace amounts of quartz, hypersthene, opaques and very small (<0.25 mm) crystals of hornblende and probably biotite (<0.25 mm). Quartz crystals are highly resorbed and some pyramidal forms are present. The plagioclase, hypersthene and opaques are mainly of subhedral to euhedral form. The hypersthenes have jagged terminal faces and these crystals may be intergrown with plagioclase.

Field Relationships

Only two basal contacts of the Waihou Ignimbrite are exposed in the study area. One occurs on Leslie Road (Locality 27; Column E, Fig. 2.8) and the other can be seen in a valley which lies along the north side of Scorpion Road (Locality 158; Column J, Fig. 2.8). The Ignimbrite overlies fluvial sediments which in turn overlie the Whakamaru Ignimbrite. At the latter locality these sediments change vertically in lithology and grade upwards from cross-bedded sandy gravels into laminated clays and silts, and then to gravelly sands (Fig. 2.13). The actual contact of the Waihou Ignimbrite and sediments here may represent only a short hiatus between deposition of the two strata. The sediments at the contact are not weathered.

Elsewhere the basal contact is hidden in seepage-swamp systems. These commonly occur in small recesses carved into the slope 10 - 20 m above, or at valley floor level. The recesses have a head wall cut in the Waimakariri Ignimbrite which often directly overlie the Waihou Ignimbrite (Fig. 2.12A). The fluvial sediments which underlie the Waihou or Waimakariri Ignimbrites commonly protrude from the swamps as buttresses 1 - 2 m high. These buttresses consist of indurated, massively bedded, silty or fine sands (Section 2.3.4).

Table 2.4 Approximate average modal mineralogical abundances of the Waihou Ignimbrite. See Appendix 2.2 for detailed calculations

%	Matrix	Rock Fragments	Total Phenocrysts	Plagioclase	Quartz	Hyperstene	Opaques	Hornblende	Biotite
W.R.	93	2	4	3	tr	tr	tr	tr	tr

Abbreviations defined in Table 2.1

Table 2.5 Approximate average modal mineralogical abundances of the Waimakariri Ignimbrite. See Appendix 2.2 for detailed calculations

%	Matrix	Rock Fragments	Total Phenocrysts	Plagioclase	Quartz	Hyperstene	Opaques	Hornblende	Biotite
W.R.	90	tr	10	8	1	tr	tr	tr	tr
P				86	6	4	4	n.d.	n.d.

Abbreviations defined in Table 2.1

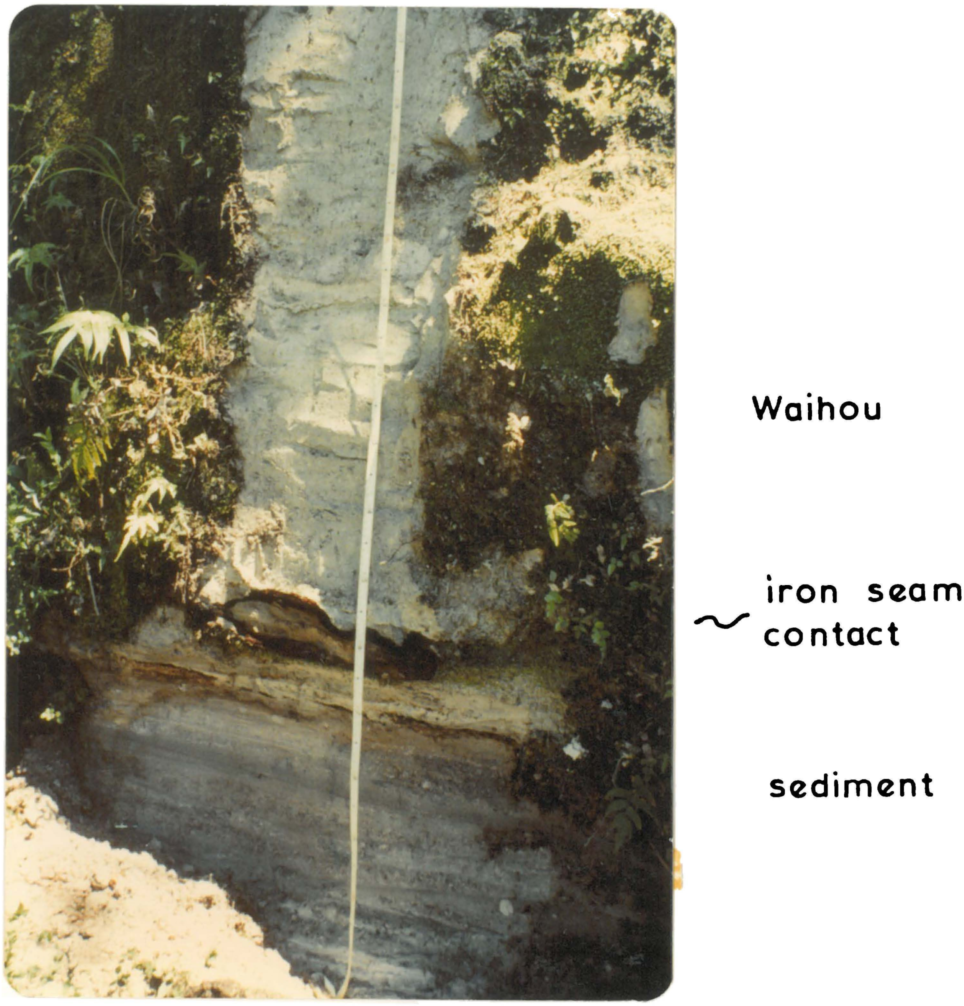


Fig. 2.13 The basal contact of the Waihou Ignimbrite with fluvial sediments is sharply defined by a black-red iron cemented seam. The Waihou Ignimbrite is white, poorly sorted and slightly cohesive. Height of section is about 1.5 m. Locality 158.

Variations in thickness and basal elevation of the Waihou Ignimbrite in the Leslie Road area indicate that it flowed over an eroded surface cut into the Whakamaru Ignimbrite, and was itself later eroded. On Leslie Road (Locality 26 and 27) the Waihou Ignimbrite is about 10 m thick. However, 200 m eastwards (Locality 43), about 15 m is exposed in the lower half of a cliff section, and the basal elevation is approximately 20 m lower. This thickening is attributed to burial of a small valley by flows of the Waihou Ignimbrite (Fig. 2.11). This valley "ponding" feature is clearly evident from outcrops along the Waihou River (Localities 42, 221, 340). The Ignimbrite is about 2 m thick and occurs about 20 m below the top of the Whakamaru Ignimbrite which crops out as cliffs nearby. This relationship suggests that a valley (or basin) existed prior to the emplacement of the Waihou Ignimbrite. Further evidence is indicated by the presence of a basal breccia zone (Fig. 2.12A). Walker *et al.* (1980b) suggests that these ignimbrite lithologies indicate a part of the pyroclastic flow travelled turbulently. Turbulent flow in the Waihou Ignimbrite probably resulted from movement along the side of a valley.

2.3.6 WAIMAKARIRI IGNIMBRITE

Age, source and distribution

The Waimakariri Ignimbrite is found throughout most of the study area. It is thicker and more voluminous than the Whakamaru or Mamaku Ignimbrites. Investigations outside the study area indicate that the Waimakariri Ignimbrite is very extensive. It extends northwards beyond State Highway No. 5., and southwards into the Te Whetu area. I have also recognised the Ignimbrite on the basis of similar lithology and field relationships in the Lower Kaimai-Omanawa area (Fig. 1.1).

The gradual thickening of the Waimakariri Ignimbrite to the east suggests that its source lies in that direction, probably beneath the Mamaku Ignimbrite or in the Rotorua or Okataina Volcanic Centres (refer to Field Relationships).

The age of the Ignimbrite is not known. However, it is not much older than the Mamaku Ignimbrite (*c*.0.14 m.y.B.P.), (Fig. 5.2). Field relationships indicate that the plateau surface of the Waimakariri was only weakly dissected and was devoid of vegetation at the time of emplacement of the Mamaku Ignimbrite.

General lithology

Case hardening of naturally cut cliff faces is common although the Ignimbrite is friable and weakly welded. This gives some of the cliff faces a massive appearance. Moderately to strongly welded Ignimbrite is characteristic of the thicker and jointed parts, and there the pumice fragments may be slightly lenticular and blackened. Pumice fragments protrude from the outcrop face. Nonwelded parts of the Ignimbrite form steep (30 - 50^{o}) slopes.

The rock is pinky-white to yellow or brown and very pumiceous. However, the lapilli fraction only accounts for 20 - 30% of the material and blocks 0 - 10%. The remainder is ash, of which 60 - 80% is pumice (analysis from sieved fractions).

The block pumice is up to 200 - 300 mm long. The lapilli vary in size and shape and are white to fawn and sometimes blackened. They predominantly have a fibrous vesicular structure. Crystals of plagioclase occur in glomeroporphyritic clots. Quartz, hypersthene and opaques are less abundant, and biotite flakes are scarce.

Lithic fragments are common and average <10 mm in size, but clasts up to 70 mm in diameter occur. They consist mainly of rhyolite, but andesite and greywacke fragments are also present.

Weathered outcrops of the upper portion of the Waimakariri Ignimbrite have an orange matrix with orange or brown and grey pumice fragments.

Variations in Lithology

The Waimakariri Ignimbrite sometimes has a distinct separate basal layer in which the size and abundance of pumice fragments varies. Three main lithologies are recognised and referred to here as Type A, B and C (Fig. 2.14). Type A is a "normal ignimbrite" where all pumice clasts (>2 mm) are matrix (ash) - supported (Sparks, 1976). Type B is a basal layer in which the ignimbrite is enriched in fine constituents (lapilli <4 mm, ash), and resembles layer 2a of Sparks *et al.* (1973). Reverse grading may occur and lithics are scarce. Type C is a breccia which

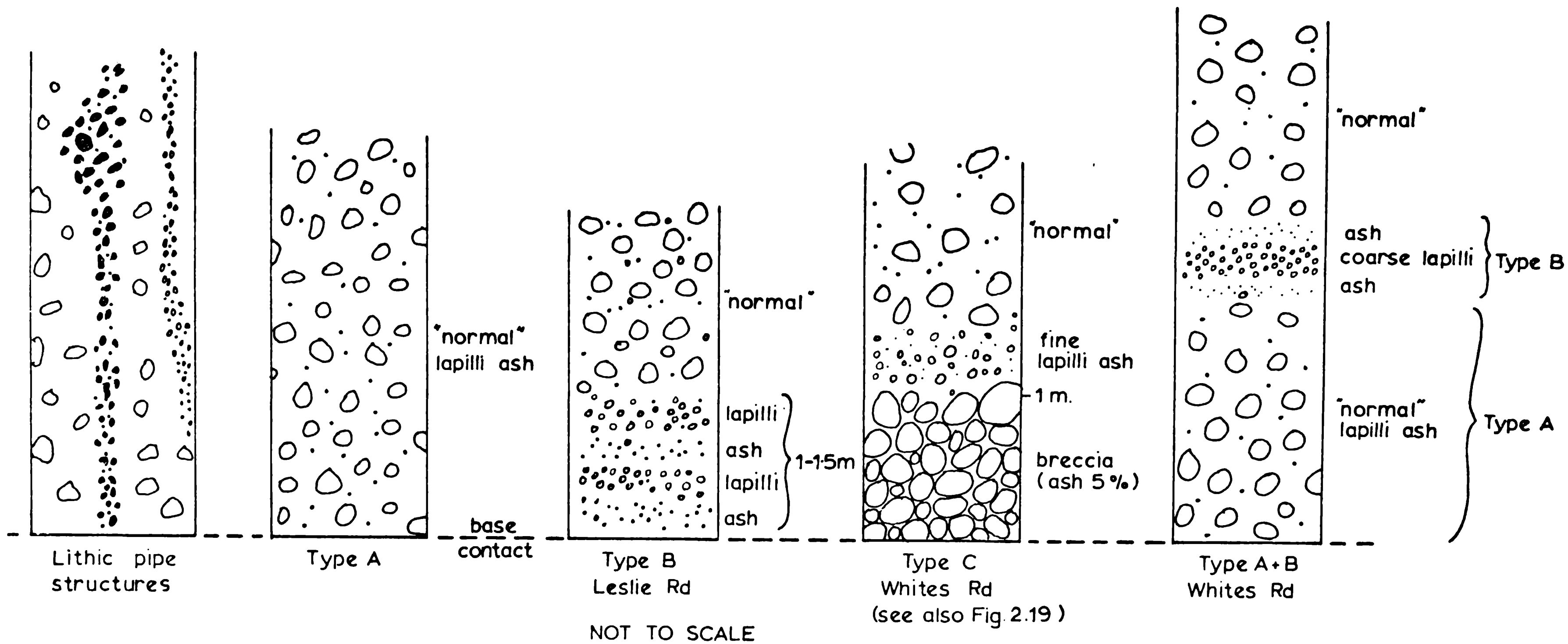


Fig. 2.14. Variations in pumice size and abundance of the Waimakariri Ignimbrite. Types defined in text.

resembles the "fines depleted ignimbrite" variant of Walker *et al.* (1980b). A variation of Type A and B is also shown.

The basal zones are laterally discontinuous, vary in thickness and occur sporadically. However, Type B appears to be common in the north-western half of the study area. Type C is similar to the breccia zone of the Waihou Ignimbrite, and is seen only once (in the Waimakariri) on Whites Road (Fig. 2.19). Lithics are scarce within these basal zones. This is in contrast to the lithic rich basal zones that are a characteristic of many pyroclastic flow deposits (Walker, 1972). Concentrations of lithics, which form small diapiric pipe-like sturctures, are rarely found in the body of the Waimakariri Ignimbrite (Fig. 2.14).

Petrography

Under the microscope the matrix is a chaotic mixture of crystals, shards, vitric dust particles, pumice and brown non-vesicular glass fragments. Thick accumulations of vitric dust surround the pumice fragments and this tends to enhance their outer cuspate structure. Where there are phenocrysts the vesicles are spherical, but otherwise they are tubular. Some phenocrysts are encased by pale-brown non-vesicular glass which explains their blackened appearance in handspecimens (refer to lithology). The small pumice fragments are ovoid to rectangular in shape and often have frayed ends.

The Waimakariri Ignimbrite is phenocryst poor and consists of plagioclase, quartz, hypersthene, opaques, hornblende, biotite, zircon and apatite (Table 2.5, p.43). Plagioclase crystals are abundant (up to 4 mm long), hornblende and biotite are scarce (up to 0.6 mm in length), and quartz, hypersthene and opaques are common (up to 2 mm in size). Hypersthene, magnetite and plagioclase are commonly intergrown and contain inclusions of hornblende, zircon, apatite and glass. The mafic minerals are often slightly oxidised along fractures and around crystal margins. Resorption embayments often occur in quartz phenocrysts, but are scarce in plagioclase, hypersthene and opaques. Biotite occurs frequently as star-like intergrowths.

Field Relationships

The Waimakariri Ignimbrite is prominent only in the deeply cut valleys as buff coloured cliffs 20 - 40 m high which have sets of vertical joints spaced 2 - 3 m apart (Fig. 2.15).

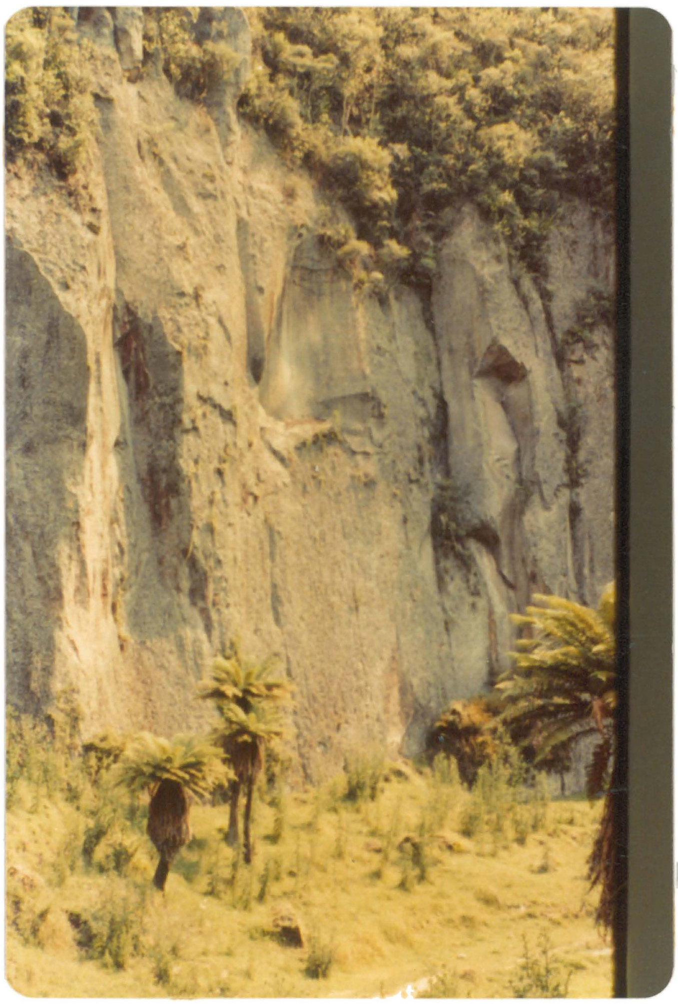


Fig. 2.15 Cliff (30 - 40 m high) of Waimakariri Ignimbrite showing characteristic features of yellow colouring, wide joint spacing and rough surface appearance (from protruding pumice). The narrow joints in the rock at the top of the cliff is the basal portion of the Mamaku Ignimbrite.

The Waimakariri Ignimbrite is thickest (approximately 80 m) near the pump house (Waihou River), although the thickness varies widely because the surface over which it flowed had considerable relief. In the vicinity of the Water Wheel the Ignimbrite is about 15 m thick and covers a hill of Whakamaru Ignimbrite. A gradual thinning to the west is apparent, but towards the interior of the plateau it averages 60 - 70 m in thickness. This suggests the source lies to the east. In the study area this ignimbrite forms one eruptive unit or sheet, as is evident from the absence of any distinct depositional breaks, tephra deposits or repetitive coarsening upward trends of pumice fragments.

The basal contact of the Waimakariri Ignimbrite is often indicated by the occurrence of seepage-swamp systems situated on the valley side or floor. This ignimbrite is usually underlain by fluvial sediments (Fig. 2.16), which are porous and serves as an aquifer for water which discharges into the swamp. This geo-hydrological relationship is a useful criterion for field mapping.

In many instances the underlying fluvial sediments are absent because of erosion and the Waimakariri Ignimbrite directly overlies the Waihou Ignimbrite. When seen together in sequence these two ignimbrites could be interpreted as separate flow deposits from a single volcanic event, but this must be precluded since, apart from their distinctive colouration (Fig. 2.17) and pumice structure, they have been observed as separate units with weathered sands and silts intercalated between them (Column J, Fig. 2.8; Fig. 2.18). This indicates that an interval of time must have elapsed between the emplacement of these two ignimbrites, during which erosion and deposition of sediments occurred.

A pumiceous gravelly sand (or lapilli-ash) layer is an important commonly occurring marker bed which underlies the Waimakariri Ignimbrite (Fig. 2.17). This layer is yellow to brown, poorly sorted, and is variable in thickness but averages 50 - 80 mm.

The contact between this sand and the Ignimbrite may bear an iron pan a few millimetres thick, and the sand layer is often oxidised due to iron precipitation.

The pumiceous gravelly sand layer is thought to be a layer 1 "ground surge" deposit similar to that documented by Sparks *et al.* (1973), (Fig. 5.18). Wilson and Walker (in prep.) divide the layer 1-type deposit into two variants. One consists of almost pure pumice (layer 1(P)), and the other of pure lithics and crystals (layer 1(H)). The pumiceous gravelly sand closely resembles the layer 1 (P), which has the following features:

(1) it is poorly sorted.

(2) it is depleted in fine (ash) constituents when compared with the Waimakariri Ignimbrite.

(3) it shows irregular lateral variations of thickness.

(4) it occurs at different elevations, indicating that it was deposited over undulating topography.

The layer is dissimilar to that described by Wilson and Walker, in that lithic clasts and fragments of carbonised vegetation are scarce. The pumiceous gravelly sand is often defined by an erosive contact (Fig. 2.17) which is attributed to shearing and scouring by the Waimakariri Ignimbrite as it flowed over this layer. Evidence for shearing is seen on Whites Road (Locality 286) where the pumiceous gravelly sand has been scoured and disrupted and is set in a fine ash matrix that is part of the Waimakariri Ignimbrite (Fig. 2.19). That the sand layer is missing from some localities (e.g. Fig. 2.18) suggests this was due to non-deposition or to penecontemporaneous erosion possibly by the Waimakariri Ignimbrite.

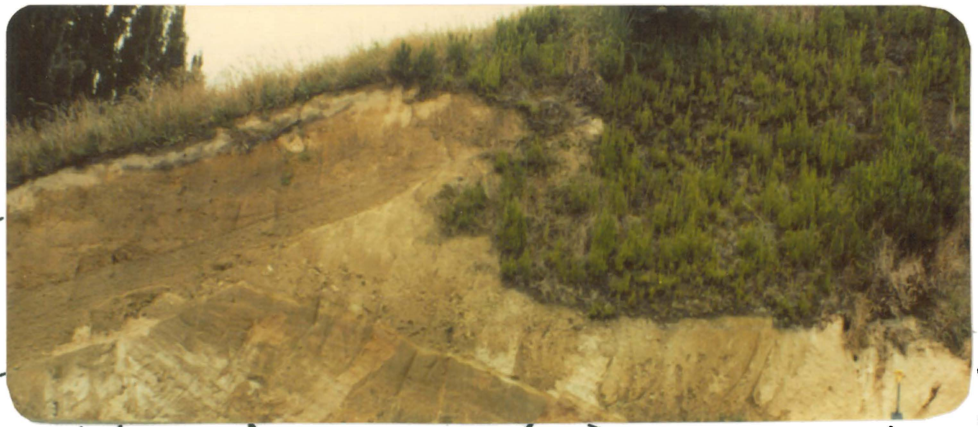


Fig. 2.16 Stratigraphic sequence exposed on Whites Road (Locality 250) showing Waimakariri Ignimbrite overlying sediments (slightly weathered at top) which dip 20°SW. These deposits are faulted against Whakamaru Ignimbrite.

Fig. 2.17 Stratigraphic sequence exposed on Leslie Road (Locality 26) showing erosive contact between the Waihou Ignimbrite (lower) and pumiceous gravelly sand (80 mm thick) and Waimakariri Ignimbrite (upper). A lapilli-ash layer (2a) is also pictured (see also Fig. 2.14).

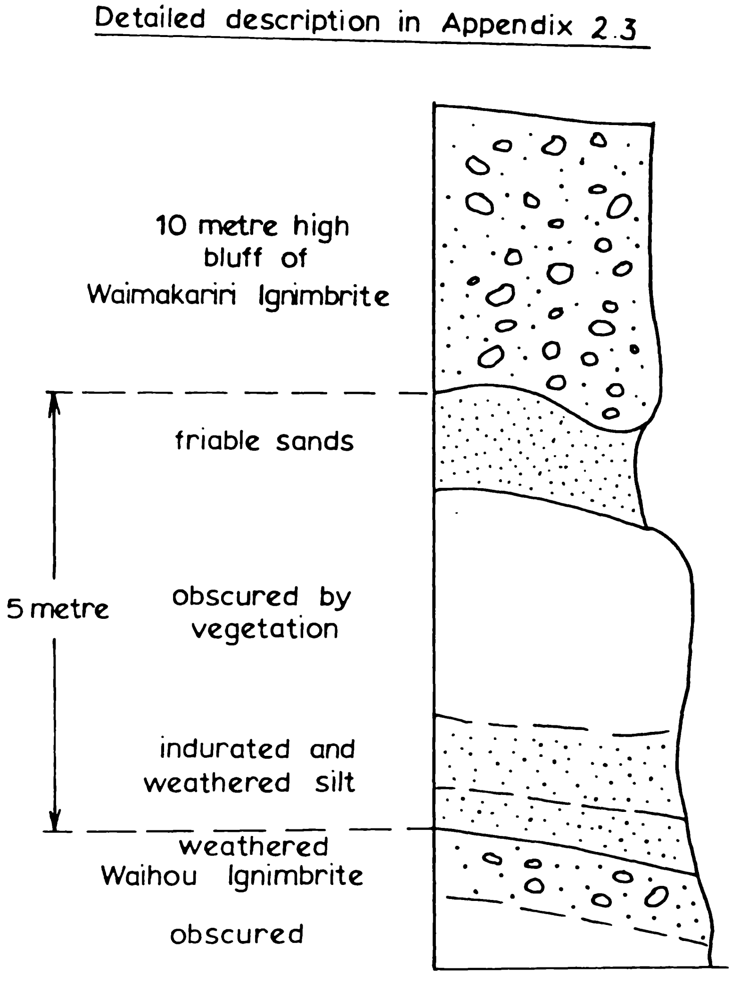


Fig. 2.18. Schematic section of locality 157 showing sediments intercalated between the Waihou and Waimakariri Ignimbrite.

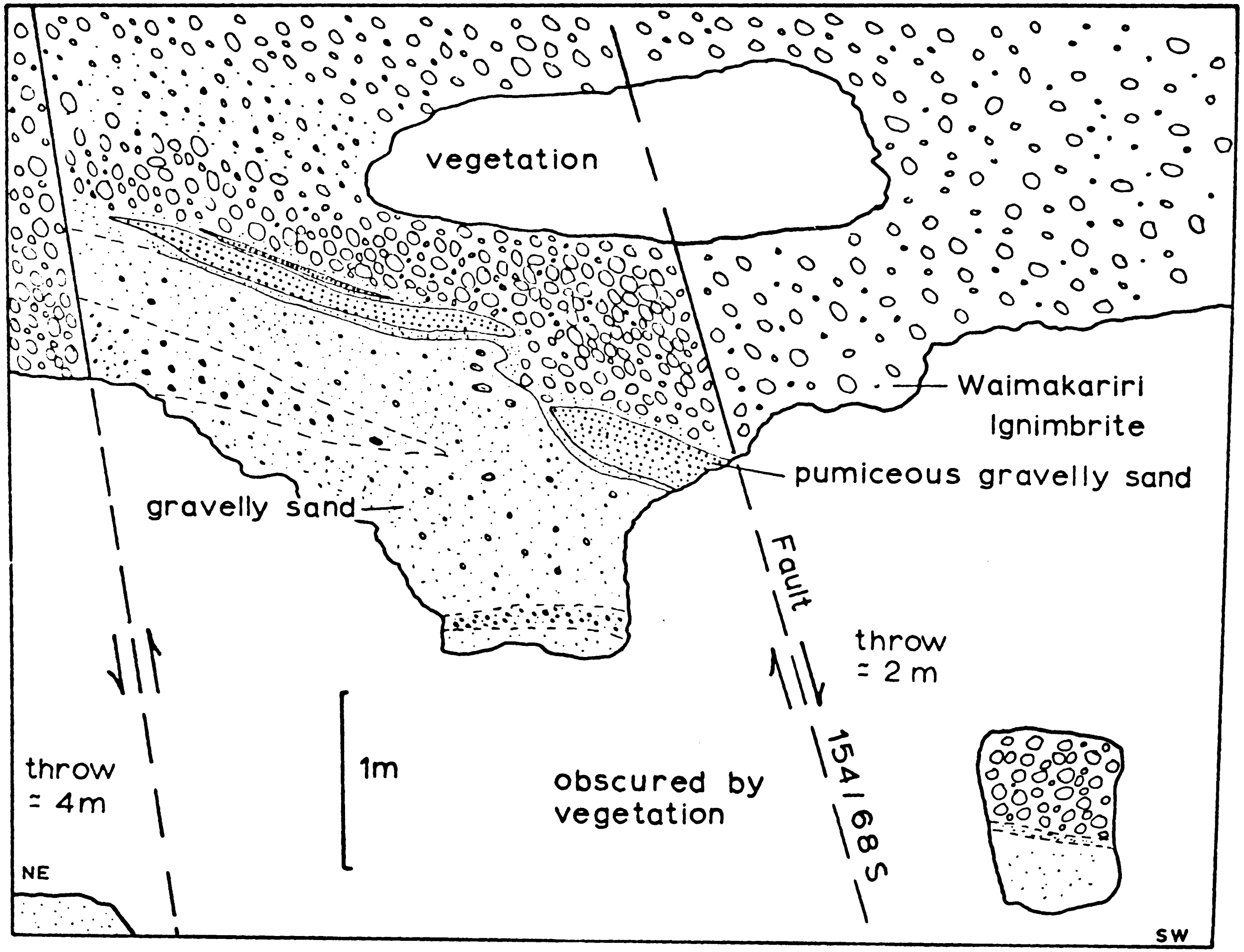


Fig. 2.19. Sketch of relations between pumiceous gravelly sand set at the base of the Waimakariri Ignimbrite which forms an erosion contact with overlying sediments.

2.3.7 COMPARISON OF THE WAIMAKARIRI WITH OTHER IGNIMBRITES

Within the study area the Waihou and Waimakariri Ignimbrites are stratigraphically distinct. Martin (1961) referred to them as tuffs and suggested that they may belong to the Whakamaru Ignimbrites. This interpretation is now changed as they are each separated by intervals of erosion and are likely to have erupted from a different source.

Investigations outside the study area have proved the Waimakariri Ignimbrite to be very extensive and that its source lies to the east, probably beneath the Mamaku Ignimbrite or the Rotorua-Okataina Volcanic Centres. It is likely, therefore, that the Waimakariri Ignimbrite occurs in other areas surrounding the source.

The Mamaku and pre-Mamaku Ignimbrites previously documented are compared and correlated on the basis of similarities in lithology and stratigraphic position (Fig. 2.20).

Lloyd (1965) described the Lower Mamaku Ignimbrite as having a grey-white to grey-brown colour and contains glassy grey or orange-brown pumice throughout. This Ignimbrite is separated from the Upper Mamaku Ignimbrite by an erosional unconformity represented by layers of sediment (Lloyd, 1965). On the basis of its similar lithology, and field relationships the Waimakariri Ignimbrite is considered correlated to the Lower Mamaku Ignimbrite.

In the description of the Lower Mamaku Ignimbrite, Lloyd states that at depths of 25 - 30 m below the top it grades into a hard grey lenticulite. On the basis of stratigraphic position and its distinctive lithology, Nathan (1975) correlated the Lower Mamaku Ignimbrite to his Unit D from the Kaharoa drill-hole (Fig. 1.1) and the Pokopoko Breccia in the Rotorua district. Nathan surmised that the Pokopoko Breccia, mapped by Thompson (1974), was a composite term for the pre-Mamaku

Fig. 2.20 Suggested stratigraphic correlations of the Mamaku and older ignimbrites. Location map: Fig. 1.1

Worker	This Study	Lloyd (1965)	Nathan (1975)	This Study	Thompson (1974)		Murphy (1977)	Dunham (1981)	Martin (1961)
Area	Western Plateau	Lower Kaimia- Omanawa	Kaharoa Drillhole	Kaituna-Rotorua District		Tureporepo Stm. Guthrie Region	Matahana Basin	Guthrie Region	West of Horohoro S.E. of Rotorua
Mapped Units	Mamaku	Upper Mamaku	Mamaku A B C	Sheet 2 Sheet 1	Mamaku	Mamaku	Mamaku	Mamaku	Mamaku
	Waimakariri Waihou Whakamaru	Lower Mamaku Waiteariki	Unit D	Lenticulite Unnamed Ign.	Pokopoko Breccia	Pokopoko Breccia	Unit D ? Marshall Lenticulite	Pumice Breccia ? Marshall	Atiamuri

ignimbrites. He notes that some outcrops (e.g. those around Lake Okareka) consist of soft unwelded pumice breccias. Therefore the stratigraphy and correlation of these pyroclastic deposits with the Waimakariri Ignimbrite has yet to be clearly established.

Murphy (1977) correlated his Unit D with the densely welded Pokopoko Breccia because of its similar lithology. Dunham (1981) made a correlation of a pumice breccia with Unit D from mineralogical similarities.

Martin's (1961) description of the Atiamuri Ignimbrite is similar to the Waimakariri Ignimbrite in this study. He also says that the Atiamuri Ignimbrite is similar to the distal parts of the Matahina Ignimbrite, and to the Taupaki member of the Marshall Ignimbrite. However, it is mineralogically distinct from both.

The Matahina Ignimbrite has a fission track age of *c*.0.2 m.y.B.P. (Murphy and Seward, 1981). Specimens from the thickest sections of the ignimbrite are dark grey to brown, and densely welded and devitrified (Bailey, 1965). The Matahina is further distinguished from the Waimakariri Ignimbrite by the lower phenocryst and plagioclase abundant and the slightly higher abundance of quartz (see Table B-G, Ewart, 1965a).

In the Kaituna-Rotorua region the Pokopoko Breccia (Fig. 2.20) is present only as a densely welded lenticulite. Thompson (1958) suggests that the upper part of this ignimbrite (present in the Te Akau 5 core, Fig. 5.1) was stripped by erosion. The high degree of welding of the Ignimbrite in this region compared to the Waimakariri in the western plateau supports the hypothesis that the source of these ignimbrites lies in the Rotorua area. However, because of the severely eroded state of the Pokopoko Breccia as compared with the poorly welded Waimakariri Ignimbrite, it is unlikely that the two are of the same age. The erosion of the Pokopoko Breccia would have taken much longer. Further research may establish if there is a possible relationship between the Pokopoko

Breccia and the lenticulite underlying the Marshall Ignimbrite of Murphy (1977), (Fig. 2.20).

2.3.8 MAMAKU IGNIMBRITE

Lithology

The Mamaku Ignimbrite in the study area is weak to moderately welded crystal-and-lithic poor, pumiceous pyroclastic flow deposit. It generally is pinkish grey to purplish grey with wide joint spacing.

The main body of the Ignimbrite consists of grey pumice fragments which often have a white rim. The pumice texture is a mass of soft granular aggregates (Fig. 2.21) which are a product of devitrification. Their internal arrangement appears to be governed by a relict tubular structure

Fig. 2.21 Pumice fragments in the Mamaku Ignimbrite showing distinct granular texture in contrast to the white fibrous-like matrix.

A subtle variation occurs in the size and abundance of pumice in the Ignimbrite (analysis of this is made in Chapter 4). Generally the average length varies between 20 and 70 mm with the maximum observed size of 100 x 140 mm (shown in two dimensions at vertical outcrops). The pumice shapes are commonly oblate to ovoid. Sub-lenticular shapes are abundant in the finer fractions and show sub-horizontal alignment in some parts.

Modal analysis of 5 specimens sampled from the Leslie Road section gives an average total phenocryst content of 9.7% (8.3 - 10.9%). Plagioclase comprises 82.2% of the crystals, quartz 7.4%, pyroxene 3.4%, opaques 6.6% with traces of biotite and hornblende. Detailed analysis of phenocryst variation is made in Chapter 4.

Lithic fragments are of a weathered reddish, lithoidal-type rhyolite which are up to 30 mm in diameter but commonly less than 10 mm and make up less than 1% of the total rock.

Throughout the Ignimbrite, large (2 - 10 m) clearly defined chimneys of deuterically altered rock occur randomly. They have a characteristic deep reddish-brown concentration of iron precipitates around the vertical joints intersecting them. The rock in these chimneys is more strongly welded than in the surrounding unaltered ignimbrite. This change is thought to be due to fumerolic activity in the Ignimbrite during cooling. These chimneys appear to be identical in many ways to the tors seen at the top of the plateau.

The jointing near the base is more closely spaced than the middle and upper parts of the Ignimbrite. Here the colour changes to a pale creamy pink or orange. The pumice fragments are purplish reddish brown. Deformed or lenticular pumice is seldom a prominent feature in outcrop. Lithic fragments are common (*c*.10%) in a 200 mm thick zone at the basal contact.

Field Relationships

The Mamaku Ignimbrite forms the upper surface of the plateau. It slopes gently westwards, and its even surface is dissected by valleys (Fig. 2.23). The interfluves are mantled by late Pleistocene tephras, the oldest of which is the Rotoehu Ash (*c*.42,000 yrs B.P., Pullar and Birrell, 1973). This view, however, is contrary to Vucetich and Pullar (1969) who describe (p.828) an older underlying "strong-brown, strongly weathered ash". Its origin is not here considered to be an airfall-tephra because the presence of rock fragments of the Mamaku Ignimbrite in the weathered "ash" suggests that it is actually the weathered surface of the Ignimbrite (Fig. 2.22). This paleosurface probably approximates the depositional slope and dips about 3° to the west.

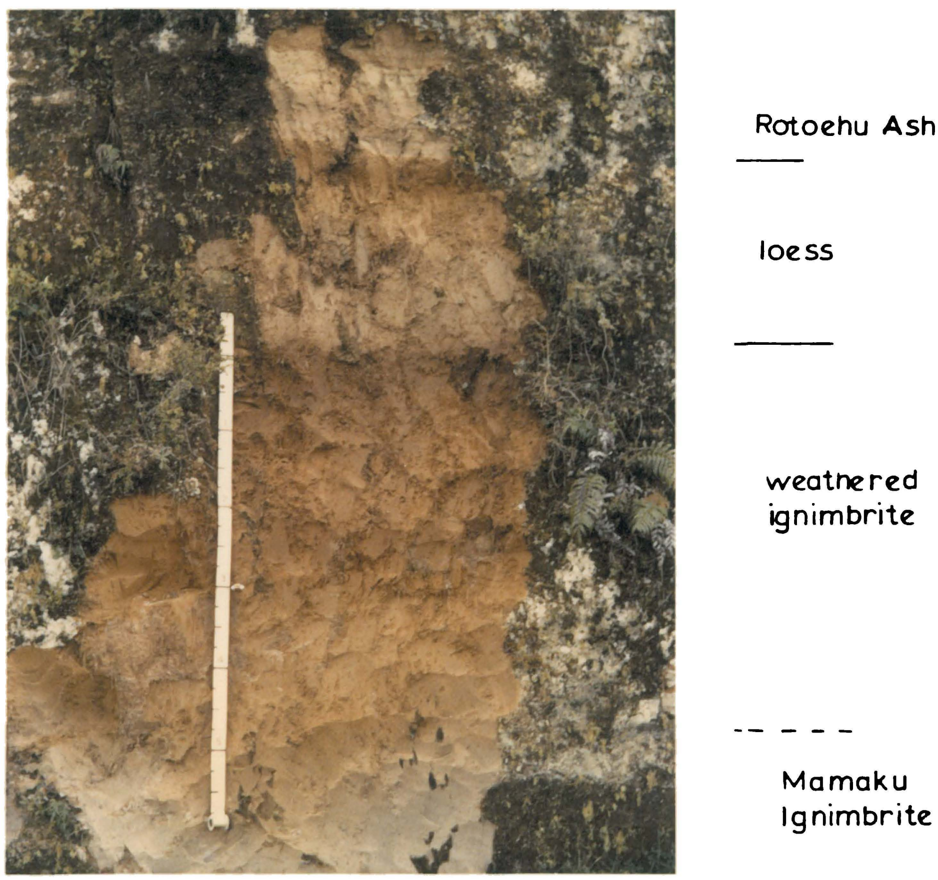


Fig. 2.22 Exposure on Leslie Road (Locality 1) showing weathered top of the Mamaku Ignimbrite overlain by slightly weathered loess and the Rotoehu Ash. Photograph by courtesy of J.D. McCraw.

Outliers of the Mamaku Ignimbrite occur at the western margin where adjacent valleys (e.g. the north and south Waihirere Stream valleys) cut into the flat-topped interfluves and coalesce and open into the plains. Towards the interior of the plateau, the interfluve surface becomes more undulating, giving rise to hummocks. It is suggested that the tops of these hummocks conceal the chimneys mentioned earlier and which may give rise to the tors at the top of the plateau.

The surface of the hummocks is covered by the distinctive pumiceous, orange Rotorua Ash (*c.*13,500 yrs B.P., Pullar *et al.*, 1973). The Mamaku Ignimbrite is clearly distinguished from the Waimakariri Ignimbrite by a break in slope along the basal contact zone. The base of the Mamaku Ignimbrite is often defined by short (3 - 5 m) vertical bluffs which are more strongly welded than the soft upper zone, and the lower Waimakariri Ignimbrite (Fig. 2.23).

The actual contact at the base of the Mamaku Ignimbrite is defined by a sudden change in pumice colour, texture and degree of weathering. The purplish grey granular textured pumice fragments of the Mamaku Ignimbrite is mixed with yellow to white fibrous pumice of the underlying Waimakariri Ignimbrite. In contrast, the top of the Waimakariri Ignimbrite is orange and has a more clayey consistency indicating slight weathering.

On Leslie Road (Locality 14), the unconformity between the two ignimbrites is sharply defined by a basal brecciated zone of the Mamaku Ignimbrite which overlies and laps against an undulating surface of the weathered Waimakariri Ignimbrite (Fig. 2.24). The reddening in this brecciated zone may be due to oxidation.

On Burma Hill Road (Locality 338) a nonwelded, vitroclastic, 3 m thick basal layer of the Mamaku Ignimbrite overlies a 50 - 100 m layer of coarse sand, bedded white silts and a chocolate brown indurated silt

Fig. 2.23 View of the even surface of the Mamaku Plateau in the Waihou Road valley looking southwest from Leslie Road. Note the abrupt break in the slope of the valley side due to bluffs of the basal portion of the Mamaku Ignimbrite (Mk) which overlie the Waimakariri Ignimbrite (Wm). Photograph by courtesy of J.D. McCraw.

(Fig. 2.25). Twenty metres up the road the basal layer grades suddenly into Ignimbrite which is strongly welded, jointed, and devitrified. It is likely that the vitroclastic basal layer is more extensive in the southern part of the study area. The basal layer was not seen north of Orion Road.

The linear outcrop pattern of the basal portion (Fig. 2.23) indicates that the Mamaku Ignimbrite flowed over a relatively smooth and gently westward sloping surface dipping 3 - 4^{o}. From a thickness of about 80 m near the eastern boundary of the study area, the Ignimbrite gradually

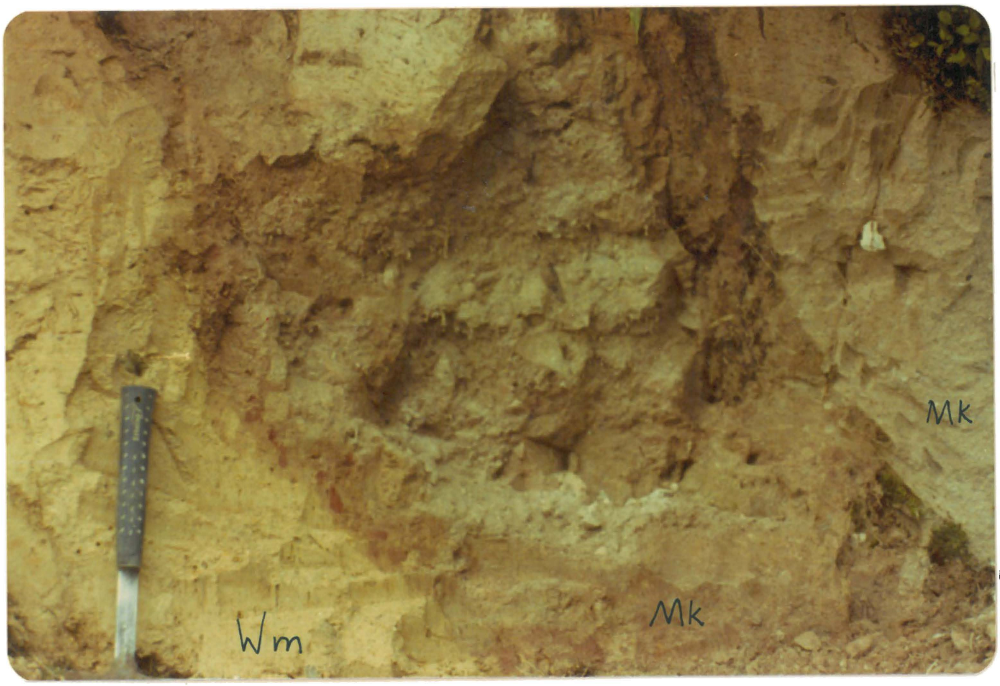


Fig. 2.24 Basal contact of the Mamaku Ignimbrite (brecciated and slightly reddened) against the Waimakariri Ignimbrite (pale yellow rock). Hammer is 300 mm long. Photography by courtesy of R.M. Briggs.

thins out to an average thickness of approximately 20 m at the edge of the sheet in the west.

2.3.9 COVER DEPOSITS

Cover deposits are defined as being younger than the Mamaku Ignimbrite. They consist of the Late Pleistocene to Holocene tephras and loess sequences, colluvial and alluvial sediments. Detailed stratigraphic description or mapping, other than of terraces comprising the Hinuera Formation, was not undertaken. Tephra formations were only examined where they could provide some chronological control. The recognition of the tephra beds is based on characteristics described by Vucetich and Pullar (1969), Pullar and Birrell (1973), and Hodder and Wilson (1976). A summary of the tephrostratigraphy of the Putaruru area is given in Fig. 2.26, and is complemented by Fig. 2.22.

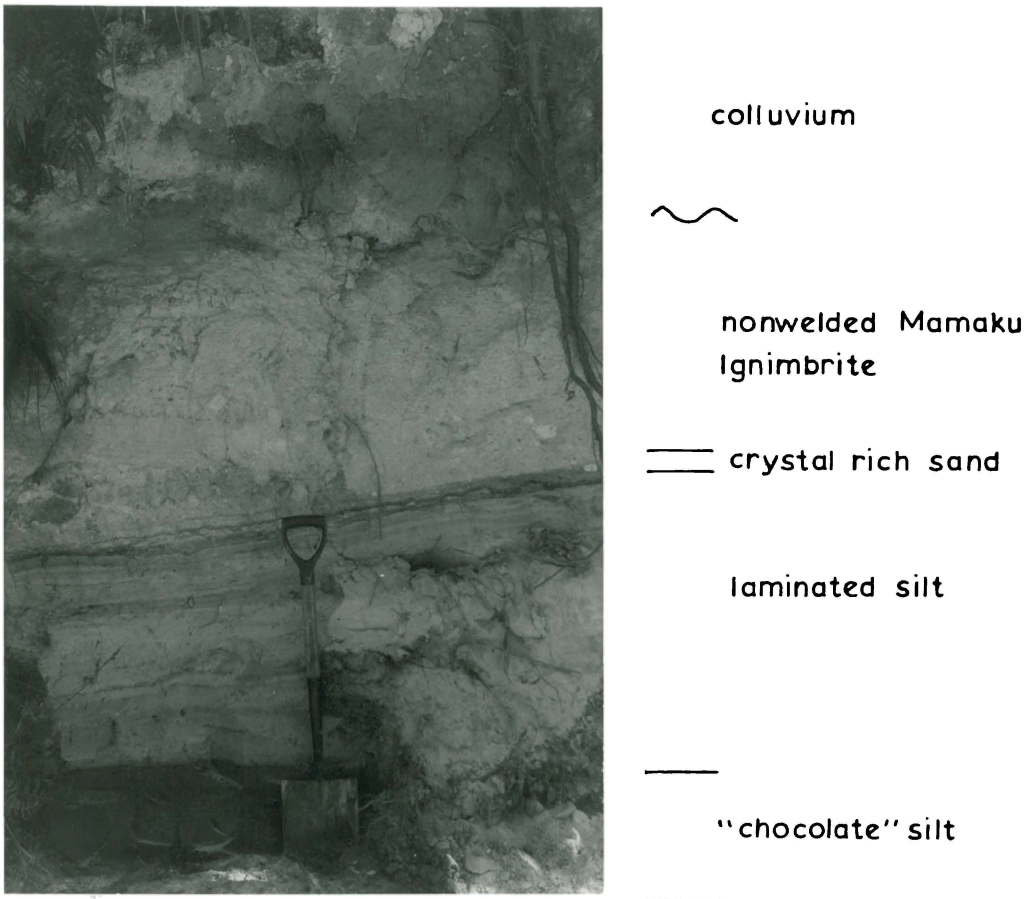
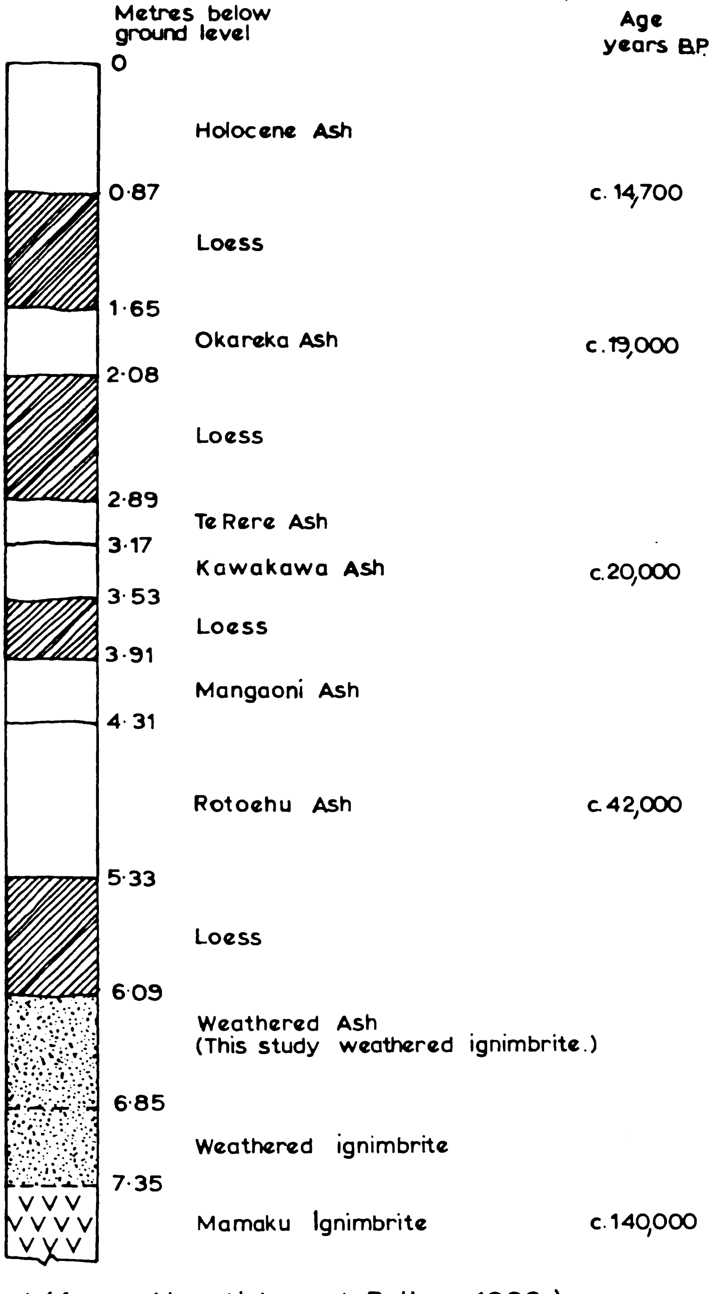


Fig. 2.25 Basal contact (top of spade) of a vitroclastic zone of the Mamaku Ignimbrite with underlying sediments.



Leslie Road (from; Vucetich and Pullar, 1969)

Fig. 2·26 Generalised tephrostratigraphy in the western Mamaku Plateau.

Late Pleistocene and Holocene Tephras

The tephras found in the study area erupted from the Okataina and Taupo Volcanic Centres and are of rhyolitic composition. Hodder and Wilson (1976) indicate that the andesitic Mairoa Ash is not present in the area.

The Rotoehu Ash (*c*.42,000 yrs B.P.) is the oldest ash bed and mantles only the even surfaced interfluves in the study area. It is a yellow to brown, pumiceous and shower bedded deposit. In places the Rotoehu Ash overlies weathered loess deposits, (Fig. 2.22), (Vucetich and Pullar, 1969) which in turn overlie a paleosol developed on the Mamaku Ignimbrite.

Further eastwards, the eroded surface of the interfluves is mantled by the distinctive orange, pumiceous Rotorua Ash (*c*.13,500 yrs B.P.). In the floor of the valleys the tephras are the light yellow to orange Tirau Ashes. Some of these ashes can be seen on Leslie Road (Locality 31) overlying the Whakamaru Ignimbrite. Pullar (1967), in a description of a profile near Tirau, suggested, that the Tirau Ashes were comprised of the Taupo Pumice, and the Rotoma and Rotorua ashes.

On Whites Road (Locality 289), the Kawakawa Ash (*c*.20,000 yrs B.P.) covers a paleosol developed on the Whakamaru Ignimbrite (Fig. 2.27). The tephra cover is discontinuous in the valleys which suggests they suffered local erosion. Tephras older than the Tirau Ashes are absent in the middle to upper reaches of the Waihou River valleys.

Pre-Rotoehu Paleosols and Loess

On a farm track near Leslie Road (Locality 263) is exposed a sequence of deeply weathered deposits in which paleosols have developed. They overlie Waimakariri Ignimbrite, and are overlain by the post-Rotoehu tephra sequence. A similar sequence is again seen in the floor of the Purere Stream valley (Locality 261), (Fig. 2.28), where the paleosols lie on the

Fig. 2.27 Cover deposits overlying Whakamaru Ignimbrite on Whites Road. The Kawakawa Ash is shown by a distinct white layer in the middle of the cutting.

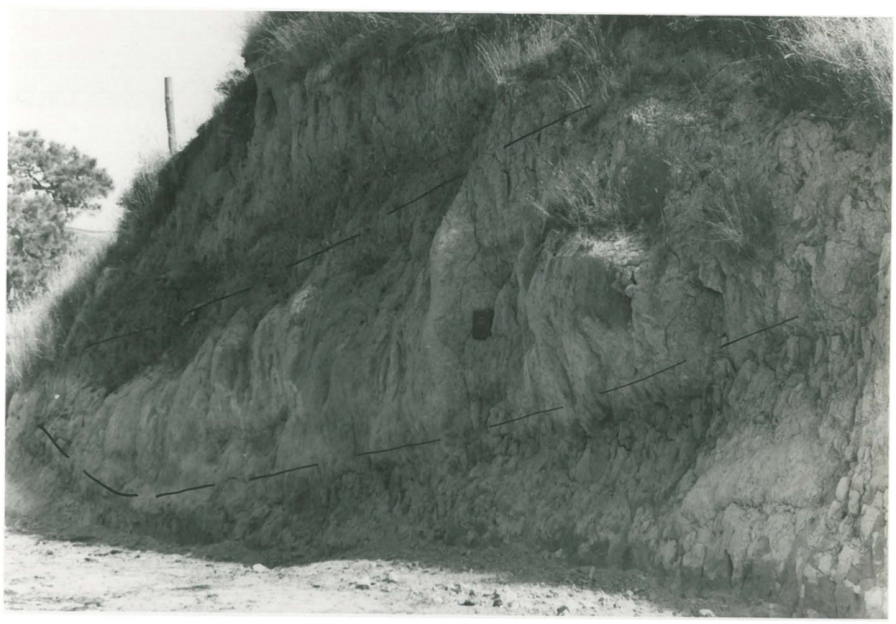


Fig. 2.28 Weathered paleosol sequence of 3 units defined by changes in thickness, structural and morphological development and unconformable contact(s).

Whakamaru Ignimbrite. At least 3 units can be distinguished by erosional unconformities, contrasting structures and outcrop morphology. The paleosols are considered to be of post-Mamaku Ignimbrite age because they occur at different elevations in the valleys and mantle the older ignimbrites. Paleosols like these (i.e. with a strong degree of profile development) have not been found between the Waimakariri Ignimbrite and Mamaku Ignimbrites or between the Whakamaru and Waimakariri Ignimbrites.

The paleosols are probably developed in loess. This is evident by their variable thickness. Exposures of these deposits are scarce and this may be attributed to local erosion since they were deposited. There is a possibility that the material on which the paleosols formed are redeposited upper members (H_5-H_7) of the Hamilton Ash Formation and weathered Mamaku Ignimbrite. McCraw (1973) places the H_5-H_7 beds above the Mamaku Ignimbrite, but they were not found on the interfluve surface probably because they were stripped off the plateau by erosion.

Colluvial Deposits

Colluvial deposits are found mainly on slopes formed on the Waimakariri and Whakamaru Ignimbrites. Their thickness varies from 0.3 - 2 m but tend to increase near the foot of the slope.

Four main lithologies are recognised:

(1) an uppermost layer of massive bedded, yellow brown, medium to fine pumiceous sands which may be reworked Holocene ashes.

(2) an underlying, pumiceous gravelly sand which is characterised by orange pumice fragments set in a black friable matrix. This deposit is probably a mixture of the Mamaku and Waimakariri Ignimbrites as it occurs at levels about the Whakamaru Ignimbrite.

(3) rockfall debris on the surface of steep, terrace slopes. These rocks are comprised of the welded portions of the Mamaku and

Waimakariri Ignimbrites which crop out as bluffs above the colluvial slope.

(4) slump debris in the Waihou River valleys. A slump deposit is exposed at the junction of Moth and Wasp Roads (Fig. 2.29). At the base, the material comprises some blocks of Mamaku Ignimbrite. These are set in massive bedded medium to fine sands. These sands dip at about 24^{o} and also contain an interbedded "slump fold" of medium sand. The top of the sequence consists of an 8 m thick poorly sorted pumiceous deposit.

On the floor of the Waihou River valley (Locality 176) a 50 m long road cutting reveals a slump deposit (Fig. 2.30) characterised by numerous fragmental clasts of Mamaku Ignimbrite up to 200 - 300 mm in size. Large slabs several metres in dimension also occur and generally overlie clast-rich zones. This sequence occurs several times in the outcrop and gives an impression that the slabs were transported on a "roller-bed" of smaller clasts during slumping.

Geomorphic features suggest that mass movement of ignimbrite occurred. This is indicated by outlines along the edge of the even-surfaced interfluves and steep valley-side slopes (Fig. 2.31). These slopes, formed on Mamaku Ignimbrite, are probably the headwalls of very large slides which were deposited on lower slopes and on the valley floor.

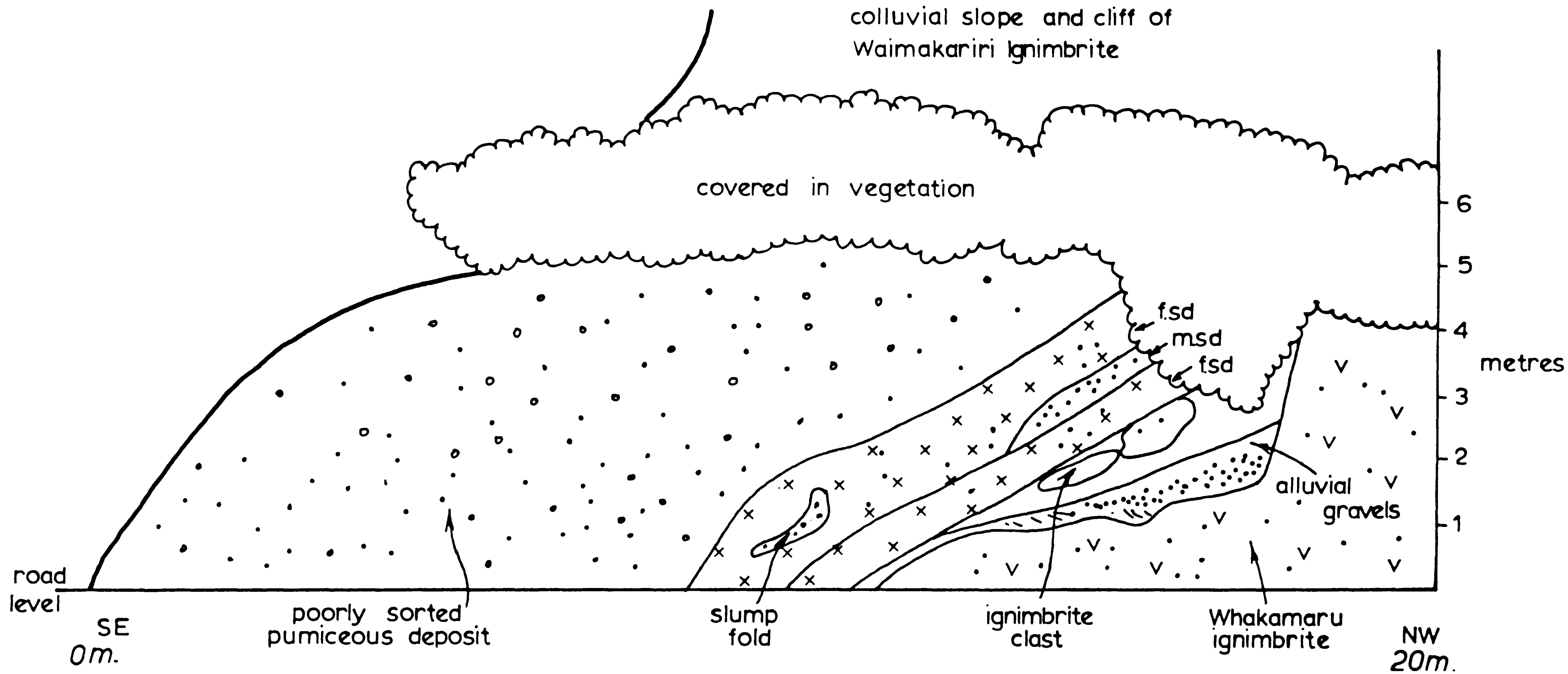


Fig. 2.29. Schematic X-section of slump deposit on junction of Moth Rd. and Wasp Rd.
f.sd = fine sand, m.sd = medium sand.

Fig. 2.30 Slump deposit, exposed on valley floor, which consists of blocks and slabs of Mamaku Ignimbrite.

Fig. 2.31 Cuspate forms outlined along the edge of the flat-topped interfluves are characterised by steep faces on upper valley-side slopes formed only on Mamaku Ignimbrite.

CHAPTER THREE

STRUCTURE OF THE WESTERN MAMAKU PLATEAU

3.1 INTRODUCTION

The southern extension of the Hauraki Depression converges with the western Mamaku and Tokoroa Plateaus which are the main physiographical features in the Putaruru area. The ignimbrite plateaus are the result of volcanism from the Taupo Volcanic Zone, whereas the depression is an active rift structure. The physiography and geological formation are therefore closely related.

3.2 FAULTS

The inferred faults in the study area can be divided into two categories:

(1) Major faults with large displacements and a broadly N-S trend.

(2) Minor faults with small displacements and a broadly NW-SE trend.

3.2.1 MAJOR FAULTS

From the apparent disparity in base leve of the Whakamaru Ignimbrite, it is suggested that there are two faults in the study area which divide the region into a simple horst-graben-horst structure. There is some evidence to suggest that repeated movement occurred along both of these inferred faults. They are described below as the western and eastern faults.

<u>The western fault</u>

The linear trend of a series of outcrops of the Pakaumanu Group along the Waihou River may indicate a fault scarp. Near the water wheel (Map 3) the postulated strike changes from NW to NNW. There appears to be a contrast in the basal elevation of the Whakamaru Ignimbrite on either side of the fault. On the southwestern side, the Ignimbrite is thicker and higher in elevation than the northeastern side, where it crops out at river level. This offset suggests a downthrow (10-15 m) to the NE along the fault. A maximum age for the fault is post-Ahuroa (<0.65 m.y.B.P.), as this ignimbrite is offset also. A minimum age for the fault is, at most, post-Whakamaru (<0.30 m.y.B.P.) but at least pre-Waihou. Although the Waihou Ignimbrite does not occur on either side of the western fault, it does on the eastern fault, which probably displaces the Whakamaru Ignimbrite also. The Waihou Ignimbrite was emplaced on an eroded surface and does not appear to be displaced by the eastern fault.

The eastern fault

The location and roughly N-S strike of this fault is inferred from surface paleorelief features of the Whakamaru Ignimbrite before it was covered by the Waihou and Waimakariri Ignimbrites (Fig. 3.1).

Field studies have established that the Whakamaru Ignimbrite was severely eroded. Valleys which were cut into this ignimbrite were later filled by the Waihou and Waimakariri Ignimbrites. A paleorelief map was constructed to show the topographical features of the surface of the Whakamaru Ignimbrite (Fig. 3.1). As the Waihou is severely eroded also, much of this landscape had evolved prior to the deposition of the Waimakariri Ignimbrite. The contours of this map were drawn through localities where the contact between the Whakamaru Ignimbrite and overlying fluvial sediments and ignimbrites were seen or inferred.

Two main physiographical features are evident from the paleorelief map: (1) an eastern paleoplateau, and (2) a western paleobasin. The paleobasin is defined by an area of relatively low relief (<160 m elevation) and low contour density. The paleoplateau is characterised by a higher contour density, which indicates valley topography. The surface of the plateau is represented by the interfluves (>200 m elevation). The fact that the Whakamaru Ignimbrite crops out at elevations above 200 m is a good indication that it formed a high plateau which was much more extensive than exposed at present. Ross and Smith (1961) indicate that

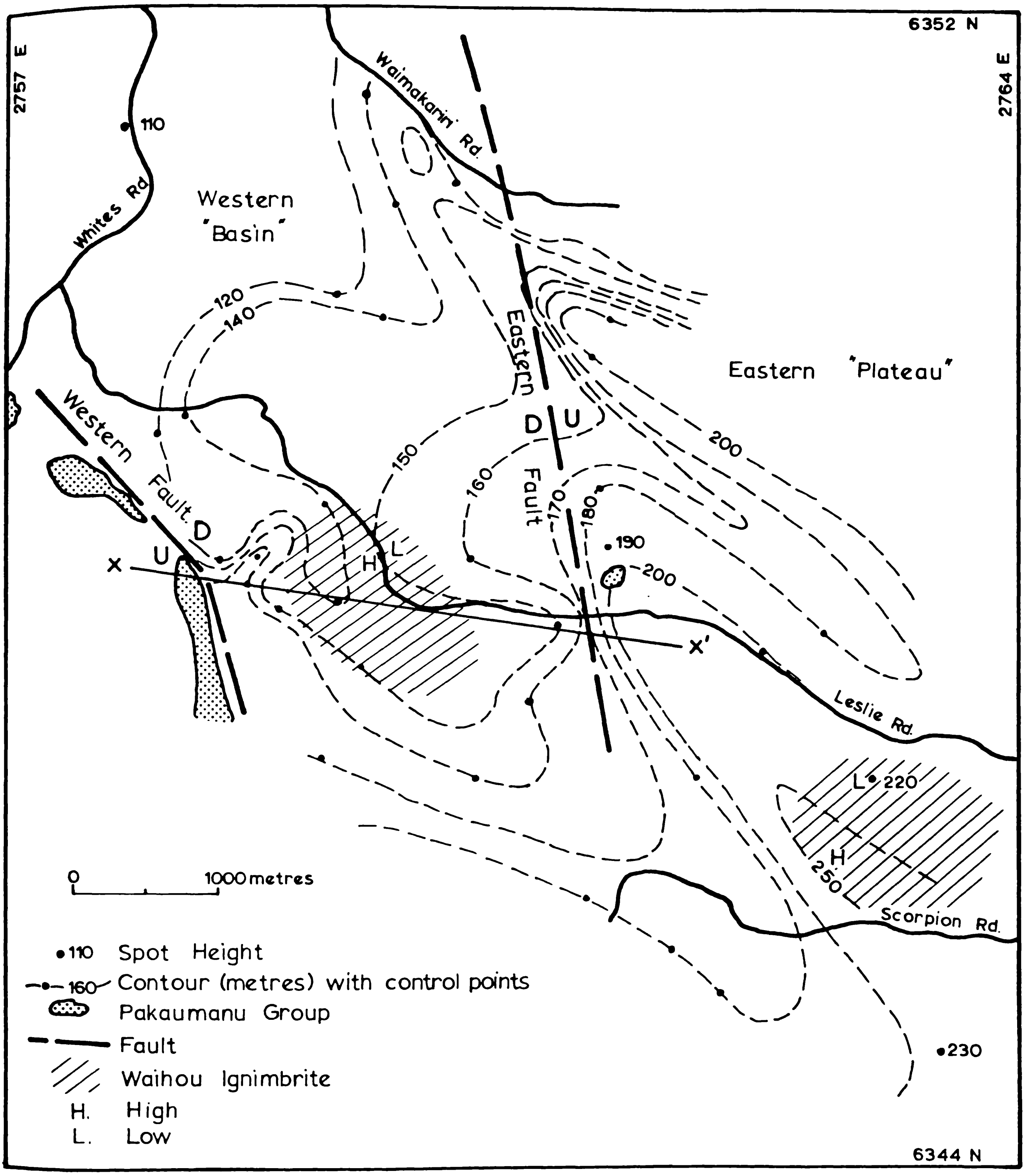


Fig. 3.1 Paleorelief map of the pre-Waimakariri Ignimbrite landscape, in the Western Mamaku Plateau. X-X' = section in Fig. 3.2.

ignimbrites are typified by even upper surfaces and low angles of dip.

The eastern fault is located approximately along the margin of the paleobasin and paleoplateau, where the change in relief is defined by the end-slope of the interfluves. This relief change is thought to be the surface expression of a buried fault scarp underlying the Whakamaru Ignimbrite. Displaced zones within the older Ongatiti Ignimbrite (Pakaumanu Group) suggest a maximum age for the fault of about 0.75 m.y. B.P. (discussed later). A large (>40 m) vertical offset of the Ongatiti occurred mainly prior to the emplacement of the Whakamaru Ignimbrite (*c*.0.30 m.y.B.P.), which buried an upthrown lower zone of the older ignimbrite, near Leslie Road (Map 3, Fig. 3.1). At this locality the Ignimbrite is strongly welded and about 20 m higher in elevation than its weakly welded counterpart, near the Gun Club 3.5 km to the west. Generally, in an ignimbrite sheet, the degree of welding increases with greater depth. Olissoff (1981, fig. 2.6.3) shows the Ongatiti Ignimbrite to be strongly welded approximately 20 m below the weakly welded zone. Assuming this welding zonation for the Ignimbrite in the study area, and the disparity in elevation of these zones, it is estimated that the strongly welded zone was upthrown at least 40 m or more. Displacement of the Ongatiti Ignimbrite is attributed to movement on the eastern and western faults, as it crops out on the upthrown side of each fault. However, it is likely that there was greater movement on the eastern fault than on the western fault. This differential movement would produce a graben which is flanked on either side by horsts (Fig. 3.2). A landscape of some considerable relief is envisaged as a result of fault movement.

Contrasting patterns of cooling formed in the Whakamaru Ignimbrite where it buried the garben, the eastern fault and horst. Cooling patterns in ignimbrite are distinguished by the degree of welding and joint development which are influenced by the volatile content, temperature and

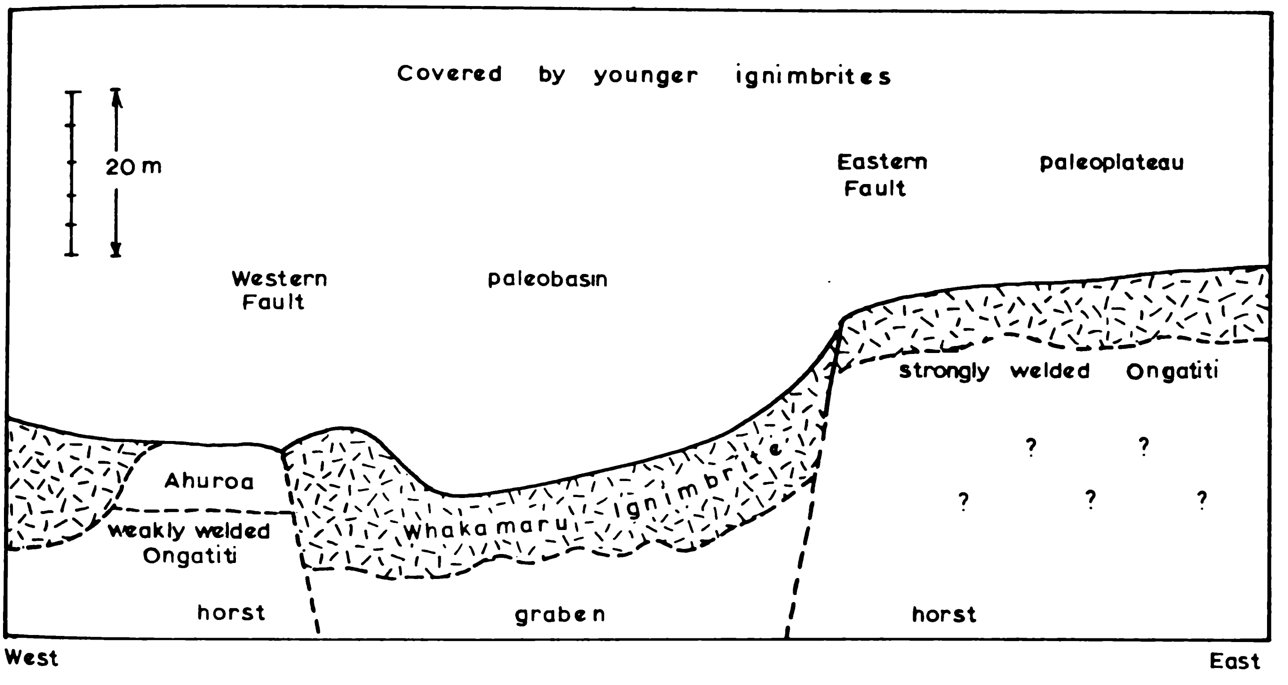


Fig. 3·2 Cross-section of the Horst-Graben system in the western Mamaku Plateau. Approximate line of section shown in Fig. 3.1.

thickness during cooling. In general, these parameters tend to decrease as the deposit becomes thinner away from its source or over pre-eruption topographic highs (Smith, 1960a, b). It is possible to predict the relationship between the thickness, the degree of welding and the basal elevation (Briggs, 1975).

The maximum exposed thickness of the Whakamaru Ignimbrite is about 40 m, in the vicinity of the Water Wheel. The cooling patterns there exhibit the highest degree of welding and compaction and vertical joint development of the Ignimbrite in the study area (Fig. 2.6). This locality is shown as a paleohigh adjacent to the western fault (Fig. 3.1) which suggests that these cooling patterns were more extensive in the western paleobasin area. However, welding, compaction and joint development are less well developed 2.5 km to the east on Leslie Road, which is attributed to the comparatively higher basal elevation and lesser thickness (about 20 m) of the Ignimbrite there. The greater thickness and lower elevation in the paleobasin area suggest that the Whakamaru Ignimbrite filled a basin or depression which formed by subsidence between the western and eastern faults.

The formation of the paleobasin is thought to be determined by the underlying garben and eastern horst. Drainage waters from the eastern paleoplateau (situated over the horst) were likely to be directed and so concentrated in the western paleobasin. This diversion would have potentially increased the erosive power of water and consequently advanced degradation of the Whakamaru Ignimbrite surface in the paleobasin area.

Evidence which suggests that water was once concentrated in the paleobasin is the unusually sudden discharge in major waterways, such as the Waihou River and the Purere and Waimakariri Streams, in the lower reaches of the valleys in the study area (i.e. in the paleobasin). The high discharge is attributed to the occurrence of large springs, which afford a continuous supply of groundwater to the waterways. This groundwater is transmitted through open joints in the Whakamaru Ignimbrite in a strongly welded zone which lies at lower levels (20-30 m) in the paleobasin than on the paleoplateau. The springs occur where the groundwater-table, which is higher beneath the paleoplateau, intersects the surface in the paleobasin. Thus the location of the springs may be indirect evidence for a structural influence. During times of severe erosion (i.e. in glacial climates) large volumes of water would have removed ignimbrite detritus, forming the paleobasin in the Whakamaru Ignimbrite.

Further renewed movement of the eastern fault probably occurred after the Whakamaru Ignimbrite was emplaced. On Leslie Road, well spaced joints are inclined 80^{o}E (Fig. 3.3, Map 3). These joints were probably once vertically disposed and suggests a 20^{o} westward tilting or warping of the Ignimbrite had occurred.

Movement on the eastern fault is thought to have ceased prior to emplacement of the Waihou Ignimbrite. Furthermore, the Waimakariri and Mamaku Ignimbrites show no evidence of having been displaced. Fault scarps on these ignimbrites appear to be absent in the study area.

3.2.2 MINOR FAULTS

Many faults with small throw(s) (13 cm to 4 m) and a general NW strike occur in the study area. They are post-Waimakariri in age and possibly pre-Kawakawa Ash (>20,000 yrs B.P.), since the faults do not displace the air-fall tephra deposits. An age in relation to the Mamaku Ignimbrite is not known since the faults have not been observed in the geographic vicinity of the Ignimbrite.

Two faults are found in a cutting on Whites Road (Fig. 2.19) and have throws of approximately 2 and 4 m. It is inferred that the strike of these faults lies roughly along a relatively straight valley which trends east-

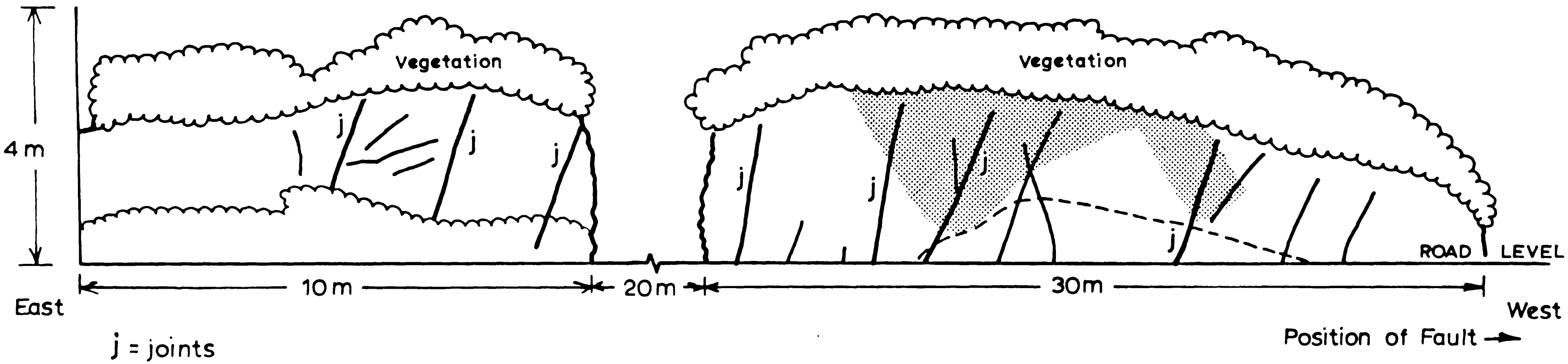


Fig. 3·3 Sketch showing tilt on joints in the Whakamaru Ignimbrite on Leslies Road, east of inferred fault. Major continuous joints are inclined 16-20° from vertical.

southeast. The faults are again seen on the crest of a hill (1.5 km away, locality 337) and here the Waimakariri Ignimbrite is juxtaposed with older fluvial sediments.

At another locality (250) on Whites Road several small faults are exposed in a road cutting (Fig. 2.16). One of these faults displaced the Whakamaru against overlying fluvial sediments (*supra*). These deposits dip about 20°SW. Smaller faults displace the Waimakariri Ignimbrite by a few centimetres (13 and 43 cm). A wedge fault is also present. The inferred strike of these faults is along a valley also.

3.3 COMPARISON OF FAULTS AND STRUCTURE TO THAT IN THE HAURAKI DEPRESSION

Faults in the study area closely approximate the trend of those in the southern Hauraki Depression (Fig. 3.4). The western fault is roughly aligned with the north trend of a belt of sediments mapped by Healy *et al.* (1964) at the western margin of the depression. Hockstein and Nixon (1979) inferred from geophysical evidence that a minor hinge fault (the Firth of Thames Fault) runs along this western margin. It probably delineates the contact between the older sediments and those of the Hinuera Formation (Cuthbertson, 1981). The trend and position of the western fault strongly suggests that it may be related to the above belt of sediments and the Firth of Thames Fault.

Near Waitoa and Matamata, Healy *et al.* (1964) mapped segmented fault traces. Hockstein and Nixon (1979) from geophysical studies inferred that these faults (the Kerepehi Fault) are the surface expression of an underlying median horst (Fig. 3.4). Their gravity measurements showed that the western side of the median horst is very steep and fault controlled. The inferred eastern fault and horst in the study area also appear to have large displacements, and approximate the position of the median horst in the Hauraki Depression. This suggests that it extends beneath the western Mamaku Plateau.

The minor fault traces in the study area do not closely follow the NE strike of the transverse faults of the Hauraki Depression as depicted by Hockstein and Nixon (1979). Because the minor faults are much younger than the eastern fault the structural relationship between them is not certain. However, the oblique attitude of the minor faults to the major trend suggests that there may be a larger fault parallel to the NE strike of the minor faults.

3.4 SIGNIFICANCE OF FAULTING

Hockstein and Nixon (1979) suggested that the Hauraki Depression is a large tectonic feature (the Hauraki Rift) about 20-30 km wide, and at least 220 km long. This rift extends southwards from the Hauraki Gulf through the Firth of Thames and into the Putaruru area. Hockstein and Tearney (1981) indicate that the maximum thickness of the unconsolidated (Quaternary) sediments between the Firth of Thames and a line from Morrinsville across the rift to Te Aroha is between 1000 to 1500 m. These sediments are thought to lie on a greywacke "basement". Active faulting and shallow earthquake activity (at *c*.12 km depth) near Matamata is evidence of present day subsidence (Hockstein and Nixon, 1979.

The presence of horst-graben structures in the study area indicates that the Hauraki Rift extends southward under the Mamaku Plateau. Further south, in the Kinleith area, this trend appears to continue. Other workers (Martin, 1961; Briggs, 1975) have produced evidence which suggests faulting and downwarping in this area (Fig. 3.4). The location of downfaulted strata (from Briggs, 1975) implies the presence of a graben which closely approximate the position of the graben of Hockstein and Nixon (1979). The buried horst is inferred to lie west of this graben in the Kinleith area, and approximates also the position of the eastern horst in the study area. It therefore appears that the Hauraki Rift extends beneath ignimbrites to the western margin of the Taupo Volcanic Zone.

There is a possibility that the throw on the faults in the rift die out southwards. The sudden termination of the Kaimai Range and the apparent disappearance of the Hauraki Fault on the Mamaku Plateau (Fig. 3.4) are evidence of this. The faults are probably buried beneath the Mamaku Ignimbrite. Displacement of the Ongatiti Ignimbrite (0.75 m.y.B.P.) by possibly more than 40 m, and the burial of this faulted strata by the Whakamaru Ignimbrite (0.3 m.y.B.P.), in the western Mamaku Plateau, suggest major rifting between these times.

Uplift of the southern part of the Kaimai Range by at least 450 m has occurred since the Waiteariki Ignimbrite (0.84 m.y. B.P.) was deposited. A block of this ignimbrite is downfaulted into the Hauraki Depression near Matamata (Fig. 3.4).

Surface fault displacements have not been found on the ignimbrite plateaus, which suggests that rifting had ceased or was negligible since their emplacement (i.e. 0.14 - 0.30 m.yrs ago). However, rifting appears to have continued in the depression, further north, as suggested by active faults and a thick sedimentary pile there. It appears that there is a northward deepening of the depression with increasing throws on the faults to the north.

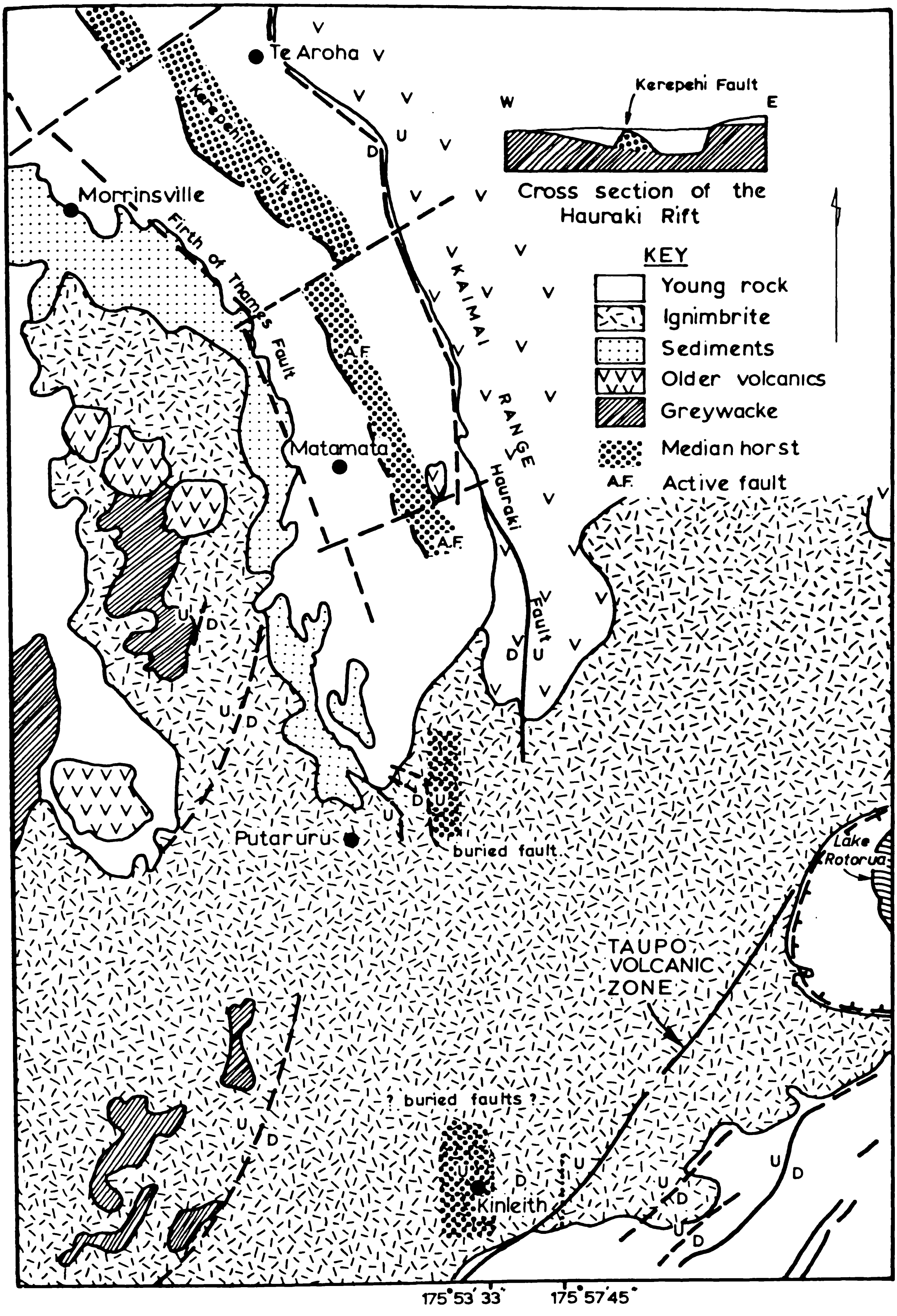


Fig. 3·4 Structural trends in the Hauraki Depression. Modified from maps of Healy et al. (1964), Hochstein and Nixon (1979), Olissoff (1981). Faults in this study lie east of Putaruru.

CHAPTER FOUR

VARIATIONS IN THE MAMAKU IGNIMBRITE

4.1 THE TE AKAU CORE SEQUENCE

4.1.1 GEOLOGICAL SETTING

The following is a resumé of the geology of Thompson's (1958) report of the Te Akau core site area (Fig. 1.1).

The oldest rock exposed is the Mamaku Ignimbrite. At Okere, near the outlet of Lake Rotoiti, it forms the steep (50 m) walls of the gorge of the Kaituna River. Outcrops occur on the main highway between 1.6 km and 3.2 km north of Otaramarae. The upper surface is flat and dips about 2^{o} north, except near Lake Rotoiti where it dips about 5^{o} east.

The weathered surface of the Ignimbrite is covered by slightly compacted tuffaceous sediments which are overlain by the nonwelded Rotoiti Breccia. These are mantled by a veneer of volcanic ash, and in some valleys there are pumiceous colluvial wash and alluvial deposits.

4.1.2 POSITION AND NATURE OF SAMPLES

The Te Akau 5 and 17 core-sites (Fig. 1.1), are about 300 m apart. The holes have a total depth of 192 m and 136 m respectively, and the Mamaku Ignimbrite in both cores is about 120 m thick. In core 17, the basal lenticulite zone of this ignimbrite occurs some 36 m lower than in core 5 (Thompson, 1958). However, core 17 did not penetrate the base of this lenticulite zone. Comparison of the modal abundance of phenocrysts (Fig. 4.9) from the two cores suggests that the actual base of the lenticulite in core 17 lies about 2 m below the end of the core.

There is wide variation in the degree of core preservation depending on the hardness of the Ignimbrite. In core 5, the complete sequence was sampled from the top of the Mamaku Ignimbrite to an older ignimbrite at a depth of about 180 m. The cores varied from between 40 to 70 mm in diameter. The cored samples from between 33 and 64 m depth are poorly preserved or frittered away because of the weak cohesion in this upper part of the Mamaku Ignimbrite. With depth the cores harden and become cylindrical. At the base, the Ignimbrite suddenly grades into a soft pumiceous fine sand which contains shattered fragments of hard Mamaku Ignimbrite core-rock. These fragments were probably mixed with the fine "basal" sand during drilling.

In core 17, the top 6 m of the Ignimbrite is soft and friable. Below this level, cylindrical samples were obtained. Descriptions of the cores and the position of the samples are given in Fig. 4.1 and 4.2.

4.2 METHODOLOGY

4.2.1 PUMICE AND LITHIC ABUNDANCES

Preliminary investigations of pumice size and abundance in the distal section of the Mamaku Ignimbrite on Leslie Road (Fig. 1.1), give some clues as to whether a laminar or turbulent flow mechanism operated during transport (discussed in section 4.7.3). The lack of cohesion of the pumice fragments and the moderately welded nature of the Ignimbrite in the lower parts of the section, means that grain size characteristics cannot be determined by sieving methods alone.

A method described by Yamazaki *et al.* (1973) was employed in this study and involves the counting of all pumice fragments in a defined area of an outcrop. A representative rectangular area of 150 x 500 mm was chosen and marked with string tied to nails. The smallest pumice particles that could be clearly distinguished (for counting) was about 5 mm. The distinction of many smaller pumice fragments was difficult because of similarities in colour and texture with the surrounding ash matrix. The average size of pumice (greater than 5 mm) was estimated by eye.

The lithic fragments were also counted but because of their paucity in the outcrop, a larger area of 500 x 500 mm was chosen. The counts for lithic fragments ranged from 1 to 13, and no systematic change in abundance occurred in the Leslie Road section.

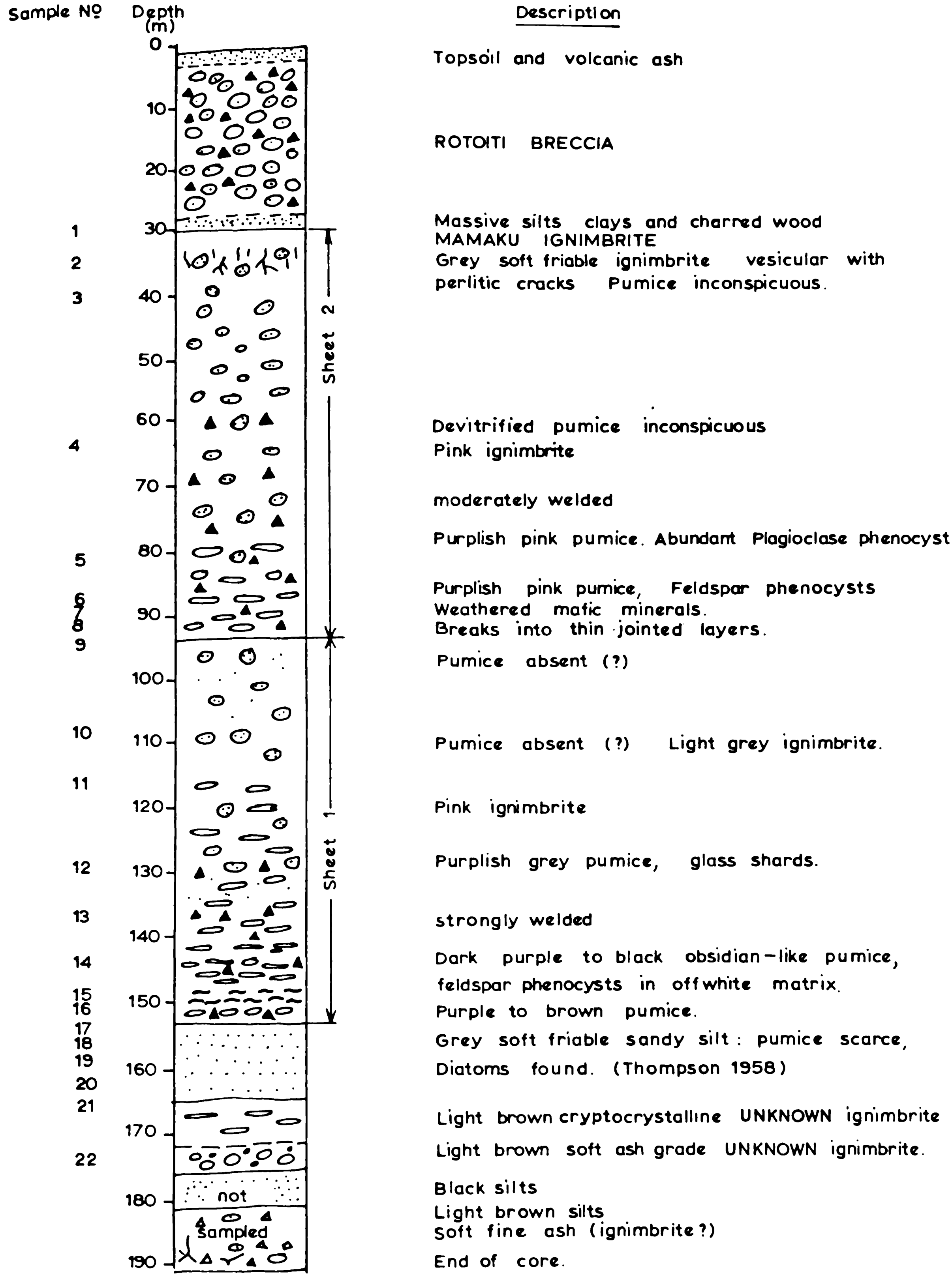


Fig. 4·1 Stratigraphic column of the Mamaku ignimbrite. Te Akau core 5. Lithological symbols described in Fig. 4·2.

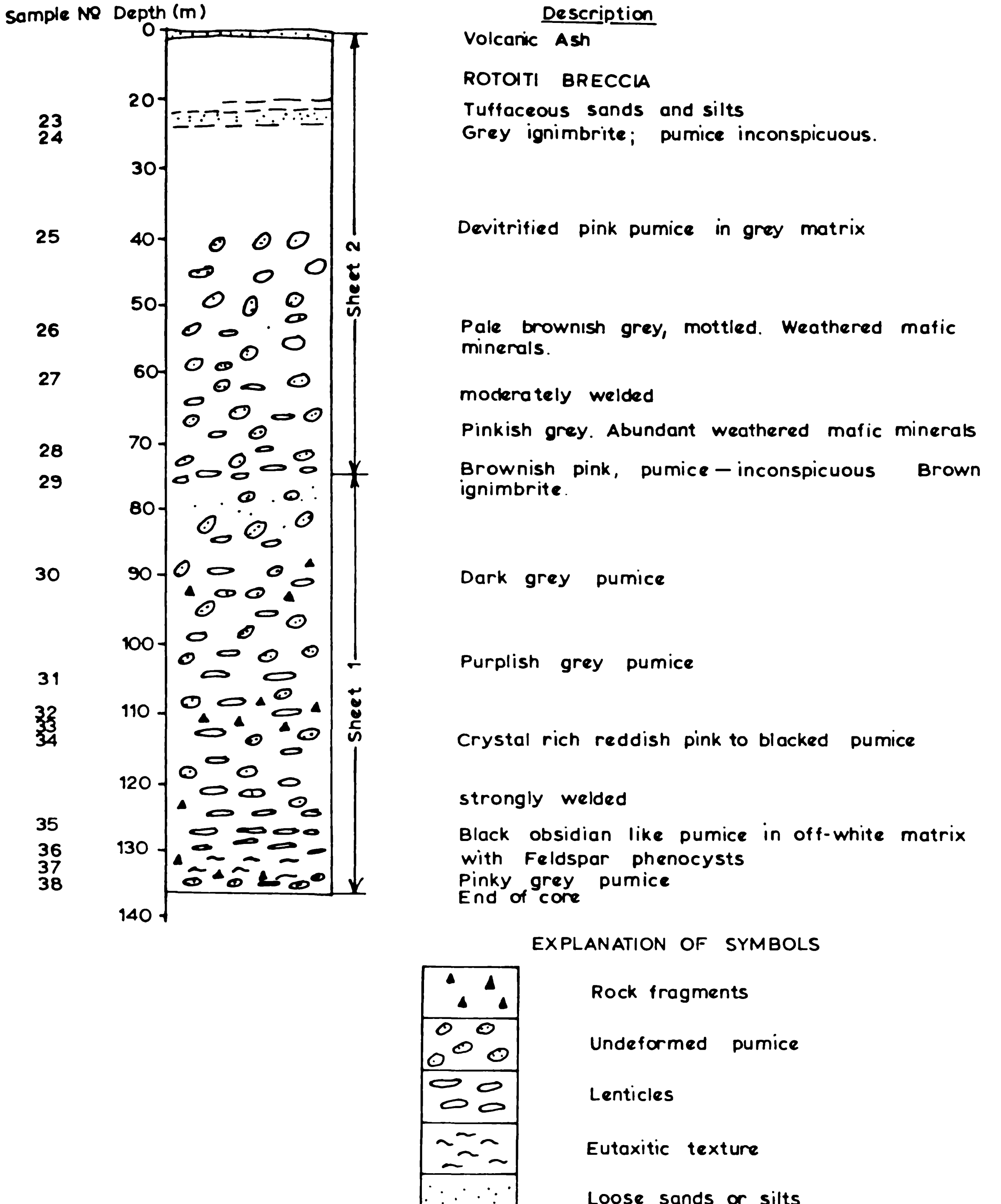


Fig. 4.2 Stratigraphic column of Mamaku Ignimbrite. Te Akau core 17.

Selection of Counting Sites

The Leslie Road section provides the most complete exposure through the Mamaku Ignimbrite. The road cutting, however, is overgrown and counting and sample collection was carried out at irregular intervals. At the counting sites the surface of the cutting was cleaned to expose fresh rock. Pumice counts were also performed at other localities so that a comparison could be made with the Leslie Road section.

Degree of Error

Errors in the counting procedure may arise through the difficulty of distinguishing the smaller pumice fragments. It is estimated that less than 10 pumice fragments remained uncounted at each site. The results are acceptable only when the differences between counts (at localities of position in a section) are large enough and do not fall within the margin of error.

4.2.2 IMPREGNATION OF ROCK SAMPLES FOR THIN SECTIONING

The examination of gross mineralogical and textural relationships of the Mamaku Ignimbrite (and other ignimbrites in the study area) is necessary for identification and the determination of changes in constituent abundances. Many samples of ignimbrite were too soft to be thin-sectioned by standard techniques. These weakly coherent rock samples had to be impregnated with resin so that they could be worked by grinding and polishing.

The impregnating agent used was Struers Epofix resin and Epoha hardener. These were mixed at a ratio of 9 parts resin to 1 part hardener. The impregnating apparatus used was the Struers water regulated vacuum chamber.

The rock samples were cut to approximately 20 x 40 x 5 mm in size. Each sample and the resin were evacuated of air within the chamber. During evacuation the sample was placed on a cardboard platform positioned over the resin. The evacuation time was 10 - 15 minutes after which the apparatus was tilted to let the sample slide into the resin. Another method tried, was to cover the sample with the resin and then evacuate. The maximum time allowed for evacuation was about 1 hour. After removal from the chamber the sample was left to harden.

By this latter method very porous samples were completely impregnated. In most cases the resin penetrated to a depth of 2 - 3 mm. The impregnation of some weathered and fine grained samples could not be accomplished.

4.2.3 MODAL ANALYSIS

The modal analysis of rock using a mechanical stage and a point-counter on a microscope stage, is an established technique which was used for obtaining quantitative estimates of relative phenocryst abundance. The phenocrysts in a rock section were counted on a symmetrical grid. Speciments of the Mamaku Ignimbrite from the distal Leslie Road section, and near-to-source Te Akau 5 and 17 cores were point counted. The grid size of 0.33 x 1 mm and a point count population of 2000 was most often chosen.

Degree of Error

Two types of error are inherent in this estimation of phenocryst abundance. The first is caused by variations within the thin sections, which arises as a consequence of the identification process being carried out at fixed points. Varying effects are created by grain size and spacing. As each point count is a binary response, not every phenocryst on the slide is counted. Some large phenocrysts were counted more than once.

The second error arises from the variation in abundance of the target mineral within the rock body (i.e. the variation is an inherent property of the rock. A modal analysis may not be representative of the average abundance if the rock is heterogeneous.

4.2.4 RATIONALE FOR THE STUDY OF PHENOCRYST ABUNDANCE

To obtain a reliable estimate of the phenocryst content when using the modal analysis method it is desirable to sample at random localities. Limiting factors in obtaining samples of the Mamaku Ignimbrite were the poor accessibility, the paucity of suitable exposures, and the relatively short time in which the Ignimbrite must be studied in detail. The problem is mitigated by considering:

(1) the scale of vertical and lateral variation likely to occur in an ignimbrite generally.

(2) using the Te Akau 5 and 17 core sections as a means of checking the degree of lateral and vertical variation in the Mamaku Ignimbrite near-to-source (Fig. 1.1).

(3) comparing the lateral variation from two specimens taken at the top of the Leslie Road section, far-from-source.

The sample spacing was determined chiefly by the expected scale of variation. Ignimbrites are considered to be relatively homogeneous rock bodies. However, recent work has shown that considerable variations in homogeneity and physical characteristics do occur. Some reasons for this are:

(1) subdivision into flow units;

(2) the occurrence of a well defined basal layer to many flow units;

(3) the presence of segregation pipes which are depleted in fine ash particles;

(4) the concentration of lithics at the base, and light pumice fragments at the top of flows.

A number of models of ignimbrite emplacement have been suggested to account for both homogeneous and heterogeneous characteristics. These are:

(1) layer-by-layer deposition (Fisher, 1966);

(2) emplacement as a coherent body, *en masse* (Sparks, 1976).

(3) deposition governed by local conditions for which several mechanisms are envisaged (Wilson and Walker, in prep.).

These models conceivably influence the scale of variation that may be expected to occur in ignimbrites. Some ignimbrites exhibit vertical changes within a few metres which are often evidence of flow boundaries.

The number of flow units (or sheets) which comprise the Mamaku Ignimbrite was not conclusively established before this study. The Ignimbrite appears to be a homogeneous deposit suggesting that emplacement occurred *en masse*. However, welding and devitrification processes after emplacement may have disguised inherent vertical irregularities which would indicate boundaries to flow units. Evidence for this is discussed in section 4.5.1. An initial assumption is that the Mamaku Ignimbrite could comprise many flow units if the model of emplacement which describes deposition of ignimbrite as a rapid succession of flows (or layers) is invoked.

A comparison of the Mamaku Ignimbrite with the well studied Whakamaru Ignimbrite may give an idea of the expected scale of variation. These two ignimbrites have similar lithological characteristics in that only minor differences occur over a distance of ten or more metres. Previous work on the Whakamaru Ignimbrite by Briggs (1973), showed that there was no real difference in the total percentage of phenocrysts over a lateral distance of at least 30 m (i.e. the difference between samples was not significantly greater than that found within one sample). This horizontal interval was therefore taken to represent a homogeneous sample of ignimbrite. Briggs (1973) assumed that any variation occurring at such intervals could be attributed to random sample variation. The total phenocryst abundances between the Te Akau 5 and 17 cores were expected to show meaningful differences because the cores were located about 300 m from each other. To test this the variation within sections (of specimens) which were point counted is expressed by a 95% binomial confidence interval and the difference in phenocryst abundance is compared at similar levels in the two core sections.

To determine vertical changes in phenocryst abundance in the cores, samples were taken whenever obvious changes in texture, colour and hardness occurred. In apparently homogeneous sections of the core, samples were taken at about 10 m intervals. The combined position of specimens taken in the two cores would enable the detection of changes over short vertical intervals.

4.2.5 DETERMINATION OF PHYSICAL PROPERTIES

Bulk Density

Roundish aggregates of ignimbrite (10 - 20 mm in diameter) were oven dried at 106^{o} for at least 12 hours. After this time the aggregates were transferred to a dessicator and left to cool.

The next steps were carried out quickly to avoid the absorption of moisture from the air. The first was to weigh the aggregate (W). The pores in the aggregate were then sealed by dipping into liquid wax of about 50^{o}C. The wax coated aggregate was weighed (W_X), and then suspended in a beaker of water and weighed again (W_W).

The formula: Bulk density

$$= \frac{\text{weight of aggregate}}{\text{volume of aggregate}}$$

$$= \frac{W}{(W_X - W_W) - \frac{(W_X - W)}{0.92}} \quad \text{(g/cc)}$$

Density of wax = 0.92 g/cc.

Particle density

Approximately 2 g of air dried ignimbrite aggregates were lightly ground using a mortar and pestle. This rock powder was placed in a vial and oven dried at 106°C for 12 hours. A density bottle with stopper was dried and weighed (W_d). The dry powder was placed in the bottle, stoppered and weighed again (W). The density bottle was then half filled with water and 2 - 3 drops of teepol added. After shaking, the bottle was completely filled with water and the stopper replaced. Care was taken to exclude all air from the bottle which was then weighed (W_W). After this the sample was discarded and the bottle washed clean and filled with water only. The water-filled stoppered bottle was then weighed (W_S).

The formula: Particle density $= \dfrac{(W-W_d)\,d}{(W_W - W_d) - (W_S - W)}$ (g/cc)

d = density of water

Porosity

Rock porosity is expressed as a percentage figure using the following formula:

$$\text{Porosity} = \left(1 - \frac{\text{bulk density}}{\text{particle density}}\right) \times 100$$

4.2.6 MEASURING PUMICE FLATNESS

In the Te Akau 5 and 17 core samples the effects of pumice compaction can be clearly seen. A study of the texture and structure of pumice in core specimens, and measurements of their shapes was carried out to assess the degree of compaction.

The degree of flattening is a measure of the ratio of the long dimension to the short dimension (Ross and Smith, 1961). Peterson (1979) expressed this ratio as the apparent flatness F_a where:

$$F_a = \frac{\text{length}}{\text{thickness}}$$

Another parameter, the flattening ratio, is the average of a number of apparent flatness measurements. This ratio may be expressed by either an arithmetical or a logarithmic mean (F_e) where:

$$F_e = \text{antilog}\left(\frac{\Sigma \log F}{n}\right) \qquad n = \text{total number of pumice fragments counted}$$

The logarithmic flattening ratio reduces the influence that random highly irregular shaped fragments have on the mean (Peterson, 1979).

Measurements of the pumice fragments were performed only on the Te Akau 5 and 17 cores of the Mamaku Ignimbrite.

4.2.7 BULK CHEMICAL ANALYSIS

Seven new analyses of the Mamaku Ignimbrite are presented and one each of the Waihou and Waimakariri Ignimbrite. The rock powders were analysed by Mr K. Palmer of the Analytical Facility, Victoria University of Wellington.

4.3 PETROGRAPHY

4.3.1 PHENOCRYST CHARACTERISTICS

Plagioclase

This mineral constitutes on average of 80.0% (from 30 samples) of the total phenocrystic mineral assemblage.

Subhedral and euhedral phenocrysts were found throughout the shard matrix and in pumice fragments, and range up to 3 - 3.5 mm in length. In the matrix, many phenocrysts are fragmental. In the pumice, the plagioclase phenocrysts commonly occurred in aggregates or clumps. This glomeroporphyritic habit does not occur in the shard matrix.

Inclusions of pyroxene, titanomagnetite, hornblende, biotite, apatite, zircon, glass and fine cryptocrystalline "dust" particles were commonly found in plagioclase phenocrysts. The trapped dust particles sometimes define the margins of early formed phenocryst cores which were later overgrown to form a dust-free rim.

Fractures in phenocrysts varied with the degree and style of development. Irregular fractures are common, but concentric and unusual "fishbone" and "palisade" patterns also occurred. Well defined irregular fractures are generally confined to the cores of phenocrysts.

Plagioclase is usually twinned and shows concentric normal and oscillatory zoning. Some phenocrysts have wavy extinction patterns, possibly caused by deformation and physical distortion of the crystals during violent eruption. Plagioclase phenocrysts are often resorbed as shown by embayed outlines, pitted margins, and internal melting of cores.

Quartz

This mineral averages 7.6% of the phenocryst assemblage. Euhedral phenocrysts often have hexagonal shapes, whereas subhedral ones were found to be fragmented and resorbed. Quartz is the most highly resorbed phenocryst, which is evident from deep embayments. The phenocrysts range from about 0.2 - 2 mm in diameter. Inclusion minerals include plagioclase, titanomagnetite, apatite, zircon and glass. Wavy extinction patterns, also possibly due to deformation during eruption, are common.

Pyroxene

Hypersthene is the predominant pyroxene mineral present and augite is also found. The distinction between augite and hypersthene is sometimes difficult because of the common highly oxidised nature of these minerals.

The pyroxenes comprise 4.5% of the phenocryst assemblage. Their average size is 0.5 - 1 mm in diameter, but some are up to 2.5 mm in diameter. Intergrowths with plagioclase and titanomagnetite are common. Inclusion minerals are hornblende, biotite, zircon and apatite. Hypersthene crystals characteristically exhibit saw-tooth fractures at the ends, which is probably caused by breakage of complete crystals during eruption.

There is vertical variation in the degree of oxidation of the pyroxene in the Te Akau 5 and 17 core sections. The phenocrysts in the upper porous parts are severely oxidised (Fig. 4.3), to a reddish brown or black amorphous mineral, possibly limonite. Relict pyroxene cores occurred only in the largest phenocrysts. The oxidation of pyroxene phenocrysts has formed a stained halo around the shard matrix. In handspecimens, the brown spots seen are these oxidised pyroxenes.

Approximately 30 m above the base of the Ignimbrite, the severe oxidation and alteration at the phenocryst margins appears to decrease downwards. In the basal lenticulite (porosity <10%) many pyroxene phenocrysts are relatively unaltered.

Opaques

Rutherford (1976) determined that the opaque phenocrysts in the Mamaku Ignimbrite were titanomagnetite and ilmenite. Titanomagnetite is found, in this study, to be the dominant opaque mineral. Ilmenite has a distinctive thin prismatic and hexagonal shape. Titanomagnetites are commonly larger than ilmenite, and reach an average in size from 0.3 - 0.4 mm, and a maximum 1 mm diameter. Subhedral phenocrysts are strongly resorbed and others consist of aggregates of smaller phenocrysts. Ewart (1965) made similar observations of the Whakamaru Ignimbrite. Euhedral phenocrysts of titanomagnetites have square shapes. Some have been altered to a reddish brown mineral, possibly limonite which coats margins and stains the surrounding shard matrix. The opaques comprise 6.8% of the phenocryst assemblage.

Hornblende

Hornblende is pleochroic from green to green-brown and makes up less than 1% of the total phenocryst assemblage. Many hornblende crystals are small, 0.2 - 0.3 mm, but few are up to 1.4 mm in size. The larger phenocrysts are found in the shard matrix whereas the smaller crystals are mainly inclusions. Opaques and apatites are often associated minerals.

Biotite

This mineral exhibits characteristic brown pleochroism and has "mottled" extinction patterns. The small 0.1 - 0.2 mm sized phenocrysts comprise less than 1% of the phenocryst assemblage. The largest phenocrysts were approximately 0.7 mm long. Some are partly or completely oxidised and have a reddish brown to black colour.

4.3.2 GROUNDMASS CHARACTERISTICS

Pumice

The glassy texture,which is one of the most characteristic petrographic features of ignimbrites,has been largely destroyed in the Mamaku Ignimbrite by processes of vapour phase crystallisation and devitrification (Fig. 4.3). The products of devitrification are generally cristobalite and alkali feldspar in most ignimbrites (Ross and Smith, 1961), whereas the main products of vapour phase crystallisation include the above minerals and tridymite. In the Mamaku Ignimbrite, the margins of the pumice fragments generally have a slender axiolitic structure of intergrown cristobalite and feldspar crystals. However, the interiors of large pumice fragments exhibit four textural types:

(1) spherulites

(2) randomly orientated crystal laths of feldspar and (?) biotite

(3) masses of fine and coarse granular crystals

(4) a mosaic of relatively larger platey crystals of tridymite.

The crystal laths are partially to completely oxidised to an opaque mafic mineral. Some are believed to be biotite crystals formed during vapour phase crystallisation. They have similar optical properties to biotite but distinction is difficult because of their minute (near cryptocrystalline) size.

Approximately 3 m below the top of the Mamaku Ignimbrite in core 5, some pumice fragments exhibit a vesicular structure. However, most fragments are devitrified. The glassy fragments may represent a transition into an upper zone of nonwelding, which was removed by erosion. Below this level glassy pumice fragments are absent, having most likely been destroyed by devitrification. With increased depth (60 - 70 m from the top), ghost outlines of the original vesicular structure are clear but severely flattened and moulded around the phenocrysts. The fragments are glassy and secondary crystals are scarce (Fig. 4.4).

Tridymite crystals are mostly found in voids which occur frequently near phenocrysts, but are less abundant than crystals of the other three textural types. Tridymite occurs throughout the core sequence except for the basal 15 m. The Low (<10%) porosity of this zone probably prevented the crystallisation of tridymite during cooling.

Shard Matrix

The shards that comprise the matrix of the Mamaku Ignimbrite generally consist of minute fragments which are short and lack curvature (Fig. 4.3). The fragments are both glassy and devitrified which gives the thin-section a starry appearance under crossed nicols. This matrix habit is unique to the Mamaku Ignimbrite (as compared with other ignimbrites of the study area) and is seen in both core and field samples. The original shard texture has been completely destroyed by secondary crystallisation. In the upper 40 - 50 m of cores 5 and 17, the Ignimbrite has an open shard fabric. Below this zone the porous spaces are absent and the shards are randomly orientated. In the basal lenticulite zone cuspate shard fragments attain their largest size and are severely flattened. Other, glassy, non-vesicular fragments also occur in the strongly welded basal zone (Fig. 4.4).

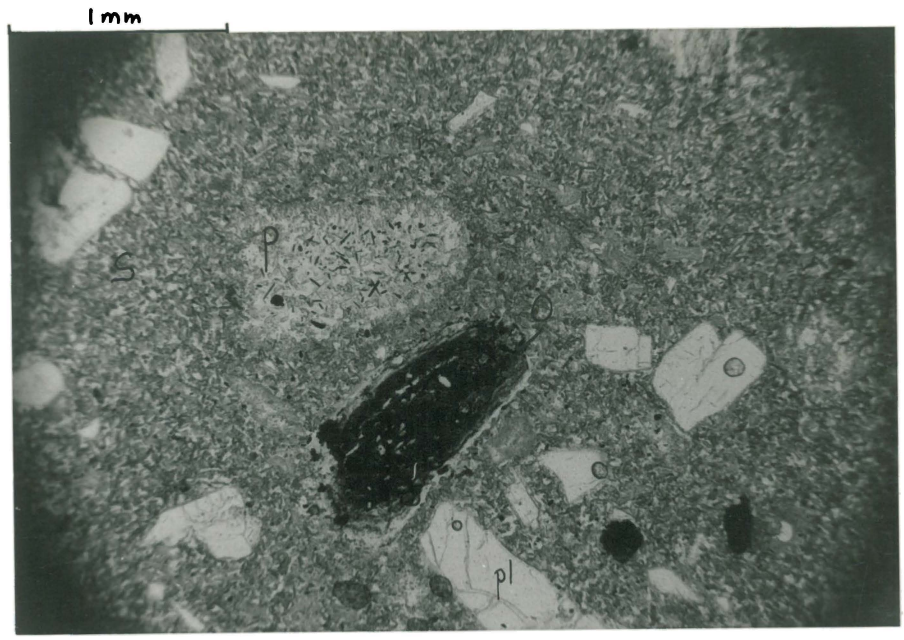


Fig. 4.3 Photomicrograph of a typical uncompacted portion of the Mamaku Ignimbrite (Sample No. W.T.18002). Devitrified pumice fragment (p), and oxidised pyroxene (o), and plagioclase (pl) phenocrysts are set in a devitrified shard matrix(s).

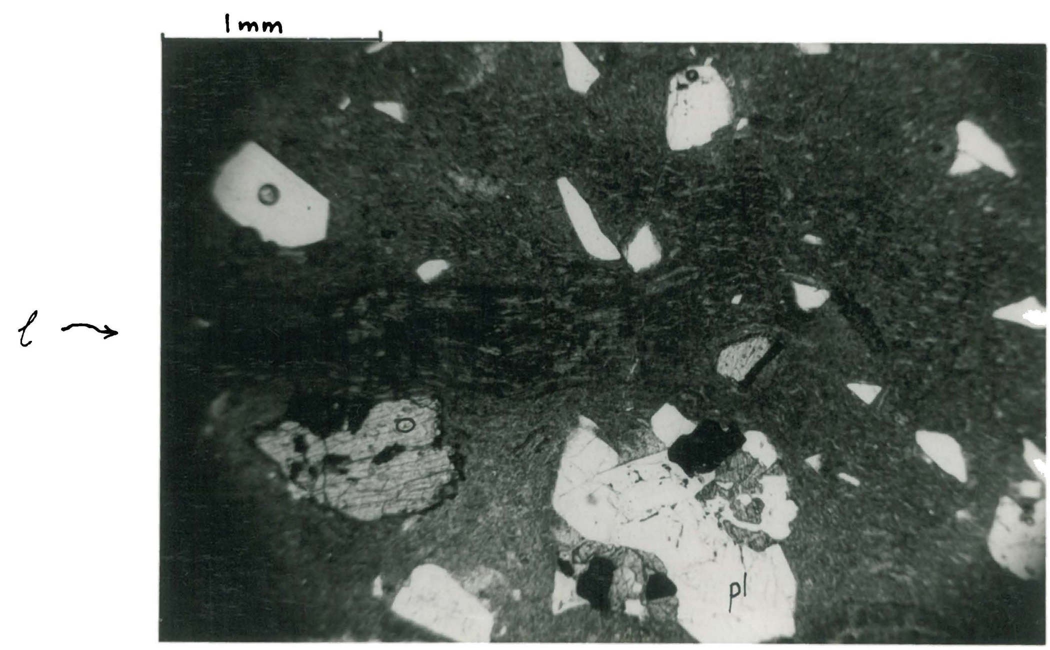


Fig. 4.4 Photomicrograph of the basal lenticulite zone (Sample No. W.T.18035). A compacted pumice lenticle (l) is partly moulded around a pyroxene phenocryst (o) which is unaltered. Intergrowths of pyroxene, plagioclase and titanomagnetite are also pictured. Note the very compacted shard matrix. (c.f. Fig. 4.3).

Lithic Fragments

Lithic fragments range from 0.5 - 9 mm in diameter and comprise less than 3% of the rock. Most lithics are oxidised reddish brown and partially opaque, which makes their identification difficult. Four types occur:

(1) spherulitic rhyolite

(2) andesite

(3) ignimbrite

(4) sandstone or siltstone

The andesites have phenocrysts which are set in a felsophyric groundmass. The sandstones show bedding comprised mainly of quartz and magnetite rich layers.

4.3.3 MINERALOGICAL SUMMARY

The Mamaku Ignimbrite is always distinguishable by its very fine shard matrix and the presence of devitrified pumice fragments. The pyroxene phenocrysts are barely recognisable because of strong oxidation and only their cores may be preserved. The phenocryst assemblage is rich in plagioclase which often occurs in a glomeroporphyritic texture in pumice fragments. Biotite and hornblende phenocrysts are very small and scarce. Quartz phenocrysts are highly resorbed and opaques are commonly found as aggregates.

4.4 VERTICAL VARIATION IN THE LESLIE ROAD SECTION

4.4.1 PUMICE AND PHENOCRYSTS

The results of pumice counts and total phenocryst abundance are plotted in Fig. 4.5. The location of observed variations in pumice and lithic fragments in the Leslie Road section is illustrated in Fig. 4.6. Fig. 4.7 shows variations in the phenocryst mineral assemblage.

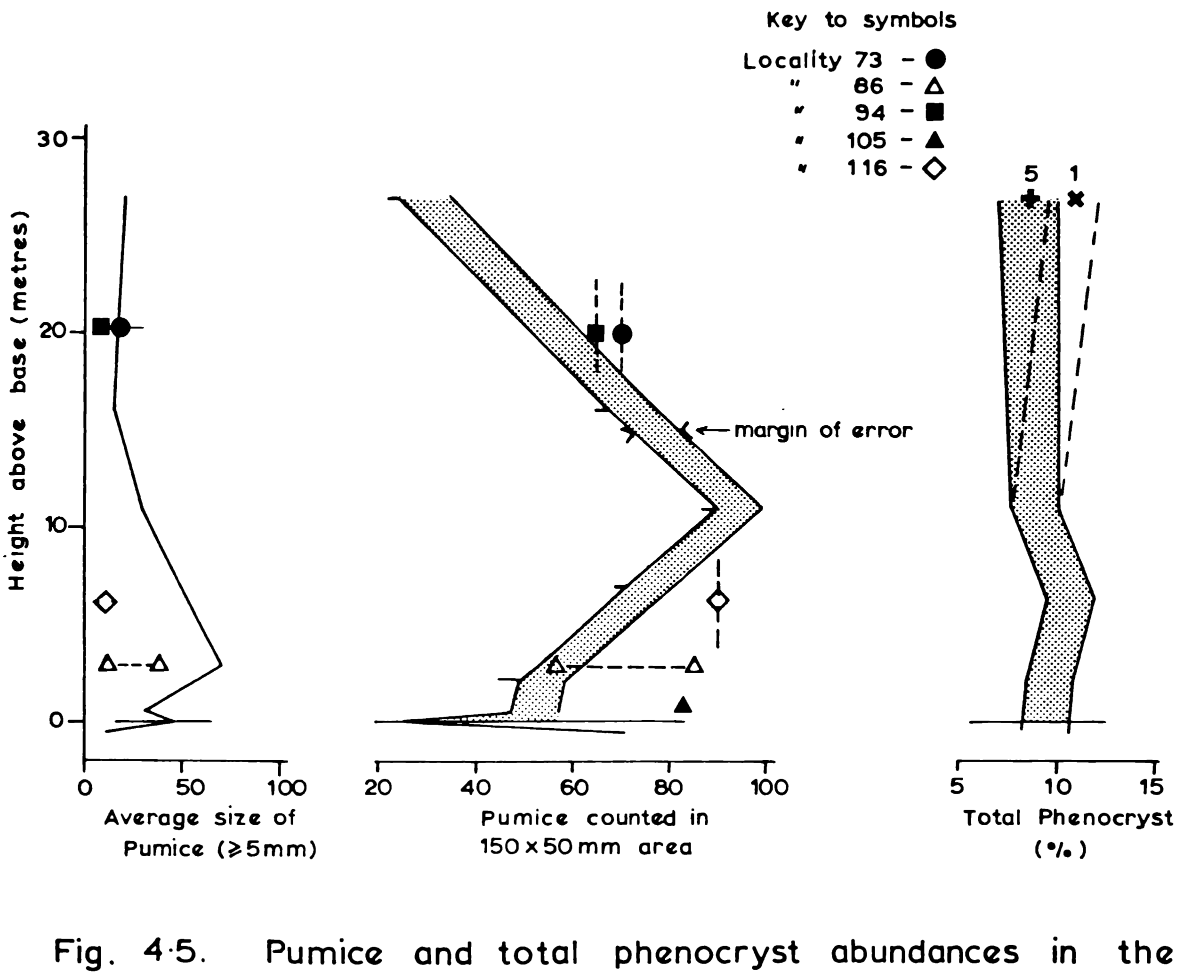


Fig. 4·5. Pumice and total phenocryst abundances in the Mamaku Ignimbrite at Leslie Road section. Counts performed at other localities are symbolised. Vertical bars indicate approximate position in the sheet. Data are in Appendix 4·3 and 4·5. Estimation of sample position is made in Appendix 4·1

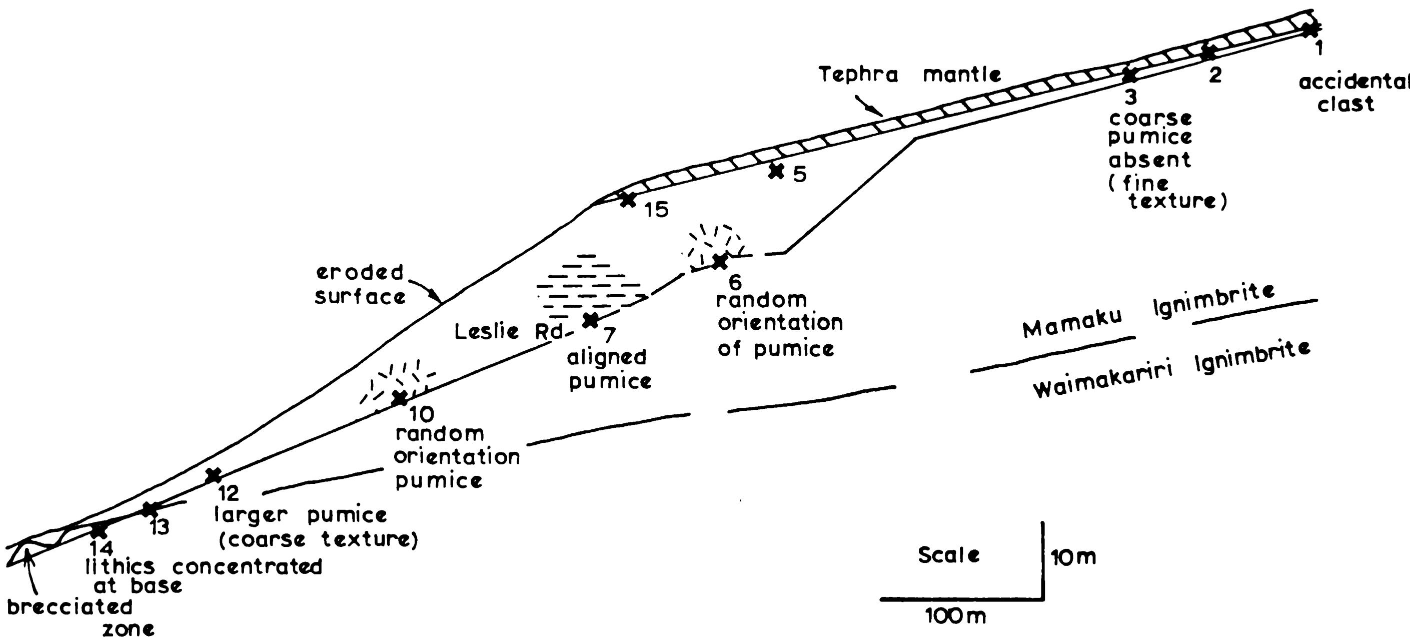


Fig. 4·6 Schematic profile showing characteristics of pumice of the Mamaku Ignimbrite in the Leslie Road Section. Numbers refer to localities sampled.

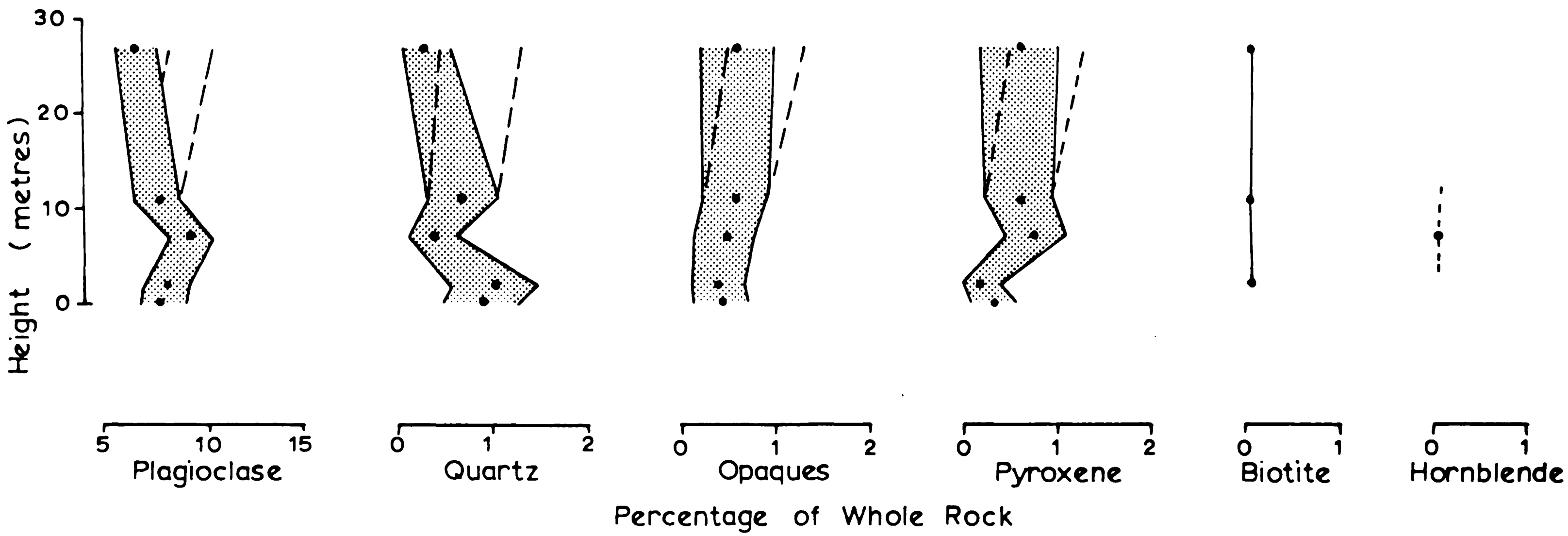


Fig. 4·7 Profiles of Crystal Variations in Mamaku Ignimbrite, Leslie Rd Section. Sites located in Appendix 4·1 and 4·2.

The lower 3 m of the basal portion of the Mamaku Ignimbrite at this locality is depleted in pumice fragments (Fig. 5.5). Within this zone there is no evidence of crude sorting or layering of pumice fragments as might be expected to occur. There appears to be little relation between the abundance and size of pumice fragments. The largest average size of pumice does not persist laterally. This may be a random occurrence only as concentrations of large pumice were not seen elsewhere in the study area. In a zone approximately 10 m from the base the abundance and average size of pumice differs markedly from those found at other localities tested. The variation suggests that pumice is concentrated randomly in this basal zone. Also, within this zone the pumice fragments were seen to be randomly orientated (Fig. 4.6).

At approximately 11 m from the base the abundance of pumice is highest and they are also aligned sub-horizontally. This is attributed to flowage during emplacement of the Ignimbrite, rather than being the result of compaction. Pumice and matrix are not consolidated as seen in thin-sections of samples from this locality.

Towards the top of the section the abundance of pumice steadily decreases. Similar counts from the other localities tested suggests that this decrease is a general trend.

The total and individual mineral phenocrystic abundance in samples show small variations (Fig. 4.5 and 4.7).

4.4.2 PHYSICAL PROPERTIES

Fig. 4.8 shows the bulk density, particle density and porosity determinations of the Mamaku Ignimbrite from the Leslie Road section. The low bulk densities (0.87 - 1.11 g/cc) and high porosities (48 - 62%) probably approximate the original values after the Ignimbrite came to rest. Smith (1960a) indicates that the initial porosity in ignimbrites must be greater

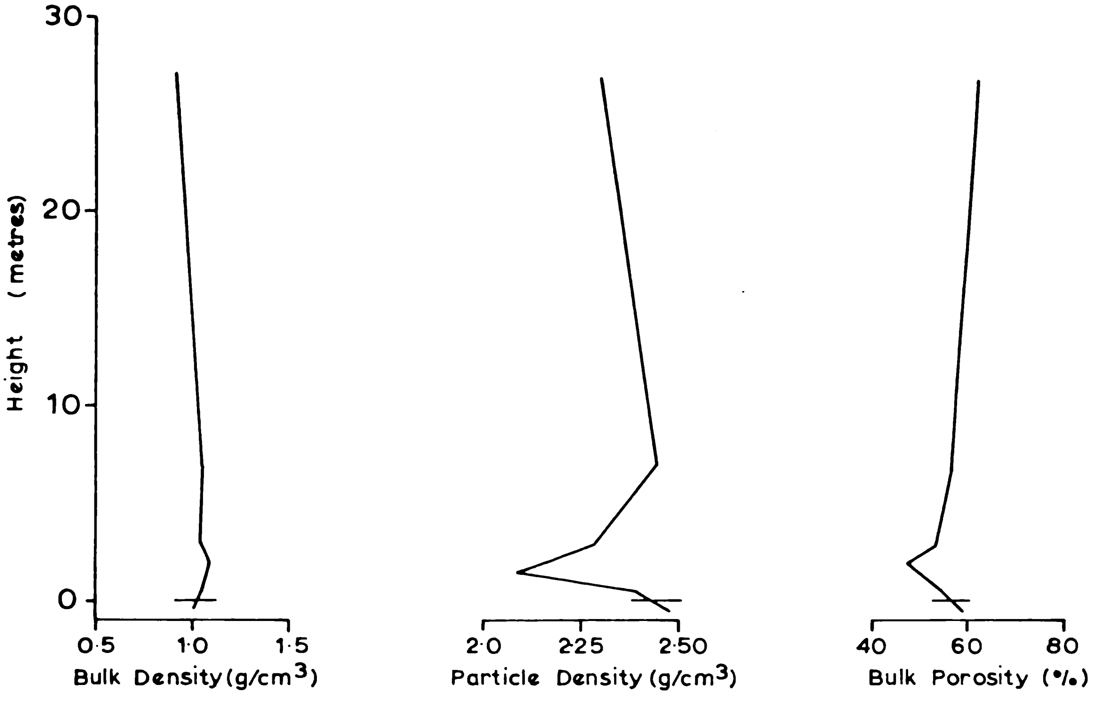


Fig. 4·8 Physical properties of the Mamaku Ignimbrite, Leslie Road Section. Data given in Appendix 4·4 than 50% because this value closely approximates that of pure shards and crystals. Vesicular pumice commonly has 70% or more pore space in rhyolitic rock (Smith, 1960a).

The weakly coherent and friable middle and upper parts of the Ignimbrite in the Leslie Road section suggest that incipient welding took place. Towards the base, the Ignimbrite is more highly welded, as shown by inflexions in the density and porosity profiles (Fig. 4.8). The slight reduction in porosity indicates that some compaction took place. Thin sections show that initial flattening of shard and small pumice fragments occurred about 3 m above the base. Compaction has not affected the coarser pumice fragments. Flattened pumice is seldom seen in this basal zone.

It is very likely that vapour phase crystallisation and devitrification have modified the bulk density and porosity after initial consolidation of the Mamaku Ignimbrite. The initial porosity of pumice fragments must certainly have been altered from the vesicular to the granular devitrified state now seen. Other evidence of modification is the occurrence of hardened zones round joints where the Ignimbrite is also iron-stained (Section 2.3.8).

4.5 VERTICAL VARIATIONS IN THE TE AKAU CORES

4.5.1 EVIDENCE OF FLOW BOUNDARIES

Variations in petrography and physical properties in the Te Akau 5 and 17 cores suggest that the Mamaku Ignimbrite consists of two major units or sheets. Changes in the lithology of handspecimens at the boundary of the sheets are confirmed by the more pertinent data of bulk density and porosity and modal phenocryst abundances. The data are plotted in a series of profiles presented in Fig. 5.9 (p.112).

The reliability of the different data varies considerably. Density and porosity measurements are considered reliable (R. Allbrook, pers. comm., 1981), but modal analyses are less reliable because they depend on how representative a thin section is of the whole rock at the position sampled. The construction of 95% confidence limits of a mode, allows for errors of 1 - 2%. Major changes in phenocryst abundance are only recognised when the differences in the point counts are so great that they change the shape of the profile as defined by the margin of error.

The total phenocryst abundance profiles show a major and identical enrichment of phenocrysts at two levels. These levels are thought to correspond to basal zones of two major flow sheets within the Mamaku Ignimbrite at this locality.

Each sheet is approximately 60 m thick. However, since the upper sheet is eroded, it must have been originally thicker. The lower sheet is named here Sheet 1, and the upper sheet, Sheet 2.

In this study, the base of Sheet 1 in the core is defined by where it was first welded. The fact that the basal contact is commonly found to be welded far-from-source (in the western Mamaku Plateau) is reason to believe that this is a characteristic of the base in most places. Comparisons of the petrography and lithology in the cores with the distal section can be now made about the ignimbrite with reference to the base.

The underlying unconsolidated sandy "basal" layer in core 5, is about 3 m thick and has a high phenocryst content like the basal phenocryst zones of Sheet 1 and 2. There are two possible origins for the sandy layer. Firstly, Thompson (1958) suggested that this layer is the ash layer of the Mamaku Ignimbrite. The high abundance of phenocrysts can be attributed to a winnowing effect of the lighter pumice particles from an early "basal surge" flow. The mineralogy of part of this layer is similar to the Mamaku Ignimbrite.

The second possibility is that the high phenocryst content and sandy texture have a sedimentary origin. Thompson (1958) also reports the finding of diatoms in this layer and suggests that the Mamaku Ignimbrite flowed into a lake in this locality. However, rivers and streams could have supplied this lake with detritus.

The absence of a similar basal layer in the most distal parts of the Mamaku Ignimbrite suggests that it is not a typical feature of the basal portion. Therefore the actual base of the Ignimbrite in the Te Akau core was likely to be welded rather than nonwelded.

Variation in particle density in the Mamaku Ignimbrite reflects mainly changes in the volume than in the weight of the matrix. The matrix comprises 80 - 90% of the rock volume and comprises mainly glass and secondary crystals (Section 4.3.2). The low abundance of phenocrystic mafic minerals (Fig. 4.9) precludes them from having a weight effect on the matrix density. A marked decrease in the matrix volume caused by an increase in the total phenocryst content, correlates well with a slight but sharp decrease in the particle density profile at a height of 5 m and 62 m. Accordingly a relatively high particle density at 9 m, 44 m and 71 m seems to correlate with the lower phenocryst content at these levels.

Near the eroded top of Sheet 2, the absence of a corresponding change in the phenocryst profiles suggests another cause (other than volume) for variation in bulk density, particle density, and porosity profiles near the top of Sheet 2. In a handspecimen, small dessication cracks were seen and the upper contact of the Ignimbrite is weathered. This would indicate that the top 3 - 4 m of the Mamaku Ignimbrite was subject to alternative wetting and drying which caused expansion and contraction of material. The change in the physical parameters is thought to be due to this weathering effect.

In Sheet 2, the particle density profile shows a perceptable upward decrease. This trend probably reflects the modifying effects of vapour-phase crystallisation and devitrification in the more porous and less welded upper parts of this sheet (Fig. 4.9). The fact that the phenocryst profiles also do not show marked changes suggest there are no flow boundaries in the middle part of Sheet 2.

Porosity ranges from 8 - 56%, and the bulk density from 1.0 - 2.0 g/cc. Their profiles are mirror images of each other indicating that changes in bulk density may be dependant on changes in porosity. Ratté and Steven (1967) also demonstrate this. Breaks in the profiles at 146 m correlate well with the breaks in the particle density, but only partly with the high phenocryst content which "peaks" at a slightly higher level (Fig. 4.9). However, there is no similar relationship in the profile at 61 m. This is probably due to the difference in density at the two levels. Low bulk densities obscure the effect that phenocryst enrichment can have at higher bulk densities. The sudden decrease in bulk density and increase in porosity towards the base (4 - 0 m) of Sheet 1 reflects a low degree of welding, caused by rapid chilling at the ground surface during cooling.

The phenocryst profiles from the middle of Sheet 1 do not show corresponding changes in the bulk density and porosity profiles. If sudden inflexions in these profiles occurred they would be a good indication of flow boundaries. Martin (1965) shows this of the Whakamaru Ignimbrite. Distinctive changes in lithology in the middle sections of the sheets are absent.

Lithic abundances determined by modal analysis (Appendix 4.6) are highest near the base of each sheet (in core 17 only). Concentrations of lithic fragments at the base of ignimbrites has been well documented by many authors (e.g. Fisher, 1966; Walker, 1972; Sparks *et al.*, 1973), and can be used to define the base of a pyroclastic flow. Lithic frag-

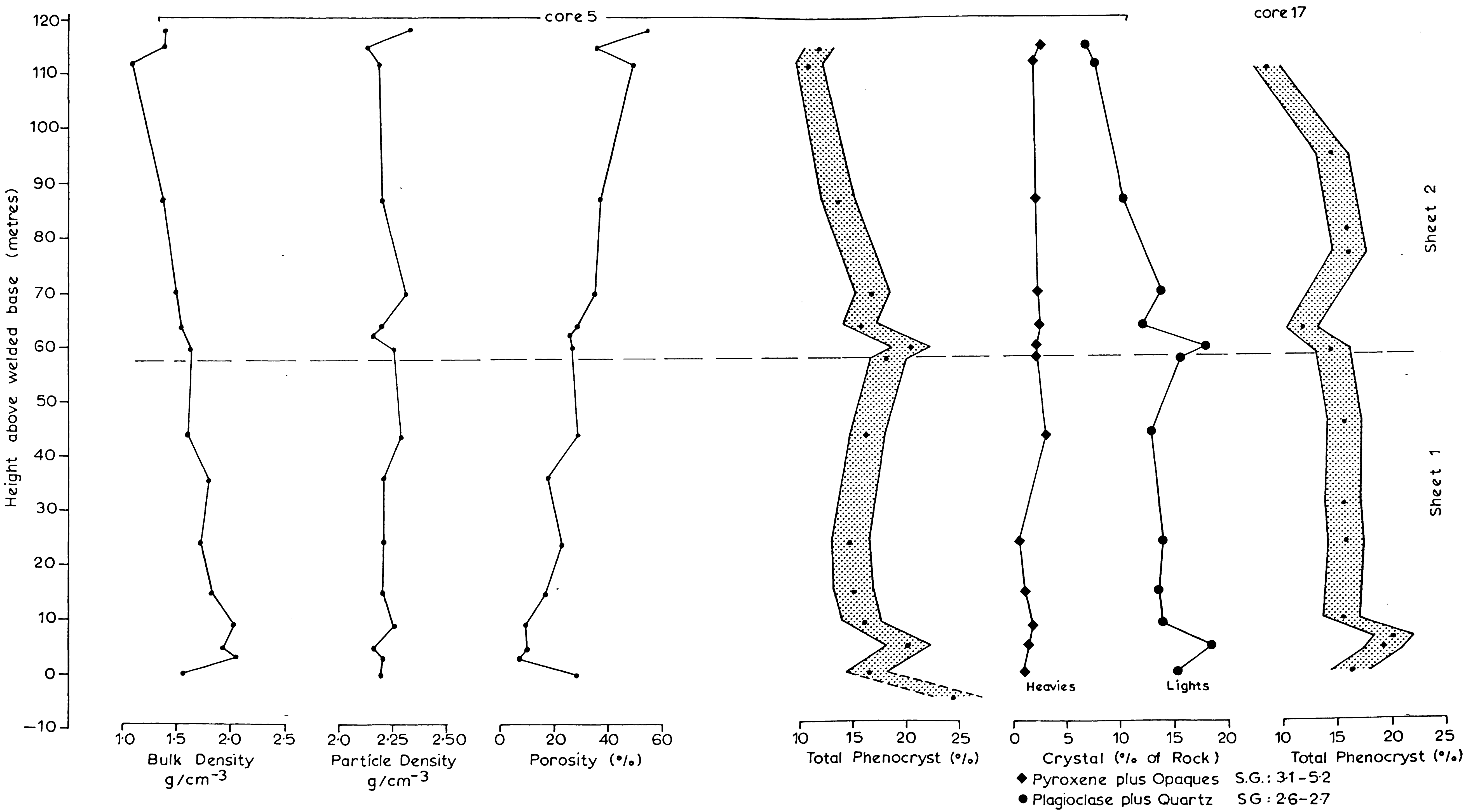


Fig. 4·9 Variations in physical and petrographical properties in the near-to-source sections of the Mamaku Ignimbrite. Results are in Appendix 4·7 and 4·9.

ments in the Mamaku Ignimbrite, however are not as highly concentrated as those reported in ignimbrites elsewhere.

4.5.2 COMPACTION OF PUMICE

Smith (1960a) related the compactibility of ignimbrites to their bulk porosity and to the ratio of pumice to solid material present. However, these relationships are also influenced by the extent of welding and secondary crystallisation.

In poorly consolidated ignimbrites large differences in the ratio of crystals to glass will not cause a significant variation in the bulk density. Initial consolidation of an ignimbrite will decrease the porosity, but an increase in the degree of welding and the ratio of pumice fragments relative to the matrix will occur with increased depth.

Peterson (1979) used the flatness ratio of pumice fragments as a direct measure of the degree of compactibility of ignimbrite. Variations in the relative flatness of pumice are related to observed macroscopic and microscopic features in the Te Akau cores in the following discussion.

The results of measurements of pumice are plotted in Fig. 4.10. The profile patterns of the logarithmic flattening ratios in the cores are not consistent with expected changes like those found by Peterson (1979), except probably at the base of Sheet 1 and 2. Peterson found pumice flatness to steadily increase with increasing depth in ignimbrite.

It is not certain if the observed differences in profiles approximate real patterns in the flattening ratio. This is because the core size, the position of pumice fragments around the cores, and the distinction of pumice clasts, influence the number than can be counted and measured. The distinction of pumice fragments near the top of each sheet is difficult because they are camouflaged by rock colour and texture. Therefore variation in the flattening profile is probably due to an insufficient number

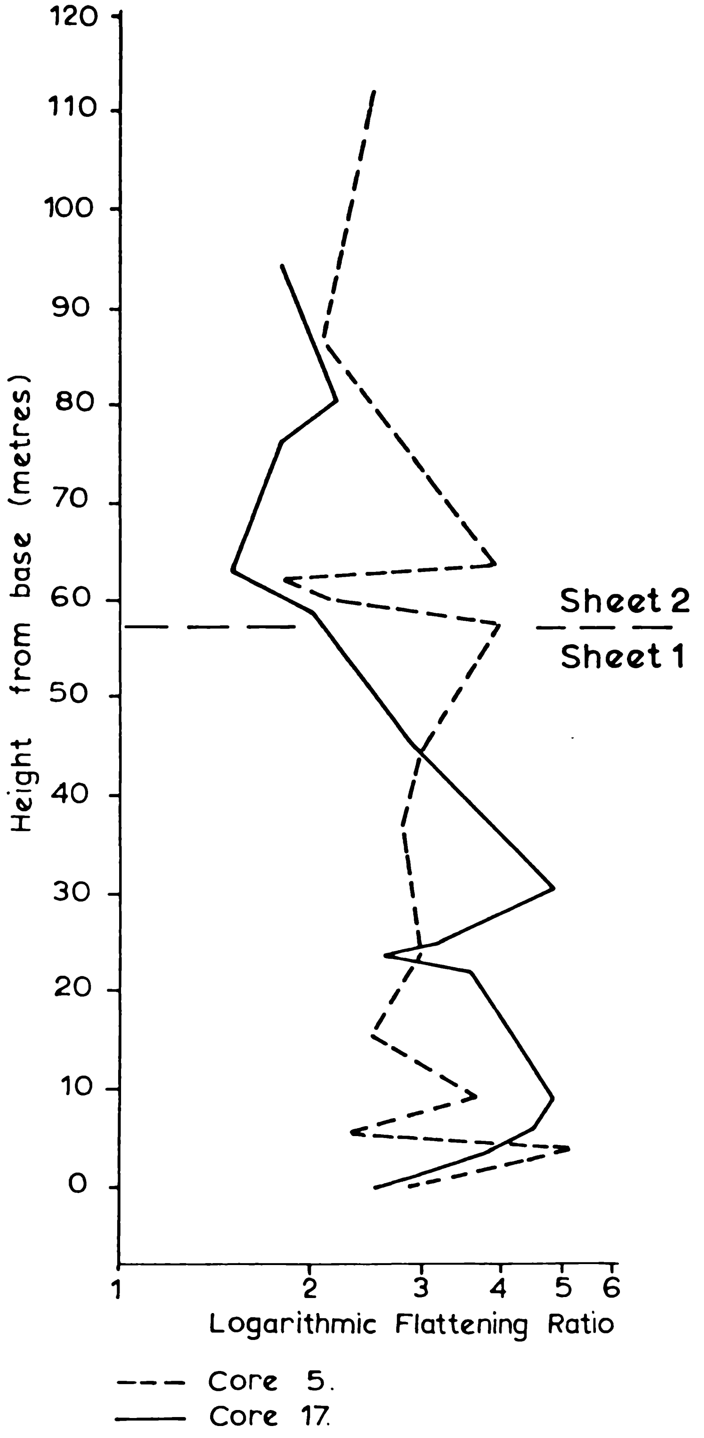


Fig. 4·10 Variations in flatness of pumice.

of measurable pumice fragments in each sample. Only at the base of the sheets are the fragments numerous and clearly defined enough to allow the actual flatness to be measured. This is shown by sudden inflexions in the profiles at these levels (Fig. 4.10).

Typically, the upper parts of both sheets contain undeformed rounded pumice fragments. With depth a gradual change to sub-lenticular to lenticular shapes occur (Fig. 4.1 and 4.2). The shape of the pumice fragments can be influenced by abrasion and flow alignment during emplacement as well as by compaction. Accordingly, the random orientation, the mixed shapes, and a lack of internal collapse structures observed in the upper parts of each sheet are probably due to original differences (Ratté and Steven, 1967). The basal zone of Sheet 2 has been subjected to only moderate compaction compared to the extreme compaction of the comparable zone in Sheet 1. This is seen by the contrast in flatness and colour of the pumice lenticles in Sheet 1 which are thinner and blackened. The flattening ratio in the basal lenticulite of Sheet 1 has a consistently higher value than it has in Sheet 2.

Deformation of pumice during compaction and welding reduces the size of their pores. Ross and Smith (1961) indicate that pumice may be flattened 3 - 20 times. Initial consolidation of the shard matrix in an ignimbrite would be the main influence on the porosity. The final porosity is determined by the degree of compaction of the pumice fragments.

The bulk porosity profile (Fig. 4.9) progressively decreases with depth and is lowest in the basal lenticulite of Sheet 1. There, the ghost outlines of collapsed vesicles are banded and remoulded around phenocrysts (Fig. 4.4). Only a few voids are evident in the lenticles and none are seen in the shard matrix. The flattening ratio of 5 correlates with the minimum 8% porosity.

The modifying effect by compaction makes detection of original variations in texture difficult. The "standard ignimbrite flow unit" of Sparks *et al.* (1973) shows that pumice clasts are usually inversely graded. There is no evidence of this in the core sequences. This may be because of the visual restrictions imposed by the core size. However, field evidence in the western Mamaku Plateau suggests that large (>30 mm) pumice fragments are generally very scarce and scattered, and reverse grading of the clasts does not occur.

4.5.3 DEGREE OF WELDING

Smith (1960b) recognised three zones of welding in ignimbrites: non-welded, partially welded and densely welded. Differentiation of the zones is usually determined by establishing macroscopic, microscopic, and porosity characteristics. Some zones of welding have transitional boundaries and others grade abruptly. Therefore the assignment of zonal boundaries becomes arbitrary.

Welding, as defined by Smith (1960b, p.151), is a process which promotes the union or cohesion of glassy fragments. The degree of welding may range from its incipient stages marked by the sticking together of glassy fragments at their points of contact, to complete welding marked by the cohesion of the surfaces of glassy fragments accompanied by their deformation and elimination of pore space, and perhaps ultimate homogenisation of the glass.

The Te Akau 5 and 17 cores exhibits a diversity of texture, colour and physical characteristics (Fig. 4.1 and 4.2) which is comparable to ignimbrites in the zone of partial welding (Smith, 1960b). This is established in the ensuing discussion.

The top of Sheet 2 consists of a weakly coherent core-rock, which tends to be friable. In thin-section the glass shard matrix is open, but the contact of fragments indicates that the Ignimbrite is in the first stages of welding. The absence of an overlying zone of nonwelding is attributed to erosion.

In the basal lenticulite zone of Sheet 1, the dark "crinkled" pumice particles impart a striking eutaxitic texture which indicates extreme welding and compaction. Thin-sections show the lenticles to be nearly homogenised to a dense welded glass. However, striated structures which co-exist with some lenticles suggest that welding was not completed (Chapin and Lowell, 1979). The absence of voids in the shard matrix suggests that the low porosity (<10%) compares with that of the pumice lenticles.

Ratté and Steven (1967) proposed that a porosity of <10% indicates dense welding. However, Peterson (1979) showed that porosity alone is not a reliable guide to the degree of welding, particularly where ignimbrites, through weathering or recrystallisation, have been subjected to diagenetic deposition of materials. Peterson's (1979) flattening ratio study combined with Ragan and Sheridan's (1972) strain study of pumice fragments suggest that dense welding occurs when the flattening ratio exceeds a value to 6. This corresponds with a bulk porosity of 6% in most ignimbrites. In this study the porosity in the basal lenticulite ranges from 8 - 10% and the flattening ratios are about 5 (Fig. 4.10), which would correspond to a transition between the zone of partial and dense welding. Following the definition of Smith (1960b, p.152) the whole of the Mamaku Ignimbrite represents a zone of partial welding.

4.5.4 MINERALOGY

The results of the modal analysis of the phenocrystic mineral assemblage from specimens of the Te Akau cores are plotted in Fig. 4.11 and 4.12. A comparison of the plagioclase with the total phenocryst abundance

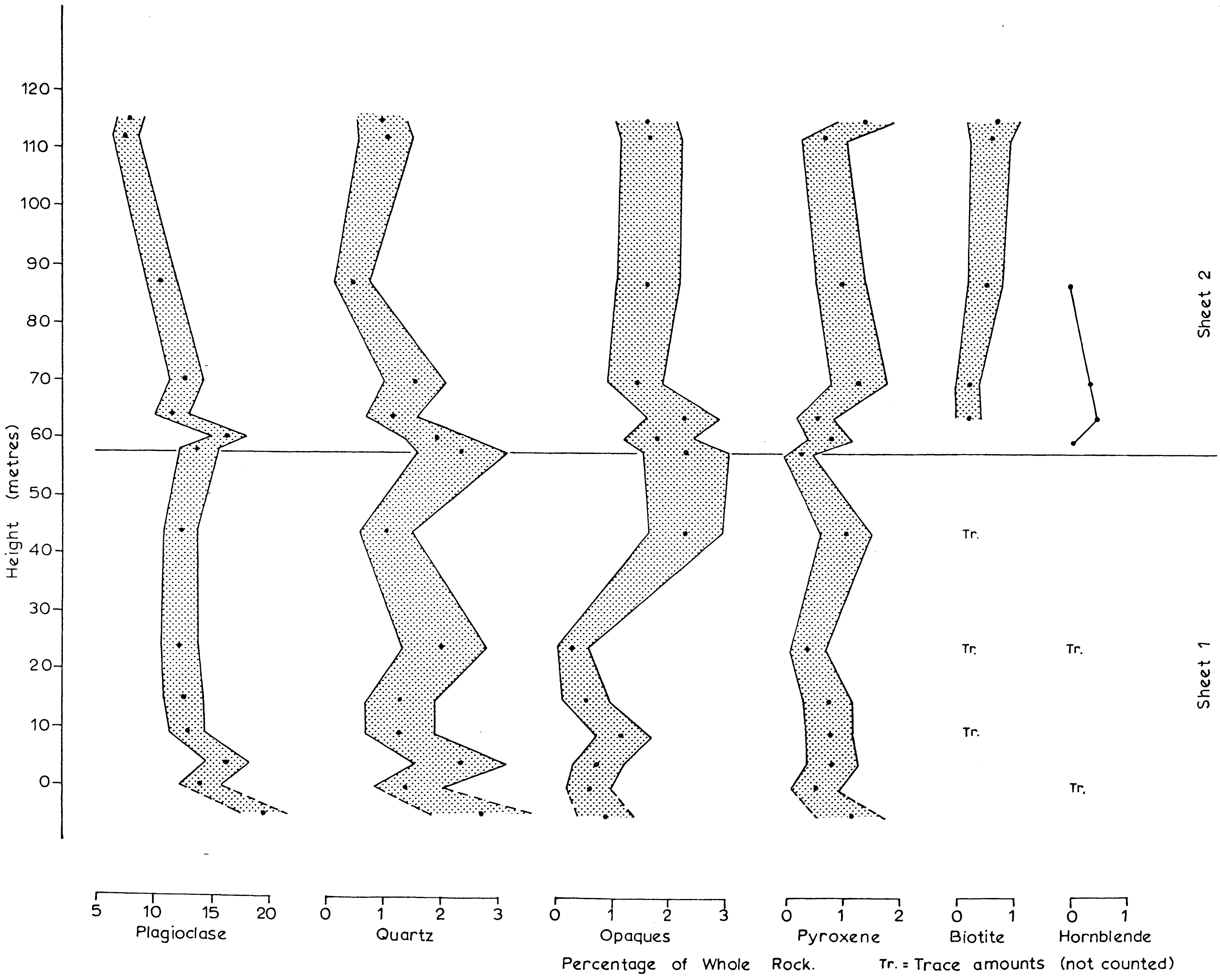


Fig. 4·11 Crystal variations in Mamaku Ignimbrite. Te Akau 5 core.

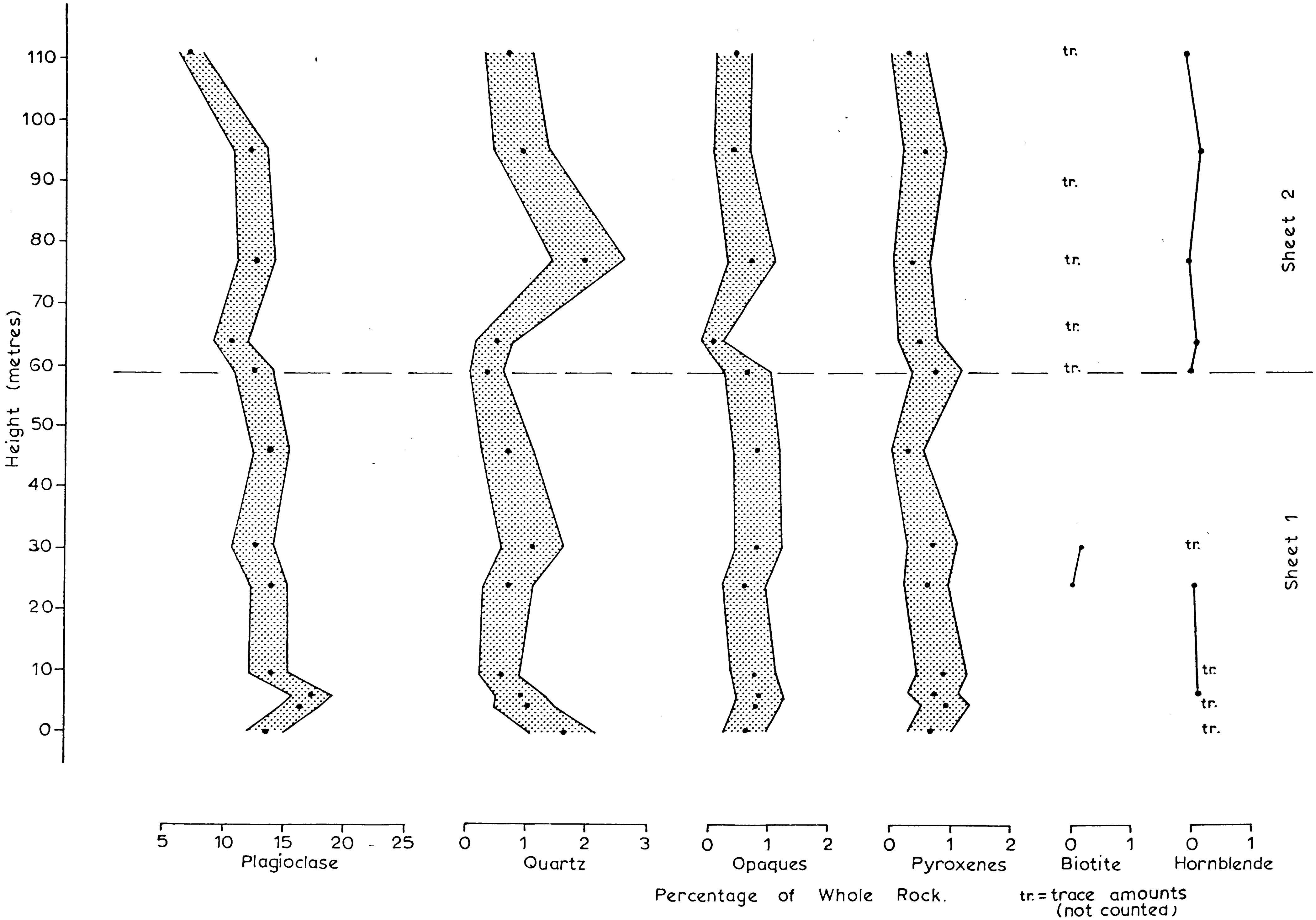


Fig. 4·12 Crystal variation in Mamaku Ignimbrite, Te Akau 17 core.

profiles (Fig. 4.9) shows that plagioclase dominates the mineral assemblage and are mainly attributable to changes in the plagioclase content. Throughout the rest of Sheet 1 there is little vertical change in the plagioclase content, in both cores. However, in Sheet 2, there is a slight decrease in plagioclase content towards the top. This trend occurs in both core profiles and suggests a real variation.

Quartz, pyroxene and opaque minerals constitute only a minor portion of the phenocryst mineral assemblage. Within each core there is little variation in their abundance and where a change occurs in one of the core profiles it is generally non-sympathetic with the other.

Biotite and hornblende occur in very small amounts and only a trace is seen in some thin-sections. Briggs (1973) suggests that the absence or presence of these less abundant phenocrysts can be used to identify mineralogical zones in ignimbrites. However, their absence could be due to the fact that the rock slice (being only 0.03 mm thick) was not cut through a mineral during thin-section preparation. The distinction of Sheet 1 from Sheet 2 on a mineralogical basis is possible only by a slight upward decrease of plagioclase (or total phenocryst) content in Sheet 2 (Figs 4.9, 4.11, 4.12).

4.5.5 BULK CHEMISTRY

The results of seven new X-ray fluorescence analyses of major and trace elements are presented in Fig. 4.13 and Table 4.1. Actual positions of samples selected for analysis are given in Appendix 4.9. The variations in bulk chemistry of the Te Akau 5 core ignimbrite are described below.

The Mamaku Ignimbrite is of rhyolitic composition ($Na_2O + K_2O = 7\%$, $SiO_2 = 73\%$, c.f. Cox *et al.*, 1979, fig. 2.2). The essential fragmental constituents of the Ignimbrite are glass (pumice and shards, 80 - 90%), crystals (10 - 17%) and lithic fragments (0 - 6%). The crystals comprise

TABLE 4.1 Bulk chemical analyses of the Mamaku Ignimbrite from Te Akau core 5.

Sample No.	TOP Mk -3	-6	-8	-10	-14	-15	BASE -17
WT %							
SiO_2	72.93	72.71	72.55	73.09	73.36	72.71	71.65
TiO_2	0.28	0.29	0.13	0.29	0.28	0.28	0.30
Al_2O_3	14.23	13.95	14.16	14.31	13.77	13.67	15.07
Fe_2O_3	2.37	2.50	2.51	2.53	2.37	2.42	2.55
MnO	0.10	0.14	0.08	0.13	0.10	0.12	0.08
MgO	0.24	0.10	0.13	0.33	0.22	0.19	0.25
CaO	1.11	1.49	1.60	1.67	1.55	1.60	1.60
Na_2O	3.49	4.84	4.40	4.47	4.16	4.88	3.78
K_2O	3.03	2.90	2.87	2.85	2.92	2.84	2.76
P_2O_5	0.00	0.03	0.05	0.03	0.03	0.03	0.04
L.O.I*	1.53	0.56	0.53	0.38	0.53	0.57	1.30
TOTAL	99.30	99.52	99.19	100.08	99.28	99.32	99.38
ppm							
Zn	45	27	26	50	49	50	46
Cu	13	12	12	11	11	11	11
Ni	11	8	9	9	6	6	9
Nb	10	8	8	8	9	9	9
Zr	231	208	223	201	214	217	220
Sr	101	123	133	142	123	132	131
Y	53	30	38	40	46	35	36
Rb	104	106	101	100	101	100	78
Pb	14	15	15	16	17	17	19
Ga	16	16	17	16	16	15	15
Cr	<2	<2	<2	<2	<2	<2	<2
V	9	5	8	8	6	5	10
Ba	670	760	700	710	700	710	720

* L.O.I. - loss on ignition

Sample number positions are in Appendix 4.9

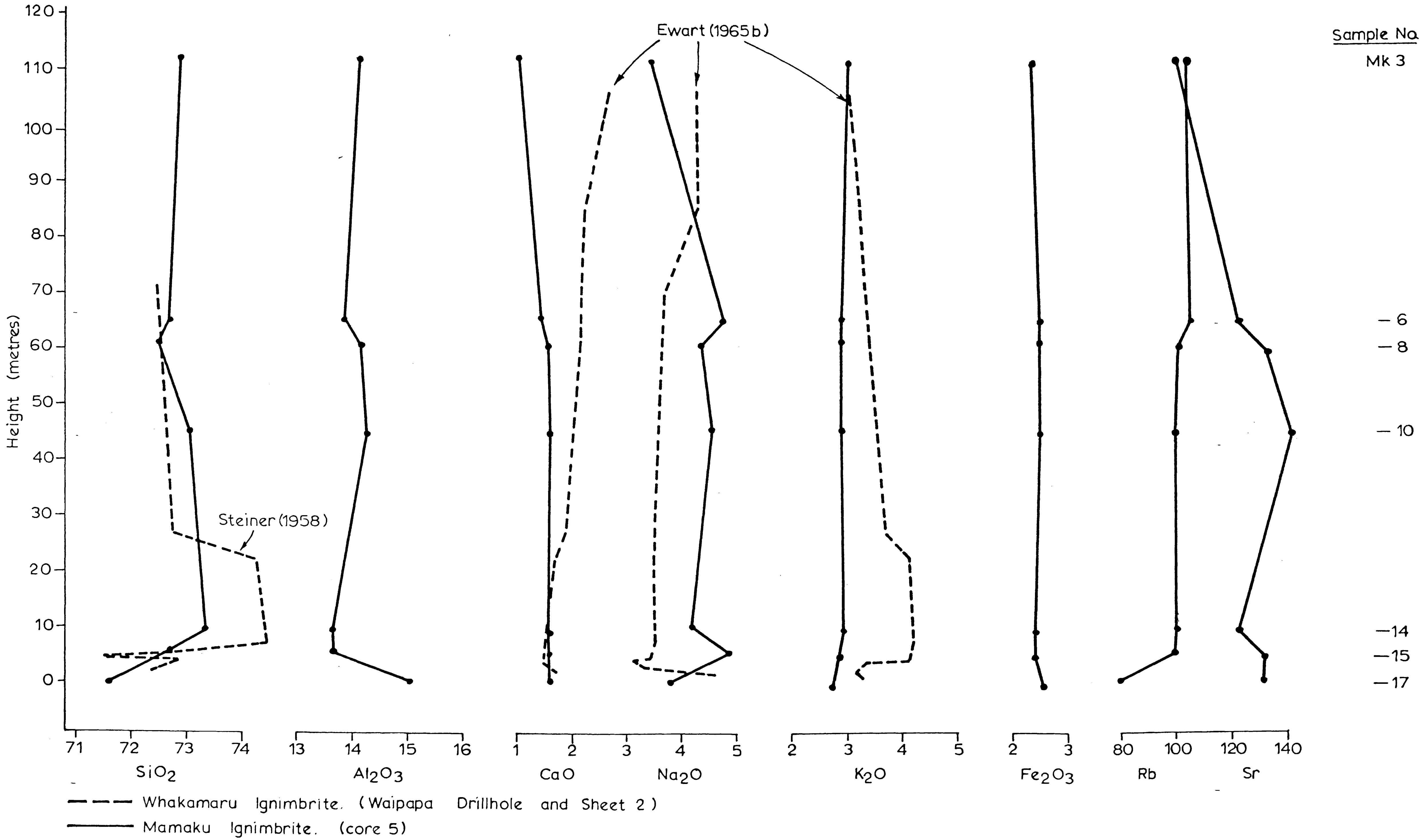


Fig. 4·13 Bulk Chemical variations in the Mamaku Ignimbrite. A comparison is made with the Whakamaru Ignimbrite to to emphasize differences between zoned and unzoned ignimbrite. Data from Ewart, (1965b) and Steiner (1958).

predominantly plagioclase (80%), with small amounts of quartz (7%), pyroxene (5%), opaques (7%) and minor biotite and hornblende (1%). The bulk chemical composition of a rock represents the sum total of elements from the various fragments. In minerals that were crystallised from a magma only small amounts of each element are present in different proportions (Table 4.2). Fractionation processes within magmas result in different levels becoming enriched or depleted in bulk or specific chemical and mineral contents. Elements may migrate through the magma body and minerals crystallise at different rates in response to thermal or pressure gradients and thus produce a variable liquid/crystal magma body. Elements may also migrate differentially in response to a compositional gradient (Cox *et al.*, 1979). Ewart (1965b) found quartz in the Whakamaru Ignimbrite to be particularly enriched where the bulk chemical content of SiO_2 was depleted.

The SiO_2 abundance in the Mamaku Ignimbrite (Fig. 4.13) exhibits an overall slight decrease (0.4%) towards the top of the core sequence. SiO_2 increases from 71.6% at the welded base to a maximum of 73.4% near the top of the glassy lenticulite zone (about 10 m above the base) of Sheet 1. At the base of Sheet 2 a similar, but less pronounced trend in SiO_2 content occurs. These changes in SiO_2 correspond to discontinuities in the abundance profiles of plagioclase and quartz (Fig. 4.11). However, the SiO_2 content profile appears to be independent to that of plagioclase and quartz in the lower 10 m of Sheet 1.

Al_2O_3 abundance ranges from 13.7 - 15.1% throughout the Ignimbrite and shows a slight increase towards the top, antipathetic with SiO_2. Alumina also appears to behave independently to the plagioclase abundance profile in the lower 10 m of Sheet 1.

The pattern of Na_2O content appears to closely follow the plagioclase abundance (Fig. 4.11). Approximately one-quarter of the sodium

Table 4.2 Generalised element distribution in some minerals of the Mamaku Ignimbrite at Ngawaro (from Rutherford, 1976)

	Whole Rock	Plagioclase		Quartz	Hypersthene		Opaques		Hornblende	
Average Mineral Abundance*	14.9%	11.9%		1.1%	0.7%		1.0%		0.1%	
Chemical Abundance		A	B	100% SiO_2	A	B	A	B	A	B
SiO_2	73.80	n.d		1.1	51.19	0.35	0.50	0.005	47.21	0.005
TiO_2	0.28	- 85	10.1	-	0.27	0.002	12.24	0.12	1.55	0.002
Al_2O_3	13.68	n.d.		-	0.60	0.004	1.34	0.01	7.27	0.007
FeO (total)	2.32	0.25	0.03	-	28.84	0.20	44.17	0.44	20.16	0.02
CaO	1.24	7.61	0.90	-	1.25	0.009	0.01	0.0001	10.23	0.01
Na_2O	4.02	6.67	0.79	-	0.04	0.0003			7.73	0.008
K_2O	3.10	0.52	0.06	-	-	-	-	-	0.33	0.0003

A = % of oxides in mineral (from Rutherford, 1976).

B = amount (in %) of a given oxide allotted to the modal abundance of a mineral in the rock (e.g. amount of CaO in plagioclase

$= \frac{7.61 \times 11.9}{100} = 0.90\%$, which is about ½ of the total Cao (1.24%) content in the rock)

n.d. = not determined

\- = absent

* = see Appendix 4.6

is contained within plagioclase (Table 4.2). An enrichment of sodium occurs at the base of Sheet 1 sympathetic with plagioclase content. However, this enrichment trend is incompatible with plagioclase content at the base of Sheet 2.

The CaO content ranges from 1.1 to 1.6%. It is relatively constant in Sheet 1, but decreases slightly (c. 0.6%) towards the top of Sheet 2. A little more than one-half of the CaO content of the Ignimbrite is taken up in plagioclase. The slight upward decrease in CaO is sympathetic to plagioclase content in Sheet 2.

The K_2O abundance varies from 2.8 to 3.0% and there appears to be a slight upward decrease (c. 0.2%) throughout the Ignimbrite core section. Approximately a fortieth of the total potassium is contained in plagioclase.

The total iron (as Fe_2O_3) content is relatively constant at about 2.5% throughout the Ignimbrite core. Titanomagnetite contains a little more than one-fifth of the total iron, and about twice-as-much than hypersthene (Table 4.2). Variation in the abundance of iron would occur mainly in the glassy constituents.

Other major elements such as TiO_2, MnO, MgO, P_2O_5 are present in small amounts (<0.3%) and show minor variation. These variations may be due to analytical errors. The trace elements Cu, Ni, Nb, Pb, Ga, Cr, V, are also present in small amounts (<17 ppm) and vary less than (5 ppm).

Zirconium (Zr) ranges from 201 ppm to 230 ppm and is commonly partitioned into zircon, an accessory mineral which is found in the Mamaku Ignimbrite. Zirconium concentrates in granitic melts and the strong resistance of zircon to weathering leads to a large concentration in resistate sediments (Taylor, 1965).

Taylor also shows Yttrium (Y) to have large abundances in granites and greywackes. In the Mamaku Ignimbrite yttrium ranges in abundance from 30 to 53 ppm and is a good indication that the Ignimbrite was derived from a granitic or a greywacke basement, if partial melting at depth is advocated for the genesis of the magma. A cognate xenolith was identified in thin-section and exhibited graphic intergrowth of feldspar and quartz minerals, typical of granitic rocks. "Granitic" boulders have been found at several localities in the Taupo Volcanic Zone and usually associated with pyroclastic flow deposits (Cole, 1979).

The rubidium (Rb) abundance in the Mamaku Ignimbrite is typical of acid rocks and generally lies within the range of values for other rhyolites and ignimbrites in the Taupo Volcanic Zone (Cole, 1979). The element ranges from 78 to 106 ppm and shows a slight increase from within the lenticulite zone of Sheet 1 to the top of Sheet 2. This trend is similar to potassium and the two elements have similar geochemical behaviour (Taylor, 1965). The bulk of the rubidium in rocks is contained in feldspars.

The abundance of strontium (Sr), overall is slightly greater in Sheet 1 than in Sheet 2 (Fig. 4.13). Strontium increases towards the top of Sheet 1 whereas in Sheet 2 it decreases upwards sympathetic with CaO and plagioclase. Sr is intermediate in ionic size between Ca and K and exists as a free ion in magmas. Strontium is too large to exhibit camouflage with Ca (Taylor, 1965).

4.6 LATERAL VARIATIONS

4.6.1 TOTAL PHENOCRYSTS

The abundance of total phenocrysts samples taken from the distal and proximal sections are shown in Fig. 4.5 and 4.9. Two categories of variation are recognised. The first is the vertical variation within the section(s), and the second is the lateral variation at the Te Akau (proximal) and Leslie Road (distal) sections.

(1) In the Te Akau 5 and 17 cores the phenocryst abundance profiles show only minor lateral variation. In Sheet 2, a small difference occurs where a decrease in total phenocrysts occurs at a higher level in core 17 than in core 5.

(2) In the Leslie Road section two specimens from the top of the Mamaku Ignimbrite (at locality 1 and 5, Fig. 4.6) show only a small difference in the total phenocryst abundance.

These small differences within the sections suggests that the Mamaku Ignimbrite is a relatively homogeneous deposit.

(3) The relative phenocryst abundances at the distal and proximal sections are compared in terms of the distance from the margin of the Rotorua Caldera (Fig. 1.1). Overall, there is an important difference in the abundance of phenocrysts. In the distal section the abundance is less by about half (Fig. 4.5 c.f. Fig. 4.9). Nathan (1975) reports of a similar decrease from the Kaharoa Drillhole to the Lower Kaimai-Omanawa area (Fig. 1.1). In the Whakamaru Ignimbrite, Briggs (1973) observed a systematic decrease in total phenocryst content away from source. Similar decreases in phenocryst abundance have commonly been observed overseas in pyroclastic flows (e.g. Fisher, 1966).

4.6.2 DISTRIBUTION OF SHEETS

Only one of the two Sheets found in the core sequence is believed to occur in the study area. There the Ignimbrite is about 30 m thick and sudden changes in lithology,which would indicate the presence of major flow boundaries,were not found. Other indications of flow boundaries in ignimbrites are the concentration of pumice blocks at the tops of flows and the enrichment of heavy fragments (e.g. phenocrysts and lithics) at the base (Fisher, 1966; Walker, 1972; Sparks, 1976). These features have not been found in the distal section of the Mamaku Ignimbrite.

The presence of zones of randomly orientated and aligned pumice fragments in the Leslie Road section could be interpreted as defining the boundary of two flow units. The zone of aligned pumice occurs in the middle portion of the section and its position may indicate the top of a sheet. However, the alignment of pumice near the base of the Mamaku Ignimbrite was also observed by Nathan (1975) in the Omanawa area. In this zone both shards and pumice are undeformed and it is thought that the alignment of the pumice occurred during deposition rather than at consolidation of the Ignimbrite.

The occurrence of zones of aligned pumice at different levels in the Ignimbrite precludes them from being markers of flow boundaries of two sheets. It is thought that the zones of randomly orientated and aligned pumice comprise the body of a single sheet in the study area. Their origin is discussed in Section 4.7.2.

It is likely that Sheet 1 is present in the western Mamaku Plateau area. This correlation to the Sheet near-to-source is based on a similar vertical pattern of the total phenocryst profile at the Leslie Road (distal) and Te Akau (proximal) sections (compare Fig. 4.5 with 4.9). The total phenocryst profile of Sheet 2 differs, showing a slight vertical upward-decrease. Sheet 1 and Sheet 2 are thought to be adjacent to each other, away from source, and that Sheet 2 forms mainly the northern portion of the Mamaku Plateau (i.e. it extends towards the Lower Kaimai-Omanawa area).

4.6.3 WELDING

Variation in the relative degree of welding at the distal and near-to-source sections is illustrated in Fig. 4.14. The degree of welding

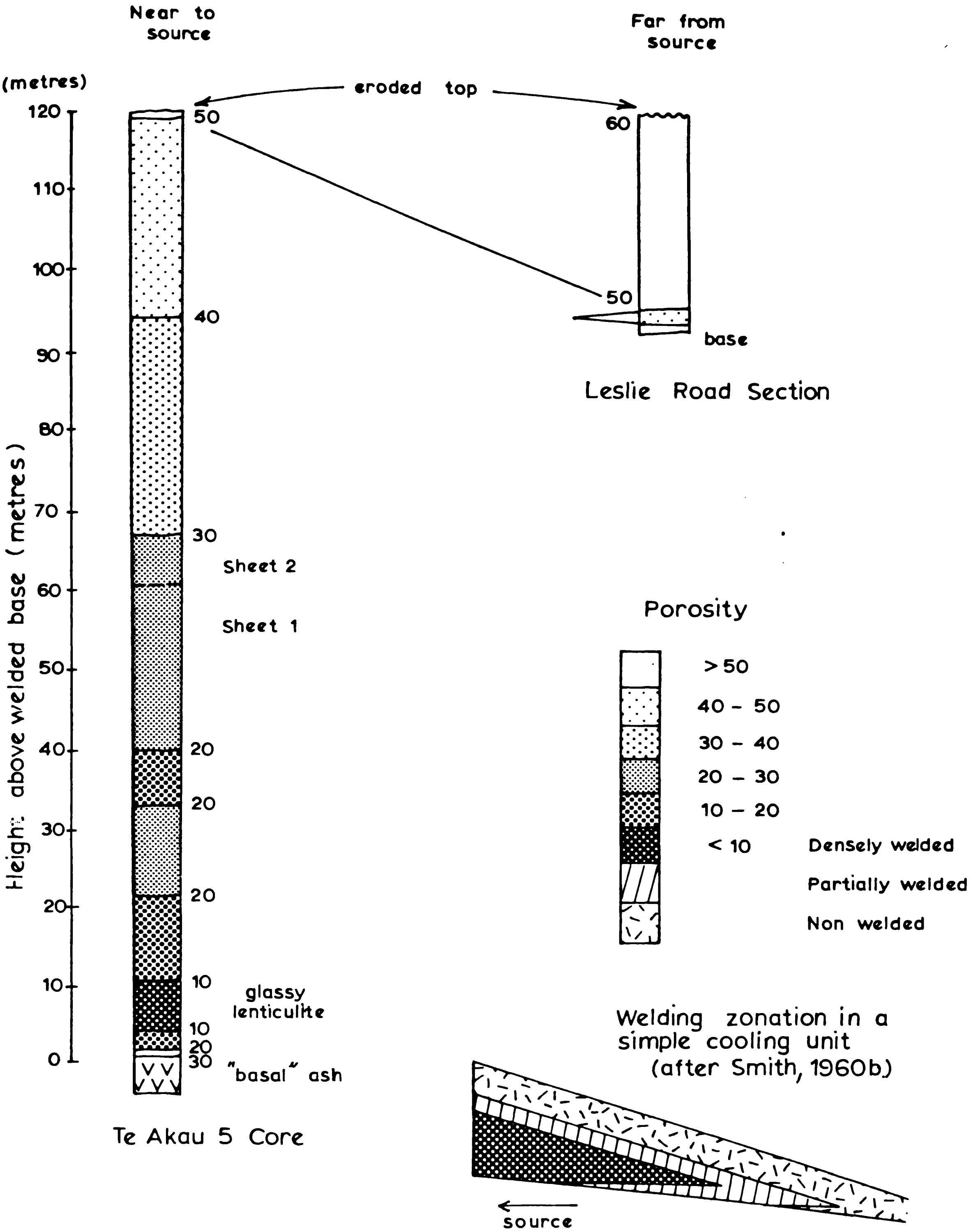


Fig. 4.14 Variation in the degree of welding of the Mamaku Ignimbrite.

in the proximal region is greater, with more diverse and gradual changes in welding. In contrast, the distal section exhibits an even smaller degree of welding and consolidation. This lateral decrease in the degree of welding in ignimbrite is attributed to heat loss during emplacement (Smith and Bailey, 1966). Generally the Mamaku Ignimbrite fits the model of a simple cooling unit as proposed by Smith (1960b), (Fig. 4.14).

4.7 DISCUSSION

4.7.1 INTERPRETATION OF VARIATIONS IN BULK CHEMISTRY

Chemical variations in ignimbrites can be explained in several ways and the likelihood of different mechanisms occurring in the Mamaku Ignimbrite are considered.

There is some evidence which suggests that the Mamaku Ignimbrite was derived from a compositionally homogeneous magma chamber. The abrupt changes in the bulk chemical profiles (Fig. 4.13), are dissimilar and indistinct as compared with those found in zoned magma sequences reported in other parts of the world (Smith, 1960a; Ewart, 1965b; Lipman *et al.* 1966; Lipman, 1967; Hildreth, 1979). Many of these magmas contain compositional gaps ranging from 2% to more than 10% SiO_2 and have corresponding discontinuities or opposing trends of many other elements (Hildreth, 1979). Both Steiner's (1958) and Ewart's (1965b) data from the Whakamaru Ignimbrite provide an excellent example of some bulk chemical differences resulting from a compositionally zoned magma (Fig. 4.13). The Mamaku Ignimbrite's roughly uniform bulk chemical patterns are in contrast to the zonal trends found in the Whakamaru Ignimbrite. The very slight overall decrease in SiO_2 with increasing thickness may reflect an actual magmatic trend in which the lowest part of the magma sequence is basic in composition. However, the absence of any enrichment of elements such as CaO, Na_2O, Fe_2O_3, Sr, and depletion of K_2O, Rb in this upper region of

Sheet 2, suggests there was little bulk fractionation of the magma. The abundance of phenocrysts through the vertical core section is relatively uniform indicating a once homogeneous magma (Section 4.7.2).

If primary magmatic differences in elemental composition were once present they could possibly be obscured by devitrification and vapour phase crystallisation. Pronouced vertical variations in the major elements (K_2O, Na_2O, etc.) were attributed by Scott (1966) to result from the secondary (deuteric) alteration. However, Lipman and Christiansen (1964) showed that no detectable compositional variation occurred by these processes. This antithesis was explained by Scott (1966), to be due to a longer period of cooling which allowed more deuteric fluids to percolate through the ignimbrite. This was also related to the lithology. In Scott's study, the ignimbrite (total 2000 m thickness) has a 30 m thick, black glassy zone, whereas the formation studied by Lipman and Christiansen was thinner (76 m thick), and did not have a black glassy zone. The Mamaku Ignimbrite is lithologically similiar to the unit of Lipman and Christiansen, and differs only in having a thin 6 m thick glassy lenticulite zone (Fig. 4.1).

From the above findings it is thought that primary magmatic differences in chemistry would not have been greatly modified by deuteric alteration.

Scott (1966) indicates that alteration due to weathering and deuteric processes is difficult to distinguish because the degree of alteration is related to the degree of welding. This is evident in the Mamaku Ignimbrite from the partial to complete destruction of pyroxene phenocrysts and recrystallisation of the shard matrix and pumice fragments. The upper porous parts of the Mamaku Ignimbrite are most affected, but this effect gradually diminishes towards the base. In the lenticulite zone the pyroxene phenocrysts are unaltered (Fig. 4.4). The Na_2O abundance is noticably higher in the basal lenticulite zone. Here the lower porosity (Fig. 4.9), is thought to have trapped the fluids and gases and this would restrict the movement of sodium. Scott (1966) found a similar pattern in Na_2O distribution in ignimbrite.

The low sodium content at the porous top of the Mamaku Ignimbrite could be attributed to leaching of this element. Here, the Ignimbrite is weathered and the presence of dessication cracks suggests that weathering processes may have modified the original chemistry.

The low content of K_2O, Fe_2O_3 and CaO suggests their uniform distribution in the Magma (Fig. 4.13). However, intensely oxidised zones in other parts of the Mamaku Ignimbrite occur around joints (Section 2.3.8), and deuteric alteration may be expected to have caused significant enrichment of iron. However, the core-rock appears to have escaped this intense iron staining and this would account for the uniform Fe_2O_3 trend.

4.7.2 INTERPRETATION OF VARIATIONS IN PHENOCRYSTS, PUMICE AND LITHIC ABUNDANCES

Vertical and lateral variations in ignimbrite appear to result from several semi-independent processes (Lipman, 1967):

(1) magmatic differentiation to yield a compositionally zoned magma chamber.

(2) mixing of magma during eruption and emplacement.

(3) sorting of phenocrysts during eruption and emplacement.

(4) post-depositional modification by compaction, welding and secondary crystallisation.

The possibility that any of these processes may have caused textural variations in the Mamaku Ignimbrite is now considered.

Magmatic Differentiation

The mineralogical phenocryst sequence near-to-source in thick ignimbrites probably provides the best picture of the magma sequence. Fisher (1966) showed that in any one vertical section the stratigraphically higher portions of an ignimbrite are youngest and therefore originate from the deeper parts of the magma chamber. Gradual vertical variations in mineral and chemical compositions in numerous zoned ignimbrites elsewhere (Smith, 1960a; Ewart , 1965b; Lipman *et al.*, 1966, Lipman, 1967; Hildreth, 1979), suggest that many erupt from the top of the magma downwards. The Mamaku Ignimbrite is likely to have been erupted from a single magma chamber in this manner.

Vertical sections far-from-source are presumably younger than those at the base of near-to-source sections, because they were emplaced last. However, churning of the original magma occurs during eruption and with increasing distance from source, magma compositions are likely to depart from the original. Vertical changes near-to-source will closely approximate any graduated changes in the magma chamber. This premise is assumed to be the case in the Te Akau core sequences.

The relatively uniform vertical distribution of phenocrysts throughout the core sequences is thought to indicate also a nondifferentiated magma (Fig. 4.11; 4.12). A comparison is made with the bulk phenocryst content of the Whakamaru Ignimbrite to demonstrate the differences in a magma which was differentiated and one that was probably not (Fig. 4.15).

It is usual to find that the phenocryst content of the eruption increases with time, indicating a concentration of crystals towards the lower part of the chamber. Eruptions of this type support ideas of gravitative crystal settling (Cox *et al.*, 1979). However, Ewart (1965b), suggested that increased crystallisation was due to the loss of volatiles at the bottom of the magma chamber from which the Whakamaru Ignimbrite orig-

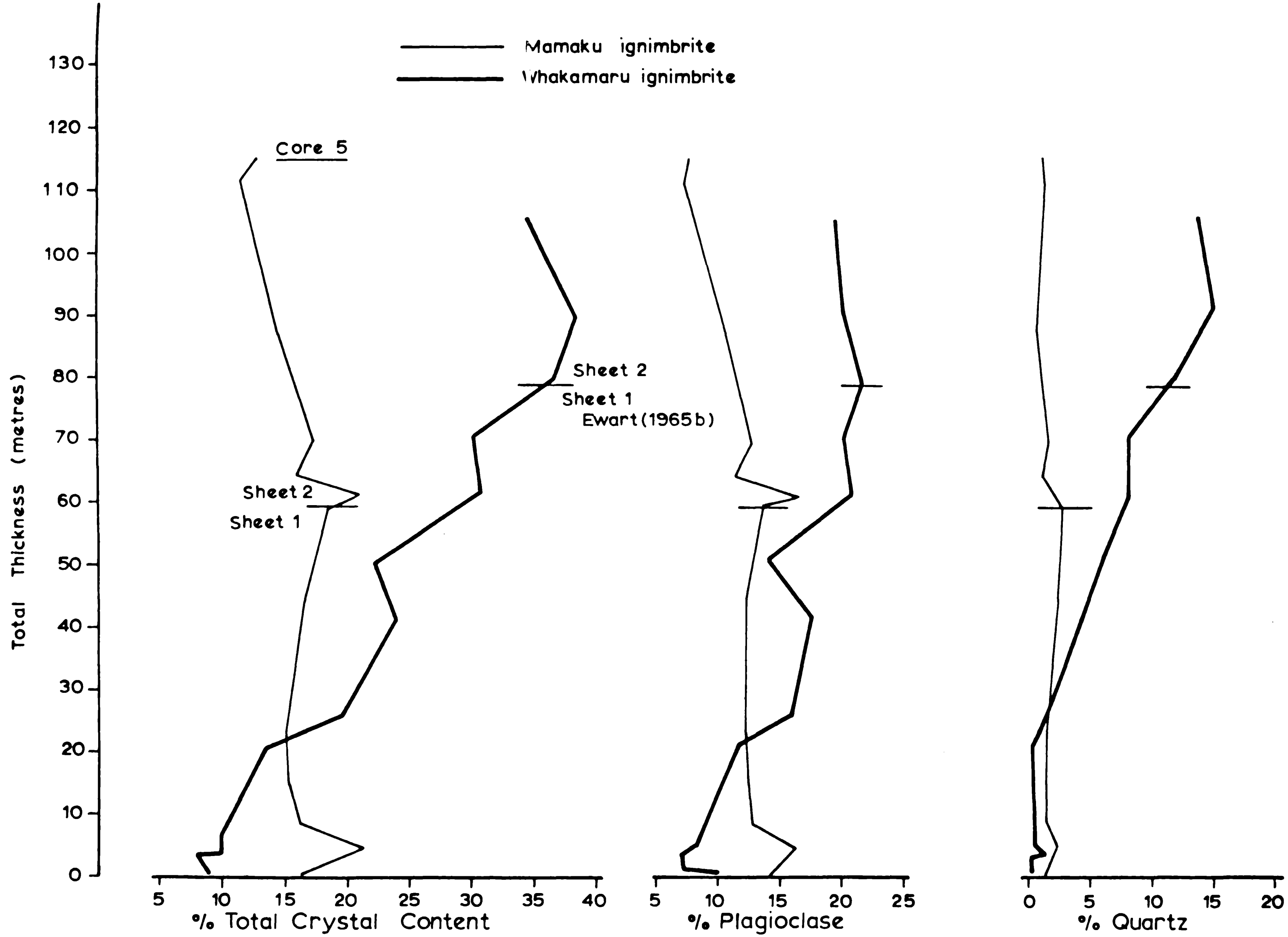


Fig. 4·15 Essential Mineralogical differences between Mamaku and Whakamaru Ignimbrites. Data for the Whakamaru Ignimbrite is from Ewart (1965b).

inated. The slight upward decrease in total phenocryst abundance, in the Mamaku Ignimbrite, opposes the expected zonal trend.

Zonal magmatic sequences often contain minerals in one section and not the other. Lipman (1967) showed that augite and hornblende were present in the upper part (originating from the deeper parts of the magma chamber) and not in the lower part of the Aso III ash-flow sheet. The presence of augite in the basal lenticulite zone of the Mamaku Ignimbrite suggests therefore, that the magma from which it was derived was not mineralogically stratified (i.e. augite is scattered throughout the Ignimbrite). Hornblende and biotite occur at random throughout Sheet 1 and 2. The absence of bulk chemical differences (Section 4.7.1) is supporting evidence of minor compositional variation.

A possible reason for the lack of zonation in the Mamaku Ignimbrite is attributed to its large volume (*c*.300 km^3). Spera and Crisp (1981) conclude that small magma chambers appear to stratify in shorter periods of time and at faster rates than large volume systems. The magma of the Mamaku Ignimbrite is thought to have issued from its chamber in two large eruptions. The eruption of Sheet 1 was closely followed by that of Sheet 2 (Section 4.7.3.), which would have allowed little or no time for the magma of Sheet 2, being of lesser volume, to stratify mineralogically or chemically.

A major constraint against a non-zoned magma hypothesis presented in this study is that the data is limited to bulk rock analyses. Lipman (1967) for instance, showed that the composition of the matrix differed significantly from that of pumice blocks. This would be true of all ignimbrites to some degree. However, Ewart's (1965b) study was based on more detailed compositional analyses of the Whakamaru Ignimbrite, that established petrogenetic reasons for phenocrystic and bulk chemical trends. His study was therefore regarded as the most suitable for comparison with the Mamaku Ignimbrite.

<u>Sorting during Emplacement</u>

The phenocryst rich zones at the base of Sheet 1 and 2 cannot be explained by a sorting mechanism during emplacement. Walker (1972), in treating sorting mechanisms, postulates that crystal enrichment at the base of ignimbrites is due to the preferential loss of ash to the atmosphere from the pyroclastic flow. An analogy can be made with nueé ardentes which travel at high speeds down the flanks of volcanoes. These ground hugging flows became rapidly depleted of ash which form high clouds. McTaggart (1960) showed that hot sand flowed farther than cold and suggests that the mobility of nueé ardentes results from the explosive mixing of cold air and hot fragments because of turbulence in the flow. Wilson and Walker (in prep.) adopt a similar hypothesis for the fluidisation of pyroclastic flows that formed the Taupo Pumice deposits. The presence of a fine grained basal layer is an important feature of many ignimbrite flow units (Smith, 1960a; Fisher, 1966; Walker, 1971; Sparks *et al.*, 1973). Three types of fine grained layers have been recognised in ignimbrite flow units. These are identified as layer 1, layer 2a and layer 3 (Fig. 4.16). Layers 1 and 3 are not integral parts of the flow unit. Sparks demonstrates that the main differences between an ignimbrite and its basal layer is that the basal layer is lacking in coarse particles.

The basal zones of Sheet 1 and 2 have relatively large lenticles which indicates that coarse fragments partly made up the basal portion before compaction occurred. The basal lenticulite zones are continuous in the cores which indicates their association with the body of the Ignimbrite.

The layer 2a may, however, be the sandy "basal" layer which underlies Sheet 1 in core 5 (Fig. 4.1). There are other possible explanations for the origin of this layer (Section 4.5.1).

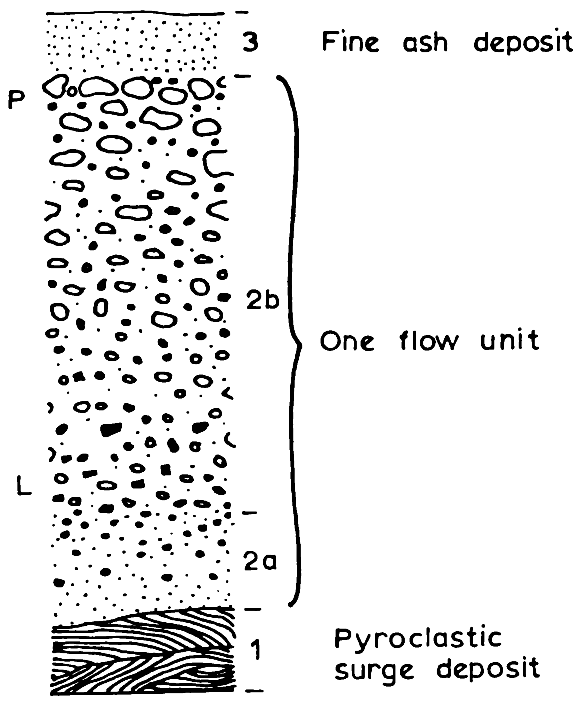


Fig 4.16 Schematic section through the products of an Ignimbrite eruption, showing one flow unit with layers 2a and 2b, underlying pyroclastic surge deposit (layer 1), and fine ash deposit (layer 3); P, pumice clasts; L, lithic clasts. (After Sparks, Self and Walker, 1973.)

Assuming that pyroclastic flows move in a fluidised or quasi-fluidised manner (Sheridan, 1979), phenocryst enrichment in the Mamaku Ignimbrite is thought not to be due to a sorting mechanism. Pyroclastic flows may be thought of consisting of two phases. The first, a continuous fluid phase, consisting of gas and fine particles. The second is a dispersed phase consisting of discrete solids. The solids are part of the flow because sustained flowage would not occur without them. The effect of solids in fluidised material would be to raise the apparent viscosity in proportion to the concentration of the dispersant (Sparks, 1976). The "concentration" is defined as the ratio of solids to transporting fluids.

Sparks (1978) showed that only three size classes would be fluidised. These lie between 0.032 and 1 mm, and constitute about 33% (by weight) of the fluidised flow. Most pyroclastic flows have more than 50% (by weight) particles of less than 2 mm in size (Sheridan, 1979). The majority of phenocrysts in the Mamaku Ignimbrite are well under 2 mm in diameter and constitute only a fraction of the total phenocryst abundance of 15-17% by volume. This volume is equivalent to 40 - 50% *(by weight) and suggests that the phenocrysts were fluidised assuming that the above particle size characterises the Mamaku Ignimbrite.

Enrichment with phenocrysts could only occur if the concentration of dispersed particles was low. The presence of coarse particles, or the absence of a fine grained layer in the basal zones, suggests that the Mamaku Ignimbrite flows had a high particle concentration and that settling of phenocrysts did not occur during emplacement.

The absence of a phenocryst rich basal layer in the distal section on Leslie Road (Fig. 4.5) further supports the hypothesis that phenocyrsts were not vertically sorted there. This seems to be related to the poor sorting of pumice fragments in this zone. At the time of deposition similar flow conditions must have existed in the distal margins as at near-to-source. A poorly sorted deposit is the result of a high particle concentration in which particles of a given size are restricted in their movement (Sparks, 1976). While the larger pumice clasts are subject to grading, the absence of graded pumice in the basal zone of the distal section suggests that a sorting mechanism, in which the pumice was buoyed and phenocrysts concentrated, did not exist.

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* % weight = % volume x density of phenocrysts

In the Mamaku Ignimbrite plagioclase is the dominant phenocryst whose density is 2.6 g/cc.

The slight enrichment of lithic fragments in the basal zones of the Mamaku Ignimbrite is likely to have occurred when they were picked up from the surface over which the Ignimbrite flowed. Alternatively, a low yield strength possibly allowed lithic fragments to sink during flowage. However, the fact that the Ignimbrite carried a large clast to the distal portion (Fig. 4.6), suggests that it had a high yield strength or, a high particle concentration. Sparks (1976, p.175) indicates that for gravitational settling of lithics of 20-100 mm diameter to take place, pyroclastic flows cannot have had a high yield strength.

Compaction

Compaction is thought to account for the enrichment of phenocrysts at the base of Sheet 1 and 2. Likewise the absence of a phenocryst-rich zone in the distal margin is attributed to the relatively uncompacted state of the Ignimbrite there (Section 4.4.2).

Measurements of pumice fragments from the basal lenticulite layer give flattening ratios of between 4 and 5 (Fig. 4.10). This value decreases to less than 3 at the base of Sheet 1, while 17 m above the lenticulite zone the pumice is relatively undeformed. This ratio suggests that the volume of pumice fragments was reduced approximately two times during compaction. Similarly, the total phenocryst maxima are 1½ times greater than the abundance above or below the level at which they occur.

This modal increase is caused solely by an increase in the abundance rather than in the size of phenocrysts. Compaction of the Mamaku Ignimbrite after emplacement is therefore considered to account for the enrichment of phenocrysts in the lenticulite zones of Sheet 1 and 2.

The deformation which formed the basal lenticulite zones is thought to result from instantaneous application of a heavy load. Compaction would take place immediately after the Ignimbrite stopped flowing. As each sheet is about 60 m thick the position of maximum load would occur at or near the base. It is thought that the actual flows of each sheet were more than 60 m thick. The absence of phenocryst rich zones and "2a" layers at other levels indicates that deposition was not by a series of flows in rapid vertical succession.

Magma erupting from the Rotorua Caldera probably supplied a continuous stream of pyroclastic material in great volume. This would account for the wide distribution and the rapid emplacement of each sheet. When the eruption ceased so would a driving force for the flows.

Settling of the Ignimbrite would then commence resulting in preferential compaction and crystal enrichment at the base of the Ignimbrite Sheets. In many other ignimbrites, zones of maximum welding occur at higher levels above the base (c.f. Ross and Smith, 1961). The Waimakariri Ignimbrite in the western Mamaku Plateau is an example. At a locality (224, Map 1) near the Waihou River, the Ignimbrite is 80 m thick and the position of maximum welding occurs about 20 m above the base. The degree of welding and compaction is, however, relatively less severe than the Mamaku Ignimbrite.

4.7.3 EMPLACEMENT MECHANISM

The orientation of pumice fragments and the inclusion of a large foreign ignimbrite clast at the top of the distal section gives clues to the possible mechanism of flow.

The predominantly sub-horizontal alignment of pumice fragments in the middle portion of the section suggests that laminar flowage took place (Fig. 4.6). Similar conclusions were reached by Schmincke and Swanson (1967), Elston and Smith (1970) and Sheridan (1979), for other ignimbrites. However, the random orientation above and below the zone of aligned pumice in the Mamaku Ignimbrite suggests that there was turbulence during emplacement.

A turbulence mechanism has been suggested by many authors to account for the poor sorting in ignimbrites (Fisher, 1966). However, if movement of an ash flow were entirely turbulent there would be no flow lineation (Elston and Smith, 1970).

Sparks 1976), on the other hand, attributes the poor sorting to a high particle concentration and not to turbulence, and suggests that many pyroclastic flows are partly or entirely laminar in their movement. The abundance of pumice is highest in the zone of alignment in the distal Mamaku Ignimbrite section. This suggests that particle concentration was at a maximum and that the movement was laminar.

The question of whether or not the Mamaku Ignimbrite was at all turbulent during emplacement remains uncertain. Turbulence is most likely to occur in the early stages of flow when it is highly inflated and travelling at maximum speed. With increasing distance from source the flow deflates, viscosity and strength increase, and velocity decreases. Sparks (1976) indicates that this results in laminar flow. During late stage laminar flow, the orientation of pumice particles becomes possible (Elston and Smith, 1970). However, the large ignimbrite clast at the top of the distal section suggests that at some stage the flow was turbulent. The clast is assumed to have been picked up from the ground over which the Ignimbrite flowed. For the clast to reach the top of the flow a turbulent eddy must have transported it. A high yield strength kept the clast at that level. It is therefore thought that turbulence as well as laminar flow occurred during emplacement of the Mamaku Ignimbrite. The inclusion of the ignimbrite clast must have occurred closer to source, probably when the flow was mainly turbulent.

4.7.4 COOLING HISTORY

The completely gradational pattern of welding throughout the Mamaku Ignimbrite cores indicates that there was only a short interval of time between the eruption of Sheet 1 and Sheet 2. This is also shown by the relatively uniform gradient of the bulk density and porosity profiles and the absence of sharp reversals in these profiles near the basal contact of Sheet 2. Sharp reversals are usually a good indication of an extended cooling interval, resulting in a lower bulk density and high porosity.

The apparent absence of any airfall ash or weathering at the top of Sheet 1 further supports the idea that there was a very short time interval between eruptions of Sheet 1 and 2. The welding at their boundaries indicates that the temperature was well above that required for welding. Cooling of the two sheets must have occurred virtually simultaneously or in a continuum over a move extended period of time (Smith, 1960a).

In simple cooling units the degree of compaction is controlled by many factors, but viscosity and total thickness are widely accepted as the most important parameters (Sparks and Wright, 1979). Ragan and Sheridan (1972) demonstrated that the maximum compaction and strain occur in the lower - central part of cooling units. This feature is not found in the Mamaku Ignimbrite where the zone of maximum compaction occurs in the basal lenticulite of Sheet 1 (Section 4.5.2).

This extreme compaction and welding must have been caused by the load pressure induced by Sheet 2 at or shortly after emplacement. This is because the base of Sheet 2 is only moderately compacted by comparison, which would have occurred under the weight of its own deposit. Sheet 1 would have had a similar degree of compaction if Sheet 2 was not emplaced on it. Compaction rates partly depend on the temperature of the ash. Therefore the conditions that govern the cooling of an ash-flow sheet must be inferred if the significance of different geometries of zone compaction is to be interpreted (Riehle, 1973). Smith (1960a) suggested that in ash-flows of less than 30 m thick, emplacement temperatures about 735°C are probably necessary for the formation of a densely welded ignimbrite. The

Mamaku Ignimbrite is four times thicker than this, and the basal portion is only in the transitional stage of dense welding (Section 4.5.2). This suggests a much lower temperature prevailed at the time of emplacement. However, emplacement temperatures far below 735°C were probably unlikely, and this is now discussed.

To assess the possible emplacement temperature for welding to occur in an ignimbrite, it is necessary to estimate the permissible cooling. The permissible cooling is defined as the difference between the initial magma temperature and the minimum temperature at which welding will take place. Rutherford (1976) calculated the quench temperature of the magma, using the titanomagnetite geothermometer, to be about 781°C for the Mamaku Ignimbrite. Boyd (1961), from welding experiments of ignimbrites, suggested that the minimum temperature at which welding begins is about 660°C. Given these figures, the permissible loss of heat for the Mamaku Ignimbrite would have been 120°C.

Emplacement temperatures in ignimbrite can be inferred from the relation between maximum density and initial (precompaction) thickness. Riehle (1973, fig. 13b) showed that an ignimbrite having an initial thickness of 20 m and a maximum density of 2.0 g/cc would have an emplacement temperature of 720°. At 40 m initial thickness, this inferred temperature is 680°C. The estimated initial thickness of the Mamaku Ignimbrite is thought to have been much greater than 150 m [estimated from fig. 12b, Riehle (1973), where thickness of the Mamaku Ignimbrite is *c*.120 m = 74% initial thickness at a maximum density of 2.0 g/cc (Fig. 4.9)]. The inferred emplacement temperature, using these figures, would be less than 600°C, which is below that required for minimum welding. This is obviously unrealistic for the Mamaku Ignimbrite because it is nearly densely welded. Furthermore, the gradual downward increase in density suggests that temperature and welding increased with depth.

Boyd (1961) indicates that the amount of heat lost from the interior of ignimbrites after emplacement would be insignificant. Riehle (1973) calculated that the centre of a sheet initially 40 m thick requires about 20 years to cool. The centres of very thick sheets, such as the Mamaku Ignimbrite in the source area, would have remained near emplacement temperature for hundreds of years.

The actual cooling during eruption and emplacement, and between the eruption of Sheet 1 and 2 is thought to be very minor. Evidence for the latter is shown by the nearly linear gradient of the bulk density and porosity profiles (Fig. 4.9). In the former, the Mamaku Ignimbrite flows are thought to have been more than 60 m thick and extended as a continuously flowing mass, which gradually deflated, to the distal margins (Section 4.7.3). In these types of flows, Boyd 1961 indicate that entrapment of cold air would not cause much cooling.

Boyd estimated that the heat lost during emplacement would be less than 5°C per hour or a maximum of 45°C if the emplacement time was 10 hours. Assuming this to apply to the Mamaku Ignimbrite, the final emplacement temperature would likely be between 730 - 740°C. The fact that the base of the Mamaku Ignimbrite is often welded at the distal margins is evidence that it had a high temperature and was able to conserve heat. Such relatively high temperatures, combined with a total thickness of 120 m suggests that a very thick zone of densely welded ignimbrite could easily develop. As this is not the case, it would appear that total thickness is not a vital factor that determines the degree of welding in the Mamaku Ignimbrite.

Other explanations are required to account for the unexpected state of welding, remembering the example of Smith (1960a) stated earlier. The effects of secondary crystallisation and volatile pressures in an ignimbrite may be important parameters which influence the degree of welding. Crystallisation may be induced by loss of volatile components (Boyd, 1961).

That volatiles persisted for great lengths of time is suggested by the presence of zones of fumerolic alteration and vapour phase minerals in the Mamaku Ignimbrite. Compaction rates apparently decrease due to the buoyant effect of entrapped volatiles (Riehle, 1973). This could account for the pattern of welding found in the Mamaku Ignimbrite.

CHAPTER FIVE

GEOLOGICAL HISTORY OF THE WESTERN MAMAKU PLATEAU

5.1 INTRODUCTION

The geology in the western Mamaku Plateau is the product of the local and surrounding regions geological events, resulting from tectonism, volcanism and climatic variation. These factors have also influenced weathering, erosion and sedimentation. Generally the stratigraphic record and relationships in the western Mamaku Plateau fill gaps in knowledge of the regions geological history. Some events are not preserved in the stratigraphic record and information from the surrounding area is brought together to construct a geological history.

Volcanic and climatic events since the Middle Pleistocene, have formed the Mamaku Plateau and its distinct physiography. Evidence of earlier tectonic movements is buried beneath the ignimbrite sheets. The Hauraki Depression and Kaimai Range, however, are features which testify to large scale tectonic movements. Hockstein and Nixon (1979) suggested that this movement resulted from crustal rifting after the collision of the Indian and Pacific plates. Cole (1979) indicates that the depression is a tensional graben structure which developed in association with the Havre Trough (approx. 5 m.y. ago). The development was probably related to re-adjustment of the Indian-Pacific plate margins about this time.

The formation of the Hauraki Depression created a site for sedimentation and the deposition of some ignimbrites which erupted from the Taupo Volcanic Zone (Fig. 5.1).

Evidence for climatic events is imputed from the degree of preservation of the deposits. Generally, periods of warm climate (interglacials) promotes vegetation and increases weathering. Soil is an end-product of weathering, and has horizons differentiated by the relative intensity of chemical processes. The relative degree of soil profile development may be divided into categories of weak, moderate and strong, and this is assumed to be criterion representing short, medium and long intervals of

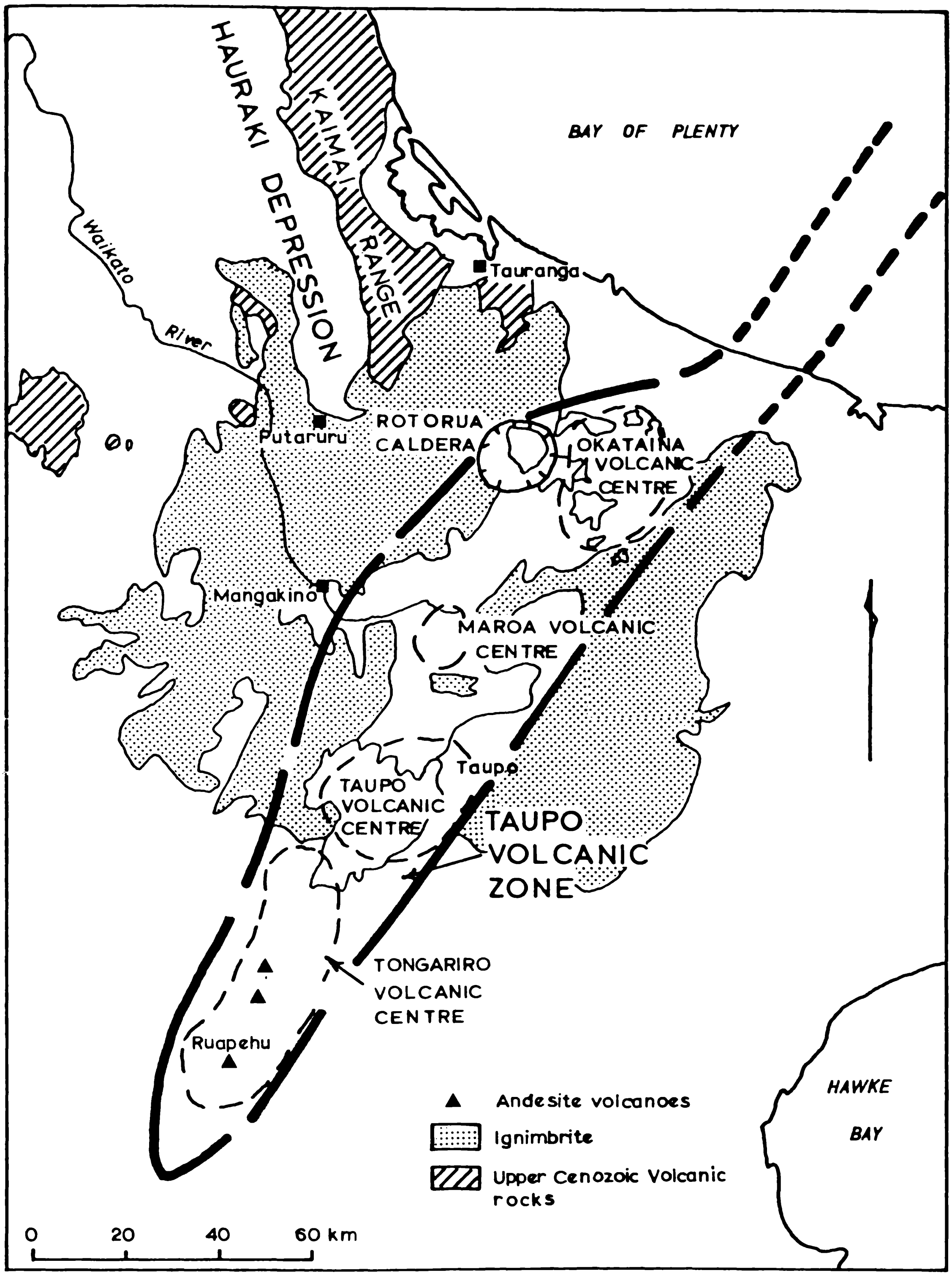


Fig. 5.1. Major geological features of the Taupo Volcanic Zone (from Nathan, 1976).

time respectively. Buried soils are an indirect record of climate (Vucetich and Pullar, 1969), and therefore can be used in environmental reconstruction as well as for correlation and dating (Bowen, 1978). The erosion and deposition of sediments during periods of warm climate is assumed to be negligible. However, erosion increases during glacial periods and large volumes of material are mobilised. Alluvial, colluvial and loess deposits are a strong indication of cold climate events (Vucetich and Pullar, 1969). The stratigraphic record on land is imperfect because geological events are discontinuous. An eroded surface represents time that is lost. Deposits that are weathered represent time that is locked up.

The most valuable means by which events on land can be ordered in time is by the oxygen isotope climatic-stratigraphic record of the deep oceans. This record represents a continuous stratigraphic subdivision of time that is of global applicability Bowen (1979). The oxygen isotope record of Shackleton and Opdyke (1973) is used in this study as a stratigraphic framework for correlating on-land geological and climatic events. Ignimbrites and airfall-tephra deposits are useful stratigraphic markers because they record a moment in geological time. If the age of an ignimbrite is known it can be positioned within the chronostratigraphic framework of the oxygen isotope record. There are difficulties in the precise dating of different pyroclastic deposits erupted within a short time interval. However, those that are well separated seem to provide good chronological control.

A summary timetable of events and effects is shown in Fig. 5.2. The Waihou and Waimakariri Ignimbrites have not been dated, but their relative occurrence in time is inferred from the degree of erosion before and after their emplacement. The geological history of the western Mamaku Plateau can be divided into three phases:

(1) an early ignimbrite emplacement, erosion and faulting phase.

(2) A plateau formation phase.

(3) A plateau erosion phase.

5.2 THE EARLY IGNIMBRITE EMPLACEMENT, EROSION AND FAULTING PHASE

The oldest lithology in the western Mamaku Plateau is the Ongatiti Ignimbrite (0.75 m.y.B.P.). This ignimbrite was erupted from an area east of Mangakino (Briggs, 1973), (Fig. 5.1), and is probably one of the most extensive ignimbrite sheets to cover the central North Island. Evidence from the Karapiro-Arapuni region suggests the Ongatiti Ignimbrite was the only ignimbrite voluminous and extensive enough to reach the Hamilton Basin (Olissoff, 1981). The paucity of outcrops of Ongatiti Ignimbrite in the study area suggests that it was severely eroded and overlain by a succession of younger ignimbrites. This is in contrast to the relatively minor degree of erosion in the Karapiro-Arapuni region, where it appears to have remained as an intact plateau (Olissoff, 1981).

The extensive erosion of the ignimbrite in the western Mamaku Plateau was caused by rivers and streams which were probably diverted from the surrounding highland regions into the Hauraki Depression. The highlands are likely to be in the central North Island, the greywacke ranges in the west and possibly the Kaimai Range.

The Kaimai Range to the north is thought to have existed, as such, at this time because the Ongatiti Ignimbrite does not appear to crop out on the range. It is likely that the range presented a barrier to the flows of the Ignimbrite. In the Hauraki Depression the Ongatiti Ignimbrite probably covered a landscape of some relief caused by an exposed median horst (Fig. 3.4). Evidence for this is the higher elevation (*c*.140 m) of strongly welded Ongatiti Ignimbrite, which crops out east of the buried fault (Map 3), to the weakly welded portion cropping out near the Gun Club (*c*.120 m) (Section 3.2.1). The movement causing the large (>40 m) total displacement of the Ongatiti Ignimbrite could indicate that faulting began much earlier and is most likely to be related to the structural development of the Hauraki Rift.

The uplifted strongly welded portion of the Ignimbrite probably sits on the median horst structure which has an axial strike approximately through the centre of the Hauraki Depression (Fig. 3.4).

Erosion products from the Ongatiti Ignimbrite resulted in sedimentation within the depression where faulting of the horst-graben system continued.

At approximately 0.65 m.y.B.P. the Ahuroa Ignimbrite erupted from the vicinity of Mangakino and flowed northward into the Putaruru area. Blank (1965) recognised three flow members in the King Country but only the upper and middle members are evident in the western Mamaku Plateau. Olissoff (1981) distinguished these two sheets in the Karapiro-Arapuni region and a cooling break between them suggests that they erupted in close succession. The upper member was extremely hot resulting in dense welding and lenticulation of pumice fragments.

A major interval of time lasting about 300,000 years existed between the emplacement of the Ahuroa Ignimbrite and the Whakamaru Ignimbrite (0.3 m.y.B.P.) in the study area. During this time erosion had removed most of the Ahuroa Ignimbrite and in places re-exposed the strongly welded Ongatiti Ignimbrite on the horst. Erosion and sedimentation may have been interrupted on two occasions with the emplacement of the Marshall Ignimbrite (0.52 m.y.B.P., Murphy and Seward, 1981) and the Waiotapu Ignimbrite (age unknown). Although they are not found in the study area they may have extended into here. This is suggested by the great thickness (*c*.100 m) of the Marshall Ignimbrite and the dense welding of the Waiotapu Ignimbrite in the nearby Te Whetu and Lichfield areas (Fig. 1.5). Both ignimbrites may have extended as thin deposits into the study area, but since, have been totally removed by erosion and redeposited in the Hauraki Depression as sediment.

The eruption of the Whakamaru Ignimbrite from the Western Bays of Lake Taupo (Briggs, 1973), produced at least fifteen separate flow sheets. Some of these sheets must have entered the western Mamaku Plateau area. Some parts of the Ignimbrite have a relatively high abundance of pumice and in other parts they are pumice poor and crystal rich. This could indicate separate flow deposits. The Ignimbrite flows covered an eroded landscape and formed the Tokoroa Plateau. The toe of this ignimbrite is thought to have extended much further northwards into the Hauraki Depression, and beneath the Mamaku Plateau. The Ignimbrite is quite thick and moderately welded in the study area which suggests that the nonwelded toe of the ignimbrite occurs further north.

The emplacement of the Whakamaru Ignimbrite is thought to mark a cessation of fault movements related to the development of the Hauraki Depression in the western Mamaku Plateau area. Evidence for this is the slight tilting of joints developed in the Ignimbrite after it had cooled, (Fig. 3.3), near the buried fault (Map 3) on Leslies Road. Also, the absence of north trending faults displacing the younger Waimakariri and Mamaku Ignimbrites in the study area suggests that there has been no movement of the horst since their emplacement. Faulting may have ceased before deposition of the Waihou Ignimbrite. Similar conclusions were also arrived at by other workers. Briggs (1975) suggested that the faulting in the Kinleith area occurred at or after the emplacement of the Whakamaru Ignimbrite. Olissoff (1981) suggested that sediments of the Piarere Alluvium (in the Karapiro-Arapuni region) were derived from the Kaimai Ranges. This suggests that the land surface across the Hauraki Depression was relatively flat. Thus rivers whose source was in the Kaimai Range flowed overland depositing sediment. These sediments are overlain by the Rocky Hill Ignimbrite (0.31 m.y.B.P.), (Olissoff, 1981).

5.3 THE PLATEAU FORMATION PHASE

The Whakamaru Ignimbrite also marks the beginning of construction of the present Mamaku Plateau. Extensive plateaus must have been formed by the emplacement of the earlier ignimbrites, but severe erosion has removed any indication of this. Uplift of the median horst probably formed high ground and depressions on either side. Rivers flowed in these depressions and eroded the earlier ignimbrites. The Whakamaru, Waimakariri and Mamaku Ignimbrites are the most extensive deposits and therefore comprise the bulk of the Mamaku Plateau, testifying to its relative youth. The Whakamaru Ignimbrite contributed a large volume of material much of which is buried. Exposures in the headwaters of the major valley systems (e.g. those valleys of the Waipare Stream and Waihou River) indicate that it extends further beneath the plateau.

The 'top' of the Whakamaru Ignimbrite is also higher in elevation towards the interior of the plateau (Fig. 3.1 and 3.2). This higher level is thought to be partly due to the median horst underlying the Ignimbrite and represents an eroded surface of a paleoplateau (Fig. 3.1).

The Whakamaru Ignimbrite erupted at the onset of a glacial period which lasted approximately 50,000 years (Stage 8, Fig. 5.2). Erosion during this time resulted in the formation of a western paleobasin (Fig. 3.1), and the NW trending valleys which dissected the eastern paleoplateau. These valleys would have collected water from the surrounding highland and streams have taken their course to the Hauraki Depression. Detritus from the eroded ignimbrite was deposited in the depression which represents the regions "sedimentary-sink".

The following interglacial climate (0.25 - 0.19 m.y.B.P.) probably promoted the weathering of sediments which overlie the Whakamaru Ignimbrite. The fine grained lithofacies of these sediments became indurated and oxidised possibly from prolonged exposure and fluctuating groundwater levels. The Waihou Ignimbrite was probably emplaced during this warm climatic period as a number of thin flow units. They filled the dissected valleys on the paleoplateau and in parts of the paleobasin. Slight weathering of the Ignimbrite is evident in some outcrops.

During the ensuing glacial period (Stage 6, Fig. 5.2) much of the Waihou Ignimbrite was eroded. The ignimbrite is poorly consolidated and the harsh physical environment of a cold climate would result in the Ignimbrite being rapidly removed. Re-exposure and continued erosion of the Whakamaru Ignimbrite is evident from contact relationships throughout the study area. A thin veneer of sediments was laid by colluvial wash and by rivers draining off the eastern paleoplateau. Flood deposits are evident in the western paleobasin overlying the Whakamaru Ignimbrite. These sediments probably become much thicker towards the Hauraki Depression.

Sometime during this period of erosion and sedimentation emplacement of the Waimakariri Ignimbrite occurred. This ignimbrite sheet covered the whole study area and formed a new plateau which descended into the Hauraki Depression. Only one sheet appears to constitute the Waimakariri Ignimbrite. The basal portions of parts of the flow was controlled by the eroded topography of the Whakamaru Ignimbrite. Sorting of pumice fragments produced layers of ash, lapilli and breccia, (Section 2.3.6), near the base.

After the emplacement of the Waimakariri Ignimbrite minor faulting occurred, near Whites Road, resulting in small displacements within the underlying sediments and the Whakamaru Ignimbrite. The fault movement is possibly related to subsidence within the Hauraki Depression. These minor faults are considered to be older than about 20,000 years, because they have not displaced airfall-tephras deposited after this time. Furthermore, fault scarps are not seen on the Waimakariri Ignimbrite because of subsequent erosion.

The Waimakariri Ignimbrite is preserved mainly as an intact plateau. Only minor erosion of this plateau is inferred and this is evident from the linear or planar contact relationship with the overlying Mamaku Ignimbrite. However, erosion was more severe at the margins of the Waimakariri Ignimbrite plateau. Near Tapapa, the Mamaku Ignimbrite has filled a small valley cut into the Waimakariri.

The planar contact of the Waimakariri and Mamaku Ignimbrite dips gently (3 - 4^{o}) to the west or northwest. This dip is believed to approximate the original dip of the Waimakariri Ignimbrite at the time of its emplacement. The surface of the Mamaku Plateau has a similar attitude. Ignimbrite flows are generally believed to be highly fluidised and this would account for their extensive distribution and low angles of rest. The great distance (*c.*22 km) of the Waimakariri and Mamaku Ignimbrite from a sourse near Rotorua, would account for their gentle dip.

The Mamaku Ignimbrite flowed much further (i.e. into the Hauraki Depression) than the mapped boundary suggests. Erosion of the ignimbrite since emplacement has removed much of the toe, although remnants of it probably occur in other areas. Valley incision by rivers and colluvial wash were erosive agents which removed large quantities of ignimbrite material.

The eruption of the Mamaku Ignimbrite occurred approximately 140,000 years ago, in the late stage of a glacial period (Fig. 5.2). The Ignimbrite was emplaced in two major eruptive episodes in close succession. Only Sheet 1 is thought to have flowed into the western Mamaku Plateau area. This correlation is made on the basis of the similar shape of the total phenocryst profiles in the distal and proximal sections of the Ignimbrite (Fig. 4.5 and 4.9). The apparent absence of Sheet 2 in the west, and its presence in the Te Akau cores, north of the Rotorua Caldera, suggests that the direction of this flow was roughly northwards. The emplacement of the Mamaku Ignimbrite marked the latest stage in the plateau's formation. From an altitude of *c*.140 m near Whites Road the plateau was built up to approximately 500 m at the southeastern boundary of the study area. This suggests that there is an average total thickness of 360 m of ignimbrite forming the plateau.

5.4 THE PLATEAU EROSION PHASE

Erosion of the Plateau occurred during three cold climatic periods (Fig. 5.2). The first, being the latest stage of a glacial period in which the Ignimbrite was emplaced. A feature of the Plateau which can be seen today is the broad flat surface of the valley interfluves that probably approximates the depositional surface of the Mamaku Ignimbrite. The retention of a flat surface during harsh climatic conditions is an enigma, because the upper vitroclastic nonwelded top of the Ignimbrite is absent. This zone is a common feature of ignimbrite which develops on rapid cooling (Smith, 1960b). The lowest part of a vitroclastic zone is evident in the Te Akau 5 core of the Mamaku Ignimbrite near-to-source (Fig. 4.1).

The emplacement of the Ignimbrite in the late stage of a cold climatic interval suggests that erosion was likely to occur on the plateau almost straightaway. Valley incision began with the drainage of water from the plateau through small channels which drained to the lowlands. Valley incision was probably more severe at the margin of the plateau where it extends into the Hauraki Depression. Winds sweeping across a bare surface of the plateau possibly stripped large portions of the vitroclastic top and a flat surface was retained.

The preservation of the interfluve surface was further aided by the development of a deeply weathered soil on the Mamaku Ignimbrite. This must have coincided with the following interglacial (0.128 - 0.075 m.y. B.P.) in which conditions were favourable for intense weathering to occur.

Renewed erosion of the plateau began with the commencement of another glacial interval about 75,000 years ago. Valley incisions by streams recommenced at the edge of the plateau and progressed towards the interior. The Waimakariri and Whakamaru Ignimbrites were re-exposed and the ignimbrite detritus is thought to have contributed sediments to the first aggradation surface (H_1) of the Hinuera Formation in the Hauraki Lowlands. Cuthbertson (1981) gives a lower radiocarbon date of the Hinuera-1 surface of about 40,000 years. However, it is thought that the first aggradation phase culminated at the end of the glacial about 64,000 years ago when the supply of sediments would be considerably reduced.

During this glacial the surface of the plateau was probably devoid of vegetation. The exposed weathered Mamaku Ignimbrite was probably eroded again by winds which deposited loess on the interfluves and in the floor of the valleys (e.g. in the Purere Stream). In the following interglacial 64,000 - 32,000 years ago the loess was probably weathered.

About 42,000 years ago a series of eruptions began at the Okataina Volcanic centre with the Rotoehu Ash, which was widely dispersed over the central part of the North Island, and is recorded in the ash sequence on the Mamaku Plateau. The Mangaoni Tephra erupted from the Okataina centre about 32,000 years ago. Prior to this, the last glacial began about 32,000 ago. A period of intense erosion between 30,000 and 20,000 years B.P. is well documented (McCraw, 1973), and is thought to correlate with a major phase of valley incision in the Mamaku Plateau. In the lower parts of the plateau the valleys widened and incision progressed towards the plateau interior (e.g. in the long Waihou River valleys). Widening of the valleys probably occurred by large scale rotational slumping of the Mamaku Ignimbrite at the top portion of the valley sides (Fig. 2.2). Valley slopes formed on the Waimakariri Ignimbrite probably receded because of cliff failures and slope wash, which produced the colluvial material on these slopes. Rivers removed the colluvium and deposited the material in the Hauraki Lowlands. There the sediments formed part of the second aggradational surface (H_2) of the Hinuera Formation, which has a lower age of about 19,000 years B.P. (Cuthbertson, 1981).

Vucetich and Pullar (1969) indicate that there was rapid climatic warming after the eruption of the Rerewhakaiitu Ash, *c*.14,000 years B.P., and that it continued until after the eruption of the Rotorua Ash *c*.13,500 years B.P. On the Mamaku Plateau the Rotorua Ash mantles loess deposits and the Mamaku Ignimbrite. The fresh appearance of the loess and Ignimbrite suggests minor weathering occurred and that physical conditions on the plateau were of a harsh cold climate. Some reworking of the Rotorua Ash is evident in the colluvial cover on valley slopes in the study area.

Approximately 13,000 years B.P. a climatic warming into the present interglacial stage is recorded in the oxygen isotope record. In the Mamaku Plateau, valley erosion diminished as forest vegetation enveloped the region.

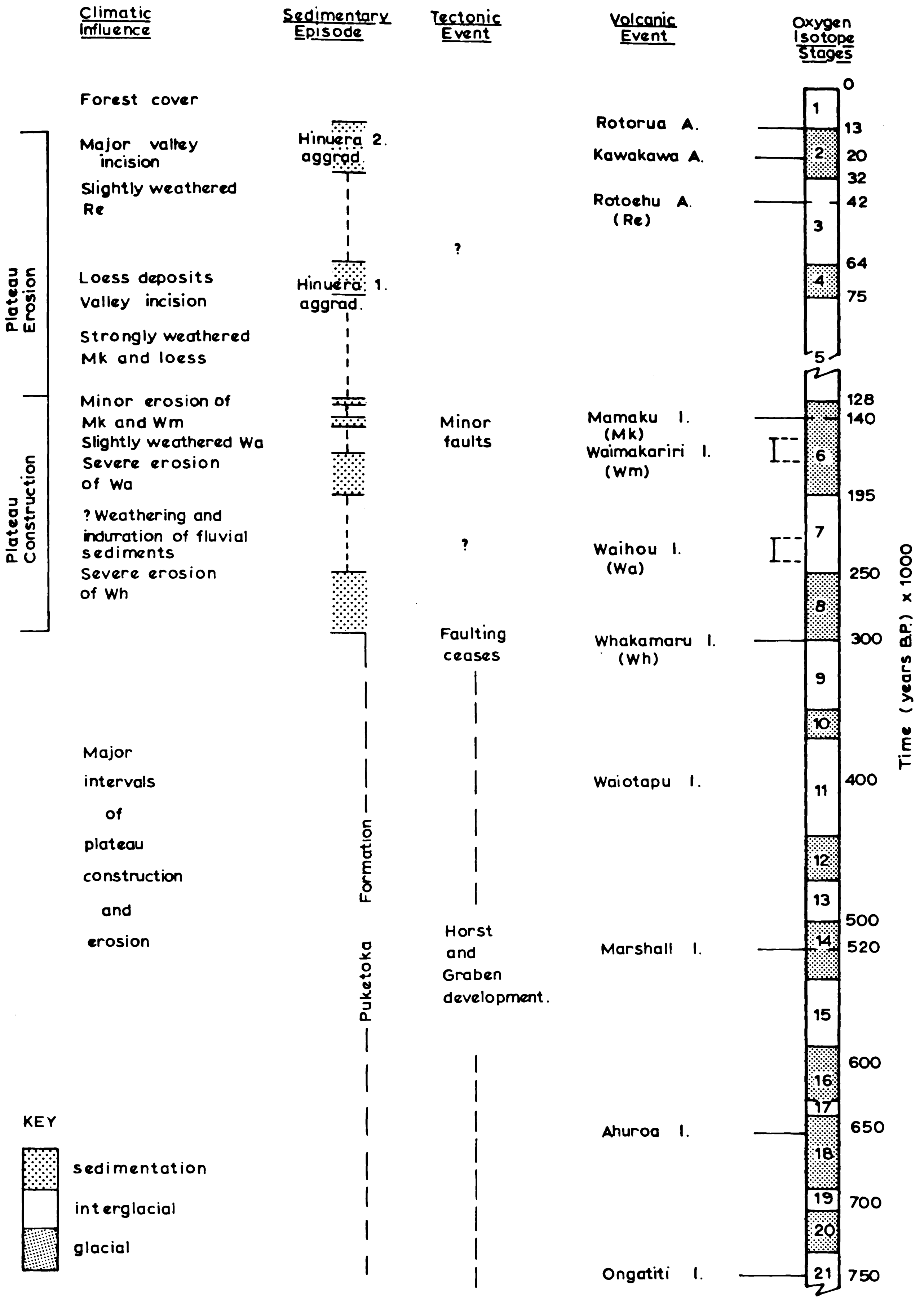


Fig. 5·2 Timetable of events and effects in the Western Mamaku Plateau.

CHAPTER SIX

SUMMARY AND CONCLUSIONS

SUMMARY AND CONCLUSIONS

The stratigraphy in the Mamaku Plateau has been re-defined with the discovery of two new formations (the Waihou and the Waimakariri Ignimbrites) and the subdivision of the Mamaku Ignimbrite into two members (Sheet 1 and Sheet 2) from two near-to-source sections. Only one of these sheets is inferred to extend into the distal, western plateau area.

Changes in lithology which would indicate the boundary of another sheet were not found. Pumice fragments are small (<40 mm) and their grading, which is a feature of "the standard ignimbrite flow unit" is absent. Correlation of Sheet 1 from the proximal - (Te Akau) to the distal (Leslie Road) sections is made on the basis of similarities in the shape of the total phenocryst profiles. Sheet 2 probably extends northwards, from the Rotorua Caldera. In the source area the ignimbrite constitutes a simple cooling unit which indicates that Sheet 1 and 2 were erupted within a short period of time. This allowed welding and cooling to take place simultaneously.

Previous workers in the Lower Kaimai - Omanawa area refer to an "Upper" and "Lower" Mamaku Ignimbrite separated by an erosional unconformity and intercalated sediments. The Waimakariri Ignimbrite is correlated to the "Lower" Mamaku Ignimbrite on the basis of lithology and field characteristics (Table 6.1). It is therefore here proposed that the terms "Upper" and "Lower" Mamaku Ignimbrite be abandoned because, firstly, these ignimbrites represent distinct periods of volcanism. Secondly, the Upper Mamaku Ignimbrite has been subdivided into a lower Sheet 1 and an upper Sheet 2, which are not separated by a time interval of consequence. They are considered to be members of a single eruptive episode. The Lower Mamaku Ignimbrite can be confused with the lower Sheet 1 of the Upper Mamaku Ignimbrite, which is a distinct lithostratigraphic unit. The former "Upper" Mamaku Ignimbrite is here called "the Mamaku Ignimbrite".

Erosional unconformities, layers of detrital sediments between ignimbrite sheets, paucity of outcrops, and buried relief testify to significant time intervals between the eruption of each ignimbrite. Some unconformities, such as the post-Whakamaru/pre-Waihou and post-Waihou/pre-Waimakariri, represent major intervals of time in which large quantities of rock were removed by erosion. However, the post-Waimakariri/pre-Mamaku unconformity was probably of short duration. Minor erosion is suggested by the nearly planar and direct contact of the Waimakariri and Mamaku Ignimbrite. The thin deposits of intercalated fluvial sediments between most of the ignimbrites, indicate that the plateau was mainly a site of erosion and removal of material by rivers. The bulk of the ignimbrite derived sediments were deposited in the Hauraki Depression (see Cuthbertson, 1981).

All of the ignimbrites are easily distinguished on the basis of lithology, outcrop characteristics and in most instances mineral composition. For example, the Mamaku and Waimakariri Ignimbrite have basically similar mineral types, but are otherwise lithologically distinct. The Mamaku Ignimbrite is "devitrified" whereas the Waimakariri Ignimbrite is "vitric". A summary of the major distinguishing features of the ignimbrites is given in Table 6.1.

A detailed study of the Mamaku Ignimbrite has revealed some distinct and unique petrographic features. The study has concentrated on two proximal core-sections and a distal section. Interpretations are limited to the findings in these sections. The basal zones of Sheet 1 and 2 are recognised by a relatively higher abundance of total phenocrysts, plagioclase,and pumice lenticles. Basal 2a layers are absent. The deformation of the pumice in this region is more severe than in the higher parts of the ignimbrite sheets, and represents positions of maximum loading subsequent to emplacement. Thus, crystal enrichment is considered to be due to compaction rather than to a sorting mechanism during deposition.

Sheet 1 and 2 are thought to be emplaced each as a single flow of more than 60 m thick. Wherever the ignimbrite crops out it has a homogeneous texture. The deposition of voluminous, widespread bodies of ignimbrite, such as the Mamaku Ignimbrite, is likely to be powered by continuous emission of magma from the vent. In the distal reaches (about 22 km from the Rotorua Caldera) the flow thinned by more than half its original thickness. A lower velocity is indicated by lower total phenocryst contents (*c*.10%) in contrast with higher abundances (15-17%) near-to-source. Pumice particles are generally, randomly orientated, but at different levels flow alignment suggests that later stage laminar flow operated during emplacement. Furthermore, different parts of the flowing mass probably moved at greater or lesser speeds and so produced distinct zones in which pumice fragments are sub-horizontally orientated.

The Mamaku Ignimbrite represents a simple cooling unit and exhibits typical vertical and lateral cooling zonation features. The ignimbrite is assigned, from physical, welding, and deformational considerations, to a zone of partial welding. This unexpected low state of welding suggests that thickness was not an important parameter in determining the degree of welding. Vapour phase crystallisation and fumerolic alteration indicates that volatile matter persisted in the ignimbrite during cooling. This was probably the major factor which prevented the welding of glass fragments into a zone of dense welding.

The Mamaku Ignimbrite was probably derived from a compositionally unzoned magma chamber. Vertical variations in major element bulk chemistry (SiO_2, Al_2O_3, Na_2O, K_2O, CaO, Fe_2O_3) and mineralogy are negligible, and contrast well with variations in zoned magma sequences elsewhere. An upward-decrease in plagioclase in Sheet 2 is antipathetic to those of other ignimbrites which show an upward-increase in crystal abundances.

The amounts of quartz, pyroxene, and opaques are low and remain relatively constant in vertical section.

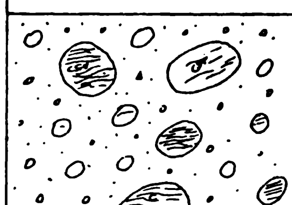
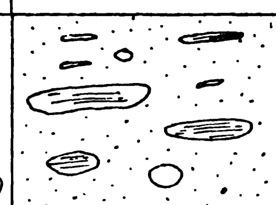
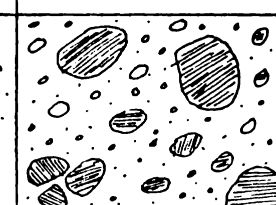
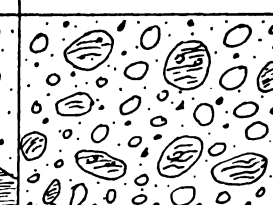
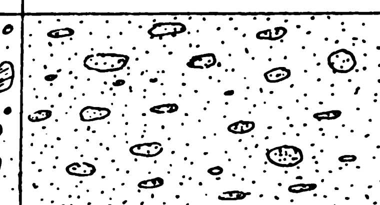
Field evidence in the western Mamaku Plateau indicates that fault movement occurred subsequent to emplacement of the Ongatiti Ignimbrite (0.75 m.y.B.P.) and ceased some time prior to the emplacement of the Waihou Ignimbrite. Much of the movement probably took place before the deposition of the Whakamaru Ignimbrite (0.3 m.y.B.P.). The apparent absence of fault traces on the surface of the plateau suggest that faulting, in the western region, has not occurred during the last 140,000 years.

The major structural feature, a horst-graben-horst system defined by the faults, is possibly linked to the buried axial median horst in the Hauraki Depression to the north. Downfaulted strata in the Kinleith area are also approximately in line with this structural trend. This north-south connection suggests that the Hauraki Rift, to which the faults are associated, extend southwards beneath the ignimbrite plateaux to the western margin of the Taupo Volcanic Zone.

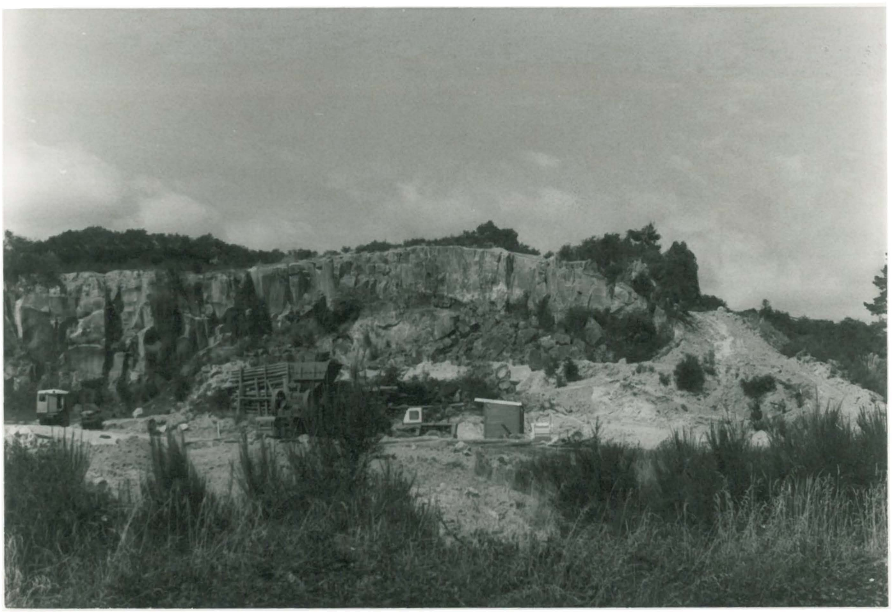
The Whakamaru, Waimakariri and Mamaku Ignimbrite are the most prominently exposed rocks in the western Mamaku Plateau and make up the body of the plateau. The formation of the plateau, as it is today, commenced about 300,000 years ago and terminated with the emplacement of the Mamaku Ignimbrite 140,000 years ago. The Whakamaru Ignimbrite flowed from its source near the western side of Lake Taupo, into the Hauraki Depression near Putaruru. It probably extends much further north and beneath the Mamaku Plateau. The Waimakariri and Mamaku Ignimbrites were derived from a source near to or within the Rotorua Caldera.

Most of the valley incision by rivers on the plateau probably took place during the last glacial stage. The Rotoehu Ash was deposited about 42,000 years ago, on a gently dipping, planar ignimbrite surface, which is now sharply truncated by the valley side slopes. Valley erosion, since that time, is attributed to large scale rotational slumping of the Mamaku Ignimbrite, cliff recession by block toppling of the Waimakariri Ignimbrite, and the removal of waste material by colluvial wash and river transport.

Table 6.1 Major distinguishing features of ignimbrites in the western Mamaku Plateau

Ignimbrite	Ongatiti	Ahuroa	Whakamaru	Waihou	Waimakariri	Mamaku
Outcrop Characteristics	poorly exposed,	jointed bluffs, case hardening	bluffs in valley floor	poorly exposed,	high buff coloured cliffs	forms surface of plateau
Welding Condition	weak - strong	moderate - strong	weak - strong	nonwelded	nonwelded - moderate	nonwelded - moderate
Colour (matrix)	yellow; pinkish grey	grey	grey	whitish grey	yellow; tan	grey; pink
(pumice)	yellow-white	orange	white; black	white; pink	yellow; orange	grey; purple/brown
Pumice (size)	variable	often large	mostly small	often large	variable	mostly small
(state)	vitric	vitric	vitric - devitrified	vitric	vitric	devitrified
Total phenocryst abundance	14.4	4.2	15.5	4.1	9.8	9.7
- plagioclase	11.5	3.7	12.0	3.5	8.4	8.1
- quartz	0.7	-	2.0	0.2	0.6	0.7
- hypersthene	0.5	0.3	0.6	0.1	0.4	0.3
- magnetite	0.4	0.2	0.6	0.2	0.4	0.6
- hornblende	0.7	tr	0.1	0.1	tr	tr
- biotite	0.6	-	0.2	tr	tr	tr
Other features	abundant mafic minerals seen in hand-specimen.	platey pumice	biotite conspicuous in handspecimen. lithic rich	often directly underlies Waimakariri Ignimbrite	large phenocryst clots in pumice ground layer, 2a layers	large areas of iron staining (fumerolic alteration)
Texture						

Appendix 2.1



A view of the Lichfield Quarry which exposes the Ongatiti Ignimbrite in the quarry floor. The Waiotapu Ignimbrite is uppermost and shows characteristic vertical jointing and is densely welded. The Ignimbrite caps a hill and thickens to the left of the photo. Deposits between the Waiotapu and Ongatiti Ignimbrite are thought to be ignimbrites but the formations have not been distinguished.

Appendix 2.2 Modal mineralogical abundance of ignimbrites in the western Mamaku Plateau.

W.R. = whole rock. P = phenocryst. tr = trace. matrix = pumice and shards. Other - apatite or zircon

University of Waikato Sample No.	%	Matrix	Rock Fragments	Total Penocrysts	Plagioclase	Quartz	Pyroxene	Opaques	Hornblende	Biotite	Other
ONGATITI IGNIMBRITE											
WT 18045	W.R.	87.30	2.60	10.10	7.55	1.26	0.15	0.25	0.60	0.30	-
	P.				74.7	12.4	1.5	2.5	5.9	3.0	-
WT 18046	W.R.	82.55	1.40	16.05	13.55	0.35	0.55	0.30	0.40	0.90	-
	P.				84.4	2.2	3.4	1.9	2.5	5.6	-
WT 18047	W.R.	79.10	3.70	17.20	13.50	0.50	0.80	0.60	1.10	0.70	-
	P.				78.5	2.9	4.6	3.5	6.4	4.1	-
Average	W.R.	83.0	2.6	14.4	11.5	0.7	0.5	0.4	0.7	0.6	-
	P.				79.2	5.8	3.2	2.6	4.9	4.2	-
AHUROA IGNIMBRITE											
WT 18048	W.R.	95.15	0.35	4.50	4.10	-	0.20	0.15	tr	-	0.05
	P.				91.1	-	4.4	3.3	-	-	1.1
WT 18049	W.R.	96.30	0.40	3.30	2.80	-	0.25	0.25	tr	-	0.15
	P.				84.8	-	7.6	7.6	-	-	3.3
WT 18050	W.R.	94.95	0.55	4.50	4.15	-	tr	0.20	tr	-	0.05
	P.				92.2	-	-	4.4	-	-	1.1
WT 18051	W.R.	99.30	1.25	4.45	3.70	-	0.60	0.10	tr	-	0.05
	P.				83.1	-	13.5	2.3	-	-	1.1
Average	W.R.	96.4	0.6	4.2	3.7	-	0.3	0.2	tr	-	0.1
	P.				87.8	-	6.4	4.4	-	-	1.6

Appendix 2.2. contd.

	%	Matrix	Rock Fragments	Total Phenocrysts	Plagioclase	Quartz	Pyroxene	Opaques	Hornblende	Biotite	Other
WHAKAMARU IGNIMBRITE											
WT 18052	W.R.	82.30	1.20	16.50	13.50	1.90	0.65	0.35	tr	0.10	-
	P.				81.9	11.5	3.9	2.1	-	0.6	-
WT 18053	W.R.	82.70	0.15	17.15	15.15	0.50	0.75	0.50	0.20	0.05	-
	P.				88.3	2.9	4.4	2.9	1.2	0.3	-
WT 18057	W.R.	83.70	-	16.30	10.35	4.45	0.55	0.55	0.20	0.20	-
	P.				63.5	27.3	3.4	3.4	1.2	1.2	-
WT 18058	W.R.	87.30	0.50	12.2	9.30	1.10	0.40	0.90	tr	0.50	-
	P.				76.2	9.0	3.3	7.4	-	4.1	-
Average	W.R.	84.0	0.5	15.5	12.0	2.0	0.6	0.6	0.1	0.2	-
	P.				77.5	12.7	3.7	3.9	0.6	1.5	-
WAIHOU IGNIMBRITE											
WT 18060	W.R.	91.35	0.30	8.35	7.25	0.60	0.15	0.35	tr	-	-
	P				86.8	7.2	1.8	4.2	-	-	-
WT 18060	W.R.	97.69	0.92	1.38	1.07	0.08	-	0.08	0.08	-	-
	P.				-	-	-	-	-	-	-
WT 18061	W.R.	89.58	7.76	2.60	2.32	-	0.17	tr	0.11	tr	-
	P.				-	-	-	-	-	-	-
Average	W.R.	92.9	3.0	4.1	3.5	0.2	0.1	0.2	0.1	-	-

Appendix 2.2. cont'd.

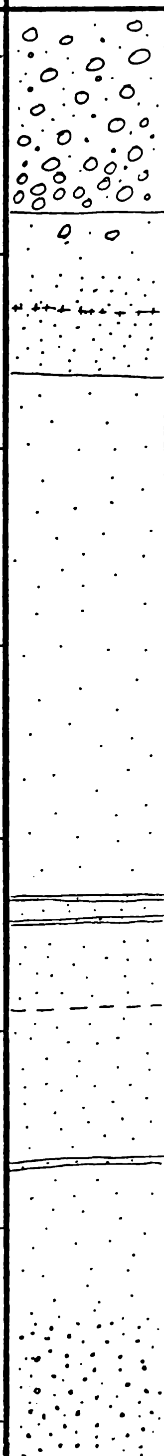
University of Waikato Sample No.	%	Matrix	Rock Fragments	Total Penocrysts	Plagioclase	Quartz	Pyroxene	Opaques	Hornblende	Biotite	Other
<u>WAIMAKARIRI IGNIMBRITE</u>											
WT 18063	W.R.	93.26	0.40	6.34	5.06	0.56	0.40	0.33	tr	tr	-
	P.				80.0	8.4	6.3	5.3	-	-	-
WT 18064	W.R.	89.26	0.20	10.54	9.20	0.20	0.40	0.73	tr	-	-
	P.				87.3	1.9	3.8	7.0	-	-	-
WT 18065	W.R.	90.20	0.47	9.33	8.30	0.33	0.13	0.53	tr	-	-
	P.				89.3	3.6	1.4	5.7	-	-	-
WT 18067	W.R.	91.40	0.40	8.20	6.60	0.86	0.47	0.27	-	-	-
	P.				80.5	10.6	5.7	3.2	-	-	-
WT 18068	W.R.	91.46	0.07	8.47	7.60	0.13	0.40	0.27	-	-	-
	P.				90.5	1.6	4.7	3.2	-	-	-
WT 18043	W.R.	90.10	0.50	9.40	7.70	0.90	0.35	0.45	-	-	-
	P.				81.9	9.6	3.7	4.8	-	-	-
WT 18069	W.R.	94.90	-	5.05	4.65	0.05	0.20	0.15	-	-	tr
	P				92.0	1.0	4.0	3.0	-	-	-
WT 18070	W.R.	78.85	-	21.15	17.85	1.60	1.05	0.55	0.05	tr	0.05
	P.				84.4	7.6	5.0	2.6	0.2	-	0.2
Average	W.R.	89.9	0.25	9.8	8.4	0.6	0.4	0.4	tr	tr	tr
	P.				85.7	5.5	4.3	4.3	-	-	-

APPENDIX 2.3

Detailed stratigrapic descriptions of sediment and ignimbrite (mainly Whakamaru, Waihou and Waimakariri Ignimbrites) relations.

Column A and F described in Fig.s 2.19 and 2.12 respectively.

Stratigraphic Column B, Fig.2.8. Locality 308 Scale 3cm = 0.5mm

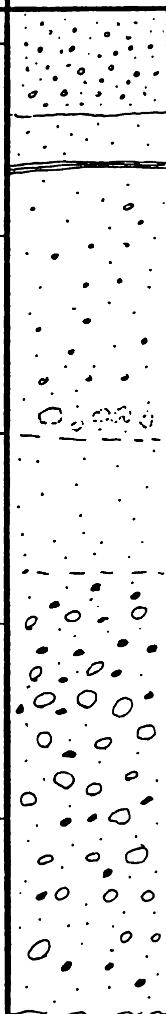


Thickness in metres and Sample No.	Lithostratigraphic Column and Description	Formation
5.5	yellow, nonwelded, pumice-rich ignimbrite with fragments up to 40mm in size. thickness = 3m	Waimakariri Ignimbrite
	grey	
	pink, richer in pumice	
	brown-grey, indurated silty sand. contains some iron stained (weathered) fragments	sediments
5.0	charcoal layer	
	grey-green to yellow, fine to medium sand	
	pink-yellow, very fine sand	
4.5	yellow-grey	
4.0		
3.5	indurated very fine sand or silt	
	red iron stained bands	
	yellow-brown, massively bedded very fine sand	
3.0	greyish white	
	red iron stained band	tephras(?)
2.5	grey, indurated very fine sand with manganese stains	
	reddish brown	
	contains white weathered pumice fragments < 1mm diametre	
2.0	yellow to pink coarse pumice sand 350mm thick	

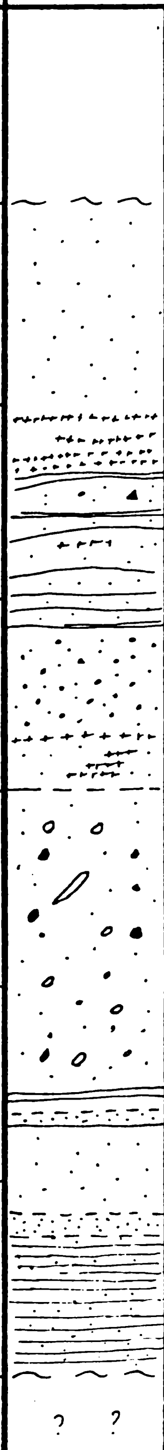
continued

Stratigraphic Column Locality 308 cont. Scale 3cm = 0.5m

Thickness in metres and Sample No.	Lithostratigraphic Column and Description	Formation
2.0	coarse pumiceous sand, water seepage zone	sediments
	pink silty sand iron staining	sediments
1.5	yellow-brown, moderately indurated, sandy silt with abundant white pumice fragments < 5mm in size	sediments
1.0	large weathered pumice(?) fragments 10-20mm in size	sediments
	grey-brown to white massive bedded silt	sediments
0.5	grades into lithic fragment bearing, nonwelded ignimbrite	Whakamaru Ignimbrite
0	yellow-brown to grey, moderately welded ignimbrite with lithics up to]0mm; pumice up to 20mm; biotite flakes are conspicuous	Whakamaru Ignimbrite
	track level	

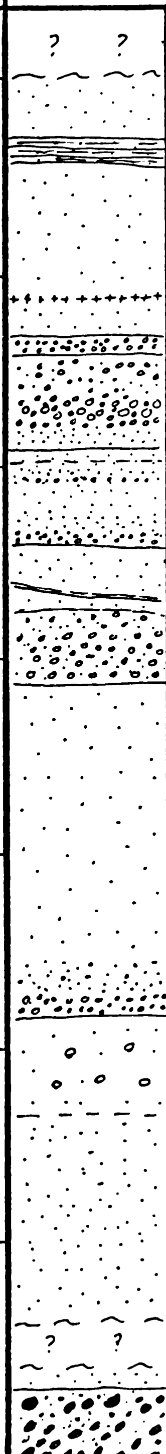


Stratigraphic Column C, Fig.2.8. Locality 269-270 Scale 3cm = 0.5m



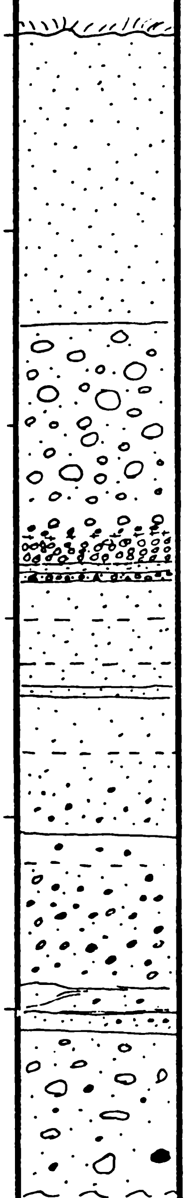
Thickness in metres and Sample No.	Lithostratigraphic Column and Description	Formation
	overlain by Waimakariri Ignimbrite	fluvial sediments
	obscured	
7.0		
	pink (with brown mottles), gritty clay	
	creamy-grey medium sand with interbedded layers of silty clay and charcoal	
6.5		
	lithic fragments scarce, up to]0mm in size	
6.0		
	abundant pebbles	
	reddish clay band	
5.5		
	whitish grey, medium sand with charcoal and lithic fragmentsup to]0 mm in size massively bedded	
5.0		
	sharp contact defined by a white silt overlying a brownish yellow sand overlying white gritty clay over pink coarse sand	
	whitish-grey to pink silt	
4.5		
	pink silt with lithic fragments <]mm	
	pink to grey silty (clayey) sand with inconspicu-ous fine laminae	
	very wet and puggy	
4.0		
	obscured for 0.5-]m	

Stratigraphic Column C, Fig.2.8. Locality 270 cont. Scale 3cm = 0.5m



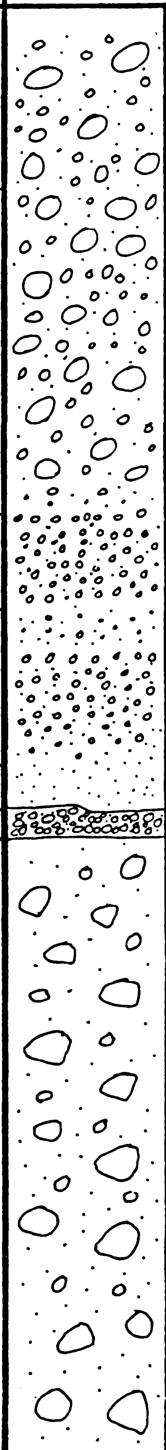
Thickness in metres and Sample No.	Lithostratigraphic Column and Description	Formation
	? ?	
3.0	yellowish brown, strongly indurated, silty sand	
	weathering bands in pink, grey and black hues	
	blue-grey to yellow-grey very fine sand	
2.5	charcoal layer	
	pink, medium sand	
	yellow and black medium to coarse pumiceous sand	
	yellow, coarse pumiceous sand with fragments up to 20mm in size. Similar to pumiceous gravelly sand at Loc. 250.	
2.0	grey to yellow-brown normal graded, med.-co. sand	
	grey, normal graded sand	
	hard indurated yellow "pan"	
	friable, grey to orange weathering(?) bands	
1.5	black, coarse pumiceous sand with normal grading to "pan" above	
	purplish grey, strongly indurated, very fine sand	tephra beds (?)
1.0	normal grading of fragments	
	medium sand mottled with yellow-brown weathering bands	
	coarse sand.	
0.5	dark brown (with black mottles), strongly indurated very fine sand	
	grey, massively bedded, medium sand	
0		
	? ? obscured for 2m	sediments
	yellow silty sand to medium sand	
	massively bedded, sandy gravels, 10-12m thick overlying Whakamaru Ignimbrite	

Stratigraphic Column D, Fig.2.8. Locality 252 Scale 3cm = 1m



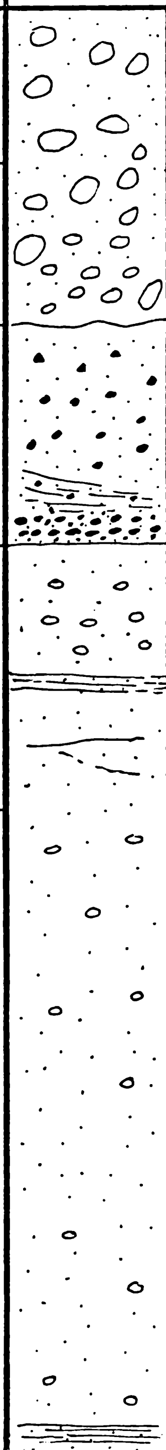
Thickness in metres and Sample No.	Lithostratigraphic Column and Description	Formation
6.0	hilltop	Waimakariri Ignimbrite
	Holocene tephra cover, orange to yellow pumiceous sand	
5.0		
	creamy white, nonwelded ignimbrite containing pumice fragments up to 50mm in size	
4.0	poorly sorted deposit	
	pumice and lithic fragments < 20mm diameter	
	pumiceous gravelly sand, fragments < 20mm in size	
	white sand overlying pumice and lithic bearing layer	sediments
3.0	sandy silt	
	brownish red sand with charcoal fragments	
	creamy grey silty sand	
	yellow-brown silty sand	
2.0	reddish brown, indurated sand with a few lithic fragments	
	yellow-orange gravelly sand. Pebbles of weathered rhyolite up to 20mm and pumice fragments	
1.0	weathering bands	
	pink sand	
	pinkish grey weakly welded ignimbrite. Pumice fragments are flattened (20×2mm), but are up to 30mm. Lithic fragments up to 25mm	Whakamaru Ignimbrite
0		

Stratigraphic Column E, Fig.2.8. Lòcaltiy 26 Scale 1m = 5cm



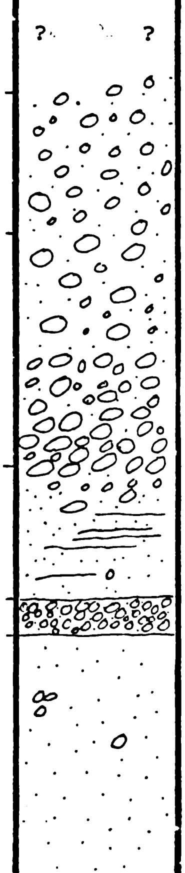
Thickness in metres and Sample No.	Lithostratigraphic Column and Description	Formation
	12m high bluff	Waimakariri Ignimbrite
	orangey-yellow nonwelded ignimbrite contain pumice with fibrous texture	Waimakariri Ignimbrite
2.0		Waimakariri Ignimbrite
	pumice up to 40mm set in glassy ash matrix	Waimakariri Ignimbrite
1.0	fine lapilli-ash	Waimakariri Ignimbrite
0.72	ash	Waimakariri Ignimbrite
	fine lapilli-ash	Waimakariri Ignimbrite
0.23	ash	Waimakariri Ignimbrite
0.08	pumiceous gravelly sand (medium lapilli-ash)	Waimakariri Ignimbrite
0	creamy white nonwelded ignimbrite with pumice fragments up to 140×100mm, average size ≃ 60mm	Waihou Ignimbrite
	approximately 15m thick	Waihou Ignimbrite

Stratigraphic Column E, Fig.2.8. Locality 27 Scale 1cm = 0.1m



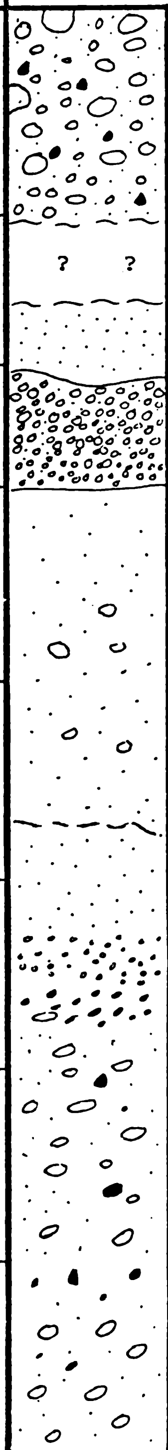
Thickness in metres and Sample No.	Lithostratigraphic Column and Description	Formation
	creamy white nonwelded ignimbrite with white pumice fragments up to 60mm in size	Waihou Ignimbrite
2.0		
1.75	sharp undulating contact	
	orange gravelly sand, pumice- poor, massively bedded	sediments
	laminated sands with some cross-bedding	
1.4	coarse sand, lithic-rich layer	
	white to grey, poorly sorted sand with scattered pumice < 10mm.	
	weak iron stain banding	
1.0		
	massively bedded sand, friable	
0	laminated bedding ROAD LEVEL	

Stratigraphic Column G, Fig.2.8. Locality 49 Scale 1cm = 0.1m



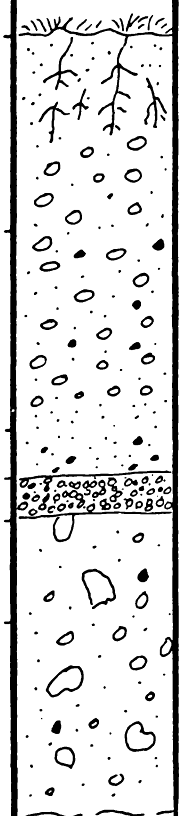
Thickness in metres and Sample No.	Lithostratigraphic Column and Description	Formation
	cliff about 10m high	Waimakariri Ignimbrite
1.2	nonwelded to weakly welded ignimbrite average size of pumice ≈10mm	Waimakariri Ignimbrite
1.0	yellowish grey pumice which contain large femic and mafic crystals , pumice ≈ 10-20mm in size	Waimakariri Ignimbrite
	pumice blocks abundant- ≈40-50mm in size	Waimakariri Ignimbrite
	block-rich zone	Waimakariri Ignimbrite
o.6	grey matrix with whitish grey pumice fragments up to 50mm, laminated medium sand	Waimakariri Ignimbrite
0.42	fragments are poorly sorted ,"2a layer"	Waimakariri Ignimbrite
0.37	white pumiceous gravelly sand, fragments up to 50mm, "ground layer"	Waimakariri Ignimbrite
	purplish orange, massively bedded fine sand, relict pumice clasts up to 10mm in size	sediment
0	water discharge from sand layer into stream	sediment

Stratigraphic Column H, Fig.2.8. Locality 60 Scale 3cm = 0.5m



Thickness in metres and Sample No.	Lithostratigraphic Column and Description	Formation
	whitish yellow pumice fragments, average size 20mm up to 80mm. pink matrix, nonwelded ignimbrite	Waimakariri Ignimbrite
10.8	obscured by vegetation	
	massively bedded fine sand. "2a layer"	
2.8	pumiceous gravelly sand "ground layer"	
2.5	pinkish brown to orange, massively bedded, well sorted, fine sand . strongly weathered with inconspicuous pumice fragments up to 40mm in size	sediments
2.0		
1.5	greyish brown medium sand with lithic fragments up to 20 mm	
	coarse sand, water seeps from this layer	
	lithic-rich	
1.0	pink to white strongly weathered pumice up to 40mm lithic fragments up to 35mm	Whakamaru Ignimbrite
0		
	pinkish grey with increasing pumice content, up to 10mm in size	
	ignimbrite exposed 20m below on Leslie Road	

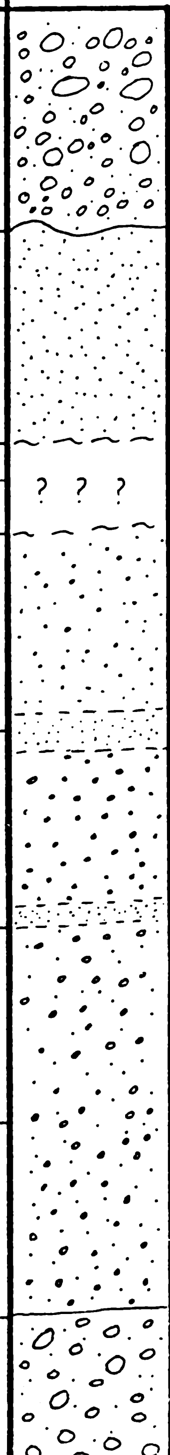
Stratigraphic Column I, Fig.2.8. Locality 76 Scale 3cm = 0.5m



Thickness in metres and Sample No.	Lithostratigraphic Column and Description	Formation
2.0	hill-top	Waimakariri Ignimbrite
	soil and roots	
	pinkish grey ignimbrite with yellow to orange fibrous pumice up to 30mm diameter, average ≈20mm lithics up to 10mm	
1.5		
	pumice-, and lithic-poor, well sorted	
1.0	"2a layer"	
0.9	creamy white pumiceous gravelly sand, crystal-and lithic-rich, "ground layer"	
0.8	pumice sheared off at contact	Waihou Ignimbrite
	creamy white ignimbrite with white pumice up to 80mm in size, lithics up to 5mm	
0.5		
	pumice greyish white 120×80mm ,set in pale yellow groundmass	
0	TRACK LEVEL	

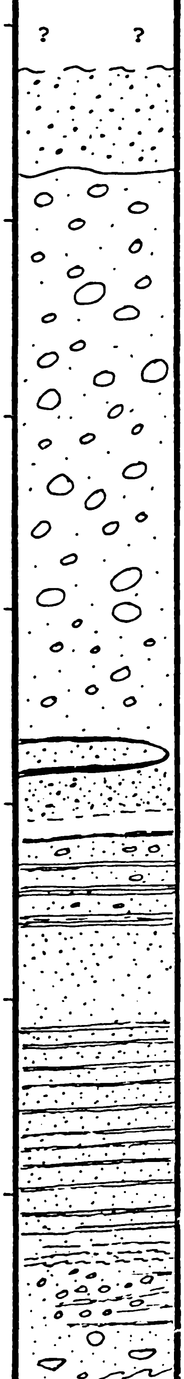
Stratigraphic Column J, Fig. 2.8. Locality 157

Scale A: 3cm = 0.5m
Scale B: 1cm = 0.25m



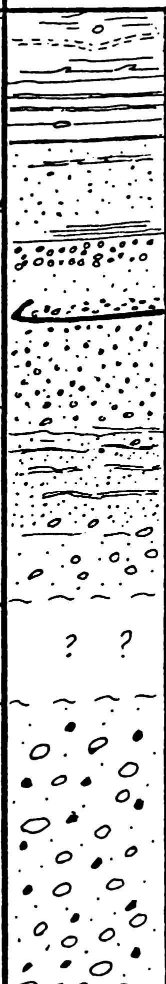
Thickness in metres and Sample No.	Lithostratigraphic Column and Description	Formation
	8m high cliff, in positive relief yellow ignimbrite with to pale grey pumice up to 80×40mm, average size ≃ 20mm	Waimakariri Ignimbrite
5.7	smaller pumice fragments, increasing in size upwards. undulating, erosional contact	
	pale brown, friable, massively bedded, well sorted very fine sand, in negative relief	sediment
5.0 / B		
A	obscured by vegetation but material expressed in positive relief, forms ledge	
2.0	purplish grey to whitish grey, indurated massively bedded medium sand that is moderately well sorted , small (< 5mm) pumice fragments	
1.5	very fine sand	
	blackish grey to yellowish brown, indurated strongly weathered. clayey silt with coarse weath. pumice (?) fragments, moderately well sorted	
1.0	friable silt	
	moderately indurated to weakly indurated with "depth" , as above with weathered pumice fragments ≤ 3mm	
0.5		
0	sharp contact is undulating ≃ 2m along slope orangey brown weathered ignimbrite with pink to yellow pumice up to 30mm diameter correlated across to ignimbrite at Loc. 158	Waihou Ignimbrite

Stratigraphic Column J, Fig. 2.8. Locality 158 Scale 3cm = 0.5m

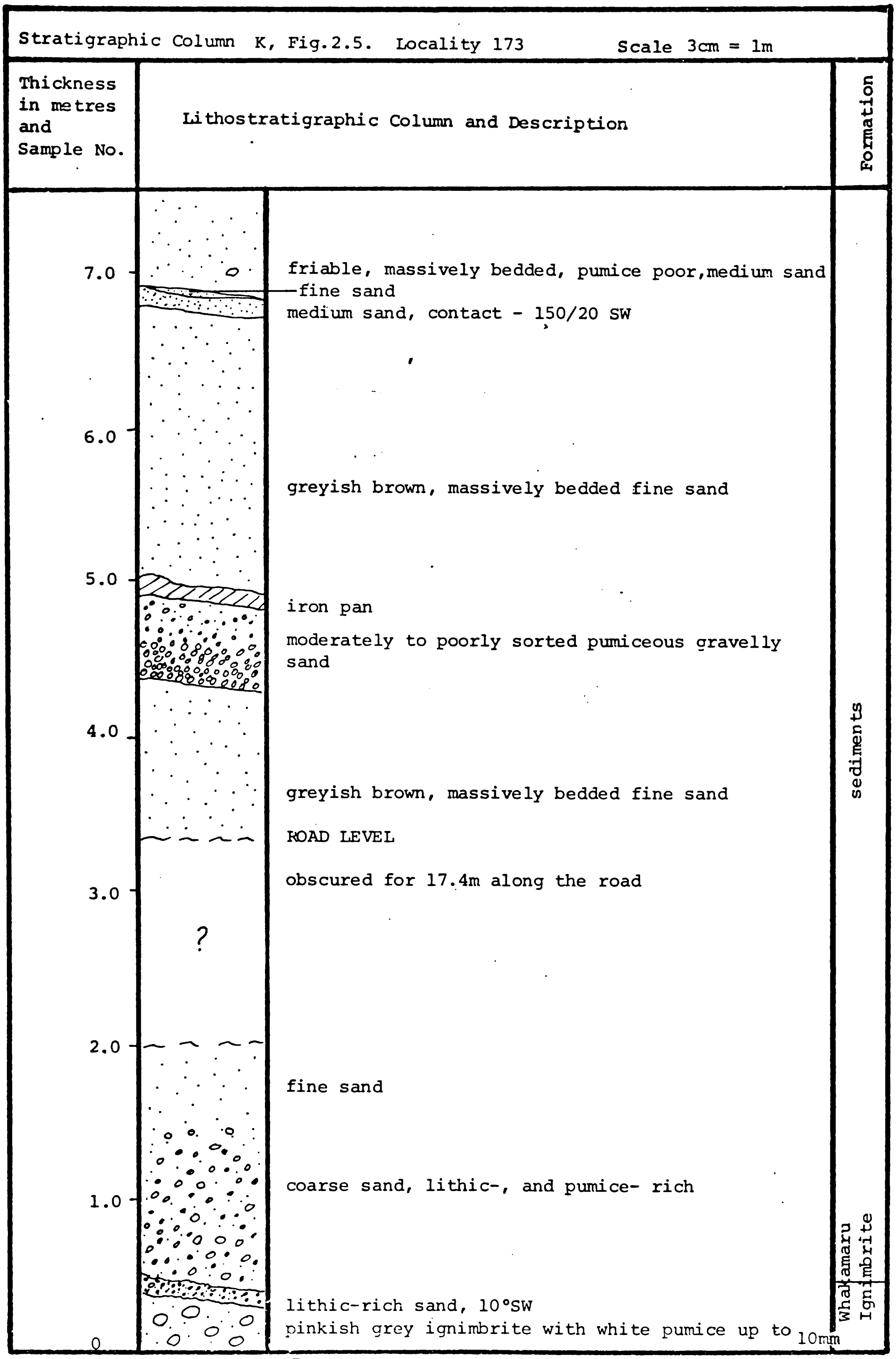


Thickness in metres and Sample No.	Lithostratigraphic Column and Description	Formation
8.0	obscured by vegetation	sediment
	creamy-yellow coarse sand, crystal-, and lithic-rich	sediment
	erosional unconformity	
7.5		Waihou Ignimbrite
	whitish grey ignimbrite with pumice up to 60mm in size but predominantly fine lapilli	Waihou Ignimbrite
7.0		Waihou Ignimbrite
6.5		Waihou Ignimbrite
	iron pan in massively bedded medium sand	sediments
6.0	pale grey	sediments
	white clay silt	sediments
	laminated very fine sand interbedded with planar bedded medium to coarse sand, pumice common	sediments
5.5	medium sand	sediments
	indurated sediments	sediments
5.0	laminated, intercalated white silts with orange brown , fine to medium sand	sediments
	wavy laminated clays	sediments
	pumice scarce	sediments
	clays interbedded with fine sands and silts	sediments

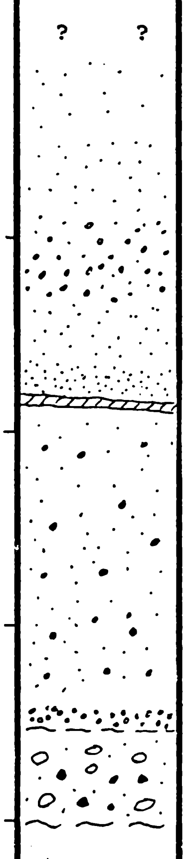
Stratigraphic Column J, Fig.2.8. Locality 158 cont. Scale 3cm = 0.5m



Thickness in metres and Sample No.	Lithostratigraphic Column and Description	Formation
4.5	pumice fragments scarce convoluted , laminated bedding of intercalated white clays and grey sand	sediments
4.0	medium to coarse sand	
	brown coarse sand with iron pan at upper contact	
	iron pan in sandy gravels, fragments up to 10mm inconspicuous planar bedding structure	
3.5	medium to coarse sand interbedded with fine sand and silts. pebbles are scarce	
3.0	? ?	
0	obscured for 3m on swampy slope	Whakamaru Ignimbrite
	pinkish grey ignimbrite with greyish white pumice up to 40mm in size, lithics common up to 10mm	
	base of exposure 15-20m above valley floor	

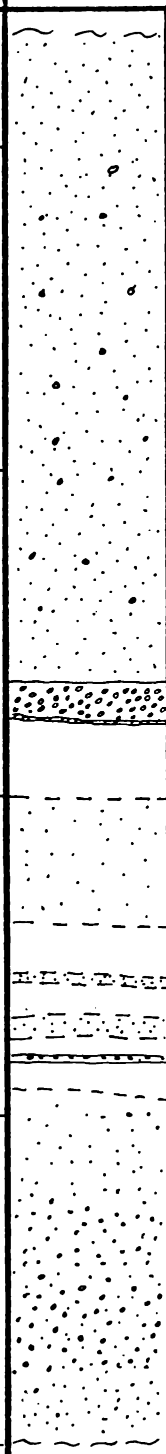

Stratigraphic Column K, Fig.2.5. Locality 173
Scale 3cm = 1m
Thickness in metres and Sample No.
Lithostratigraphic Column and Description
Formation
7.0
friable, massively bedded, pumice poor, medium sand
fine sand
medium sand, contact - 150/20 SW
6.0
greyish brown, massively bedded fine sand
5.0
iron pan
moderately to poorly sorted pumiceous gravelly sand
4.0
greyish brown, massively bedded fine sand
ROAD LEVEL
obscured for 17.4m along the road
3.0
?
2.0
fine sand
coarse sand, lithic-, and pumice- rich
1.0
lithic-rich sand, 10°SW
pinkish grey ignimbrite with white pumice up to 10mm
0
ROAD LEVEL
sediments
Whakamaru Ignimbrite

Stratigraphic Column L, Fig.2.8. Locality 175 Scale 3cm = 0.5m



Thickness in metres and Sample No.	Lithostratigraphic Column and Description	Formation
	bluff approximately 8m high	
	orangey brown fine sand	
1.5	yellow medium to coarse sand	
	fine sand	
	medium sand	
	iron pan	
1.0	purplish grey, massively bedded coarse sand with lithics up to 10mm	sediments
	indurated	
0.5		
	pumice fragment-rich layer, contact ill-defined	
0	pinkish grey ignimbrite with pumice up to 20mm in size, lithic-rich	Whakamaru Ignimbrite
	ROAD LEVEL	

Stratigraphic Column M/N Fig.2.8. Locality 180. Scale 5cm = 1m

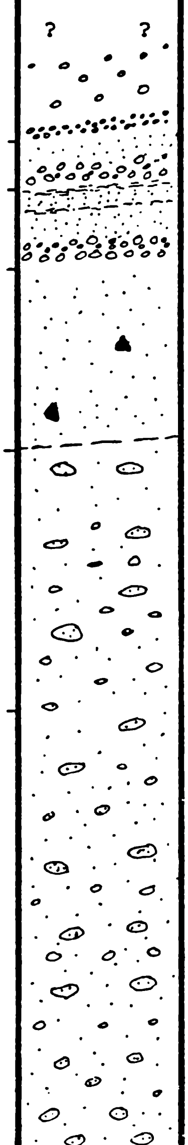


Thickness in metres and Sample No.	Lithostratigraphic Column and Description	Formation
4.0		
	cream-yellow, poorly sorted sand. Lithic fragments common, pumiceous	
3.0		
	pumiceous gravelly sand, fragments < 20mm	
	iron pan	
	brown, massive bedded silt	
2.0		
	yellow, massive bedded medium sand	sediment
	yellow-pink silty sand	
	medium sand	
	silty sand	
	yellow sand	
	brown sand	
1.0		
	yellowish grey massively bedded medium to coarse sand	
	brownish pink sand with yellow pumice fragments up to 5mm in size	
	creamy white medium sand	
0	ROAD LEVEL — overlies Whakamaru Ignimbrite	

Stratigraphic Column Locality 5

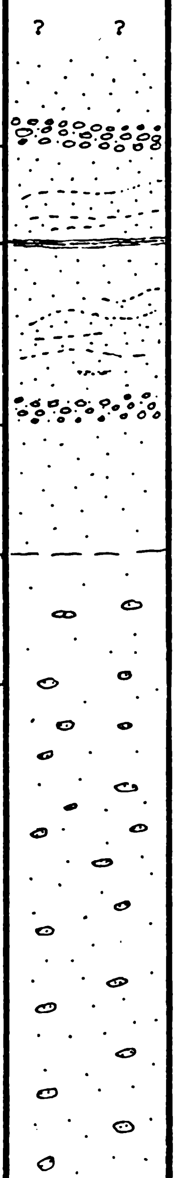
Scale A: 1cm = 1m

B: 1cm = 0.25m

Thickness in metres and Sample No.	Lithostratigraphic Column and Description		Formation
		orange silt with white pumice fragments	Rotoehu Ash
14.6		moderately sorted coarse pumice sand, discontinuous, overlies fine sand	Rotoehu Ash
14.3		coarse pumiceous sand	Rotoehu Ash
		pink to grey ,laminar bedded silt and sand	Rotoehu Ash
14.0		yellow pumiceous sand, discontinuous in section	Rotoehu Ash
		yellowish brown silty sand	Mamaku Ignimbrite
		brown	Mamaku Ignimbrite
11.0		yellowish brown silty sand containing weathered rhyolite fragments	Mamaku Ignimbrite
7.0		pinkish grey nonwelded ignimbrite with grey pumice fragments <30mm in size	Mamaku Ignimbrite
		ROAD LEVEL	

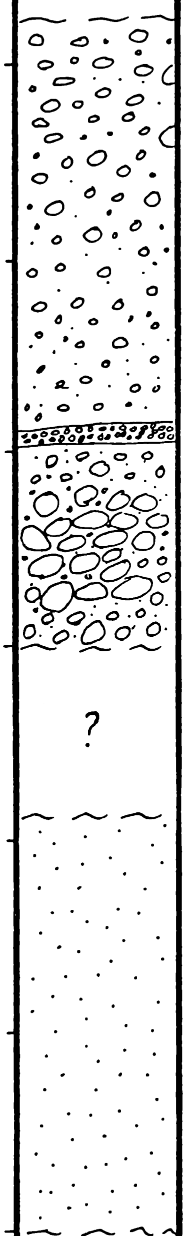
Stratigraphic Column   Locality 15   Scale A: 1cm = 1m
B: 1cm = 0.1m

Thickness in metres and Sample No.	Lithostratigraphic Column and Description	Formation
	? ? obscured by vegetation	
	brown pumiceous silt	Rotoehu Ash
16.4	yellow-orange coarse pumiceous sand	Rotoehu Ash
	yellow very fine sand or silt	Rotoehu Ash
16.2	pink silt	Rotoehu Ash
	silt / sand / silt — crude wavy bedding marked by dark brown to orange weathering bands	Rotoehu Ash
B 16.0	yellow coarse pumiceous sand	Rotoehu Ash
A	brown silt loam	Mamaku Ignimbrite
14.0	fresh grey nonwelded ignimbrite with grey-orange pumice 20-30mm in size	Mamaku Ignimbrite
12.0		Mamaku Ignimbrite
	ROAD LEVEL	



Stratigraphic Column Locality 221 Scale 3cm = 1m

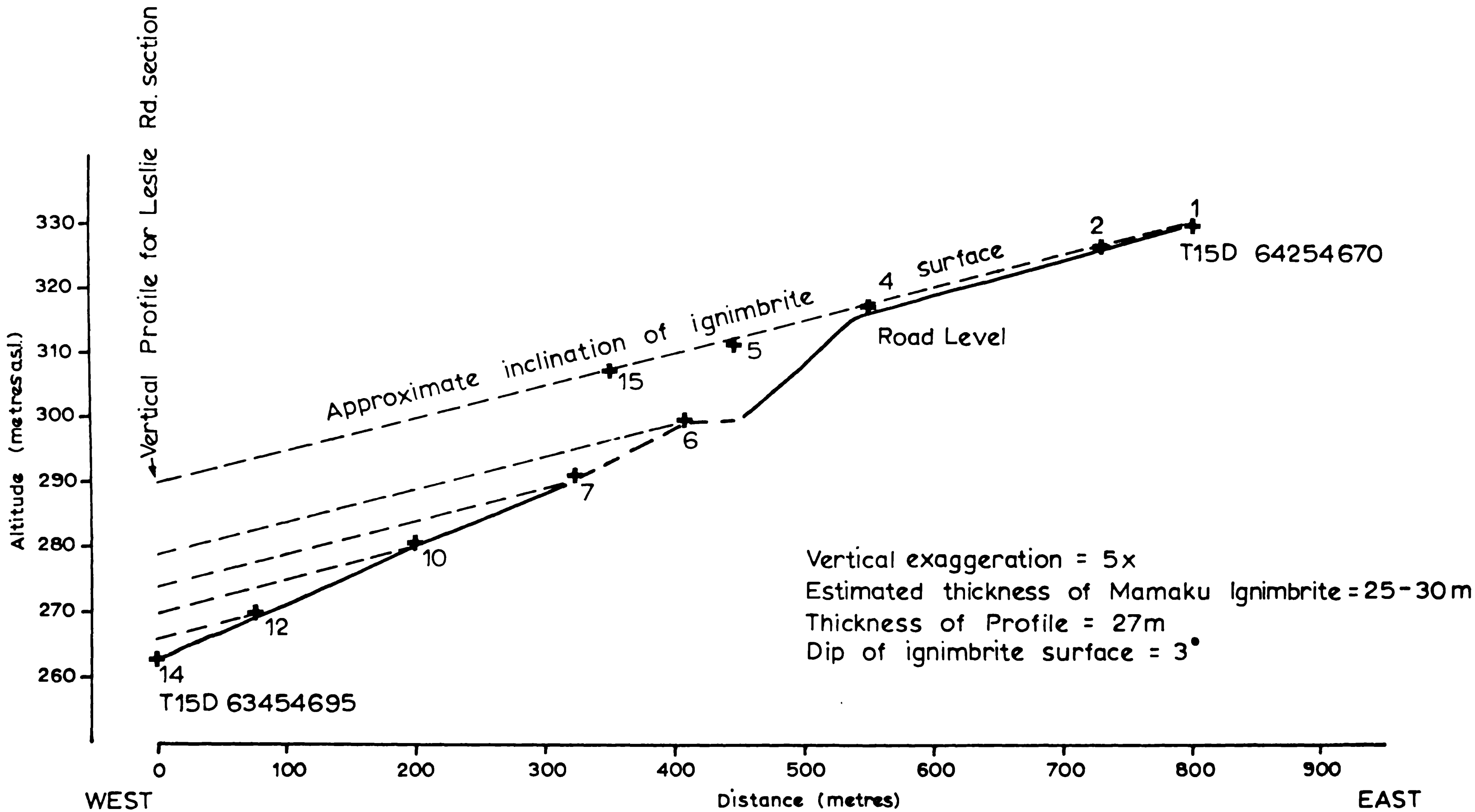
Thickness in metres and Sample No.	Lithostratigraphic Column and Description	Formation
	overgrown. Ignimbrite constitutes 60-70m of the valley slope	Waimakariri Ignimbrite
6.0	weakly welded ignimbrite, pumice fragments up to 50mm	Waimakariri Ignimbrite
5.0	pinkish brown	Waimakariri Ignimbrite
	"2a layer" pumice fragments < 20mm, generally fines (ash) rich	Waimakariri Ignimbrite
	pink, pumiceous gravelly sand, "ground layer"	Waimakariri Ignimbrite
4.0	blue-grey, nonwelded ignimbrite with pumice fragments up to 150mm, lithic-poor	Waihou Ignimbrite
3.0		
	? obscured by swamp vegetation	
2.0		sediment
1.0	brown, indurated, massive, sand	sediment
0	indurated (bluff-form) fine to medium sand	sediment



Appendix 2.4 Bulk chemical analyses of the Waihou and Waimakariri Ignimbrites

	Waihou Ignimbrite WT 18071	Waimakariri Ignimbrite WT 18072
Wt %		
SiO_2	72.29	72.00
TiO_2	0.23	0.23
Al_2O_3	13.43	13.32
Fe_2O_3	2.05	2.12
MnO	0.11	0.11
MgO	0.15	0.31
CaO	1.26	1.16
Na_2O	3.68	3.68
K_2O	3.27	3.48
P_2O_5	0.00	0.01
L.O.I.	2.95	3.18
TOTAL	99.40	99.60
ppm		
Zn	62	54
Cu	9	8
Ni	8	5
Nb	9	10
Zr	183	189
Sr	97	93
Y	39	39
Rb	116	110
Pb	18	20
Ga	15	16
Cr	<2	<2
V	3	4
Ba	730	790

Appendix 4·1



Longitudinal section of Mamaku Ignimbrite, Leslie Road. Sample sites are extrapolated from aerial photograph and contour map and their positions projected to produce a vertical profile.

Appendix 4.2 Location of samples used in laboratory studies from the Leslie Road Section. Site localities are also shown in Appendix 4.1.

Site Locality	Sample No. Field	WT	Height above base	Point counted	Physical properties	Ignimbrite
1	39	18038	27	√	√	Mamaku
5	46	18039	27	√		"
7	48	18040	11	√		"
10	49	18041	7	√	√	"
12	50	18042	3		√	"
14	53	18043	0	√	√	Waimakariri
14	54	18066	0.4		√	Mamaku
14	55	18044	2	√	√	"

WT = Waikato University number

Appendix 4.3 Pumice counts: Mamaku Ignimbrite

Site Locality (see Map 1)		Number counted in 15 x 50 cm	Average Size (cm)	
Leslie Rd.	1	24	2	
	6	67	1.5	
	7	90	5	
	10	69	n.d.	
	12	54	7	
	14, 2m*	49	3	
	14, 0.4m	48	3	
	14, ⁻0.4m	69	1	Waimakariri Ignimbrite
	15	33	2	
Other	73	74	2	
	86	55	1	
	86	87	4	
	94	65	1	
	105	83	?	
	116	91	1	

* Distance above base.

Appendix 4.4 Physical properties: Leslie Road Section.

Mamaku Ignimbrite

Height from base	Bulk Density (g/cm^3)	Particle Density (g/cm^3)	Porosity (%)
27	0.87	2.30	62.1
7	1.06	2.44	56.6
3	1.05	2.28	53.9
2	1.09	2.09	47.8
0.4	1.07	2.39	55.2
0	1.02	2.48	58.9

Appendix 4.5 Modal Analyses of the Mamaku Ignimbrite from the Leslie Road Section.

Sample	%	Matrix	Rock Fragments	Total Phenocrysts	Plagioclase	Quartz	Pyroxene	Opaques	Hornblende	Biotite
WT 18038	W.R.	85.80	3.30	10.90	9.15	0.30	0.55	0.90		
	±2σ		0.78	1.37	1.26	0.24	0.32	0.41		
	P				83.9	2.7	5.1	8.3		
WT 18039	W.R.	91.20	0.50	8.30	6.25	0.95	0.30	0.75		0.05
	±2σ		0.31	1.21	1.06	0.43	0.24	0.39		0.10
	P				75.3	11.5	3.6	9.0		0.6
WT 18040	W.R.	89.15	1.85	8.90	7.55	0.70		0.60		0.05
	±2σ		0.59	1.25	1.16	0.37		0.34		0.10
	P				84.8	7.9		6.7		0.6
WT 18041	W.R.	82.64	6.56	10.80	9.16	0.40	0.68	0.52	0.04	
	±2σ		0.97	1.22	1.13	0.25	0.32	0.28	0.08	
	P				84.8	3.7	6.3	4.8	0.4	
WT 18044	W.R.	89.70	0.65	9.55	7.85	1.05	0.20	0.40		0.05
	±2σ		0.35	1.29	1.18	0.45	0.20	0.28		0.10
	P				82.2	11.0	2.1	4.2		0.5

W.R. % of whole rock

±2σ % standard deviation $p \pm 1.96\sqrt{\frac{pq}{n}}$ where $p = \frac{x}{n}$,

P % of phenocrysts

1.96 = value of spread at 95% level

n = total points counted

x = target fragment e.g. all phenocrysts, plagioclase

q = 1 - p

Appendix 4.6 Modal Analyses of the Mamaku Ignimbrite from the Te Akau cores.

W.R. = whole rock; ±2σ = error at the 95% level of confidence; P = phenocryst

Sample	%	Matrix	Rock Fragments	Total Phenocrysts	Plagioclase	Quartz	Pyroxene	Opaques	Hornblende	Biotite
Core 5										
WT 18001	W.R.	87.50	0.05	12.45	7.65	0.95	1.45	1.60	-	0.75
	±2σ	-	-	1.45	1.16	0.43	0.52	0.55	-	0.39
	P	-	-		61.7	7.7	11.7	12.9	-	6.0
WT 18002	W.R.	88.60	0.05	11.55	7.30	1.05	0.70	1.65	-	0.65
	±2σ	-	-	1.40	1.14	0.45	0.37	0.56	-	0.35
	P	-	-	-	64.3	9.3	6.2	14.5	-	5.7
WT 18003	W.R.	85.85	-	14.15	10.50	0.45	1.00	1.60	0.05	0.55
	±2σ	-	-	1.53	1.34	0.29	0.44	0.55	0.10	0.32
	P	-	-	-	74.2	3.2	7.1	11.3	0.3	3.9
WT 18004	W.R.	82.70	-	17.30	12.75	1.55	1.35	1.40	-	0.25
	±2σ	-	-	1.66	1.46	0.54	0.51	0.51	-	0.22
	P	-	-	-	73.7	9.0	7.8	8.1	-	1.4
WT 18005	W.R.	83.90	-	16.10	11.40	1.15	0.55	2.25	0.50	0.25
	±2σ	-	-	1.61	1.39	0.47	0.32	0.65	0.31	0.22
	P	-	-	-	70.8	7.1	3.4	3.1	1.6	14.0
WT 18007	W.R.	78,95	-	21.05	16.40	1.95	0.85	1.80	0.05	-
	±2σ	-	-	1.79	1.62	0.61	0.40	0.58	0.10	-
	P	-	-	-	77.9	9.3	4.0	8.6	0.2	-
WT 18008	W.R.	81.40	-	18.60	13.66	2.40	0.20	2.33	-	-
	±2σ	-	-	1.71	1.74	0.77	0.23	0.76	-	-
	P	-	-	-	73.5	12.9	1.1	12.5	-	-
WT 18009	W.R.	83.35	-	16.65	12.20	1.05	1.10	2.30	-	-
	±2σ	-	-	1.63	1.43	0.45	0.46	0.66	-	-
	P	-	-	-	73.3	6.3	6.6	13.8	-	-
WT 18011	W.R.	85.00	-	15.00	12.20	2.07	0.40	0.33	-	tr
	±2σ	-	-	1.81	1.66	0.72	0.32	0.29	-	-
	P	-	-	-	81.3	13.8	2.7	2.2	-	-
WT 18012	W.R.	84.60	0.07	15.27	12.60	1.33	0.80	0.53	tr	tr
	±2σ	-	-	1.82	1.68	0.58	0.45	0.37	-	-
	P	-	-	-	82.5	8.7	5.2	3.5	-	-
WT 18013	W.R.	83.55	0.05	16.25	12.90	1.30	0.85	1.20	tr	tr
	±2σ	-	-	1.62	1.47	0.50	0.40	0.48	-	-
	P	-	-	-	79.4	8.0	5.2	7.4	-	-
WT 18014	W.R.	79.40	0.07	20.53	16.47	2.40	0.86	0.73	0.07	tr
	±2σ	-	-	2.04	1.88	0.77	0.47	0.43	0.13	-
	P	-	-	-	80.2	11.7	4.2	3.6	0.3	-
WT 18016	W.R.	82.00	1.40	16.47	13.93	1.40	0.53	0.60	tr	-
	±2σ	-	-	1.87	1.75	0.59	0.37	0.39	-	-
	P	-	-	-	84.6	8.5	3.2	3.6	-	-
WT 18018	W.R.	74.24	1.07	24.69	19.72	2.75	1.22	0.92	0.08	tr
"basal	±2σ	-	-	2.34	2.16	0.89	0.59	0.52	0.15	-
sand"	P	-	-	-	79.9	11.2	4.9	3.7	0.3	-
Core 17										
WT 18022	W.R.	90.80	-	9.20	7.40	0.80	0.40	0.55	0.05	tr
	±2σ	-	-	1.27	1.15	0.39	0.28	0.32	0.10	-
	P	-	-	-	80.4	8.7	4.4	6.0	0.5	-
WT 18024	W.R.	84.85	-	15.15	12.70	1.00	0.65	0.50	0.30	-
	±2σ	-	-	1.57	1.46	0.44	0.35	0.31	0.24	-
	P	-	-	-	83.8	6.6	4.3	3.3	2.0	-
WT 18026	W.R.	83.30	-	16.70	13.15	2.10	0.45	0.95	0.05	-
	±2σ	-	-	1.63	1.48	0.63	0.29	0.43	0.10	-
	P	-	-	-	78.7	12.6	2.7	5.7	0.3	-
WT 18027	W.R.	87.75	-	12.25	10.80	0.55	0.55	0.15	0.20	-
	±2σ	-	-	1.44	1.36	0.32	0.32	0.17	0.20	-
	P	-	-	-	88.2	4.5	4.5	1.2	1.6	-

Appendix 4.6 cont'd.

Sample	%	Matrix	Rock Fragments	Total Phenocrysts	Plagioclase	Quartz	Pyroxene	Opaques	Hornblende	Biotite
WT 18028	W.R.	82.90	2.05	14.95	12.85	0.40	0.85	0.75	0.10	-
	±2σ	-	-	1.56	1.47	0.28	0.40	0.39	0.14	-
	P	-	-	-	85.9	2.7	5.7	5.0	0.8	-
WT 18029	W.R.	83.40	0.45	16.10	14.10	0.75	0.35	0.90	-	-
	±2σ	-	-	1.61	1.53	0.39	0.26	0.41	-	-
	P	-	-	-	87.6	4.7	2.2	5.6	-	-
WT 18030	W.R.	84.10	-	15.90	12.85	1.15	0.75	0.90	-	0.25
	±2σ	-	-	1.60	1.47	0.47	0.39	0.41	-	0.22
	P	-	-	-	80.8	7.2	4.7	5.7	-	1.6
WT 18032	W.R.	83.45	0.40	16.15	13.90	0.75	0.65	0.65	0.10	0.10
	±2σ	-	-	1.61	1.52	0.39	0.35	0.35	0.14	0.14
	P	-	-	-	86.1	4.6	4.0	4.0	0.6	0.6
WT 18034	W.R.	84.35	0.05	15.60	13.25	0.60	0.90	0.80	tr	-
	±2σ	-	-	1.59	1.49	0.34	0.41	0.39	-	-
	P.	-	-	-	85.2	3.9	5.8	5.1	-	-
WT 18035	W.R.	79.45	0.10	20.35	17.60	0.95	0.75	0.90	0.15	-
	±2σ	-	-	1.76	1.67	0.43	0.39	0.41	0.17	-
	P	-	-	-	86.5	4.7	3.7	4.4	0.7	-
WT 18036	W.R.	80.35	0.15	19.40	16.50	1.10	0.95	0.85	tr	-
	±2σ	-	-	1.73	1.63	0.46	0.43	0.40	-	-
	P	-	-	-	85.0	5.7	4.9	4.4	-	-
WT 18037	W.R.	82.15	1.4	16.40	13.45	1.65	0.65	0.65	tr	-
	±2σ	-	-	1.62	1.50	0.55	0.35	0.35	-	-
	P	-	-	-	82.0	10.0	4.0	4.0	-	-
Average from 30 samples (inc. core and Leslie Road samples)	W.R.			14.9	11.9	1.1	0.7	1.0	0.1	0.1
	P				80	7.6	4.5	6.8	0.4	0.7

Average Total Phenocrysts:	Leslie Road	Sheet 1 (Cores)	Sheet 2 (cores)
	9.7	15.0	17.0

Appendix 4.7 Results of physical properties determination for the Mamaku Ignimbrite and Whakamaru Ignimbrite.

Mamaku Ignimbrite Te Akau core 5

Sample	g/cc Bulk Density	g/cc Particle Density	% Porosity
WT 18000	1.43	2.38	56.4
18001	1.40	2.23	37.3
18002	1.09	2.19	50.4
18003	1.38	2.21	37.6
18004	1.50	2.32	35.7
18005	1.55	2.20	29.4
18006	1.60	2.16	25.7
18007	1.64	2.26	27.3
18008	1.65	2.26	27.3
18009	1.61	2.28	29.2
18010	1.81	2.21	17.9
18011	1.72	2.22	22.6
18012	1.84	2.21	16.9
18013	2.04	2.26	9.8
18014	1.95	2.17	10.0
18015	2.04	2.21	7.8
18016	1.56	2.19	28.9

Whakamaru Ignimbrite

Sample	g/cc Bulk Density	g/cc Particle Density	% Porosity
WT 18052	1.13	2.41	52.9
18053	1.75	2.44	28.4
18054	1.41	2.36	40.4
18055	1.53	2.35	35.0
18056	1.43	2.52	43.1

Appendix 4.8 Results of pumice flatness ratios

Te Akau core 5

Sample No.	n	F_a	F_ℓ
1	-	-	-
2	-	-	-
3	2	3 - 4	2.5
4	3	1.4 - 3	2.1
5	-	-	-
6	10	3 - 13	4.0
7	11	1 - 4	1.9
8	8	0.8 - 6	2.2
9	7	1.5 - 9	4.0
10	5	1.3 - 3	3.0
11	6	2 - 5	2.8
12	22	0.8 - 8.5	3.1
13	17	1.3 - 8	2.5
14	27	0.8 - 14.6	3.7
15	13	0.1 - 6	2.4
16	21	2 - 25	5.3
17	19	1 - 10.6	2.9

Te Akau core 17

Sample No.	n	F_a	F_ℓ
23	-	-	-
24	-	-	-
25	19	1 - 3.5	1.8
26	12	1.3 - 6	2.2
27	15	0.8 - 2.8	1.8
28	9	1 - 2.6	1.5
29	14	1.2 - 3.6	2.0
30	16	1 - 8.6	2.9
31	7	3 - 20	4.9
32	12	1.3 - 6	3.2
33	22	1.5 - 5.5	2.6
34	14	2.1 - 10	3.6
35	12	3 - 8	4.9
36	25	2 - 13	4.5
37	21	1.3 - 10	3.9
38	10	1 - 7	2.5

n = number counted

F_a = range arithmetic flattening ratio

F_ℓ = logarithmic flattening ratio

See methodology - section 4.2 for formulae.

Appendix 4.9 Te Akau 5 and 17 core sample positions and samples point counted

	Field No.	Waikato University No.	Depth below surface (m)	Height (m) above base of Mamaku Ignimbrite	Point Counted
Core 5	Mk	WT			
	1	18000	32.9	118.3	
	2	18001	36.2	115.0	✓
	* 3	18002	39.3	111.6	✓
	4	18003	63.7	57.2	✓
	5	18004	81.1	69.8	✓
	* 6	18005	86.6	64.3	✓
	7	18006	87.8	62.9	
	* 8	18007	90.5	60.4	✓
	9	18008	91.8	59.1	✓
	* 10	18009	106.7	44.0	✓
	11	18010	115.2	35.7	
	12	18011	127.4	23.5	✓
	13	18012	136.0	14.9	✓
	* 14	18013	142.0	8.9	✓
	* 15	18014	146.3	4.6	✓
	16	18015	147.9	3.0	
	* 17	18016	150.9	0	✓
	18	18017	154.0	-3.0	
	19	18018	155.5	-4.5	✓
	20	18019	157.0	-6.0	
	21	18020	163.7	-11.3	
	22	18021	175.0	-29.0	
Core 17					
	23	18022	23.8	111.0	✓
	24	18023	25.9	108.7	
	25	18024	39.6	95.4	✓
	26	18025	53.4	81.4	
	27	18026	57.8	77.0	✓
	28	18027	71.6	63.2	✓
	29	18028	76.2	58.6	✓
	30	18029	89.0	45.8	✓
	31	18030	104.5	30.3	✓
	32	18031	110.1	24.7	
	33	18032	111.6	23.2	✓
	34	18033	112.8	22.0	
	35	18034	125.6	9.2	✓
	36	18035	129.3	5.5	✓
	37	18036	130.5	4.3	✓
	38	18037	134.8	0	✓

* Samples chemically analysed

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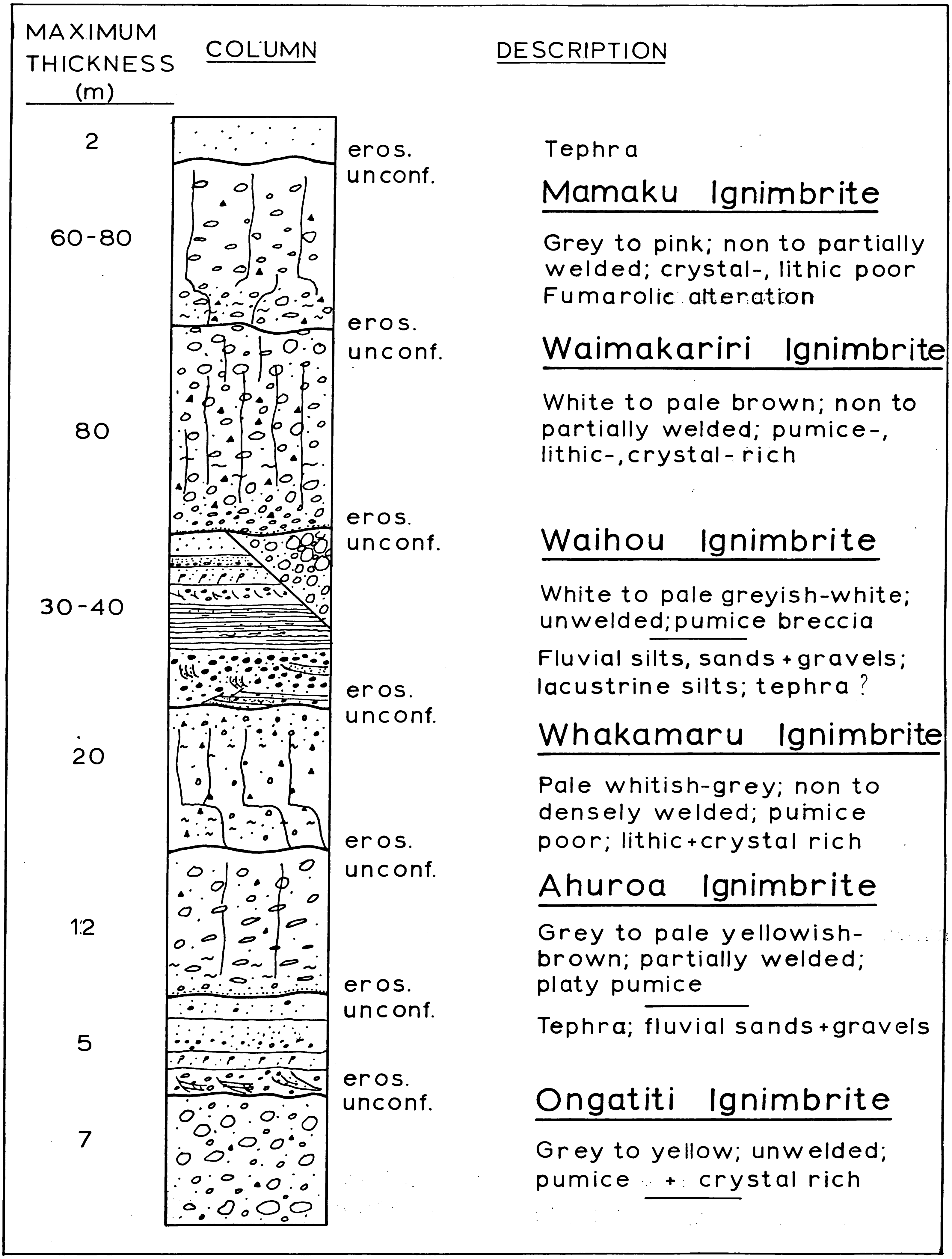

Fig. 2.1. A generalised stratigraphic column for the western Mamaku Plateau, east Putaruru. eros. unconf. = erosional unconformity.