Frontispiece: Foreground, eastern Kaimai Ranges abutting against the northern Mamaku Plateau. Background from right to left, Mt Misery, Papamoa Ranges, Tauranga Basin.

GEOLOGY OF THE NORTHERN MAMAKU PLATEAU

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ABSTRACT

The geology of the northern Mamaku Plateau is dominated by the rhyolitic Mamaku and Waimakariri Ignimbrites, although exposures of the dacitic Waiteariki Ignimbrite are common in river gorges.

The Mamaku Ignimbrite comprises 4 flow units (sheets 1 to 4). The base of sheet 2 (the bulk of the ignimbrite) is an uncompacted pyroclastic breccia to lapilli tuff grading into a moderate to strongly welded zone, often lenticulitic. The upper zone is incipiently welded, often light pinkish grey, with poor to moderate crystal contents. Fossil fumeroles are common in the upper middle of the flow, devitrification and vapour phase alteration is extensive.

The upper zone of the Waimakariri Ignimbrite is usually light grey and incipiently welded. Towards the lower middle of the flow this grades down into a welded lenticulite, occasionally eutaxitic. The base is usually an incipiently welded pyroclastic breccia enriched in lithics. This ignimbrite has a poor to moderate crystal content, is composed of at least three flow units and often has an underlying Plinian airfall. Gas escape structures appear in distal outcrops.

The unwelded top of the Waiteariki Ignimbrite is often eroded. Usually only the middle of the flow, a densely welded lenticulitic with eutaxitic texture is present. The base of the flow is a moderately devitrified, incipiently welded, pyroclastic breccia to fine tuff. Evidence suggests the Waiteariki Ignimbrite comprises 2 cooling units both of which are crystal rich.

With increasing distance from source plagioclase crystal percentages, pumice size and pumice percentages decrease in the Mamaku Ignimbrite (sheet 2). For the Waimakariri Ignimbrite, there is a decrease in crystal lengths with distance from source (assumed to be the Taupo Volcanic Zone). There is an increase in crystal percentages from a medial to distal position, and a moderate increase in pumice percentages. This is explained by elutruation of vitric material from the Waimakariri as a co-ignimbrite air fall ash concentrating pumice and crystals.

No relationship exists between crystal length and vertical position in the Mamaku ignimbrite. Pumice percentages often increase towards the top of the flow, while pumice numbers increase towards the middle of the flow. Welding is at a minimum at the base, at a maximum in the lower middle of the outcrop, reducing towards the top of the flow. Phenocryst increase towards the base of sheet 2 is attributed to welding/compaction. No relation exists between crystal length and vertical position in the Waimakariri Ignimbrite; pumice percentages and size increase towards the base of the flow, while pumice numbers often increase towards the base and top of the flow.

Horizontal sections over distances of 194 and 350 m for the Mamaku and Waimakariri Ignimbrites respectively, demonstrated that they are relatively homogeneous over short distances.

Both the Mamaku and Waimakariri Ignimbrites traveled as moderately fluidized laminar flows, but the surge deposits separating Mamaku flow units were turbulent as were parts of distal Waimakariri. The surges (probably foward jetting from the front of the flow) imply the Waimakariri flowed faster than the Mamaku Ignimbrite. A new flow unit is presented, perhaps more applicable to distal large ignimbrite eruptions, than the standard ignimbrite flow unit. Most field evidence indicated the Mamaku and Waimakariri Ignimbrites were emplaced en masse. The diversity of facies in both Mamaku and Waimakariri Ignimbrites implies a single large pyroclastic flow can operate under several flow regimes, dependent to some extent on local paleo-surface conditions.

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A number of people accompanied me in the field from time to time and for their company and assistance I am grateful.

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INTRODUCTION

1.1 LOCATION

The study area covers an area of 132 km^2, 14 km SW of Tauranga City. Based on geology and topography it can be divided into the northern Mamaku Plateau (which comprises the bulk of the area), the lower eastern Kaimais and the southern Whakamarama Plateau. The Opuiaki River provides an approximate boundary between the north western Mamaku Plateau and the eastern Kaimais, while the Mangakarengorengo River separates the northern Mamaku Plateau from the southern Whakamarama Plateau (Fig. 1.1).

Two topographic maps cover the study area: NZMS (Topographical) 260, Sheet U14 Tauranga, Sheet U15 Ngongotaha, 1:50 000, Lands and Survey, 1980. The four boundary points of the mapped area are: 1/2 km east of Kaikaikaroro trig (U14/750750), 1.5 km south west of the junction of Oropi and Warner roads (U14/860750), 1 km south west of Ngatuhoa Youth Lodge (U15/750630) and 1.2 km north west of the intersection of Taumata and Pyes Pa road (U15/860630). This is illustrated in Fig. 1.2. From State Highway 29 the main access roads are Soldiers, Omanawa, Belk and Pyes Pa roads which tend to follow the middle of interfluves. In the south west there is a network of private forestry and hydro roads which provide access.

1.2 HISTORY AND LAND USE

The study area lies in the tribal lands of the Ngatiranginui. A pa site with some well preserved earth works lies 500 m S of the end of Belk road (U14/827703). Archaeological examination in the Ruahihi area (McFadgen and Sheppard, 1984) revealed that it was an important staging post between the bush and coastal resources. Earthworks of a military redoubt (circa 1860) can just be discerned 150 m SW of the junction of Peers and McLarens Falls Rd (U15/801670). In 1915 the

Fig. 1.1 View of northwestern study area. Clockwise from lower left of photo, interfluve of Mamaku Ignimbrite, Lake Mangapapa and dam, Opuiaki River gorge, edge of lower eastern Kaimais, and Whakamarama Plateau.

Fig. 1.3 Old tramway tunnel, distal Mamaku Ignimbrite (U14/825711)

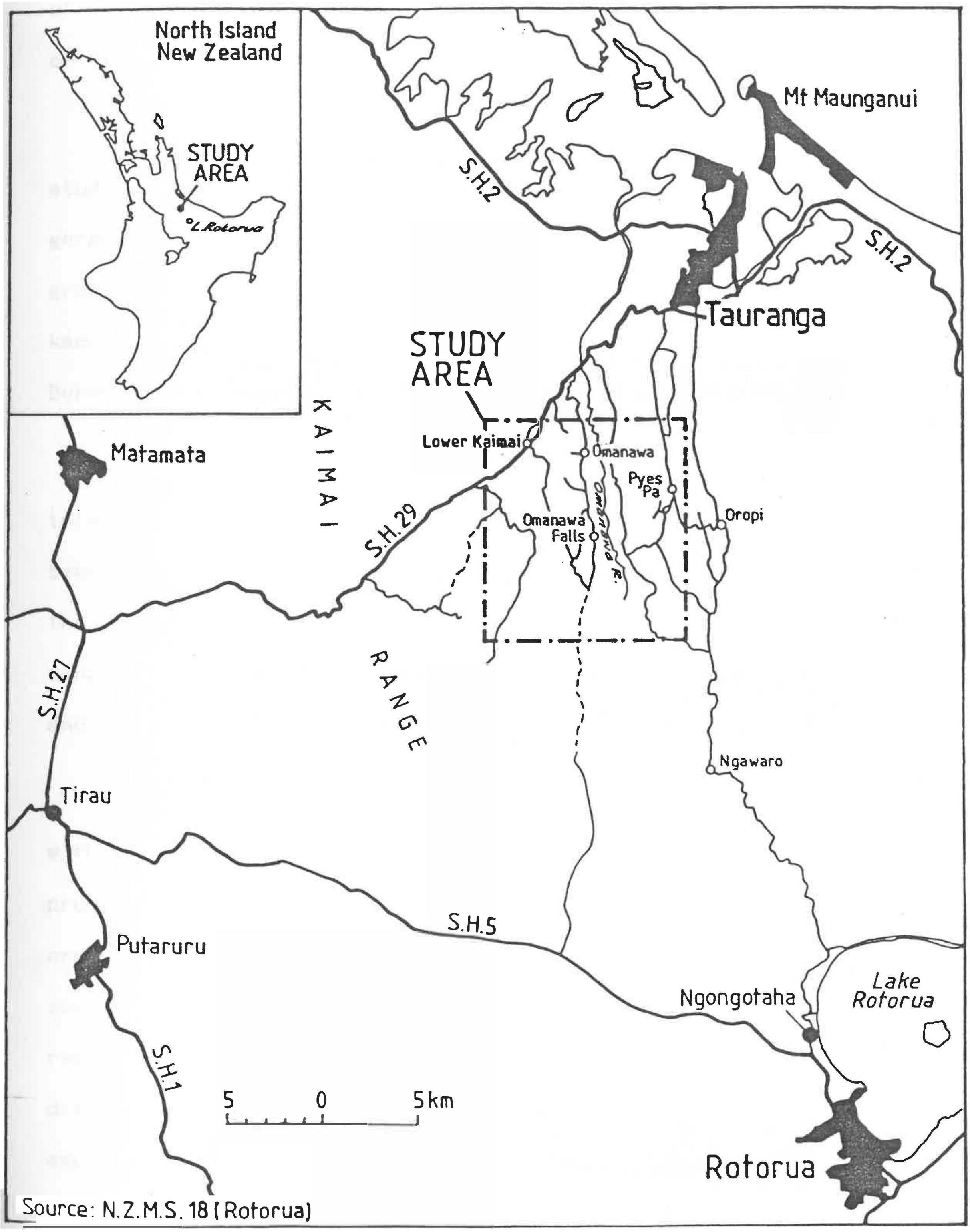

Fig. 1.2 Location map of the study area.

Tauranga Rimu Company was formed to mill the bush between Oropi and Omanawa. Some of their tramways and cuttings still exist. The best example is a 50 m tunnel and 100 m cutting which lies to the southwest of the end of Belk Rd (U14/825711). This provided some good exposure of distal Mamaku Ignimbrite (Fig. 1.3).

A variety of native trees grow in the gorges and valleys of the study area, particularly in the more inaccessible areas. In the upper gorge of the Mangapapa River a reserve of scattered kauri occurs, growing at its most southerly natural limit. Immediately north of the kauri is a stand of hard beech in a very rugged section of the gorge. Bordering the edges of Lake Mangapapa are dense stands of tanekaha.

In the headwaters of the Opuiaki are thick stands of rimu, totara, miro and tanekaha. Downstream in the valley, the bush has been cut over and secondary growth now predominates. Intermixed are the occasional pine and scrubby thickets of bushlawyer, supplejack, mangemange and tea tree. These thickets are common in cut over areas and make for difficult access

In the northwest sector farming is mostly sheep and dry stock with the occasional deer unit. In the northeast horticulture predominates with kiwifruit being the most common crop. These orchards have replaced the traditional dairy and sheep farms though several such farms are still being worked. Exotic forestry is rapidly replacing mixed secondary and native growth in the far southwest, with deer farms and horticulture common at lower altitudes. Dairying and exotic forestry predominate in the southeast.

1.3 HYDRO-ELECTRIC DEVELOPMENT

The Wairoa River hydro-electric power development comprises a system of tunnels, dams and canals that direct water through a progression of power stations. The scheme is illustrated in Fig. 1.4. Water resources were first developed in 1915 with the opening of the 700 KW underground station at Omanawa Falls. McLarens Falls was selected as the site of the second station and began generating (2.75 MW) in 1925. These stations have been superseded by the Mangapapa scheme. The first stage, joining the Mangapapa, Opuiaki and Omanawa rivers, under a total head of 274 m was completed in 1972 with the commissioning of the 15.4 MW Lloyd Mandeno station. The 6 MW Lower Mangapapa station opened in 1979, followed by the 20 MW Ruahihi station in 1982. The scheme is operated by the Tauranga Joint Generation Committee except the Omanawa Falls Station which is run by the Tauranga City Council.

Bracegirdle (1973) notes that floods passing through McLaren Falls Station have been measured as nearly twice as great as those passing through the Arapuni station on the Waikato River which has 40 times the catchment area. During Hurricane Diana in 1967 10 cm of silt was deposited on the floor of the generator room at McLaren Falls and 1 m on the turbine basement.

1.4 GROUNDWATER

Mean annual rainfall is closely related to the topography of the Kaimai Ranges. In the upper Kaimais annual rainfall averages 2500 mm, falling to 1250-1500 mm in the Tauranga Region (Davis, 1985). In the Ruahihi area rainfall has averaged 1980 mm per year over the last 16 years, with a maximum of 2318 mm in 1970 (Cowbourne, 1985).

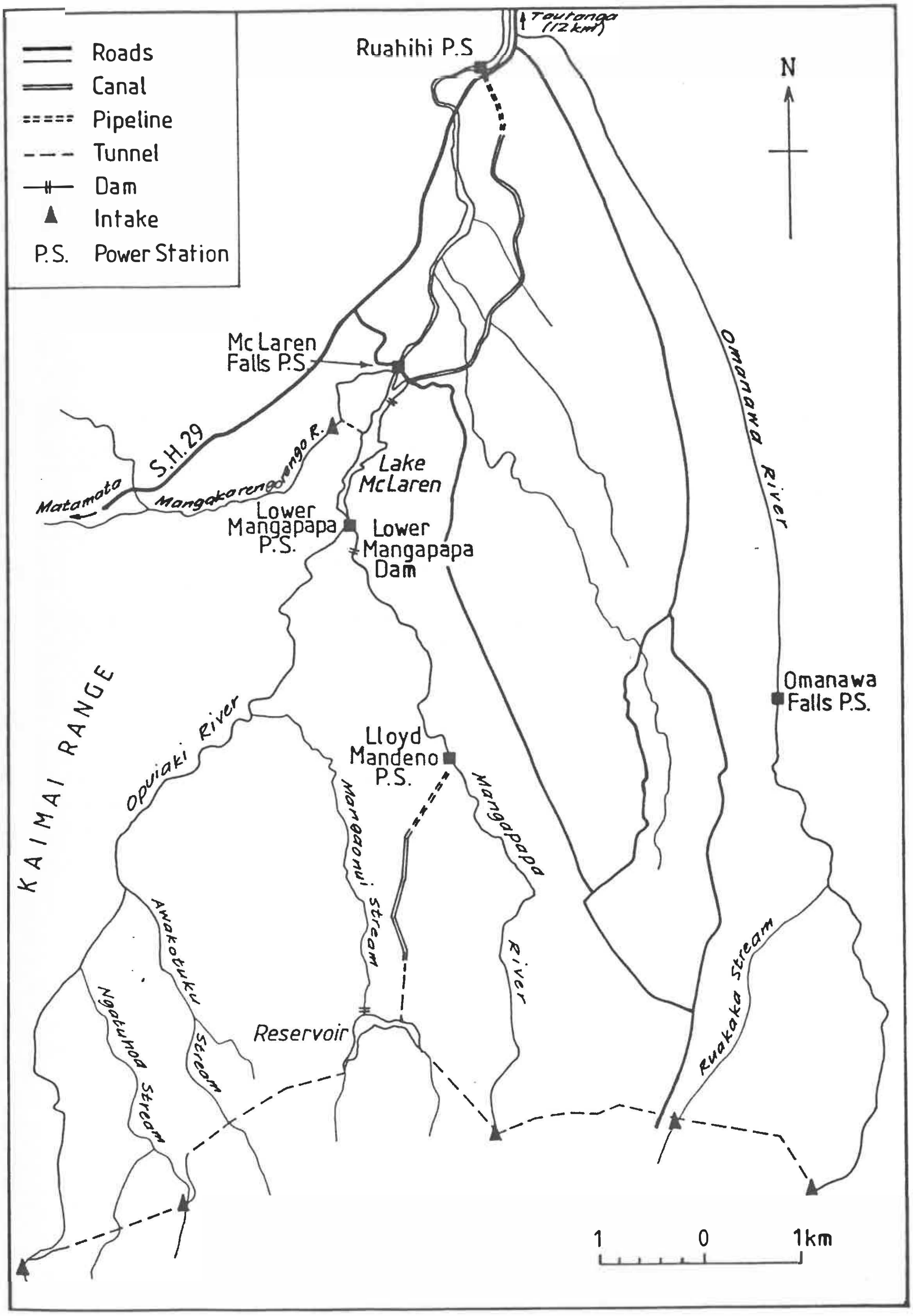

Fig. 1.4 Wairoa river hydro-electric scheme.

The ability of ignimbrites to store the rainwater and release it over a long period is well known. From tritium analysis Dell (1982) calculated a residence time of 50-100 years for groundwater in the Mamaku Plateau. He suggests the ignimbrites store large volumes of water which provides a constant low flow water resource. This is important to the operation of the hydro schemes as the lakes themselves are small and provide little storage.

A number of springs and seepages were noted, especially at contacts and in the lower less welded zones of the Mamaku and Waimakariri Ignimbrites. It is quite common to find swampy zones in these areas which act as informal hydro-geological boundaries. Adjacent to a youth camp off Merrick Road (U14/839739) several springs have tunnelled caves. A substantial flow exists in the access tunnel leading to Omanawa Falls station. Below the spring the ignimbrite seeps water which has necessitated a lining. At the base of the Waimakariri Ignimbrite on the Waiorahi Stream, 200 m upstream of the weir (U15/857738), several springs of large volume emerge.

Springs and seeps are common in the Ruahihi area. Cowbourne (1985) also saw them and states the catchment area is too small for the volume produced. Penstock leakage is precluded and Cowbourne suggests "the area marks an exit point of an extensive hydrological system involving the Mamaku Plateau and perhaps the Kaimai Range". However, a possible partial source could be Ruahihi canal and Lake McLaren though this could only be proved by the addition of tracers to the water.

1.5 HYDROLOGY

Main rivers in the northern Mamaku Plateau are the Opuiaki, Mangapapa and Omanawa. Those in the lower eastern Kaimais are the Te Aruhu and Ngamuwahine which join to form the Mangakarengorengo River. All rivers are tributaries of the Wairoa.

The major waterways in the northwest Mamaku Plateau flow in roughly parallel directions to the north (tributaries draining into these rivers tend to flow north east) enclosed in vertical or steep sided gorges and valleys 60-110 m deep, separated by interfluves. These drainage patterns have been most effective in modifying the landscape and have imparted a distinctive dendritic pattern (see geologic map in back pocket).

The headwaters of the Opuiaki River lie to the SW of the study area and consist of a series of rapids and waterfalls enclosed in steep gorges (which are difficult to impossible to traverse) widening to occasional valleys. At Ngatuhoa Falls (U15/755647) the stream has cut through the overlying Mamaku Ignimbrite with the Waimakariri Ignimbrite acting as the fall rock (Fig. 1.5). The same also occurs at the Mangapapa and upper Omanawa Falls. From where the Mangaroa, Ngatuhoa and Awahotuhoa streams join the Opuiaki River it widens to a narrow valley about 100 m deep and may be tramped for about 4 km. Good exposures of lacustrine sediments overlain by Waimakariri Ignimbrite outcrop in the river bed and valley walls (Fig. 1.6). Downstream of the ford (U14/767694), mineralised ignimbrite is exposed for about 300 m. From this point the Opuiaki begins to downcut again into an impenetrable gorge falling approximately 80 m until it meets the Mangapapa River.

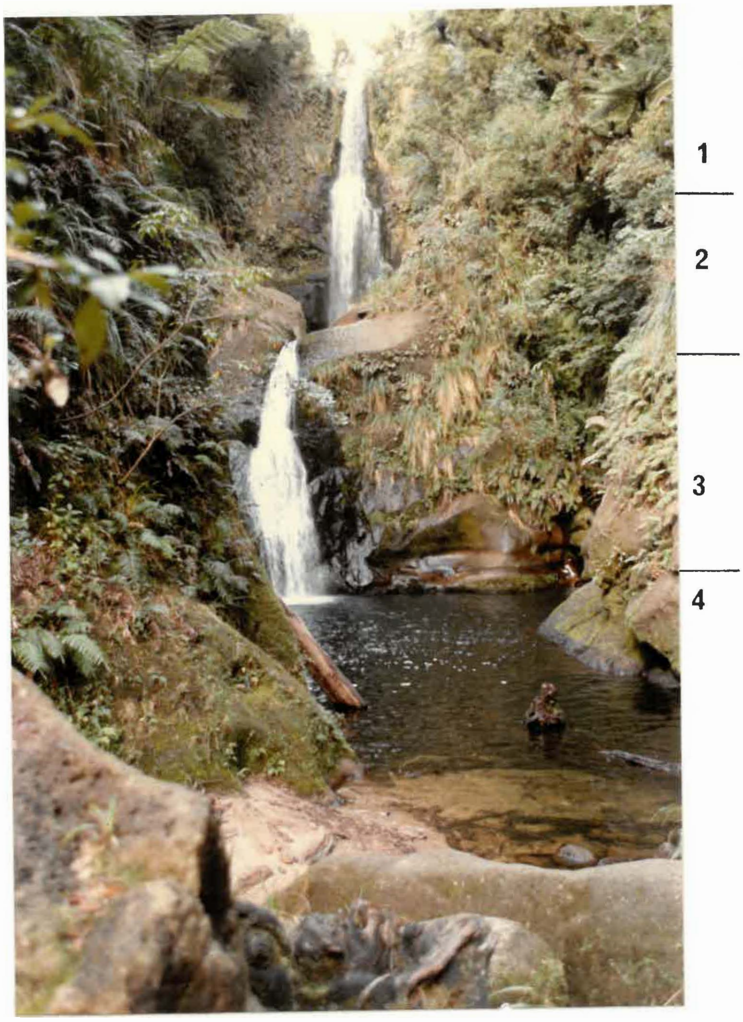

Fig. 1.5 View of Ngatuhoa Falls. The step like effect is due to zonal variation in welding. (1) Basal Mamaku Ignimbrite, (2) Upper middle Waimakariri, (3) Welded lenticulite, (4) Basal Waimakariri.

Fig. 1.6 Diatomaceous horizontally graded sandy silts. Opuiaki Sediments Opuiaki River (U15/753677).

The Mangapapa River falls approximately 200 m from the southern boundary to Lake McLaren and provided some of the most difficult terrain encountered. Upstream of the first dam on this river the rock is entirely Mamaku ignimbrite, below the dam occasional outcrops of Waimakariri were found up to an 80 m high waterfall. Below the falls there is an extremely rugged gorge and all efforts to penetrate to the river bed in this area were unsuccessful. It was often possible to get quite close to the river but the sheer cliffs in the final 10-15 m defeated all attempts. Downstream of the Lloyd Mandeno station Lake Mangapapa has been formed by damming in a narrow gorge of Waiteariki Ignimbrite. The lake was explored by rowboat and outcrops of Opuiaki Sediments and welded Waimakariri Ignimbrite observed.

Below the dam, the Omanawa River flows through a series of rapids and small falls in a gorge about 100 m deep. The gorge widens after 2.5 km to a narrow valley extending for about 1.8 km which can be tramped with relative ease. The river bed comprises moderately welded Waimakariri Ignimbrite with an unusual frittered appearance. Below Omanawa Falls, which exposes basal Waimakariri Ignimbrite is a gorge which continues for 2 km before widening to a narrow valley with Waiteariki Ignimbrite as bed rock. This can be tramped (with some difficulty) for about 4 km until the river cuts out of the gorge.

Downstream of the Taumata Road bridge, the Kopurererua Stream downcuts into Waimakariri Ignimbrite and Waiteariki Ignimbrite. Generally the stream bed is broad and sandy with the occasional outcrop of Waiteariki. From U14/837712 onward the stream narrows and it is only possible to follow for short distances. One ridge leading to a tributary of the Kopurererua (U14/832707) appeared to have been well used in the past although now it is mostly heavily overgrown. It may be an old water or fishing track for the adjacent abandoned pa.

The Tautau Stream flows north west on Waiteariki Ignimbrite in a valley 70-80 m deep, carved in Mamaku Ignimbrite and discontinuous Waimakariri Ignimbrite. Travel is easy as a cut track follows the stream. Downstream of the T.C.C weir on the Waiorahi Stream geologic conditions are similar though the stream flows more to the north.

In the lower eastern Kaimais, the northeasterly flowing Mangakarengorengo River is formed at the junction of the Ngamuwahine River and Te Ahuru Stream and is relatively easy travelling apart from one gorge. The river falls 45 m over rapids and a 15 m waterfall until it joins the Wairoa River. Rock outcrops in the river bed are all Waiteariki Ignimbrite, with occasional outcrops of Waimakariri Ignimbrite along the southern bank. The Wairoa River begins at the junction of Lake McLaren and the Mangakarengorengo River. It drops 10 m to form McLaren Falls and continues to drop rapidly, falling a further 60 m through a series of rapids before reaching sea level at the Ruahihi Power Station.

1.6 PREVIOUS WORK

General Geology

Reference to the geology of the study area was first made by Thompson (1953) to a pozzalana deposit in the lower Kaimais. He compiled two stratigraphic columns and divided the rocks outcropping into three formations, siltstone (Opuiaki sediments), dacite (Waiteariki Ignimbrite) and alluvium. The latter two were not described. Thickness of the sediment at the quarry was measured at about 55 m with total quarryable siltstone estimated at 382275 m^3 while volumes in the immediate vicinity of the quarry exceeded 45873 m^3. Thompson states the sediments exposed in the quarry range from extremely fine siltstone, through siltstone, to sandstone, some of which are rich in diatoms while others contain carbonaceous fragments. The beds dip at angles between 1-2° except for a tilted section at 12°. Thompson believed this was not related to faulting. Some beds show excellent graded bedding from coarse sandstone to fine siltstone. Generally they are white but upon weathering bedding planes yellow and become obvious. Local iron pans are interbedded with the sediments.

Thompson returned in 1956 and re-examined the area to assess the material for use in the concrete structures of the Atiamuri hydro scheme, and about 13 476 m^3 was suitable for this purpose. A further three columns were described and intraformational bedding, carbonaceous fragments and minor faulting in the southern section noted. The quarry was visited by the writer but it is no longer being worked and is heavily overgrown in scrub and gorse which obscured outcrop and made examination difficult. However one column was described.

Thompson (1958) visited a proposed water supply dam site on the Waiorahi Stream (U14/858739). He discussed jointing and suitability of the rock (Waiteariki Ignimbrite) as a foundation for a small dam. Lloyd (1969) examined the same area, also for water supply potential and logged a 30 m core of Waiteariki Ignimbrite.

Healy *et al.* (1964) in their regional 1:250 000 geologic map recognised the Mamaku and Waiteariki Ignimbrites in the study area and drew a number of Late Quaternary fault traces.

Fransen (1982) mapped and described seven Pleistocene ignimbrites in the western Mamaku Plateau. One new ignimbrite was discovered and named the Waihou and another renamed the Waimakariri, previously called the Lower Mamaku Ignimbrite. A major part of Fransen's work was concerned with examining vertical and lateral variations in the Mamaku Ignimbrite by describing petrogaphic, welding, texture and bulk chemical variations. He found that the Te Akau core sequence (proximal Mamaku) consisted of two sheets that were emplaced within a short time and cooled as a single unit. The base of each sheet was characterised by an enrichment of phenocrysts. Sixteen columns were presented, the structure of the plateau described and geologic history interpreted.

Harmsworth (1983) produced a 1:25 000 scale geologic map of the southern Tauranga Basin, compiled 11 stratigraphic columns and demonstrated that some of the fluvial sediments in the Matua Subgroup are detritus eroded from the northern Mamaku Plateau. His was the first comprehensive work in the area. Three new ignimbrites were identified: the Wairoa, Te Puna and Te Ranga. None were found in this study area and the writer suspects the Te Ranga is distal Waimakariri after examining Harmsworth's Te Ranga sites. The Matua Subgroup was adopted as a formal name for all Pleistocene material overlying the Waiteariki Ignimbrite in the Tauranga Basin (Fig. 1.7).

Cowbourne (1985) investigated lithology, rock strength, defects and paleotopography in the Ruahihi area. A column was also described at the Opuiaki River intake. These locations border or comprise part of the writer's study area. Cowbourne defined the ignimbrites in the area as Waiteariki Ignimbrite which is overlain by Grey, Waihou and Waimakariri Ignimbrites respectively (Fig. 1.7). Cowbourne states his lithostratigraphic sequence is based on a number of small highly weathered exposures and bore hole data. Nowhere can a complete sequence be seen between between the younger ignimbrites and basement Waiteariki in one exposure.

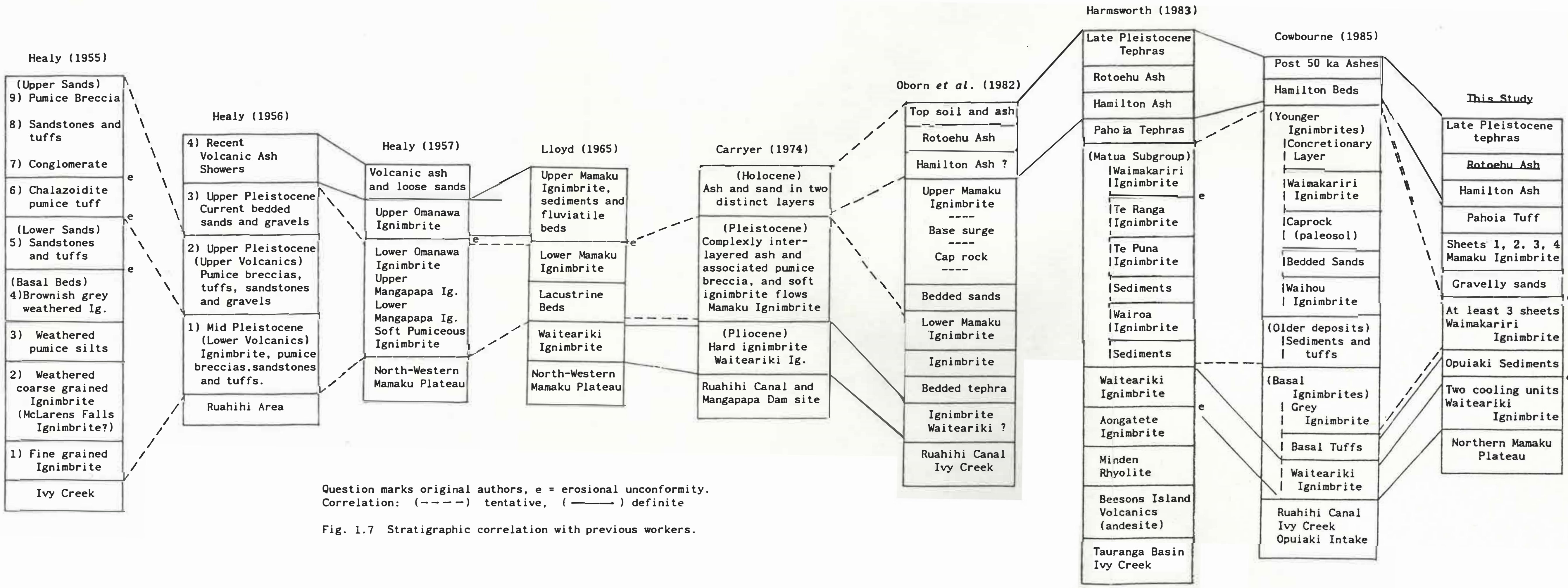

Fig. 1.7 Stratigraphic correlation with previous workers.

Ivy Creek was revisited by the author in response to Cowbournes thesis. The 'Grey Ignimbrite' is Waimakariri Ignimbrite that has infilled a paleo valley and is considerably more welded than where Waimakariri Ignimbrite overlies paleo ridges in the area. In outcrop it bears no superficial relationship to adjacent Waimakariri and it is only by examining numerous exposures in other localities that it can be confidently correlated. Though the basal section at Ivy Creek is less pumice rich than normally seen this is interpreted to be the front of the flow (gas charged, possibly turbulent and mostly fine particles) infilling the paleo valley as opposed to the body of the flow which is deposited on adjacent valley walls.

Cowbourne in his column of the Opuiaki River intake describes an outcrop of Waiteariki overlain by sediments, Waihou and Waimakariri Ignimbrites. This site was also visited by the author and consists of strongly welded, dark grey crystal rich Waiteariki Ignimbrite which changes to a weathered pale grey colour as it approaches the contact with the Opuiaki sediments. This sedimentary sequence of about a metre thick includes a chalazoidite layer (the chalazoidites fine up over 10 cm) and an iron pan which has stained underlying sediments. Overlying the sediments is a 15 m mixture of basal Mamaku Ignimbrite and welded cobbles of hard welded Mamaku that is derived from a small landslide which adjoins the site and/or debris from bulldozed terraces which overlie the area. This in turn is overlain by basal Mamaku which grades into 'normal' looking devitrified Mamaku Ignimbrite. Basal Mamaku could easily be mistaken for a separate ignimbrite unless continuous exposures had been seen at other sites, for example Oropi Gorge (U15/687876). The surprising factor here is the absence of Waimakariri Ignimbrite as it is 30 m thick 2 km NE at Ngatuhoa Falls and was identified in core logs along the proposed tunnel routes by Lloyd (1965).

Geology relating to the hydro-electric schemes

Healy (1955) visited Ivy Creek in response to the proposed replacement of the McLarens Falls Power Station and described the rock outcropping (Fig. 1.7) and sketched the area. Healy suggested the chalazoidite bed could be an important marker bed if it was widespread. The deposit is indeed widespread, it was seen at the Opuiaki River intake by Cowbourne (1985), at Motuhoa Island and Omokoroa by Harmsworth (1983) and at Oropi Gorge by the writer.

The Ivy Creek section in a sense misled Healy as he related the stratigraphy seen further south back to this 'type site' of what is a complex sequence of distal, weathered, incipiently to densely welded ignimbrites.

In 1956 Healy revisited the Ruahihi area. Fifteen cores were described though they were taken at only a few levels. He makes the comment:

"there is a tendency for sandstone pumice breccia (Waimakariri) that normally may appear to be moderately compacted in outcrops to be in a plastic state when first removed in wet condition from the core barrel. These cores harden up as they dry out".

This is an important point as it implies that incipiently welded Waimakariri Ignimbrite is best strength tested insitu. For engineering purposes the geology was divided into four main groups (Fig. 1.7).

Healy (1957), investigated further south in response to proposals to further develop hydro electricity in the Omanawa-Mangapapa area. He examined potential tunnel routes, dam and station sites and logged 6 drill holes. Healy noted that cores were not taken in sufficient quantities and drillers were not able to take cores at critical intervals. Five ignimbrites were recognised (Fig. 1.7). The McLarens Falls (Waiteariki) Ignimbrite was mentioned in his 1955 and 1956 reports.

Lloyd (1965) prepared a report on the proposed Omanawa-Mangapapa-Opuiaki development which superseded the scheme described by Healy (1957). The geology in relation to the proposed tunnel lines was based on field surveys and cores from 16 holes (these were taken about every 20 m and were about 1 m long). Lloyd drew several useful cross sections showing the generalised stratigraphy and recognised that Healy's Upper and Lower Mangapapa Ignimbrites were variations of the Lower Mamaku Ignimbrite (Waimakariri).

In 1968 Lloyd logged a further 31 holes, the objective being where possible to locate the proposed diversion tunnels within either the welded zone of the Upper Mamaku Ignimbrite or the welded zone of the Lower Mamaku Ignimbrite to avoid lining the tunnels. This exercise was only partially successful, owing to restrictions placed by the engineers on the amount of core extracted and the highly variable nature of the ignimbrite. Lloyd noted that the Upper Mamaku Ignimbrite is thickest where it was deposited in paleovalleys carved in the Lower Mamaku (Waimakariri) Ignimbrite.

Riddols (1971) visited the scheme and prepared a report on the geology encountered by initial tunneling. The soft ground tunneling machine being used had considerable difficulty in coping with hard ignimbrite (which Lloyd had tried to locate) and some tunnel routes were relocated in an attempt to avoid as far as possible hard layers. A map was prepared by Riddols showing the probable extent of hard ignimbrite. At this stage as many as two hundred holes had been drilled, though most were of limited value in interpreting the geology as few cores were obtained, the engineers using rates of penetration for locating favourable routes.

A further report by Riddols (1972) described tunnelling problems and possible solutions. It seems that much of the rock was too hard for the machine and a considerable amount of tunnelling was undertaken by hand.

Carryer (1974) examined the geology in the Ruahihi and Omanawa area and logged 8 drill holes from which it seems continuous cores were taken. The objective was to suggest a potential dam site and tunnel routes. A canal leading to the Ruahihi power station was recommended though it was recognised the canal would be through highly pervious material. However, a compacted ash lining was thought suitable. His stratigraphic column of the area is outlined in Fig. 1.7. Several dam sites for the Lower Mangapapa Station were examined and the gorge in the lower reaches of the Mangapapa River was suggested as the most suitable site.

Carryer (1975) returned to the Ruahihi area and logged a further 28 cores. He stated that for most of the length of the suggested route of the canal, sand and pumice breccia is overlain by a sequence of silts and sands often sensitive. Two layers of weathered ignimbrite were identified overlying Waiteariki Ignimbrite plus a local area of swamp deposits. The route adopted by the engineers was significantly different from that suggested by Carryer. A stratigraphic column was not erected, the geology being defined in engineering terms: (1) Silty sand (pumice breccia). (2) Sensitive silts and silty sands (lake sediments). (3) Clays (ash and weathered ignimbrite).

A report on site investigations and laboratory tests was prepared by the engineers Mandeno Chitty and Bell (1975). Thirty two holes were logged with about 90% core recovery. These were described in engineering terms and the writer had some difficulty in interpreting them (ie moderately hard ignimbrite rock).

Mitchell (1980) reviewed the 'soil' conditions at Ruahihi for Fletcher Construction in an attempt to revise the tender contract due to conditions being different from that stated at the time of tendering. Mitchell's main conclusions were that: (1) the physical properties of the soil were different from that expected, (water contents, silt clay contents, sensitivities and high allophane levels). (2) Geological sections provided were different from conditions found in the field. (3) A wide range of soil physical properties occurred over short distances in the north eastern half of the site.

Oborn *et al.* (1982) as part of a submission to the Ministry of Works and Development on the Ruahihi Canal Failure described the geology and geological features related to that failure (Fig. 1.7). Note, Mamaku Ignimbrite identified by Oborn (1982) (and Carryer (1974)) in the Ruahihi area has not been found by this writer, the closest outcrop being about 3 km due south. Perhaps they misidentified weathered Waimakariri which can resemble Mamaku Ignimbrite.

1.7 TECTONIC SETTING

This section reviews the tectonic setting of the North Island for two purposes. First, it is argued that volcanism in the Taupo Volcanic Zone (TVZ) can be used to model previous volcanism in the Tauranga Volcanic Zone (the products of which are described in regional geology). For example, Kamp (1984) noted that there are broad similarities in eruptive environments, compositional ranges and eruptive volumes of andesites in the Northland-Hauraki Volcanic Region to those of the TVZ. This would appear to be supported by Houghton and Cuthbertson's (in press) interpretation of the Pukepenga Formation (andesitic and dacitic lava flows in the Kaimai Ranges) as part of a chain of stratovolcanoes that resemble the lava fields of Ruapehu. Second, current landforms and Late Quaternary geology in the Tauranga Region are largely derived from volcanic activity in TVZ.

The North Island of New Zealand occupies the leading margin of the Australia Plate where it is obliquely underthrust by the oceanic Pacific Plate. This convergence dates from about 23 m.y., and consequently throughout the Neogene-Quaternary the North Island has been subject to a complex pattern of arc volcanism, regional compression, extension and transcurrent displacement (Kamp, 1984), collectively referred to as the Kaikoura Orogeny (Suggate, 1978).

Ballance (1976), Cole (1979), and Cole and Lewis (1981) have interpreted the radiometric ages as a series of NNW-SSE oriented Neogene arcs, whereas Kamp (1984) showed that the andesites actually migrated to the southeast and into the TVZ as a series of NE-SW frontal arcs. A similar conclusion was arrived at by Brothers (1984) and indeed the ideas of Brothers and Kamp were pre-empted by a speculation of Skinner (1979).

It is known that about 6 m.y. a major change in volcanism took place, probably caused by a readjustment of the Indian and Pacific plate margins. This was accompanied by the development of the Hauraki Graben and the Havre Trough at 5 m.y. Tensional faulting on the eastern side of the Coromandel Peninsula and rhyolitic and ignimbrite eruptions related to this faulting allowed volcanic activity to develop in Tauranga and adjacent regions. To the north and south of this acid volcanism there were andesitic eruptions and extensive hydrothermal mineralisation of previously erupted andesites and dacites. At approximately 3 m.y. the Tauranga Volcanic Zone is thought to have formed in response to tensional graben structures. Thereafter rhyolitic volcanism dominated by ignimbrites and minor andesite continued (Ballance, 1976; Cole, 1979).

The currently subducted Pacific Plate dips at an angle of 12-15° for 250 km beneath the North Island before it steepens to to a dip of 50° at a depth of 80 km. This line of marked change in dip corresponds at the surface with the trend of the TVZ, a calc-alkaline province of Quaternary volcanics (Cole, 1979).

The TVZ is a graben structure which extends for about 300 km (NE) by about 75 km wide across the central North Island (Fig. 1.8). It can be divided into three segments. The northern segment contains the andesite volcanoes of Whale and White Island. Most of the rhyolitic volcanism is concentrated in the central segment, a 125 x 60 km area comprising the Maroa, Okataina, and Taupo Centres (each associated with multiple caldera collapse) and the Rotorua Centre, a simple collapse structure. The Rotorua Caldera is 15 km in diameter and is thought to have formed by basement collapse during and following the eruption of the Mamaku Ignimbrite, one of the youngest and most widespread ignimbrites in the TVZ. The southern segment consists of

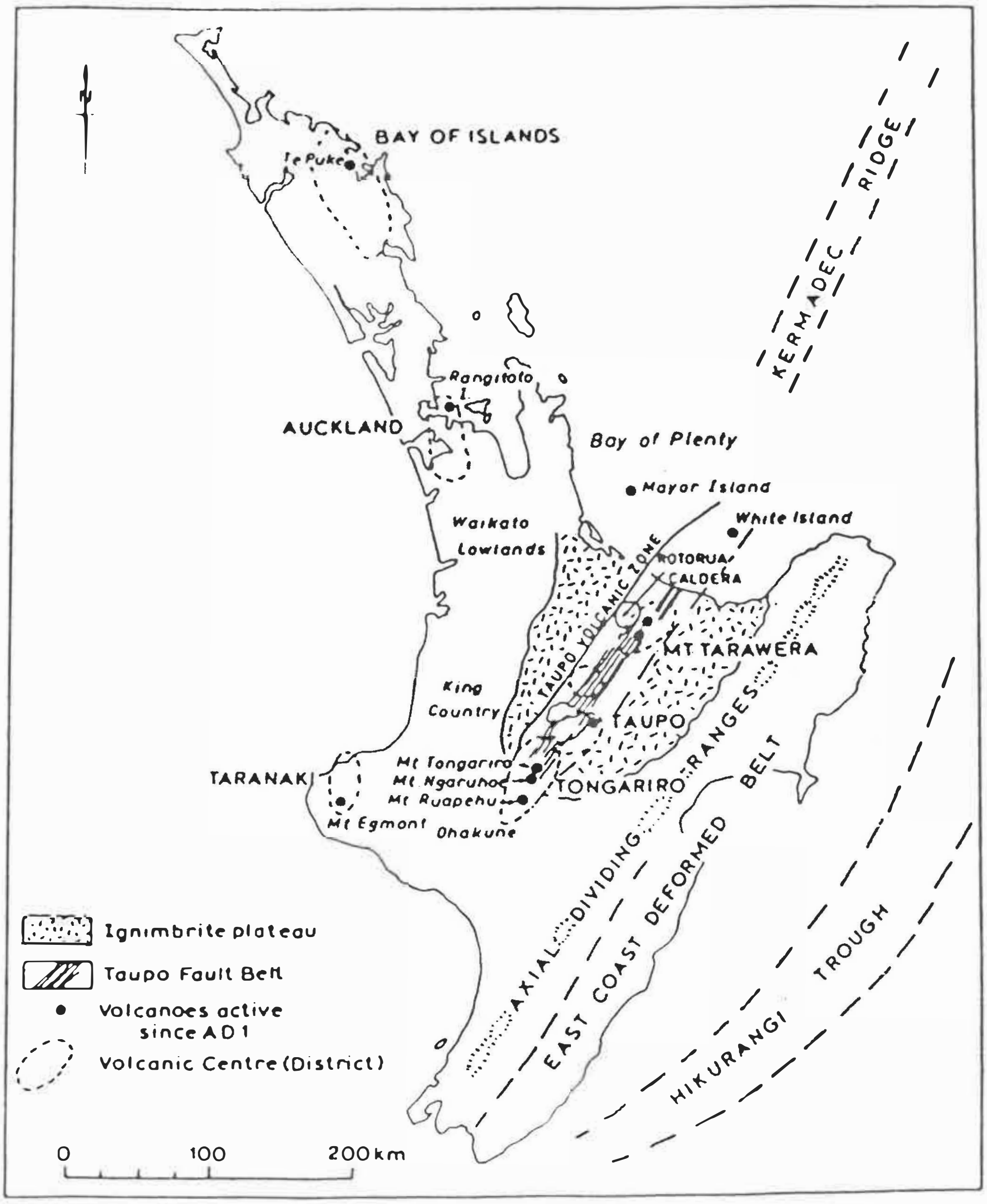

Fig. 1.8 Upper Quaternary volcanic zones and major tetonic features of the North Island (from Prebble, 1984).

the andesite volcanoes of the Tongariro Centre. It is estimated that 16,000 km^3 of rhyolite, 260 km^3 of andesite, 5 km^3 of dacite and 2 km^3 of high Al basalt has been erupted from the TVZ (Cole, 1979).

The TVZ is now clearly appreciated as part of the Hikurangi subducton margin (Cole and Lewis, 1981). This margin consists of a shallow structural trench (Hikurangi trough), a 150 km wide thrust controlled accretionary borderland (continental slope, shelf and coastal hills of the central North Island), a frontal ridge (greywake ranges of the North Island) and a frontal arc (andesite-dacite volcanics) and a behind arc tensional graben where the rhyolites were erupted and along the margin of which are minor basalt eruptions. Based on strontium isotope studies the ignimbrites and lavas are thought to be derived from partial melting of basement greywakes and argillites (Cole, 1979). This rift zone is flanked by plateaus, made up of ignimbrite sheets; together this region is referred to as the Central Volcanic Region. On the basis of 25 major tephra eruptions during the last 20,000 yrs, an average rate of one eruption every 800 yrs is calculated, though the interval between eruptions does not seem to be random (Hodder 1983; Berryman and Hull 1984). Major ignimbrite eruptions are calculated to have taken place at the average rate of one every 30,400 yrs since 0.7 m.y. ago (Berryman and Hull, 1984).

Initial faulting in the Taupo Fault block started in the early Pleistocene and still continues. The faults north of the TVZ are all normal and mostly linear. Several show a scissors type displacement with throws of up to 3.5 km. Although the fault planes are rarely observed. Grindely (1965) infers steep dips. The occurrence of these differentially uplifted blocks and the character of the faults which bound them are primary evidence of NW-SE crustal extension (Kamp, 1985).

The Yellowstone volcanic region of the western USA and the TVZ are similar in size, eruption rate and age though they have different eruptive styles, the TVZ having a shorter eruptive cycle (Wilson *et al.*, 1984). This is attributed to the TVZ's having a thin continental crust which is of insufficient strength to allow a large accumulation of magma.

In summary some of the volcanic products and landforms in the Tauranga area are derived from previous loci of volcanism in the Coromandel-Tauranga region and it is proposed that they were similar in style to that currently active in the TVZ. However much of the recent land form development in the Tauranga/Rotorua area owes its origin to tephra and ignimbtites from the TVZ to the SE. This activity (in the TVZ) can be compared with overseas examples in similar tectonic environments. That is the TVZ is a zone of intense activity in which faulting, a range of lava flows, hydrothermal activity, large scale pyroclastic deposits and rifting have been especially active over the last 1 m.y. These frequent pyroclastic eruptions have produced a varied and complex lithology not only in the TVZ but over the adjacent plateaus.

1.8 REGIONAL GEOLOGY

Healy (1969) described the Beeson's Island Volcanics as andesite lavas and associated interbedded flow breccias which make up the core of the Kaimai Range. These are dark grey and fine grained containing phenocrysts of plagioclase, augite, hypersthene and magnitite. The rocks are often mineralised and faulted and have a maximum eruptive age of 16.2 m.y. (mid Miocene), suffering hydrothermal alteration 7 to 2.6 m.y. ago (Adams *et al.* 1974). These volcanics, some of which have been mineralised, also outcrop in the Papamoa Ranges (Fig. 1.9)

Houghton and Cuthbertson (in press) have redefined the geology of the Kaimais; their subdivisions do not coincide exactly with earlier workers (Henderson and Bartrum, 1913; Healy, *et al.*, 1964; Healy, 1969). Comparing geologic maps, Houghton and Cuthbertson's Waipupu Formation (Kaimai Subgroup) approximates Healy *et al's* (1964) Beeson's Island andesite. The Waipupu Formation is a sequence of andesitic, matrix supported tuff breccias. Lava flows are 10-100 m thick, with margins typically brecciated and oxidized. Steeply dipping dykes cut the sequence in several locations.

Minden Rhyolite is defined to include all hypersthene, hornblende, and biotite rhyolites within the Coromandel Bay of Plenty area, north of the Taupo Volcanic Zone (Houghton and Cuthbertson, in press). They have renamed the Minden Rhyolite previously identified in the Kaimais as Te Weraiti Rhyolite and state it has been substantially changed by faulting and erosion. It is a tabular body of massive, grey and pink, often spherolitic rhyolite with steep isoclinally folded, flow banding close to margins. Generally it is exposed in streams crossing the Whakamarama Plateau. Minden Rhyolite was seen by this writer outcropping just outside the study area in an unnamed stream 0.75 km WNW of Kaikaikaroro trig (U14/738749). Based on fission track dates from obsidians at Bowentown and Mt Maunganui a Pliocene age (2.29 to 4.34 m.y.) is suggested (Houghton and Cuthbertson).

The southern Kaimai Range consists of rhyolite domes, while domes in the Tauranga area include Mt Minden, Mt Misery, and Mt Maunganui. Harmsworth (1983) suggests they could be part of a large volcanic complex extending north and south of the Tauranga Basin and west of the Whakamarama Plateau.

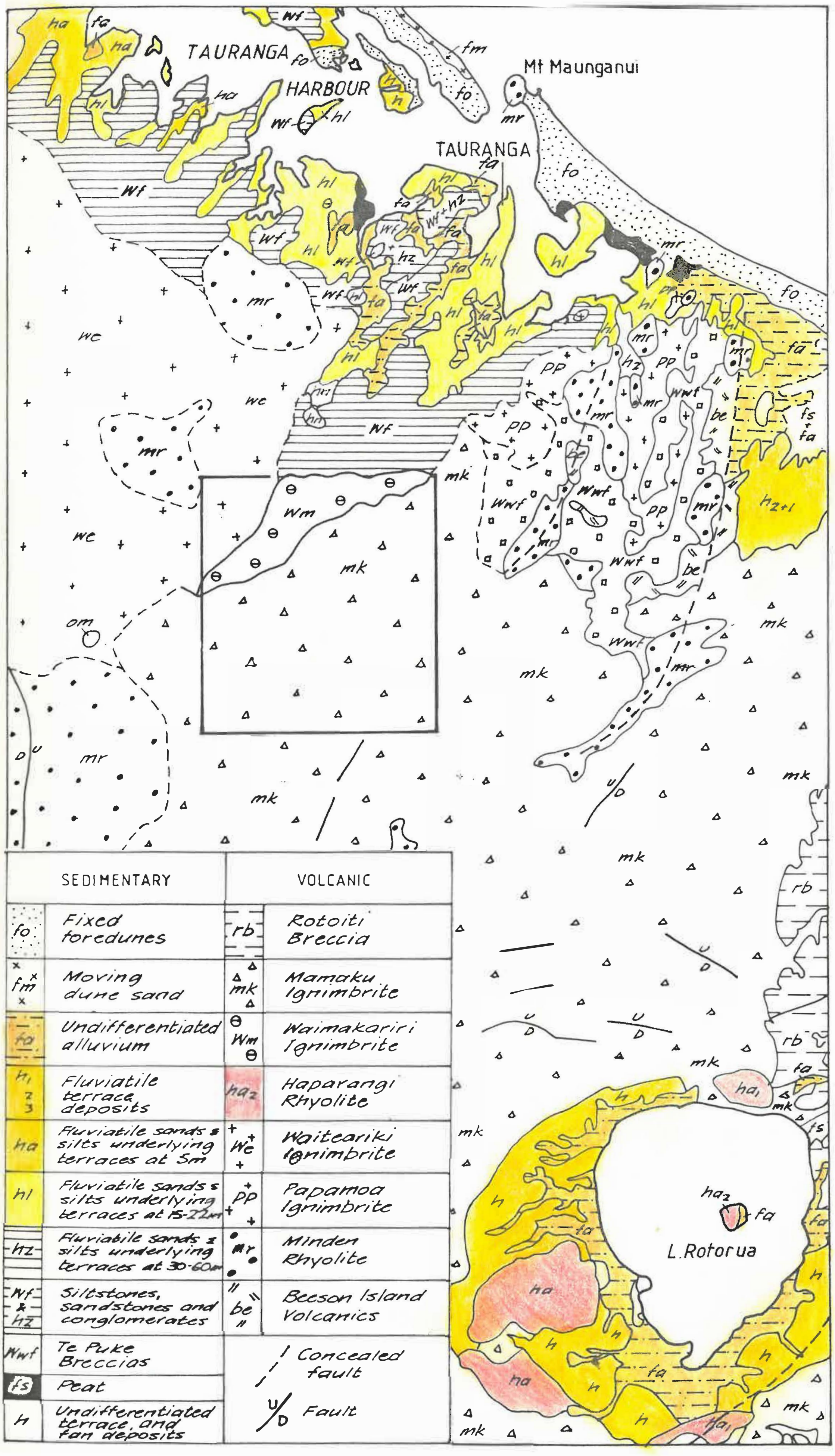

Fig. 1.9 Geological map of Tauranga-Rotorua district. After Healy *et al.* (1964) and Harmsworth (1983).

The Aongatete Volcanics are divided into Upper tuffs and breccias, Aongatete Ignimbrite, and Lower tuffs and breccias which together are about 146 m thick. The rocks distinctive characteristics are an abundance of pumice and a lack of quartz, hornblende, and biotite which differentiate it from the Waiteariki Ignimbrite (Healy, 1969). Several erosional contacts occur within the Aongatete Volcanics and a significant time break separates the Aongatete Volcanics from the Waiteariki Ignimbrite (Brenion and Hegan, 1977). Houghton and Cuthbertson prefer the term Aongatete Ignimbrite for the whole formation rather than the middle member. They describe it as a range of unwelded, partly welded and lenticular dacitic tuff breccias, with minor reworked sediments. These volcanics have fission track ages dating from 0.86 ±0.14 m.y. to 1.26 m.y. for the oldest flow (Houghton and Cuthbertson). The ignimbrite overlies Beeson Island Volcanics to the northwest of the Mamaku Plateau and overlies Minden Rhyolite in the Tauranga Basin.

Underlying the Papamoa Ignimbrite are the Te Puke Breccias, (named by Healy *et al.*, 1964) described as sediments with interbedded andesitic flows and pumiceous tuffs and a suggested mid Pliocene age.

The Papamoa Ignimbrite is considered by Healy *et al.* (1964) to closely resemble the Waiteariki Ignimbrite. Based on a day's inspection of outcrop on and adjacent to Rocky Cutting, Upper Papamoa and Waitao Roads plus investigation at Kaiate Falls, the impression obtained was that the ignimbrite was considerably more pumiceous and less welded than Waiteariki seen in the Kaimais and Northern Mamaku Plateau. Therefore this author is of the opinion that Papamoa Ignimbrite is not part of the pyroclastic flows that emplaced the Waiteariki Ignimbrite. However more work in the Papamoa Ranges would be necessary to confirm this view.

This study has shown the Waiteariki Ignimbrite underlies the northern Mamaku Plateau where it acts as local basement. In turn it is overlain by fluvial and lacustrine sediments which have been given the informal name of Opuiaki Sediments. The Waimakariri Ignimbrite overlies these sediments and is often separated from the Mamaku Ignimbrite by a sandy gravel lens of 2-5 cms. Air fall tephra up to 6 m thick mantles the interfluves. The Waiteariki, Waimakariri and Mamaku Ignimbrites are discussed in some detail in Chapter 3.

The Matua Subgroup comprises up to 150 m of Pleistocene estuarine, fluvial and volcanic deposits which overlie the Waiteariki Ignimbrite in the Tauranga Basin (Harmsworth 1983). This can be further subdivided into an informal upper Matua Subgroup up to 40 m thick originally described by Healy *et al*. (1964) as fluviatile terrace deposits (ha h1 h2 h3). These terraces are not mappable as extensive features, are of varying elevations and are composed of a wide range of lithologies including gravels, sands, clays, and silts. These deposits are often characterised by rapid vertical and lateral variations and are capped by sequences of air fall tephra.

1.9 PHYSIOGRAPHY

Major physiographic features are illustrated in Fig. 1.10. The Hauraki Plains is a graben, occupying a broad valley 25 km wide extending over 200 km from Tirau to the Hauraki Gulf, infilled by late Pleistocene to Recent rhyolitic volcaniclastic sediments (Cuthbertson, 1981). Houghton and Cuthbertson (in press) state the graben can be subdivided into a number of blocks caused by faulting, paralleling the graben margins.

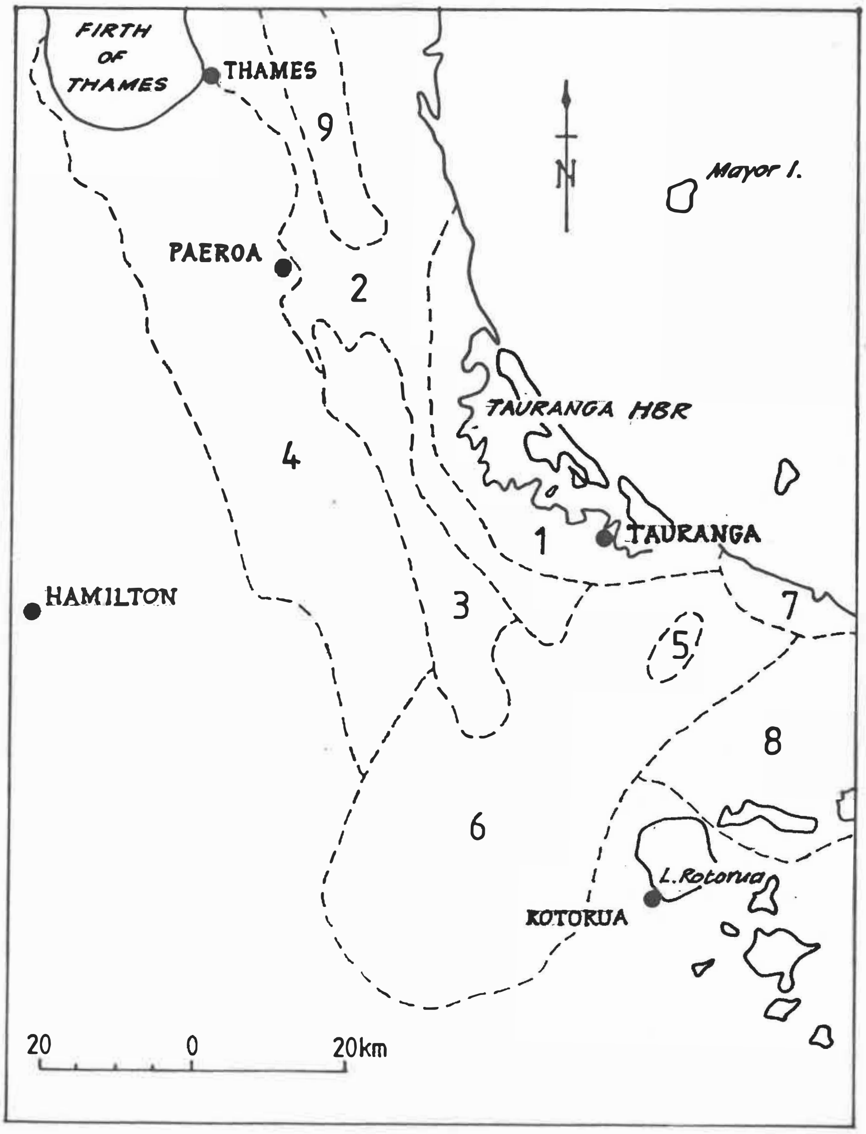

Fig. 1.10 Physiographic regions: Hauraki Plains to Tauranga Basin.

1. Tauranga Basin;
2. Whakamarama Plateau;
3. Kaimai Ranges;
4. Hauraki Plains;
5. Papamoa Ranges;
6. Mamaku Plateau;
7. Maketu Basin;
8. Kaharoa Plateau;
9. Coromandel Ranges.

Rising abruptly from the Hauraki plains is the upfaulted block of the Kaimai Ranges, bounded to the west by steep fault scarps dissected by streams. (Fig. 1.11). To the east the transition is more gentle with the Mamaku and Waiteariki Ignimbrites abutting against the Kaimais. The range trends NW/SE usually as a single chain but becomes multiple in the Te Aroha district. Mt Te Aroha is the highest point (952 m) in the Kaimais; south of this peak the range averages 500-800 m. The range consists of of a core of andesites (some have been mineralised) of Beeson Island Volcanics capped at higher levels by dacites (Healy, 1969).

The Whakamarama Plateau, bounded to the south by the Kaimai Ranges lies to the north of the study area and is an old feature (approximately 0.84 m.y.) which dips gently (4-8°) under and is overlain by the sediments and volcanic products of the Tauranga Basin and northern Mamaku Plateau.

The Mamaku Plateau is a geologically young structure (0.14 m.y.), covering an area of 4350 km^2 (Fig. 1.12). It fans out from the Rotorua Caldera, with its apex at Mamaku (600 m) and extends west to Tokoroa and Putaruru and north to Tauranga and Te Puke where it has been divided by the Papamoa Ranges (these contain a number of northeastly trending volcanic vents). Isolated outcrops east of the Rotorua Caldera suggest that the Mamaku Ignimbrite originally surrounded its presumed source, the caldera. The presence of tors at Mamaku and 5 km north of the Mamaku Ignimbrite type site (U15/887554) indicates that some of the unwelded material has been eroded. However, the flat interfluves in the study area indicate that much of the original plateau profile has been preserved.

Fig. 1.11 View of western Kaimais and Hauraki Plains. Note the steep Hauraki fault scarp.

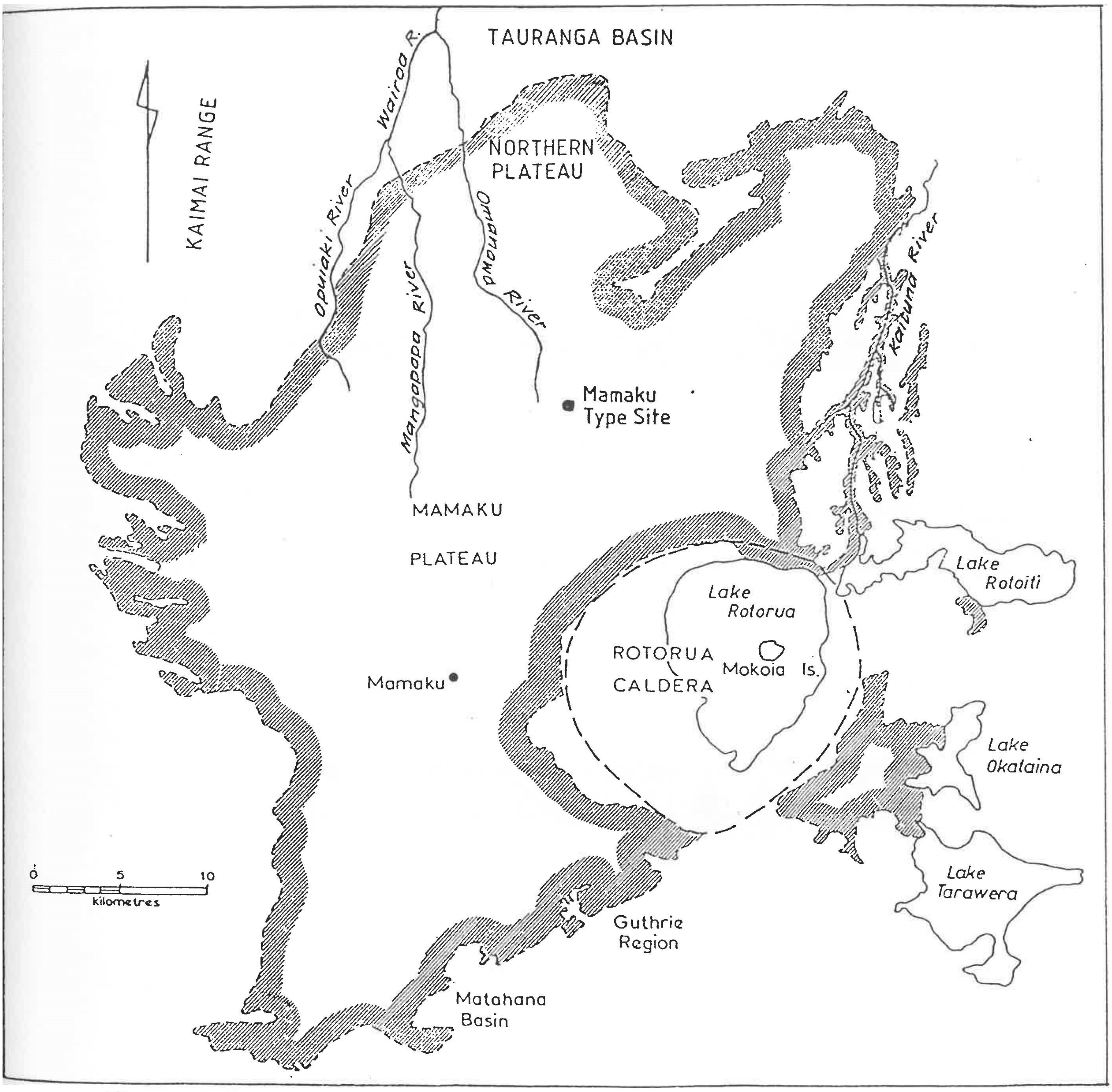

Fig. 1.12 Location map showing the outcrop area of the Mamaku Ignimbrite. After Healy *et al.* (1964) and Fransen (1982).

The northern Mamaku Plateau dips about 2° in a northerly direction towards the the Tauranga Basin, falling 300 m over 12 km in the study area. The streams and rivers flow north, entrenched in steep to vertical gorges. Interfluves with concordant heights separate the waterways. Streams have cut small gullies on these interfluves through the soft upper Mamaku Ignimbrite to its harder middle layer.

At the north eastern boundary of the study area, where the rivers have mostly cut out of their gorges, lies the late Pleistocene-Holocene Tauranga Basin, covering an area of about 570 km^2. It is a north easterly dipping block, dominated by the tidal estuarine lagoon of Tauranga Harbour. The basin, in which subsidence still continues, is infilled by fluvial, estuarine and volcanic deposits (Matua Subgroup) with Waiteariki Ignimbrite acting as local basement (Harmsworth, 1983).

1.10 NOMENCLATURE

Three groups of pyroclastic rocks are recognised in the literature. These are derived from flows, falls and surges (Wright *et al.*, 1980). The overall geometry is the main feature used to differentiate between these deposits, though Walker (1981b) notes that there can be overlap between these processes. Pyroclastic flows and surges are the end members of a range of hot gas-rich, sediment gravity flows, which vary from concentrated laminar and plug flows through to dilute turbulent density currents (Sparks, 1976; Sparks *et al.*, 1978; Sheridan, 1979; Wright *et al.*, 1980). The deposit of a single flow, is a flow unit (Smith, 1960ab). A commonly used term for this or multiple flow units is ignimbrite, which is adopted by the writer regardless of the degree of welding in preference to ash flow tuff or welded tuff. Terminology in this work generally follows that of Smith (1960a,b); Wright *et al.*, (1980); Schmidt (1981); Wright *et al.*, (1981); Fisher and Schmincke (1984).

1.11 AIMS

(1) To differentiate between the Mamaku, Waimakariri and Waiteariki Ignimbrites by petrographic techniques, by field examination and prepare a geological map of the northern Mamaku Plateau.

(2) To construct detailed stratigraphic columns that highlight crystal, pumice and lithic variations within each ignimbrite and to estimate welding with the use of a PT Schmidt hammer.

(3) To suggest eruptive mechanisms, and modes of transportation and deposition of these ignimbrites.

CHAPTER TWO

METHODS

2.1 FIELD METHODS

2.1.1 Introduction

Preliminary reconnaissance of the study area was made in late 1983 and most of the mapping was undertaken during the summer of 1984. A total of 588 samples were collected, 21 columns described and 57 days spent in the field.

2.1.2 Mapping

Initial mapping was undertaken at a scale of 1:10 000 with base maps obtained by photo-enlarging the appropriate sections of topographic maps U14 and U15. Information was transferred to the final map, prepared at a scale of 1:25 000.

Exposures along interfluves are usually poor and to map it was necessary to find ridges which could be followed to the waterways. Thick scrub and precipitous slopes made this difficult. Occasionally, farmers' tracks and public and private roads allowed easy access to the geology and provided many of the columns. Air photos at a scale of 1:30 000 and 1:25 000 were used to locate outcrops, to identify ridges that might be followed, and in final mapping.

Units were mapped in the traditional lithostratigraphic manner as formations. However it was recognised that the Mamaku and Waimakariri Ignimbrites contained several members (flow units) within each formation. For example the Mamaku Ignimbrite in the study area contains 4 flow units and the Waimakariri at least 3 flow units. These are discussed in Chapter 3.

2.1.3 Column Descriptions

A major aim of this thesis was the construction of detailed stratigraphic columns, of the tephras, sediments and particularly ignimbrites. This study is thus primarily a field study. Sample sites in the ignimbrite columns were mostly selected every 5 to 15 m if the deposit was appeared homogeneous, though this depended on the height of the column and available exposure. Where there were obvious changes these were described and so the sample program is to some extent biased.

2.1.4 Ignimbrite Descriptions

For ignimbrites, a number of different parameters were measured at each site of a column. The procedure was to first note outcrop characteristics, particularly joint orientations and intensity and then a hand specimen description was recorded (see Appendix 2 for a copy of the field guide).

Colour was noted and then total crystal percentages were estimated with a hand lens. For pumice, a 30 cm by 13 cm clear plastic bag acting as a sample area was placed over cleaned outcrop and every pumice clast down to a few millimetres diameter counted within the area. Percentages within the sample area were estimated with the use of the comparison chart of Andrews (1982). The colour and physical characteristics were noted and pumice lengths measured, these provided minimum, maximum and average values. The pumice measurements gave upper limits to grain size while the smaller to medium size ranges (glass and crystals) were estimated by visual and hand lens examination. If pumice appeared to be flow aligned the bearing was recorded. Welding was estimated with a PT type Schmidt hammer. Lithics were identified, and lengths measured to give average and maximum values, percentages were estimated using Andrews comparison chart (1982). The groundmass was described and degree of sorting estimated using a grain size comparator. Approximate rock strength was estimated using Selby's (1982) table. The degree of weathering was estimated using the field guide of Andrews (1982). The field guide developed does not cope with all eventualities and if pyroclastic structures, charcoal logs elutriation pipes or any interesting phenomenon was seen this was also noted. A sample was usually taken from each site for more detailed examination.

2.1.5 Welding

To obtain quantitative measurements of the degree of welding of the ignimbrites, the PT type Schmidt hammer was used. This is a pendulum type hammer, devised for carrying out in situ, non destructive tests on weak building materials with a compressive strength of 23 to 345MPa (Operating Instructions).

The N, R, P and PT Schmidt hammers were experimented with in the field on the ignimbrites under study. The N and R types were reliable only on densely welded Waiteariki, while the P type left indentations in less welded sections of the Mamaku and Waimakariri Ignimbrites.

While experimentation demonstrated that the PT hammer gave the best overall results, for greater accuracy the N, R and P types could have been used in more densely welded sections. However it was not practical to carry more than one Schmidt hammer. Ten to fifteen impacts were made on cleaned outcrop and obvious low values were disregarded in the calculation of the mean. Joints and pumice were avoided and each impact was made on a fresh area. The measurements obtained are meant only as an index to welding.

2.1.6 Errors

Pumice was occasionally difficult to see owing to similarity in the colour to that of the matrix, its texture or its small size. Thus it can be expected that in some cases numbers and percentages were underestimated. As only a two dimensional view of pumice can be obtained in a cleaned face, it not being practical or in some cases physically possible to excavate each pumice, it can also be expected that lengths in some cases were underestimated. Potential errors in estimating more densely welded rocks with the PT Schmidt hammer and bias in the data have been mentioned.

2.1.7 Descriptions of Sedimentary Rocks

Descriptions of sediments were recorded in a systematic manner similar to ignimbrites (see Appendix 2). At each site, outcrop characteristics were noted, particularly sedimentary structures and thickness of units.

A handspecimen description was then made of the lithological units exposed. The colour was noted and induration estimated. Composition was both estimated in the field and a sample retained for later examination. Sizes were measured and percentages estimated of crystals, matrix, rock fragments and also pumice which was common. These measurements enabled the grain size based on the Udden Wentworth system to be determined. Sorting was then estimated with the grain size comparator.

2.1.8 Column Height Estimations

Initially an Abney level was used to measure changes in height when describing columns. However the Paulin altimeter was found to be much quicker and is accurate to approximately 2 m. The Littlejohn pocket altimeter, accurate to about 14 m was useful for measuring thickness of ignimbrites when travelling down ridges. The Sununto clinometer, a precision slope angle and height meter, was used in measuring the height of cliffs. The word height is used extensively in this thesis. The reader should take it to mean the distance from the base of a column to the top.

2.2 LABORATORY METHODS

2.2.1 Binocular Examination

It was realised that hand lens estimation of crystal percentages was unreliable, and while pointcounting is the best method of estimating crystal percentages it was originally thought impractical to make slides of all samples that required modal analysis. To overcome this difficulty a binocular microscope at 20 and 40 power was used to examine three chips from each sample and percentages estimated. However a large number of thin-sections were made and the data obtained from binocular estimations was not required. Often, binocular estimations were within 1-2% of estimates from point-counting.

Probes of known size were used to reestimate the small to medium grain sizes (glass, crystals) of incipiently to non welded zones of the Mamaku and Waimakariri Ignimbrites. Interestingly it was found that felsic crystals particularly feldspar could be disaggregated with ease. In some particularly devitrified samples of the Mamaku Ignimbrite, snow like crystals had formed, presumably a product of devitrification.

2.2.2 Thin Section Preparation

Because of their often weak nature, ignimbrite samples prepared for petrological examination were impregnated with resin under vacuum. Ignimbrites were found to be more difficult than loose sands to impregnate and several methods were tried, including various ratios of acetone to resin. However, the most satisfactory method was to impregnate the sample using pure resin under vacuum for half an hour (or until bubbles stopped). It was allowed to stand overnight to cure, and then placed in an oven for eight hours at 60°C to harden. The sample was then ground flat and glued to a glass slide with the excess trimmed by diamond saw. Before final grinding by diamond lap and carborundum powder the sample was reimpregnated and allowed to harden and cure.

By this method full impregnation was possible and few crystals were plucked from the slide while grinding. Exceptions were pumice slides where many crystals were plucked out, rendering them unsuitable for pointcounting. Oxidized mafic crystals in Mamaku Ignimbrite were also often partially plucked out. A total of 107 slides was made.

To investigate mineralised Waimakariri, three polished slides were prepared for examination under reflected light. The method followed that of thin section preparation, with additional stages of progressive grinding with finer grades of carborundum powder, and then polishing with jewellers' rouge, moving to finer grades of diamond paste until a glossy shine was achieved.

2.2.3 Modal Analysis

The use of a mechanical stage on a petrographic microscope is an established technique for obtaining quantitative estimates of relative mineral abundances. A point count of 400 was most often chosen. Errors are caused by: (1) variations within the thin section due to grainsize and spacing, (2) not every grain was counted and some larger crystals were counted more than once; (3) as mentioned previously the ferromagnesian crystals in the Mamaku Ignimbrite are often heavily oxidised and weathered which rendered them prone to plucking. Hence it is likely that mafic crystals were underestimated in the Mamaku Ignimbrite. All unidentifiable ferromagnesian crystals were recorded as hypersthene.

2.2.4 X-ray Fluorescence

Qualitative analysis using an ORTEC energy dispersive XRF was used for the following purpose. When mapping a Mr Peer drew the author's attention to the observation that sheep had been selectively eating 'rhyolite' (Mamaku Ignimbrite) on his farm for many years. It seemed appropriate to investigate this and samples were prepared to see if there were trace or major element variations (see Appendix 1).

2.2.5 Fossil Analysis

Six samples were prepared for diatom analysis in the following manner: 0.25 gm of sediment was added to 50 ml of hydrogen peroxide and boiled for an hour. One drop of solution was placed on a glass slide, allowed to dry and covered by plearax suspension(which has a high refractive index) and cover slip added. Slides were examined under a 400 power binocular microscope and in three cases abundant diatoms were found, and traces in two other slides.

CHAPTER THREE

STRATIGRAPHY AND STRUCTURE

3.0 INTRODUCTION

The geology of the study area consists of a sequence of Middle to Late Pleistocene and Holocene tephras, sediments and ignimbrites, discussed here in that order. This is followed by a discussion of structural features. This chapter describes some of the more important stratigraphic columns. Their location is shown in Fig. 3.1. Names given to the columns indicate a specific location or the property owner s name, type of farm, or hydro-electric station name. Features seen in the field and described in vertical columns and horizontal sections of the ignimbrites allow a variety of information to be deduced. For example, welding, flow directions, source, environments of deposition, and separation of the ignimbrites into flow units.

3.1 TEPHRAS

Previous investigators have described and identified, largely by field methods, the principal Late Quaternary tephras in the McLarens Falls - Ruahihi area. Named tephras include Kaharoa Ash, Rotorua Ash, Rerewhakaaitu Ash, Okareka Ash, Kawakawa Tephra (Oruanui Ash), Mangaone subgroup tephra(s), Rotoehu Ash, and Hamilton Ash (Pullar *et al.* 1973; Harmsworth 1983; Cowbourne 1985). Tephric loess (as described by Kennedy 1980, 1984) have also been recognised.

Two sections at Joyce Road and Ngamanawa are described in Fig. 3.2. Identification of undifferentiated Holocene tephras including the tephric loess are tentative as they are based only on their field appearance. The older units, especially Rotoehu Ash, have more distinctive properties (Fig. 3.3) that enable them to be traced over the whole study area. Pullar *et al.* (1973) refer to the Mangaone Subgroup as undifferentiated Mangaoni Lapilli (Vucetich and Pullar

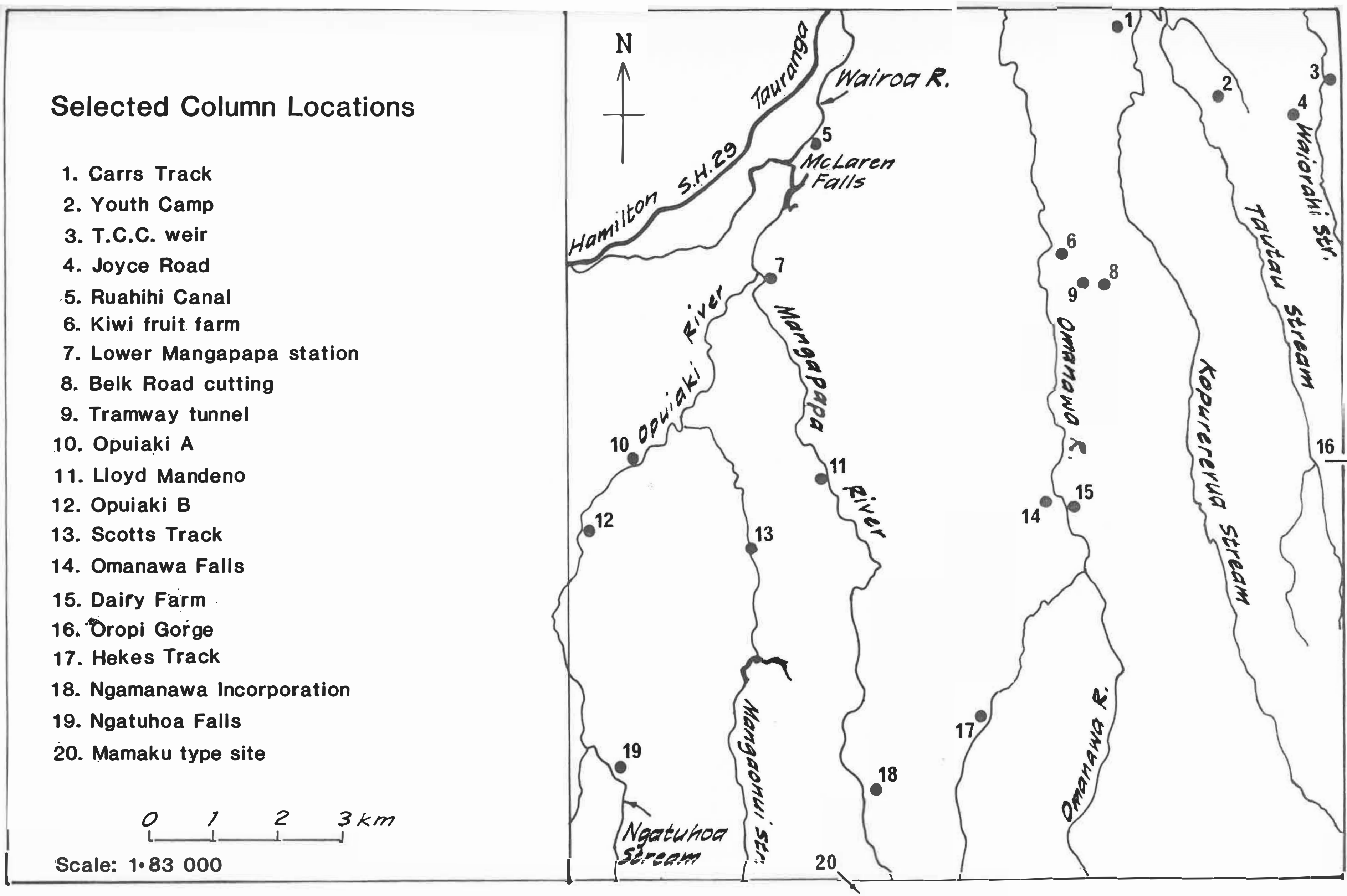

Fig. 3.1 Selected column locations.

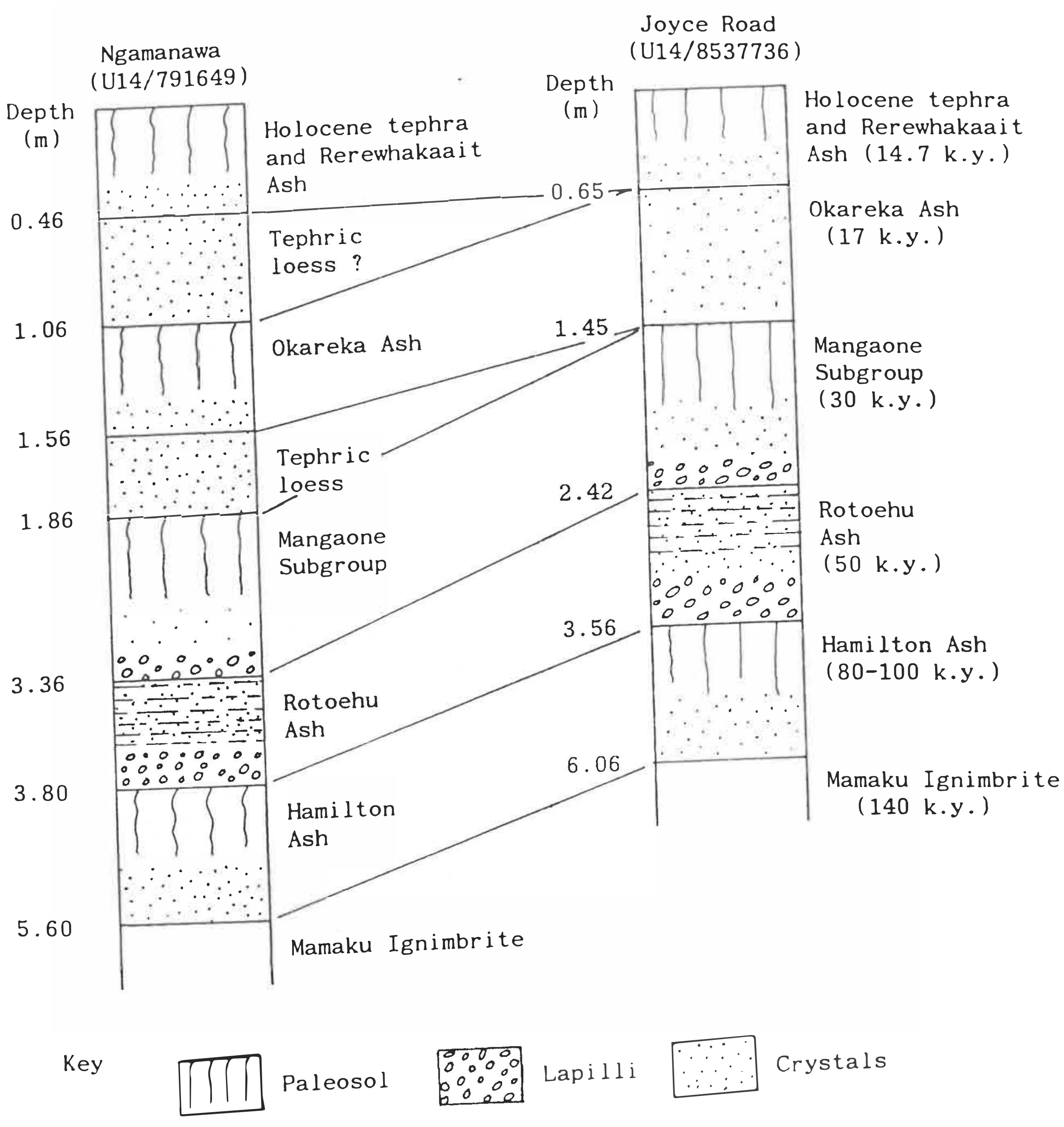

Fig. 3.2 Comparison of two tephra columns. The Joyce Road column is 11 km NE from Ngamanawa. See text for a discussion of the ages. Columns not to scale.

Fig. 3.3 Close up of (1) Hamilton Ash, (2) Rotoehu Ash and (3) Mangaoni Lapilli. Note the strongly shower bedded nature of the Rotoehu Ash and the Mn stains at the contact between the Rotoehu and Hamilton Ashes. T.C.C Weir (U14/859739).

Fig. 3.4 Exposure of about 6 m of tephra on Ngamanawa Incorporation land (U15/785654). Note this photo was taken 0.5 km west of where the soil profile was described. Contact with the Hamilton ash is at the mans head. (1) Mamaku Ignimbrite, (2) Hamilton Ash, (3) Rotoehu Ash (4) Mangaone lapilli, (5) Tephric loess and (6) Holocene Tephras.


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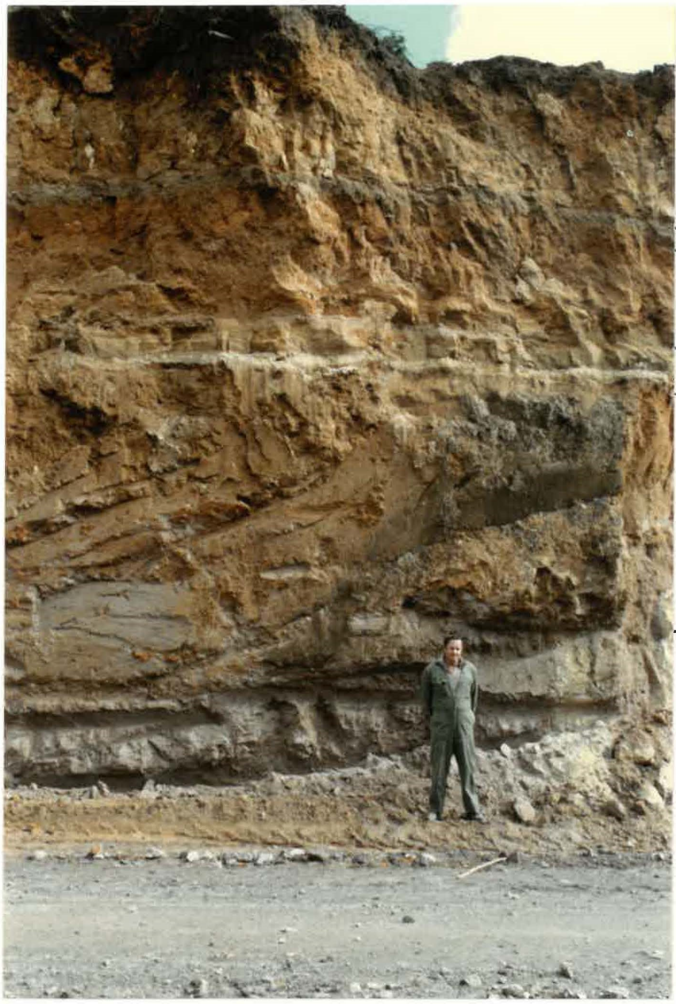
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1969). This formation was redefined by Howorth (1975) and Howorth *et al.* (1981) as the Mangaone Subgroup comprising 8 tephra formations. It is not known which of these formations is represented here, but Maketu Tephra (c. 37 k.y.) and Hapuparu Tephra (c. 36 k.y.) are possible contenders, being identified in the coastal Tauranga area by Birrell *et al.* (1977) and Hogg and McCraw (1983) respectively. Ages for the Rerewhakaaitu and Okareka tephras are from Pullar *et al.* while the Rotoehu Ash dated at 42 k.y. by ^{14}C, is now estimated to be 50 k.y. old (McGlone *et al.*, 1984).

The Rotoehu Ash is a distinctive and widespread marker bed (Fig. 3.4). The basal unit is shower bedded, very pale grey to white and comprises pumice (2-3 mm), glass, small lithic fragments and crystals. There is a gradational change to fine vitric material that has been deposited in 1-3 cm shower bedded layers that have weathered to a light yellow brown colour as it approaches the contact with the Mangaone Subgroup tephra. This upper zone is extremely firm and compact and often stands proud of the outcrop. Samples when broken, fracture in a subconchoidal fashion.

The Hamilton Ash is widespread throughout the study area with a maximum thickness of 4.8 m at the end of Belk Road, although it generally averages 2 m. It is reddish brown and is a clay loam to silty clay. The structure is often massive towards the base and grades upwards into a well developed paleosol, with a nutty, blocky structure as it nears the contact with the Rotoehu ash (Fig. 3.4). McCraw (1975) showed that beds H5-H8 (terminology of Ward, 1967) overlie Mamaku Ignimbrite elsewhere; hence, one or more of these units is likely to be represented here. The age for the Hamilton Ash has been estimated from the overlying Rotoehu Ash and underlying Mamaku Ignimbrite (Mamaku Ignimbrite has been dated at 0.14 m.y.; Murphy and

Seward 1980). Therefore it is suggested that the Hamilton Ash's age (in the study area) may lie in the range 80-100 ky. Earlier Hamilton Ash beds (H1-H4) have a maximum age of possibly 254 k.y. (Froggatt *et al.*, 1986).

Occasionally a 2-3 m thick strongly weathered tephra can be found underlying Hamilton Ash. It is a light yellow orange, sandy clay, friable, with a well developed prismatic structure (Fig. 3.5) and comprises one airfall unit. The tephra may represent the rather loosely defined Pahoia Tuff of Pullar *et al.* (1973). The unit overlies Mamaku Ignimbrite and hence it too must be between 100 to 140 k.y. old.

3.2 RECENT ALLUVIUM

Recent alluvium is defined as the pale grey, massive, unconsolidated sands exposed in the Omanawa and Kopurererua Valleys in the northern study area. These are levee/overbank deposits of the rivers and are about 1.5 m thick. A black sandy charcoal lens (1-2 cm thick) occasionally found near the top is probably the result of bush burning in the early part of this century. These small deposits are not discussed further.

3.3 OPUIAKI SEDIMENTS

3.3.1 Introduction

The Opuiaki Sediments (informal name) are widespread throughout the northern Mamaku Plateau and refer to the deposits overlying the Waiteariki Ignimbrite and underlying the Waimakariri Ignimbrite. These sediments comprise a wide range of textures (clay to cobbles), sedimentary structures (massive to crossbedded), induration (loose to indurated), thickness (3 to 20 m) and paleoenvironments (lacustrine to

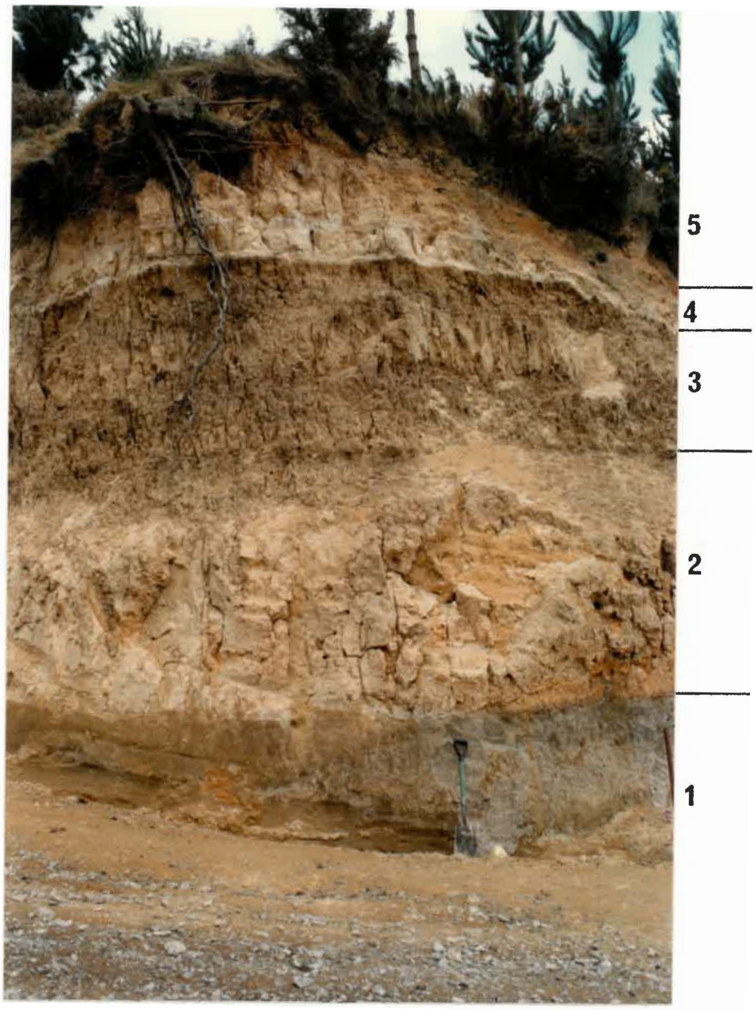


Fig. 3.5 Exposure of the Pahoia Tuff and overlying ashes: (1) Mamaku Ignimbrite, (2) Pahoia Tuffs, (3) Hamilton Ash (4) Rotoehu Ash (5) Holocene Tephras. Farm track, upper Omanawa area (U15/795697).

fluvial). This means that no one column or locality characterises the diverse features of the Opuiaki Sediments. One of the better exposed columns is shown in Fig. 3.6; 6 others are included in Appendix 2. Stratigraphic units have been divided into lithotypes to facilitate a brief interpretation of depositional environments.

3.3.2 Lithology

The following is a summary of the Opuiaki A column in the middle reaches of the Opuiaki River (U15/753682, Fig 3.7). The basal unit is 1.8 m thick, white with yellow-white varves every 1-1.5 cm and is a well sorted siltstone (lithotype 1). When dried the rock has a low specific gravity which reflects the rock's abundant diatom content (see section 4.5.1). This is in sharp contact with, and overlain by, a 4 cm, medium grey, massive, loose, silty sandstone (lithotype 2). This layer, in turn, is overlain by a 1.2 m thick normally graded unit composed of a number of sets of strata (lithotype 3). These alternating coarse/fine sand and siltstone strata have on average a basal sandstone unit 1-2 cm thick (a clean, white, medium sandstone) that grades into a siltstone 3-4 cm thick (pale yellow grey, firm, silty sandstone). This bedded unit is overlain by a 1.9 m massive light yellow sandy siltstone (lithotype 4). In turn this layer is overlain by a 1 m thick, light pinkish grey, firm siltstone (also lithotype 4). A similar sequence was described at the pozzalana quarry (U14/732723).

At Oropi Gorge, 20 m of sediments are well exposed (Fig. 3.6). These are divided into three main lithotypes. Type 4 are massive (with the occasional lamination), pale grey to light yellow siltstone. A 10 cm thick, normally graded, chalazoidite layer lies at the top of lithotype 4. The matrix is a light yellow orange siltstone. The chalazoidites average 8 mm diameter and when broken open have brown

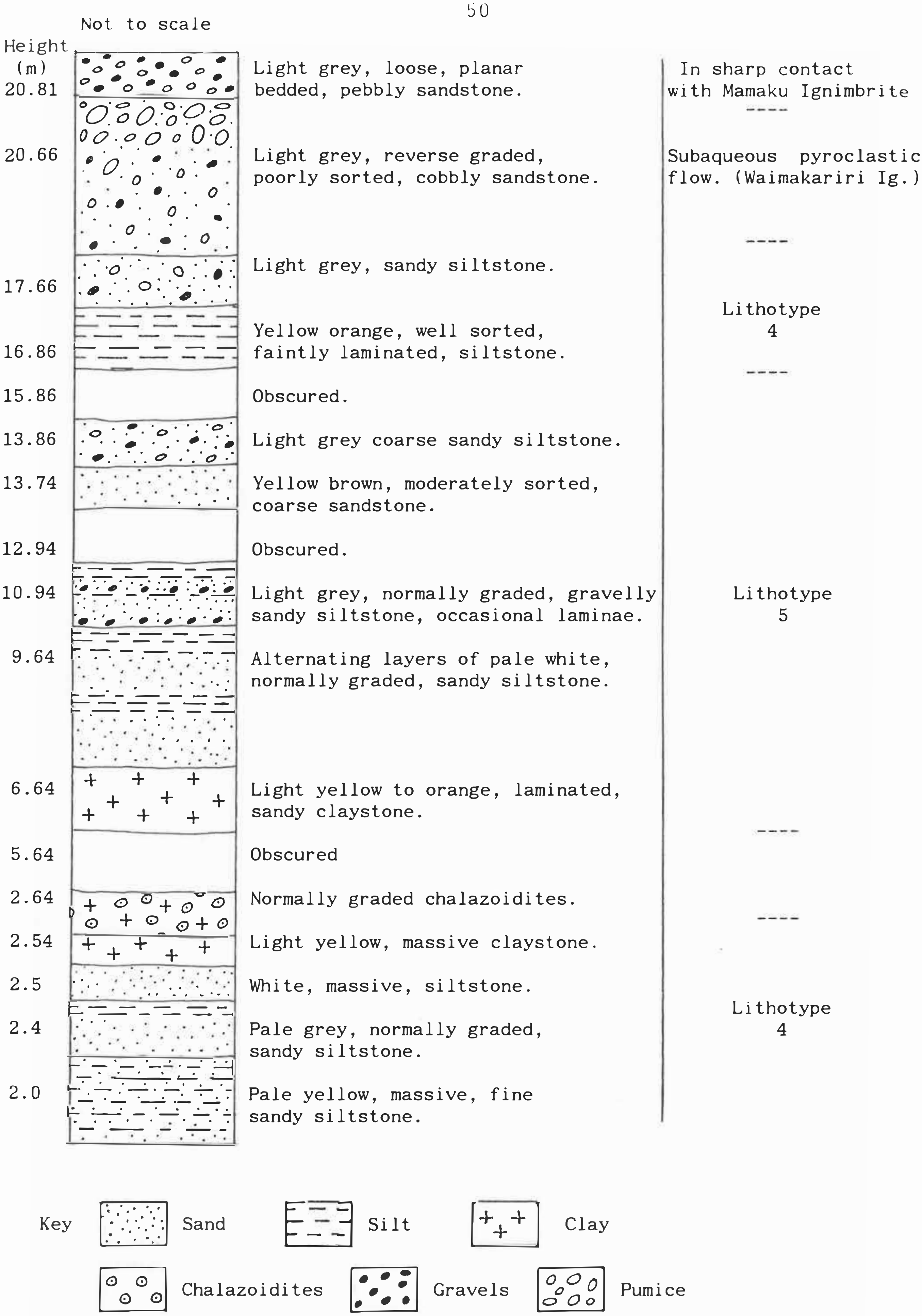


Fig. 3.6 Sediments at Oropi Gorge (U15/877687).

Fig. 3.7 Horizontally bedded sands and siltstones, lithotypes 1, 2 and 3. The sandy lens has been partly eroded out. Opuiaki A column (U15/753682).

Fig. 3.8 Medium scale trough crossbeds. Hammer at base of 3 cm thick iron pan. Lithotype 5, Carrs Track (U14/830750).

concentric rings. Type 5 deposits are normally graded, with the basal unit usually a 2-3 cm thick silty sand and the overlying unit a few centimetres to half a metre thick.

At the top of the sedimentary sequence there is a 3 m layer of matrix supported, poorly sorted, Waimakariri Ignimbrite. However as it is both under and overlain by sediments and is strongly reverse bedded, the deposit is considered to be a subaqueous pyroclastic flow. An alternative hypothesis is a debris flow, though these are typically massive and not graded, therefore this idea is rejected. Diatoms were not found in any of the samples from this column.

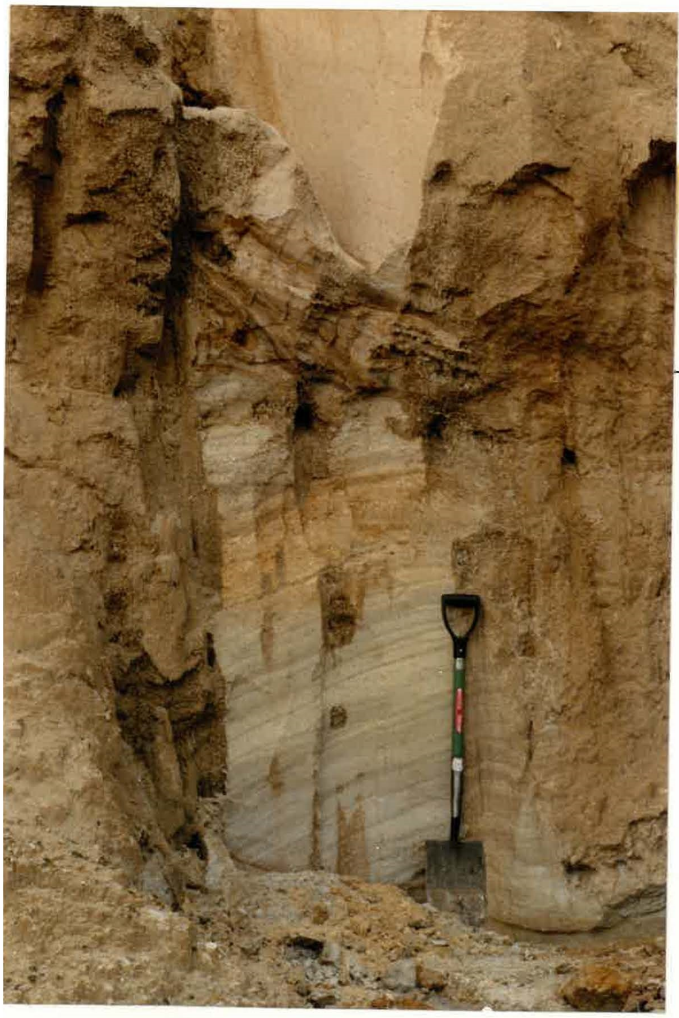
At the base of Carrs track (U14/828748) there is a 2 m exposure of low angle crossbedded sands and gravels interspersed with several iron pans and a gravel lens (Fig. 3.8). These are referred to as lithotype 6. Petrographic examination of the gravel clasts demonstrated their Waiteariki Ignimbrite and Minden rhyolite parentage. Overlying the sands is a fine grained, well sorted, Plinian airfall which is interpreted as precursory to the Waimakariri Ignimbrite. Usually it is massive, though bedding was seen once, in the gorge of the Kopurererua Stream (U14/829735). The gravelly sands are somewhat similar to other low-angle crossbedded units seen at the Lower Mangapapa station, but because they are free of silts and clays they are referred to as lithotype 7 (Fig. 3.9). Lithotype 8 consists of pumiceous gravelly sand, with large scale crossbedded sets. These are rare (Fig. 3.10).

3.3.3 Depositional Environment

Friedman and Sanders (1978) note that the deposits of braided streams consist mostly of sand or gravel, muds are subordinate or absent. This absence distinguishes braided fluvial deposits from

Fig. 3.9 Crossbedded sets of sandy silts, lithotype 7. Lower Mangapapa station (U15/787688).

Fig. 3.10 Large scale tabular cross bedded sets of pumiceous gravelly sands, lithotype 8, in contact with Waimakariri Ignimbrite, Mangapapa River (U15/777714).



Contact

those of meandering streams. As the majority of the Opuiaki Sediments are sands, silts, and clays it is assumed that the main paleoenvironment of the Opuiaki sediments is a meandering river (flood plain) system associated with lakes.

A lake basin environment is suggested for lithotypes 1, 2 and 3. These deposits are rare and confined to two localities: the pozzolana quarry and middle reaches of the Opuiaki River. Lithotype 1 has light and dark coloured laminae which probably represent summer and winter deposition from suspended material (i.e., varves). This in combination with abundant diatoms and silt sized vitric material excludes the smaller still water environments such as ox-bow lakes and localised ponds and suggests a lake environment. Lithotype 2, a massive, coarse sand is probably formed by slump generated turbidity currents from previously deposited sediments of an oversteepened lakeside (Collinson, 1978). It is suggested that lithotype 3 formed in response to finer grained components settling out of the water in response to the turbidity current. An alternative hypothesis is sediment brought to the lake by an inflowing stream or river in flood as described by Irwin (1975). In either case the material appears to be derived from tephric inputs. Healy (1975) notes that lakes have been a feature of lowland areas in the TVZ since it first developed. They were ephemeral, becoming infilled by volcanic sediment washed in from surrounding higher areas or obliterated by larger eruptions. Previously, (section 1.7) it has been suggested a comparison can be drawn between activity in the TVZ and the Tauranga Volcanic Zone. Irwin (1975) notes likely origins of lakes are: (1) tectonic basins formed by faulting, (2) as a result of volcanic activity, or as a combination of 1 and 2. Possibly one of these processes was responsible for the formation of paleo lake basins in the study area.

Lithotype 4 is considered to have been deposited within abandoned channels (ox-bow lakes) or other topographic lows within a fluvial system. Lithotype 5 is considered to be a flood plain deposit. These overbank deposits form by suspended sediment dropping out of the flood waters and form a widespread thin blanket of silts (Friedman and Sanders, 1978). An alternative origin is that of direct tephric input into a small shallow lake, as implied by the presence of chalazoidites. Paleosols might be expected in some of these sediments though only one outcrop seen in the Opuiaki River suggested that it may originally have been subject to soil formation.

The coarse nature of the deposit (gravels and sands) and sedimentary structure (Nu crossbedding) of lithotype 6 imply a channel fill and/or point bar deposits (Lewis, 1984). A crevasse splay or scour fill environment is suggested for lithotype 7, while the relatively coarse texture and sedimentary structures of lithotype 8 suggests a point bar or cross-over region of deposition (Lewis, 1984).

3.4 MAMAKU IGNIMBRITE

3.4.1 Introduction

The Mamaku Ignimbrite was named by Martin (1961) who designated the gorge of the Mangorewa River at the Kohoroa-Tauranga road bridge as the type site (U15/887554). The author visited the area, the aim being to compare a relatively proximal exposure (10 km from source, 130 m thick) with the more distal Mamaku outcrops in the study area. Its maximum known drilled thickness is 180 m on the NW side of Lake Rotorua (Nathan, 1976), which is its source (Healy, 1962). An erupted volume of at least 300 km^3 is estimated (Wilson *et al.*, 1984). The ignimbrite was originally described in the study area by Healy (1957) who called it the upper Omanawa Ignimbrite. While Lloyd (1965) named it the upper Mamaku Ignimbrite, Mamaku Ignimbrite in Martins (1961) original sense is currently recognised as being the most appropriate. Fig. 3.11 is an idealised column of this ignimbrite and it is derived from distal, medial and proximal exposures.

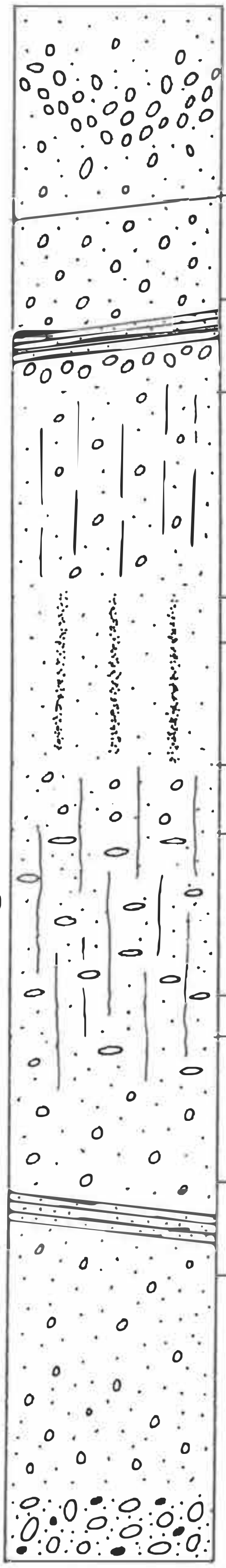
3.4.2 Age and Source

Healy (1962) considers the source of the Mamaku Ignimbrite, to be the Rotorua caldera, collapse after emission resulting in its present shape. The steady thickening of the Mamaku to the south and the wide-spread distribution in the study area supports Healy's contention. Grange (1937); (cited in Briggs, 1973) states the ignimbrite was preceded and followed by the extrusion of rhyolite domes. The ignimbrite has been fission track dated at 0.14 m.y. (Murphy and Seward, 1980).

3.4.3 Distribution

The Mamaku Ignimbrite forms the upper surface of the northern Mamaku Plateau and dips about 2° to the north. In the southern study area the ignimbrite is widespread and thick, a maximum of 70 m being recorded at the entrance to the Ngamanawa Incorporation's land (U15/791647). The following discussion is related to distal outcrop in the northern area and is discussed in a clock wise direction from west (Soldiers Road) to the east (Pyes Pa Road). The ignimbrite was not found outcropping in the far northwestern study area (southwest Whakamarama Plateau): the most northwesterly outcrop seen was a 5 m thick deposit, 20 m below interfluve level on a track leading to the Opuiaki River (U15/767697). The deposit is an example of topographic inversion, as at the start of the track there is an outcrop of Waimakariri Ignimbrite which stratigraphically overlies Mamaku Ignimbrite. This is best explained by distal Mamaku Ignimbrite

Not to scale



(m)	Description	Remarks	
2-5	Matrix yellow brown, moderately weathered. Pumice (2 types): type A (groundmass pumice) light yellow, not devitrified often weathered, type B light grey rounded, not able to be disaggregated by hand. Poorly sorted pyroclastic breccia to fine tuff.	Pumice B often concentrated in a lens	Sheet 4
2-3	Mn layer Very similar characteristics to top of sheet 3. Light pink matrix and pumice, both devitrified.		Sheet 3
0.2	Matrix light brownish grey, crystals 10%, noticeably bedded. Occasional pumice and lithic	Bedded surge deposit	
3-15	Pumice concentration zone Matrix light pink, or reddish grey or grey, always devitrified. Pumice as above, occasionally a relic fibrous texture can be seen. Incipiently welded. Poorly sorted lapilli to fine tuff.	Incipient columnar jointing	
	Gradational change to above		
4-20	Matrix red pink and white, highly altered fumarolic zone. Pumice destroyed-removed ?. Well sorted coarse to fine tuff.	Marks transition between moderate to incipient welding	Sheet 2
5-30	Gradational reduction in welding and jointing.		
10-30	Matrix light pinkish grey and devitrified. Pumice as for matrix, lenticular. Poorly sorted lapilli to fine tuff. Occasional swarm of joints.	Strongly welded columnar jointed zone	
	Rapid increase in welding.		
3	Matrix light orange brown, weathered/devitrified. Pumice pink and brown, semi lenticular. Poorly sorted lapilli to fine tuff. Incipiently welded.	Base of columnar jointed zone.	
0.1	Matrix orange to dull brown. No pumice. 35% crystals. Well sorted coarse to fine tuff. Lithics common	Crystal concentration zone	Bedded surge layer
2-5	Matrix pinkish brown, semi weathered Pumice light orange, relic fibrous texture, semi weathered-devitrified Lithics rare.	Noticeable reduction in pumice size	
1-2	Matrix light reddish brown, occasionally reddish brown, fresh not devitrified. Pumice light yellow grey, fresh coherent. Very poorly sorted pyroclastic breccia to fine tuff. Non to incipiently welded. Occasional lithic.	Pumice concentrated at the base.	Sheet 1

Key

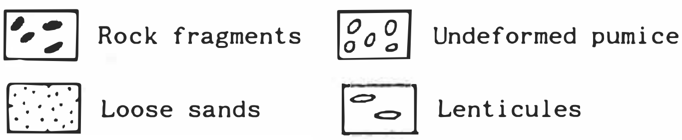


Fig. 3.11 Idealised column of the Mamaku Ignimbrite, compiled from 11 detailed stratigraphic columns.

flowing into a paleo-valley carved into Waimakariri Ignimbrite by the Opuiaki River. Further south (end of Soldiers Road) the ignimbrite begins to outcrop extensively.

A small, unnamed tributary (U14/787713) of McLarens Falls Lake has exposed a 15 m thick outcrop. Further south from this point, it outcrops extensively in farmers' tracks and stream and river gorges. Two kilometres due east a very weathered outcrop is exposed in a small gully off Tomsett Road (U14/805712). Four kms NE at Carrs track (U14/828748, off Belk Road), a 2 m thick layer of Mamaku Ignimbrite can be seen overlying Waimakariri Ignimbrite: this flow unit is here named sheet 4. Three kilometres south, towards the end of Belk Road, the first extensive deposits of Mamaku Ignimbrite begin to outcrop (U14/824712). One of the most northerly Mamaku exposures is a 20 m deposit in the Joyce Road gully, this comprises three flow units, sheets 2, 3 and 4 which are discussed in some detail further in the chapter. The T.C.C Weir column is the most northerly exposure (29.5 km from source) though only sheet 2 was identified.

The overall distribution of the Mamaku Ignimbrite in the study area is a fan shape which is at its furthest extent in the northeast sector of the study area (see geologic map in back pocket). The first is a gradual but steady decrease in thickness from the south to the north. The ignimbrite is 70 m thick at the upper Omanawa Dam at the far southern end of the study area.

Four and a half kilometres due north at Omanawa Falls the rock is 40m thick. Three kilometres north from the falls, at the end of Belk Road, Mamaku Ignimbrite is about 15 m thick. Three kilometres north at Carrs track only a 2m veneer (sheet 4), remain.

Apart from the fact that the Ignimbrite steadily diminishes in thickness in a northerly direction, the importance of the sheet 4 deposit at Carrs track is that sheets 1, 2, or 3 are not present (it seems unlikely that they would be eroded but sheet 4 remains). From this the writer concludes that the main body of the Mamaku Ignimbrite lost the ability to transport its load before entering the Tauranga Basin. This is contrary to the view of Harmsworth (1983) and Cowbourne (1985) who state that the Mamaku Ignimbrite probably entered the Tauranga Basin.

3.4.4 Lithology

The Mamaku type site is 10 km NW from source and 8 km SW from the south-western boundary of the study area. Road reconstruction now provides an excellent exposure of the Mamaku Ignimbrite. The base is strongly welded with columnar joints every 1.5 m. Matrix colour is medium grey, pumice is lenticular with a greyish brown colour. Jointing and welding decrease in intensity as altitude increases while pumice becomes steadily less lenticular, though remaining much the same colour. In the strongly welded zone the pumice are often in roughly parallel alignment which is the result of compaction and/or indicates laminar flow. In the less welded zones only occasionally could preferred pumice orientation be observed, usually the orientation is random. Over 5 m in the lower middle of the outcrop the rock changes from a devitrified but welded and coherent outcrop to a highly altered fumarolic zone with numerous vertical fumarolic pipes of fine pink to red material. Most pumice has been removed or destroyed in this zone and the rock is weak. The fumarolic activity is concentrated in a 20 m horizontal distance and reduces in intensity over 8 m vertically. In all, the zone extends for about 30 m (Fig. 3.12). In the uppermost few metres of outcrop there is a sharp

Fig. 3.12 Close up of fossil fumarole. Original texture largely destroyed, Mamaku type site (U15/887554).

Fig. 3.13 Illustration of the variation in colour of Mamaku Ignimbrite. This is either related to fumarole - vapour phase activity, or differential weathering. Lloyd Mandeno column (U15/787685)

contact with an overlying flow unit here called sheet 3. The identification of a new flow unit was made on the basis of a manganese lens which separates the flows, a change in colour, changes in pumice numbers and percentages, and change in welding (see the type site column, Appendix 2).

At the entrance to the Ngamanawa Incorporation's land (U15/791647, hereafter referred to as Ngamanawa) there is a 70 m exposure of the ignimbrite. The outcrop can be summarised as having a light pink matrix with abundant brown to brownish black spots. All pumice and matrix has been devitrified, pumice is mostly pink though white examples are common in the upper half of the flow. Occasionally a relict fibrous texture can be detected. In the lower part of the flow, pumice is semi-lenticular. This effect reduces with height. Pumice is everywhere randomly orientated. The base of the rock is moderately columnar jointed and welded; both these effects decrease in intensity as height increases. At Hekes track, 1.5 km E of Ngamanawa, the textural characteristics are similar, although vertical fumarolic pipes, depleted in coarse material, are common. They are not nearly as well developed as at Ngamanawa.

Four kilometres NNW, at the Lloyd Mandeno column (U15/787685) a 24 m thick outcrop of Mamaku Ignimbrite overlies Waimakariri Ignimbrite. Matrix colour is variable (Fig. 3.13) and ranges from light brown, to a light grey and shades of pink. Towards the top of the flow, colour changes to the more usual light pink with brown spots. These variations are attributed to a combination of weathering, fumarolic activity and vapour phase activity. Three and a half kilometres NE at Omanawa Falls only the basal strongly welded zone is exposed, the pumice is markedly lenticular and is strongly aligned NW-SE.

Scotts track (U15/777677) lies 2 km SW from the Lloyd Mandeno column. Exposed is the base, the columnar jointed and welded middle, and upper incipiently welded zone, often with marked changes in lithology (Figs 3.14, 3.15). The lithological variation is not considered to be caused by separate flow units.

At the end of Belk Road, 3 km NNW from Omanawa Falls and 0.25 km due S of the road cutting there is an abandoned tramway tunnel and several cuttings (U14/825711) about 15 m below the level of Belk Road. The groundmass is devitrified, slightly weathered and brownish pink. Pumice averages 1-2 cm, and varies from light yellow, to light pink. The rock is incipiently to moderately welded, the tunnel being able to stand unsupported. Lithics are very scarce in this outcrop.

Basal Mamaku Ignimbrite at the T.C.C weir (U14/857737) column has a light reddish brown matrix, pumice is fresh, has a fibrous texture and a very pale orange colour and averages 2 cm with a maximum of 11 cm (Fig. 3.16). The rock is poorly sorted and ranges mainly from a fine to coarse tuff with some breccia. In the lower section of the columnar jointed zone a lithic concentration zone was noted (Fig. 3.17). Generally these are devitrified and best seen in thin section. Lithologic characteristics at the basal zone at Scotts track are similar and not repeated. The basal groundmass at Oropi gorge (U15/877687) is light yellow grey and pumice has a similar colour as the groundmass.

3.4.5 Contact Relations

The Mamaku Ignimbrite is generally separated from the Waimakariri Ignimbrite by a graveley sand lens 3 to 5 cm thick. In contrast, exact contact between the Mamaku Ignimbrite and overlying tephras (usually Hamilton ash) can be hard to define, as the top of the Mamaku

Fig. 3.14 Hand specimen of moderately welded, coarse and fine tuff, upper basal zone. Mamaku Ignimbrite, Scotts track (U14/777677).

Fig. 3.15 Close up of strongly devitrified lapilli tuff. Note the well preserved lenticular, fibrous texture of the relic pumice. From the upper middle columnar jointed zone. Mamaku Ignimbrite, Scotts track.

Fig. 3.16 Contact between the overlying Mamaku and underlying Waimakariri Ignimbrite. Note the 2-5 cm gravelly sandy lens which separates the two flows, T.C.C Weir (U14/860739).

Fig. 3.17 Rare lithic concentration zone, basal moderately welded layer Mamaku Ignimbrite T.C.C. Weir.

is often heavily weathered. Usually there is a gradational change over 0.5 m to where tephra can be separated confidently from ignimbrite.

3.4.6 Flow Units

Four flow units (Smith 1960a) are here recognised in the Mamaku Ignimbrite. At the Mamaku type site, near the top of the flow, the ignimbrite was divided into two flow units (sheets 2 and 3) from field characteristics. From sheet 2 to sheet 3 there is a change from reddish grey to purple grey, an increase in pumice from 5 to 12 %, an increase in welding 18 to 30 PT units, a slight decrease in total crystals from 10 to 8% and the sheets are separated by a Mn layer (Fig. 3.18).

Only sheet 2 is recognised in the southern study area (Ngamanawa, Hekes) though probably the upper units were eroded. However sheet 3 was identified at Joyce Road (one of the most northerly exposures) based on a pumice concentration zone and a 3-8 cm thick surge layer which directly underlies sheet 3.

Oropi gorge is 6 km E of Omanawa Falls and has complete exposure of the Mamaku Ignimbrite. The immediate basal zone (sheet 1) is a pyroclastic breccia to lapilli and coarse tuff, incipiently welded, although over a vertical distance of about 2.5 m pumice and groundmass steadily becomes more devitrified. The matrix is pinkish brown, while pumice is light orange and devitrified except the immediate (0.3-0.5 m) basal zone (in contact with the underlying sediments) which has unaltered vitric material. This 2.5 m thick unit is overlain by a bedded crystal (35.5 %) concentration zone, 7 cm thick. It strikes 140° and dips 2° S, it is interpreted as a surge deposit preceding the front of the advancing flow unit (Fig. 3.19). In sheet

Fig. 3.18 Contact between sheets 2 and 3 marked by the Mn lens at the spade handle. Mamaku Ignimbrite, Mamaku type site (U15/887554).

Fig. 3.19 Contact between sheets 1 and 2 marked by a bedded crystal concentration zone (at spade handle) interpreted as a surge deposit. Note the onset of columnar jointing in sheet 2 in the upper part of the photo. Orópi Gorge (U15/877687).


Sheet 3
Contact
Sheet 2


Sheet 2
Surge
Sheet 1

2, welding and columnar jointing steadily increase, reaching a maximum intensity at 10 m from the base of sheet 2, these effects gradually reduce in effect with height. The most common groundmass colours are shades of light grey, and reddish grey. Pumice tends to be the same colour as the groundmass and is also heavily devitrified. Sheet 3 was not found at Oropi Gorge but sheet 4 is present. This is a conspicuous non welded flow unit, found in the north to northwestern study area.

Sheet 4 Mamaku Ignimbrite is in sharp contact with sheet 2, separated by a Mn layer (Fig. 3.20) at a cutting at the end of Belk Road (U14/826712). Because its characteristics are best expressed here, the cutting is proposed as the sheet 4 type site. The matrix is yellow/brown, pumice (pumice 1) is light yellow with a well preserved relic fibrous texture. In the middle of sheet 4 there is a pumice (pumice 2) concentration lens, pumice 2 is pinkish white and range up to 8 cm long though averages 2 cm (Fig. 3.21). The pumice in this zone differs from the groundmass pumice (differences in colour, larger size and not able to be disaggregated by hand), perhaps due to its larger size and therefore smaller specific surface area having a greater resistance to weathering. The lens is overlain by a 10 cm dark brown layer with numerous manganese stains. In turn, this is overlain by a 4 m yellow brown layer containing pumice 1 and occasional pumice 2. This last layer is that seen in other northern outcrops of sheet 4, the underlying layers of sheet 4 seen at Belk Road being absent in other sheet 4 outcrops. This sheet is nonwelded and therefore easily eroded and probably why it has been seen at only four locations. Sediments derived from sheet 4 are easily recognizable and were identified at the top of reworked Mamaku Ignimbrite sediments at the northern end of Joyce Road (5 km N of the southern end of Joyce Road) in Harmsworths' (1983) study area by this

Fig. 3.20 Contact between sheets 2 and 4, Mamaku Ignimbrite, Belk Road (U14/826712).

Fig. 3.21 View of pumice lens, just below the black Mn layer. Sheet 4, Mamaku Ignimbrite, Belk Road (U14/826712).

author.

Sheet 4 has some of the characteristics of an ignimbrite veneer deposit IVD (Walker *et al.*, 1981). It (sheet 4) is thin (2-3 m), contains stratified, rounded, lenses of coarse pumice. However the largest pumice in it are not consistently smaller than in the underlying flows and it does not pass laterally into the valley ponded ignimbrite (sheets 2 and 3) perhaps the most diagnostic characteristic of an IVD (Walker *et al.*, 1981).

At the Joyce Road column (U14/853736), a 30 m exposure of Mamaku Ignimbrite contains 3 flow units (sheets 2, 3, and 4) identified by the following characteristics. For a vertical distance of 27 m the ignimbrite has the normal characteristics of sheet 2 until pumice begins to concentrate markedly immediately before a bedded (occasionally with low angle cross bedding) crystal concentration zone (surge deposit) which strikes NW-SE (Fig. 3.22). This zone is not correlated with that in the basal section at Oropi Gorge though it is also interpreted as the front of an advancing flow unit and marks the top of sheet 2 and base of sheet 3. This has similar colour and textural characteristics to the top of the underlying sheet 2 and is identified as a separate unit only because of the concentration of pumice immediately before the bedded crystal concentration zone. Sheet 3 is 2 m thick and overlain by sheet 4 with the usual identifying characteristics of orange brown matrix with pumice 1 while pumice 2 is concentrated in a lens towards the base of the flow.

It is not possible to state definitely that sheet 3 at the Type site is sheet 3 at Joyce Road as there are differences in colour, texture and welding. This is probably to be expected as there is a distance of about 18 km between the two columns. However it is assumed they are the same owing to their stratigraphic positions.

Fig. 3.22 Bedded zone (surge layer) which seperates sheets 2 and 3. The pumice concentration zone which directly underlies the surge layer is only just apparent in the photo. Distal Mamaku Ignimbrite, Joyce Road (U14/853736).

This does not apply to sheets 1, 2 and 4 as they are readily identifiable. Sheet 2 comprises the bulk of the Mamaku Ignimbrite.

The crystal enriched surge or ground layer which often separates these flow units was probably the head of a flow which due to entrapped over-ridden air is more fluidised than the rest of the flow and is highly turbulent, and enriched in crystal and lithic fragments as described by Walker *et al*. (1981), similar to the layer 1 of Sparks *et al*. (1973) or the turbulent boundary layer of Valentine (1986). Another possible and similar origin is by forward jetting from the flow head (Walker, 1983). Note the surge layer that separates sheet 1 from sheet 2 is considerably more crystal rich (35.5%) than the surge (10%) that marks the boundary between sheet 2 and 3. This is assumed to be because they are different types of 'surges', though which type is unclear.

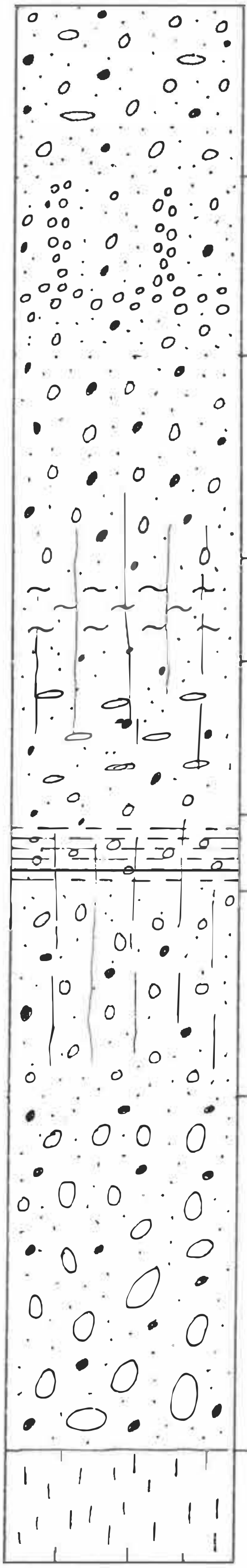
3.5 WAIMAKARIRI IGNIMBRITE

3.5.1 Introduction

The Waimakariri Ignimbrite was originally described by Healy (1955, 1956, 1957). Both he and Cowbourne (1985) have several different names for the rock (see Chapter 1). Lloyd (1965) recognised it was a separate ignimbrite and called it the lower Mamaku Ignimbrite. Fransen (1982) renamed it the Waimakariri. A generalised stratigraphic column for this ignimbrite is presented in Fig. 3.23.

Bedrock in the rivers and streams in the west is usually Waimakariri Ignimbrite and is often potholed (Fig. 3.24). However its most common occurrence in the study area is as steep sided to vertical cliffs in the streams and valleys that dissect the northern Mamaku Plateau (Fig. 3.25). Case hardening of the rock is common and can give an appearance of apparent welding that the rock does not

Not to scale



(m)		
2-5	Matrix light brown. Pumice light greyish brown, rounded, fibrous texture. Poorly sorted lapilli tuff. Non-incipiently welded. Lithics common.	No jointing
4-8	Matrix light grey. Light grey pumice, fibrous knotty texture, rounded. Moderately to incipiently welded. Poorly sorted, lapilli tuff.	Horizontal pumice sheets Incipient columnar jointing Vertical pumice pipes
10-14	Matrix light grey, flakes of obsidian. Pumice greyish white, semi lenticular, semi fibrous. Moderately welded. Lithics common. Poorly sorted lapilli tuff.	Gradual reduction in welding and compression Abundant columnar joints
1-2	Matrix dark grey. Pumice has an eutaxitic texture.	Strongly welded zone
8-12	Matrix light grey, obsidian clumps common. Pumice brownish grey strongly compressed, not fibrous.	Abundant columnar joints
1	Zone of bedded pumice and matrix.	Very rare
10-14	Matrix dark grey. Pumice dark grey, semi compacted and lenticular. Moderately welded. Lithics common. Poorly sorted lapilli to ash tuff.	Noticeable decrease in pumice Incipient columnar joints
3-5	Matrix light grey, tinge of brown or yellow. Pumice white to light grey, occasionally a tinge of orange, fibrous knotty texture. Non to incipiently welded. Charcoal fragments common. Lithics abundant, up to 2 cm Very poorly sorted, pyroclastic breccia some lapilli, coarse and fine tuff	Large increase in pumice size and percentages No jointing
1-3	Very well sorted fine grained Plinian airfall	Usually massive, once seen with some structure

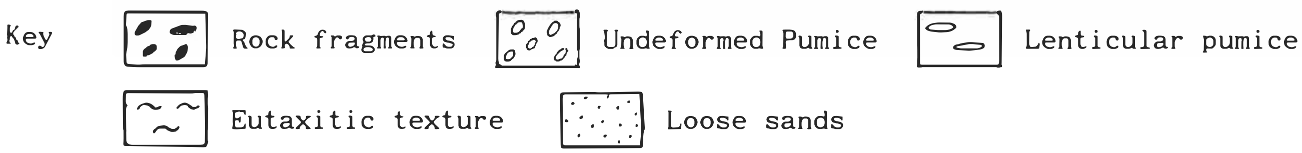


Fig. 3.23 Idealised column of the Waimakariri Ignimbrite, compiled from 7 detailed stratigraphic columns.

Fig. 3.24 Basal Waimakariri Ignimbrite, note preferential removal of pumice and pothole scouring. Mangapapa River (U15/786685).

Fig. 3.25 Vertical cliffs (about 30 m high) of Waimakariri Ignimbrite. Note the unusual oblique angle of the joints, upper right of the photo. Lake Mangapapa (U14/780705).

possess. This is probably caused by water with silica in solution evaporating when reaching the outcrop face, leaving the silica behind. A particularly thick silica deposit can be seen by the penstock outlets at the Lower Mangapapa station.

3.5.2 Age

The age of the Waimakariri is not known and only fission track dating will solve the debate. Fransen (1982) believes it is not much older than the Mamaku Ignimbrite (0.14 m.y). Harmsworth (1983) suggests an age of about 0.18 m.y. Field evidence this writer has seen is contradictory.

A thin (5 cm) sandy gravel separates the Waimakariri and Mamaku Ignimbrites at Scotts Track (U15/777677) in the eastern study area, At the T.C.C Weir (U14/857737) 9.5 km NE almost identical conditions exist (Fig. 3.16). Both these columns suggest only minor erosion has occurred based on the following evidence: (1) the thin sediment layer implies a short period of erosion before deposition of the Mamaku. (2) the incipiently welded top of the Waimakariri is present in some locations.

Opposing evidence is as follows. The upper incipiently welded top of the Waimakariri is missing at Omanawa Falls and adjacent areas. Twenty metres below interfluve level and stratigraphically overlain by Waimakariri a small deposit of Mamaku Ignimbrite outcrops on a track leading to the Opuiaki River. For this to occur there must have been a pre-existing valley carved in the Waimakariri. Based on drill cores Lloyd (1965) states the Waimakariri was extensively eroded before emplacement of the Mamaku Ignimbrite, which filled paleo valleys carved in the Waimakariri. The question is how much time is required for substantial erosion in some locations. Collins *et al.* (1983)

calculated that 11% of the tephra deposited on hillslopes from the 1980 Mt St Helens eruption was eroded within one year of the eruption, while Hildreth (1981) notes that 10% of the 1912 sheet at Katmai (Valley of Ten Thousand Smokes) has been stripped. This suggests that substantial erosion of pyroclastic deposits can occur (especially unwelded material) within a relatively short time. Though erosive effects of course depend on the topography as well as the material being eroded.

In spite of the contradictory evidence, the impression gained during mapping and column construction was a period of a few hundred years elapsed before the arrival of the Mamaku Ignimbrite.

3.5.3 Source and Distribution

To the north of the study area the ignimbrite has penetrated about 1 km into the Tauranga Basin as incipiently welded lobes. Fransen (1982) states the Waimakariri is found throughout most of his study area (20 km SW from the area examined here) and is relatively thick and voluminous. On the basis of lithology Nathan (1975) correlated unit D from the Kaharoa drill hole (15 km SE) to the the Lower Mamaku Ignimbrite. This, combined with the distribution in the study area outlined below suggests the ignimbrite is widespread.

Drill logs (Healy, 1957; Lloyd, 1965, 1968) and mapping show that the Waimakariri is widespread in the middle, northern and northwestern sectors. The rock is thickest in the middle and western study area (about 50 m), while it thins to the north (25 m at Carrs Track and 23 m at Ruahihi Canal) and has not been found north of the Mangakarengorengo River although it can be seen occasionally along its southern banks. The rock thins to the east where it is discontinuous along the Tautau Stream and in the lower reaches of the Waiorahi

Stream and found as sediments in the Waiorahi's upper reaches (Oropi Gorge).

Dips and bearings were taken of carbonised log moulds (Fig. 3.26) at Ruahihi Canal (SW bank) in an attempt to infer flow direction and thus possible vent position (Froggatt *et al.*, 1981). The following three recordings (dip and bearing respectively) were obtained yielding directions of 2° S, 5° SSW and 1° SW. Charcoal fragments are common in the Waimakariri and occasionally elutriation structures can be observed (Fig. 3.27). Surprisingly these are not seen with the tree moulds. Morgan (1986) found that tree moulds were restricted to the lower horizons of the ignimbrites she studied and suggests that for preservation a minimum load pressure is necessary and quenching of the pyroclastic material must occur shortly after the tree is incorporated into the flow.

One of the most strongly welded sections of the ignimbrite is at Lake Mangapapa. Overall there is a gradual decrease in welding towards the north and east. Note, the ignimbrite in distal sections can be strongly welded where it has flowed into paleo topographic lows. This is not uncommon, Sparks *et al.* (1985) state that the Cerro Galan Ignimbrite is densely welded where it has been deposited in topographic lows.

From the above lines of evidence a southerly source for the Waimakariri Ignimbrite is suggested, perhaps the Rotorua Caldera. Though an argument exists for a SE source in the Southern Kaimais based on the decrease in welding to the east.

Fig. 3.26 Mould left by mostly vapourised log, some carbonised material remains. Ruahihi Canal (U14/783727).

Fig. 3.27 Elutriation of fines by gas given off from the charcoal fragments. Ruahihi Canal (U14/7837270.

3.5.4 Lithology

The tors exposed in the west (Soldiers Road area) have a light yellow orange matrix, pumice is light yellow, lenticular with a fibrous, knotty, crystal-rich texture (Fig. 3.28). In stream beds the pumice has often been removed; this, coupled with potholeing, leaves a cavernous appearance (Fig. 3.24). Welded Waimakariri exposed in the bed of the Opuiaki River to the east of Soldiers Road has semi-lenticulite pumice with a cream colour tinged with orange. Upstream of the ford several contacts with the underlying Opuiaki sediments can be seen. Downstream of the ford the ignimbrite has an unusual frittered appearance seen at two other locations, upstream of Omanawa Falls (U15/822683) and the waterfall at Ivy Creek (U14/796761). This appears to be related to the constant wetting and drying of the rock at these locations.

East of the Opuiaki River in the vicinity of the Lloyd Mandeno station, Lake Mangapapa and Scotts farm, the ignimbrite can be seen to have varying degrees of welding, texture and colour. A good example of the upper incipiently welded section is at Scotts track (U15/777677). Here the groundmass is a pale orange red, obsidian is common and pumice is light grey with the usual textural characteristics. The middle welded zone crops out along the less steep banks of Lake Mangapapa as benches of grey lenticulite. Here the pumice has been heavily compressed and welded and tends to a light yellow colour. Several examples of a eutaxitic zone in which flattened and stretched fiamme are recognizable. This zone of very strong welding can also be seen in some of the vertical cliffs that line parts of Lake Mangapapa. As height reduces there is a gradational change to a basal pumice rich zone (Fig. 3.29). This basal zone also outcrops by the bridge that crosses the Managapapa

Fig. 3.28 Tor (about 20 m high) Waimakariri Ignimbrite. Opuiaki Region (U15/775688).

Fig. 3.29 Basal breccia zone, Waimakariri Ignimbrite. By Lake Mangapapa (U14/783700).

River. It is light grey, very pumiceous, usually lithic rich, with the occasional charcoal fragment. This is in sharp contact with the underlying Opuiaki Sediments (see the Lloyd Mandeno column).

To the north there is an excellent exposure of 50 m of Waimakariri at Omanawa Falls (U15/821682). The basal zone is pumice (up to 7.5 cm in length) and lithic-rich with a light brownish grey matrix. Field evidence from downstream suggests that the contact with the Opuiaki Sediments is not far beneath this zone (Fig. 3.30). For 20 m compaction and welding increase with height and include a 5 m zone of strongly welded medium grey lenticulite. The upper part of the sheet is moderately welded, pumice and matrix colour is light grey and pumice has the familiar knotty, crystal-rich texture. In the last few metres of the flow where it approaches the contact with the Mamaku Ignimbrite, matrix colour is light grey, pumice is devitrified and the upper incipiently welded zone is missing. Omanawa Falls drop 20 m from the lower middle welded part of the sheet into a large pool cut from the basal breccia zone. The power station has also been constructed in this zone. The upper Waimakariri is also missing from the Dairy Farm column (U15/828681) which lies 0.5 km to the south of Omanawa Falls and at the junction of Ruakaka Stream and Omanawa River (U15/824673).

Six kilometres NW from Omanawa Falls, the construction of the Ruahihi Canal has exposed a 30 m high by 250 m long outcrop (U14/7837727). At the base of the exposure, the ignimbrite is a light grey (slight tinge of pink), is poorly sorted with pumice clasts up to 23 cm long though these average 2-3 cm (Fig. 3.31). Pumice is light grey with a fibrous vesicular, crystal-rich texture. Along the northwestern bank of the cutting, a horizontal pumice concentration zone can be seen which extends for several metres. The rock is

Fig. 3.30 Close up of basal Waimakariri Ignimbrite matrix. Omanawa Falls (U15/821682).

Fig. 3.31 Close up of matrix and pumice clast (23 cm in length) Waimakariri Ignimbrite at Ruahihi Canal (U14/783727). The size of the clast suggests that the flow was still quite dense at this distal site. Note the variation in matrix colour compared with Figs 3.30 and 3.29.

incipiently welded throughout, though there is a tendency for a slight increase in welding in the zone along the base of the roads which run on either side of the canal. Natural outcrop in the area is columnar jointed with a silica veneer about 1 cm thick.

Exposed in the southern cutting there is a bedded sequence which consists of a series of alternating coarse and fine beds. These can be interpreted either as bedding caused by turbulent flow, separate flow units or as a pre-Waimakariri air fall sequence (Fig. 3.32). The author favours the latter option as the deposit is moderately shower bedded. However this deposit is quite different from the usual, well sorted, fine grained, Plinian deposit which often underlies the Waimakariri Ignimbrite.

Sparks and Wilson (1976) found that ignimbrites preceded by a Plinian phase tend to less welded than those without the Plinian deposit because the high eruption column allows cooling by ingested air. However a time period (probably hours to several days, based on slight sedimentary reworking of one Plinian outcrop) seems to have elapsed before the eruption of the Waimakariri. Therefore the ignimbrite probably did not undergo considerable cooling in a high eruption column. This view is supported by the strongly welded nature of the rock in medial regions.

Five kilometres NE from Ruahihi Canal at Carrs track (U14/828748) there is a complete exposure of the Waimakariri Ignimbrite including overlying tephras and sheet 4 Mamaku to the underlying Plinian air fall (Fig. 3.33). Pumice is concentrated at the base and is mainly clast-supported. The preferred hypothesis for the pumice concentration is that the larger particles settled out under the influence of gravity, probably as the result of degassing and reduction in density and momentum. An alternative explanation for the

Fig. 3.32 Sequence of pre Waimakariri Ignimbrite shower bedded air falls, Ruahihi Canal. The carbonaceous zone at the contact between the air fall and ignimbrite suggests some vegetation growth before deposit of the ignimbrite as may the two small charcoal fragments at upper right of photo.

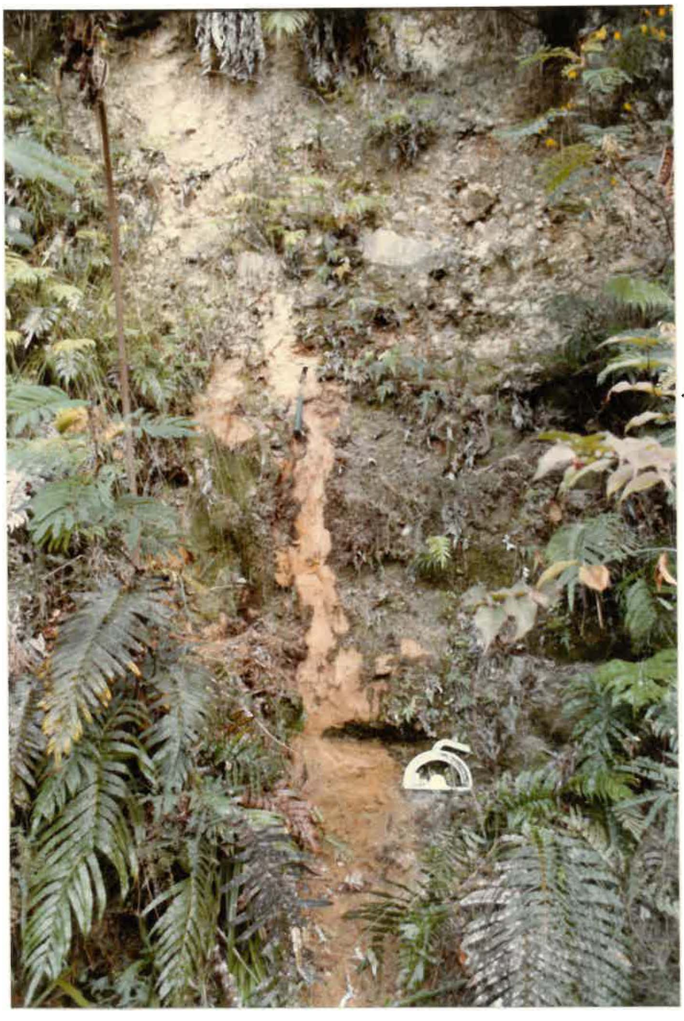


Fig. 3.33 Basal zone of Waimakariri Ignimbrite (1) and Plinian airfall (2). Contact is at geological hammer, note the angular nature of the large pumice (27 cm). Carrs track (U14/828748).

fines depleted nature of the igniimbrite (only at this location) is that the flow was turbulent Walker *et al.* (1981). The basal zone is underlain by the Plinian airfall which has petrographic similarities to the Waimakariri (prisms of green hornblende) and is baked at contact with the Waimakariri Ignimbrite. With increasing height pumice size reduces and the pumice is matrix-supported, averaging 1 to 1.5 cm through most of the flow. In the middle of the outcrop, vertical pumice pipes depleted in fines are obvious. Pumice is white to very pale grey and the groundmass is much the same colour. The rock is incipiently welded throughout with a slight increase in the lower middle of the zone. Towards the top of the flow the ignimbrite is weathered and the pumice is long and lenticular.

A track leading to a youth camp (U14/838743) 1.5 km SE of Carrs Track has complete exposure of the Waimakariri, Opuiaki Sediments and several metres of Waiteariki Ignimbrite. The Waimakariri exposure here has similar features to that at Carrs track though there are more charcoal fragments.

3.5.5 Contact Relations

The upper sheet of the Waimakariri Ignimbrite at the T.C.C Weir (U14/857737) is separated from the Mamaku Ignimbrite by a gravelly sand lens 1 to 5 cm thick (Fig. 3.16). The groundmass of the ignimbrite is light grey, pumice is the same colour and averages 2.7 cm long with a maximum of 4.8 cm. It is mainly a coarse tuff, with about 1% lithics. The rock is incipiently welded (25 PT units). At Scotts track the groundmass is orange brown while pumice is pale grey, averaging 3 cm with a maximum of 5 cm. The unit is more welded (PT=45) than at the T.C.C weir, perhaps indicating greater erosion at this site (i.e., the incipiently welded zone has been removed).

Three types of basal Waimakariri layers can be seen in contact with the underlying Opuiaki sediments. The most common is a gradual change in welding often accompanied by an increase in grain size (Type 1). This basal zone is incipiently welded to non welded, light grey pyroclastic breccia to lapilli tuff (Fig 3.33). Type 2 basal units show a sharp change in welding with little change in grain size (Fig. 3.34). The thickness of this zone is variable, and ranges from 2-7 m. Type 3 basal units are rare, and there is little apparent change in welding, colour and texture of the rock before it makes contact with the underlying sediments (Fig. 3.35).

3.5.6 Flow Units

Three sites suggest that the Waimakariri Ignimbrite is the product of several flow units. Following a ridge down to the Omanawa River (U14/822722) at 55 m below interfluve level in the upper quarter of the Waimakariri, at least three flow units were seen. The ignimbrite changes sharply from a very light brown to a light grey unit which is about 2 m thick and noticeably less welded (65 versus 25 PT units) than the overlying unit. There is also a sharp change from this middle unit to a lower unit, the thickness of which was not able to be determined. It is a light tan colour, more welded than the middle flow unit (PT=35), and in hand specimen appeared to be more crystal-rich.

At a track leading to the youth camp, a noticeable break (contact) in a cliff of Waimakariri about half way through the flow was seen. Pumice could be seen concentrated directly below the contact. unfortunately the contact is inaccessible (Fig. 3.36).

Fig. 3.34 Type 2 basal unit, Waimakariri Ignimbrite. Note the sharp break in welding at the basal zone. The yellow stains are lichen, height of outcrop about 22 m. Mangapapa River (U15/789684).

Fig. 3.35 Type 3 basal unit, Waimakariri Ignimbrite. In sharp contact with underlying Opuiaki Sediments. Opuiaki River (U15/764690).

Tributary 1 draining into Ruahihi Canal has cut through the Waimakariri and exposed a contact between two flow units (Fig. 3.37). There is little change in welding but a marked increase in pumice in the upper flow and a change in colour from a light grey to a yellow orange with horizontal laminations every 2 to 3 cms. These are interpreted as laminar flow layer by layer deposition. Adjacent to these two flow units at the end of the cutting, bedding was noted in the outcrop which suggests a turbulent environment. Whether the flow was turbulent or laminar is discussed in Chapter 6.

It has not been possible to correlate flow units nor assign sheet numbers as with the Mamaku Ignimbrite, due to the lack of similarities between the flow units.

3.5.7 Mineralisation

The Waimakariri Ignimbrite has been mineralised downstream of a weir crossing the Opuiaki River (U14/767695) for an area of about 400 m by 20 m. In hand specimen the rock is either a pale blue colour (unweathered) or a yellow orange (weathered, Fig. 3.38). The ignimbrite is silicified and very hard. The large amounts of silica present in this rock have also caused pebbles to cement to the rock where they have been deposited in potholes or similar quiet water environments. Several sinter deposits are found in the more strongly mineralised zones (Fig. 3.39). These have a slight sulphurous smell and small pyrite crystals can be seen.

Fig. 3.36 Contact between two Waimakariri flow units, pumice concentration zone is just visible immediately below the contact. Although the ignimbrite is only incipiently welded it is capable of maintaining a vertical face. Youth camp track (U14/838743).

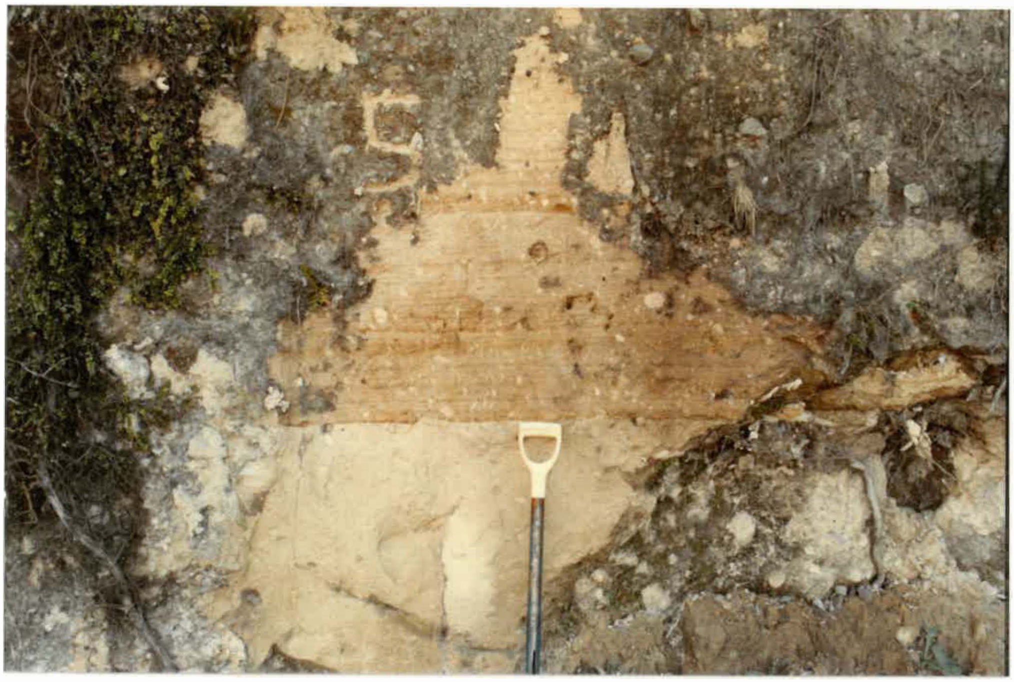


Fig. 3.37 Contact between two Waimakariri flows, note laminations in upper unit and complete absence in lower unit. Ruahihi Canal (U14/783727).

Fig. 3.38 Hand specimen examples of fresh (blue) and weathered (orange) mineralised Waimakariri Ignimbrite. Pumice is just visible in far left orange sample. Opuiaki River (U14/767695).

Fig. 3.39 Sinter deposit, Opuiaki River (U14/767695).

3.6 WAITEARIKI IGNIMBRITE

3.6.1 Introduction

The Waiteariki Ignimbrite was named by Healy *et al.* (1964). Houghton and Cuthbertson (in press) suggest a type site for the rock at Waiteariki Falls between T14/641797 and T14/647798. The rock in the study area is usually easily recognised and is phenocryst rich, with a greyish pink devitrified groundmass and dark grey lenticular strongly compressed and welded pumice.

3.6.2 Age

The Waiteariki Ignimbrite is reversely magnetised (Cox, 1969) and has been fission track dated at 0.84 m.y. (Kohn, 1973).

3.6.3 Source

Houghton and Cuthbertson (in press) suggest on field evidence a source in the TVZ or north of the Rotorua Caldera, for the Waiteariki Ignimbrite. However the following argument supports a source in the Kaimais. At the ignimbrites type site the rock is 220 m thick and strongly welded (Houghton and Cuthbertson). Harmsworth (1983) notes the ignimbrite is 30 m thick (drill logs) in the Otumoetai and Matua areas and increases to 60 m to the west of the Tauranga Basin. Healy (1967) states it is 120 m thick on the Whakamarama Plateau. While drill logs at the Waiorahi Stream, northern Mamaku Plateau, show it is about 50 m thick. The south to north cross-section of the geology in the study area shows the Waiteariki Ignimbrite dipping to the north but this is considered to be the result of erosion rather than the ignimbrites true dip.

Lithics found in the Ngamuwahine River in basal Waiteariki (particularly in the area of the concrete ford (U14/737734), are numerous, large (up to 50 by 40 cm) and angular. Lithics are also common at the Ministry of Works quarry 5.5 km NE though these tend to be smaller (Fig. 3.40). It is difficult to envisage lithics of this size being transported more than a few tens of kilometres. Houghton and Cuthbertson describe the lithics found in their area as mostly rhyolite and some andesite.

However rhyolite lithics are rare in the Waiteariki Ignimbrite in the writer's study area, lithics are almost all densely welded Waiteariki (the question of how lithics of Waiteariki can be found in the same ignimbrite is discussed in section 3.6.6). This suggests that the lithics seen by Houghton and Cuthbertson are derived from Minden Rhyolite and Beeson Island Volcanics from a source in the Kaimais rather than the TVZ. Thus it is argued that the size and type of lithics and the thickness of the rock is greater than would be expected from a distal ignimbrite from the TVZ. Further it seems more likely that a source may lie close to where the rock is at its thickest, in the vicinity of its type site at the Waiteariki Falls.

If this hypothesis is true the absence of a readily identifiable caldera for the Waiteariki (and Waimakariri) Ignimbrites must be explained. Lipman (1984) notes that caldera formation, rather than conforming to a limited number of distinct types, involves a spectrum of diverse and overlapping styles. For example small calderas may form in the summit of single volcanoes, while distinct vents for major pyroclastic flow eruptions have rarely been identified in the geologic record. Nor is it clear what sort of record should be expected. Vent distributions may be complex for many ignimbrites owing to regional tectonic influences or the disruptive effects of caldera collapse.

Fig. 3.40 Lithics, Waiteariki Ignimbrite, Ministry of Works quarry (U14/785748). Hammer is 30 cm in length.

Fig. 3.41 Well developed spherodal weathering in welded Waiteariki Ignimbrite, Kaimai Mill Road (U14/701691).

Some caldera structures in the Mogollon-Datil volcanic field are obscure, with voluminous post-collapse rhyolitic volcanics tending to conceal deeper features (Lipman, 1984). Perhaps this is the case with the rhyolite domes in the southern Kaimais. Also the possibility that caldera filled by subsequent eruptions and sedimentation must be taken into account. However if the Waiteariki has a source in the TVZ then its source is equally likely to have been eroded or concealed by subsequent eruptions.

3.6.4 Distribution

The Waiteariki Ignimbrite is very widespread and it is difficult to envisage its being derived from anything other than a caldera forming event. It has been down-faulted 450 m to the Hauraki Basin, though Cuthbertson (1981) suggests that this may be a step block left stranded during uplift of the Kaimai Ranges along the Hauraki Fault. The ignimbrite may underlie the Hauraki Lowlands (Houghton and Cuthbertson), forms the Whakamarama Plateau and the eastern foothills of the Kaimai Range, and acts as basement for the Tauranga Basin. This study has shown it underlies the northern Mamaku Plateau.

3.6.5 Lithology

In the northwestern study area the ignimbrite is exposed in the streams that dissect the Whakamarama Plateau. It is heavily weathered and often has an iron veneer several centimetres thick. Erosion has stripped the rock of most its less welded upper sheet.

As the Waiteariki is overlain by ignimbrites and sediments in the northern Mamaku Plateau, it is usually exposed only in the deeper stream and river valleys. Here the rock is a light pinkish grey, mafic crystals are heavily weathered, lenticular pumice can only rarely be detected and the rock can just be spaded (PT values in the low to upper 60's). However not all of this rock is weathered in this manner and fresh specimens can usually be found. Occasionally welded outcrop is spheroidally weathered (Fig. 3.41).

One of the best exposures of Waiteariki Ignimbrite in the study area is at McLarens Falls (U14/783728). Here the rock is intensely jointed and potholed (Fig. 3.42), strongly welded (PT values 95-105) and relatively fresh. In hand specimen the matrix is greyish pink, mafic and felsic crystals are abundant while lenticular, black highly welded and compressed pumice are common. The rock can be classified as lapilli to mainly coarse and fine tuff. Other good exposures can be found up and downstream of the falls and in a road cutting immediately after the bridge crossing the Ngamuwahine River (U14/764723) fresh rock is exposed.

Healy (1969) subdivided the ignimbrite into four units and noted biotite was absent in the lower part of the flow. Houghton and Cuthbertson (in press) recognise three units: (1) a soft unwelded to welded top with extensive alteration of the pumice to cristobalite; (2) a thick (up to 150 m) zone of welded material, containing alternating moderately to densely welded and glassy lenticulite zones; and (3), a 3-5 m unwelded base consisting of pumiceous tuff breccia and ash.

The unwelded top is missing in the study area, though in the Kaimai State Forest in a gully of an unnamed stream (U14/738742) a weathered 10 m outcrop of the upper zone was seen with preferential weathering of the pumice to a brown clay, and the remaining rock retaining much of its original form. However, the most common outcrops are weathered examples of zone 2 of Cuthbertson and Houghton in many of the beds of rivers that dissect the plateau.

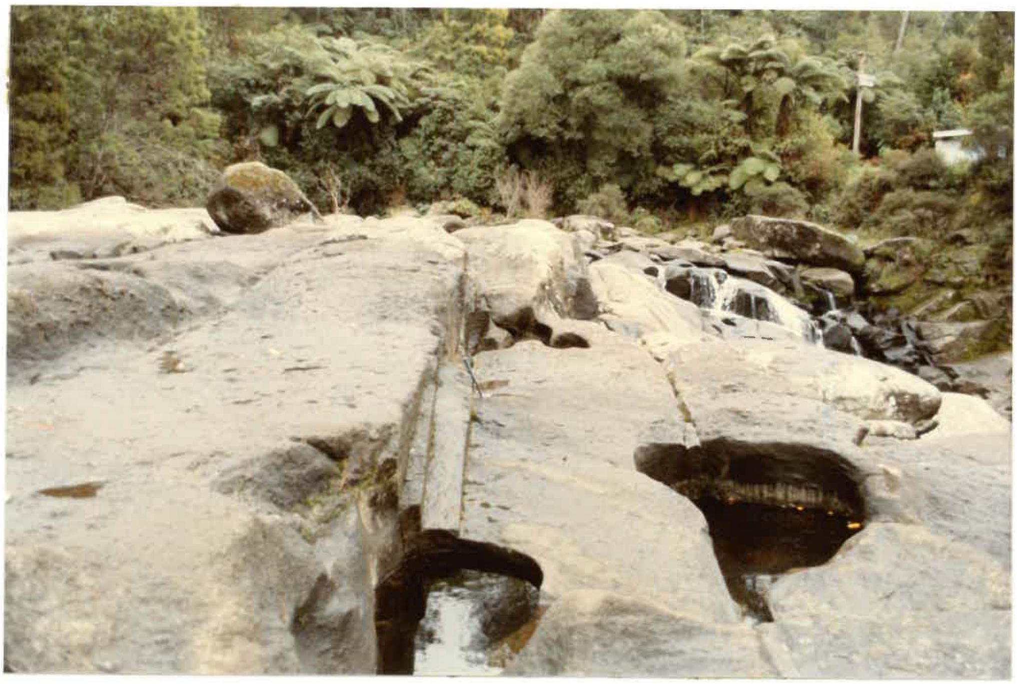


Fig. 3.42 Horizontal jointing and pothole scouring Waiteriki Ignimbrite McLarens Falls (U14/783728), hammer is 30 cm.

Exposure of the partially welded base is rare and was seen in only two localities: the ford crossing the Ngamuwahine River (U14/737734) and in the middle reaches of the Mangakarengorengo River (U14/765715). In both cases lithics are large (average 15-20 cm), abundant and are composed of highly welded Waiteariki Ignimbrite. The groundmass in this basal zone is slightly devitrified, light yellow with a tinge of pink. Mafics are more abundant than in the welded zone and biotite was identified (which is contrary to Healy, 1969). Pumice is whitish yellow with a fibrous texture and averages 3 cm with a maximum of 17 cm. The rock is partially welded with PT values averaging 52. The basal zone ranges from a pyroclastic breccia to a fine tuff.

A core log sheet dated 1959 from Geological Survey files summarizes the lithological characteristics of the ignimbrite. It describes 61 m of core taken from the vicinity of the proposed dam on Waiorahi Stream (U14/858739). The log is as follows; from 5 to 8 m the rock (Waiteariki Ignimbrite) is heavily weathered and and occasionally fractured. With increasing depth (8-47 m) cores become a fresh light blue grey colour, gradually harden up and pumice becomes more lenticular and numerous. From 47 to 53 m cores became softer, with recovery poor though some devitrified pumiceous material was recovered. Only sand was recovered in the basal section (53-55 m). At 55 to 61 m a hard lenticulite similar to that found at 8-47 m was recovered. Lloyd (1969) recorded a similar description for the first sheet though the drill hole was abandoned in the soft basal zone at 30 m depth.

3.6.6 Cooling Units

Houghton and Cuthbertson (in press) state the Waiteariki consists of numerous flow units and at least two cooling units. The writer is unconvinced that pumice increases necessarily define a new flow unit though evidence supports Houghton and Cuthbertson's latter view. First, there is the abundance of strongly welded, large Waiteariki lithics in the basal zone implying a pre-existing Waiteariki sheet for their incorporation. These were probably plucked from the ground along the route of travel. The lithics can not be confused with Aongatete Ignimbrite as they contain quartz, hornblende, and biotite (see section 1.8). Second, the drill log sheet (Waiorahi Stream) describes a hard lenticulite underlying the basal zone of the Waiteariki that is similar to the lenticulite that overlies the basal zone.

3.7 STRUCTURAL FEATURES

3.7.1 Faults

Outside the study area the main, NNW trending, westward dipping Hauraki Fault, is mostly obscured but the Kaimai tunnel excavation revealed a zone of highly shattered and crushed andesite 37 m wide (Healy *et al.* 1964; Bennion and Hegan 1977). This fault is continued by the Miranda Fault complex, and the Firth and Okauia Faults within the Hauraki Graben. Exposed in the Kaimai Ranges are a series of thin N to NW zones of crushing and slickensliding (Houghton and Cuthbertson, in press). The NNW trending faults are all classified as active (Berryman 1985; cited in Cowbourne 1985). On the eastern side of the Kaimai Ranges the andesitic volcanics are cut off by a scarp which dips E about 40°. Bennion and Hegan (1977) suggest this may be an eroded fault scarp. Healy *et al.* (1964) describes a series of NNE striking faults in the Papamoa Ranges. To the south, the Taupo Fault Belt contains a number of north easterly striking faults, previously described in Chapter 1.

In the study area, Healy (1957) noted a number of terrace-like features which cross the area in a NE direction and resemble fault scarps. Lloyd (1965) claims one of these features in the Opuiaki and Mangapapa valleys is a fault. Ground search failed to reveal strong evidence for any displacement such as dislocated tephras and Healy's and Lloyd's faults are not recognised.

It is tempting to ascribe a tectonic origin for the northerly flowing waterways in the study area especially as this would link with the general tectonic trend for northerly faults described above. However the drainage pattern is considered to be the result of the Mamaku Ignimbrite dipping to the north. A similar drainage pattern can be seen in the Te Puke region where the Mamaku Ignimbrite dips NE.

One definite and one probable fault were identified while mapping. The former is a step-faulted sequence at the Lower Mangapapa station (Fig. 3.43). Here there is a repeated sequence of Waiteariki Ignimbrite, Opuiaki Sediments and Waimakariri Ignimbrite. The surface expression of the fault on average dips 30° N and strikes 100° E. As there is little sign of erosion of the sediments which include loose sands (Fig. 3.44), the faulting is inferred to have occurred shortly before deposition of the Waimakariri Ignimbrite. The inferred fault occurs at the mineralised Waimakariri Ignimbrite outcrop previously described in this chapter. For mineralising fluids to have altered the rock its probable faults allowed fluids to percolate from the source. In addition 0.25 km upstream of the mineralised area the Opuiaki Sediments were found to be dipping 9° NW.

Fig. 3.43 Step faulted sequence at the Lower Mangapapa Station (U14/778713). Contact between the Opuiaki Sediments and Waimakariri Ignimbrite is marked by the spade.

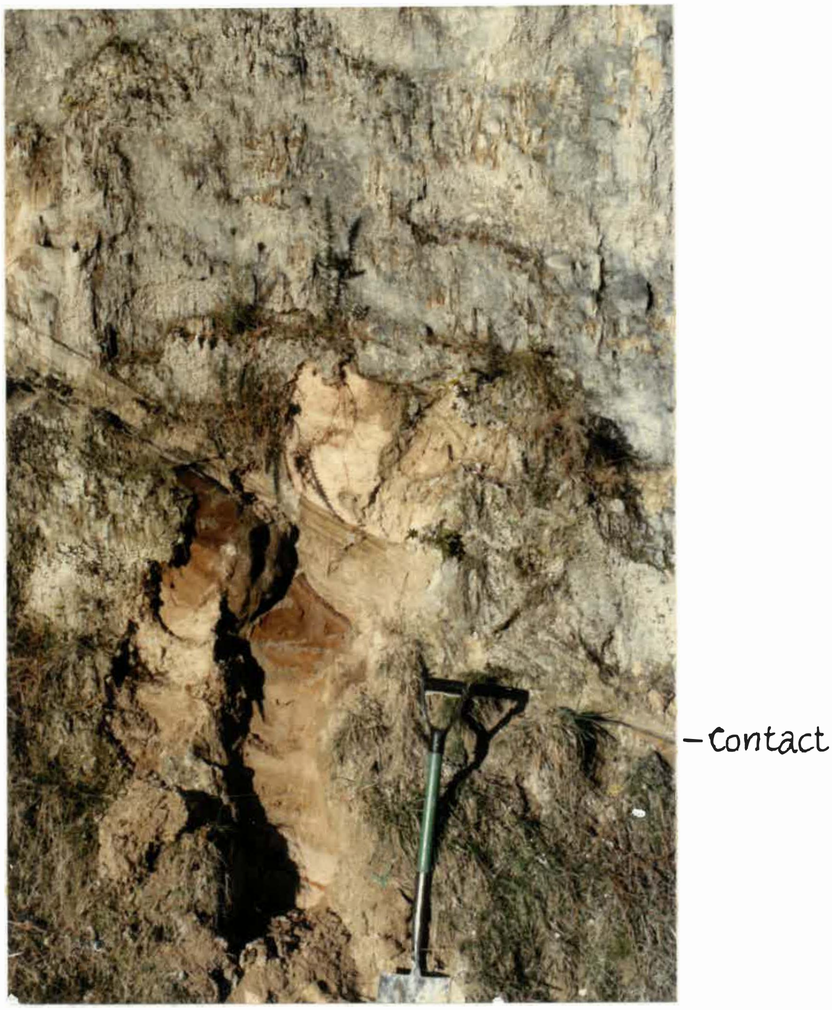


Fig. 3.44 Close up of contact between the tilted (45°) Opuiaki Sediments and overlying Waimakariri Ignimbrite. Note the baked sequence directly underlying the low angle crossbedded sediments.

3.7.2 Joints

The Mamaku Ignimbrite is columnar jointed in most outcrops apart from the basal zone and towards the top of the flow (Fig. 3.45). Jointing is at its strongest in the more welded sections. For example at the Mamaku type site there are very well developed large, widely spaced joints occur every 1.5 m. An unusual form of polygonal jointing is found in the southern study area in basal Mamaku outcropping in the streams and rivers (Fig. 3.46). A plot of joint orientations by Riddols (1971) in tunnel 3 and 5 (Mamaku Ignimbrite) yielded one group from 60° to 120°, second 160° and 180° and a third at 20° is also apparent.

The Waimakariri Ignimbrite is columnar jointed in all welded zones (Fig. 3.47) with the basal and upper zones occasionally showing incipient columnar jointing. Where the rock is strongly welded the intensity of jointing increases with columnar joints every 0.5 m though joints up to several metres apart are not uncommon. Subhorizontal joints every 3 to 4 m can be seen at the Lower Mangapapa Station. It is possible that these joints are tension cracks similar to those described by Chapin and Lowell (1979) in the Wall Mountain Tuff.

In welded outcrop Waiteariki Ignimbrite has large coarse, columnar joints every 2-3 m (Fig. 3.48). In stream beds this rock can be seen horizontally jointed with master joints, cross joints and oblique joints. In the bed of the Ngamuwahine River (U14/752727) a master joint, continuous for 100 m, was measured striking at 140°. Similar readings were noted in two other places in the vicinity while about 1 km NW upstream the master joint continued with a strike at 135°. A tectonic origin is suggested for this joint pattern.

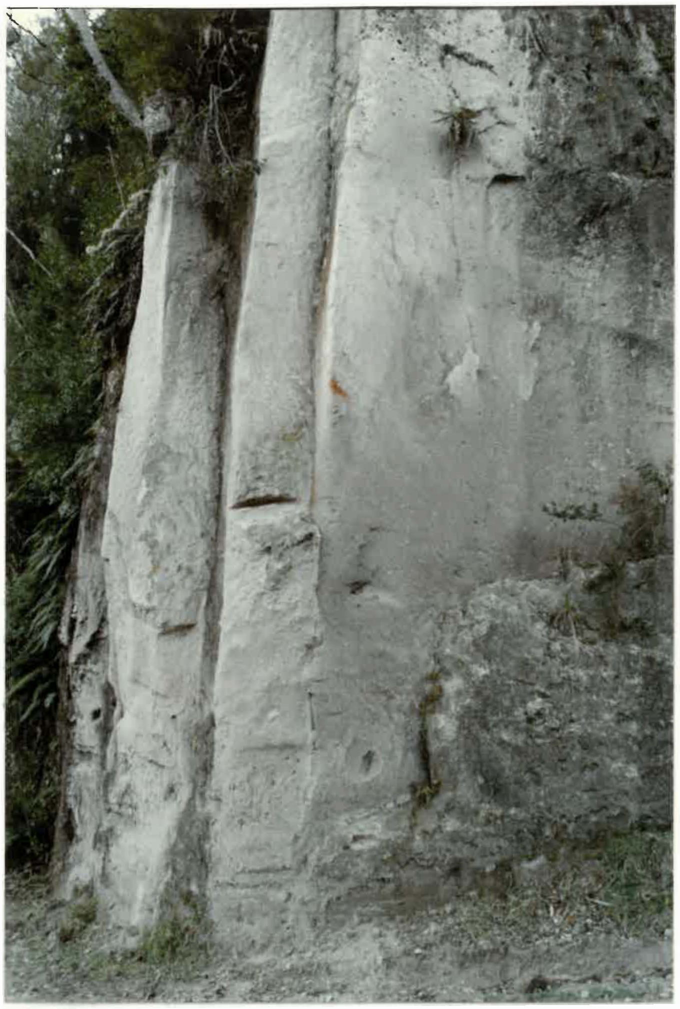


Fig. 3.45 Well developed, closely spaced (≈0.5 m) columnar joints, Mamaku Ignimbrite. Note holes in the outcrop (top right of photo) caused by lithics falling out. Hammer is 30 cm, Hekes track (U15/808651).

Fig. 3.46 Polygonal jointing, welded upper basal zone, Mamaku Ignimbrite. Dried bed of Mangapapa River (U15/789647).

Fig. 3.47 Moderately spaced (1 m) and developed columnar joints, Waimakariri Ignimbrite, Omanawa Falls (U15/821682).

Fig. 3.48 Widely spaced (2-3 m) well developed columnar joints. Waiteariki Ignimbrite, Ministry of Works quarry (U14/785748).

3.7.3 Terrain Evaluation

Examination of aerial photographs and fieldwork showed that the steep upper edges of valleys which have been cut through flat interfluves of Mamaku Ignimbrite are often crescent shaped, presumably in response to slope failures. These particularly noticeable features are suggestive of terrain formed through landsliding and probably were and still are a source of considerable colluvium.

Further sources of colluvium and alluvium are incipiently welded slopes of distal Waiteariki Ignimbrite to the north of the study area, while the debris from slab failure was often seen in the rivers. In valleys that are relatively wide the incipiently to nonwelded basal zones of the ignimbrites had been eroded, undercutting the harder welded zones. The same effect on a smaller scale was noted in the Opuiaki Sediments where unconsolidated gravelly sands were removed, undercutting more indurated sediments. It is considered that the vertical and lateral variations (which can be highly variable over short distances) in welding have been the dominant effect in the terrain currently developed.

Two terraces are often present in the gorges of the study area. Fieldwork suggests the first was caused by the river spreading laterally when incipiently welded Mamaku Ignimbrite was acting as bed rock, a narrow gorge forming in the welded zone, the erosional sequence then being repeated with the Waimakariri Ignimbrite. As such the terraces proved a useful tool when mapping. Small paleo river channels are a common feature in both the Mamaku and Waimakariri Ignimbrites adjacent to river valleys. Presumably these were left stranded when the rivers downcut to their present beds.

In the far western study area, the Waimakariri is occasionally exposed as tors. As Rotoehu Ash is missing in tephra columns overlying the ignimbrite in the area, this indicates that erosion has occurred since 42-50 k.y.

CHAPTER FOUR

PETROGRAPHY

4.1 INTRODUCTION

This chapter describes the petrology of the ignimbrites and sediments of the northern Mamaku Plateau in terms of phenocryst characteristics, grain sizes (length) and groundmass textures. Thin sections were made primarily from samples taken during column construction. Graphs show the variations between column height and crystal percentages estimated from modal analysis.

Correlation analysis (Pearson product moment) was considered the most appropriate method of testing the hypothesis of linear relationship of changes in crystal percentages (correlation is also used in Chapter 5). The SAS statistical package includes with each correlation coefficient (r) the probability of its statistical significance for a two tailed test. For example (r=0.8 [0.05]) signifies that the correlation can be accepted with a 95% probability that r=0.8 is statistically significant. This feature is particularly useful as sample sizes (sites per column) are often small and occasionally contained extreme values; thus, spurious correlations are able to be disregarded.

The objectives of describing the mineralogy and groundmass characteristics of the ignimbrites and sediments were to:

(1) Compare vertical and lateral variations in the ignimbrites from phenocryst characteristics and matrix alteration.

(2) Help define flow units and possible zonation within the ignimbrites.

(3) Suggest sources of the sediments.

4.2 PETROGRAPHY OF THE MAMAKU IGNIMBRITE

4.2.1 Mamaku Type Site (U15/887554)

At its type site the Mamaku Ignimbrite is 10 km from source, 125 m thick and has excellent exposure.

Groundmass: Under plane polarised light the matrix colour changes from a medium brown at the base of the outcrop, to light tan, then a pale grey in the middle, proceeding to yellow grey and then a brownish yellow at the top of the outcrop. This is probably the result of oxidation and devitrification. All slides showed that the original vitric matrix had been devitrified, this effect increased with height, though towards the top of the outcrop there is a marginal reduction in devitrification of the matrix and pumice.

Shards in the basal slides are strongly welded and have been compressed, flattened and moulded against crystals. This indicates the shards were plastic at the time of deposition and, thus, high temperatures were involved. This effect reduced with height.

Under crossed polarisers felsic crystallites (cristobalite and feldspar) are abundant in all slides. From the middle to the top of the flow, the microlites in pore spaces are often accompanied by black to dark brown prisms of slightly pleochroic clinopyroxene.

Pumice Fragments: Pumice is heavily devitrified except for slide 618 where small (0.5-1 mm) pumice have been only moderately affected. Coarse grained microlites of alkali feldspar (tridymite and cristobalite) are found in all relict pumice especially slide 616.

Lithic Fragments: Two types of lithics were identified: dark coloured cryptocrystalline argillite, and a moderately welded ignimbrite with phenocrysts of plagioclase, quartz, hornblende and hypersthene. In both cases lithics have been altered by vapour phase activity. Usually only trace amounts of lithics are present.

Hypersthene: In the basal slides hypersthene is common, though edges are often rimmed by brown stains. Fracturing is intense, ends are often ragged with hacksaw terminations. Magnetite inclusions are common. As height in the column increases oxidation and vapour phase activity begin to destroy these crystals, making identification more difficult.

Augite: Augite is present in trace amounts in the basal zone.

Hornblende: Pleochroic green hornblende is present in trace amounts.

Biotite: Very rare biotite crystals were identified.

Quartz: Forms range from euhedral to anhedral, though subhedral is the most common. All crystals have a fresh appearance, though occasionally an edge may show slight alteration from vapour phase activity. Crystals tend to be free of inclusions. Fracturing of quartz is slight except in slide 621b (near the top of the flow) where it is often intense.

Plagioclase: Plagioclase sometimes are resorbed and delicate altered edges are common, probably from vapour phase activity. Tabular subhedral forms are the most common. The occasional hypersthene and opaque inclusion was found. Fracturing is moderate to heavy in the middle and upper parts of the flow and broken fragments are common.

Opaques: Magnetite has a square, euhedral form and is generally unaltered though occasionally it is rimmed with limonite. Ilmenite is anhedral, with a skeletal, ragged form. Opaques are often intimately associated with mafic crystals.

Fig. 4.1 illustrates a relatively steady decrease in total crystals (bulk rock) with a maximum (18.5%) at the base and minimum (9.75%) at the top of the flow. Quartz has a gradual decrease in percentage though there is a marked fall from 3.5% at 76 m to 0.25% at 81 m (the altered fumarolic zone) and then increases to 2.75% at 104 m. Plagioclase is the dominant phenocryst, with 4.45% at the top and 10.5% at the base of the outcrop. There is little variation in opaques and for mafic crystals all percentages are less than 1%. Table 4.1 outlines maximum and average crystal lengths. There is no apparent trend in length of any of the phenocrysts in their position in the column.

Table 4.1 Average and maximum crystal length (mm) Mamaku Type Site

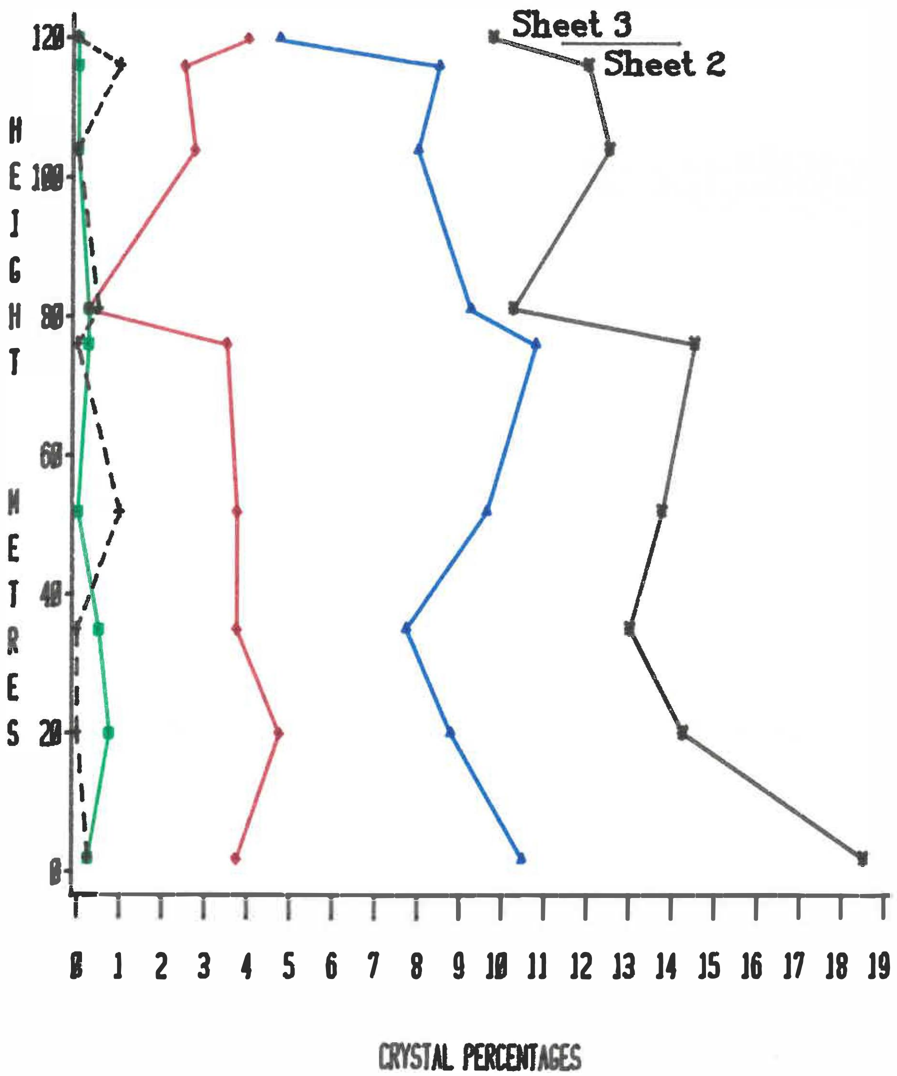
QTZ AVE	QTZ MAX	PLAG AVE	PLAG MAX	HYP AVE	HYP MAX	OPA AVE	OPA MAX	HEIGHT (M)
1.26	1.70	0.95	1.40	0.78	1.40	0.17	0.21	120
0.90	1.10	1.10	2.40	0.47	0.60	0.06	0.10	116
0.93	1.40	1.10	1.25	0.30	0.54	0.15	0.22	104
0.77	1.20	0.66	1.70	0.40	0.70	0.10	0.20	81
0.94	1.30	1.90	3.50	0.10	0.30	0.13	0.30	76
0.66	1.10	0.60	1.30	0.28	0.50	0.10	0.40	52
0.72	1.25	0.65	1.25	0.51	0.80	0.20	0.30	35
1.7	3.00	1.17	2.00	0.38	0.60	0.15	0.20	20
0.73	1.10	1.00	1.70	0.23	0.50	0.07	1.50	2

4.2.2 Interpretation of results

Petrographic examination showed that devitrification and vapour phase activity became more intense as height increased up to the middle of the outcrop. The effect reduced towards the top of the outcrop. Welding and compression effects are at a maximum at the base of the column. No pattern could be detected for lengths of any phenocryst. This suggests that phenocrysts were not being fractionated by gravity settling during flowage at this relatively proximal site, and that probably a semi expanded, laminar flow regime was operative.

Fig. 4.1 CRYSTAL PERCENTAGES FROM MODAL ANALYSES VERSUS HEIGHT

MAMAKU IGNIMBRITE TYPE SITE U15 677554



BLACK=TOTAL CRYSTAL PERCENTAGES

RED=QUARTZ CRYSTALS BLUE=PLAGIOCLASE CRYSTALS

GREEN=MAFIC CRYSTALS BLACK DOTTED LINE=OPAQUE CRYSTALS

Zonation and Magma Chambers

Smith (1960a) suggested a relationship exists between ignimbrites and granitic batholiths and noted that there are few compositional differences between intrusive and extrusive silicic rocks from individual magmatic centers. This view has since been developed and it is now generally agreed that if the period of a volcanic eruption is short and on a large scale (as in the case of ignimbrites) then the examination of the resulting deposit can give an instantaneous view of the interior of the magma chamber with regard to zonation (Cox *et al.*, 1979; Lipman, 1984). The premise is that the earliest parts of the erupted sequence came from the upper parts of the chamber and these became the basal section of the ignimbrite. Proximal ignimbrites provide the best opportunities for the interpretation of zonation of phenocrysts in the magma chamber as they are less likely to have mixed during travel and are assumed to be older than distal sections. However, regardless of how close to source an ignimbrite is, some mixing is likely to have taken place (Cox *et al.*, 1979).

Although the Mamaku type site is 10 km from source, and, therefore not strictly proximal, it is an excellent exposure and to the writer's knowledge the thickest available outcrop near to source. Therefore it seems reasonable to use this column in an attempt at interpretation of zonation in the Mamaku Ignimbrite.

Fisher and Schmincke (1984), summarising the work of Smith (1979) and Hildreth (1981) note the following points concerning zoned ash flow deposits related to calderas: (1) All pyroclastic eruptions exceeding 1 km^3 are compositionally zoned and many smaller ones show pronounced zonations. (2) Erupted parts of magma chambers range from nearly uniform rhyolite composition to strongly contrasting basalt-rhyolite composition. (3) With depth, magma chambers become hotter, more mafic chemically and more phenocryst-rich. (4) There are pre-eruptive gradients in: temperature, fO^2, major and trace element composition, volatiles (H_2O,Cl,F), and mineralogy. (5) A zoned magma column may be vertically layered with abrupt transitions between zoned subunits. (6) Wide compositional gaps are common at all levels of SiO_2 concentrations and must have developed within a magmatic system. (7) Small-volume systems tend to show stronger composition contrast than large-volume systems. (8) Volatile rich aphyric boundary layers or cupolas occur on top of more crystal rich zoned magma columns. (9) Crystal fractionation is only one of several processes resulting in compositional gradients, and is much less important than liquid state thermodiffusion and liquid complexing in some highly silicic or highly alkali systems.

Expanding on this last point Hildreth (1981) states that for the Bishop Tuff, compositional variation cannot be explained by crystal fractionation, assimilation or progressive melting. Instead zonation may result from diffusion-convection controlled differentiation mechanisms which develop along the temperature gradient as the result of volatile activity. However, Wolf and Storey (1984) question Hildreth's view as chemical variations have been modelled successfully for the Bishop Tuff using crystal fractionation. What is clear is that zonation in ignimbrites remains a challenge for igneous petrologists (Lipman, 1984).

Walker (1972) suggests that fines are removed during a pyroclastic flow, resulting in the concentration of crystals in bulk rock relative to that in pumice. Pumice is considered to have the same phenocryst content as the magma as opposed to bulk rock which is enriched in crystals. Sparks and Walker (1977) confirm this view. Pumice therefore is the most reliable guide to pre-eruptive magmatic processes (Wolff and Storey, 1984). However, as the Mamaku Ignimbrite is strongly devitrified, (and strongly welded in the basal zone at the type site) the extraction of pumice is not possible. As an alternative the argument is advanced by the writer that magma chamber zonation (if the chamber was zoned) can be detected by changes in relative abundances of phenocrysts from bulk rock thin-sections though it is recognised that this is an approximation only.

A marginal [r=-0.59 (0.09)] trend can be seen (Fig. 4.1) of total crystal percentages decreasing as height increases with two noticeable irregularities in Fig. 4.1 at the fumarolic zone (83 m) and at sheet 3. This decrease in crystals as height increases is the reverse to what is reported in the literature with respect to crystal zonation of ignimbrites. Often there is an increase in crystals with height, reflecting a zoned magma chamber with crystals concentrated at the base of the chamber perhaps by gravity settling. This part of the chamber is the last to be erupted and thus forms the top of the ignimbrite at a proximal outcrop (Cox *et al.*, 1979).

Sheridan and Ragan (1976) note there is a steady increase in crystals per unit area in an ignimbrite as welding increases (p.680). As welding increases, more shards (due to their plastic condition) are compressed into the same area but as crystals are incompressible there is a relative increase in crystals with welding. This relationship was examined using correlation analysis, the aim being to compare welding (PT units) versus total crystal percentages for columns that are strongly welded. Two Mamaku and one Waimakariri Ignimbrite columns were examined; the results are as follows: Type site (r=0.65 [0.07]), Ngamanawa (r=0.74 [0.06]), and Omanawa Falls (r=0.93 [0.02]). Statistically there is a significant relationship between increased levels of welding and increasing crystals.

Therefore, it is considered that the decrease in crystal percentages with increase in height is the result of reduced compaction/welding as height increases. If this hypothesis is correct then this implies the magma chamber was essentially homogeneous, perhaps by crystals being spread randomly through the melt by thermo convective currents as described by Hildreth (1979, 1981), or alternatively the chamber did not have time to develop crystal zonation before eruption. Homogeneous ignimbrites are not unknown, an example is the large volume Fish Canyon Tuff (Whitney and Stormey, 1985) or the Cerro Galan Ignimbrite (Sparks *et al.*, 1985).

The compaction/welding viewpoint is supported by Fig. 4.2 (for the Ngamanawa thin-sections) where the trend for a decrease in crystal abundances as height increases is stronger [r=-0.94 (0.001)]. Considerable mixing is assumed to have taken place during travel, the ignimbrite being 23 km from source. Therefore this trend at Ngamanawa cannot be accounted for by a zoned magma chamber. Although possibly a strict laminar flow could preserve magma chamber zonation or crystal settling in a semi expanded flow could cause such zonation, these ideas are considered unlikely.

To achieve crystal fractionation and settling and hence a zoned magma chamber requires a long residence time for the magma or possibly a rather rapid cooling regime or any other mechanism that inhibits convective overturn. As petrography does not indicate a concentration of crystals at the top of the type site, this suggests that zonation did not occur. This is consistent with a thin continental crust being unable to withstand a long-term batholithic development. Another possibility is recurring intrusions of batches of magma from a deep source into a shallow crustal reservoir. These silicic chambers are believed to be less than 10 km thick, with the larger chambers slab like and smaller ones more cylindrical (Fisher and Schmincke, 1984). Lipman (1984) notes that the area and volume of caldera collapse are approximately equal to the volume of the material erupted.

Although volcanic glass has an inherent tendency to crystallize spontaneously this effect is accelerated under the influence of trapped gases and incipient metamorphism (Hatch *et al.*, 1972). As the Mamaku Ignimbrite is strongly devitrified from almost the base to the top of the flow it is assumed that the magma was heavily saturated with volatiles before eruption, a considerable quantity remaining in the ignimbrite at the time of deposition. This view is supported by the common presence of fumaroles,

Flow Units

A further aim in the petrographic examination was to see if the presence of flow units could be determined by modal analysis from slides at the Mamaku type site. Fig. 4.1 shows a decrease in plagioclase and increase in quartz crystals in sheet 3 resulting in an overall reduction in total crystals which confirms the field evidence of a new flow unit at this site. However, if field examination had not showed a new flow was present it is debatable whether sheet 3 would have been recognised as a new unit on the basis of changes of the percentages of minerals (eg, quartz increases from 2.5 to 4%, and plagioclase reduces from 8.5% to 4.75%). For example there are changes of 1% quartz at 20 m, an increase from 7.75% to 9.65% at 52 m with feldspars and a reduction in quartz percentages (3.5-0.25%) at the fumarolic zone (81 m), none of which are recognised as a separate flow unit. Field examination seems the most satisfactory method of defining flow units though petrographic examination can support this.

4.2.3 Ngamanawa (U15/791647)

The medial Ngamanawa column was selected to provide a comparison between distal and proximal Mamaku Ignimbrite exposures. The column is 70 m thick and 22 km from source.

Groundmass: Under plane polarised light the colour of the groundmass gradually changes from a medium brown at the base of the outcrop to a pale grey at the top. There has been widespread devitrification, though curved relic shards can be seen in most slides. Under crossed polarisers, very fine grained felsic crystallites are scattered throughout the groundmass in all slides. Occasional incipient radiating spherulitic textures (axiolitic structure) occur as the result of shards devitrifying to cristobalite and feldspar. Small (0.15 mm) felsic plate-like minerals (microlites) with grey and white interference colours were observed in devitrified pumice in all slides, though they are especially well developed in the base of the flow. This coarse texture (compared with the crystallites) suggests vapour phase crystallisation. The dominant crystals are alkali feldspar, tridymite and cristobalite. There are signs of post-emplacement flowage and distortion of shards against crystals towards the base of the flow.

Lithic Fragments: Two types of lithics were identified: a moderately welded, ignimbrite somewhat similar to the Waimakariri, but too devitrified to make a confident identification, and a fine grained, brownish-black lithic possibly argillite, also heavily devitrified. The highest percentages of lithics were recorded in two slides towards the middle of the flow with 2.25% and 1.75% respectively.

Hypersthene: Hypersthene is often anhedral to subhedral and it is common to see it completely oxidised with little trace of original fabric. Opaque (magnetite) inclusions are common. Field estimations of the brown stains which have often replaced these crystals and are characteristic of the ignimbrite suggest total mafic crystals were originally about 1-2%. Mafic crystals were probably underestimated because of alteration by vapour phase gases and destruction while making thin-sections.

Hornblende: Usually only traces of hornblende were seen, though in slide 306 they comprised 1%. Crystals were moderately to heavily oxidized but less so than hypersthene. Dominant forms are small laths and prisms (0.2-0.5 mm).

Biotite: Biotite crystals are extremely rare; only one tabular euhedral example with mottled straight extinction and brownish pleochroism was seen in slide 303.

Quartz: Quartz is dominantly subhedral and tabular; anhedral examples are common and euhedral crystals rare. With the exception of slide 303, all crystals are moderately to heavily corroded. Fracturing is generally slight, but examples of non-to moderately fractured and broken crystals can be seen in all slides.

Plagioclase: Plagioclase is moderately to heavily fractured and broken crystals are abundant, but the occasional euhedral crystal can be found. Edges are moderately altered, with alteration penetrating inwards and along fractures. Delicate altered rims are attributed to vapour phase activity. Magnetite and glass are the most common inclusions although needles of apatite and oxidised hypersthene were occasionally seen.

Opaques: Titanomagnetite is the dominant opaque mineral and exhibits a cubic form. Usually fresh, occasionally rims have been altered to limonite. Occasional intergrowths of clumped magnetite were noted.

Irregular platey and elongated opaques were identified as ilmenite.

Crystal abundances and lengths are given as a function of height up the column in Fig. 4.2 and Table 4.2 respectively. There is no observable trend for crystal length of any crystal type.

Table 4.2 Average and maximum crystal lengths (mm) Ngamanawa

QTZ AVE	QTZ MAX	PLAG AVE	PLAG MAX	HYP AVE	HYP MAX	OPA AVE	OPA MAX	HEIGHT (M)
0.88	1.2	0.9	2.5	0.5	1.0	0.17	0.30	70
0.83	1.4	0.8	1.3	0.6	1.3	0.15	0.32	59
1.10	1.4	1.3	2.3	0.7	0.8	0.15	0.17	44
0.63	1.0	1.7	2.6	1.1	1.4	0.11	0.30	35
0.51	0.6	0.9	1.8	0.4	0.6	0.10	0.34	19
0.63	1.2	1.6	4.0	0.7	1.2	0.23	0.41	7
0.82	2.0	1.3	2.5	0.6	1.0	0.14	0.51	2

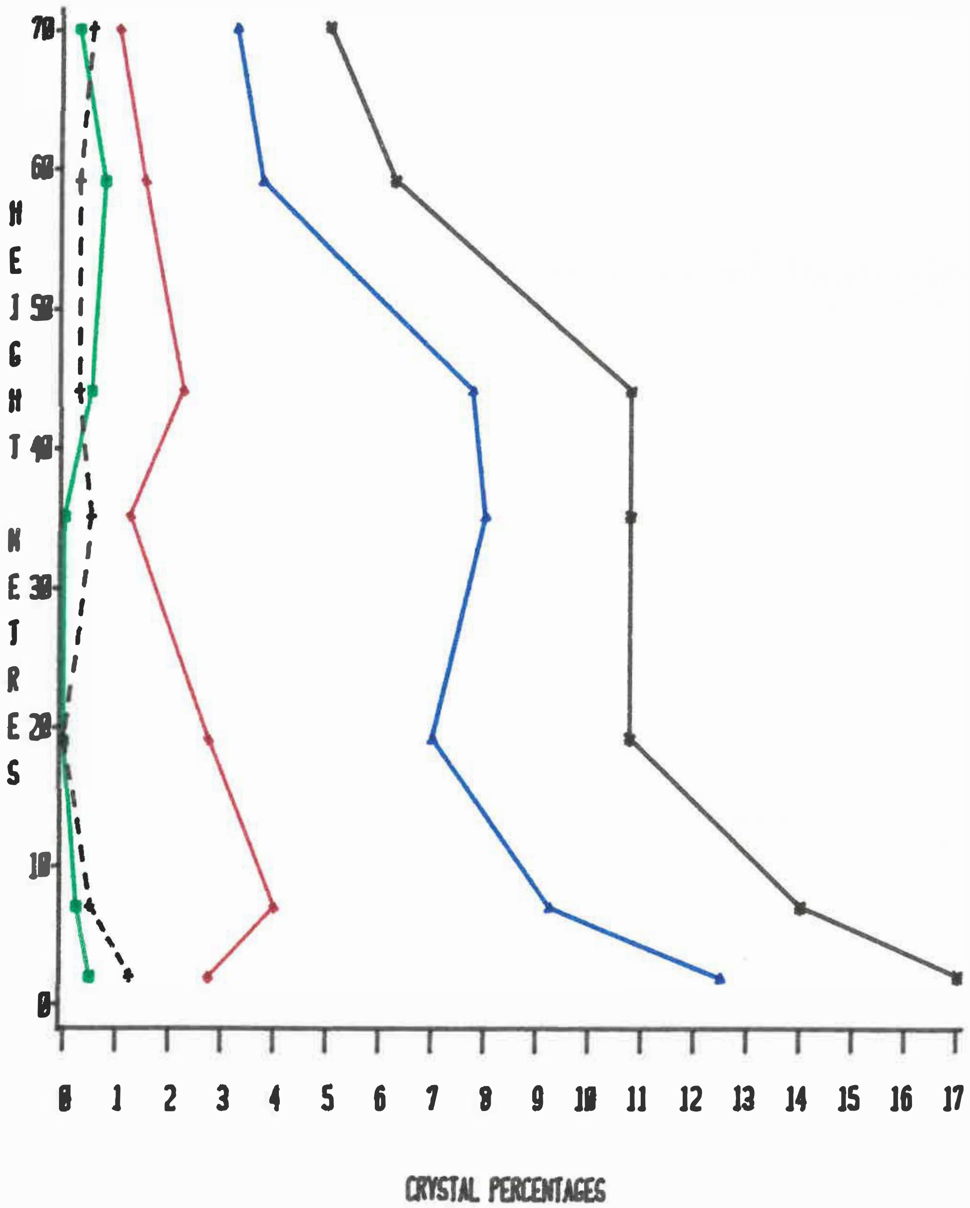
Discussion: Fig. 4.2 illustrates a decrease in total crystal percentages as height increases supported by a correlation of [r=-0.95 (0.001)]. If linear regression is used the equation for the line is Y= -5.9X+96.57, the slope is -5.9 and the intercept 96.57. As the distance from source, (22 km) implies mixing would have occurred during flowage. This zonation can not be attributed to zonation in the magma chamber. As the flow was dense enough to buoy pumice to the top of the sheet and crystal lengths appear randomly distributed, (Table 4.2) the possibility of gravity settling (or buoying) of crystals during flowage is rejected, crystal zonation is considered to be the result of welding, following Sheridan and Ragan's (1976) ideas.

4.2.4 Belk Road (U14/827712)

The outcrop exposed in the cutting is 6 m thick (total thickness is estimated at about 25 m, but not all is accessible) and 26.5 km from source. This is an interesting site as it is distal and comprises at least two flow units of the Mamaku Ignimbrite. In

Fig. 4.2 CRYSTAL PERCENTAGES FROM MODAL ANALYSIS VERSUS HEIGHT

MAMAKU IGNIMBRITE ENTRANCE NGAMAHAWA CORP U15 791647



BLACK=TOTAL CRYSTAL PERCENTAGES

RED=QUARTZ CRYSTALS BLUE=PLAGIOCLASE CRYSTALS

GREEN=MAFIC CRYSTALS BLACK DOTTED LINE= OPAQUE CRYSTALS outcrop the overlying flow unit (sheet 4) is in sharp contact with sheet 2.

Groundmass: Under plane polarised light, the colour of the sheet 4 matrix changes from a yellow orange at the top of the outcrop to a yellow at the base. The groundmass has been weathered (in parts to clay), although shards are moderately preserved in the upper part of the outcrop. Weathering has generally obliterated the vitric texture in the basal section, the converse of what might be expected. This is probably the result of ground-water activity, there being two manganese layers, one above the pumice concentration zone and the second at the contact with sheet 2. Under crossed polarisers crystallites are rare at the base, but were occasionally seen in the upper middle of the outcrop. Sheet 2 groundmass is pale grey and partially devitrified, with a relict vitric structure. Crystallites are abundant, though coarse microlites were not seen. The occasional lithic of ignimbrite? was noted.

Pumice Fragments: Moderately preserved vitric structure can be see in small (0.5-2 mm) pumice fragments in sheet 4. However, these differ in texture from the 3 to 6 cm pumice in the pumice concentration zone. Vitric texture in the latter has been largely obliterated by weathering. Occasional plagioclase and quartz but no mafics were identified. This contrasts with sheet 2 where pumice has been completely destroyed by devitrification with almost no trace remaining of the original structure.

Hypersthene: Hypersthene is quite fresh in the top of the outcrop (sheet 4), though brown stains often mantle the crystals. Magnetite and the occasional zircon are found as inclusions. Crystals are anhedral and heavily fractured. Weathering has progressively reduced them to brown stains from the middle to the base of the outcrop.

Sheet 2 hypersthenes are similar to those in sheet 4 in that they have often been altered to brown stains, but were preserved they tend to be more prismatic rather than tabular.

Augite and Hornblende: Both these minerals were identified in the top of the flow. It is probable that they were present in the other slides, but weathering and oxidation make precise identification impossible.

Plagioclase: Plagioclase is generally anhedral and tabular. Edges are slightly altered except for the manganese layer (slide 404) in the pumice concentration zone, where plagioclase is strongly altered. Basal examples are more heavily fractured than elsewhere, with abundant broken crystals. Magnetite is a common inclusion.

Quartz: Quartz is dominantly subhedral. Edges have occasionally been slightly resorbed and the middles corroded, suggesting disequilibrium in the melt. Fracturing is slight though rare broken fragments can be found. No inclusions were seen.

Opaques: Magnetite is fresh with a subhedral square tabular shape and occasionally slightly fractured. Ilmenite is platey and tends to be ragged. Opaques in sheet 4 tend to be more common and larger than in sheet 2.

Table 4.3 Average and maximum crystal lengths (mm) Belk Road

QTZ AVE	QTZ MAX	PLAG AVE	PLAG MAX	HYP AVE	HYP MAX	OPA AVE	OPA MAX	HEIGHT (M)	
0.94	1.24	1.2	3.0	0.36	0.9	0.10	0.6	3.1	
1.10	1.60	1.5	3.0	not possible to measure		0.15	0.2	2.2	Sheet 4
0.65	0.80	0.6	0.8			0.16	0.6	2.1	
0.82	1.00	1.2	1.3			0.10	1.3	1.2	Sheet 2

Crystal percentages and lengths are given in Fig. 4.3 and Table 4.3 respectively. Briefly, no trend is apparent for crystal lengths or percentages, even when sheet 4 is examined individually. Hypersthene was too altered for reliable crystal measurements to be made appart from the top of the outcrop.

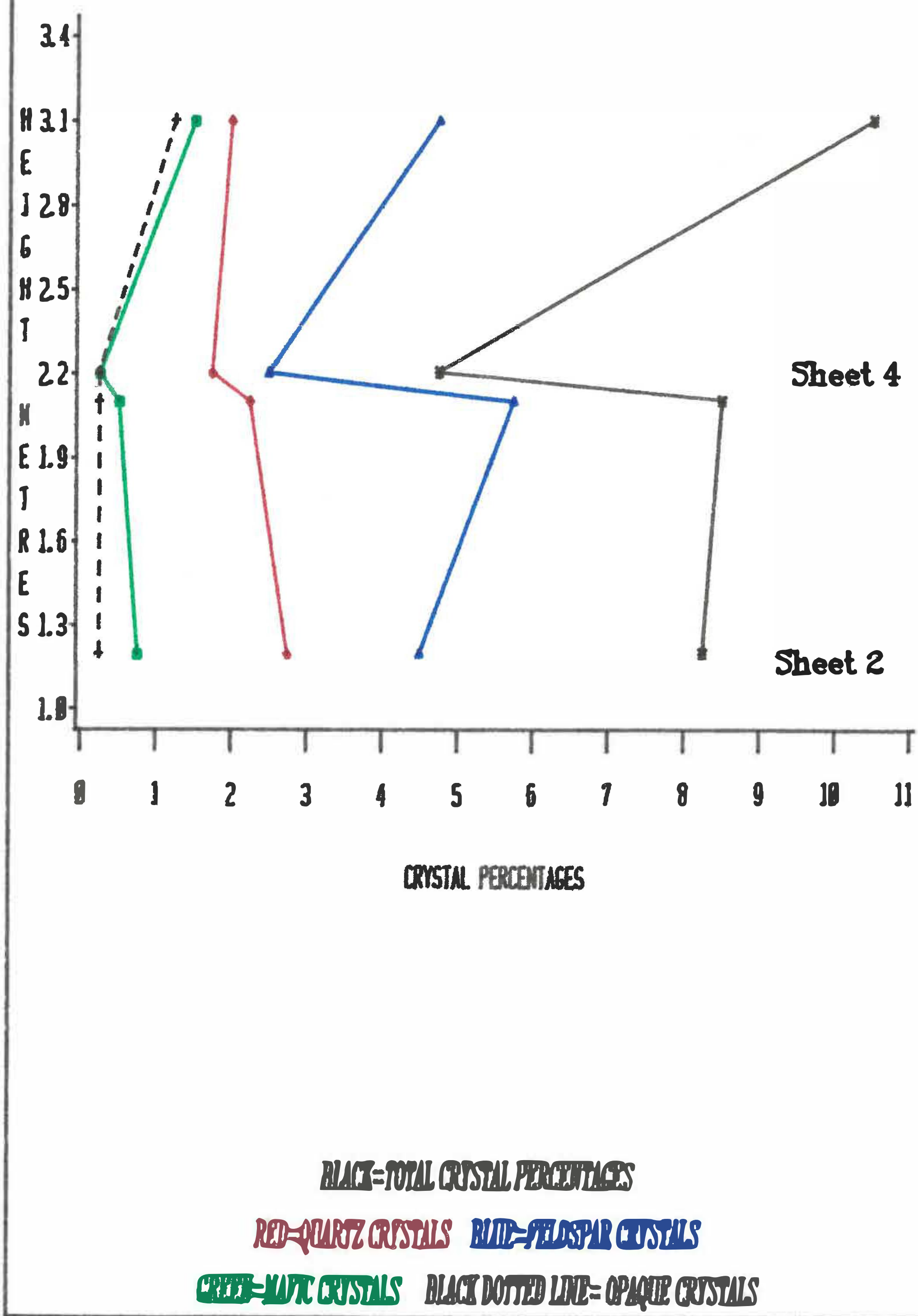
4.2.5 Joyce Road (U14/853736)

This site is the second most northerly outcrop of the Mamaku Ignimbrite in the study area. The outcrop is 29 km from source, 30 m thick and comprises sheet 2, 3 and 4. Slides were made from sheet 2, the surge deposit (which directly overlies sheet 2), sheet 4 and a fourth from the pumice in the pumice lens in sheet 4. Data for this column is not tabulated separately; the aim here was to compare sheets 2 and 4 and pumice from the lens with those at Belk Road to see if petrological characteristics were the same: they are. A slide was not made of sheet 3 as it has very similar characteristics in hand specimen to sheet 2. Total crystals (bulk rock) for sheet 2, the surge and sheet 4 are 6.2%, 10.2% and 17.3% respectively.

Groundmass: The groundmass of the surge deposit is greyish brown and partially devitrified, though the vitric structure has been well preserved with Y shaped, angular, prismatic and semicircular shards clearly recognizable. This is probably the result of the ignimbrite degassing during travel; insufficient vapour being available for devitrification to proceed to the extent normally seen in this ignimbrite. Felsic crystallites are common in both slides, patches of microlites in pumice were not seen. Very occasional traces of post-emplacement flowage are detectable. Sheet 2 has a similar well preserved structure, but tends to a pale yellow pink colour under plane polarised light. The groundmass of sheet 4 is light yellow

Fig. 4.3 CRYSTAL PERCENTAGES FROM MODAL ANALYSIS VERSUS HEIGHT

MAMAKU IGNIMBRITE BELK ROAD U14 826712



orange. Although weathered to clay, relict shards are recognizable in places. Occasional micro crystals are scattered through the groundmass. Several unidentifiable (2 mm) lithics were noted.

Pumice in sheet 2 and the surge deposit has been devitrified with little trace of original structure. Pumice from the pumice concentration zone in sheet 4 is weathered, though traces of the original vitric structure can be seen. Most crystals were plucked from the slide, though plagioclase and quartz were identified. Quartz in the pumice (sheet 4) is anhedral, moderately fractured and heavily corroded. The occasional weathered hypersthene was identified.

Hypersthene: Hypersthene in both sheet 2 and the surge deposit are altered to brown stains, probably limonite, and is often found with opaque inclusions. Fracturing is intense and broken fragments abound. Magnetite inclusions are common and opaques often rim these crystals. Several zircon inclusions were found.

Hornblende: Traces of pleochroic brown hornblende were identified in all slides. These phenocrysts seem more resistant to oxidation than augite and hypersthene in this column.

Plagioclase: Plagioclase is mostly subhedral. Fracturing is intense, with alteration proceeding along fracture lines for sheet 2. Broken fragments abound. Mean length is 0.92 mm and maximum 1.4 mm. Sheet 2 has 2% plagioclase compared with the surge layer's 5.5% and sheet 4's 14%. Sheet 4 plagioclase is twinned and tabular though occasionally lath shapes were seen. Ends are ragged and broken; fracturing and corrosion are moderate. Rare apatite inclusions were seen. Average length is 0.7 mm and maximum 1.4 mm.

Quartz: Quartz in the surge deposit (3.5%) is subhedral to anhedral. Fracturing is slight, and corrosion moderate. Average length is 0.55

and maximum 1.2 mm. Sheet 4 quartz (2%) is subhedral to anhedral, tabular, moderately fractured and slightly corroded. No inclusions were seen. Mean length is 0.95 mm and maximum 1.1 mm.

Opaques: Ragged platey ilmenite is the dominant opaque (1.3%) for the surge layer though cubic subhedral magnetite is common and often found as overgrowths in mafic crystals. Sheet 2 has 0.5% opaques, while sheet 4 opaques (1%) are euhedral to anhedral, generally tabular and range from cubes of magnetite to ragged laths of ilmenite.

4.2.6 Oropi Gorge (U15/877687)

The Mamaku Ignimbrite is 40 m thick at this column, 24 km from source and comprises sheets 1, 2 and 4. The mineralogy and matrix is similar to descriptions previously given, apart from the following. Sheet 1 has fresh groundmass and crystals. The surge layer has a very strong glomeroporphyritic texture as compared with the slightly glomeroporphyritic texture for most other Mamaku Ignimbrite thin sections. Also there is the large increase in total crystal percentages (35.5%) for the surge layer when compared with the range of total crystals for the rest of the column.

Table 4.4 Average and maximum crystal length (mm) Oropi Gorge

QTZ MEAN	QTZ MAX	PLAG MEAN	PLAG MAX	HYP MEAN	HYP MAX	OPA MEAN	OPA MAX	HEIGHT (M)	
0.55	0.8	1.02	1.5	0.75	1.0	0.05	0.1	35	
0.9	1.1	0.75	1.3	0.56	1.2	0.15	0.2	25	sheet 2
1.45	1.8	1.14	1.6	0.53	0.8	0.17	0.3	15	
1.1	1.3	1.10	1.8	0.4	0.5	0.26	1.0	9	
0.6	0.7	1.15	2.5	0.85	1.0	0.10	0.2	6	surge
1.1	1.3	1.18	2.5	0.58	0.9	0.13	0.2	4	sheet 1

Ignoring sheet 1 and the surge deposit there is a minor decrease in total crystals (Fig. 4.4) from the base of sheet 2 (12%) to its top (9%). Quartz varies from 3.5% at the base to a minimum of 1% at the next site. As at other columns, plagioclase is the dominant crystal and ranges from 8.75 at 15 m to 5.5% at the top of the flow. Mafics vary from a maximum of 1% to a minimum of 0.25%. Opaques cluster around 0.5%. There is no apparent trend for phenocryst length (Table 4.4).

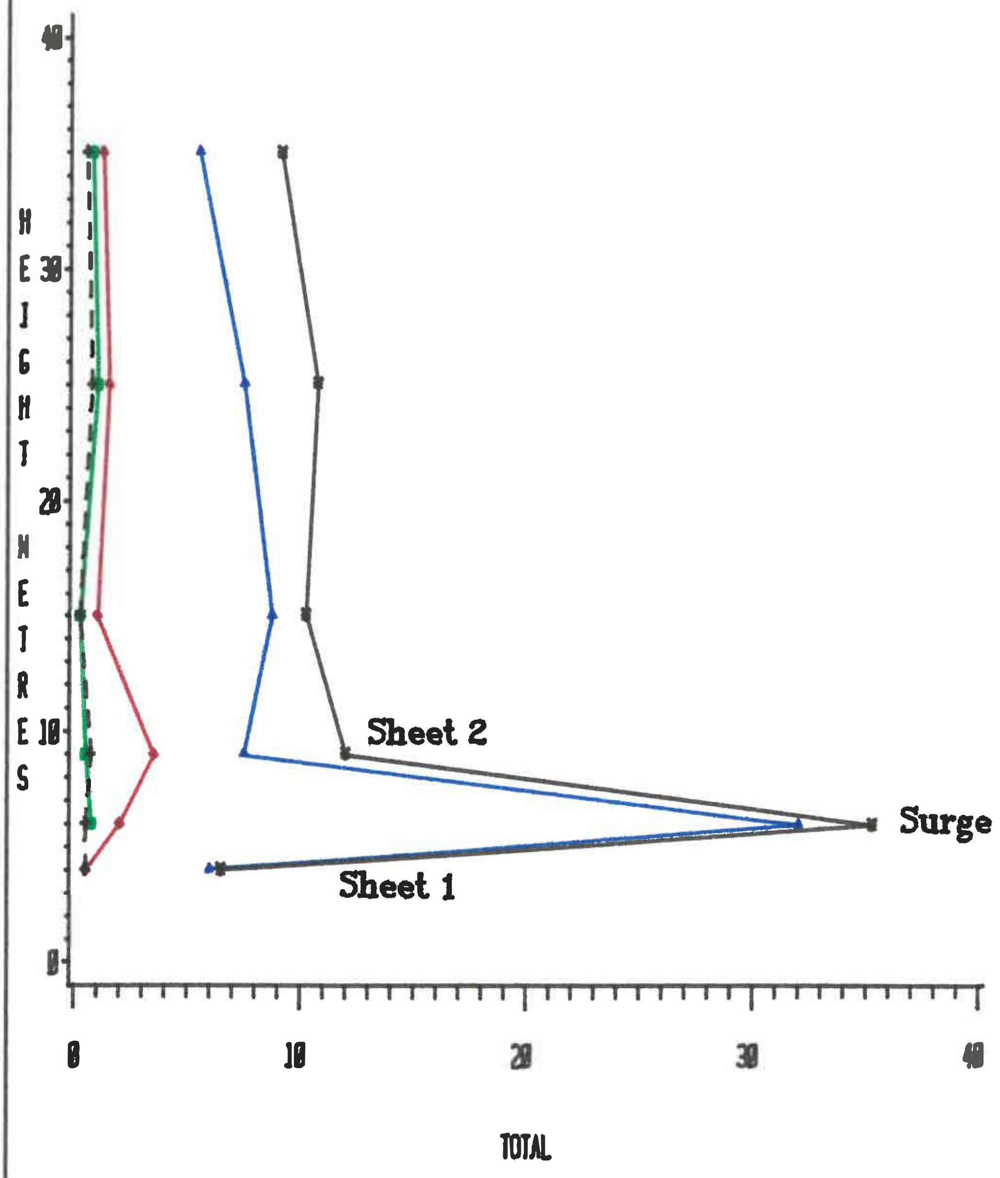
4.2.7 Lateral variations in phenocryst lengths

The behaviour of crystals has some similarities to that of lithics. Briggs (1976a) reports a decrease in mean length of crystals with distance away from source for the Whakamaru Ignimbrite. Walker *et al.* (1981) note that at more than 60 km from source, the maximum crystal length in the Taupo Ignimbrite decreased from 2 mm to less than 1 mm. They found that the amount of crystals also steadily decreases until the groundmass is almost all vitric. However, Fisher (1966) reports no significant decrease in median diameter of feldspar crystals over distance, though he notes a lateral decrease in crystal content.

Two approachs are used in comparing lateral variations. The first is outlined below. Three Mamaku Ignimbrite columns are compared, these are the Type Site, Ngamanawa, Oropi Gorge and Belk Road. These sites are proximal medial and distal respectively, all have excellent exposure and have a relatively large number of sample points (sites). Each column lies further from source, distances have previously been given. Only quartz and plagioclase mean lengths are compared. The rationale being these two crystal types are the most abundant of the phenocrysts, and presented a greater and more reliable number of samples (usually 10 from each slide) during measurement. As

Fig. 4.4 CRYSTAL PERCENTAGES FROM MODAL ANALYSES VERSUS HEIGHT

MAMAKU IGNIMBRITE OROPI GORGE U15 877687



BLACK=TOTAL CRYSTAL PERCENTAGES

RED= QUARTZ CRYSTALS BLUE=PLAGIOCLASE CRYSTALS

GREEN=MAFIC CRYSTALS BLACK DOTTED LINE=OPAQUE CRYSTALS

maximum lengths represent extremes and represent only 1 measurement from each slide, less importance is attached to them by the writer though they are compared. Only sheet 2 (the bulk of the flow) is compared as it is considered more appropriate to compare a flow unit from the ignimbrite rather than to compare sheets 2 and 3 from the type site with sheet 2 at Ngamanawa and sheets 1, 2 and 4 at Oropi gorge.

The procedure was to calculate the mean of the means from each column of crystal lengths of sheet 2. Table 4.5 shows a decrease from the type site to Ngamanawa for quartz average lengths though there is an increase at Oropi Gorge. There is a steady decrease in quartz maximum lengths over a 14 km distance. A decrease from the Type site to Ngamanawa was recorded but there is also an increase at Oropi Gorge for quartz maximum lengths. Plagioclase mean lengths show a steady decrease. In summary an argument exists for a decrease in crystal lengths (using the method outlined above) for the Mamaku Ignimbrite with distance from source though it is not conclusive.

Table 4.5 Mean crystal length (mm)

	QTZ AVE	QTZ MAX	PLAG AVE	PLAG MAX	KM FROM SOURCE
Type Site	0.93	1.43	1.01	1.8	10
Ngamanawa	0.77	1.3	1.21	2.4	22
Oropi Gorge	1.00	1.25	1.00	1.5	24

The second method was to compare mean and maximum lengths from only the top of sheet 2 (Table 4.6). Quartz shows small decreases in mean length with distance from source, there is a marked fall at Oropi Gorge. No trend exists for quartz maximum and plagioclase mean lengths. Plagioclase maximum lengths decrease from source appart from

Oropi Gorge, there is also a small increase in length at Joyce Road. Thus a weak argument exists for a decrease in crystal lengths with distance from source, which is the same conclusion when all sample points from sheet 2 were compared.

Table 4.6 Mean crystal length (mm), top of sheet 2

	QTZ MEAN	QTZ MAX	PLAG MEAN	PLAG MAX	KM FROM SOURCE
Type Site	0.9	1.1	1.1	2.4	10
Ngamanawa	0.88	1.2	0.9	2.5	22
Oropi Gorge	0.55	0.8	1.0	1.5	24
Belk Road	0.82	1.0	1.2	1.3	26.5
Joyce Road	0.80	1.2	0.9	1.4	29

4.2.8 Lateral variations in crystal percentages

Sheridan and Ragan (1976) state increased welding implies an increased relative percentage of crystals. If this is correct then it is inappropriate, for example, to calculate the mean of total crystal percentages from each site of sheet 2 at the type site and attempt to compare them with the mean of total crystal percentages from each site of the Ngamanawa column.

Table 4.7 Crystal percentages, top of sheet 2

	TOTAL	QTZ	PLAG	KM FROM SOURCE
Type Site	12	2.5	8.5	10
Ngamanawa	5	1.0	3.2	22
Oropi Gorge	9	1.2	5.5	24
Belk Road	8	2.7	5.4	26.5
Joyce Road	6	3.0	2.0	29

Therefore it is argued a more useful comparison is that of crystal percentages from zones with about the same degree of welding. Thus total plagioclase and quartz crystals from the top of sheet 2 are compared. The results in Table 4.6 show there is a moderate trend towards a decrease in total crystals with distance from source (r=-0.74 [0.15]), no trend is apparent for quartz, but there is a good decrease for plagioclase crystals (r=-0.81 [0.09]). If the Ngamanawa column is not included in the calculations the trend towards a decrease in crystals with distance from source is more apparent.

Summary: There is a statistically significant trend for crystals to decrease in percentage as height increased at the Type and Ngamanawa columns. This is explained by welding/compaction rather than magma chamber zonation. There is an argument (but certainly not conclusive) for a decrease in crystal lengths with distance from source for the Mamaku Ignimbrite. This suggests that for this ignimbrite, crystal length was a relatively unimportant parameter in determining whether crystals were deposited out of the flow. No trend can be seen for vertical changes in phenocryst lengths at any column and it is inferred from this that gravity settling or conversely a buoying effect was not operating for crystals. This finding supports the view expressed for crystal lengths. Conversely pumice was buoyed to the top of the flow in the medial columns (see section 5.3). There is little vertical variation in crystal percentages at the distal columns apart from a slight increase in the more welded zones. Statistically and visually there is a decrease in total and plagioclase crystal percentages with distance from source. Therefore crystals were sedimenting out of the flow, but the evidence on crystal lengths suggests length was not an important factor in the deposition of crystals.

4.3 PETROGRAPHY OF THE WAIMAKARIRI IGNIMBRITE

4.3.1 Omanawa Falls (U15/821682)

On the Omanawa Falls track to the underground power station, 4 m of strongly welded basal Mamaku Ignimbrite and 41 m of incipiently to strongly welded Waimakariri Ignimbrite is exposed. In thin-section the ignimbrite is vitrophyric and slight to moderately glomeroporphyritic.

Groundmass: The colour of the groundmass under plane polarised light gradually changes from a light grey at the base to a light yellow, then light yellow brown, followed by a light brown and then brown at the top. This is caused by devitrification and groundwater, especially in the upper part of the flow. A variety of shard forms can be seen: these include Y-shapes, semi-circles, rare circles and prisms. Most fragments had broken jagged edges, ranging in size from dust to 0.75 mm.

The first sign of post-emplacement flowage was seen around some crystal margins in the upper basal slide. With increasing height welding and compaction steadly increased, although at the top of the outcrop the vitric structure is less obvious due to oxidation and devitrification. However, it is still possible to discern that it is welded, suggesting the unwelded top has been removed. Under crossed polarisers all slides showed some felsic crystallites, although the absence of microlites in void spaces indicated little vapour phase activity. Groundmass percentages varied from 88.7 at the top of the flow to 85.3% at the base (the inverse of total crystals, Fig. 4.7).

Pumice Fragments: Pumice becomes more lenticular and less vesicular with increasing height, though this effect decreased towards the top of the flow. Occasional ragged plagioclase and subhedral quartz made up approximately 5% of the pumice fragments. This should indicate the true magma content at the time of eruption.

Lithic Fragments: Lithics of flow banded and spherulitic rhyolite are quite common. These range in length from 0.3 to 1.7 mm.

Hypersthene: Crystals tend to anhedral tabular and prismatic forms; rims are often slightly altered especially in slides taken from the top of the outcrop. Hypersthene is moderately to heavily fractured with small broken fragments quite common. Magnetite is the dominant inclusion though occasionally glass was seen. Hypersthene ranges from trace amounts to 0.5% of the rock.

Augite: Augite is common (0% to 0.5%); it tends to a subhedral semi cubic, moderately fractured form.

Hornblende: Traces of green pleochroic laths of hornblende were found in most slides, though they tended to be slightly more abundant in slides of basal to lower middle parts of the flow.

Quartz: Quartz tends to be slightly fractured. Forms are tabular and subhedral though anhedral shapes are common. They tend to be free of inclusions though rare glass is present. Corrosion is moderate to heavy in most quartz, except towards the base of the flow where it is slight.

Plagioclase: Although plagioclase forms range from anhedral to euhedral, subhedral was the most common. Edges tend to be slightly resorbed and fracturing is moderate and occasionally perlitic. Opaque and hornblende inclusions are common, some crystals contained abundant dust particles.

Opaques: Most opaques (approximately 75%) are magnetite, of a cubic subhedral form, fresh and slightly fractured and occasionally clumped together. Platey opaques were identified as ilmenite. Opaques at the top of the outcrop are often surrounded by a brown stain.

Discussion: Crystal percentages as a function of height are shown in Fig. 4.5. Plagioclase increase with height which corresponds approximately with the welding pattern recorded for this column. Other crystals remain relatively constant apart from quartz at the top of the flow where 0% was recorded.

The correlation between welding (PT units) and crystals is (r=0.93 [0.02]). Therefore, this zonation is attributed to compaction/welding effects rather than magma chamber zonation. It is possible that zonation may have been preserved if a strict laminar flow regime was operating and little mixing of the crystals occurred but this is considered unlikely. The lack of crystal settling (or buoying) suggests that there was little gravity sorting of larger crystals during flowage (Table 4.8).

Table 4.8 Average and maximum crystal lengths (mm) Omanawa Falls

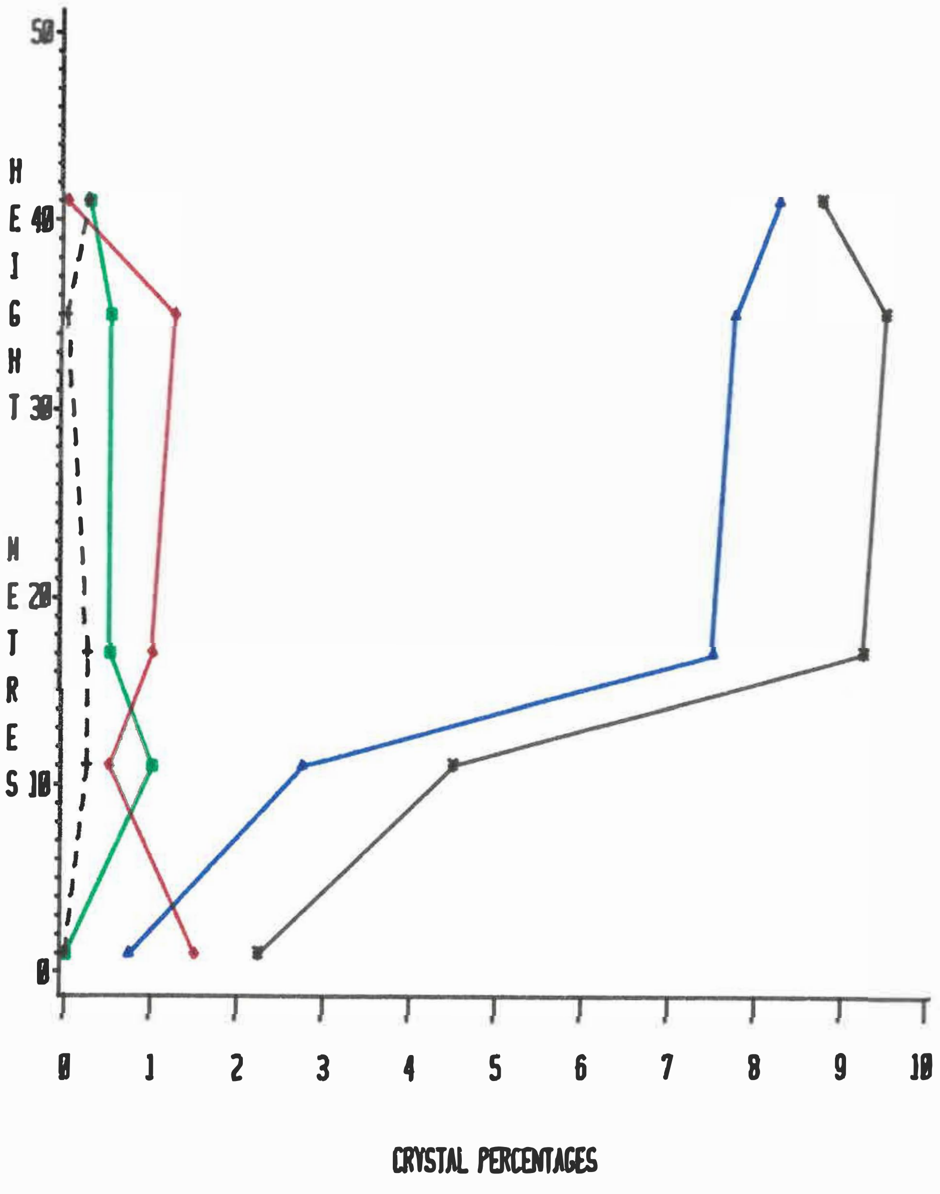
QTZ AVE	QTZ MAX	PLAG AVE	PLAG MAX	HYP AVE	HYP MAX	OPA AVE	OPA MAX	HEIGHT (M)
0.67	1.0	0.65	0.80	0.24	0.50	0.10	0.15	44
0.87	1.0	0.50	0.90	0.36	0.60	0.06	0.57	38
0.48	0.9	0.63	1.20	0.48	0.90	0.13	0.30	18
0.53	1.4	0.80	1.10	0.30	0.70	0.27	0.45	11
0.68	0.9	0.53	0.80	0.50	0.75	0.20	0.30	1

4.3.2 Carrs Track

Carrs track provides a 30 m exposure of distal, incipiently to non- welded Waimakariri Ignimbrite. The mineralogy is very similar to that at Omanawa Falls. Only shards from the lower middle and middle parts of the flow show slight signs of welding. Sizes range from dust

Fig. 4.5 CRYSTAL PERCENTAGES FROM MODAL ANALYSIS VERSUS HEIGHT

WAIMAKARIRU IGNIMBRITE OMANAWA FALLS U15 821682



BLACK=TOTAL CRYSTALS

RED=QUARTZ CRYSTALS BLUE=FELDSPAR CRYSTALS

GREEN=MAFIC CRYSTALS BLACK DOTTED LINE= OPAQUE CRYSTALS to 1.0 mm, although most are 0.05-0.3 mm. Occasional brownish black obsidian flakes were noted. Pumice (0.5-1.5 mm) is abundant in all slides, though they change from a rounded shape at the base to semi lenticular in the lower middle and middle slides. Often edges were broken. Lithics of rhyolite, devitrified ignimbrite and argillite were identified. Interestingly, one argillite had a quartz vein running through it.

Fig. 4.6 shows a moderate increase in quartz for the first three data points and then a small fall to 2%. There is a steady increase in plagioclase crystals from 1.75% at the base of the flow to 11.75% at the top of the outcrop. This is the reverse to that found with the Mamaku Ignimbrite and described by Fisher (1966) and Walker *et al.* (1981).

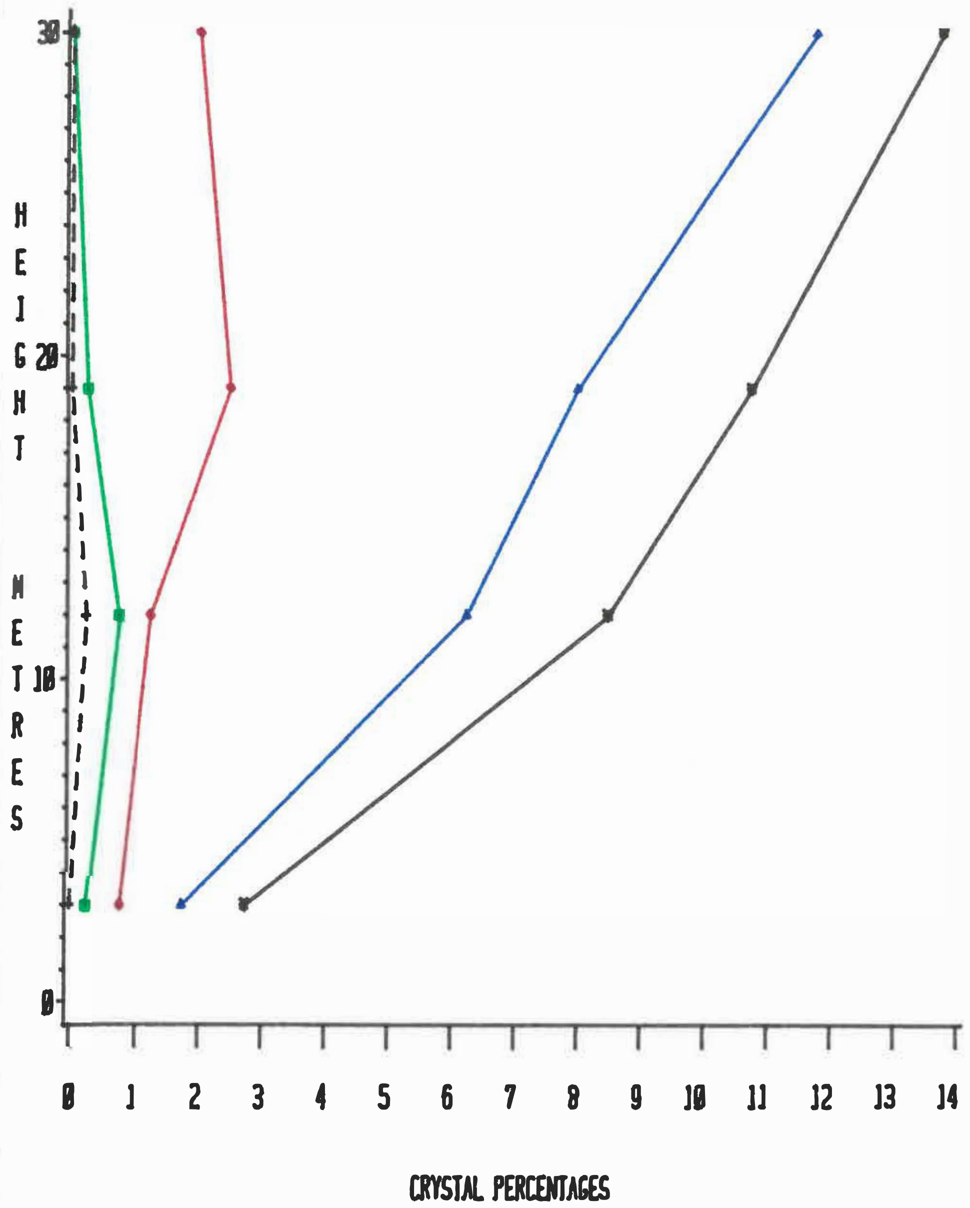
Table 4.9 Average and maximum crystal lengths (mm) Carrs Track

QTZ MEAN	QTZ MAX	PLAG MEAN	PLAG MAX	HYP MEAN	HYP MAX	OPA MEAN	OPA MAX	HEIGHT (M)
0.27	0.6	0.66	1.44	0.75	1.0	0.1	0.3	30
0.57	1.0	0.78	1.25	0.29	0.7	0.6	0.9	19
0.56	0.9	0.97	1.40	0.6	0.9	0.1	0.6	12
0.60	0.8	0.52	1.00	0.53	0.7	0.04	0.1	3

The hypothesis advanced for the increase in crystals (at Carrs track) is that fines were being steadily elutriated from the flow as a co-ignimbrite ash fall as described by Fisher (1979). As this site is distal, extensive mixing and/or gravity settling of crystals should have occurred and it is considered unlikely that magma chamber zonation was preserved. Reference to Table 4.8 shows there is no preferential size grading of crystals apart from mean plagioclase, though this is not a clear cut trend. Thus significant gravity settling (or buoying) during flowage is unlikely to have occurred.

Fig. 4.6 CRYSTAL PERCENTAGES VERSUS HEIGHT

WAIMAKARIRI IGNIMBRITE CARRS TRACK U14 831739



BLACK=TOTAL CRYSTAL PERCENTAGES

RED=QUARTZ CRYSTALS BLUE=PLAGIOCLASE CRYSTALS

GREEN=MAFIC CRYSTALS BLACK DOTTED LINE=OPAQUE CRYSTALS

4.3.3 Lateral variations in crystal lengths and percentages

Similar procedures were used to compare mean and maximum crystal lengths for the Omanawa and Carrs Track columns for the Mamaku Ignimbrite. First the mean of the means was calculated for the entire two columns. The results are summarised in Table 4.10. Carrs Track is 6.8 km NNE from Omanawa Falls and is considered further from source owing to the reduction in welding and thickness. Only quartz average and maximum lengths show a decrease in size with distance, the data for plagioclase show a reverse trend. No conclusion can be reached about any decrease in crystal lengths from source for the Waimakariri Ignimbrite using this method.

Table 4.10 Mean crystal length (mm)

	QTZ MEAN	QTZ MAX	PLAG MEAN	PLAG MAX
Omanawa Falls	0.65	1.04	0.62	0.96
Carrs Track	0.50	0.82	0.73	1.27

If only the basal sites are compared then a clear trend towards a decrease in crystal length with distance from source can be seen apart from plagioclase maximum lengths (Table 4.11).

Table 4.11 Mean crystal length (mm) basal sites

	QTZ MEAN	QTZ MAX	PLAG MEAN	PLAG MAX
Omanawa Falls	0.68	1.0	0.65	0.8
Carrs Track	0.60	0.8	0.52	1.0

Reference to Table 4.12 shows there is an increase in total, plagioclase and quartz crystals from the medial Omanawa Falls column to the distal Carrs Track column. This is the reverse to what might be expected and is explained by progressive elutriation of the fines during flowage concentrating crystals in the top of the flow. But if this theory is correct then obtaining the mean crystal percentages from the two columns is probably an inappropriate method.

Table 4.12 Comparison of mean crystal percentages

	TOTAL	QUARTZ	PLAG
Omanawa Falls	6.8	0.85	5.4
Carrs Track	8.8	1.6	6.9

If the two basal sites (Table 4.13) are compared then quartz shows a decrease in percentages, though the converse is true for total and plagioclase crystals. Therefore no conclusion is made for the hypothesis of decreasing crystal percentages with distance from source for the Waimakariri Ignimbrite.

Table 4.13 Comparison of crystal percentages from basal sites

	TOTAL	QUARTZ	PLAG
Omanawa Falls	2.2	1.5	0.75
Carrs Track	2.7	0.75	1.75

4.3.4 Thin-section petrography of a strongly welded sample

A dark grey strongly welded Waimakariri Ignimbrite sample with eutaxitic texture was collected from vertical cliffs surrounding Lake Mangapapa (U14/778707, sample and slide 450). The mineralogy is similar to that described at Omanawa Falls but the following is noteworthy. Hornblende is the dominant mafic crystal (0.5%) showing green and rare brown pleochroism. Dominant forms are prismatic though occasional small cubes were seen. Several rare hypersthene crystals were noted. This relative abundance of hornblende and hypersthene is the reverse to all other Waimakariri slides examined. As the sample was taken near the upper base of the flow this could suggest a form of zonation indicating a flow unit or perhaps the slide is unrepresentative. Shards have the usual variety of shapes seen in the Waimakariri Ignimbrite, but there is little fracturing or breakage and they are more compressed with long laths the dominant shape. Shards in contact with crystals are moulded against them, and occasionally small shards are moulded against larger shards. These characteristics indicate that the groundmass was in a plastic state at the time of deposition. Pumice fragments (0.7 to 1.3 mm) are lenticular and flattened though they still retain some pore space. However, welding had not proceeded to the stage seen in the Waiteariki Ignimbrite. The groundmass makes up 89% of the rock. Total crystals comprise 8.7% of the rock.

4.3.5 Lithics in the Waimakariri Ignimbrite

Introduction: Lithics are a common feature of the Waimakariri Ignimbrite. Larger specimens (0.5 cm-2 cm) were hand picked from incipiently welded outcrop and exhibit a black, hard, rounded to subangular exterior. Smaller lithics (3-5 mm) were picked out under a binocular microscope. Five slides were made.

Discussion: Two types of ignimbrite lithics were identified. One is vitrophyric, moderately welded, slightly devitrified (though shards are clearly recognizable) with a light brown matrix. Abundant felsic crystallites are found in the groundmass. Crystals total about 2% of the rock. The dominant phenocrysts are twinned, tabular, subhedral plagioclase with slightly resorbed edges. Moderately corroded quartz and subhedral magnetite are common, while hypersthene and hornblende are rare. A dark brown lenticular pumice with ragged edges is common. The other lithic is similar except it is densely welded, the groundmass is dark brown, crystal percentages are approximately 7% and pumice is extremely compressed and difficult to differentiate from the shards of the groundmass. It is considered both lithics are from the same ignimbrite (same mineralogy), though from different zones of welding. These ignimbrite lithics suggest the Waimakariri was not the first ignimbrite to be erupted from its volcanic center (Rotorua Caldera?). Though it is possible that the lithics were plucked from the ground during travel but as they are spread (tendency for lithic percentages to increase in the base of the flow) through the ignimbrite it is suggested that they are derived from a collapsing caldera during eruption.

Two other lithics were identified as andesite and rhyolite. The andesite is strongly porphyritic with weathered plagioclase the dominant phenocryst; augite, pleochroic green hornblende and hypersthene are common. Microcrystalline, pilotaxitic laths of feldspar comprise the groundmass. Two types of rhyolite were identified. One is mildly porphyritic with the occasional twinned small plagioclase set in a cryptocrystalline pale grey groundmass. The other is strongly devitrified, porphyritic with phenocrysts of quartz, feldspar and opaques. The groundmass is a pale white colour with cryptocrystalline felsic crystals and is occasionally spherulitic.

4.3.6 Mineralised Waimakariri Ignimbrite

An area of about 400 m by 20 m of hydrothermally altered Waimakariri Ignimbrite is exposed downstream of the weir (U14/767695) over the ford crossing the Opuiaki River. Two specimens (sample 232, sinter deposit, sample 230a, blue unweathered), were examined under reflected light.

The sinter showed cataclastically shattered pyrite and marcasite suggesting faulting in a shear zone. Quartz and feldspars were also shattered with some examples showing flowage supporting the hypothesis of deformation by faulting. In slide 230a pyrite, marcasite, and hydroxide (a brick red appearance) were identified. The pyrite had been broken and annealed with silicate trails, suggesting deformation.

The changes noted due to hydrothermal alteration are as follows. Phenocrysts of feldspar, augite, hypersthene and hornblende have been strongly altered or completely destroyed, but quartz remains fresh. Magnetite and ilmenite have been altered to hydrous iron oxide, probably limonite. Abundant fine grained radial fibrous marcasite and lesser amounts of cubic pyrite are scattered through the groundmass. The vitric nature of the groundmass has been completely obliterated and replaced by a low birefringent cryptocrystalline silica groundmass.

4.4 PETROGRAPHY OF THE WAITEARIKI IGNIMBRITE

4.4.1 McLarens Falls (U14/783728)

Introduction: Two slides (40, 411) were made of the Waiteariki Ignimbrite at McLarens Falls. The rock is vitrophyric, moderate to strongly glomeroporphyritic and crystal rich (33% total phenocrysts). This site is used as the standard to compare other Waiteariki slides.

Groundmass: The groundmass is devitrified, cryptocrystalline light pinkish grey matrix with little sign of the original vitric texture. Under crossed polarisers the occasional patch of felsic crystallites can be seen. Pore spaces (possibly created by trapped gas) are common which casts doubt on the validity of describing the degree of this ignimbrite's welding using bulk density - porosity experiments. It is clear in thin-section (and in hand specimen) that the rock is very strongly welded yet these spaces would reduce the rock's apparent degree of welding when examined using conventional methods.

Pumice Fragments: Pumice has been so strongly welded that it bears little resemblance to its likely original structure. It is dark grey under plane polarised light, with shards having a well developed parallel alignment (eutaxitic texture) indicating extreme flattening. They resemble a flow structure, but lack the continuity of a flow rock. Owing to the intense compression and welding, shards have been moulded around crystals without breaking indicating a degree of plasticity at the time of deposition. Where voids exist in crystals (from corrosion in the melt) these have been infilled by shards.

Hypersthene: Hypersthene is moderately fractured, subhedral to anhedral with tabular and prismatic forms. Ends are broken and ragged. Magnetite is a common inclusion. These crystals comprise 1.5% of the rock with a mean size of 0.4 mm and maximum of 1.25 mm.

Hornblende: Hornblende is pleochroic in shades of brown and occasionally green. It comprises 0.5% of the rock with a mean size of 0.7 mm and maximum of 1.2 mm. Fracturing is slight and ends have hacksaw terminations. Plagioclase and opaques are often found as inclusions.

Biotite: Biotite is rare, occurring as partially oxidized, prismatic laths, with a brown pleochroic colour and straight extinction. Mean size is 0.7 mm and maximum 1.2 mm.

Plagioclase: Plagioclase is twinned, zoned and moderately fractured, commonly with broken crystals. They are often partially weathered and under crossed polarisers, a gold coloured weathering product tends to infill the margins of these and other crystals. Average size is 1.4 mm and maximum 2.0 mm. These are the most abundant of the phenocrysts, comprising 25.75% of the sample.

Quartz: Quartz is heavily corroded and slightly fractured. Forms are dominantly subhedral, though some are anhedral. Several hexagonal high temperature examples were seen. Mean size is 0.8 mm and maximum 1.4 mm. This phenocryst comprises 4% of the rock.

Opaques: The dominant opaque is ragged anhedral tabular ilmenite though subhedral to euhedral cubes of magnetite are often found clumped together. Sizes ranged from 0.1 to 0.65 mm, while it makes up 0.5% of the sample.

4.4.2 Densely welded pumice

A slide (442) was also made of noticeable protuberances from Waiteariki Ignimbrite at McLarens Falls. In hand specimen, they are very dark grey and noticeably harder than the surrounding rock. They are interpreted as original large pumice which have collapsed under extreme temperature and compaction. The mineralogy is similar too Waiteariki Ignimbrite previously described and is not repeated here. The groundmass is greyish brown with only the occasional very densely welded vitric patch to betray the rock's pyroclastic origin. Most of the slide is comprised of well developed spherulites resembling a spherulitic rhyolite, although the mineralogy is similar to that of 'normal' Waiteariki Ignimbrite, with an occasional patch of welded shards. This spherulitic development may result from extreme compaction and welding where rapid devitrification has developed under extreme pressure-temperature conditions. Another difference between pumice and other samples at McLarens Falls is the common presence of biotite comprising 0.5% of the sample and having a mean size of 0.63 mm and a maximum of 1.3 mm.

4.4.3 Basal Waiteariki Ignimbrite (U14/737733, sample 742)

Only differences from the McLarens Falls slides are discussed. The matrix is yellow brown under plane polarised light. Shards are slightly devitrified, though clearly recognizable. They have been moderately welded and compressed with post-depositional flowage apparent, especially around crystal margins. Pumice is light yellow and is quite lenticular with sizes ranging from 0.5 mm to 1.3 mm. Under crossed polarisers a moderate amount of felsic crystalites is seen, though no vapour phase minerals were visible.

Biotite is pleochroic with a reddish brown colour and straight extinction and more common than elsewhere. It is tabular, subhedral and usually unfractured, though edges tend to have hacksaw terminations. Mean size is 0.6 mm and maximum 1.4 mm and comprises 0.5% of the rock. The main difference between the basal slide and those from the densely welded zone (apart from the reduction in welding) is an increase in the percentages of mafic crystals and an overall reduction in total crystals. The former may signify a zonation and the latter is probably due to a reduction in welding/compression effects.

4.5 PETROGRAPHY OF THE OPUIAKI SEDIMENTS

4.5.1 Lake Sediments

Sediments previously considered to be possible lake sediments (lithotype 1) were examined for fossils and the following diatoms were identified to Genus level based on Cramer (1979). Slide 710 contained: Cyclotella, Eunotia, Diploneis, Achnanthes, Cymbella, Navicula, Melosira, Epithenia, Cocconeis, and Pinnularia. Slide 745 contained the above with the addition of Gomphonema, Frustulra, and the exception of Eunotia, Achnanthes, Navicula and Pinnularia. Although the presence of diatoms by no means proves that these sediments were derived from a lake (Green, *pers comm.*) the variety and abundance plus varves suggests samples 710 and 745 were lake sediments. One slide was prepared from sample 745 using the techniques outlined in Chapter 2 for ignimbrites, the aim being to identify any crystals present. Rare fine grained plagioclase were seen, abundant silt particles and diatoms. Probably the plagioclase are derived from indirect tephric input from streams.

4.5.2 River Gravels

Two slides (435, 516) were made of gravels from the Opuiaki sediments. Both were identifed as rhyolite and Waiteariki Ignimbrite. The rhyolite has a weathered light brownish grey, fine grained mildly spherulitic groundmass and is quite similar to the lithics seen in the Waimakariri Ignimbrite. Under crossed polarisers abundant felsic crystalites were noted. No ferromagnesiams or opaques were observed. Scarce plagioclase is highly fractured, moderately corroded and with tabular forms. Two quartz were identified and these were slightly fractured, corroded and tabular. Although the rhyolite gravels examined vary slightly they are probably from the same source.

As the Waiteariki Ignimbrite gravels have a similar mineralogy to that described at McLarens Falls these are not repeated here. The main difference noted was slightly less welding.

4.5.3 Sands

One slide was made up from sands from a massive layer between diatomaceous varved deposits at the old pozzolan quarry (U14/732723). It is estimated that about 70% of the slide comprised pale grey rounded vesicular pumice (0.2-0.7 mm), 20% plagioclase (weathered, slightly fractured), 5% quartz (fractured and embayed), 3% opaques and 1% hornblende and augite. This sand may be reworked tephra.

CHAPTER FIVE

VERTICAL AND LATERIAL VARIATIONS

5.1 INTRODUCTION

The textural and compositional variations in the Mamaku and Waimakariri Ignimbrites are presented in this chapter. Exposure of the Waiteariki Ignimbrite is usually limited to river beds and so construction of stratigraphic columns in this ignimbrite is not practicable. These variations fall into several logical groupings: pumice numbers, pumice percentages and size, degree of welding, and lithic percentages.

The purpose of collecting and examining these data is to discuss the vertical and lateral variations within the two ignimbrites, which in turn may suggest processes acting on the ignimbrite during flowage and deposition. The approach for the Mamaku Ignimbrite was to concentrate on sheet 2 which forms the bulk of this ignimbrite and largely ignore sheets 1, 3 and 4 (though occasionally they have been included in the graphs for interest sake but not in the calculations). Sheet 2 was identified at all sites and this is the flow unit used to investigate lateral variations.

Correlation analysis (see section 4.1) is often used. Where strong correlations were found (i.e., some columns showed pumice percentages to increase with height) factors such as density of the pumice, density of the flow, extent of fluidisation and energy imparted from the eruptions are assumed to be responsible.

Cooling Unit: Smith (1960a,b) states that an ignimbrite can be understood from the cooling unit concept. An ignimbrite is a flow or a number of flows that were erupted so rapidly that that little or no cooling occurred between successive emplacements. In a simple cooling unit, then, a more or less systematic pattern of zonation will exist, differing in degree of welding. For example, the top and bottom parts of a simple cooling unit are composed of friable, incipiently welded to unwelded rock, while the middle is moderately to densely welded. In a compound cooling unit, an interruption or change occurred, sufficient to disturb this cooling zonation.

Flow Unit: A flow unit is a depositional unit - a single pyroclastic flow deposited in one lobe, in a time interval of minutes to hours. The thickness can vary from a few centimetres to many tens of metres. Boundaries are marked by changes in grain size, composition, fabric, and bedding zones (Smith 1960a). Fisher and Schmincke (1984) state a single bed may be massive, progressively graded, and have internal continuous laminations or crossbedding. This grading can result from recurrent surging within the flow (Smith 1960a) or mechanical differentiation from shearing during laminar flow (Fisher and Schmincke (1984). In contrast, however, Wilson and Walker (1982) conclude that the thickness of an ignimbrite flow unit bears no relation to the thickness of the parent pyroclastic flow, and that the grain size and compositional characteristics of an ignimbrite at a given point bear no relationship to the grain size and compositional characteristics of the parent pyroclastic flow. If this conclusion were correct it would seem that little purpose would be served by examining flow deposits with a view to understanding flow behaviour. However, other workers have found parameters that appear associated with flow units and these are described and subsequently used in this study.

Several criteria for the recognition of flow units are now outlined. Yamazaki (1974) found for the Donzurubo Ignimbrite that pumice was evenly distributed in the lower and middle parts of the flow, but became concentrated in the uppermost zone. He states this clearly defines the top part of the flow unit. Smith (1960a) asserts that sharp breaks in grain size such as that between pumice-rich tops and basal layers indicate a new flow unit. Fisher and Schmincke (1984) state that field recognition of a flow unit may be straightforward if it is internally structureless or bounded by sharp bedding planes, but becomes subjective if boundaries are gradational or composed of many texturally distinct smaller units. Separate layers within a unit are often interpreted as separate flow units, but unless there are marked compositional changes, soil horizons or erosional irregularities between units such an interpretation may be dubious.

This view is adopted and flow units have not been defined on the basis of an increase in pumice numbers alone. The reason for this, apart from Fisher and Schmincke's (1984) comments, is that an obvious flow unit was seen near the top of the type site column (sheet 2 and 3) but pumice numbers were not observed to increase at the top of the underlying unit. In fact, numbers increased in the overlying unit. To define a flow unit on the basis of an increase of pumice numbers alone would lead to a multitude of flow units being identified which may not exist. An example of this scenario is the Lloyd Mandeno column (Fig. 5.2). However it should be noted in some examples a pumice concentration zone did indicate a new flow unit (Joyce Road, Scotts track, Youth camp columns). Flow units in the study area were recoginzed where there were several lines of evidence. For example, sheet 3 at the type site was defined on the basis of a change in color, a Mn lens which separates the flow units, a change in pumice parameters and a change in welding.

5.2 PUMICE NUMBERS

Several diagrams are presented which summarize counts of pumice numbers from a 13x30 cm rectangular sample area taken from vertical columns and horizontal sections of the Mamaku and Waimakariri Ignimbrites.

Mamaku Ignimbrite (Figs 5.1 and 5.2)

Pumice numbers at the Mamaku type site (10 km from source) steadily increase in the first 50 m (maximum of 19 at 52 m), followed by a fall at 76 m and then a decrease to 0 at 81 m. The latter reading was obtained from a highly altered devitrifed, fumarolic zone, where vitric texture including pumice, is largely obliterated. Thus, it is likely that the reading is not representative of original numbers at this site. The recording of 0 pumice has been plotted in Fig. 5.1 but not included in the calculations for the reasons outlined above. As height increases pumice numbers rise again. Several metres below the top of the outcrop a contact was seen between two flow units (sheets 2 and 3 marked by the dotted line). Interestingly, numbers are greater in sheet 3 which is contrary to Yamazaki's (1974) view that pumice numbers increase immediately before a new flow unit. As might be expected no statistical trend can be calculated for this outcrop (r=0.01 [0.96]).

Twelve km NW of the Type Site is a 70 m cutting at the entrance to Ngamanawa. Pumice numbers rise from 15 at the base of the outcrop to 23 at 7 m, then fall to 16 at 19 m above base level. At the next two data points increases are recorded with a maximum of 33 pumice at 44 m. Numbers fall to 16 and then jump to 57 at the top of the flow. The correlation (r=0.66 [0.1]) and Fig. 5.1 suggest there is an overall increase in pumice numbers as height increases.

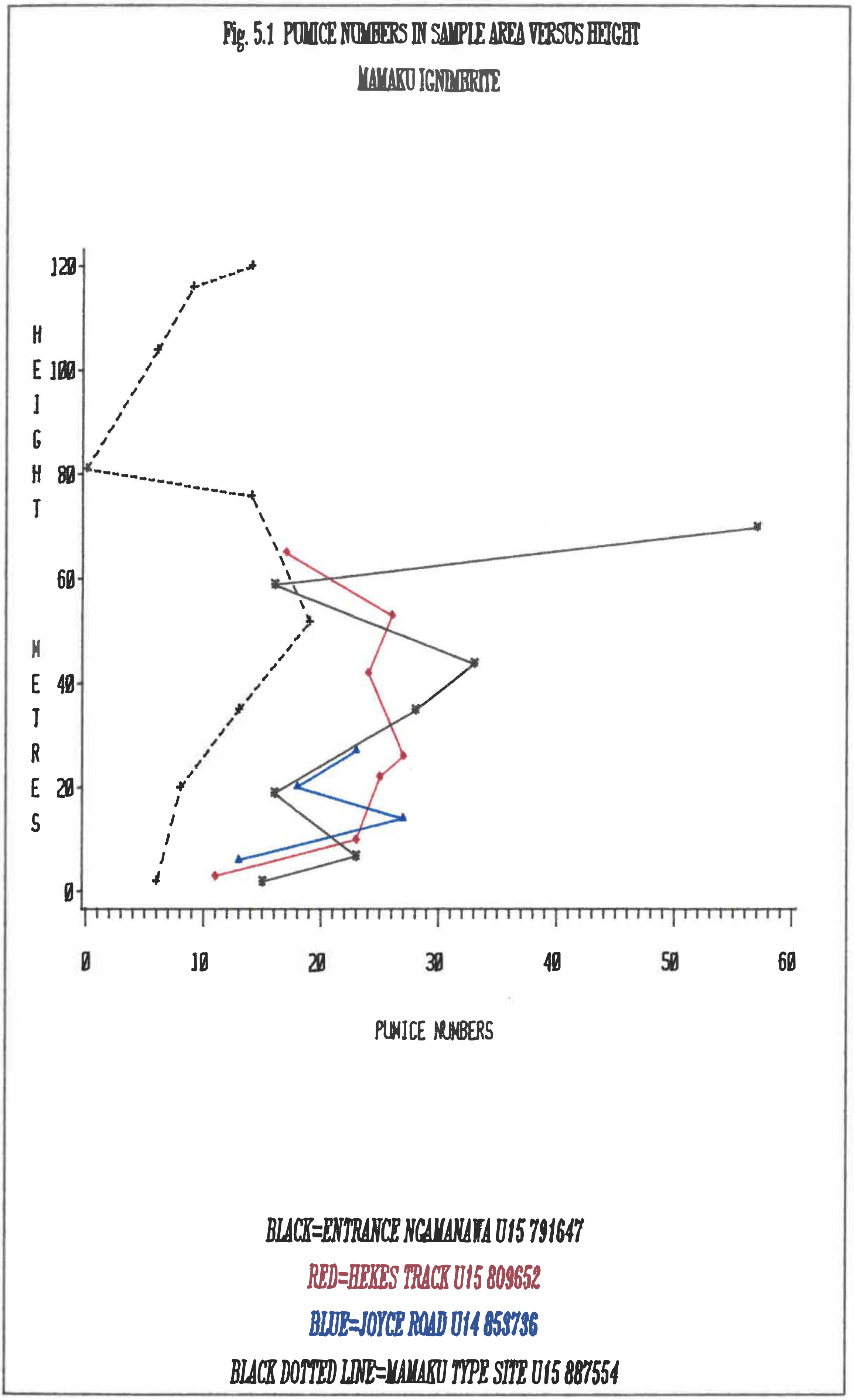


Fig. 5.1 PUMICE NUMBERS IN SAMPLE AREA VERSUS HEIGHT
MAMAKU IGNIMBRITE
HEIGHT METRES
0
20
40
60
80
100
120
0
10
20
30
40
50
60
PUMICE NUMBERS
BLACK=ENTRANCE NGAMANAWA U15 791647
RED=HEKES TRACK U15 809652
BLUE=JOYCE ROAD U14 853736
BLACK DOTTED LINE=MAMAKU TYPE SITE U15 887554

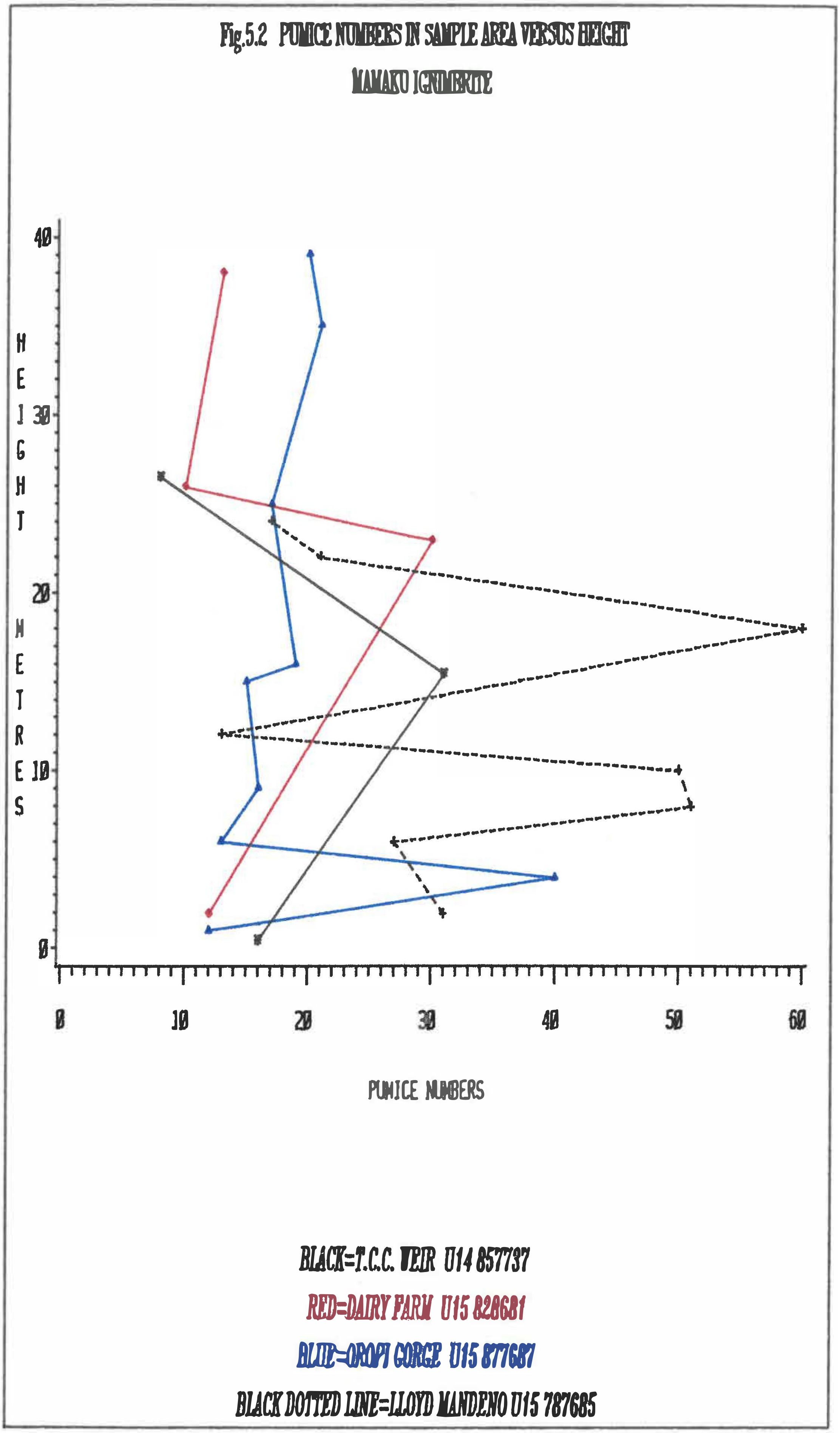


Fig.5.2 PUMICE NUMBERS IN SAMPLE AREA VERSUS HEIGHT
MAMAKU IGNIMBRITE
HEIGHT METRES
0
10
20
30
40
0
10
20
30
40
50
60
PUMICE NUMBERS
BLACK=T.C.C. WEIR U14 857737
RED=DAIRY FARM U15 820681
BLUE=OROPI GORGE U15 877687
BLACK DOTTED LINE=LLOYD MANDENO U15 787685

The Heke track column shows pumice numbers are highest in the middle part of the ignimbrite and decrease at the base and the top of outcrop. No correlation between height and numbers exists for this column (r=0.22 [0.63]).

Heke track is about 0.5 km NE of the Ngamanawa column, at the same altitude and with about the same amount of exposure. Visually and statistically (r=-0.16 [0.75]) there is little comparison between the Ngamanawa and Heke pumice numbers. This suggests there can be significant variation in a pyroclastic flow regime over a horizontal distance of 0.5 km.

Joyce Road is 29 km from source and 27 m thick (base not exposed). No trend can be detected, with numbers vacillating from a minimum of 13 at the base to a maximum of 27 at 14 m. Numbers reduce at the next site and increase again to 23 at 27 m. This latter site underlies by a few metres a surge zone which is interpreted as the front of an advancing flow unit. The surge separates sheet 2 from sheet 3, the latter is about 2 m thick, and in turn is overlain by sheet 4. Pumice numbers and percentages increase markedly (not shown on Fig. 5.1) in the 0.5 m before the crystal concentration zone in agreement with the model proposed by Yamazaki (1974).

The T.C.C Weir column (29.5 km from source and most northerly of the Mamaku Ignimbrite outcrops) has only three data points owing to lack of exposure. However, the basal site directly overlies the contact with the Waimakariri Ignimbrite (16 pumice counted). Site 2 is half way through a strongly welded columnar jointed zone (31 pumice) and the third site is at the top of the interfluve and directly underlies 4 m of tephra (8 pumice). Thus this relatively distal outcrop shows a minimum of numbers at the base followed by a maximum in the welded zone and a fall off in the upper part of the flow.

The Dairy Farm column (25 km from source) is one of the better exposures of Mamaku Ignimbrite in the lower Omanawa region. Eleven pumice were counted in the basal zone, followed by an increase to 23 in the lower middle zone, numbers reduce to 10 and rise to 13 in the upper middle and top of the outcrop respectively.

The Oropi Gorge column lies 2 km to the east of the eastern boundary of the study area and has complete exposure from a basal breccia to the heavily devitrifed top (24 km from source). Ignoring the two sites in sheet 1 (which was defined on the basis of the rapid rise in numbers, change in lithology and overlying surge deposit) minimum numbers (13) were counted at 6 m and maximum 21 at 35 m. The positive correlation (r=0.85 [0.02]) and visual inspection suggests there is an increase in numbers as height increases.

Table 5.1 Primary statistics from pumice numbers

	Number	Mean	Std Dev	Minimum	Maximum	km from source
Type Site	7	10.7	4.8	6	19	10
Ngamanawa	7	26.8	14.9	15	57	22
Hekes Track	6	21.8	5.7	11	27	22.5
Oropi Gorge	7	17.3	2.9	13	21	24
Lloyd Mandeno	8	33.8	17.6	12	60	28
Joyce Road	4	20.3	6.0	13	27	29

<u>Summary:</u> Table 5.1 summarizes statistics for selected columns. There is considerable variation in numbers of pumice, both within each column and when columns at various distance from source of the Mamaku Ignimbrite are compared. Only in two columns (Ngamanawa and Oropi Gorge) is there a statistical trend towards an increase in numbers with height. Note about 0.5 km E of Ngamanawa at Hekes Track no such

trend in numbers could be detected, and the two columns have marked differences in standard deviations which suggests a significant variation in the pyroclastic flow regime over relatively short distances. Reference to Table 5.1 demonstrates a lack of conclusive evidence for a reduction in mean numbers with increasing distance from source. This is attributed to fragmentation of the pumice during travel. Though if the type site and Lloyd Mandeno columns are ignored, there is a modest decrease in mean numbers. Similar minimum numbers were recorded for all columns except for the type site which has the least numbers. Maximum numbers were counted at the medial/distal Lloyd Mandeno column. Pumice numbers at first inspection seem distributed in a random manner in outcrop, though there is a tendency to concentrate in the middle of the flow.

Waimakariri Ignimbrite (Figs 5.3 and 5.4)

Carrs Track has a minimum value of 6 pumice 12 m above the base of the outcrop. This increases to 44 at 19 m. This site directly overlies a zone of vertical pipes of pumice which have been partially winnowed of fines. At the top of the flow, numbers return to approximately the values recorded in the lower parts of the flow.

Omanawa Falls has increases in pumice numbers in the basal and upper parts of outcrop with similar numbers (16, 17, 19) counted in the middle parts of the flow. This has resulted in a convex shape of the pumice to height profile.

The Lower Mangapapa column is an unusual outcrop in that the underlying Waiteariki Ignimbrite and Opuiaki Sediments have been step-faulted and the Waimakariri Ignimbrite has flowed over these deposits, the paleotopography of which varies considerably in relief. Thus, it is possible to examine a basal outcrop by the hydro station

Fig.5.3 PUMICE NUMBERS IN SAMPLE AREA VERSUS HEIGHT
WAIMAKARIRI IGNIMBRITE

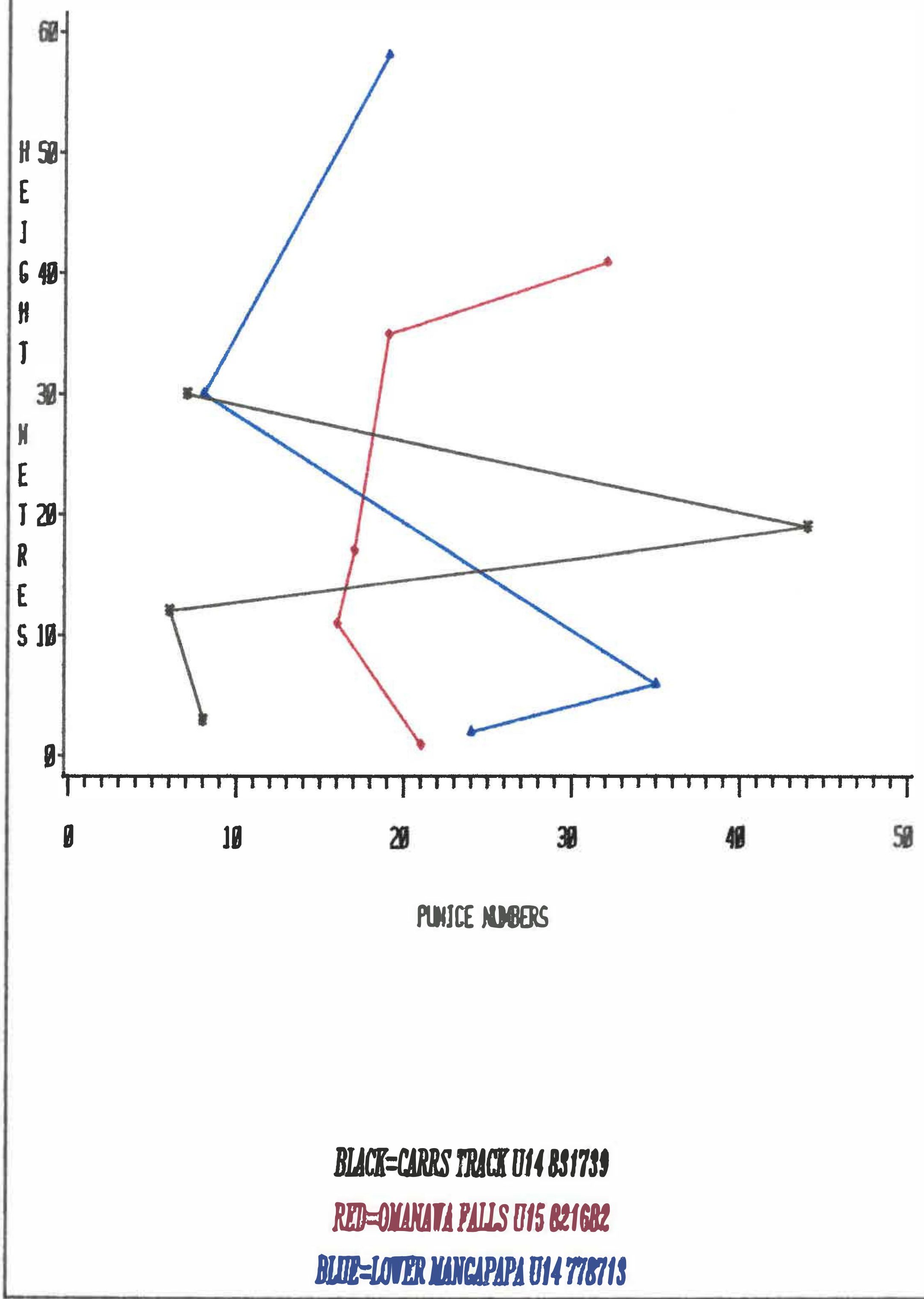
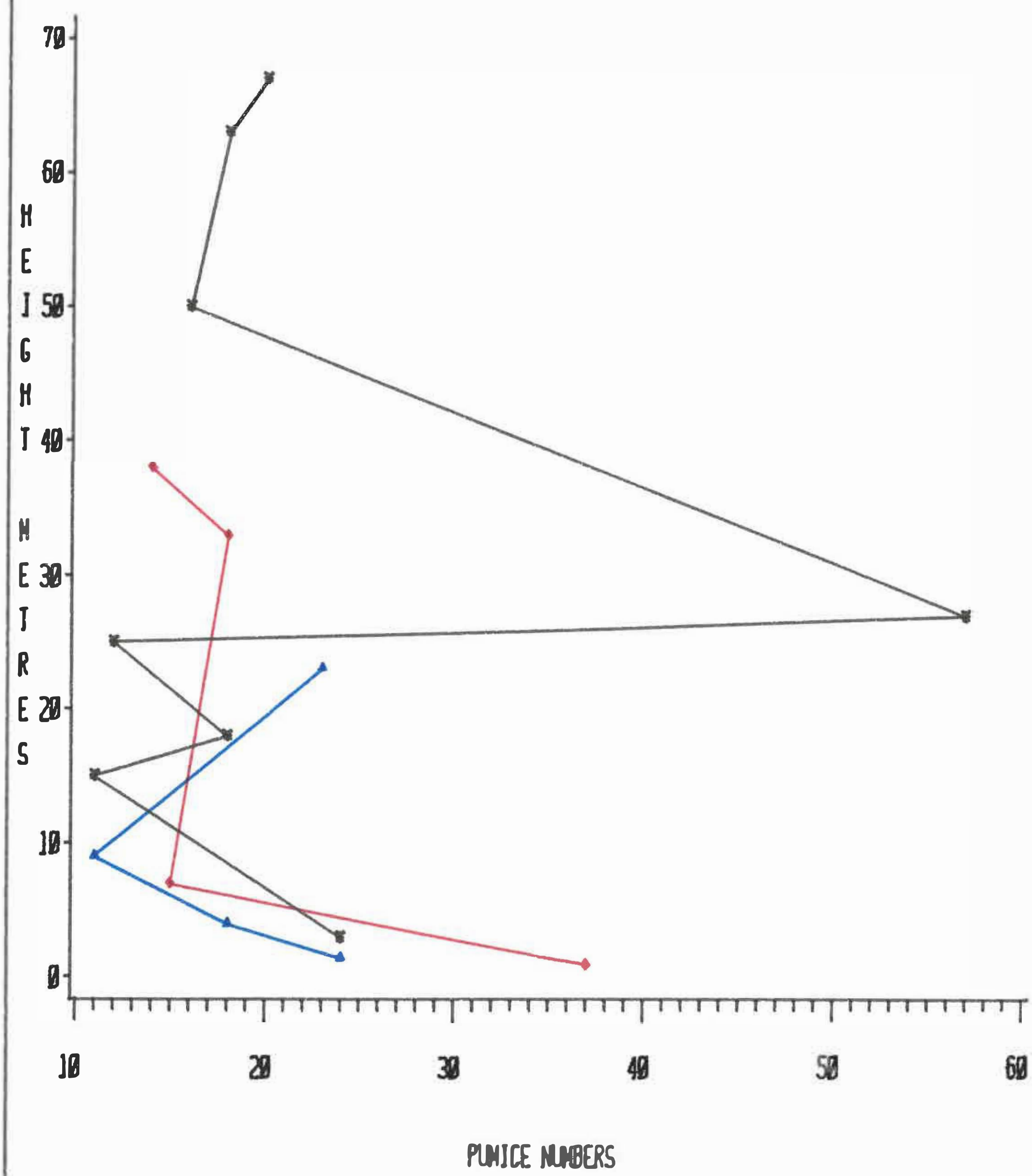


Fig. 5.4 PUMICE NUMBERS IN SAMPLE AREA VERSUS HEIGHT

WAIMAKARIRI IGNIMBRITE



BLACK=LLOYD MANDENO U15 786675

RED=SUN CLUB TRACK U14 827707

BLUE=RUAHIHI CANAL U14 783728

(moderately welded), climb 30 m and again examine basal Waimakariri. The sites described are representative of the base, lower middle, upper middle and top of the flow. This column shows a minimum of 8 pumice in the upper middle of the flow, with pumice numbers concentrating in the upper basal zone. Numbers are much the same at the base and top of the flow (24, 23 respectively).

Pumice numbers in the Lloyd Mandeno column generally range from 11 to 24 pumice but a marked peak of 57 can be seen at 27 m above base level. This is similar to the peak in the Carrs track column and a possible correlation is suggested between them.

For Ruahihi Canal, values of 24 and 23 were recorded at the bottom and top of the flow respectively with a minimum value of 11 counted in the middle of the flow. Table 5.2 summarizes statistics for selected columns.

Table 5.2 Primary statistics for pumice numbers

	Number	Mean	Std Dev	Minimum	Maximum
Carrs Track	4	16.2	18.5	6	44
Omanawa Falls	5	21	6.4	16	32
Lower Mangapapa	4	21.5	11.2	8	35
Lloyd Mandeno	8	22	14.7	11	57
Sun Club	4	21	10.8	14	37
Ruahihi Canal	4	19	5.9	11	24

Summary: Visual inspection suggests no correlation exists between height and numbers. However, if extreme values are removed from Figs 5.3 and 5.4 then concave shapes can be seen, that is numbers are greater at the base, fall slightly in the middle parts of the flow and rise again near the tops. This trend can be seen in the Omanawa Falls and Ruahihi Canal Columns and to some extent in the Sun Club and Lower

Mangapapa columns. The mean values for this ignimbrite are remarkably similar from column to column, but whether this is a coincidence or of significance is unclear.

Horizontal Distance: One section of the Waimakariri (Ruahihi Canal) and Mamaku (Tramway tunnel) Ignimbrites were examined over horizontal distances of 350 and 194 m respectively (Fig. 5.5). The objective was to see whether a significant variation in numbers existed with distance at the ignimbrites' respective outcrops. Visually this may seem to occur but this is more a function of scale rather than real variation. This is confirmed by reference to Table 5.3. Standard deviations are small and there is little range between maximum and minimum values. Thus, it is concluded that no significant variation in pumice numbers over distances of several hundred metres exists.

Table 5.3 Primary statistics pumice numbers

	Number	Mean	Std Dev	Minimum	Maximum
Ruahihi Canal	7	24	2.3	21	28
Tramway tunnel	6	4	1.2	3	6

5.3 PUMICE PERCENTAGES

Pumice percentages were estimated from the same sample area that pumice numbers were counted from, with the use of Andrews' (1982) chart. As with pumice numbers only sheet 2 is included in the calculations.

Mamaku Ignimbrite: (Figs 5.6 and 5.7)

The Type Site column shows a steady increase in percentages with height until 81 m where only occasional pumice clasts can be found and a reading of 0% was thought most appropriate. It has previously been mentioned that the area comprised a highly altered fumarolic zone and

Fig. 5.5 PUMICE NUMBERS IN SAMPLE AREA VERSUS HORIZONTAL DISTANCE

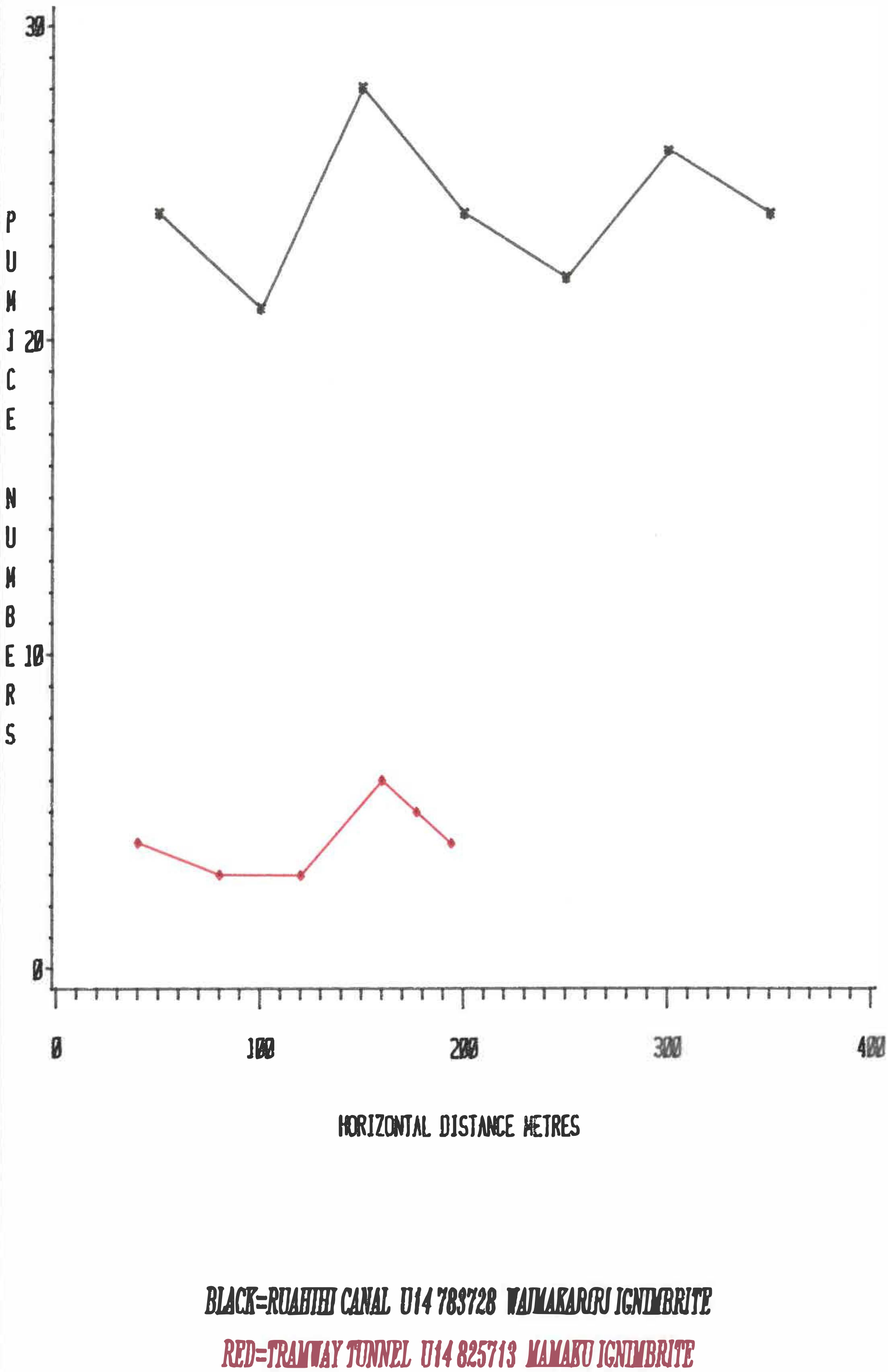
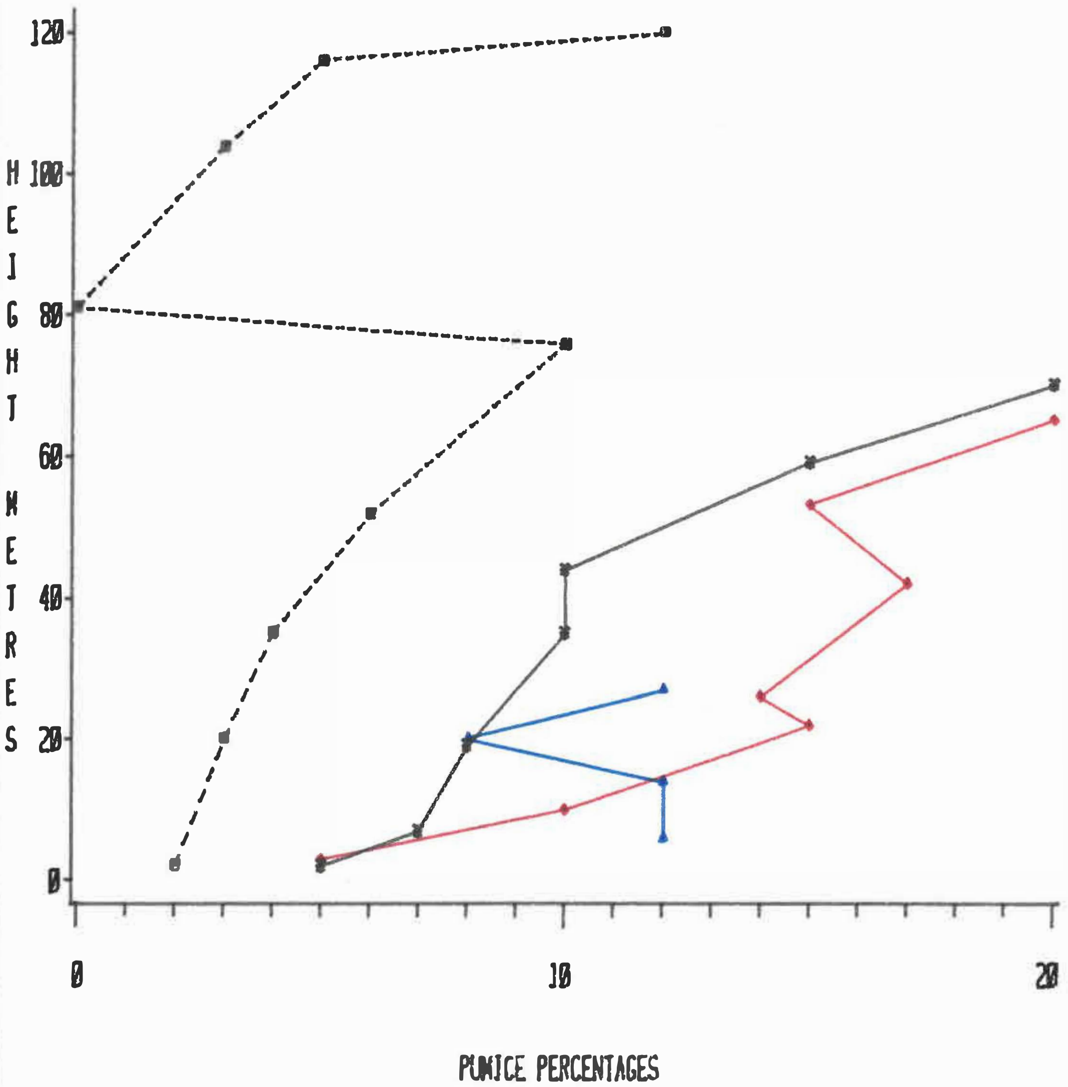


Fig. 5.6 PUMICE PERCENTAGES IN SAMPLE AREA VERSUS HEIGHT

MAMAKU IGNIMBRITE



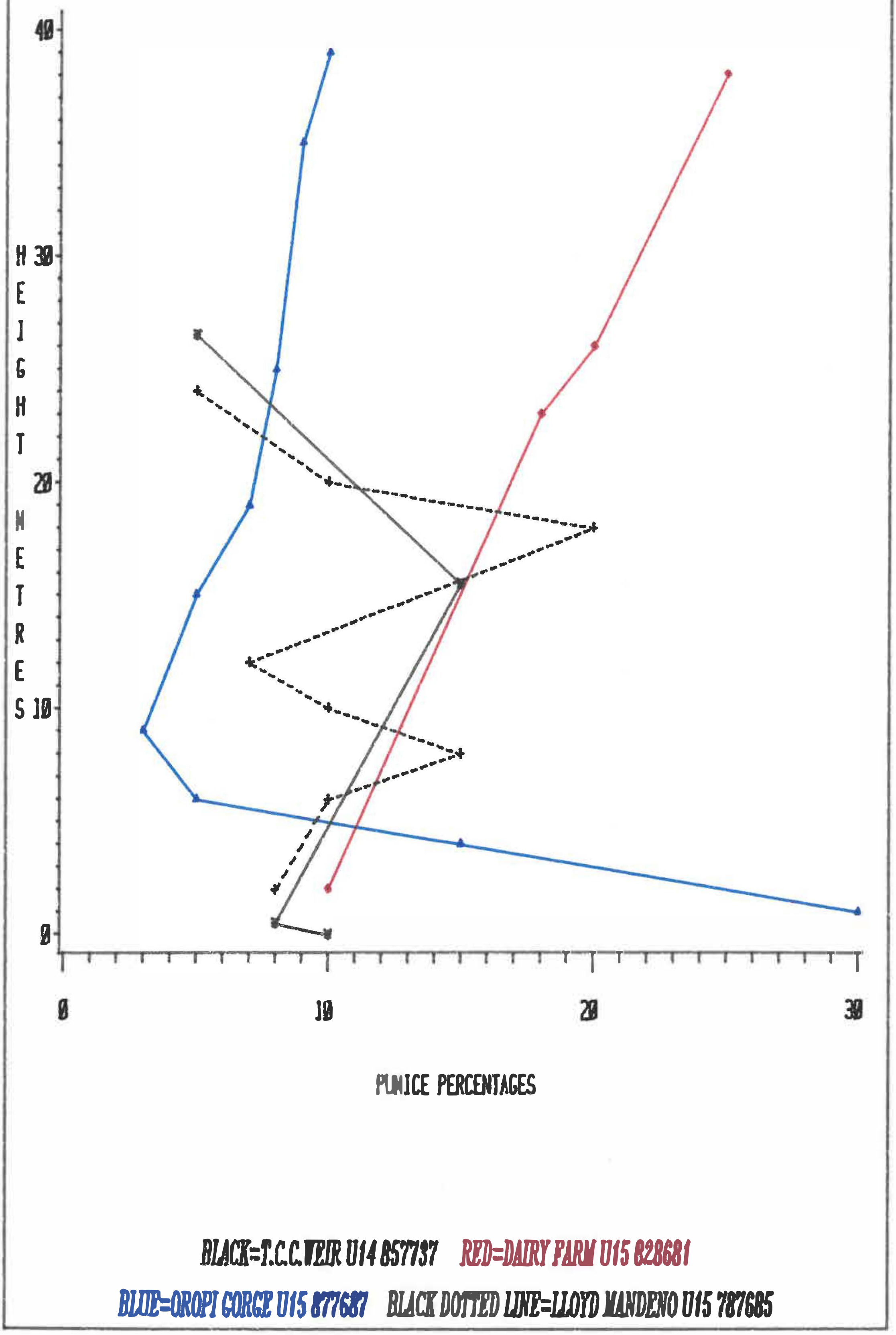
BLACK=ENTRANCE NGAMANAWA U15 791647

RED=HEKES TRACK U15 809652

BLUE=JOYCE ROAD U14 858736

BLACK DOTTED LINE=MAMAKU TYPE SITE U15 887554

Fig. 5.7 PUMICE PERCENTAGES IN SAMPLE AREA VERSUS HEIGHT
MAMAKU IGNIMBRITE



this reading is not thought a real reflection of original conditions (note sheet 3 and the reading of 0% in the fumarolic zone are not included in calculations). Percentages increase from this zone. Note the increase from 5 to 12% from sheet 2 to sheet 3.

The Ngamanawa and Heke columns both show a steady trend of an increase in percentages as height increases, supported by correlations of (r=0.94 [0.001]) and (r=0.88 [0.009]), respectively. Interestingly although the Heke column showed a decrease in pumice numbers (Fig. 5.1) pumice percentages increased which illustrates that pumice numbers and percentages are not necessarily correlated.

At the distal Joyce Road column there is an identical recording of 12% at all sites apart from a decrease to 8% at 20 m. This is interpreted as a waning in velocity and density of the flow, with pumice not being buoyed to the top of the flow as in the medial/proximal sites.

At Oropi Gorge (Fig. 5.7) maximum percentages are concentrated at the base in sheet 1 (not used in calculations) and then decrease markedly to to a minimum of 3% at 9 m in sheet 2. Percentages then start to increase slowly as the top of the outcrop is approached. Note the flow in sheet 2 was sufficiently dense to buoy smaller and medium sized pumice, giving a positive slope to the curve in sheet 2, (r=0.93 [0.001]).

An almost perfect linear relationship exists at the Dairy Farm column and this is reflected in the strong correlation of r=0.99 (0.001). The Lloyd Mandeno column is quite variable in pumice percentages and no trend is apparent. A maximum of 20% was recorded at 18 m, while the minimum of 5% is seen at the top of the flow. This is at variance with other Mamaku outcrops.

The T.C.C Weir column has a maximum of 15% half-way through the deposit, dropping to 5% at the top of the flow. Only marginal changes in percentages can be seen between the basal contact zone and a strongly welded columnar jointed zone.

Table 5.4 Primary statistics from pumice percentages

	Number	Mean	Std Dev	Minimum	Maximum
Type Site	7	4.7	2.7	2	10
Ngamanawa	7	10.7	5.1	5	20
Hekes Track	7	13.7	4.9	5	20
Lloyd Mandeno	8	12.5	7.5	2	24
Joyce Road	4	16.7	8.9	6	27
Oropi Gorge	7	6.7	2.5	3	10

<u>Summary:</u> Table 5.4 contains the statistics for pumice percentages in the Mamaku Ignimbrite. Three medial columns (Ngamanawa, Hekes and Dairy Farm) showed statistically significant increases in pumice percentages with increases with height. The proximal column (Type Site) also showed an increase in pumice percentages though the relationship is not as strong as for the medial columns. However, this column had been severely altered by fumarolic activity in its upper middle zone and the decrease in percentages in this zone is not real, as occasionally pumice can be found even in the most strongly altered zone. At the distal sites, T.C.C Weir and Joyce Road there is little variation in percentages. Oropi Gorge, a medial/distal Mamaku column, both statistically and visually has a trend of an increase in pumice percentages as height increases (for sheet 2). It is suggested from this that the Mamkau Ignimbrite was dense with particles (pumice) of lighter density floating to the top of the flow. If the flow had been turbulent this stratification would be unlikely to have occurred; thus, it is argued that the Mamaku Ignimbrite was a relatively dense,

concentrated laminar flow in proximal, reaches. However, there are exceptions to this which are discussed in Chapter 6. This study, therefore, supports the work of Sparks (1979) who notes that reverse grading of pumice is common and is contrary to that of Sparks *et al.* (1973) who comment that the absence of grading is equally common.

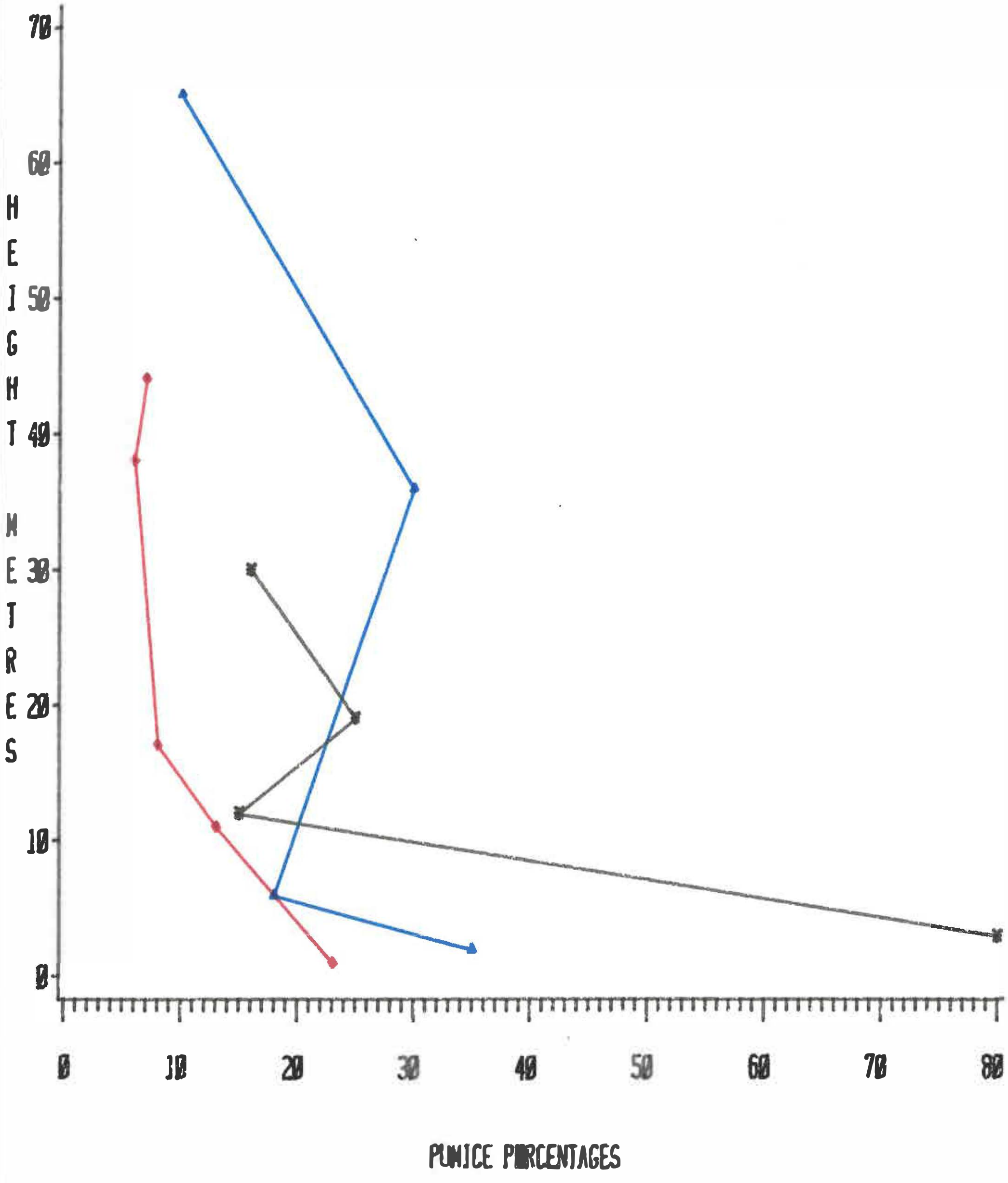
Waimakariri Ignimbrite (Figs 5.8 and 5.9)

The Carrs Track column has 80% pumice at the base which was the maximum recorded for any ignimbrite in the study area. Twelve metres up the column this falls to 15%, increases to 25% at 19 m and falls to 16% at the top of the outcrop. This can be attributed to either the flow being strongly fluidised implying an expanded flow which cannot support larger particles, or the flow approaching its distal reaches losing speed, heat and fluidizing gas, is unable to support larger clasts and preferentially dumps pumice by gravity settling during flowage. Vertical gas escape pipes and petrologic evidence (see section 4.3.2) suggests there was winnowing of fines at this column (surface water from the paleo sedimentary system which the ignimbrite overlies, may have contributed to the available gas supply). Both lines of evidence imply the flow was gas charged during and after deposition The second hypothesis is preferred although a combination of both is possible.

The curve for Omanawa Falls has a mild negative slope, i.e., percentages fall from 23% at the base of outcrop to 13% in the upper basal region, decrease to 8%, further to 6% and then rise marginally to 7%. There is a reasonable negative correlation between height and numbers (r=-0.75 [0.07]).

Fig. 5.8 PUMICE PERCENTAGES IN SAMPLE AREA VERSUS HEIGHT

WAIMAKARIRI IGNIMBRITE



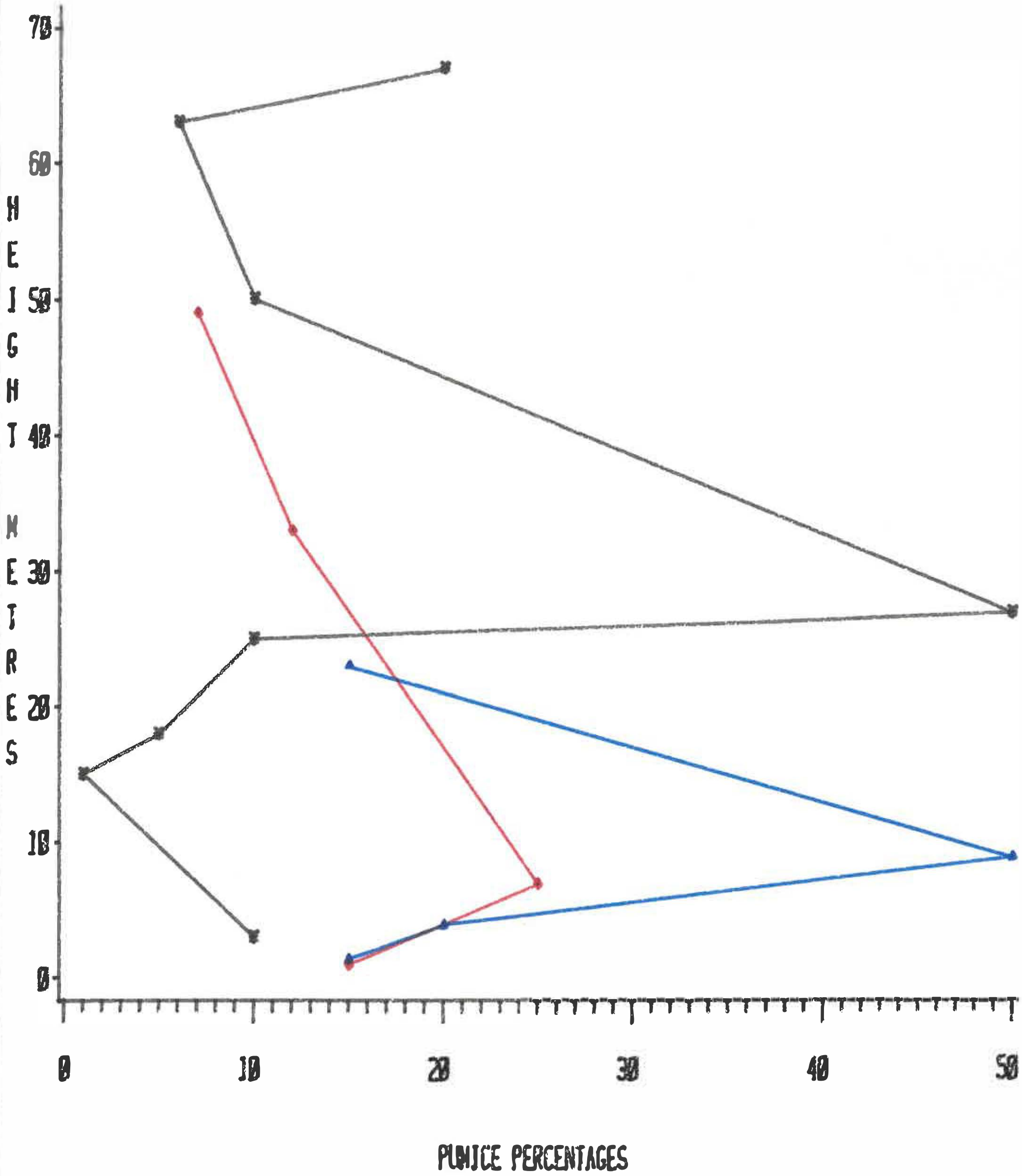
BLACK=CARRS TRACK U14 831739

RED=OMANAWA FALLS U15 821682

BLUE=LOWER MANGAPAPA U14 778713

Fig. 5.9 PUMICE PERCENTAGES IN SAMPLE AREA VERSUS HEIGHT

WAIMAKARIRI IGNIMBRITE



BLACK=LLOYD MANDENO U15 787685

RED=SUN CLUB TRACK U14 827707

BLUE=RUAHIHI CANAL U14 783727

The Lower Mangapapa column shows marked fluctuations between 35% and 10% with no discernible trend. If the pumice concentration zone (57% pumice at 37 m) is regarded as an aberration it could be argued that this column has a mildly concave shape.

The Sun Club column generally shows a decrease in pumice as height increases. Percentages rise from 15 to 20%, 7 m above base. Near the top of the outcrop percentages have fallen to 12% and decrease again to 7% at the top.

Maximum percentages were recorded in the lower middle of the flow 9 m above base level (50% pumice) at Ruahihi Canal (Fig. 5.9). Identical percentages are recorded at the top and bottom of the flow.

Table 5.5 Primary statistics for pumice percentages

	Number	Mean	Std Dev	Minimum	Maximum
Omanawa Falls	5	11	7	6	23
Lower Mangapapa	4	23	11.3	10	35
Lloyd Mandeno	5	24	19.1	11	25
Sun Club	4	14	8.3	5	25
Carrs Track	4	34	31	15	80
Ruahihi Canal	4	25	16.8	15	50

<u>Summary:</u> Table 5.5 contains the statistics for pumice percentages in the Waimakariri Ignimbrite. Two trends can be seen for pumice percentages in the Waimakariri Ignimbrite. Firstly, pumice tends to concentrate in basal sections (an exception is the Lloyd Mandeno column). This is the reverse to that found in the Mamaku Ignimbrite. In Table 5.6 the columns have been grouped in order of distance from an inferred source to the S, possibly the Rotorua Caldera. Examining means, it could be argued there is a mild trend towards an increase in pumice percentages with distance from source, possibly due to

winnowing of fines during flowage. However the high standard deviation associated with the means may make such a hypothesis of debatable worth. The lack of a increase in pumice with height suggests the Waimakariri Ignimbrite was not as dense a flow as the Mamaku Ignimbrite.

Horizontal Pumice Percentages: Fig. 5.10 illustrates the variation in pumice percentages of the Waimakariri and Mamaku ignimbrites over horizontal distances of several hundred meters at the Ruahihi and Tramway sections. Both are distal outcrops. The Waimakariri percentages vary from 7 to 18% at Ruahihi with the majority clustering between 7 and 9%. The Mamaku column at the Tramway tunnel fluctuates from 1% to 5% though it is dominantly 1%. It is considered that no significant variation in pumice percentages exists over short distances in either ignimbrite and that moderate variations from the mean are as expected. Table 5.6 describes the primary statistics for these columns.

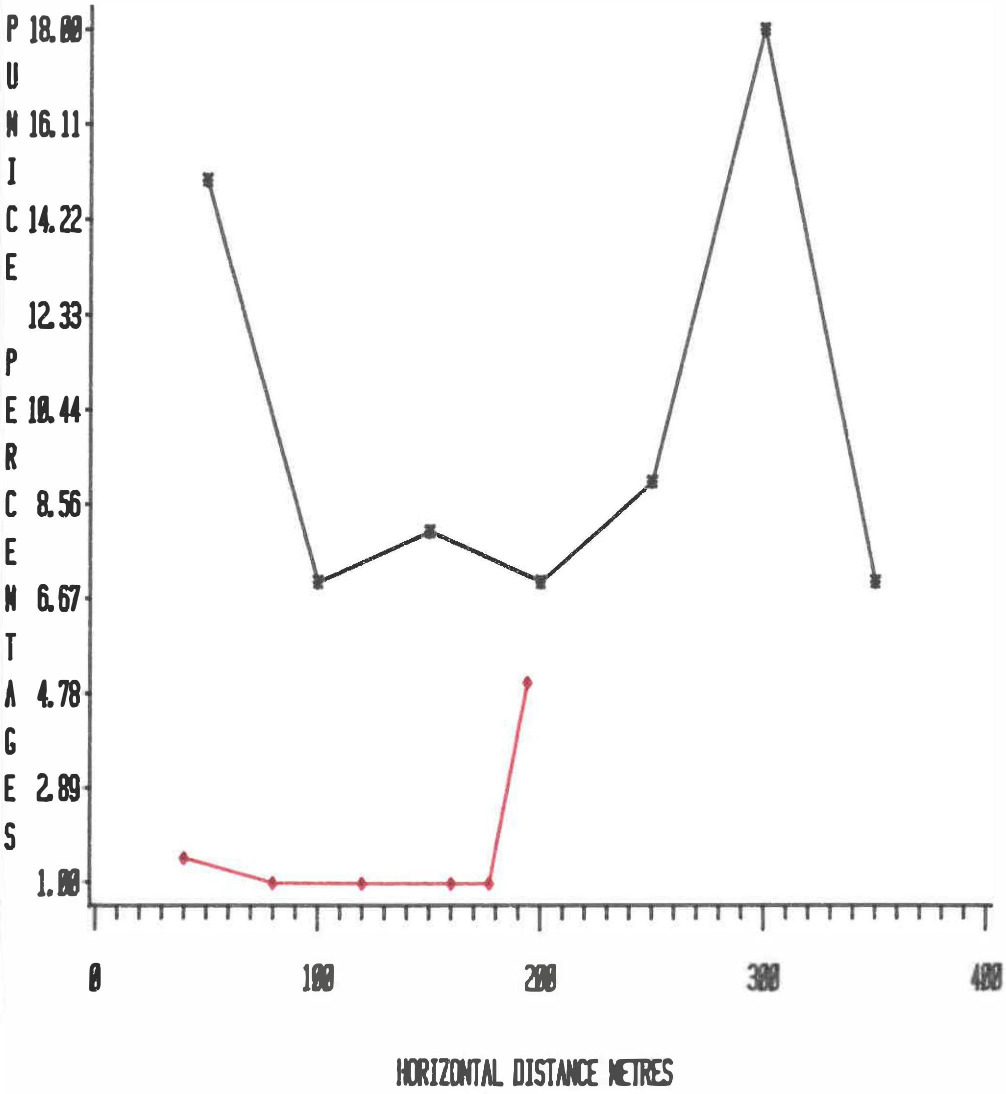
Table 5.6 Primary statistics for pumice percentages

	Number	Mean	Std Dev	Minimum	Maximum
Ruahihi Canal	7	10.4	4.5	7	18
Tramway Tunnel	6	1.7	1.6	1	5

5.4 AVERAGE AND MAXIMUM PUMICE LENGTHS

Introduction: The following discussion examines variations of maximum and average pumice lengths with respect to height. Approximately 10 pumice lengths were measured from the same sample area as numbers and percentages. The maximum pumice length was taken from the general area of the site and not necessarily from the sample area. Maximum pumice lengths represent extremes and probably deserve less emphasis in the discussion than average lengths. Only sheet 2 for the Mamaku

Fig. 5.10 PUMICE PERCENTAGES IN SAMPLE AREA VERSUS HORIZONTAL DISTANCE



RED=RUAHIHI CANAL U14 703728 WAIMAKARIRU IGNIMBRITE

BLACK=TRAMWAY TUNNEL U14 025713 MAMAKU IGNIMBRITE

Ignimbrite is included in calculations.

Mamaku Ignimbrite (Figs 5.11 and 5.12)

At the Mamaku type site there is a steady increase in mean length (with one exception at 20 m) from 1.2 cm at the base to 3.1 cm at 76 m. Lengths drop to 0.5 cm at 104 m (readings are not possible from the fumarolic zone) and again begin to increase to a mean length of 3.1 cm at the top of the flow. No significant correlation can be calculated. Maximum size tends to mirror mean length though variations are more extreme.

The Ngamanawa column shows a general trend towards a decrease in average length up the outcrop. This is reflected in a strong negative correlation (r=-0.83 [0.02]). Maximum length is subject to much greater variation than average length.

Hekes Track shows a mean length of 1 cm at the base with size gradually increasing apart from two fluctuations at 26 and 53 m, to 3.3 cm at the top of the outcrop. Apart from these exceptions a trend towards pumice lengths increasing with height can be discerned. The correlation confirms this (r=0.92 [0.02]).

The Joyce Road column shows a general decrease in mean pumice lengths with increase in height (1.5 cm at base, 0.5 cm top of outcrop) with one fluctuation at 27 m. This is confirmed by a good negative correlation of (r=-0.73 [0.16]). Maximum length reflects the trend shown by average size though it has a stronger correlation (r=-0.84 [0.07]).

The three data points for the T.C.C Weir column suggest there is a decrease in pumice size with increase in height. At the base of the outcrop 3 cm was recorded, 15 m further up 1.3 cm and at the top

Fig. 5.11 AVERAGE AND MAXIMUM PUMICE LENGTHS VERSUS HEIGHT
MAMAKU IGNIMBRITE

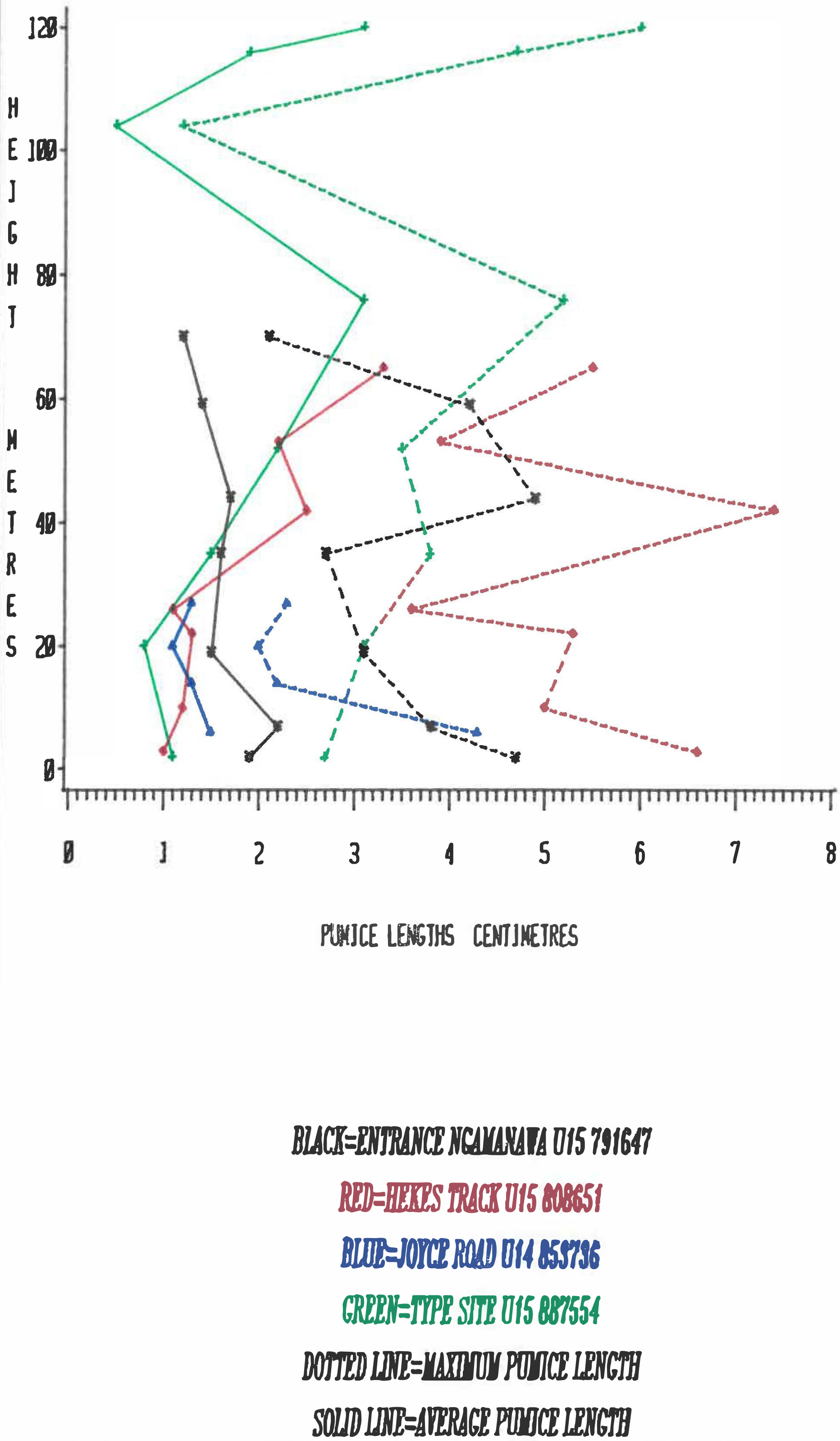
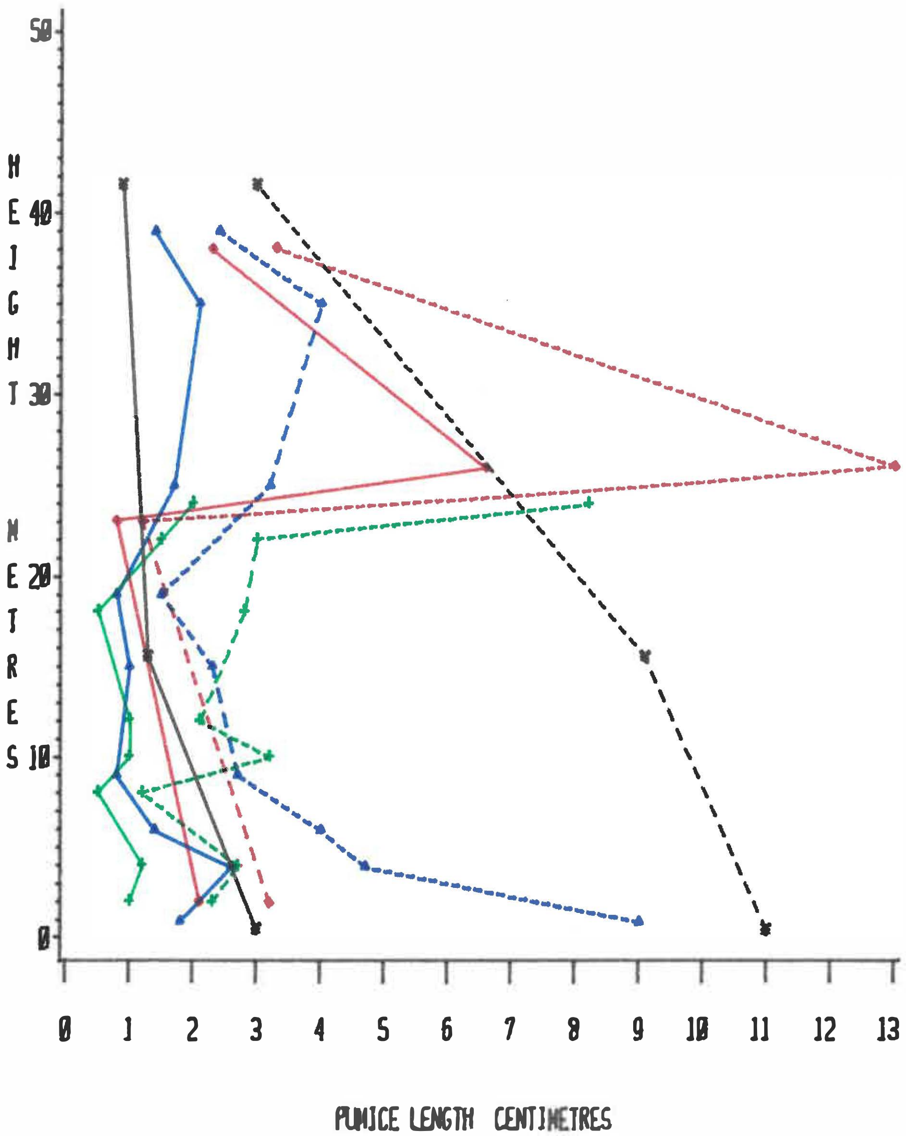


Fig. 5.12 AVERAGE AND MAXIMUM PUMICE LENGTHS VERSUS HEIGHT

MAMAKU IGNIMBRITE



BLACK=T.C.C. WEIR U14 859739   RED=DAIRY FARM U15 826672

BLUE= OROPI GORGE U15 877687   GREEN=LLOYD MANDENO U15 787685;

BLACK DOTTED LINE=MAXIMUM PUMICE LENGTH. SOLID LINE=AVERAGE PUMICE LENGTH

0.9 cm. Maximum length has more pronounced variations but follows the pattern set by mean size.

Pumice lengths are variable for the Dairy Farm column both for average and maximum size, and no conclusion is reached for this outcrop. There are minor increases in average pumice length with height in the Oropi Gorge column, a minimum of 0.8 cm being recorded at the base and 1.4 cm at the top of the flow. This is reflected in the moderate correlation (r=-0.56 [0.15]). Maximum pumice length steadily decreases as height increases until 20 m above base (9.0 to 1.5 cm). Thereafter, maximum length rises slightly at 25 and 35 m respectively and then falls at the top of the flow. This suggests the flow was sufficiently dense to buoy smaller clasts and larger clasts though larger clasts were only just able to be supported. This inference may be contrasted with the more distal Joyce Road findings of a decrease in length with height.

Table 5.7 Primary statistics for mean pumice lengths

	Number	Mean	Std Dev	Minimum	Maximum
Type Site	7	1.58	0.89	0.5	3.1
Ngamanawa	7	1.64	0.33	1.2	2.2
Hekes Track	7	1.8	0.87	1.0	3.3
Lloyd Mandeno	8	1.14	0.49	0.5	2.0
Oropi Gorge	7	1.31	0.48	0.8	2.1
Joyce Road	4	1.3	0.16	1.1	1.5

<u>Summary:</u> Primary statistics are presented in Table 5.7. An argument exists for an increase in pumice size as height increases for proximal, medial and medial/distal columns, though this hypothesis is not supported by the Ngamanawa and Joyce Road columns. It is suggested this is best explained by the pyroclastic flow having a greater density than pumice which 'float' to the top. The same

explanation was presented to explain the trend in pumice percentages.

Various authors report a decrease in the size of pumice clasts with distance from the vent (e.g., Walker, *et al.*, 1981; Briggs, 1976a; Wright, 1981). The means of Table 5.7 for the Mamaku Ignimbrite show moderate agreement with the above authors. The decrease in standard deviations show less variation of pumice lengths with distance from source. Note the exception of Hekes Track and Oropi Gorge.

<u>Waimakariri Ignimbrite</u> (Figs 5.13 and 5.14)

Average size at Carrs Track shows a trend towards a mild concave shape. As height increases, mean size falls from 3.2 cm to 1.3 cm, falls again to 1.1 cm and at the top of the outcrop rises to 2.7 cm. This lack of linearity is reflected in a very low correlation (r=-0.16 [0.84]). Maximum size follows the trend shown by mean size. Note the largest pumice seen in the Waimakariri (27 cm) was measured at the base of this column. It is inferred that the flow must have been quite dense to transport a pumice clast of this size, though by the time the flow reached this location it was beginning to lose competence and larger debris were settling out. Further, the angularity of the clast suggests only minimal abrasion and contact with other material, implying a laminar flow regime, though most pumice are rounded.

At Omanawa Falls there is a moderate decrease in average pumice lengths as height increases, (r=-0.68 [0.24]). However, this is not true for maximum size where a convex shape to the plot is revealed.

Fig. 5.13 AVERAGE AND MAXIMUM PUMICE LENGTH VERSUS HEIGHT
WAIMAKARIRI IGNIMBRITE

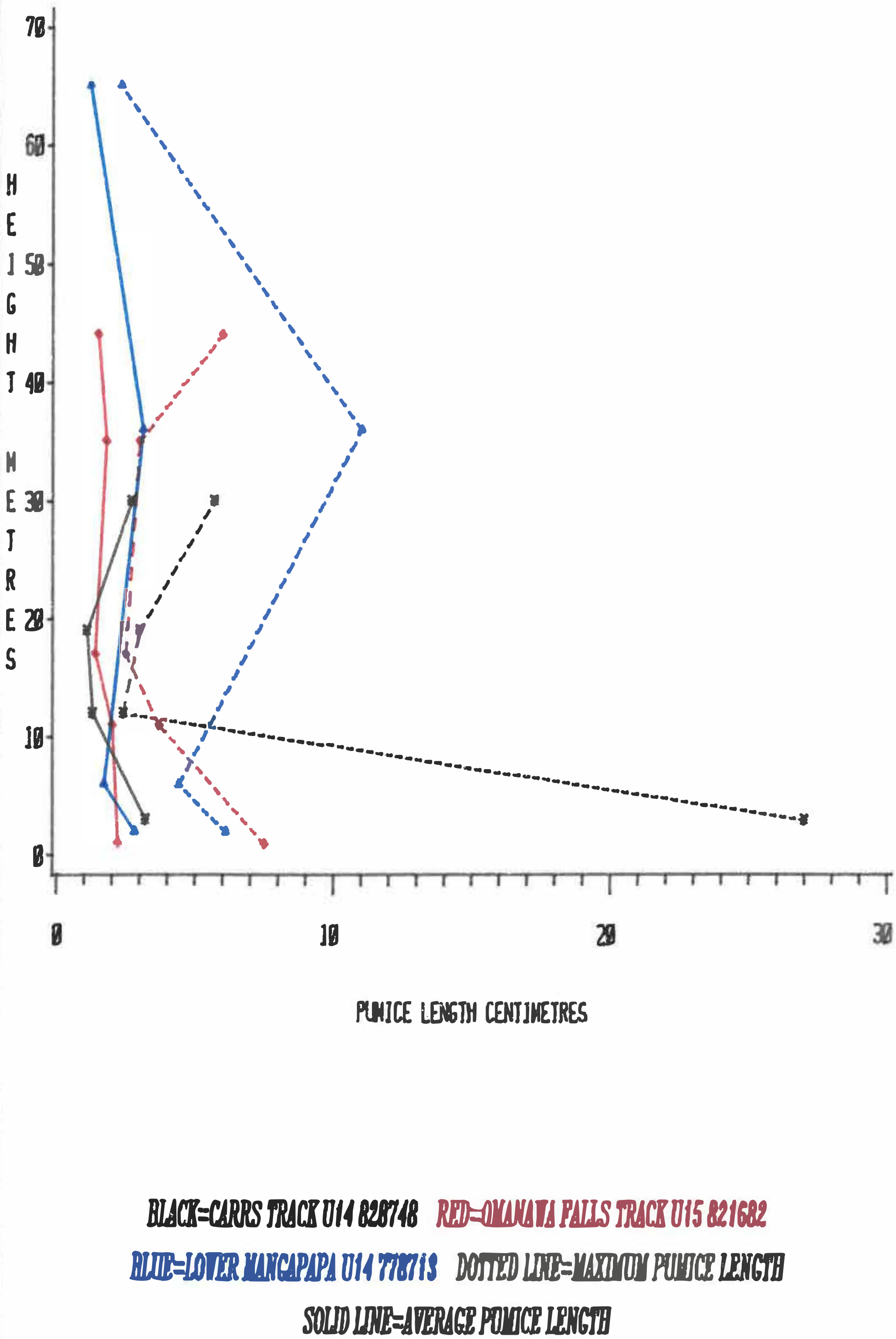
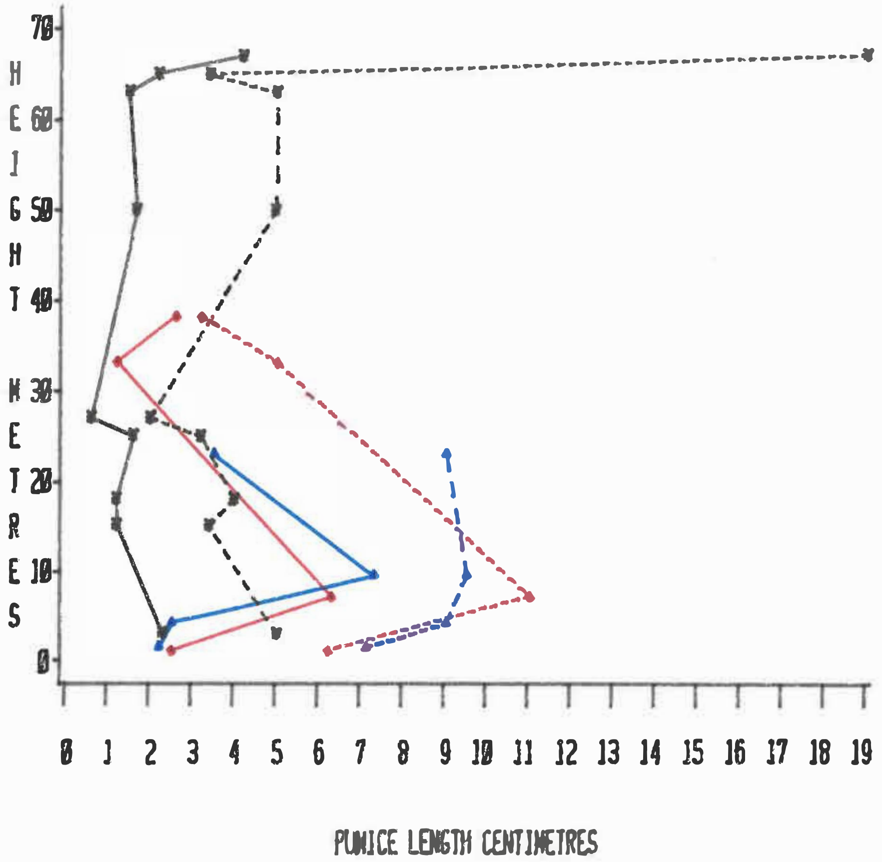


Fig. 5.14 AVERAGE AND MAXIMUM PUMICE LENGTHS VERSUS HEIGHT
WAIMAKARIRI IGNIMBRITE



BLACK=LLOYD MANDENO U15 787685

RED=SUN CLUB TRACK U14 827707

BLUE=RUAHIHI CANAL U14 783727

DOTTED LINE=MAXIMUM PUMICE SIZE

SOLID LINES=AVERAGE PUMICE SIZE

At the Lower Mangapapa column pumice lengths decrease slightly from the basal incipiently welded zone to the moderately welded zone, a distance of 6 m. Mean size rises at the next outcrop to 3.1 cm and falls to 1.2 cm near the top of the flow. No simple correlation between height and length exists. Maximum size mirrors the trend shown for mean size with a maximum peak of 11 cm, 30 m above base level in approximately the middle of the flow.

No particular trend in mean pumice length can be seen for the Lloyd Mandeno column. Values range from a minimum of 0.6 cm at 27m to 4.2 cm at the top of the flow. However, the more common lengths are 1.2 to 2.3 cm. Maximum size mirrors mean size, apart from a large jump to 19 cm at the top of the flow.

Largest mean length (6.3 cm) at the Sun Club column is found 7 m above base level. Size falls to 1.2 cm, 5 m below the top of the flow and rises to 2.6 cm at the top. As the Mamaku Ignimbrite does not overly the Waimakariri at this site, but does at adjacent areas, it is suspected that the non-welded to incipiently welded top has been eroded.

Table 5.8 Primary statistics for mean pumice sizes

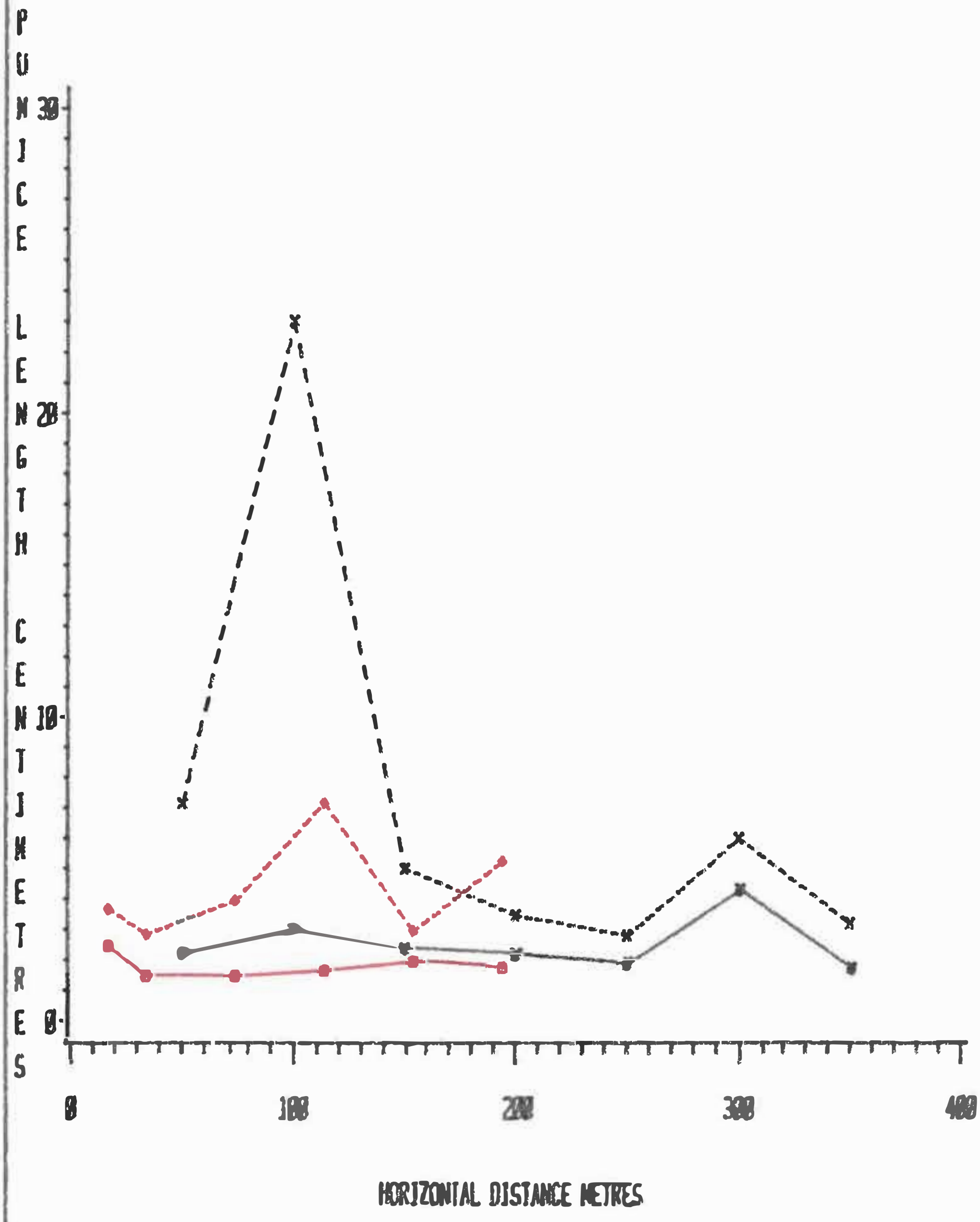
	Number	Mean	Std Dev	Minimum	Maximum
Omanawa Falls	5	1.7	0.33	1.4	2.2
Lower Mangapapa	4	2.2	0.9	1.2	3.2
Lloyd Mandeno	9	1.8	1.0	0.6	4.2
Sun Club	4	3.1	2.2	1.2	6.3
Ruahihi Canal	4	3.8	2.3	2.2	7.3
Carrs Track	4	2.1	1.0	1.1	3.2

The vertical column at Ruahihi Canal shows average length versus height to have a concave shape caused by the jump to 7.3 cm at 9.5 m, falling to 3.5 cm near the top. Maximum size follows this trend, though changes are not as marked as for mean size.

Summary: Table 5.8 summarizes statistics for pumice lengths. The more proximal sites (Omanawa, Lower Mangapapa and Lloyd Mandeno) demonstrated that mean lengths varied by only small amounts over vertical distances. Those in distal regions such as Ruahihi, Sun Club or Carrs track have concave shapes with larger pumice tending to concentrate in the lower middle to base of the flow. The average of the mean pumice lengths of each column (Table 5.8) was found not to fall over distance. In fact, lengths increase with distance from source. This is the converse, compared with findings for the Mamaku Ignimbrite. However, sample sizes are small for the Waimakariri Ignimbrite.

From Fig. 5.15 it can be seen there is no significant variation in average pumice size for either the Ruahihi or Tramway sections over a horizontal distance of several hundred metres. The small standard deviations of 0.88 and 0.38 for the Ruahihi and Tramway columns, respectively, support this view (Table 5.9). Maximum size follows the same pattern set by mean size apart from a jump to 23 cm at 100 m for Ruahihi and 7.2 cm at 114 m for Tramway Tunnel.

Fig. 5.15 AVERAGE AND MAXIMUM PUMICE LENGTHS VERSUS HORIZONTAL DISTANCE



BLACK=RUAHIHI CANAL U14 783728 WAIMAKARIRI IGNIMBRITE

RED=TRAMWAY TUNNEL U14 825713 MAMAKU IGNIMBRITE

DOTTED LINES=MAXIMUM PUMICE LENGTH

Table 5.9 Primary statistics for average pumice size

	Number	Mean	Std Dev	Minimum	Maximum
Ruahihi Canal	7	2.5	0.88	1.7	4.3
Tramway Tunnel	6	1.8	0.38	1.5	2.5

5.5 WELDING

Introduction: The degree of welding was estimated with the use of a PT Schmidt hammer. This test is related to the elastic rebound properties of construction materials giving an indication of the extent of bonding between grains, rather than a measure of strength (Attewell and Farmer, 1976), and is ideal for obtaining an index value of welding (see Chapter 2).

Discussion: From Boyd's (1961) calculations it seems that pyroclastic flows may lose little heat during travel. They are probably emplaced at near magmatic temperatures, though this depends on the thickness of the flow, height of the eruption column etc. Such a heat conserving mechanism causes marked zonal variations in an ignimbrite due, at least in part to welding.

Rhyolitic tuffs are derived from magmas with an initial temperature not greater than 1000°C and probably below 900°C (Ross and Smith 1961) and this is inferred to be similar for the Mamaku and Waimakariri Ignimbrites.

Smith (1960b) defines welding as "that process which promotes the union or cohesion of glassy fragments". He recognises three zones of welding based on progressive loss of pore space and deformation of shards and pumice. These are: (1) the zone of no welding. (2) the zone of partial welding, which ranges from incipient welding to that which has lost virtually all its pore space. (3) the zone of dense welding which ideally has lost all its pore space. Complete welding may form a black obsidian in which vitric structure may be difficult to detect.

During field examination it was felt that more than three zones of welding could be recognised. Consequently the following classification was used to relate welding to PT Schmidt hammer readings (Table 5.10).

Table 5.10

Degree of welding	PT Schmidt hammer readings	Smith (1960b)
Non	<20	(1)
Incipiently	20-45	
Partially	45-65	(2)
Moderately	65-85	
Strongly	85-110	
Densely	>110	(3)

Experimental evidence suggests that welding may commence at about 600°C if water vapour is present, though temperatures up to 900°C may be required for less hydrous flows (Boyds. 1961; Ross and Smith, 1961; Riehle, 1973). Fisher and Schmincke (1984), in discussing empirical evidence for welding, summarised the following two authors' work: Allen and Zies (1922) found temperatures up to 645C in fumaroles of pyroclastic deposits in the valley of Ten Thousand Smokes Alaska seven years after emplacement; Banks and Hoblitt (1981) at Mt St Helens found emplacement temperatures were 850 to 750°C near the vent and 300 to 730°C further away. Later deposits were found to be emplaced at hotter temperatures than earlier deposits.

From remnant magnetism experiments Zlotnicki *et al.* (1984) inferred temperatures of 350°C, 400°C and 530°C for assorted pyroclastic deposits of Guadeloupe, French West Indies. However, Zlotnicki does not mention the degree of welding of these deposits and it is assumed they are unwelded. The presence of charred wood indicates setting temperatures above 200°C (Maury *et al.*, 1973; in Zlotnicki *et al.*, 1984). This suggests the emplacement temperatures at the Ruahihi Canal for the Waimakariri Ignimbrite must have exceeded 200°C owing to the charcoal fragments and carbonised tree moulds present in this outcrop.

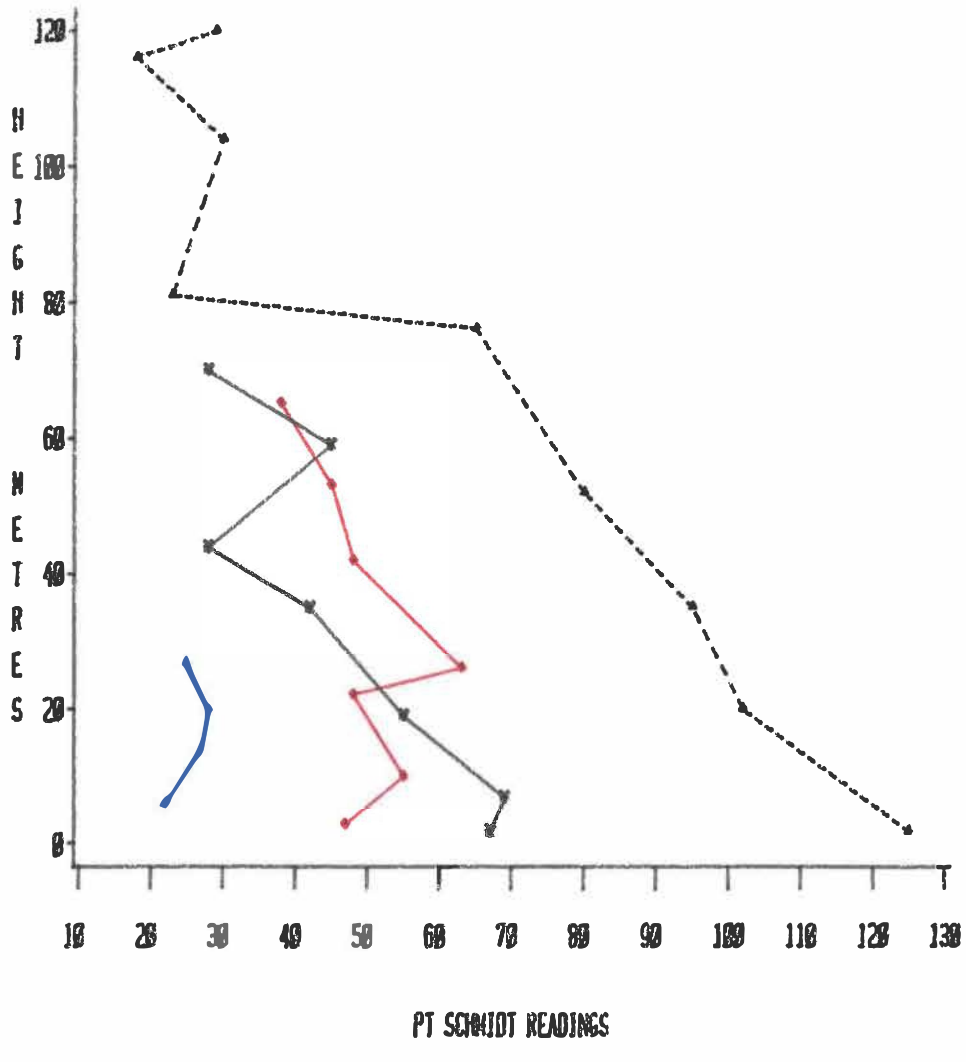
Also important in welding is the effect of compaction. Sheridan and Ragan (1976) recognise mechanical compaction which can significantly reduce porosity, though its effect on resulting texture (grain orientation and shape) is relatively minor. The other type of compaction, welding compaction, is the result of slow viscous deformation; the controlling factor is the residence time above the threshold for welding (Riehle, 1973).

Also to be borne in mind is the effect of vapour phase crystallisation, fumarolic alteration, and devitrification which probably has altered the apparent welding in most examples of the Mamaku Ignimbrite.

<u>Mamaku Ignimbrite</u> (Figs 5.16 and 5.17)

At the Type Site there is a steady decrease in welding from 125 units 2 m above the base of the outcrop to 65 units at 76 m. The degree of welding falls to 23 units at 81 m. This marked change is interpreted as the result of extensive devitrification and vapour phase alteration previously discussed. Welding increases at the next site to 30, drops to 18 just before the contact between two flow units

Fig. 5.16 PT SCHMIDT HAMMER READINGS
MAMAKU IGNIMBRITE



BLACK=ENTRANCE NGAMANAWA CORP U15 791647

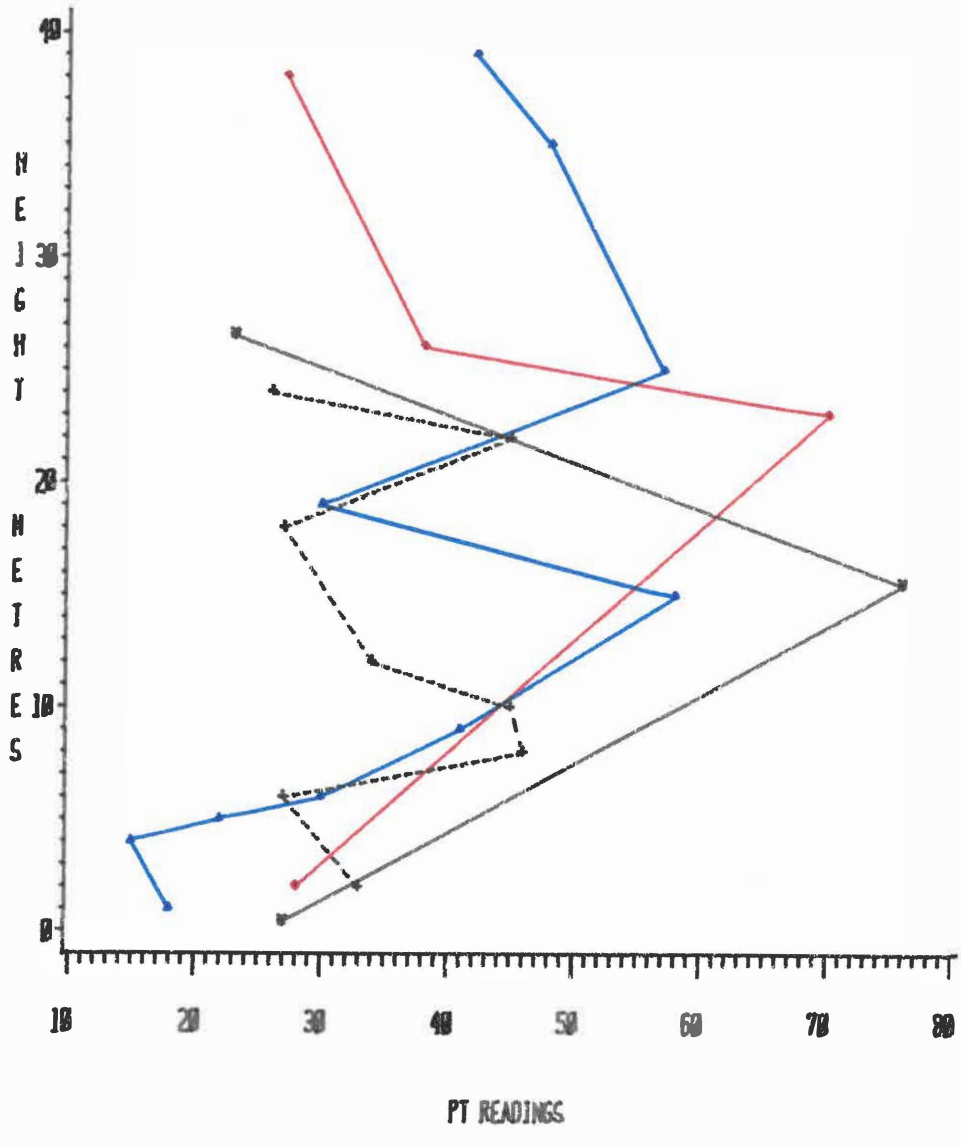
RED=HEKES TRACK U15 808651

BLUE=JOYCE ROAD U14 853736

BLACK DOTTED LINE=MAMAKU TYPE SITE U15 887554

Fig. 5.17 PT SCHMIDT READINGS VERSUS HEIGHT

MAMAKU IGNIMBRITE



BLACK=T.C.C. WEIR U14 859739

RED=DAIRY FARM U15 826672

BLUE=OROPI GORGE U15 877687

BLACK DOTTED LINE=LLOYD MANDENO U15 887687 marked by the dotted line. There is a pronounced negative correlation of (r=-0.95 [0.0001]) between height and welding.

The Ngamanawa column shows a general trend of a decrease in welding as height increases, with several fluctuations. This is reflected in the strong negative correlation (r=-0.87 [0.01]). At the base welding falls from 69 to 67 units suggesting the basal zone is not far away. Interestingly, at 59 m above base level welding increases to 45 units, which is followed by a fall to 28 units at the top of the outcrop. This change is attributed to post emplacement alteration rather than indicating a new cooling unit.

At the base of Hekes Track, welding values of 47 units were recorded, this rises to 55 at 10 m, falls to 48 at 22 m and jumps to 63 units at 26 m. Thereafter, welding falls steadily as height increases. This variation is reflected in the moderate correlation (-0.56 [0.18]) between height and welding. As previously mentioned this column is close to Ngamanawa and the variation in welding between these columns at comparable heights is indicative of the internal variability of an ignimbrite.

The distal Joyce Road column (Fig. 5.17) has a mild concave shape with maximum welding of 28 units at 20 m. However, the small variation between PT units (22 to 28) reflects the uniformity and lack of welding of the ignimbrite in its distal reaches.

The three data points for the T.C.C Weir column (Fig. 5.17) show what might be expected for welding in a basal zone (27 units), moderately welded columnar jointed zone (76 units) and top of the outcrop (23 units).

Four data points were recorded for the Dairy Farm column. These indicate a soft incipiently welded base (28 units), and a welded columnar jointed zone (70 units). A fall off in PT units indicates a progressive lessening in welding as height increases above the moderately welded zone.

From the contact with reworked Waimakariri-derived sediments at Oropi Gorge (Fig. 5.17) welding steadily increases (one fluctuation at 4 m) from 18 units at the base to 58 units at 15 m in the upper middle of the columnar jointed zone. At the next site (19 m) welding falls to 30 units, but as a contact or significant variation was not seen this is attributed to devitrification or vapour phase activity. Welding increases again at the next site but steadily falls thereafter.

A summary of statistics is presented in Table 5.11. Note the steady reduction in welding (mean values) with distance from source. This is also reflected in maximum values.

Table 5.11 Primary statistics for PT Schmidt Hammer

	Number	Mean	Std Dev	Minimum	Maximum
Type Site	7	73	38.6	18	125
Ngamanawa	7	46	16.5	28	69
Hekes Track	6	51	6.8	45	63
T.C.C Weir	3	42	29.5	23	76
Oropi Gorge	7	43	11.4	30	58
Joyce Road	4	25	2.6	22	28

Waimakariri Ignimbrite (Figs 5.18 and 5.19)

At the Carrs Track column a reading of 27 units was recorded at the base of the ignimbrite, directly above the pre-Waimakariri Plinian airfall. Welding increases to a maximum value of 42 units in the lower middle of the flow. This falls to 23 at 19 m and rises slightly to 30 units near the top of the outcrop. The column shows there is moderate but significant variation in welding at this distal outcrop. The standard deviation is quite large (8.1) and a difference of 19 units separates the largest and smallest values.

There is a steady increase in welding as height increases at Omanawa Falls, though welding begins to fall at the top of the outcrop. The incipiently welded top that could be expected is missing at this site. Either it was never deposited, or it was removed, though sediments were not seen at the contact with the overlying Mamaku Ignimbrite. The difference in welding between the Omanawa and Carrs basal sites is notable.

The Lower Mangapapa column has a sharp change in welding from 52 to 87 units over only a few metres. This strongly welded zone is about 18 m thick, the upper part is inaccessible and could not be described. Welding had decreases markedly at the next measurable section and continues to fall, reaching a minimum value of 39 units at the top of the outcrop.

Parts of the Lloyd Mandeno column (Fig. 5.19) were subject to weathering, probably when the Mangapapa River was downcutting to its present bed; therefore some parts of the column cannot be regarded as representative of original welding conditions (by comparison pumice sizes, numbers and percentages are usually readily estimated and are considered reliable). The Mamaku Ignimbrite overlying the Waimakariri

Fig. 5.18 P T SCHMIDT HAMMER READINGS

WAIMAKARIRI IGNIMBRITE

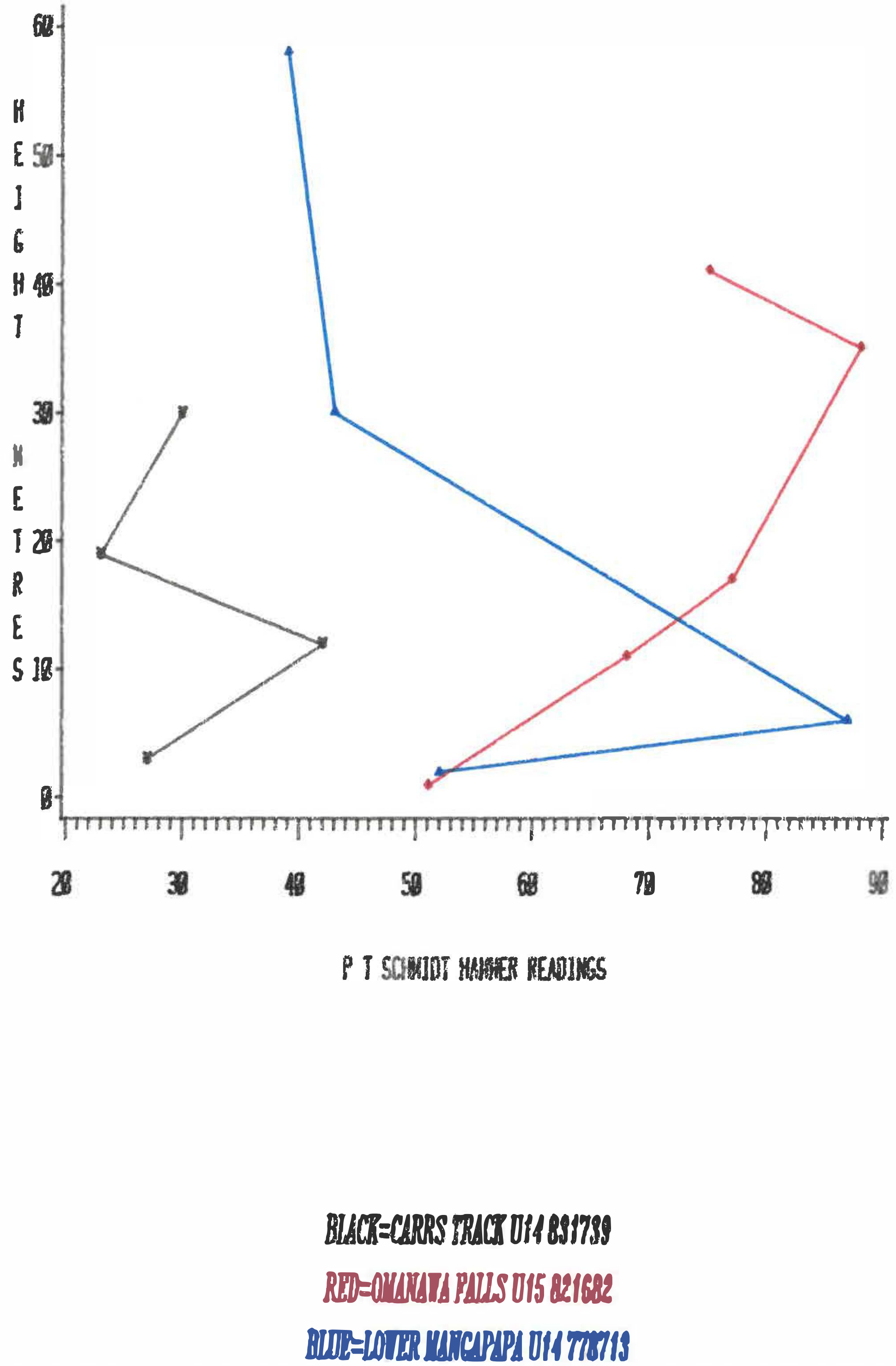
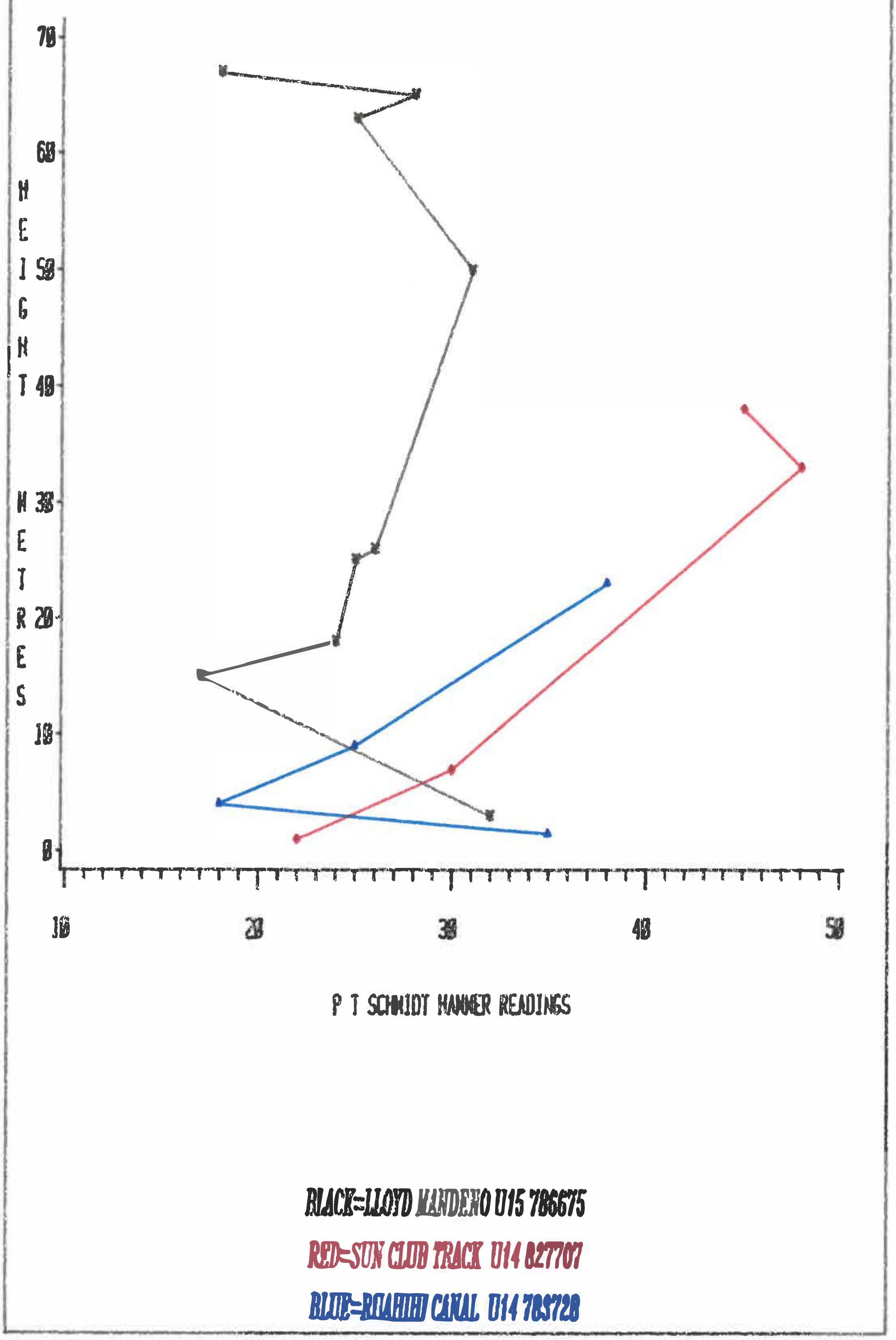


Fig. 5.19 P T SCHMIDT HAMMER READINGS VERSUS HEIGHT

<u>WAIMAKARIRI IGNIMBRITE</u>



is in an acceptable condition for estimation of welding by the PT Hammer.

At the Sun Club column (Fig. 5.19) welding is at a minimum at the base (22), rising to 30 units at 7 m. At 33 m welding rises to 48 and drops slightly to 45 units at the top of outcrop. It is considered that erosion has removed the incipiently welded top from this column.

The Ruahihi column is unusual as the maximum value was recorded at the top of the outcrop. This was the result of weathering turning the upper part of the ignimbrite to a hard consolidated clay (pumice is still recognizable). If this upper reading is disregarded then maximum welding is found at the lowest part of the column, which field evidence suggests is about three quarters through the flow. As height increases, welding falls to 18 units and increases to 25, 9 m from the base.

Basic statistics are presented in Table 5.12. These show a steady decrease (mean) in welding from an inferred source to the south with the exception of the Lloyd Mandeno column which is probably due to weathering. At the distal Carrs Track and Ruahihi Canal, mean readings are very similar.

Table 5.12 Primary statistics for PT readings

	Number	Mean	Std Dev	Minimum	Maximum
Omanawa Falls	5	71	13.7	51	88
Lower Mangapapa	4	55	21.8	39	87
Lloyd Mandeno	9	25	5.1	17	32
Sun Club	4	36	12.2	22	48
Ruahihi Canal	4	29	9.6	18	38
Carrs Track	4	28	4.6	23	34

Welding over horizontal distance: The Ruahihi section (Fig. 5.20) shows moderate variation in welding ranging from a minimum of 37 units at the start of the column (start of the canal) to 50 units at the end. However this is considered a coincidence, and no particular trend is indicated. The cutting is thus considered homogeneous in its degree of welding The same is true for the Tramway column where PT units cluster in the upper forties. The small standard deviations for both columns imply there is little difference in welding with distance (Table 5.13).

Table 5.13 Primary statistics for welding over horizontal distance

	Number	Mean	Std Dev	Minimum	Maximum
Ruahihi Canal	7	42	4.7	37	50
Tramway Tunnel	6	47	3.6	43	54

5.6 LITHICS

Sparks (1979) notes that lithics can be derived from magmatic stoping, by fragmentation of the walls of the chamber and vent and by plucking of loose debris from the ground during flowage. It is generally agreed that lithic size decreases both vertically and with distance from the vent. The largest lithics settle near the vent as a lag fall deposit and smaller ones as a lithic concentration zone near the base. Sheridan (1979) notes that in a turbulent or fluidised flow, lithics are concentrated in lower or proximal regions owing to their higher density. However, in large volume non-welded tuffs, pumice and lithic lapilli may be randomly arranged in vertical and horizontal planes (Sheridan 1979). Wilson and Walker (1982) found a steady decrease in the the size of lithics for the Taupo Ignimbrite. flowage. Lithics in the Mamaku Ignimbrite are usually hard to differentiate from groundmass and are best recognised under the

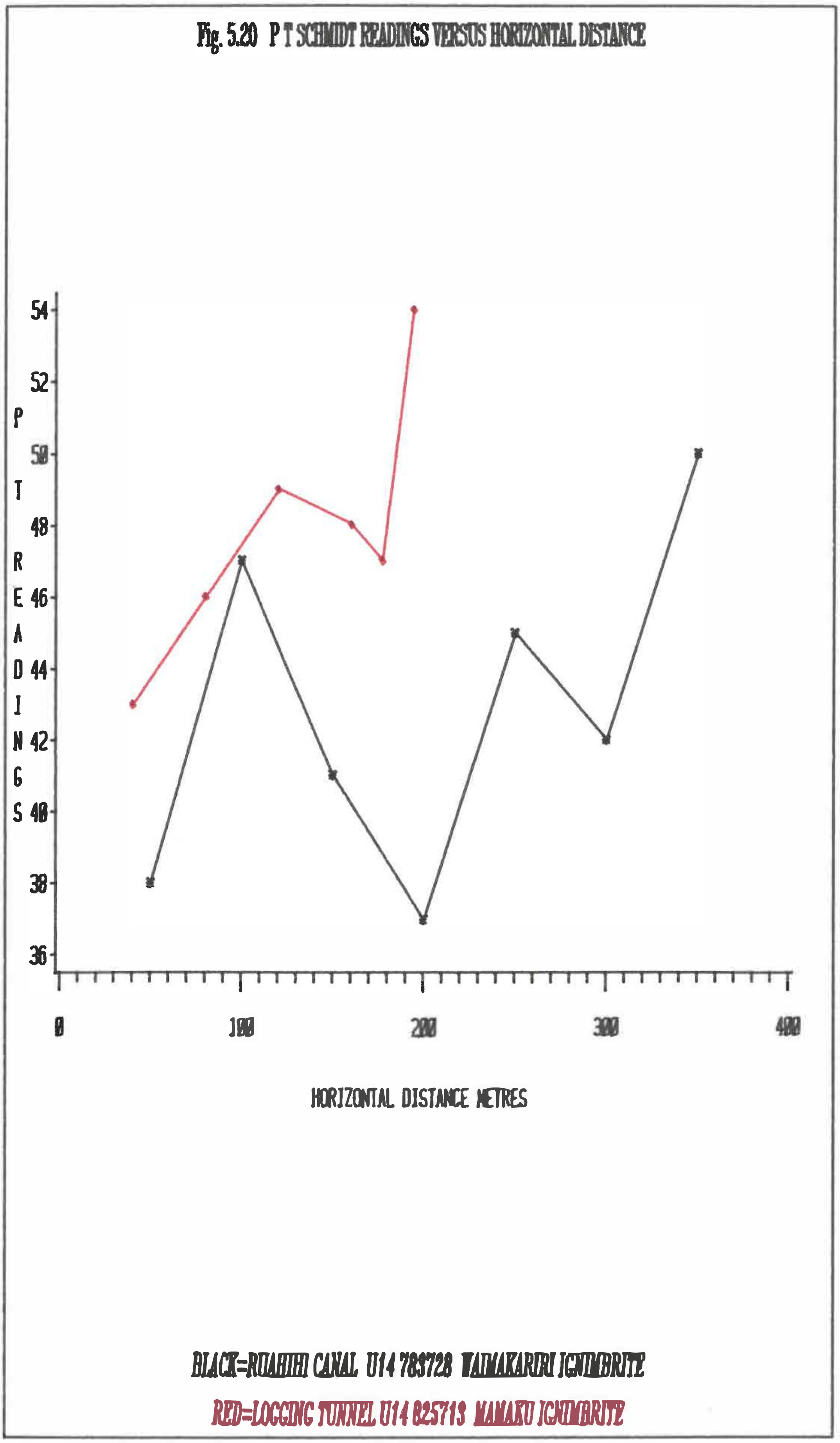


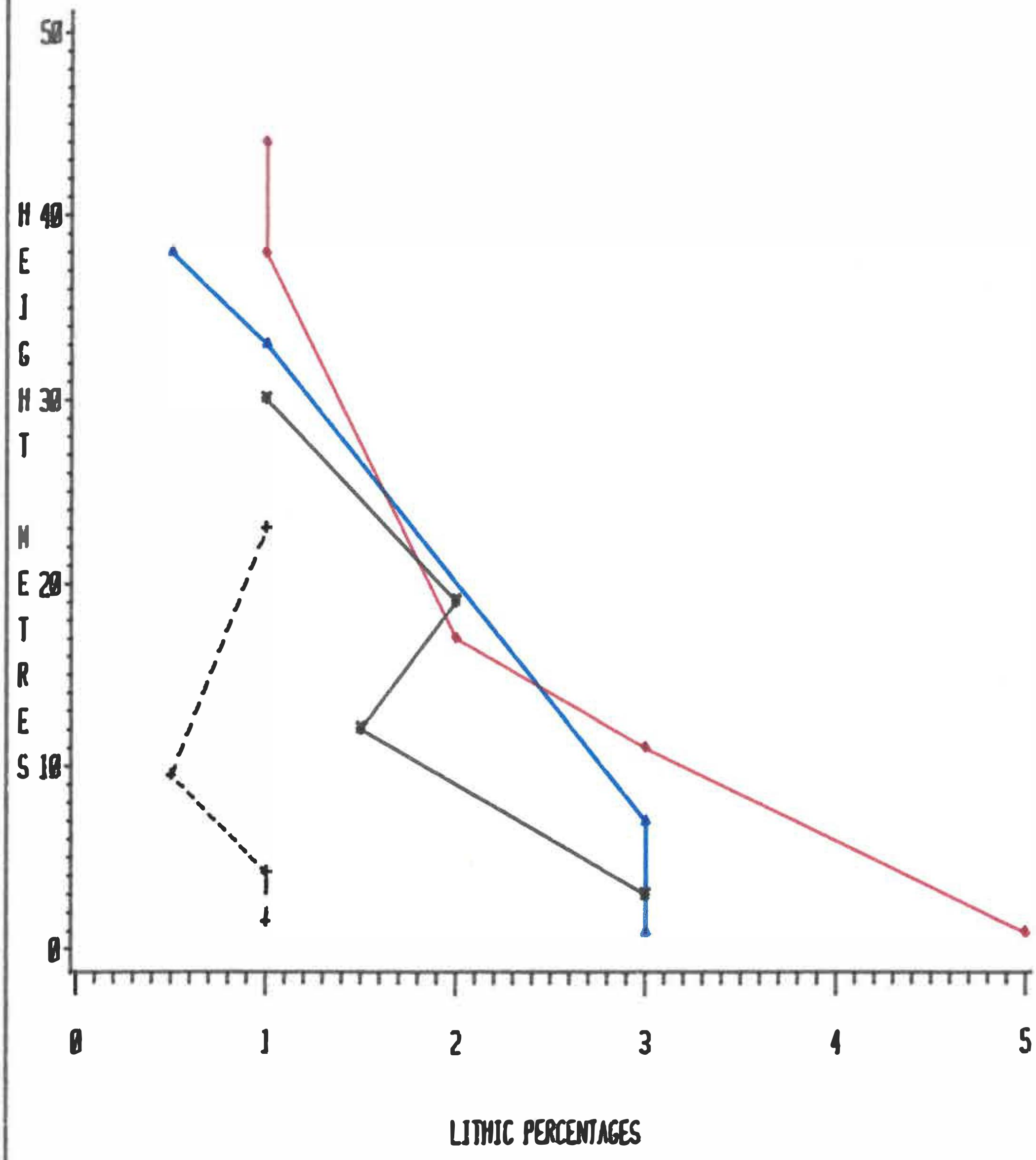
Fig. 5.20 P T SCHMIDT READINGS VERSUS HORIZONTAL DISTANCE
P T READINGS
54
52
50
48
46
44
42
40
38
36
0
100
200
300
400
HORIZONTAL DISTANCE METRES
BLACK=RUAHIHI CANAL U14 789728 WAIMAKARIRI IGNIMBRITE
RED=LOGGING TUNNEL U14 825713 MAMAKU IGNIMBRITE

microscope and even then are usually present in only trace amounts. Only four outcrops of lithics in the Waiteariki Ignimbrite were found. All are relatively close to each other in the northwestern study area, and they were not considered suitable to use in predicting source, although the largest lithic (50 cm) was found to the north in the vicinity of the ford crossing the Ngamuwahine River These have been discussed in Chapter 3.

There is a relatively steady decrease in lithics percentages in the Waimakariri Ignimbrite from the base to the top of outcrop for all columns (Fig. 5.21) except Ruahihi Canal, where there is little variation. However the base at Ruahihi was not exposed whereas Carrs Track (further to the north than Ruahihi) has full exposure and shows a trend towards a decrease in lithic size as height increases. Overall, the vertical variations are in accordance with Wilson and Walker's (1982) findings. Comparing mean lithic percentages, in order of assumed distance from source, the results are as follows: Omanawa Falls (1.9%), Sun Club (1.9%), Ruahihi Canal (0.9%) and Carrs Track (1.9%). There is insufficient change of mean lithic percentages to adequately define the source direction of the ignimbrite.

Fig. 5.21 LITHIC PERCENTAGES IN SAMPLE AREA VERSUS HEIGHT

WAIMAKARIRI IGNIMBRITE



BLACK=CARRS TRACK U14 831739

RED=OMANAWA FALLS U15 821682

BLUE=SUN CLUB U14 827707

BLACK DOTTED LINE=RUAHIHI CANAL U14 783728

CHAPTER SIX

LITERATURE REVIEW

6.1 INTRODUCTION

The intention of this Chapter is to compare the observations made in the field with those reported in the literature on the generation, movement and emplacement mechanisms of ignimbrites.

6.2 ERUPTIVE MECHANISMS

The most popular model for the generation of pyroclastic flows is the gravitational collapse of a Plinian eruption column, using the equations of continuity and motion developed by Sparks and Wilson (1976) and Sparks *et al.* (1978). The derived flows travel as hot, concentrated laminar flows, with high particle to gas ratios in which clasts are supported in a fluidised gas/particle matrix of finite yield strength (Walker, 1981b, 1982a). Large-volume flows probably form by continuous collapse of a high intensity eruption column while smaller volume flows are most likely generated by intermittent collapse of columns from discrete explosions (Wright, *et al.*, 1980, 1981b).

Only small flows have ever been observed. Thus, an understanding of large pyroclastic flows depends largely on field examination of ignimbrites. The largest closely observed eruption yielded less than 5 km^3 of material (Steven and Lipman, 1976) while the 18 May 1980 Mt Saint Helens eruption produced less than 1 km^3 of ejecta (Lipman and Mullineaux, 1981). This is insignificant compared with the volumes of greater than 3000 km^3 reported by Whitney and Stormer (1985) for the Fish Canyon Tuff. Lipman (1984) states an ignimbrite with a volume greater than 100 km^3 is a large volume flow. The Mamaku Ignimbrite has an estimated volume of about 300 km^3 (Wilson *et al.*, 1984) Volumes for the Waimakariri and Waiteariki Ignimbrites are difficult to estimate as they are overlain by sediments and ignimbrites but mapping suggests they are both widespread and derived from large scale eruptions, probably caldera-forming. Lipman (1984) notes that most silicic eruptions of more than 25-50 km^3 volume are associated with failure of roof rocks over a source magma chamber and are associated with caldera collapse.

The collapse of an eruption column to form pyroclastic flows has been witnessed. Often there is a preceding blast, basal avalanche and related surge (Sheridan, 1979). These phenomena may occur alone or together. Fisher and Schmincke (1984) note that pyroclastic flows may also form by an inclined blast from the base of an emerging spine or dome, the collapse of a growing dome, the boiling over of highly charged magma from a vent, or the explosive disruption of the front of a lava flow.

An eruption can be triggered by magma rising from the top of a magma column, perhaps by buoyancy-induced fracturing of the roof of the magma chamber (Fisher and Schmincke, 1984). The magma chamber can be divided into a high pressure root zone in which volatiles are still dissolved (Fig. 6.1). This is separated by an exsolution surface from a middle zone containing magma and exsolved bubbles. This in turn is separated by a fragmentation surface in the magma column of a dispersion of liquid to plastic pyroclasts and released gases. Often the vent is eroded to a flared shape by the high pressure gases. This enhances the velocity of the particle/gas mixture leading to a transition from subsonic to supersonic flow at the conduit's minimum diameter (Fisher and Schmincke, 1984).

Within the eruption column there are usually two components: the lower gas thrust caused by high velocity discharge and the convective thrust resulting from buoyancy (Plinian phase, Fig. 6.1). The main controlling factors are the vent radius, gas content and initial

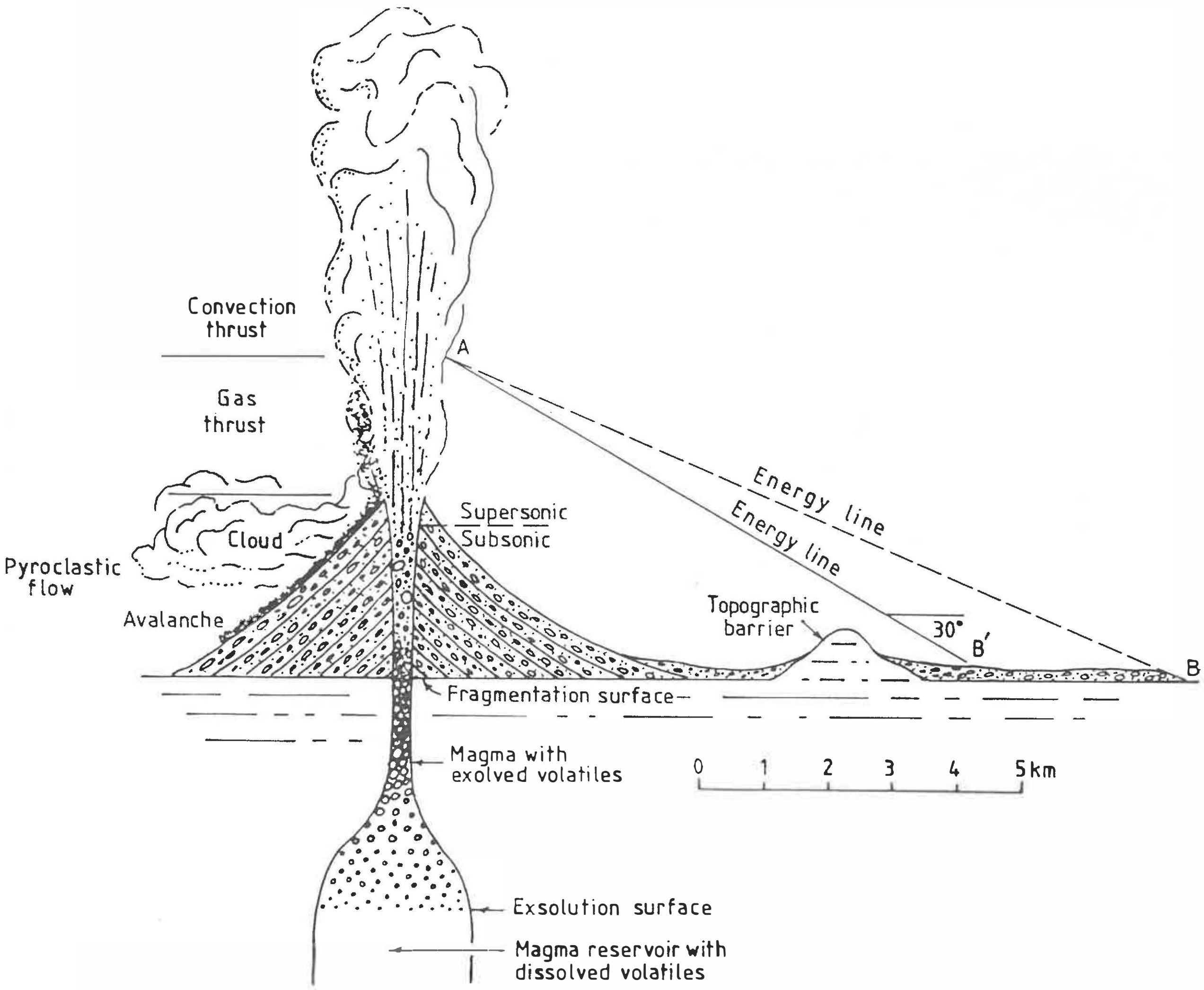


Fig. 6.1 Schematic outline of a plinian volcanic system. After Fisher and Schmincke (1984) and Sherdian (1974).

velocity of the gas (Sparks *et al.*, 1978; Sheridan, 1979). Deposition from a low eruption column favours heat retention and welding, the converse being true for high eruption columns (Sparks *et al.*, 1978).

Transition between these two zones may occur when large ballistic clasts fall back, inferred to occur at 0.6-9 km depending on the controlling factors discussed above (Sparks *et al.*, 1978). The convective thrust may reach 30 to 40 km (Sparks and Wilson, 1976). If the fallback of the larger clasts and expansion of incorporated air does not induce buoyant uplift, gravitational collapse occurs in the gas thrust zone and a pyroclastic flow develops (Sparks *et al.*, 1978). The flow then comprises a dense basal avalanche (the true pyroclastic flow, Smith and Roobol, 1982) and a dilute overriding cloud which may become detached from the basal avalanche (Sheridan, 1979) and contain up to one half the erupted ash (Walker, 1979).

Transportation and deposition mechanisms are varied. Fines may elutriate out as a co-ignimbrite ash fall (Sparks and Walker, 1977). This may have occurred at the distal Carrs track column with the Waimakariri Ignimbrite, based on an increase in total crystal percentages with height (section 4.3.2). Alternatively the ash cloud may travel as a pyroclastic flow or surge (Fisher 1979; Fisher *et al.*, 1980), while high density, poorly expanded flows may not separate into a basal avalanche and ash cloud (Buck, 1981), but instead remain as a coherent body.

Speeds of observed flows are quite variable and range from 8 to 45 m/s, most having average speeds of 20 m/s (Smith and Roobol, 1982). For large flows, Sparks *et al.* (1978) estimate initial speeds of up to 300 m/s with speeds of up to 100 m/s at tens of kilometers from source. Wilson and Walker (1981) calculated an average speed of 100 m/s for the Taupo Ignimbrite which has a modest volume (30 km^3), though it is the product of a particularly violent eruption. Wilson and Walker (1981) suggest that there is a wide variation in speeds of pyroclastic flows, from low velocity flows, which stop when they run out of energy (i.e. the Valley of Ten Thousand Smokes Ignimbrite), to the high velocity flows such as the Taupo Ignimbrite, which end when they run out of material.

The energy line AB' (Fig. 6.1) defines the theoretical head of the flow along the line of transport and is a function of the vertical drop and runout of the flow. The flow could override any topographic barrier that does not extend above the energy line. Large flows have a runout extending beyond that predicted, giving a shallower energy line as depicted by line AB (Sheridan, 1979). The mobility and longer runout are attributed to fluidisation.

6.3 FLUIDISATION

Fluidisation, generally agreed as playing an important role in the transportation and mobility of pyroclastic flows, is defined by Sparks (1976):

"When a bed of loose particles is placed in a tube with a porous base and a gas is passed through the system at increasing gas velocities, it is found that at a certain critical velocity the bed of particles no longer acts as a coherent mass, but adopts a fluid-like appearance and is said to be fluidised. Fluidisation occurs when the gas velocity is sufficiently great to support the weight of individual particles. For the geologist, a very important property of a fluidised system is that it radically alters the mechanical behaviour of granular material."

The ability of a flow to transport dense clasts depends on its degree of fluidisation. Poorly fluidised flows may be capable of transporting very large blocks because of their high yield strength, whereas strongly fluidised flows have a low yield strength and large dense blocks can rapidly settle out from them (Wilson and Walker, 1984).

Ignimbrites are often poorly sorted, a characteristic feature of high concentration dispersions such as mud flows. Concentration is the ratio of dispersant (solid particles) to transporting fluid (lubricant). While mud flows and turbidites cannot be regarded as fluidised, they may be aided by fluidisation (Sparks, 1978). Fisher (1971), in describing characteristic features of such deposits, notes that the bottom-most fragments are not necessarily deposited at an earlier time, and that the dispersion's entire mass and internal fabric becomes frozen in place. An alternative view is expressed by Chapin and Lowell (1979) who believe the Wall Mountain Tuff accreted upwards like ice when water flows over a frozen stream bed. This may have occurred at one outcrop at Ruahihi Canal (Fig. 6.2). Note Figs 6.2 and 6.4 are within 20 m of each other and at the same altitude.

Lowe (1976) notes that uniform fluidisation is achieved only with difficulty even in carefully controlled industrial and laboratory conditions. His observations suggest that fluidisation occurs principally within vertical cylindrical or irregular sheet-like channels, termed channelling beds in industrial systems. Because confining stresses increase with depth, fluidisation commonly begins with surface layers and progresses downward.

Fig. 6.2 Subhorizontal layering in the Waimakariri Ignimbrite at Ruahihi Canal (U14/783728) by No 1 tributary. This may have been caused from layer by layer deposition.

Fig. 6.3 Sheets 2 and 3, Mamaku Ignimbrite separated by a low angle cross bedded surge layer. Mafic crystals have concentrated in this layer and weathered to brown/black spots. The concentration of pumice at the top of sheet 2 is just visible. Pyes Pa Road (U15/850699).

From a number of particle size ranges (grain size cuts) of an ignimbrite, Sparks (1976) found that it was not possible for a system with a wide size distribution to be fluidised simultaneously. Ignimbrites often cover a size range of 8-12 ϕ but the fluidised range is only about 3 ϕ with 30-60% of the clasts unable to be fluidised. Thus, ignimbrites may be considered only semi-fluidised. In a refinement of his model, Sparks (1978) suggests that up to 50% of the particles in a pyroclastic flow may be fluidised and that the lifetime of an active flow may be from about a minute and a half to just under an hour, with fluidisation smoothly diminishing with increasing distance from source. Degassing takes place long after the flow has been emplaced. Evidence of degassing, fossil fumarolic pipes, are common in the Mamaku Ignimbrite and occasionally seen in the Waimakariri Ignimbrite.

Wilson's (1984) fluidisation experiments with poorly sorted ignimbrite samples demonstrate that segregation structures develop with increased gas velocities which cannot be destroyed by reducing gas velocity. At low fluidising velocities there is a minimum amount of expansion. At moderate gas velocities segregation structures are formed which consist of pods and sub vertical pipes and channels. When these channels develop they tend to be composed of coarse pumice and fine lithics. With increasing velocities segregation channels are more uniformly rich in lithics and crystals (the fossil fumarolic pipes in the Mamaku Ignimbrite are mostly fine devitrified material, with some crystals). At gas velocities sufficient to induce layering, coarser pumice, lithics and crystals tend to gather at the base and fine vitric material goes to the top of the bed. The fluidization structures seen in the in the Waimakariri and Mamaku Ignimbrites suggest that both ignimbrites were moderately fluidized based on Wilson (1984).

6.4 SOURCE OF THE FLUIDISING GAS

Reynolds (1954) established fluidisation as a geological process and ascribed to it the mobility of nuée ardentes. McTaggets' (1960) experiments demonstrated that hot sand flowed further than cold sand, and further that:

"the hot ever diminishing avalanche engulfs, rolls over, draws in, and momentarily entraps cool air. In this way the front part of the mass is constantly fluidised by fresh supplies of air that on heating expand progressively and explosively as they rise through the avalanche".

Wilson (1980), developing this theory, writes that at the front of the flow, basal friction causes an overhang which acts as a funnel. The part of the flow that has undergone this process should show an increase in pumice density, crystal and lithic concentration, pumice rounding, and generally be less welded than the body of the flow. If flow velocity is low, a section will show the head deposit at the base, overlain by the main body of the flow. The bedded crystal concentration zones (called surge deposits, and seen in distal Mamaku columns, Fig. 6.3) may have originated under similar conditions. Though they may possibly be the layer 1 ground surge of Sparks *et al.* (1973) which moves in front of the flow. Though Valentine (1986) considers it unlikely that a dilute pyroclastic surge can travel to distal locations. Walker *et al's* (1981b) ground layer seems too coarse to be considered as a possible alternative. Walker's (1983) (somewhat similar to Wilson's (1980) theory) forward jetting from the front of a pyroclastic flow is considered the most likely process which formed the surge deposits seen in the Mamaku Ignimbrite.

The layer separating flow units of the Mamaku Ignimbrite has been called a surge layer in this work, although the turbulent boundary layer (TBL) of Valentine (1986) is just as appropriate a label. However, it is probable that the Mamaku pyroclastic flow was slow enough for the surge (layer 1, head deposit, or TBL) to move ahead of the main body of the flow whereas the velocity of the Waimakariri pyroclastic flow was too high for dilute surges to move in advance of the flow.

Brown's (1962) observations of a self-fluidised gypsum dehydration reaction demonstrate that gas emission by individual particles of a nuée ardente could maintain the fluidised state for the time necessary for emplacement. McTagget (1962) notes that particles in the lower section of a flow emitting reasonable quantities of gas could fluidise the upper parts. Hence, the thicker the bed the longer the upper part will stay fluidised and the further this will travel as the lower part drops behind. He also notes that one textural feature that might be preserved is size sorting by upward streaming gas with fines at the top.

Usually pumice percentages and size decrease towards the top of the Waimakariri Ignimbrite, the converse often being true for the Mamaku Ignimbrite. This suggests the Waimakariri Ignimbrite was a less dense flow (implying a greater gas content) than the Mamaku Ignimbrite though the common presence of fossil fumaroles in the Mamaku Ignimbrite indicates it contained a significant gas content.

Two main sources of gas are suggested: firstly either internal release from breakage and/or diffusion, or external by gas trapped at initial flow formation, air incorporated at the head of the flow, or gases released by combustion of vegetation and/or surface water changed to vapour by passage of the hot flow. In places, the

Waimakariri Ignimbrite has flowed over the Opuiaki Sediments (some of which presumably were part of active river and stream channel systems at the time of deposition of the ignimbrite) and considerable water is assumed to have been vaporized and incorporated in the flow. Further, charcoal is often found in this ignimbrite and carbonised log casts can be seen at Ruahihi Canal. Probably the Waimakariri flowed over extensive forests. If this hypothesis is correct the gases released from ignition of vegetation would have added to the available gas supply. Conversely, charcoal has not been seen in the Mamaku Ignimbrite and only a thin sedimentary layer separates the two ignimbrites. Therefore it is argued that surface water and vegetation did not play an important role in providing fluidising gas for the Mamaku Ignimbrite.

6.5 KINETIC ENERGY EXCHANGE

Fluidisation by gas should not be regarded as the only means of particle support. Large rock avalanches commonly generate fast-moving streams of debris termed sturzstroms (Hsu, 1975). A sturzstrom is similar to a pyroclastic flow in that it achieves high velocities (90-350 km/hr), appears to flow as a flexible debris sheet with high efficiency of transport, cover a large area compared with source, contain large volumes and is capable of climbing topographic barriers (Selby, 1982).

Heim (1882) (cited in Hsu, 1975) was the first to recognise that sturzstroms did not slide but flowed, and that the long distance of travel was the result of low internal friction, with the coefficient of friction decreasing with increase in velocity. The idea of fluidised avalanches was explored by several workers, with trapped air acting as the lubricant. However it has been observed that sturzstrom-like deposits occur on the moon (Guest, 1971; Howard, 1973;

in Hsu, 1978) where neither gas nor water exist. The mobility of rock avalanches has therefore been restated (Hsu, 1975) using Heim's theory that the kinetic energy of one rock is transferred to another through impact.

Selby (1982) states that in a large aggregate of small blocks the motion of a given block is confined to its bouncing back and forward between its neighbours with only the outer blocks being able to escape. Kinetic energy is exchanged between particles by elastic collisions and the same energy keeps the particles separated during countless elastic contacts. The presence of fine particles increases both the frequency of collisions and the dispersion of large blocks, which may then pass each other. The mass, therefore, behaves as a fluid with very low internal friction, it has a high fluid viscosity which prevents internal turbulent mixing and moves as a thin flexible sheet with plastic behaviour and shearing at the base of the flow.

From this discussion it seems reasonable that kinetic energy exchange by elastic collision between particles may be an important component in maintaining the mobility of pyroclastic flows. Although this view does not seem to have been discussed in any detail in the pyroclastic literature, Sheridan (1979) developed the energy line concept by analogy to sturzstroms. Wilson (1984) notes that viscosity measurements on gas-fluidised systems show that interparticle contacts dominate their rheological behaviour and the same is inferred by Wilson to hold for pyroclastic flows. Fisher and Valentine (1986) note that processes other than fluidisation, such as grain to grain momentum exchange and fluid strength may support particles in pyroclastic flows.

6.6 POST-EMPLACEMENT PROCESSES

While cooling after emplacement, an ignimbrite is often acted upon by secondary processes dependent on its thickness (lithostatic load), emplacement temperature and trapped gases. These processes influence welding, compaction and recrystallization (described in Chapters 3, 4 and 5) and are quite well understood (Smith, 1960ab; Ross and Smith, 1961; Ragan and Sheridan, 1972; Reihle, 1973; Sheridan and Ragan, 1976).

The Mamaku Ignimbrite is devitrified almost from the base to the top of the flow and contains fossil fumaroles (gas escape structures and evidence of fluidization) where pumice has been removed and/or destroyed. This type of fumarole does not seem to be described in the literature and it is argued that the Mamaku Ignimbrite contained a considerable amount of gas at the time of deposition in juvenile clasts which was released gradually over a period of time. This contrasts with the Waimakariri Ignimbrite, in which the products of devitrification are only occasionally seen, suggesting trapped gas was released much more quickly. The composition of the residual volatiles and the physical properties of the glass also effect devitrification (Smith and Roobol, 1982), but allowing for these effects is beyond the scope of this study.

6.7 FIELD EVIDENCE

Laminar Versus Turbulent Flow

Sparks (1976) adopts the view that pyroclastic flows are dense, poorly expanded, partially fluidised debris flows which come to rest en masse. A flow behaves as a dispersion of larger clasts in a medium of fluidised fines which acts as a lubricant. Because ignimbrites are often poorly sorted and relatively homogeneous, they were originally thought to travel as turbulent flows. However, Sparks (1976) argues that poor sorting can be attributed to high particle concentrations rather than turbulence, and that ignimbrites travel as laminar flows. In very large flows, turbulence is likely in the initial stages of flow, while laminar flow is probable as the flow deflates. Chapin and Lowe (1979) state that laminar flow exists along the boundary layer of the flow and that all ignimbrite deposits pass through such a layer during deposition. Elongate fragments aligned roughly parallel to boundaries are indicative of laminar flow. Some degree of sorting could be expected from laminar flow (Best, 1982).

Alternatively some flows may be be at least partly turbulent. Walker *et al.* (1981) consider the fines-depleted Taupo Ignimbrite was a turbulent flow and that the major factor in determining turbulence was a high flow velocity, implying a high Plinian eruption column. Turbulence was greatest in the head of the flow where the ingestion of air and gas from combustion of forest takes place. Field evidence which Walker *et al.* state indicates turbulence is: (1) a loss of fines (the most distinctive characteristic) implying a high gas throughput and turbulent flow (retention of fines is favoured by laminar or plug flow). (2) large lithic fragments which extend considerable distances from the vent (remixing by turbulence delays settling). (3) erosion of the underlying surface and 'hoisting' of large lithics in the flow. An irregular topography and/or a thick forest cover increases surface roughness and yields gases, both factors contribute to turbulence (Walker *et al.*, 1981).

Giovanni *et al's* (1986) work on the Vico and Vulsini Volcanic complex suggests the following features indicate turbulent pyroclastic flow: (1) presence of many flow units, (2) presence of a ground surge within each unit, (3) ability to pass over obstacles, (4) maximum thickness near the eruption center, (5) abundance of round shaped lithics and pumice, (6) widespread pisoliths in the matrix, (7) vesiculation of the matrix, (8) absence of fines-depleted matrix (converse to Walker *et al's* (1981) view), (9) presence of fumarolic pipes in the peripheral facies.

Self (1986) suggests the following features indicate a high concentration, partially fluidised and turbulent pyroclastic flow: (1) stoss side truncations, (2) up flow stacking or accretion of bed forms, (2) fines depletion, (3) gas escape pipes, (4) poor sorting, (5) coarse, supported pumice and lithic clasts. Self notes that some of the Mt St Helens flows were originally laminar, became turbulent and then returned to laminar flow.

Although the literature is undecided on field evidence suggesting turbulent flow, the following is an attempt to discuss whether either the Mamaku or Waimakariri Ignimbrites traveled as turbulent or laminar pyroclastic flows.

Pumice in the Mamaku and Waimakariri Ignimbrites is usually rounded though angular examples are common, lithics in the Waimakariri are almost all semi-rounded. This suggests an abrasive environment. Fumarolic pipes (strongly fines-enriched) are common in the Mamaku Ignimbrite from proximal to distal reaches. Pipes (fines-depleted) are found in the Waimakariri in distal outcrops implying turbulence. As charcoal is common (and tree moulds are present at Ruahihi Canal) it is argued that the Waimakariri Ignimbrite flowed over a forest, the gases from which would have contributed to turbulence. However Froggat *et al.* (1981) state only a laminar flow is capable of orientating logs in an ignimbrite and that turbulent flow would probably have fragmented them. Although charcoal fragments are common the tree moulds are aligned approximately in a N-S direction suggesting laminar flow. Both ignimbrites are poorly sorted. Surge deposits occasionally seen, separate some Mamaku Ignimbrite flow units and it is suggested that these were turbulent. The rare occurrence of bedding (Figs 6.4, 6.5) in the Waimakariri Ignimbrite at Ruahihi Canal and the Lower Mangapapa station is considered to be the result of local surface irregularities and/or the effect of vegetation and surface water. Neither ignimbrite is noticeably fines depleted or vesiculated.

The field evidence is contradictory but based mainly on the lack of fines depletion (Walker *et al.*, 1981; Self, 1986) it is suggested both ignimbrites traveled as laminar flows. But the surges preceding Mamaku flow units were turbulent and parts of distal Waimakariri Ignimbrite that show bedding were also turbulent.

<u>Flowage</u>

Flowage as an emplacement mechanism of ignimbrites has been discussed by many authors, particularly Smith (1960b). He summarized his observations as follows:

(1) *There is a general lack of sorting even far from the vent.* This is true for the ignimbrites under study though the Waimakariri and Mamaku Ignimbrites do show signs of bedding in distal reaches. Walker (1972) notes that local eddies caused by topographic irregularities may produce stratification. Evidence of this was seen at the Lower Mangapapa station (Fig. 6.5), with the Waimakariri Ignimbrite. An alternative explanation is laminar sheering of the compacting and welding mass to form a primary foliation as discussed by Chapin and Lowell (1979). Bedding in this ignimbrite in more distal reaches is thought to be the result of a transition from laminar to turbulent flow possibly due to travel over a rough surface

Fig. 6.4 Subhorizontal bedding in the Waimakariri Ignimbrite at Ruahihi Canal. Weathering has accentuated the 2-3 mm thick fine vitric layers every 5-8 cm. Bedding is probably the result of turbulence.

Fig. 6.5 Subhorizontal bedding at the base of the Waimakariri Ignimbrite at the Lower Magapapa station (U14/778713). Note also the moderately welded nature of the ignimbrite in this basal section which is in sharp contact with the Opuiaki Sediments at the bottom of the photo.

as described by Walker (1972); Froggat *et al.* (1981) and Self (1986).

(2) *High temperatures have been preserved in the deposit for long periods of time, evidence being fumarolic pipes.* These are common in the Mamaku Ignimbrite; a particularly good example is a fumarolic zone extending for approximately 20 m at the Mamaku type site (U15/886555).

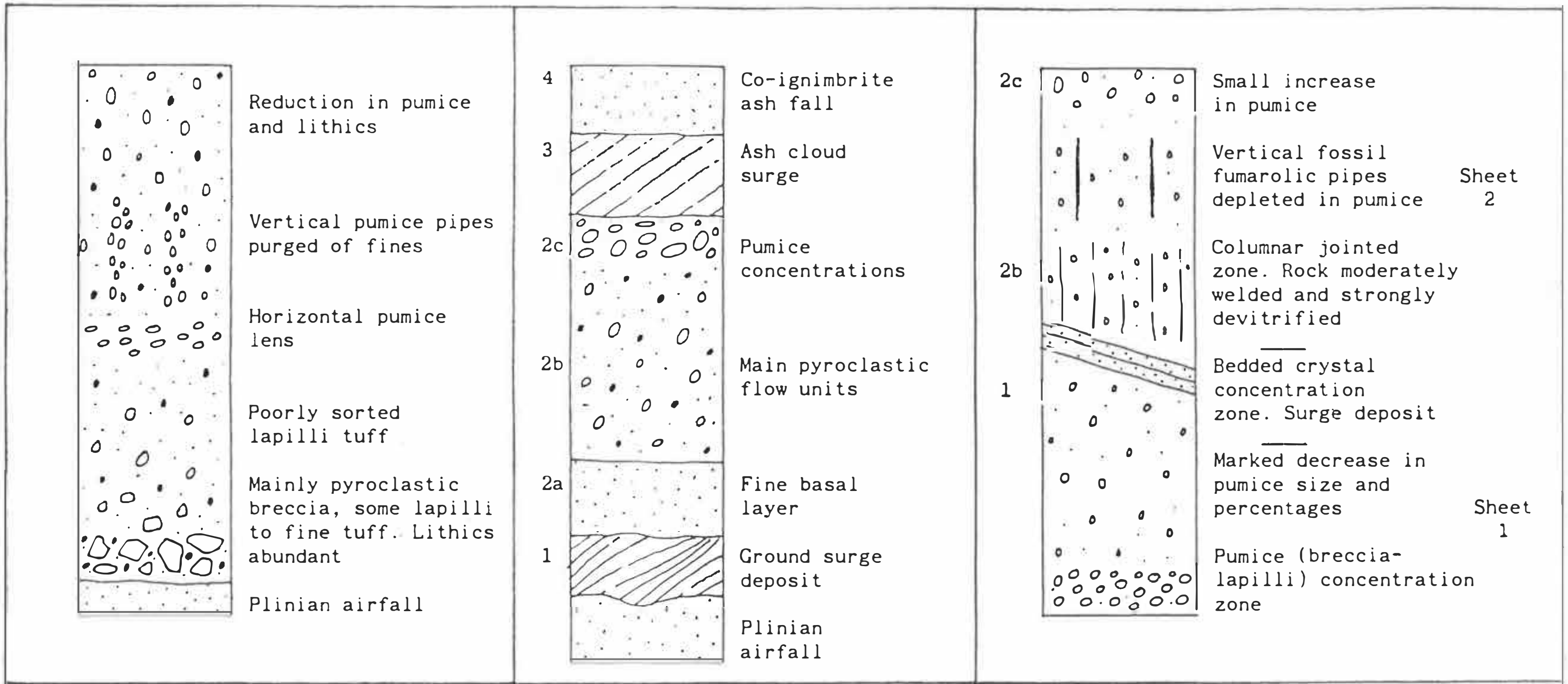
(3) *Debris from the ground and vent walls is incorporated.* Small rounded lithics, mainly rhyolite and ignimbrite (0.5-2 cm), are common throughout the Waimakariri Ignimbrite. Lithics in the Mamaku Ignimbrite can be difficult to see as they have been devitrified; however even when present they are not as abundant as the Waimakariri Ignimbrite. Strongly welded Waiteariki lithics (up to 50 cm) are found in basal Waiteariki. This is one line of evidence suggesting the Waiteariki Ignimbrite was emplaced as two cooling units. As the lithics are densely welded it is suggested that a period of erosion was necessary to expose welded ignimbrite, with lithics being plucked from the ground along the line of travel. Though it is possible that the lithics could be derived from a collapsing caldera during eruption. In either case a preexisting Waiteariki sheet is required (see section 3.6.6).

(4) *Small flows are restricted to topographic lows, while large flows are thickest over paleovalleys and have nearly level upper surfaces.* Interfluves of concordant height are a characteristic feature of the southern study area. Drill logs demonstrate that the Mamaku Ignimbrite flowed into paleovalleys carved into the Waimakariri Ignimbrite (Lloyd 1965, 1968). Poorly expanded, low velocity flows from low eruption columns are controlled by topography. Their deposits have a low aspect ratio, up to 1:300 (Wright, 1981) and often consist of many separate flow units (Wright, 1981; Wilson and Walker, 1981).

Models

Sparks *et al.* (1973) suggested an idealised vertical sequence through a single pyroclastic flow (Fig. 6.6). Beneath many ignimbrites allegedly formed by column collapse there is a Plinian airfall unit. Above this there may be a thin plane or cross-bedded unit (layer 1) which represents the dilute ground surge and precedes the main flow. The basal layer (2a) is finer grained than the rest of layer 2 and frequently shows reverse grading. Layer 2b is transported by concentrated laminar or plug flow above the sheared basal layer. It is characteristically unsorted and matrix-supported, clasts rarely exceeding a few tens of centimetres across. The base of 2b is often rich in lithic fragments which sank during transport. This contrasts with pumice fragments which often show reverse grading, being segregated towards the top of the flow by their buoyancy and thereby forming layer 2c. If the overriding ash cloud separates from the pyroclastic flow there may be a thin ash flow surge (layer 3) consisting of lenses of laminated or crossbedded ash (Fisher, 1979). This layer is often absent near source. At the top of the sequence the elutriated fines may settle out to form a thin widespread co-ignimbrite ash fall, but this is often absent suggesting its potential for preservation is low.

Two distal columns of Waimakariri and Mamaku Ignimbrite that have complete exposure from the base to the top of their respective sheets are compared with the standard ignimbrite flow unit (SFU) in Fig. 6.6. At Carrs track, Waimakariri Ignimbrite is underlain by a Plinian air fall deposit (found at many basal Waimakariri exposures). This is overlain by a pyroclastic breccia and lithic concentration zone. The number of pumice clasts, their size and percentage decrease markedly with height. Slightly below the middle of the flow, horizontal pumice



Carrs track (U14/831739), height 30 m. Distal Waimakariri Ignimbrite.

The standard ignimbrite flow unit. After Sparks *et al.* (1973) and Fisher (1979). Scale and thickness highly variable.

Oropi Gorge (U14/787685), height 39 m. Distal Mamaku Ignimbrite. Sheet 4 has not been included in this description.

Fig. 6.6 Sequences in pyroclastic flow deposits concentration zones were noted. Overlying these by about 5 m are vertical pumice pipes depleted of fines. These are thought to result from post-emplacement degassing, creating segregation channels. Comparing this column with the standard flow unit the main correlation is the basal Plinian air fall deposit and the lithic concentration zone.

The Oropi Gully column of Mamaku Ignimbrite has pumice concentrated at the base, though pumice size and percentages decrease rapidly over several metres as height increases to a lapilli ash with weathered relic fibrous pumice. Overlying the ash is a bedded crystal concentration zone which is interpreted as a ground surge deposit (layer 1). Thus the material comprising and overlying the crystal concentration zone of this particular deposit is interpreted as a second flow unit. From the bedded zone there is a gradational change to a moderately welded columnar jointed zone. This zone gradually reduces in intensity of jointing and welding and several fumarolic pipes can be found above it. These fumaroles are composed of fines only, all pumice having been destroyed or removed. Towards the top of the flow there is a slight increase in pumice content inferred to be layer (2c). This is overlain by a new flow unit marked by a sharp contact and changes in groundmass colour, texture and pumice. This is interpreted as a further flow unit of the Mamaku Ignimbrite (sheet 4).

Each of the Mamaku (layers 1 and 2c) and Waimakariri Ignimbrites (Plinian airfall) have some features in common with the SFU. As such the SFU has some use in interpreting the processes operating during flowage and deposition. However the SFU was developed from smaller ignimbrite (peléan) deposits and an alternative model (Fig. 6.7) may be more suitable for medium/large volume ignimbrites from caldera-forming events. This is an idealised flow unit derived from a number of distal and some medial Waimakariri and Mamaku Ignimbrite columns described in Chapter 3 and Appendix 2. The terminology (layer 1, 2 etc) of Sparks *et al.* (1973) is continued. However, until it is compared and contrasted with other studies, Fig. 6.7 cannot be termed a facies model.

At the base of the outcrop a Plinian airfall deposit is capped by a bedded crystal concentration zone (layer 1 ground surge) implying the passage of a new flow unit. This, in turn, is overlain by a basal pyroclastic breccia zone which is produced as the flow loses competence, with larger clasts settling out. It may also indicate turbulence and fines depletion. A moderately to incipiently welded columnar jointed zone follows, indicating that a pyroclastic flow is a very efficient heat conserving mechanism and welding is possible even in distal reaches. This zone is overlain by semi-horizontal and vertical pumice pipes. This in turn is overlain by a pumice concentration zone.

Fig. 6.7 is predictive, for example if the pipes are fines-depleted and the ignimbrite is not devitrified, then it is suggested there was considerable post-depositional gas activity with relatively rapid degasing. Further, if charcoal is present and the ignimbrite overlies sediments then the flow was significantly fluidized by external sources (surface water, vegetation). If the vertical fossil fumarolic pipes contain only fines and the ignimbrite is strongly devitrified, then it can be inferred that the flow at time of deposition also contained considerable gas, though this was contained mostly in juvenile clasts which was released gradually and the flow was mainly fluidized by internal gas sources.

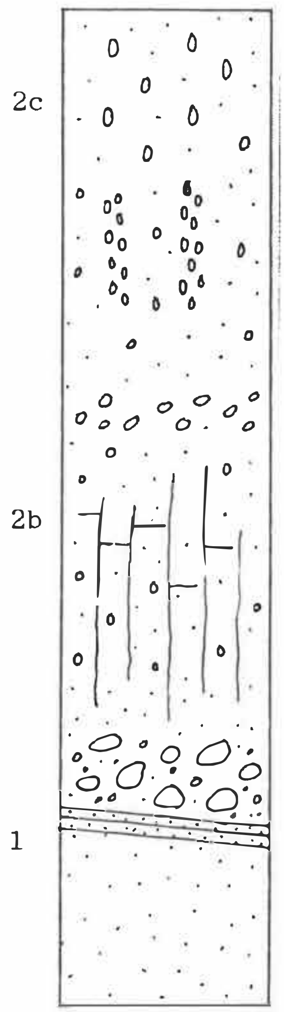


Fig. 6.7 Idealised distal flow unit for medium/large volume ignimbrites. Based on distal Waimakariri and Mamaku Ignimbrite columns.

If the flow was relatively dense and laminar, then as height increases there may be a corresponding moderate increase in pumice. This suggests the pumice was buoyed up by having a lighter density than the flow itself. Fig. 6.7 may be overlain by a further flow unit. The contact between the flow units may be marked by some or all of the following: a pumice concentration zone, change in colour of the groundmass, change in pumice texture, change in total crystal percentages or a surge layer which is occasionally crossbedded.

Fluidization

From his experiments Wilson (1980) developed a threefold classification of ignimbrites, depending on their level of fluidisation (Fig. 6.8). The least fluidised (type 1 flows) are characterised by a lack of expansion implying a high yield strength which prevents gravitation-induced grading and a morphology similar to mud flows (high concentration dispersions). A type 2 flow occurs when the bed has been partially fluidised and expanded (note there is still a yield strength) to accommodate the gas flow (a 2a layer may be present). Expansion can allow coarse tail grading to develop; also there may be normal or reverse grading, depending on the density relationship of the clasts to matrix.

A type 3 flow is fully fluidised, and like type 2 deposits, shows coarse tail grading, but also has segregation structures of coarse dense material concentrated by gas flow and fossil fumaroles. In extreme cases the bed may be completely gas-sorted. Fossil fumaroles can represent a primary gas flow feature surviving from the flow or reflect gas flow rates as the pyroclastic flow comes to rest.

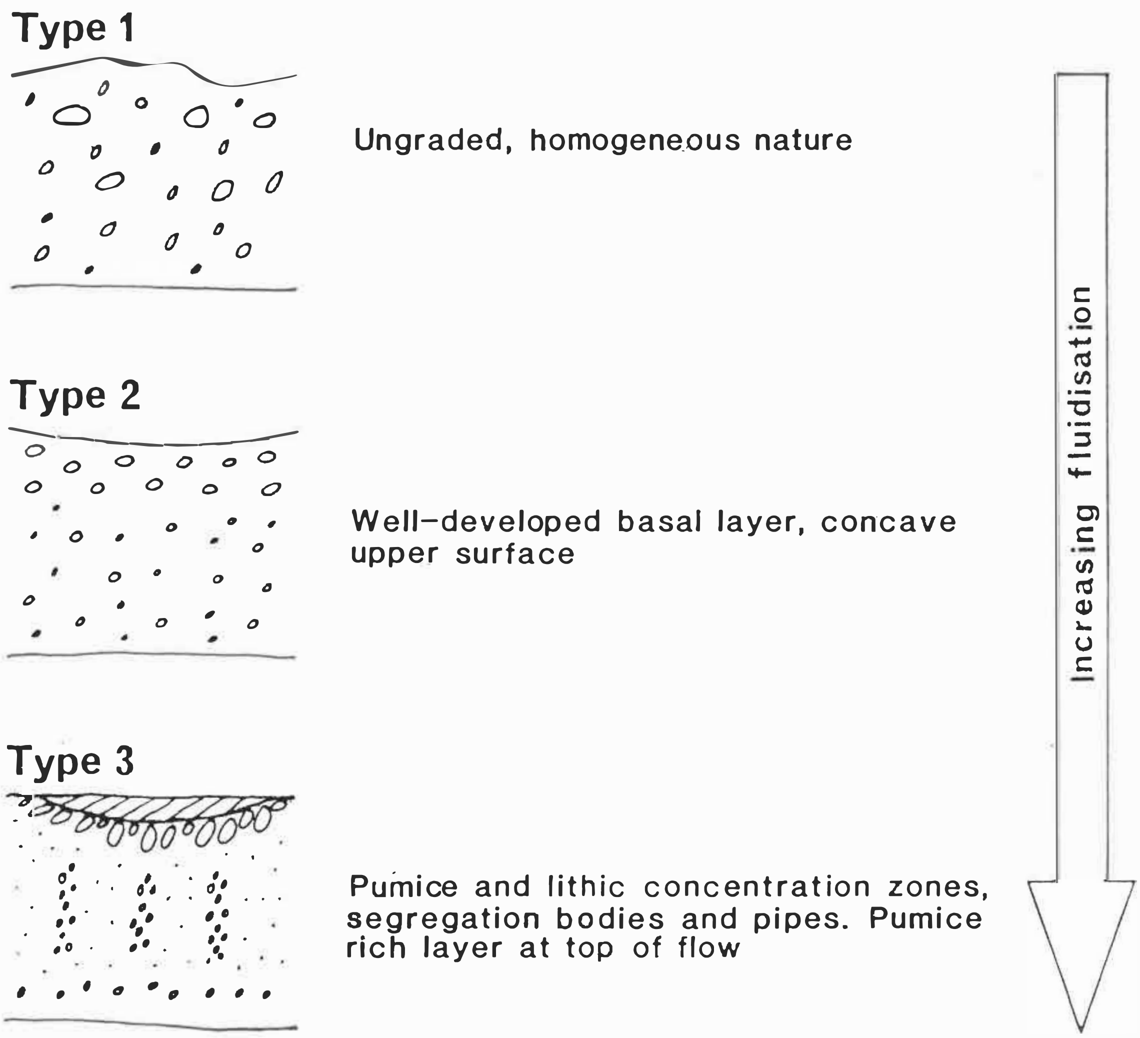


Fig. 6.8 Sketch to show Wilson's (1980) three flow types with increasing fluidizing gas velocities.

Pumice gradually increase in percentage towards the top of the Mamaku Ignimbrite (implying that pumice was less dense than the flow though this does not necessarily mean that the Mamaku Ignimbrite was a dense flow). Another possibility is that the size/shape of the pumice allowed preferential buoying up, but the former hypothesis is preferred. This pumice increase is not immediately obvious in the field (as possibly it might be in a type 3 flow), and was only detected by detailed column construction. Segregation structures are also present in the Mamaku Ignimbrite in the form of fossil fumaroles purged of coarse clasts. Although segregation structures are not strictly permitted in type 2 flows, Wilson states that broad post depositional zones of vapour phase alteration can be expected in type 1 and 2 flows. Therefore it is suggested that the Mamaku Ignimbrite was at the upper end of a type 2 flow.

Pumice usually increases towards the base of columns in the Waimakariri Ignimbrite (both in medial and distal columns) suggesting it was not as dense a flow as the Mamaku Ignimbrite. Segregation structures in distal columns of horizontal pumice sheets and vertical pumice pipes that are fines depleted. Further there is some bedding indicating that the flow was occasionally turbulent. Petrologic evidence suggests that the Carrs track column is depleted of fines towards the top of the flow. This suggests the Waimakariri Ignimbrite was at the lower end of a type 3 flow. However this may be partly the effect of surface roughness, surface water and vegetation rather than a particularly fast flow resulting from a high eruption column incorporating large quantities of air.

6.8 DISCUSSION

Spark's (1976) standard flow unit has limited use for interpreting the processes operating on the Waimakariri and Mamaku Ignimbrites. However, a new model is presented for medium to large volume flows at distal outcrops. Developed from empirical observations of the Mamaku and Waimakariri Ignimbrites, it explains some of the processes the ignimbrites underwent during flowage and deposition. For example, the model suggests that if an ignimbrite is almost completely devitrified and vertical fossil fumaroles are present, depleted in pumice, then the flow was mostly self fluidized and a significant quantity of gas was trapped in the ignimbrite at the time of deposition which was gradually released over a long period of time. Whether the model (Fig. 6.7) is applicable to other distal large volume flows remains to be seen.

One of the diagnostic characteristics of laminar flow is pumice clasts in parallel alignment and lack of fines depletion. The former is only seen occasionally in the ignimbrites under study apart from strongly welded/compacted zones where alignment is probably the result of welding/compaction. The latter is seen only at the base of some Waimakariri Ignimbrite columns. Therefore it is considered that the Mamaku and Waimakariri Ignimbrites generally traveled as laminar/plug flows. At the front of Mamaku Ignimbrite flow units, the flow was turbulent, evidence being bedding and crystal concentration which often separated flow units.

At Ruahihi Canal the Waimakariri Ignimbrite was emplaced essentially as a laminar flow, though there was some turbulence. Bedding in the outcrop near number 1 tributary suggests the latter, while evidence of the former is the poorly sorted nature of the deposit, and presence of fossil tree moulds. Also the Waimakariri was able to transport pumice clasts up to 23 cm in size to Ruahihi Canal indicating a relatively high particle concentration and moderate fluidisation. However, petrographic examination at the Belk Road column suggests the ignimbrite is partly fines-depleted towards the top of the flow. This is explained by a large gas content elutriating fines during flowage. An alternative possibility is a turbulent flow depleting fines. Probably the Waimakariri was moderately gas charged and fluidized with local variations (vegetation and surface water) influencing gas content and degree of fluidization. The base of the flow is also fines-depleted but this is thought to be the result of pumice clasts settling under gravity through a relatively low concentration dispersion. It is suggested the Mamaku Ignimbrite was at the upper end of a type 2 flow (Wilson, 1980) whereas the Waimakariri Ignimbrite was at the lower end of a type 3 flow.

A diverse ignimbrite facies can be seen in both the Mamaku and Waimakariri Ignimbrite, perhaps suggesting that a single large pyroclastic flow can operate under a variety of flow regimes, depending to some extent on local paleo surface conditions.

CHAPTER SEVEN

SUMMARY

7.1 STRATIGRAPHY

Airfall Tephras: The following tephras were identified by field methods. Rerewhakaaitu Ash, Okareka Ash, tephric loess, Kawakawa Tephra (Oruanui Ash), Mangaone Subgroup tephra(s), Rotoehu Ash, Hamilton Ash and Pahoia Tuff. These tephras mantle the interfluves and often form a 4-7 (m) thick veneer.

Opuiaki Sediments: The Opuiaki Sediments overlie the Waiteariki Ignimbrite and underlie the Waimakariri Ignimbrite. They are widespread, and vary in texture, sedimentary structures, induration, thickness and paleoenvironments.

Stratigraphic units were divided into lithotypes to facilitate a brief interpretation of depositional environments. A lake basin environment is suggested for lithotypes 1, 2 and 3 which are rare and confined to two localities. Lithotype 4 is considered to have been deposited within abandoned channels (ox-bow lakes) or other topographic lows within a fluvial system. Lithotype 5 is considered to be a flood plain deposit. The coarseness of the deposit (gravels and sands) and Nu crossbedding of lithotype 6 imply a channel fill and/or point bar deposit. A crevasse splay or scour fill environment is suggested for lithotype 7, while the relatively coarse texture and sedimentary structures of lithotype 8 suggest a point bar or cross-over region of deposition. As the majority of these sediments are silts and clays with some sands, it is assumed that the main paleoenvironment is a meandering river (flood plain) system associated with lakes.

Mamaku Ignimbrite: The Mamaku Ignimbrite (sheet 2) has an upper zone which is incipiently welded with pink devitrified pumice and pink groundmass with brown spots (weathered mafics). The lower middle zone is moderately compacted and welded and is lenticulitic in places. At increasing depth this grades down into uncompacted, nonwelded pyroclastic breccia.

With the exception of the immediate basal pyroclastic breccia zone almost all of the rock has been strongly devitrified. Most pumice is devitrified to the point where very little of the original texture remains, though occasionally a relict fibrous texture can be seen. Pumice colour is also variable, but is usually light pink or a very light yellow. Pumice occasionally has a white or brown rim.

The ignimbrite, based on field characteristics can be separated into 4 flow units, sheets 1, 2, 3, and 4. Only sheets 2 and 4 can confidently be traced any distance, mainly because basal Mamaku (sheet 1) is not often exposed while sheet 3 is seen in only three localities. An erosional unconformity separates the Mamaku and Waimakariri Ignimbrites, marked by a thin gravelly sand.

The Mamaku Ignimbrite varies considerably in total phenocryst content (bulk rock) depending on whether the sample has been taken from a strongly (18-16%) moderately (14-12%) or incipiently (10-8%) welded outcrop. The surge layers that separate the flow units contain above average total crystal contents (up to 35.5%, although 14-12% is more common) compared with overlying or underlying flow units. The dominant crystal is plagioclase with subordinate quartz and lesser amounts of augite, hornblende, hypersthene, and Fe-Ti oxides.

Almost all groundmass and pumice show the effects of devitrification and vapour phase activity (some mafic and plagioclase crystals also were affected). Usually petrography demonstrated that post-depositional activity increased with height, the converse being true for welding and compression effects.

Lateral Variations in phenocrysts: Comparing total, plagioclase and quartz percentages from the top of sheet 2 over lateral distances, there is a moderate trend towards a decrease in total crystal percentages with distance from source. No trend is apparent for quartz, but there is a significant decrease in abundance of plagioclase crystals over lateral distances. As there is no significant decrease in crystal lengths with distance from source for the Mamaku Ignimbrite, crystal length was probably a relatively unimportant parameter in determining whether crystals were deposited out of the flow.

Zonation: There is a significant trend for crystals to decrease in percentage as height increased at the proximal Type site and medial Ngamanawa columns. This is thought to be the result of welding/compaction rather than magma chamber zonation. This hypothesis if accepted implies that the magma chamber was essentially homogeneous, perhaps by crystals being spread randomly through the melt by convective currents or the chamber did not have time to develop crystal zonation before eruption.

Waimakariri Ignimbrite: The upper part of the Waimakariri Ignimbrite (missing in some exposures) is slightly compacted and incipiently welded. It contains mostly grey, rounded pumice with a ropey, knotty, texture with abundant crystals. At greater depth the percentage of flattened pumice increases and below the middle of the sheet there is a hard grey lenticulite with abundant brown and dark grey, strongly compacted and welded pumice. Below this the ignimbrite usually grades into less welded pyroclastic breccia of variable thickness.

In hand specimen, colour ranges from a dull orange to a light pinkish red, though a pale grey is most common. Weathered outcrops are often a light pink with mafics weathering to brown stains; and at first glance can resemble Mamaku Ignimbrite. Colour seems dependent on the flow unit under observation and the effects of weathering. At least three flow units are present, though it has not been possible to correlate between them or trace them over any distance.

Lithics are common to abundant throughout the ignimbrite and tend to concentrate in the bottom of the sheet. Their size ranges from dust to 2 cm, though 0.5-1 cm are more common. Most lithics and pumice are rounded suggesting an abrasive environment. The paleotopography of the Waiteariki Ignimbrite and Opuiaki Sediments was an important factor in determining the thickness and degree of welding of the Waimakariri Ignimbrite.

The relationship between the Mamaku and Waimakariri Ignimbrite magmas is not yet clear (if in fact one exists) as this depends on the time interval between the two eruptions and whether the Waimakariri was erupted from the Rotorua Caldera. The mineralogy of the Waimakariri Ignimbrite is similar to of the Mamaku Ignimbrite except that the matrix and pumice of the latter has been devitrified and altered by vapour phase activity. The dominant phenocryst is plagioclase with lesser quartz and minor augite, hypersthene, hornblende and opaques.

At the Carrs track column it was found that crystal percentages increased with height. This is explained by fines being steadily elutriated from the flow as a co-ignimbrite ash fall similar to that described by Fisher (1979). The column is distal and zonation cannot be explained by magma chamber effects. The Plinian airfall that underlies the Waimakariri Ignimbrite at this and several other columns suggests that a volatile-rich cap was present before the ignimbrites' eruption.

Mineralised Waimakariri Ignimbrite: A sample of sinter from a hydrothermally altered zone, examined under reflected light showed cataclastically shattered pyrite and marcasite suggesting faulting in a shear zone. Quartz and feldspars were also shattered; that some examples showed flowage supports a hypothesis of deformation by faulting. Phenocrysts of feldspar, augite, hypersthene and hornblende have been strongly altered or completely destroyed by hydrothermal alteration but quartz remains fresh. Magnetite and ilmenite have been altered to hydrous iron oxide, probably limonite. Abundant fine grained radial fibrous marcasite and lesser amounts of cubic pyrite are scattered through the groundmass.

Waiteariki Ignimbrite: In hand specimen, unweathered samples of the Waiteariki Ignimbrite are pinkish grey, crystal-rich, usually strongly welded with very dark grey lenticular pumice up to 5 cm in length. The upper incipiently welded zone has been eroded in the study area (seen once outside the study area), though a 50 to 30 m grey strongly welded middle zone is present which overlies a pumiceous incipiently welded basal zone about 10 m thick. This overlies a very strongly welded lower cooling unit seen only in two locations and described in one drill log.

Very densely welded outcrop can resemble andesite and where the rock is overlain by Opuiaki Sediments (which are often saturated and perhaps induce leaching of the rock) it is similar to a light grey vesicular rhyolite. Where it is subject to surface weathering, it superficially resembles Mamaku Ignimbrite with large brown spots from weathered mafics. However, in all cases close examination reveals a characteristic high crystal content and occasional lenticular pumice.

Mapping confirmed the Mamaku Ignimbrite was derived from the Rotorua Caldera. A source for the Waimakariri Ignimbrite is probably the Rotorua Caldera whereas a source near the type site of the Waiteariki Ignimbrite is possible but contentious. The Waimakariri and Waiteariki Ignimbrites are of sufficient volume to have formed calderas, but there is no evidence yet found to demonstrate their existence.

The Waiteariki Ignimbrite is crystal-rich (up to 38% in densely welded zones, though it tends to average 23%). Dominant phenocrysts are plagioclase, lesser quartz, and minor hornblende, hypersthene, augite, biotite, ilmenite and magnetite. The groundmass is devitrified, with a cryptocrystalline light pinkish grey matrix with little sign of the original vitric texture, occasional felsic crystallites can be seen. Pumice has been densely welded and compressed with shards having a well developed parallel alignment (eutaxitic texture) indicating extreme flattening. Shards have been moulded around crystals without breaking, indicating a degree of plasticity at the time of deposition. Where voids exist in crystals (from corrosion in the melt) these have been infilled by shards.

The Mamaku and Waimakariri Ignimbrites may be classified as rhyolitic ignimbrites and the Waiteariki as a dacitic ignimbrite (Best, 1982).

Vertical and lateral variations within ignimbrites

Only sheet 2 of the Mamaku Ignimbrite was used for comparisons in pumice variations, the same (as previously mentioned) is true for crystal variations. Two sections of horizontal distances of 350 and 194 m for the Waimakariri (Ruahihi Canal) and Mamaku (Tramway Tunnel) respectively were constructed. No significant variation in pumice numbers, percentages, lengths or welding was found, and both ignimbrites are considered relatively homogeneous over short horizontal distances.

Pumice Numbers: Often the largest counts of pumice numbers in the Mamaku Ignimbrite were found in the middle of the flow, though in two columns, numbers increased with height. There is a moderate reduction in mean numbers with increasing distance from source. For the Waimakariri Ignimbrite pumice numbers are greater at the base of outcrops, fall towards the middle of the flow and increase towards the top of the exposure. For both the Mamaku and Waimakariri Ignimbrites a correlation between pumice numbers and percentages does not necessarily exist.

Pumice Percentages: The proximal Mamaku Type Site column has a moderate increase in pumice percentages, compared with three medial columns of Mamaku Ignimbrite which have significant increases in pumice percentages with increases in height. A medial/distal column shows a trend towards an increase in pumice percentages as height increases, while distal columns have little variation. This is interpreted as the Mamaku Ignimbrite being a relatively dense flow with particles of lighter density (pumice) floating to the top of the flow. If the flow had been turbulent it is unlikely that this stratification would have occurred.

Pumice often concentrates in basal sections of the Waimakariri Ignimbrite, implying that it was not as dense a flow as (and thus more expanded than) the Mamaku Ignimbrite.

Pumice Lengths: Mean pumice lengths increase with height for most columns of the Mamaku Ignimbrite. A decrease in pumice lengths with increasing distance from source was also found. Medial Waimakariri

Ignimbrite columns show moderate increase of pumice lengths towards the base of columns. At distal columns this is more pronounced.

Welding: A PT type Schmidt hammer was used to estimate welding in the field. At columns where the base of the ignimbrite was exposed, this was usually (with several exceptions in the Waimakariri Ignimbrite) the zone of minimum welding. Welding increased to about the lower middle of the flow and then decreases until the top of the outcrop was reached. Welding also decreased with distance from source for the Mamaku and Waimakariri Ignimbrites. While Smith (1960b) recognizes three zones of welding, this study divides welding into 6 zones (Table 5.10).

Lithics: There is a relatively steady decrease in lithic percentages in the Waimakariri Ignimbrite from the base to the top of outcrop for all columns except Ruahihi Canal, where there is little variation. There was insufficient change of mean lithic percentages to adequately define the source direction of the ignimbrite by this technique. As the Waimakariri Ignimbrite has abundant lithics, it is proposed that during eruption a cauldron block collapsed into the caldera. Lithics are scarce and difficult to see in the Mamaku Ignimbrite though very occasionally a lithic concentration zone was seen. Lithics are concentrated in the base of the Waiteariki and are there quite large (up to 50 cm) though they are scarce in other zones of the ignimbrite.

7.2 ERUPTIVE MECHANISMS

It is suggested that the bedded crystal concentration zones seen in distal Mamaku columns and referred to as surge deposits are probably Walker's (1983) forward jetting from the front of a pyroclastic flow. If the speed of a pyroclastic flow is low, a pyroclastic surge can precede the main body of the flow (Wilson and

Walker, 1982). This implies that the Mamaku Ignimbrite travelled more slowly than the Waimakariri Ignimbrite and the speed of the Waimakariri was too high for a dilute surge to move in advance of the flow.

The evidence is somewhat contradictory as to whether the Mamaku and Waimakariri Ignimbrites were turbulent or laminar flows. Based on the lack of fines depletion, it is inferred that both ignimbrites traveled esentially as laminar flows. However, the surges preceding Mamaku flow units were turbulent, and those parts of distal Waimakariri Ignimbrite that show bedding were also turbulent. Nevertheless the bedding (and perhaps turbulence) in the Waimakariri is probably the result of local surface irregularities and/or the effect of vegetation and surface water.

Both the Mamaku and Waimakariri Ignimbrites have some features in common with the standard ignimbrite flow unit (Sparks *et al.* 1973; Fisher, 1979). While the SFU is of some use in interpreting the process operating during flowage and deposition on the ignimbrites under study it was developed from smaller ignimbrite (peléan) deposits and an alternative model (Fig. 6.7) is presented for medium/large volume distal ignimbrites. This idealised flow unit is derived from a number of distal and some medial Waimakariri and Mamaku Ignimbrite columns. Until it is compared and contrasted with other studies it can not be claimed to be a facies model. Although the flow unit is predictive, for example it suggests that if an ignimbrite is almost completely devitrified and vertical fossil fumaroles are present and these are depleted in pumice then the flow was mostly self fluidized. Probably a significant quantity of gas remained in the ignimbrite (possibly in the pumice) at the time of deposition, which was gradually released over a long period of time. It is suggested that this occurred with the Mamaku Ignimbrite.

Based on Wilson (1980) and field investigation it is suggested the Mamaku Ignimbrite is at the upper end of a type 2 flow and the Waimakariri is at the lower end of a type 3 flow. Both the Waimakariri and Mamaku Ignimbrites are thought to have been deposited en masse although one outcrop at Ruahihi Canal suggests layer by layer deposition.

The Mamaku Ignimbrite was not seen with a basal Plinian deposit, and hence it is assumed that the eruption developed rapidly to massive proportions with apparently no initial period of low discharge where a convecting column could be sustained (Sparks *et al.*, 1978, 1985). However as the Waimakariri Ignimbrite is underlain by a Plinian airfall, the converse is thought to apply. The Mamaku and Waimakariri Ignimbrites contain several flow units, which suggests that this involved pulse type eruptions with collapsing pyroclastic columns of relatively low height, interspersed with brief pauses during eruption. All three ignimbrites are thought to be derived from column collapse along major regional faults.

APPENDIX 1

Inferred Co-status of Mamaku Ignimbrite

While mapping several farmers (especially a Mr Peer, who also mentioned that the Omanawa area had suffered from bush sickness) drew attention to the fact that sheep were selectively gnawing at 'rhyolite' (Mamaku Ignimbrite). This was not an isolated phenomenon, two other farmers reported that sheep and cows also ate Mamaku Ignimbrite. When examining the outcrop the animals appeared to be selectively attacking the upper part of the flow, overlying fossil fumaroles. It was originally thought the animals were probably trying to obtain salt, however this could not be tasted. Therefore, it seemed likely that trace elements (probably Co) were the likely target of the animals.

Since Co was not measured directly (by XRF analysis), some element is needed that proxies for Co, or at at least has similar geochemical associations. In early work, Co deficiencies were incorrectly diagnosed as Fe deficiencys, since sheep improved when fed with limonite which is Co carrying (Underwood and Filmer, 1935) thus Fe is considered a suitable element.

Table 1 Data compiled from N.Z. Soil Bureau, Bull. 26.

Locality	Horizon	Co (ppm)	Fe/Ti
Kaingaroa	O1	<0.1	10.62
Tirau	A11	0.7	16.7
Tirau	AB	1.0	12.55
Kaingaroa	A1	1.5	17.50

The ratios in Table 1 were then regressed against Co to obtain the best relationship. The following empirical equation was obtained, though this relationship may work for rhyolite and ignimbrite only.

$$n=4,\ Co=0.13(Fe/Ti)-1.01\ [r=0.73]$$

From semiquantative XRF analysis of sheep eaten and control Mamaku Ignimbrite, the following ratios for Fe/Ti are obtained (Table 1). Counts ratios are assumed comparable to concentration ratios. Substitution in the equation of these ratios yields the results outlined in Table 2. Also shown in Table 2 are the Co contents of two soils that are quoted in the literature as having Co <1 ppm. The predicted values agree with this which increases the confidence in this admittedly rather empirical method of obtaining cobalt values. The values for the ignimbrite suggest that the zone in the Mamaku Ignimbrite attacked by the sheep is marginally higher in cobalt than other parts of the flow.

Table 2

	Sample	Fe/Ti	Co (ppm)
sheep eaten	51a	24.64	2.20
	51b	24.17	2.10
control	2	1.47	1.78
	6	0.88	1.70
literature (Co <0.1 ppm)	Taupo A	13.33	0.72
	Waiteti A	10.00	0.29

In summary reasonable estimates seem to be given by the equation in that it predicts good values for Taupo and Waiteti soils. If this is correct it would seem that the ignimbrite eaten by the sheep is enriched in Co over the control. The Co is presumably selectively concentrated by vapour phase/fumarolic activity.

APPENDIX 2

Appendix 2 comprises stratigraphic columns of the tephras, sediments and ignimbrites in the study area. Tables 1 and 2 are the field guides used in the construction of the following columns. A 30 cm by 13 cm clear plastic bag was used as sample area. See Chapter 2 for a discussion of techniques.

Table 1 Field guide for ignimbrite hand specimen descriptions. Some data from Schmidt (1981) and Andrews (1982).

(1) Location: Grid reference, Notable landmarks, Direction of travel.

(2) Outcrop characteristics: Colour, Jointing [intensity and bearing] Height, Fumaroles, Bedding, Elutriation structures.

(3) Hand specimen description:

- (a) Colour: blue, brown, green, grey, olive, orange, pink, purple red, white, yellow. Dark, dusky, light, moderate, mottled pale, variegated.
- (b) Crystals: identification, size[>5mm=coarse, 5mm-1mm=medium, <1mm=fine]. Percentage in hand specimen
- (c) Pumice: Numbers and percentages from sample area size (length), n=10, colour, texture, imbrication and/or bedding.
- (d) Grain size: [>64mm=pyroclastic breccia, 6-2mm=lapilli tuff, 2mm-1/16mm=coarse tuff, <1/16mm=fine tuff.
- (e) Strength, hardness, welding: PT Schmidt hammer n=10.
- (f) Lithics: Identification, percentage in sample area, size.
- (g) Groundmass: lithic, crystal or vitric, combination.
- (h) Sorting: Very well, well, moderately, poorly.

Key

Rock fragments — Undeformed pumice — Lenticules

Eutaxitic texture — Loose sands

Table 2 Field guide to sedimentary handspecimen descriptions. Some data Andrews (1982).

(1) Location: Grid reference, Direction of travel, Noteable landmarks.

(2) Outcrop characteristics: Sedimentary structures, thickness, imbrication of pebbles.

(3) Hand specimen description:

(a) Colour: as for ignimbrites.

(b) Induration: [loose, firm, indurated]

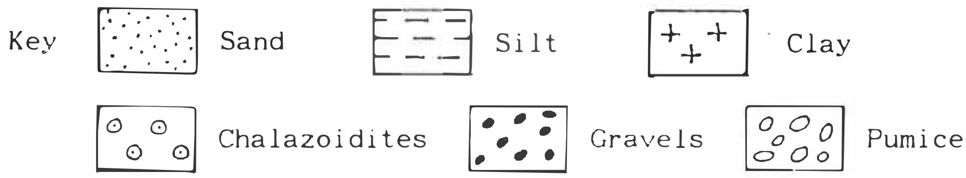
(c) Weathering:

(d) Composition: Crystals [identification, percentage]
Rock fragments [identification, percentage]
Pumice [size, colour, percentage]

(e) Grain size estimation.

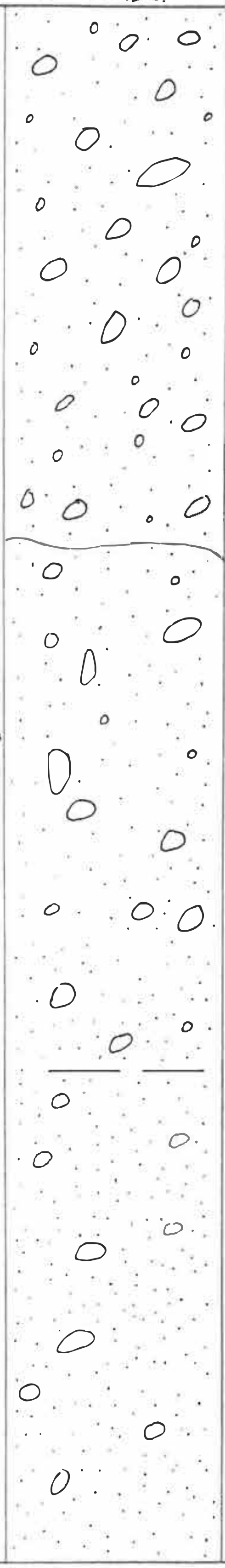
(f) Sorting: Very well, well, moderaetly, poorly.

(g) Name of unit (based on grain size).



Stratigraphic Column : MAMAKU TYPE SITE, BY MANGAREWA RIVER.

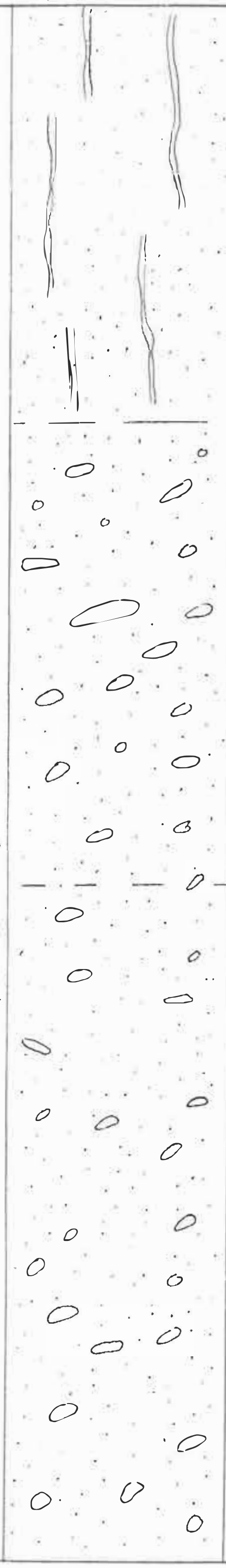
G.R.: U15/ 887554



TOTAL THICKNESS	THICKNESS	PROFILE NOT TO SCALE.	HANDSPECIMEN DESCRIPTION	COMMENTS
metres				
123	3	MAMAKU IGNIMBRITE	a) LIGHT PURPLE/GREY. b) CRYSTALS: QUARTZ, FELDSPAR, MAFICS: 8%. c) PUMICE: 14, 12% 31 [2- 60] mm LIGHT GREY, DEVITRIFIED THOUGH RELIC FIBROUS TEXTURE CAN BE SEEN. d) LAPILLI TO FINE TUFF, MAINLY COARSE TUFF. e) WEAK, PT = 30, UNWEATHERED. f) NO LITHICS SEEN. g) RELIC VITRIC. h) POORLY SORTED	OVERLAIN BY 3m OF ASH. FIRM TO SPADE. SEPARATE flow UNIT SHEET 3 SAMPLE 621C WT 23475 SITE 9
120	4		a) LIGHT REDDISH GREY. b) CRYSTALS: AS ABOVE 10%. c) PUMICE: 9, 5%, 19 [5- 47] mm LIGHT GREY, DEVITRIFIED. d) LAPILLI TO FINE TUFF, MAINLY COARSE TUFF. e) VERY WEAK, PT = 18, UNWEATHERED. f) NO LITHICS SEEN. g) RELIC VITRIC h) MODERATELY SORTED.	SHARP CONTACT. NO SEDIMENTS AT CONTACT. VERY THIN Mn LAYER. EASILY DUG OUT WITH PICK, CRUMBLES UNDER FINGER PRESSURE
116	12		a) PINKISH GREY. b) CRYSTALS: AS ABOVE 12%. c) PUMICE: 6, 3%, 5 [3 - 12] mm LIGHT PINK, DEVITRIFIED. d) LAPILLI TO FINE TUFF, MAINLY COARSE TUFF. e) WEAK, PT = 30, f) AS ABOVE. g) RELIC VITRIC h) POORLY SORTED	GRADATIONAL CHANGE INCIPIENT COLUMNAR JOINTING. SAMPLE 619 WT 23474 OUT OF FUMEROLE ZONE. FIRM/EASY TO SPADE. SITE 7

Stratigraphic Column : MAMAKU TYPE SITE.

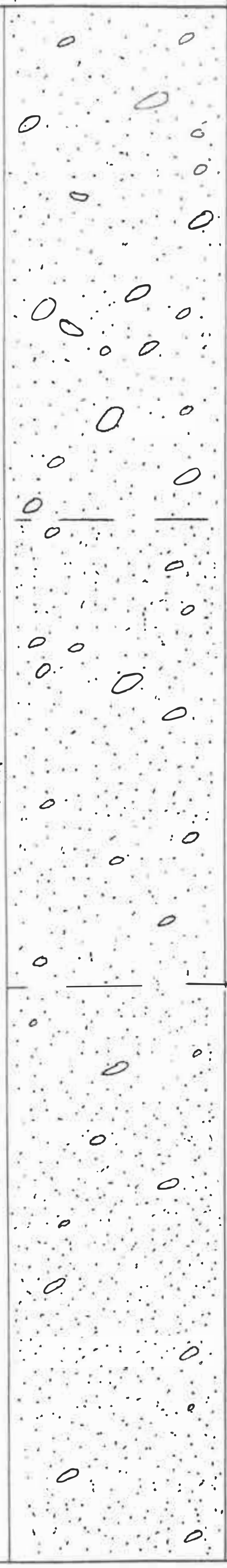
G.R.: U15/887554



TOTAL THICKNESS	THICKNESS	PROFILE (NOT TO SCALE)	HANDSPECIMEN DESCRIPTION	COMMENTS
metres				
104	23	MAMAKU IGNIMBRITE	a) ½ LIGHT PINK ½ WHITE. b) CRYSTALS 8%. c) PUMICE: NONE SEEN, REMOVED, DESTROYED? d) COARSE AND FINE TUFF e) VERY WEAK, PT = 23. SLIGHTLY WEATHERED. f) NO LITHICS g) RELIC VITRIC h) WELL SORTED	HIGHLY ALTERED FUMEROLIC ZONE NUMEROUS VERTICAL PIPES EVERY 1-2m OCCASSIONAL UNALTERED LENS. SAMPLE 618 WT 23473 SITE 6
81	5		a) PINK/GREY TINGE OF RED. b) CRYSTALS: 12%. c) PUMICE: 14, 10%, 31 [3 - 52] mm WHITE, DEVITRIFIED, SEMI LENTICULAR d) LAPILLI TO FINE TUFF, MAINLY LAPILLI AND COARSE TUFF. e) MODERATELY STRONG, PT = 65 f) NO LITHICS g) RELIC VITRIC. h) POORLY SORTED	GRADATIONAL CHANGE TO FUMEROLIC ZONE NO COLUMNAR JOINTING. CHIPPED OUT WITH SOME DIFFICULTY SAMPLE 617 WT 23472 SITE 5
76	24		a) PINKISH GREY. b) CRYSTALS 12%. c) PUMICE: 19, 6%, 22 [1 - 35] LIGHT PINK, DEVITRIFIED, LENTICULAR. d) LAPILLI TO FINE TUFF. MAINLY LAPILLI AND COARSE TUFF. e) STRONG, PT = 80, SLIGHTLY WTHD. f) NO LITHICS, g) DENSE VITRIC. h) MODERATLY SORTED.	CAN JUST CHIP WITH SPADE SAMPLE 616 WT 23471 SITE 4 COLUMNAR JOINTING DYING OUT.

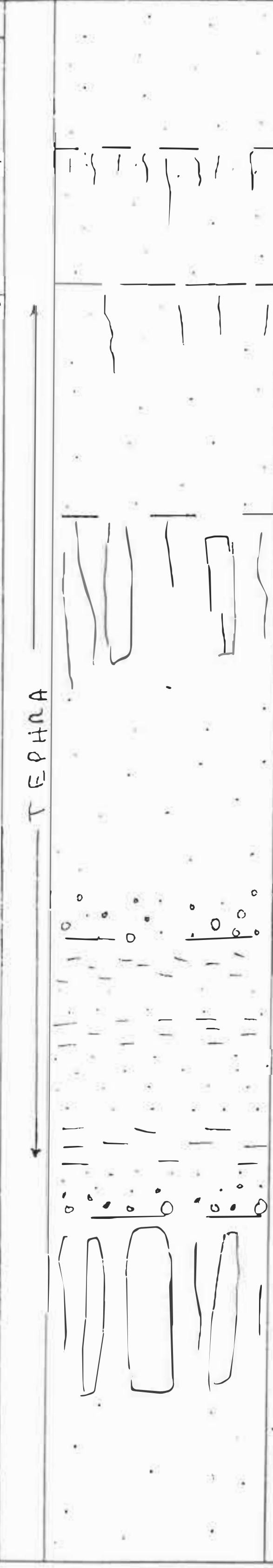
Stratigraphic Column: MAMAKU TYPE SITE

G.R.: U15/ 887554.



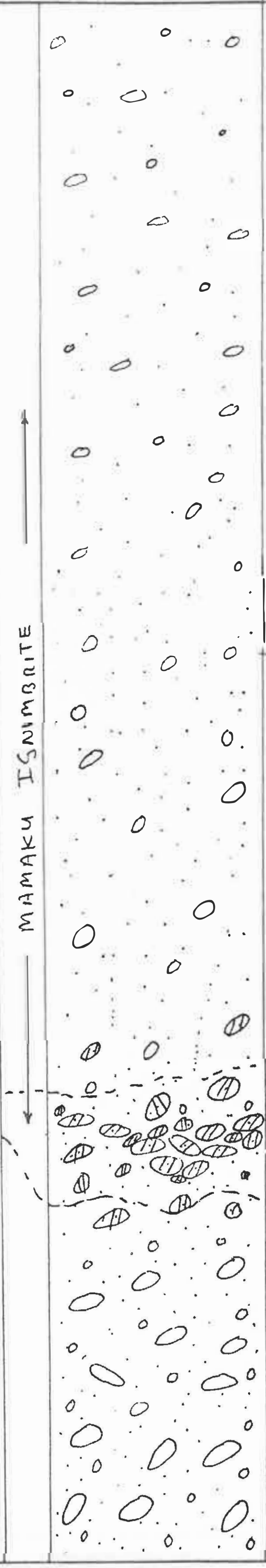
TOTAL THICKNESS	THICKNESS	PROFILE NOT TO SCALE	HANDSPECIMEN DESCRIPTION	COMMENTS
metres				
52	17	MAMAKU IGNIMBRITE	a) PINKISH GREY b) CRYSTALS: 13% c) PUMICE: 13, 4%, 15[1–38] PALE PINK, DEVITRIFIED, LENTICULAR d) LAPILLI TO FINE TUFF. MAINLY COARSE TUFF. e) STRONG, PT= 95, SLIGHTLY WEATHERED. f) NONE SEEN. g) DENSE VITRIC. h) MODERATLY SORTED.	POSSIBLE TO JUST CHIP WITH SPADE. COLUMNAR JOINTED EVERY 0·8(m).
35	15		a) PINKISH GREY. b) CRYSTALS 16% c) PUMICE: 8, 3%, 8[1-20]mm LIGHT GREY, LENTICULAR d) LAPILLI TO FINE TUFF. MAINLY COARSE TUFF. e) STRONG/VERY STRONG, PT=102 SLIGHTLY WEATHERED. f) NONE SEEN. g) DENSE VITRIC h) MODERATELY/WELL SORTED.	COLUMNAR JOINTED EVERY 1(m). OCCASIONAL SWARM OF JOINTS SAMPLE 614 WT 23470 SITE 2 CAN CHIP WITH PICK.
20	20		a) MEDIUM GREY b) CRYSTALS: 17% c) PUMICE: 6, 2% 27[2–50]mm LIGHT GREY, DEVITRIFIED. d) LAPILLI TO FINE TUFF. MAINLY COARSE TUFF. e) VERY STRONG, PT= 125, SLIGHTLY WEATHERED. f) NONE SEEN g) DENSE VITRIC GROUNDMASS. h) WELL SORTED.	COLUMNAR JOINTED EVERY 1·5(m). BASE OF ROAD BY MANGOREWA RIVER SAMPLE 613 WT 23469 SITE 1
	0			

Stratigraphic Column : JOYCE ROAD G.R.: 414/853736



TOTAL THICKNESS (metres)	THICKNESS (metres)	PROFILE NOT TO SCALE	HANDSPECIMEN DESCRIPTION	COMMENTS
38·12	0·06		BROWNISH BLACK 10YR 3/2. SILTY CLAY LOAM, WELL DEVELOPED, NUTTY STRUCTURE.	A HORIZON ABUNDANT ROOTS.
38·06	0·65		BRIGHT YELLOW BROWN 10YR 5/8 SILT LOAM, PLASTIC, SLIGHTLY STICKY	PALESOL AT TOP REREWHAKAAITA ASH. MASSIVE AT BASE
37·41	0·75		YELLOW BROWN 10YR 5/6 SANDY LOAM, NON STICKY NON PLASTIC. FRIABLE, STRONGLY DEVELOPED AT TOP. MEDIUM NUT BROWN MASSIVE CLAY AT BASE.	WELL DEVELOPED PALESOL. OKAREKA ASH. FIRM TO SPADE AT BASE SHARP CONTACT.
36·66	1·42		BROWN 10YR 4/4. SANDY CLAY, PRISIMATIC STRUCTURE TOWARDS TOP. TOWARDS BASE: YELLOW ORANGE 10YR 7/8, SANDY PUMICE. STRUCTURLESS. CRYSTALS 50%: QTZ, FELDS + MAFICS. PUMICE 45%: PALE YELLOW, FIBROUS LAPILLI [2-5 mm]. UITRIC MATERIAL 5%, SOME OBSIDIAN	WELL DEVELOPED PALESOL. MANGAONI LAPILLI GRADITIONAL CHANGE FROM PALESOL TO CLAY TO SANDY PUMICE. SHOWER BEDDED
35·24	0·74		UPPER LAYER: PALE YELLOW 2·5Y/8·3 SANDY SILT 95% UITRIC, OCCASIONAL CRYSTAL OR ROCK FRAGEMENT. BASAL LAYER: BRIGHT YELLOW BROWN 10YR 6/6. PUMICE 30% PALE YELLOW (1-5 mm).	DISTINCTIVE WHITE LENS, STANDS PROUD OF CUTTING. UPPER LAYER DENSE, STANDS PROUD OF CUTTINGS. SHOWERBEDDED.
34·5	2·5		BROWN 10YR 4/6. CLAY LOAM WELL DEVELOPED PRISIMATIC STRUCTURE, SLIGHTLY STICKY, PLASTIC. AS ABOVE FOR BASAL ZONE EXCEPT STRUCTURLESS. UNDERLYING MAMAKU IGNIMBRITE	STRONGLY DEVELOPED PALEOSOL. HAMILTON ASH.

Stratigraphic Column : JOYCE ROAD CUTTING G.R.: U14/853736

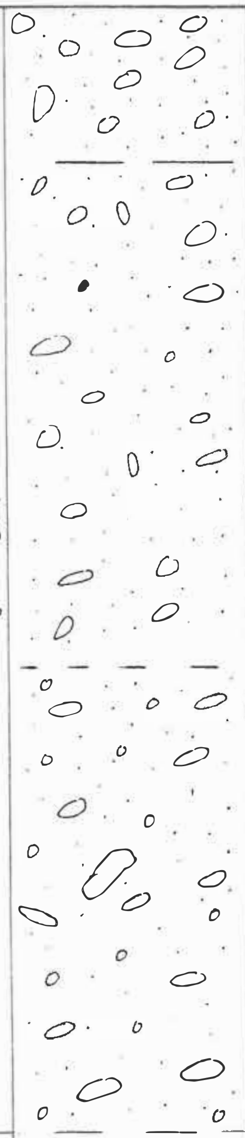


TOTAL THICKNESS (metres)	THICKNESS (metres)	PROFILE NOT TO SCALE	HANDSPECIMEN DESCRIPTION	COMMENTS
32	2	MAMAKU IGNIMBRITE	a) ORANGE BROWN. b) CRYSTALS: QUARTZ, FELDSPARS, STUMPY MAFICS 15%. c) PUMICE: 5%, 18[3-35]mm YELLOW, WEATHERED RELIC FIBROUS TEXTURE, NOT DEVITRIFIED. d) MAINLY LAPILLI AND COARSE TUFF SOME FINE TUFF. e) VERY WEAK, PT = 24, HIGHLY WEATHERED. f) NO LITHICS g) CLAY h) MODERATELY SORTED.	CONTACT WITH TEPHRA. EASY TO SPADE. SHEET 4. SAMPLE 546 WT 23445 SITE 7. PUMICE FROM THE UNDERLYING LENS INTRUDES SLIGHTLY INTO THIS IGNIMBRITE.
30	0.64		DESCRIPTION OF GROUNDMASS IN PUMICE LENS: a) LIGHT BROWN GREY, ABUNDANT BROWN STAINS. b) CRYSTALS: AS ABOVE EXCEPT MAFICS WEATHERED. 12%, 15% IF BROWN STAINS COUNTED. c) PUMICE LIGHT PINK, WEATHERED RELIC FIBROUS TEXTURE, PARTLY CLAST AND MATRIX SUPPORTED. 40[5-60]mm d) MAINLY LAPILLI TUFF, SOME FINE TUFF. e) VERY WEAK, HIGHLY WEATHERED PT READING NOT TAKEN. f) NONE SEEN g) CLAY/VITRIC. g) POORLY SORTED.	GRADATIONAL CHANGE IN GROUNDMASS COLOUR. NOTE: PUMICE HAS CONCENTRATED IN A LENS BUT EXTENDS ABOVE AND BELOW THE LAYER. SAMPLE 545 WT 23444 SITE 6. SHEET 4
29	2		RETURN TO 'NORMAL' MAMAKU SIMILAR TO THAT DESCRIBED IN CRYSTAL CONCENTRATION ZONE	SHEET 3

Stratigraphic Column : JOYCE ROAD CUTTING G.R.: U14/853736

TOTAL THICKNESS	THICKNESS	PROFILE NOT TO SCALE	HANDSPECIMEN DESCRIPTION	COMMENTS
metres				
	2		'NORMAL' MAMAKU	NO JOINTING. FIRM TO SPADE
	0.28		a) LIGHT BROWN GREY b) CRYSTALS: QUARTZ, FELDSPAR, MAFICS, 12%. c) PUMICE: 5%, 3[0.5-5]mm BROWN GREY DEVITRIFIED. d) MAINLY COARSE SOME FINE TUFF. e) VERY WEAK, PT=27, MODERATELY WEATHERED. f) NO LITHICS g) VITRIC/CLAY h) WELL SORTED.	NOTICEABLE BEDDED CRYSTAL ZONE STRIKES NW/SE BEDDING JUST DETECTABLE IN OUTCROP, BUT STANDS OUT WELL WHEN SPADED. SITE 5 SAMPLE 544, WT 23443
27	7	MAMAKU IGNIMBRITE	PUMICE BECOMES CONCENTRATED [50%] BEFORE BEDDED CRYSTAL CONCENTRATION ZONE. THIS DESCRIPTION OF MAMAKU 2m BEFORE PUMICE CONCENTRATION ZONE a) LIGHT PINKY GREY b) CRYSTALS: AS ABOVE 5% c) PUMICE 23, 12%, 13[5-23]mm 1/3 LIGHT PINK, 2/3rds LIGHT BROWN. DEVITRIFIED, RELIC FIBROUS TEXTURE. d) COARSE AND FINE TUFF e) VERY WEAK, PT=18, MODERATELY WEATHERED. f) NONE SEEN g) VITRIC/CLAY h) MODERATELY/POORLY SORTED.	EASILY SPADED. SAMPLE 543 WT 23442 SITE 4
20	6		a) LIGHT GREY, BROWN SPOTS b) CRYSTALS: AS ABOVE 3%. c) PUMICE: 18, 8%, 11[2-20]mm VERY LIGHT PINK, DEVITRIFIED. d) AS ABOVE e) VERY WEAK, PT=28,	SAMPLE 542 WT 23441 SITE 3 CONT'D

Stratigraphic Column : JOYCE ROAD CUTTING G.R.: U14/853736

TOTAL THICKNESS (metres)	THICKNESS (metres)		PROFILE	HANDSPECIMEN DESCRIPTION	COMMENTS
		MAMAKU IGNIMBRITE		f) NO LITHICS. g) VITRIC h) MODERATELY SORTED.	WT 23441 SAMPLE 542 SITE 3
14	8			a) LIGHT YELLOW ORANGE b) CRYSTALS AS ABOVE 3% c) PUMICE: 27, 12%, 13 [2 - 22] mm LIGHT PINK DEVITRIFIED. LENTICULAR d) LAPILLI TO FINE TUFF, MAINLY COARSE. e) VERY WEAK, PT = 35, SLIGHTLY WEATHERED. f) 1 UNIDENTIFIABLE LITHIC g) MODERATELY SORTED.	SAMPLE 541 WT 23440 NOTICABLY HARDER TO CHIP FROM OUTCROP SITE 2
6	6			a) LIGHT YELLOW, BROWN SPOTS. b) CRYSTALS: AS ABOVE 5%. c) PUMICE: 13 12% 15 [1 - 43] mm GREYISH PINK, DEVITRIFIED, SLIGHTLY LENTICULAR. d) LAPILL TO FINE TUFF MAINLY COARSE TUFF. e) VERY WEAK PT = 22 f) NONE SEEN, POORLY SORTED	BASE OF COLUMN. EASILY SPADED.
	0				

Stratigraphic Section: HORIZONTAL SECTION OF MAMAKU IGNIMBRITE, LOGGING TUNNEL AND CUTTINGS BY BELK ROAD - G.R.: 825 711

TOTAL THICKNESS (metres)	THICKNESS (metres)	PROFILE (NOT TO SCALE)	HANDSPECIMEN DESCRIPTION	COMMENTS
114	40	MAMAKU IGNIMBRITE	a) TAN BROWN b) CRYSTALS: QUARTZ, FELDSPARS AND WEATHERED MAFICS. 7%. c) PUMICE: 3, 1%, 17[5–72]mm ½ YELLOW ½ PINK, DEVITRIFIED. d) LAPILLI TO MAINLY COARSE AND FINE TUFF. e) WEAK ROCK, PT = 49, SLIGHTLY WEATHERED. f) ONE RHYOLITE (6mm). g) VITRIC/CLAY h) WELL SORTED	START OF SOUTHERN END OF CUTTING. WALLS UP TO 8m HIGH. NO JOINTING FIRM TO SPADE. SAMPLE 412. WT 23591 SITE 4.
154	40		a) LIGHT BROWN. b) CRYSTALS: AS ABOVE, 10% c) PUMICE: 7, 2%, 20[10–30]mm LIGHT YELLOW, ROUND, DEVITRIFIED d) LAPILLI TO MAINLY COARSE AND FINE TUFF. e) WEAK ROCK, PT = 46 f) NO LITHICS SEEN. g) VITRIC / CLAY h) WELL SORTED	MIDDLE OF CUTTING. SLIGHTLY COLUMNAR JOINTED FIRM TO SPADE. SAMPLE 413 WT 23592 SITE 5.
194	40		a) BROWNISH PINK. b) CRYSTALS: AS ABOVE, 11% c) PUMICE: 4, 1.5%, 25[5–54]mm PINK, DEVITRIFIED, ROUNDED TO SEMI LENTICULAR. d) LAPILLI TO MAINLY COARSE AND FINE TUFF. e) WEAK, PT = 54, MODERATLY WTHD. f) NO LITHICS, g) VITRIC/CLAY GROUNDMASS h) MODERATLY SORTED.	NORTHERN END OF CUTTING. FIRM TO SPADE SAMPLE 414 WT 23593 SITE 6.

Stratigraphic Section: HORIZONTAL PROFILE OF MAMAKU IGNIMBRITE, LOGGING TUNNEL AND CUTTING BELK ROAD

G.R.: U14/825711

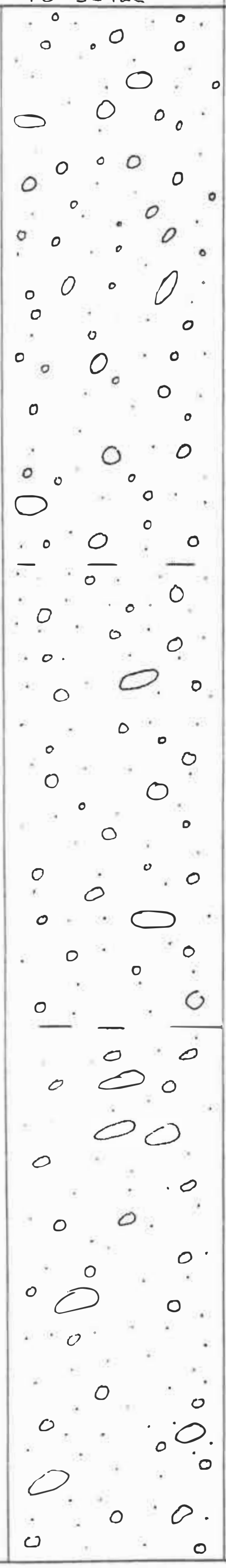
TOTAL THICKNESS (metres)	THICKNESS (metres)	PROFILE (NOT TO SCALE.)	HANDSPECIMEN DESCRIPTION	COMMENTS
0–17	0–17	MAMAKU IGNIMBRITE	a) BROWNISH PINK, BROWN SPOTS. b) CRYSTALS: QUARTZ, FELDSPARS AND WEATHERED MAFICS, MEDIUM SIZE, 10%. c) PUMICE: 4, 1.5%, 25[4-37] mm YELLOW AND BROWN, DEVITRIFIED, OCCASIONAL TUBE LIKE GROWTHS. NOT LENTICULAR. d) LAPILLI TO FINE TUFF. e) WEAK, PT = 55, SLIGHTLY WTHD. f) NO LITHICS g) VITRIC/CLAY. h) MODERATLY SORTED	SOUTHERN END OF TUNNEL. FIRM TO SPADE. SLIGHTLY COLUMNAR JOINTED. SAMPLE 416 WT 23595 SITE 1.
34	17		a) TAN PINK, BROWN SPOTS. b) CRYSTALS: AS ABOVE, 7%. c) PUMICE: 5, 1%, 15 [3 - 29] mm LIGHT YELLOW, DEVITRIFIED d) LAPILLI TO FINE TUFF. e) WEAK, PT = 47, SLIGHTLY WTHD. f) 1 RHYOLITE? LITHIC. g) VITRIC/CLAY h) MODERATLY / WELL SORTED	NORTHERN END OF TUNNEL. WELL DEVELOPED COLUMNAR JOINTING EVERY 1m. SAMPLE 411 WT 23590 SITE 2.
74	40		a) TAN BROWN, BROWN SPOTS. b) CRYSTALS: AS ABOVE, SOME STUMPY MAFICS SUGGESTING AUGITE. 9%. c) PUMICE: , 1%, 15 [3-40] mm TAN PINK, DEVITRIFIED, NOT LENTICULAR. d) LAPILLI TO MAINLY COARSE TO FINE TUFF. f) NONE SEEN g) VITRIC / CLAY h) MODERATLY SORTED.	HALF WAY BETWEEN CUTTING AND TUNNEL. FIRM TO SPADE. SAMPLE 415. WT 23594 SITE 3.

Stratigraphic Column : NGAMANAWA INCORPORATION G.R.: U15/791647

TOTAL THICKNESS (metres)	THICKNESS	PROFILE NOT TO SCALE	HANDSPECIMEN DESCRIPTION	COMMENTS
76.11	0.46	AIRFALL TEPHRA	BROWN 10YR 4/4 CLAY LOAM. NUTTY STRUCTURE, MODERATELY STICKY & PLASTIC. MANY BLACK SPOTS - BIOTITE	A HORIZON NOT PRESENT, PROBABLY REMOVED BY BULLDOZER REREWHAKAAITU ASH
75.65	0.6		LIGHT GREY 10YR 7/1 SANDY CLAY SLIGHTLY NUTTY STRUCTURE, MORE SANDY TOWARDS BASE.	SHARP CONTACT WITH ABOVE. TEPHRIC LOESS
75.05	0.5		ORANGE YELLOW 10YR 8/6 SANDY LOAM, MODERATELY DEVELOPED NUTTY STRUCTURE. PUMICEOUS TOWARDS BASE	OKAREKA ASH SHARP CONTACT
74.55	0.3		BROWNISH GREY 10YR 5/1. SILTY CLAY MASSIVE, NO STRUCTURE	TEPHRIC LOESS.
74.25	1.5		BRIGHT BROWN 7.5YR 5/8 SANDY CLAY. PLASTIC & STICKY. WELL DEVELOPED PRISMS, BREAKS INTO A NUTTY STRUCTURE. PUMICEOUS TOWARDS BASE. MOTTLED BROWN (7.5YR 4/3) AND LIGHT GREY (5YR 8/1)	PALEOSOL (WELL DEVELOPED) MANGAONI LAPILLI SHARP CONTACT
72.75	0.45		LIGHT GREY 10YR 8/1, SILTY SAND FIRM, MASSIVE. GRADES INTO A LIGHT YELLOW ORANGE. 10YR 8/3 PUMICEOUS SAND	EXCELLENT SHOWER BEDDING. ROTOEHU ASH SHARP CONTACT
72.3	1.8		REDDISH BROWN 5YR 4/6, SILTY CLAY WELL DEVELOPED NUTTY STRUCTURE, PLASTIC	WELL DEVELOPED AT TOP MASSIVE TOWARDS BASE. HAMILTON ASH
70.5 70	0.5 11	MAMAKU IGNIMBRITE	GRADES INTO WEATHERED MAMAKU A) PALE PINK WITH BROWN MOTTLES B) CRYSTALS : QUARTZ, FELDSPARS WEATHERED MAFICS. MEDIUM - 4%. C) PUMICE : 57, 20%, 12 [2-21] mm. WHITE, DEVITRIFIED, ROUNDED D) COARSE TO FINE TUFF. E) VERY WEAK ROCK, P.T = 28 SLIGHT TO MODERATELY WEATHERED F) NO LITHICS SEEN G) VITRIC / CLAY H) MODERATELY SORTED	IGNIMBRITE EASILY SPADED OUTCROP 9m HIGH SAMPLE 303 WT 23384 SITE 1

Stratigraphic Column : ENTRANCE TO NGAMANAWA INCORPORATION G.R.: U15/791647

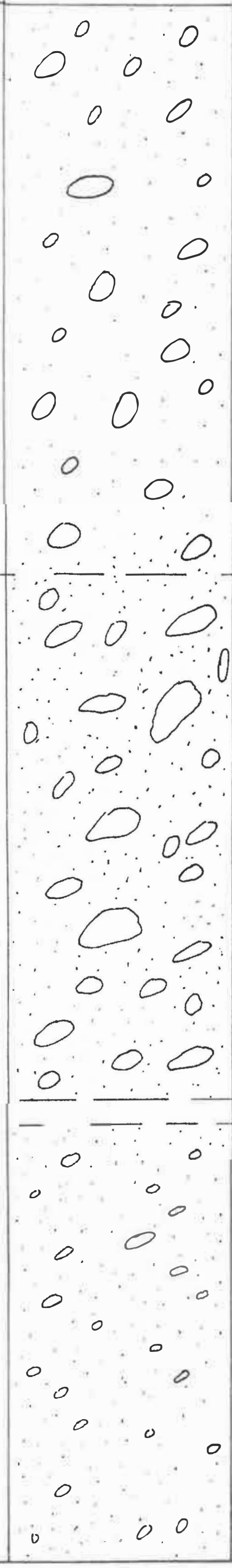
TOTAL THICKNESS (metres)	THICKNESS (metres)	PROFILE NOT TO SCALE	HANDSPECIMEN DESCRIPTION	COMMENTS
59	15	MAMAKU IGNIMBRITE	a) PALE PINK, BROWN MOTTLES b) CRYSTALS: AS ABOVE. 6%. c) PUMICE: 16, 15%, 14[3 - 42]mm RELIC FIBROUS TEXTURE EVIDENT IN SOME PUMICE, ROUNDED. DEVITRIFIED COLOUR LIGHT PINK d) LAPILLI TO MAINLY COARSE AND FINE TUFF. e) VERY WEAK/WEAK. PT = 45 SLIGHTLY WEATHERED. f) NO LITHICS SEEN. g) VITRIC h) MODERATLY SORTED.	MODERATLY FIRM TO SPADE SAMPLE 304 WT 23385 SITE 2.
44	9		a) PINK WITH BROWN MOTTLES b) CRYSTALS: AS ABOVE, 5% c) PUMICE: 33, 10%, 17[3 - 50]mm LIGHT PINK, DEVITRIFIED, ROUNDED. d) LAPILLI TO MAINLY COARSE AND FINE TUFF. e) VERY WEAK, P = 28, SLIGHTLY WEATHERED. f) NO LITHICS SEEN. g) VITRIC h) MODERATLY SORTED.	MODERATLY FIRM TO SPADE. SAMPLE 305 WT 23386 SITE 3. CLIFF 6m HIGH.
35	16		a) PINKISH RED, BLACK MOTTLES. b) CRYSTALS: AS ABOVE. 8%. c) PUMICE: 16, 10%, 15[4 - 30]mm WHITE, SLIGHTLY LENTICULAR, DEVITRIFIED d) LAPILLI TO MAINLY COARSE AND FINE TUFF. e) WEAK, P = 55, SLIGHTLY WEATHERED. f) SEVERAL RHYOLITE? LITHICS. (g) VITRIC h) MODERATLY SORTED.	FIRM TO SPADE SAMPLE 306 WT - 23387 CLIFF 4m HIGH.



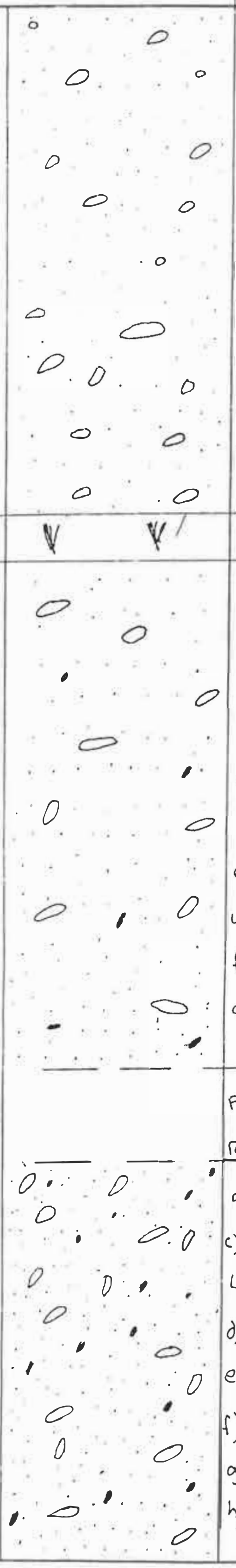
Stratigraphic Column : ENTRANCE TO NGAMANAWA INCORPORATION G.R.: U15/791647

TOTAL THICKNESS (metres)	THICKNESS (metres)	PROFILE (NOT TO SCALE)	HANDSPECIMEN DESCRIPTION	COMMENTS
19	12	MAMAKU IGNIMBRITE	a) PINK WITH BLACK MOTTLES b) CRYSTALS: AS ABOVE 10%. c) PUMICE: 28, 15% 16[3-27]mm WHITE, DEVITRIFIED, SEMI LENTICULAR d) LAPILLI TO MAINLY COARSE TO FINE TUFF. e) WEAK, PT=42, SLIGHTLY WEATHERED. f) RHYOLITE LITHIC (10mm) g) VITRIC. h) MODERATLY SORTED.	MAMAKU COLLUVIUM OVERLYING. SITE 5 SAMPLE 307 WT 23388 FIRM TO SPADE.
7	5		a) PINK WITH BLACK MOTTLES b) CRYSTALS: AS ABOVE, 12%. c) PUMICE: 23, 7%, 22[2-38]mm. PINK, DEVITRIFIED, LENTICULAR. d) AS ABOVE e) MODERATLY STRONG, PT.=69 f) NO LITHICS. g) VITRIC h) MODERATLY TO POORLY SORTED.	SITE 6. SAMPLE 308 WT 23389 DIFFICULT TO SPADE. PICK STARTING TO 'RING'. BANK 5m HIGH.
2	2		a) PINK WITH BROWN MOTTLES. b) CRYSTALS: AS ABOVE 15%. c) PUMICE: 15, 5%, 19[2-47]mm PINK, SEMI LENTICULAR, DEVITRIFIED. d) AS ABOVE e) WEAK/MODERATLY STRONG, PT=67. f) SEVERAL RHYOLITE? LITHICS 10-15mm. g) VITRIC GROUNDMASS h) MODERATLY SORTED.	SITE 7 SAMPLE 309 WT 23390 AT No 3 OUTLET. DIFFICULT TO SPADE. PUMICE BECOMING A LITTLE LESS LENTICULAR AND LESS PUMICE RICH.
	0			

Stratigraphic Column : DAIRY FARM NEAR OMANAWA FALLS. G.R.: U15/828681

TOTAL THICKNESS	THICKNESS	PROFILE NOT TO SCALE	HANDSPECIMEN DESCRIPTION	COMMENTS
metres			4 m OF OVERLYING TEPHRA.	
65	12	 MAMAKU IGNIMBRITE	a) LIGHT PINK, ABUNDANT BROWN SPOTS b) CRYSTALS: QUARTZ, FELDSPARS AND MAFICS [WEATHERED]. 4% c) PUMICE: 13, 25%, 23 [5-33] mm SLIGHTLY LENTICULAR, NO BEDDING. LIGHT PINK, DEVITRIFIED. d) LAPILLI, COARSE AND FINE TUFF. e) VERY WEAK, PT = 27, MODERATELY WEATHERED. f) NO LITHICS g) RELIC VITRIC h) POORLY SORTED.	ABOUT 6 m FROM CONTACT WITH TEPHRA. EVIDENCE OF CATTLE EATING THE IGNIMBRITE. [TEETH MARKS] EASILY SPADED SAMPLE 621 WT 23476. SITE 1
53	5		a) LIGHT GREYISH PINK. b) CRYSTALS: AS ABOVE 6%. c) PUMICE: 10, 20%, 66 [10-130] mm. LIGHT PINK, DEVITRIFIED, SEMI LENTICULAR. d) PYROCLASTIC BRECCIA TO FINE TUFF. MAINLY LAPILLI TO COARSE TUFF. e) WEAK, PT = 38, MODERATELY WELDED. f) NO LITHICS. g) RELIC VITRIC. h) VERY POORLY SORTED	EASILY CHIPPED OUT WITH SPADE. NOTICE INCREASE IN PUMICE SIZE. SAMPLE 622 WT 23477 SITE 2
48	18		OBSCURED	
30	4		a) DARK GREYISH PINK, BROWN SPOTS b) CRYSTALS: AS ABOVE 10%. c) PUMICE: 30, 18%, 8 [3-13] mm. LIGHT BLUISH GREY, DEVITRIFIED LENTICULAR. d) LAPILLI, COARSE AND FINE TUFF. e) MODERATELY STRONG, PT = 70 SLIGHTLY WEATHERED. f) NO LITHICS, g) RELIC VITRIC h)	CAN JUST CHIP WITH SPADE. SAMPLE 623 WT 23478 SITE 3

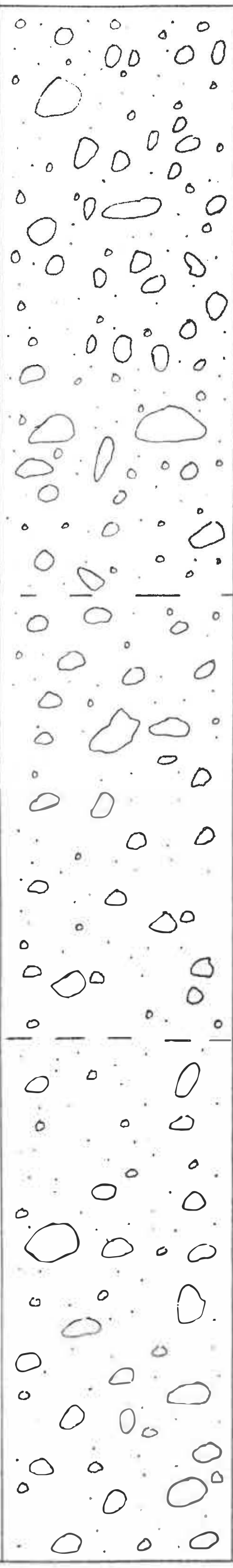
Stratigraphic Column : DAIRY FARM NEAR OMANAWA FALLS G.R.: U15/828681



TOTAL THICKNESS	THICKNESS		PROFILE	HANDSPECIMEN DESCRIPTION	COMMENTS
metres					
26	5	MAMAKU IGNIMBRITE		a) BROWNISH GREY b) CRYSTALS: AS ABOVE 8%. c) PUMICE: 12, 10%, 21 [3-32] mm SLIGHTLY LENTICULAR, NO LAYERING LIGHT ORANGE, WEATHERED FIBROUS TEXTURE d) LAPILLI TO FINE TUFF, MAINLY COARSE TUFF. e) VERY WEAK, PT = 28, SLIGHTLY WTHD. f) NO LITHICS. g) VITRIC G/M. h) MODERATELY SORTED.	SOFT UNCONSOLIDATED EASILY SPADED BASAL MAMAKU SAMPLE 626 WT 23481 SITE 4 CONTACT WITH WAIMAKARIRI NOT SEEN
21	3		V V	OBSCURED BY COLLUVIUM AND SOIL.	
18	13	WAIMAKARIRI IGNIMBRITE		a) LIGHT GREY. b) CRYSTALS: 10%. c) PUMICE: DIFFICULT TO ASSESS. ≤1% ?, DEVITRIFIED WHITE. d) LAPILLI TO FINE TUFF, MAINLY COARSE TUFF. e) STRONG, PT = 85, SLIGHTLY WEATHERED f) OCCASIONAL RHYOLITE 1%. g) DENSE VITRIC, h) MODERATELY WELL SORTED.	JUST CHIP WITH SPADE. SAMPLE 624 WT 23479 SITE 5 NOTE: NEXT DESCRIPTION OF WAIMAKARIRI, OBTAINED BY
				PUSHING 1 km ALONG RIVER BANK RIVER BED. FOLLOWING SITE DOES NOT	TO REACH DIRECTLY UNDERLYING SITE 5
5	5			a) LIGHT GREY. b) CRYSTALS 10%. c) PUMICE: 13, 8%, 15[1-25] mm LIGHT GREY, FIBROUS - KNOTTY, LENTICULAR d) MAINLY LAPILLI / COARSE TUFF. e) MODERATELY STRONG, PT = 67 f) ABUNDANT LITHICS, 3-10 mm, 5% g) VITRIC GROUND MASS. h) MODERATELY SORTED	STREAM BED OF OMANAWA RIVER. ABUNDANT POTHOLING AND UNUSUAL FRITTED APPEARANCE SAMPLE 625 WT 23480 SITE 6
0	0				

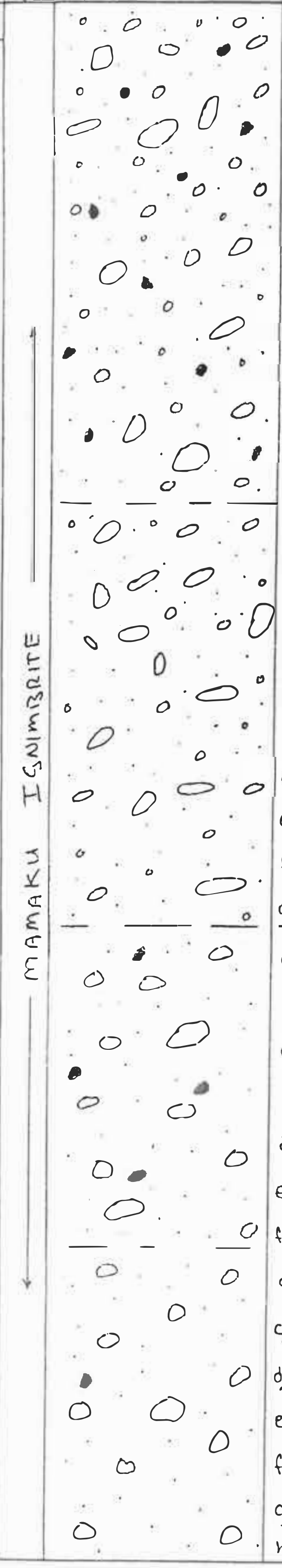
Stratigraphic Column : HEKES TRACK

G.R.: U15/ 809652

TOTAL THICKNESS	THICKNESS		PROFILE (NOT TO SCALE.)	HANDSPECIMEN DESCRIPTION	COMMENTS
metres					
67	4			FOUR METERS OF OVERLYING TEPHRA. NOT DESCRIBED.	
65	18	MAMAKU IGNIMBRITE		a) PINK, NO BROWN SPOTS. b) CRYSTALS: QUARTZ, FELDSPARS AND FRESH MAFICS. 2%. c) PUMICE: 17, 20%, 33[4 – 55]mm PALE PINK, DEVITRIFIED, NO BEDDING OR IMBRICATION. d) MAINLY LAPILLI AND COARSE TUFF, SOME FINE TUFF. e) VERY WEAK, PT = 38, SLIGHTLY WEATHERED. f) NO LITHICS. g) RELIC VITRIC. h) POORLY SORTED.	NEAR TOP OF THE MAMAKU IGNIMBRITE. EASILY SPADED. SAMPLE 336 WT 23576. SITE 7.
53	11			a) LIGHT PINK, BROWN SPOTS. b) CRYSTALS: AS ABOVE, MAFICS WEATHERED, 3%. c) PUMICE: 26, 15%, 22[2 – 40]mm DEVITRIFIED LIGHT GREY, A RANDOM LAYERING d) LAPILLI, COARSE AND FINE TUFF. e) VERY WEAK/WEAK, PT = 45. f) NO LITHICS. g) VITRIC h) POORLY SORTED.	SITE 6 FIRM IN PLACE EASILY SPADED. SAMPLE 335 WT 23575
42	16			a) LIGHT PINK, BLACK SPOTS. b) CRYSTALS: AS ABOVE 5%. c) PUMICE: 24, 17%, 25[3 – 74]mm WHITISH PINK, DEVITRIFIED, RANDOM ORIENTATION. SLIGHTLY LENTICULAR. d) PYROCLASTIC BRECCIA TO FINE TUFF. e) WEAK, PT = 48, SLIGHTLY WEATHERED f) NO LITHICS, g) VITRIC h) POORLY SORTED.	FIRM IN PLACE EASILY SPADED. SAMPLE 334 WT 23574 INCIPIENT COLUMNAR JOINTING. SITE 5

Stratigraphic Column HEKES TRACK

G.R.: U15/ 809652

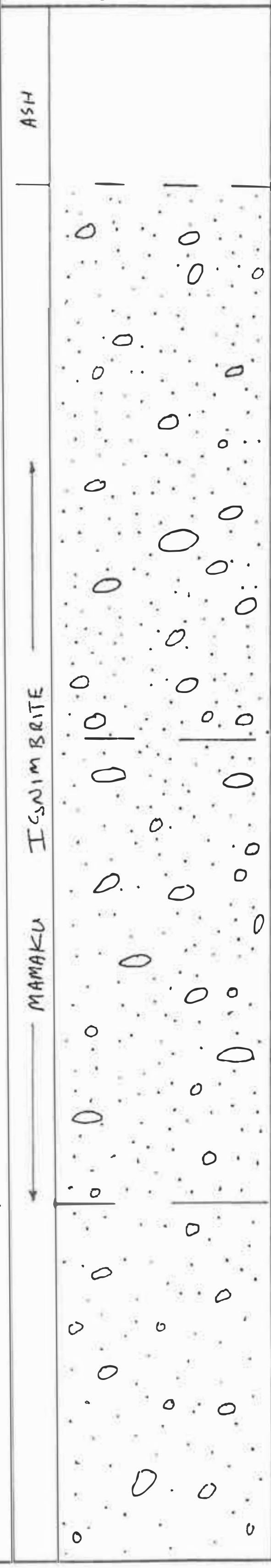


TOTAL THICKNESS	THICKNESS	PROFILE (NOT TO SCALE)	HANDSPECIMEN DESCRIPTION	COMMENTS
metres				
26	4	MAMAKU IGNIMBRITE	a) LIGHT PINK WITH BLACK SPOTS. b) CRYSTALS: AS ABOVE, 7%. c) PUMICE: 27, 14%, 36[3-62]mm WHITISH PINK, DEVITRIFIED, SEMI LENTICULAR. d) LAPILLI TO MAINLY COARSE AND FINE TUFF e) WEAK/MODERATELY STRONG, PT=63 SLIGHTLY WEATHERED. f) ABUNDANT RHYOLITE LITHICS, 3% AVERAGE=15mm, MAXIMUM=30mm. g) VITRIC, h) MODERATELY/POORLY	COLUMNAR JOINTS EVERY ½ m. LITHIC CONCENTRATION ZONE. MANY HAVE FALLEN OUT OF THE FACE, GIVING A HOLLOWED APPEARANCE SAMPLE 333 WT 23573 FIRM TO SPADE SITE 4.
22	12		a) LIGHT PINK TO YELLOW, BLACK SPOTS. b) CRYSTALS AS ABOVE, 10%. c) PUMICE: 25, 15% 15[3-5]mm WHITE + PINK, DEVITRIFIED, LENTICULAR. d) LAPILLI, COARSE AND FINE TUFF. e) WEAK, PT=48, SLIGHTLY WEATHERED. f) NO LITHICS g) VITRIC, h) MODERATLY/POORLY SORTED	INCIPIENT COLUMNAR JOINTS. FIRM/EASY TO SPADE SAMPLE 332 WT 23572 SITE 3.
10	7		a) PINK WITH BLACK SPOTS. b) AS ABOVE 13%. c) PUMICE: 23, 10% 12[4-50]mm PINK, SEMI LENTICULAR. d) LAPILLI, COARSE AND FINE TUFF. e) WEAK, PT=55, SLIGHTLY WHTD f) 1% RHYOLITE LITHICS. g) VITRIC. h) MODERATLY	NO JOINTING SAMPLE 331 WT 23571 SITE 2.
3	3		a) LIGHT PINK BROWN SPOTS. b) AS ABOVE 15% c) 11, 5% 10[2-66]mm; PINK DEVITRIFIED. d) PYROCLASTIC BRECCIA TO MAINLY COARSE TO FINE TUFF e) VERY WEAK, PT=47, SLIGHTLY WTHD. f) VERY OCCASIONAL LITHIC. g) VITRIC h) MODERATELY/WELL SORTED.	NO JOINTING. SAMPLE 330 WT 23570 SITE 1
	0			

Stratigraphic Column : OROPI GORGE

G.R.: U15/877687

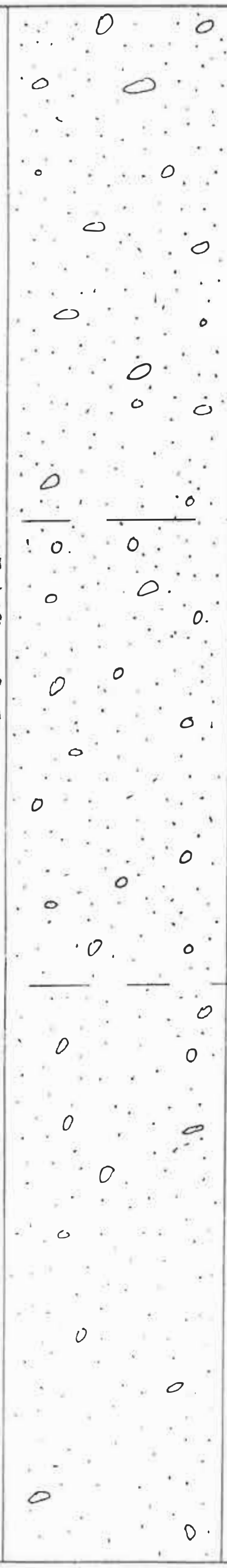
TOTAL THICKNESS (metres)	THICKNESS (metres)	PROFILE NOT TO SCALE	HANDSPECIMEN DESCRIPTION	COMMENTS
		ASH	CAPPED BY 4 m OF ASH AND 3 m OF SHEET 4. TOP OF COLUMN.	
59	4	MAMAKU IGNIMBRITE	a) LIGHT REDDISH GREY. b) CRYSTALS: QUARTZ, FELDSPARS AND WEATHERED MAFICS. 8%. c) PUMICE: 20, 10%, 14[3-24]mm MOSTLY REDDISH GREY, OCCASIONALLY LIGHT GREY, DEVITRIFIED d) LAPILLI TO FINE TUFF, MOSTLY COARSE TUFF. e) SLIGHTLY WEATHERED, VERY WEAK, PT=42. f) NONE SEEN. g) RELIC VITRIC. h) MODERATLY SORTED.	EASILY DUG WITH SPADE. SAMPLE 908. WT 23545 SITE. 20
55	10	MAMAKU IGNIMBRITE	a) LIGHT PURPLISH GREY. b) CRYSTALS: AS ABOVE 10%. c) PUMICE: 21, 9%, 21[5-40]mm BLUE/GREY, SLIGHTLY LENTICULAR. d) LAPILLI TO FINE TUFF. MOSTLY COARSE TUFF. e) VERY WEAK/WEAK, PT= 48 UNWEATHERED f) NONE SEEN. g) RELIC VITRIC. h) MODERATELY SORTED.	FIRM TO SPADE. SAMPLE 907 WT 23544 SITE 19 INCIPIENT COLUMNAR JOINTING.
45	6		a) LIGHT PINKISH GREY b) CRYSTALS: AS ABOVE 8% c) PUMICE: 17, 8%, 17[5-32]mm LIGHT GREY, DEVITRIFIED, ROUNDED TO SUB LENTICULAR. RELIC FIBROUS TEXTURE d) AS ABOVE e) WEAK, PT=57, UNWEATHERED. f) NONE SEEN. g) RELIC VITRIC h) MOD SORTED	COLUMNAR JOINTING MORE DEFINED. SAMPLE 906 WT 23543 SITE 18



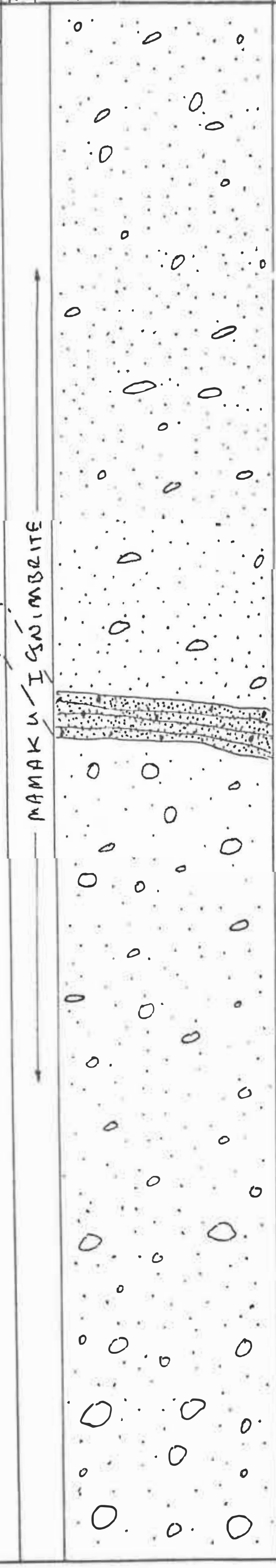
Stratigraphic Column : Oropi Gorge

G.R.: 415/877687

TOTAL THICKNESS	THICKNESS	PROFILE (NOT TO SCALE)	HANDSPECIMEN DESCRIPTION	COMMENTS
metres				
39	4	MAMAKU IGNIMBRITE	a) LIGHT PINKISH GREY b) CRYSTALS: AS ABOVE 10%. c) PUMICE: 16,7%, 8[0.5-17]mm PINKISH GREY, OCCASIONAL RELIC FIBROUS TEXTURE, GENERALLY VERY DEVITRIFIED. d) AS ABOVE, PERHAPS A LITTLE MORE FINE TUFF. e) VERY WEAK, PT=30, MODERATELY WEATHERED. f) NONE SEEN g) RELIC VITRIC.	INCIPIENT COLUMNAR JOINTING, THOUGH THIS HAS MOSTLY DIED OUT. OCCASIONAL JOINT HAS FILLED WITH YELLOW CLAY. SAMPLE 905 WT 23542. SITE 17
35	6		a) REDDISH GREY b) CRYSTALS. 9%. c) PUMICE: 15, 5%, 10[5-23]mm PURPLE GREY, DEVITRIFIED, "SNOW LIKE" CRYSTALS FOUND IN SOME PUMICE d) LAPILLI TO FINE TUFF, MAINLY COARSE TUFF. e) MODERATELY STRONG, PT = 58, UNWEATHERED. f) NONE SEEN. g) RELIC VITRIC h) MODERATELY SORTED.	UPPER MIDDLE OF COLUMNAR JOINTED ZONE. CAN JUST CHIP WITH SPADE. SAMPLE: 904 WT 23541 SITE 16
29	3		a) PINKISH GREY b) CRYSTALS: 8 c) PUMICE: 13, 3%, 8[2-27]mm DIFFICULT TO ASSESS, PUMICE ABOVE ESTIMATE ONLY. PINK BROWN. SEMI LENTICULAR. d) LAPILLI TO FINE TUFF. MAINLY COARSE TUFF. e) VERY WEAK, PT=41, MOD WTHD. f) NO LITHICS g) RELIC VITRIC h) MODERATELY SORTED.	CHIPPED OUT WITH SPADE EASILY. BASE OF COLUMNAR JOINTED ZONE



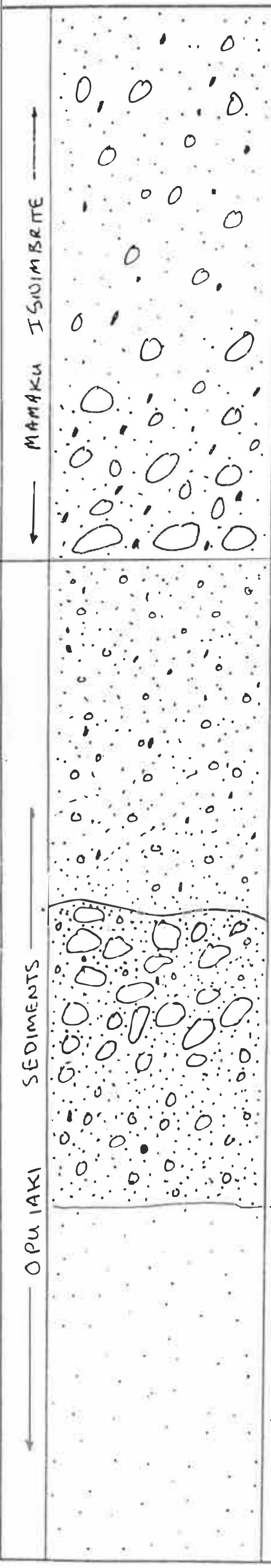
Stratigraphic Column: Oropi Gorge G.R.: U15/877687



TOTAL THICKNESS (metres)	THICKNESS (metres)	PROFILE	HANDSPECIMEN DESCRIPTION	COMMENTS
26	2	Mamaku Ignimbrite	a) Light orange brown. b) Crystals: 12% c) Pumice: 16, 5% 14[3-40] mm. Highly weathered, fibrous texture [WTHD not devitrified] yellow brown. d) Lapilli to fine tuff, e) Very weak, PT = 30, highly weathered. f) Occasional rhyolite lithic [<1%] [quite weathered] 2-5 mm. g) Vitric/clay. h) Moderately to well sorted.	Easily spaded. Directly above bedded zone. Below columnar jointed zone. Sample 903 WT 23540. Site. 14.
23.9 23.8	0.07 2.5	Mamaku Ignimbrite	a) Orange to dull brown. b) Crystals: 50% c) No pumice seen. d) Mostly coarse tuff, some fine. e) Very weak, PT = 22, f) Rhyolite lithics, 1%, g) Vitric groundmass. h) Moderately/well sorted.	High crystal concentration zone. [Bedded]. 140/2/S Sample 901 WT 23538 Site 13
		Mamaku Ignimbrite	a) Tan to pinkish brown. b) Crystals: 10%. c) Pumice; 40, 15% 26[4-47]mm light yellow grey vesicular and fibrous, highly weathered d) Lapilli to coarse tuff, mainly coarse to fine tuff. e) Very weak, PT = 15, moderately weathered. f) Rhyolite lithics, 1%, 2-5mm. g) Vitric/clay groundmass. h) Moderately/poorly sorted.	Very noticeable increase in weathering and decrease in pumice size before crystal concentration zone Sample 900 WT 23537 Site 12 Easily spaded.

Stratigraphic Column OROPI GORGE

G.R.: U15/877687

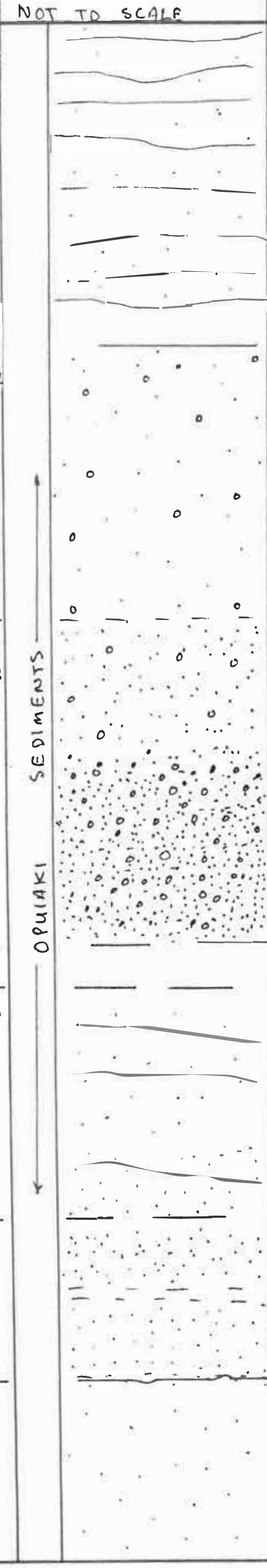


TOTAL THICKNESS (metres)	THICKNESS (metres)	PROFILE (NOT TO SCALE)	HANDSPECIMEN DESCRIPTION	COMMENTS
21.3	1.5	MAMAKU IGNIMBRITE	a) LIGHT YELLOW ORANGE, WITH TINGES OF GREY. b) CRYSTALS: 8%. c) PUMICE: 12, 30%, 18[2-60] mm LIGHT YELLOW GREY, SLIGHTLY VESICULAR AND FIBROUS RELATIVELY FRESH AND UNWEATHERED. d) LAPILLI TO FINE TUFF. e) VERY WEAK, PT=30, SLIGHTLY WEATHERED. f) LITHICS: RHYOLITE, 3%, 4[1-60]mm g) VITRIC. (h) Very Poorly Sorted	BASAL PUMICEOUS ZONE OF MAMAKU IGNIMBRITE. THIS ZONE = 0.2m FINES UP OVER 1m. EASILY SPADED. SAMPLE 911 WT 23547 SITE 11 SHARP PLANAR
19.75	0.15	OPUIAKI SEDIMENTS	a) LIGHT GREY. b) LOOSE, SLIGHTLY WTHD. c) CRYSTALS: 60%, ROCK: 5% RHYOLITE. PUMICE: 35% 15[2-28] mm. d) PEBBLES, TO MOSTLY COARSE TO FINE SAND. e) MODERATELY SORTED f) PEBBLY SANDSTONE.	NON EROSIONAL CONTACT PLANAR BEDDED. Homogeneous DEPOSIT. REWORKED WAIMAKARIRI SAMPLE 910 WT 23547 SITE 10
19.6	3		a) LIGHT GREY. b) LOOSE c) CRYSTALS: 10%, ROCK: 3% PUMICE: 87% 15[2-110] mm d) COBBLE TO SILT. e) POORLY SORTED AT TOP MODERATELY SORTED AT BASE. f) COBBLE SANDSTONE.	SHARP EROSIONAL CONTACT. REVERSE BEDDED. REWORKED WAIMAKARIRI. INTERPRETED AS DEBRIS FLOW SITE 9 SAMPLE 909 WT 23546
16.6	0.8		a) LIGHT GREY. b) FIRM IN PLACE c) CRYSTALS: 2%, ROCK < 1%, GLASS: 97%. d) FINE SAND TO SILT. e) VERY WELL SORTED f) FINE SANDY SILT STONE	SHARP CONTACT. HOMOGENEOUS MASSIVE DEPOSIT. INTERPRETED AS AIRFALL. SITE 8

Stratigraphic Column : OROPI GORGE

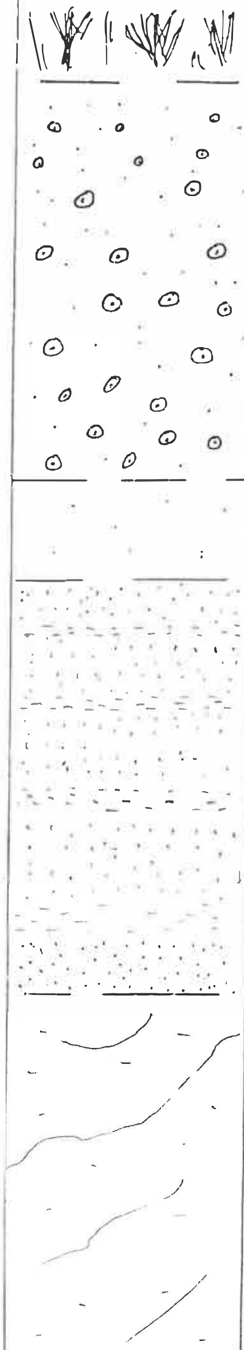
G.R.: U15/877687

PROFILE NOT TO SCALE

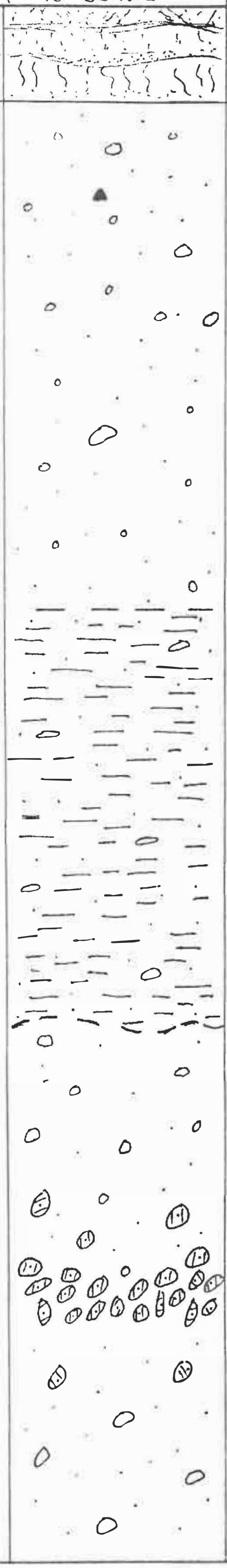


TOTAL THICKNESS (metres)	THICKNESS (metres)	HANDSPECIMEN DESCRIPTION	COMMENTS
15.8	1	a) YELLOW ORANGE b) FIRM c) CRYSTALS 1%, 99% VITRIC. d) VERY FINE SAND TO SILT. e) VERY WELL SORTED. f) FINE SANDY SILTSTONE. SUB PARALLEL LAMINATIONS.	SHARP CONTACT WITH ABOVE. FINE MICRO LAMINATIONS EVERY 2-5 mm. SITE 7
14.8	2	2(m) OBSCURED	
12.8	0.12	a) LIGHT GREY. b) LOOSE/FIRM c) CRYSTALS 4%, PUMICE 1%, GLASS [SLIGHTLY WTHD] 95%. d) GRANULES TO SILT. e) WELL SORTED f) COARSE SANDY SILTSTONE.	SAMPLE 805b. WT 23527 GRADATIONAL CONTACT.
12.7	0.08	a) YELLOW BROWN. b) LOOSE, WTHD. c) CRYSTALS: 50%, PUMICE (1-2 mm) 30%, ROCK 3%, VITRIC 25%. d) VERY COARSE, TO MEDIUM SAND. SOME SILT. e) MODERATELY SORTED. f) COARSE TO FINE SANDSTONE	NORMALLY BEDDED. SITE 6 805(a) SLIGHTLY REWORKED TEPHRA.
12.64	2	OBSCURED.	
10.64	1.3	a) LIGHT GREY (b) FIRM, SLIGHTLY WTHD. c) CRYSTALS 7%, ROCK 2% VITRIC 91%. d) SOME COARSE SAND, MOSTLY SILT. e) WELL SORTED. f) SANDY SILTSTONE.	ORANGE LAMINATIONS EVERY 10-30 mm. [SUB HORIZONTAL]. SAMPLE 804 WT 23525 SITE 5
9.34	3	THREE METRES OF NORMALLY BEDDED SAND AND SILTY CLAY. NO SAMPLES TAKEN.	
6.34	1	a) LIGHT YELLOW b) FIRM, WTHD. c) CRYSTALS: 3%, VITRIC MATERIAL WEATHERED TO CLAY. d) SOME SAND, MOSTLY CLAY. e) WELL SORTED. f) SANDY CLAYSTONE.	SHARP CONTACT. EROSIONAL SAMPLE 803 WT 23524 SITE 4

Stratigraphic Column : OROPI GORGE   G.R.: U15/877687

TOTAL THICKNESS (metres)	THICKNESS		PROFILE	HANDSPECIMEN DESCRIPTION	COMMENTS
5.34	3			OBSCURED	
2.34	0.1			a) LIGHT GREY / YELLOW. b) FIRM IN PLACE. SLIGHTLY WTHD. c) CRYSTALS 2%, CHALAZOIDITES AVERAGE 8 mm, WHEN OPENED HAVE CONCENTRIC RINGS. d) PEBBLES SAND MOSTLY SILT AND CLAY. e) MODERATELY SORTED. f) SANDY SILTSTONE	CHALAZOIDITES FINE UPWARDS. SAMPLE 802 WT 23523 SITE 3
2.24	0.04	OPUIAKI SEDIMENTS		AS ABOVE EXCEPT NO CHALAZOIDITES	
2.2	0.4			a) VERY LIGHT GREY, ALMOST WHITE. b) LOOSE, UNWEATHERED. c) CRYSTALS 90%, PUMICE < 1%, VITRIC 9%. d) COARSE, MEDIUM + FINE SAND e) WELL SORTED. f) SILTY SANDSTONE	FIRM IN PLACE. SAMPLE 801 WT 23522 SITE 2 NORMALLY BEDDED ALTERNATING COARSE SAND TO FINE SAND
1.8	1.8			a) PALE YELLOW b) FIRM IN HAND. c) NO CRYSTALS, ROCK FRAGMENTS OR PUMICE. 100% VITRIC, OBSIDIAN COMMON. d) FINE SAND TO SILT e) VERY WELL SORTED. f) SILT STONE	SHARP CONTACT WITH ABOVE. CHECKED FOR DIATOMS NONE FOUND. OCCASIONAL CURVED NON PARALLEL LAMINAE. SAMPLE 800 WT 23521 SITE 1
0	0				

Stratigraphic Column : Cutting at the end of Belk Rd. G.R.: U14/ 826712

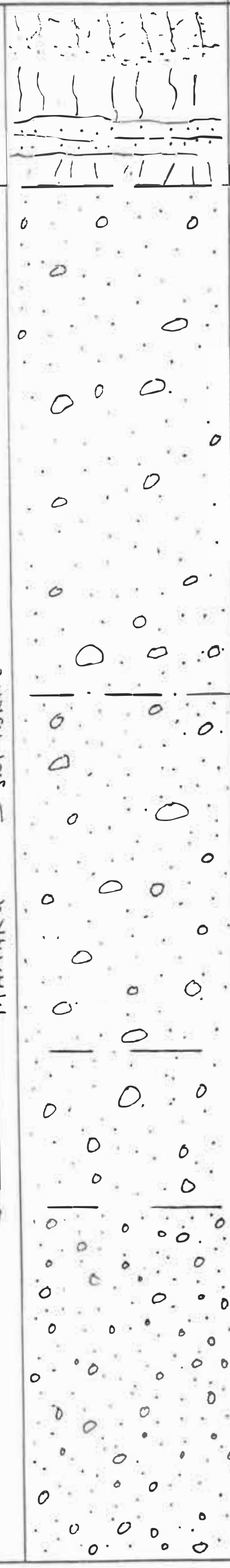


TOTAL THICKNESS	THICKNESS		PROFILE NOT TO SCALE	HANDSPECIMEN DESCRIPTION	COMMENTS
metres					
12.1	6	ASH		6m of overlying tephra Hamilton Ash measured at 4.8m.	
6.1	4	MAMAKU IGNIMBRITE		a) Yellow brown b) Crystals: quartz, feldspars, slightly weathered mafics. 7%. c) Pumice: 11, 7%, 10[1–30] mm. Yellow, weathered not devitrified. Relic fibrous texture. d) Lapilli to fine tuff. e) Very weak, moderatly wthd, PT=25 f) 1 lithic seen. g) Clay/vitric h) Well sorted.	Layer 1 Sample 402 WT 23582 Easy to spade. Sharp contact
2.2	0.1			a) Dark brown. Numerous Mn stains b) Crystals: as above, 3%. c) Pumice: Difficult to assess. About 4, 1%, 3[1–10]mm, weathered. d) Lapilli to mainly coarse and fine tuff e) Very weak/weak PT=40, f) No lithics. g) Clay-relic vitric. h) Well sorted.	Layer 2 Sample 404 WT 23583 Firm to spade
2.1	0.9			a) Pinkish brown. b) As above 8%. c) Pumice: Two distinct types: 1) Groundmass pumice; brown, [0] fibrous texture, highly weathered 8, 3%, 15[3–25] mm. 2) Pumice lens: [⊘] This pumice is concentrated in a lens, though can be found above and below the lens in layer 3. Whitish pink, relic fibrous texture. But coherent when handled 48[20–80]mm	Layer 3 Sharp undulating contact with the above. Suggestion of erosion but no sediments at contact.

Stratigraphic Column : CUTTING AT THE END OF BELK ROAD. G.R.: U14/826712

TOTAL THICKNESS	THICKNESS	PROFILE	HANDSPECIMEN DESCRIPTION	COMMENTS
metres				
			f) NO LITHICS	LAYER 3 CONTINUED.
			g) CLAY/VITRIC	SAMPLE 407
			h) MODERATELY SORTED.	WT 23586
	0.04		MANGANESE LENS	SHARP CONTACT
1.2	1.2	MAMAKU IGNIMBRITE	a) PINK WITH BLACK MOTTLES.	'NORMAL' LOOKING MAMAKU.
			b) CRYSTALS: QUARTZ, FELDSPARS AND WEATHERED MAFICS, 6%.	
			c) PUMICE: 5, 3% 20[4-47]mm	FIRM IN PLACE.
			PALE PINK, OCCASIONALLY BROWN ROUNDED, DEVITRIFIED	SAMPLE 408
			d) SOME LAPILLI TUFF, MOSTLY COARSE TO FINE TUFF.	WT 23587
			e) WEAK, SLIGHTLY WEATHERED PT = 48	SITE 1
			f) NO LITHICS SEEN.	
			g) VITRIC/CLAY	
	0		h) MODERATLY/WELL SORTED.	BASE OF ROAD.

Stratigraphic Column.: BY LLOYD MANDENO STATION G.R.: U15/787685
[PENSTOCK ROAD]



TOTAL THICKNESS (metres)	THICKNESS (metres)	PROFILE	HANDSPECIMEN DESCRIPTION	COMMENTS
	8	ASH	EIGHT METRES OF OVERLYING TEPHRA. HAMILTON ASH MEASURED AT THREE METRES. GRADES INTO WEATHERED MAMAKU.	
98	2	MAMAKU IGNIMBRITE	a) LIGHT GREY, WITH GREY BROWN STREAKS AND BLACK MOTTLES b) CRYSTALS: QUARTZ FELDSPARS AND WEATHERED MAFICS 8%. c) PUMICE 17,5%, WHITE, DEVITRIFIED, ROUNDED. BROWN RIM ON OUTER EDGE OF PUMICE d) LAPILLI TO FINE TUFF, MAINLY LAPILLI AND COARSE TUFF. e) VERY WEAK, PT = 26, MODERATELY WTHD. f) NO LITHICS SEEN. g) RELIC VITRIC h) MODERATELY SORTED.	EASILY SPADED. SAMPLE 25* WT 23353 SITE 19
96	2	MAMAKU IGNIMBRITE	a) PINK WITH BLACK MOTTLES. b) CRYSTALS 9%. c) PUMICE 21, 10%, 15[3-30]mm DEVITRIFIED WITH BLACK RIMS. d) AS ABOVE. e) WEAK, PT = 45, MOD WTHD. f) NO LITHICS SEEN. (g) RELIC VITRIC h) POORLY SORTED.	FIRM TO SPADE SAMPLE 24* WT 23352 NO JOINTING SITE 18
94	2	MAMAKU IGNIMBRITE	NOTICEABLE LOCALISED HARDNESS VARIABLE COLOUR: SHADES OF YELLOW, WHITE AND PINK.	[DUE TO FUMEROLIC ACTIVITY?]
92	2	MAMAKU IGNIMBRITE	a) PINK WITH TINGES OF YELLOW. b) CRYSTALS 8%. c) PUMICE: 60, 20%, 5[1-28]mm YELLOW, DEVITRIFIED d) LAPILLI TO FINE TUFF, MAINLY COARSE TUFF. e) VERY WEAK, PT: 27, MODERATELY WEATHERED.	NOTICEABLE PUMICE CONCENTRATION ZONE. SAMPLE 23* WT 23351 SITE 17 CONT'D

Stratigraphic Column : LLOYD MANDENO COLUMN. [PENSTOCK ROAD]

G.R.: U15/787685

TOTAL THICKNESS	THICKNESS	PROFILE NOT TO SCALE.	HANDSPECIMEN DESCRIPTION	COMMENTS
metres				
			f) NO LITHICS g) RELIC VITRIC GROUNDMASS h) POORLY SORTED	SAMPLE 23 * WT 23351 SITE. 17
	4		GRADUAL CHANGE IN COLOUR TO PINKISH GREY AS HEIGHT INCREASES TEXTURAL PARAMETERS REMAIN MUCH THE SAME. ABUNDANT BLACK MOTTLED	
86	2	IGNIMBRITE	a) LIGHT PINK WITH BLACK MOTTLES. b) CRYSTALS 2%. c) PUMICE: 13, 7%, 10[2 – 21] mm DEUITRIFIED. d) AS ABOVE. e) VERY WEAK, PT=30. MODERATELY WEATHERED. f) NO LITHICS. g) RELIC VITRIC. h) MODERATELY SORTED.	SAMPLE 22* WT 23350 SITE 16 EASY TO SPADE
84	2	MAMAKU	a) PALE WHITE, WITH TINGES OF PINK TO YELLOW. b) CRYSTALS 7% c) PUMICE: 51, 10%, 10[2 – 32] mm LIGHT PINK, DEUITRIFIED, SLIGHTLY LENTICULAR d) LAPILLI TO FINE TUFF, MAINLY COARSE TUFF. e) WEAK, PT= 45, MODERATELY/ SLIGHTLY WEATHERED. f) OCCASIONAL RHYOLITE? LITHIC ~0.5%, LITHICS HAVE BEEN DEUITRIFIED/ALTERED, CAN CRUSH BETWEEN THUMB AND FORE FINGER. g) CLAY / RELIC VITRIC h) MODERATELY SORTED	FIRM TO SPADE
82	2		SIMILAR TO UNDERLYING MATERIAL BUT INCREASE IN PUMICE SIZE TO 20 – 30 mm. SEMI LENTICULAR. DEUITRIFIED.	SITE 14 CONTD.

Stratigraphic Column LLOYD MANDENO G.R.: U15/787685

TOTAL THICKNESS	THICKNESS		PROFILE	HANDSPECIMEN DESCRIPTION	COMMENTS
metres					
80	2	MAMAKU IGNIMBRITE		a) LIGHT YELLOW WITH BROWN SPOTS c) PUMICE: 51, 15% 10[3-32] mm WHITE WITH A TINGE OF YELLOW. DEVITRIFIED. b) CRYSTALS: 3%. e) VERY WEAK/WEAK. PT = 46. MODERATELY WEATHERED. f) VERY OCCASIONAL WEATHERED RHYOLITE. g) MOSTLY CLAY — RELIC VITRIC. h) MODERATELY SORTED.	FIRM TO SPADE SAMPLE 17* WT 23349 SITE. 14.
78	4			a) OFF WHITE b) CRYSTALS 3%. c) PUMICE: 27, 10% 15[5-27]mm WHITE WITH A TINGE OF YELLOW. RELIC FIBROUS TEXTURE. d) LAPILLI TO FINE TUFF. e) VERY WEAK, PT = 27, MODERATELY WEATHERED f) AS ABOVE. g) AS ABOVE. h) MODERATELY SORTED.	EASY TO SPADE SAMPLE 16* WT 23346 SITE 13
74	2			a) LIGHT BROWN. b) CRYSTALS: 5%. c) PUMICE: 30, 8%, 10[3-23]mm LIGHT YELLOW ORANGE d) AS ABOVE e) VERY WEAK, PT = 33, MODERATELY WEATHERED. f) AS ABOVE g) AS ABOVE. h) AS ABOVE.	EASILY SPADED SAMPLE 15* WT 23345 SITE 12
72	4	ASH		CONTACT IN THIS AREA; OBSCURED BY COLLUVIUM AND ASH	
68	3	WAIMAKARIRI		a) VERY PALE BROWN/GREY b) CRYSTALS: 10%. c) PUMICE: 20, 20% 42[7-190] mm VERY LENTICULAR, VERY WHITE	LITHICS PROTRUDING FROM OUTCROP. SITE 11 CONTD.

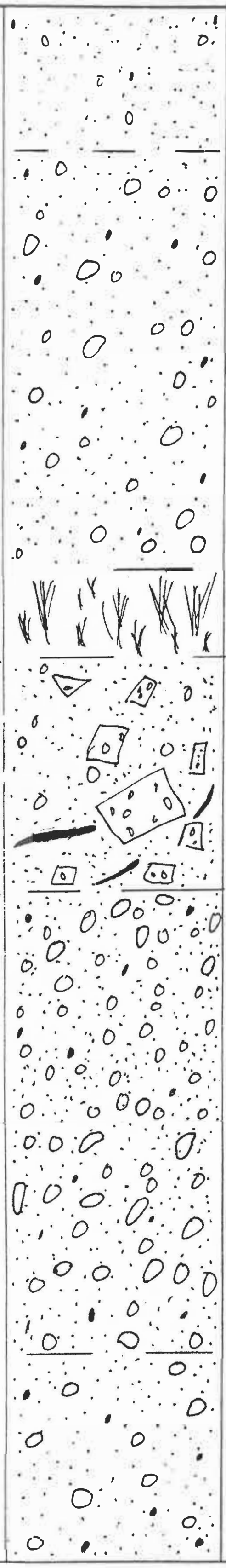
Stratigraphic Column : LLOYD MANDENO

G.R.: U15/787685.

TOTAL THICKNESS (metres)	THICKNESS (metres)	PROFILE	HANDSPECIMEN DESCRIPTION	COMMENTS
			d) PYROCLASTIC BRECCIA TO FINE TUFF. e) VERY WEAK, PT=18, VERY WEATHERED. f) LITHICS: 0.5%, 5[1-15] mm. g) VITRIC/CLAY h) POORLY SORTED.	
65	2	WAIMAKARIRI IGNIMBRITE	a) LIGHT BROWN. WITH MOTTLES OF YELLOW ORANGE AND PURPLE. b) CRYSTALS 7%. c) PUMICE: WEATHERED, DIFFICULT TO ESTIMATE. 18, 10%, 22 [4-34] mm. d) LAPILLI TO FINE TUFF. e) VERY WEAK, PT=28, MODERATELY WTHD f) LITHICS: RHYOLITE?, 0.5% 8[2-20] mm g) VITRIC/CLAY. h) POORLY SORTED.	SAMPLE 12 * WT 23343 SITE 10 TERRACES LEFT BY RIVER DOWN CUTTING INTO GORGE QUITE DISTINCTIVE AT THIS ALTITUDE.
63	2	WAIMAKARIRI IGNIMBRITE	a) VERY LIGHT BROWN [TAN], BLACK SPOTS. b) CRYSTALS: 8% c) PUMICE: 18, 6% 15[5-50] mm WHITE, FIBROUS-SLIGHTLY KNOTTY. d) LAPILLI TO FINE TUFF. MAINLY COARSE TUFF. e) VERY WEAK, PT=25, MODERATELY WTHD. f) LITHICS: NONE SEEN. g) VITRIC/CLAY h) ____ SORTED.	SAMPLE 11 * WT 23342 SITE 9 EASILY SPADED.
61	2	WAIMAKARIRI IGNIMBRITE	a) LIGHT BROWN. b) CRYSTALS 8%. c) NONE SEEN. d) COARSE TO FINE TUFF. e) VERY WEAK, PT=30, MODERATELY WTHD f) LITHICS: OCCASIONAL PINK RHYOLITE.. g) AS ABOVE h) WELL SORTED.	SAMPLE 10* WT. 23341 SITE 8 POSSIBLY COLLUVIUM?
59	6		CLAY VENEER	
53	1	FLUVIAL	NORMALLY BEDDED SILTY SAND. PROBABLY DEPOSIT LEFT BY RIVER DOWNCUTTING.	SHARP CONTACT
52	2	WAIMAKARIRI	a) LIGHT ORANGE GREY. b) CRYSTALS 5%. c) VERY OCCASIONAL PUMICE. d) AS ABOVE. f) VERY WEAK, PT=30 HIGHLY WEATHERED.	SAMPLE 9* WT 23340 SITE 7 CONT'D.

Stratigraphic Column : LLOYD MANDENO

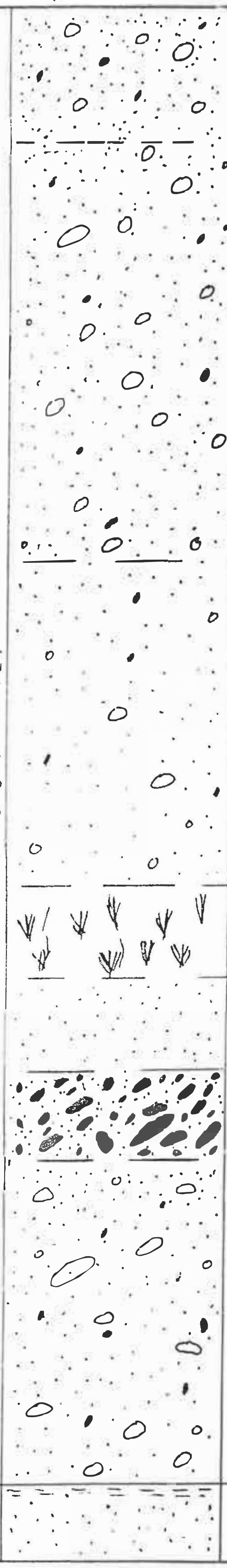
G.R.: U15/787685.



TOTAL THICKNESS (metres)	THICKNESS (metres)	Unit	HANDSPECIMEN DESCRIPTION	COMMENTS
			MAINLY COARSE TUFF. f) OCCASIONAL RHYOLITE < 0.5% g) RELIC VITRIC. h) WELL SORTED.	SAMPLE 9* WT 23340 SITE 7
50	2	WAIMAKARIRI IGNIMBRITE	a) LIGHT PINK/ORANGE b) CRYSTALS: 7% c) PUMICE 16, 10% 17[5-50] mm WHITE, FIBROUS, OCCASIONALLY LIGHT YELLOW d) LAPILLI TO FINE TUFF, MAINLY COARSE TUFF e) VERY WEAK, UNWEATHERED, PT = 30. f) LITHICS: DARK RHYOLITE, 1%, 3[1-10] mm g) VITRIC GROUNDMASS, SOME OBSIDIAN. h) MODERATELY SORTED.	SAMPLE 8* WT 23339 SITE 6
48	20		VENEER OF CLAY AND HIGHLY WEATHERED IGNIMBRITE.	
27.7	1	FLUVIAL	MIXTURE OF UNWELDED WAIMAKARIRI AND WELDED MAMAKU BLOCKS. NOTICABLE LENS OF HEAVY MINERALS:	INTERPRETED AS FLUVIAL DEPOSIT. PART OF RIVERS DOWNCUTTING PHASE.
26.7	2	WAIMAKARIRI IGNIMBRITE	a) LIGHT GREY, TINGE OF ORANGE. b) CRYSTALS: 8%. c) PUMICE: 57, 50% 6[2-26] mm WHITE, FIBROUS, OCCASIONALLY LIGHT ORANGE. d) MAINLY LAPILLI AND COARSE TUFF. e) VERY WEAK, MODERATELY WTHD. PT = 2 f) LITHICS: 1% 3[1-7] mm. g) VITRIC SOME OBSIDIAN. h) POORLY SORTED.	SAMPLE 7*. WT 23338 SITE 5 EASILY SPADED. SMALL PUMICE CONCENTRATION ZONE.
24.7	7		a) LIGHT GREY. b) CRYSTALS 5% c) PUMICE: 12, 10%, 16[5-32] mm WHITE, FIBROUS, ROUNDED. d) MAINLY LAPILLI AND COARSE TUFF. e) VERY WEAK, PT = 25. SLIGHTLY WTHD.	SAMPLE 6* WT 23337 SITE 4 CONT'D.

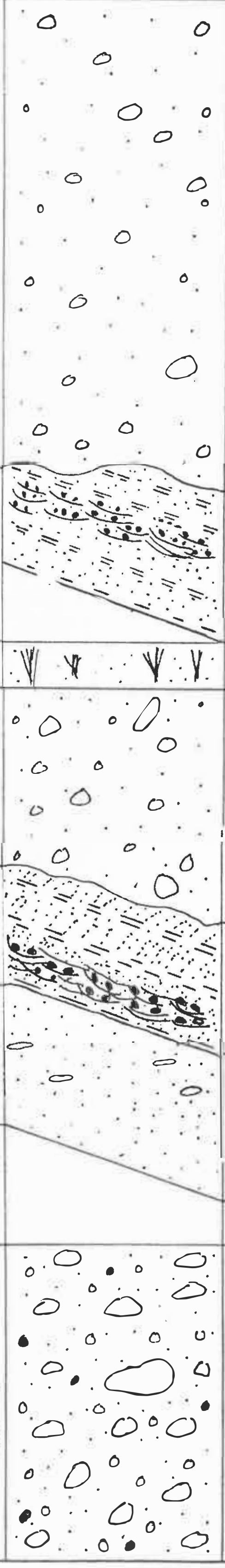
Stratigraphic Column : LLOYD MANDENO

G.R.: U15/787685



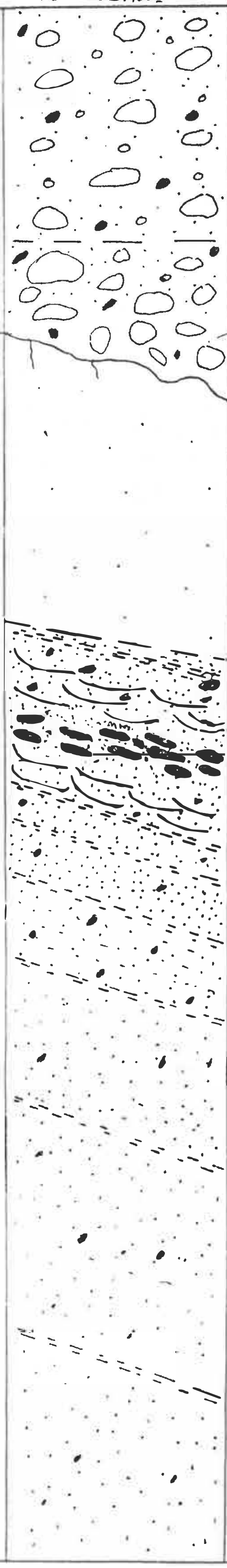
Total thickness (metres)	Thickness (metres)	Unit	Profile (not to scale)	Handspecimen description	Comments
		Waimakariri Ignimbrite		f) Lithics: 1% 3[1-20] mm. g) Vitric some obsidian. h) Moderately sorted.	Site 4 Sample 6* WT: 23335
17.7	3	Waimakariri Ignimbrite		a) Light grey. b) Crystals: 4%. c) Pumice: 18, 5%, 12[3-40] mm white, slightly devitrified, fibrous. d) Lapilli to fine tuff.. mainly coarse and fine tuff. e) V weak, PT=25, slightly wthd. f) Lithics: rhyolite ?, 2%, 4[2-30] mm. g) Vitric groundmass, some obsidian. h) Moderately sorted.	Sample 5* WT 23336 Site 3 Easily spaded
14.7	2	Waimakariri Ignimbrite		a) Light grey. b) Crystals 3%. c) Pumice: 11, 1%, 10[1-34] mm light grey, fibrous. d) As above. e) Very weak, PT=17, unweathered. f) Lithics: 2% 3[1-20] mm. g) As above h) Well sorted	Site 2 WT 23334 Sample 4* Noticeable silica veneer ~10 mm. Charcoal common.
12.7	9	Waimakariri Ignimbrite		Veneer of brown ash. Outcrop obscured.	
3.7	0.2			Massive light grey sand probably fluvial deposit.	
3.5	0.5	Fluvial		Gravels, cobbles and sands.	Interpreted as part of the Mangapapa Down cutting phase. Sharp erosional contact.
3	3	Waimakariri		a) Light grey, tinge of orange. b) Crystals: 3%. (c) Pumice: 24, 10%, 23[4-50] mm. light grey, fibrous. d) Mainly coarse tuff, some lapilli and fine tuff. e) Very weak, PT=32, unweathered. f) Lithics: 3%, 7[1-10] mm. g) As above h) Poorly sorted.	Sample 1* WT 23333 Site 1 By bridge. Charcoal common.
	0				
		Opuiaki seds		Sharp contact with indurated sand stone [under bridge]	

Stratigraphic Column : Lower Mangapapa Power Station G.R.: 414/778713.



TOTAL THICKNESS	THICKNESS	PROFILE (NOT TO SCALE)	HANDSPECIMEN DESCRIPTION	COMMENTS
metres				
65	9	WAIMAKARIRI	a) YELLOW ORANGE. b) CRYSTALS: QUARTZ, FELDSPAR AND MAFICS 5%. c) PUMICE 19, 10% 10[2-20] mm YELLOW, RELIC FIBEROUS TEXTURE, WEATHERED. d) LAPILLI TO COARSE AND FINE TUFF. e) VERY WEAK, PT = 33, f) NO LITHICS, g) CLAY/VITRIC h) MODERATELY SORTED.	TOP OF WAIMAKARIRI I. EASILY SPADED SITE 7 SAMPLE 520 WT 23433 BECOMES LESS WEATHERED AS CONTACT APPROACHED. SHARP CONTACT WITH SEDIMENTS
56	1	OPUIAKI	FAULTED, CROSS BEDED SANDY GRAVELS WITH WELL BEDDED SANDY SILTS	95/32/NNE
55	3		OBSCURED	
52	7	WAIMAKARIRI	THE WAIMAKARIRI IGNIMBRITE IN SHARP CONTACT WITH THE UNDERLYING SEDIMENTS IS NOT DESCRIBED, BEING SIMILAR TO UNDERLYING WAIMAKARIRI.	
45	1	OPUIAKI	FAULTED, CROSS BEDDED SANDY GRAVELS WITH WELL BEDDED SANDY SILTS.	100/30/N
44	2	WAITEARIKI	FAULTED WAITEARIKI IGNIMBRITE SIMILAR TO THAT DESCRIBED BY THE POWER STATION.	SEE SITE 1
42	6		OBSCURED	
36	5	WAIMAKARIRI	a) LIGHT YELLOW GREY b) CRYSTALS: QUARTZ, FELDSPARS AND MAFICS; MEDIUM, 5% c) PUMICE: 8, 30%, 30[2-110]mm YELLOWISH WHITE, SEMI FIBROUS COMPACT, SEMI LENTICULAR. NO BEDDING OR ALIGNMENT	BY SIGNPOST COLUMNAR JOINTED EVERY ½ m. SAMPLE 519 WT 23432 SITE 6

Stratigraphic Column : Lower Mangapapa Power Station G.R.: 415/778713



TOTAL THICKNESS (metres)	THICKNESS (metres)	PROFILE (NOT TO SCALE)	HANDSPECIMEN DESCRIPTION	COMMENTS
31	4	WAIMAKARIRI	d) Pyroclastic breccia to fine tuff. Mainly lapilli to coarse tuff. e) Very weak, PT = 43, slightly weathered. f) Lithics: 2%, 5[2 - 30] mm g) Vitric h) Poorly sorted. Basal zone of Waimakariri unable to describe.	Site 6 cont'd. Sample 519. WT 23432. Sharp contact.
27	3	OPUIAKI SEDIMENTS	a) Orange yellow b) Firm. c) Slightly wthd. d) 99% vitric, very occasional crystal. e) Medium silt. Some fine sand f) Very well sorted g) Fine sandy silt stone	Appears baked at contact. Incipient columnar jointing at contact.
24	2	OPUIAKI SEDIMENTS	a) Light brown. b) Firm. c) Sands slightly weathered. Gravels moderately weathered. d) Crystals: quartz, feldspars, and slightly weathered mafics. 90% of sample. Gravels: two types of rhyolite: one = flow banded, second = spherolitic. Max size = 48x24 mm. Also andesite 8% sample. Pumice: white fibrous 2% soft, easily crushed in fingers. e) Pebble to coarse silt, mainly coarse sand f) Poorly sorted. g) Gravelly sand stone.	Sharp contact. Nu cross bedding. Cross beds = 300 mm length, 50 mm width. Gravels imbricated in N-S direction. Sediments 89/27/NNW. Mostly normally bedded. Gravel sands. Very occasional clay lens.

Stratigraphic Column : Lower Mangapapa Power Station G.R.: U15/778713.

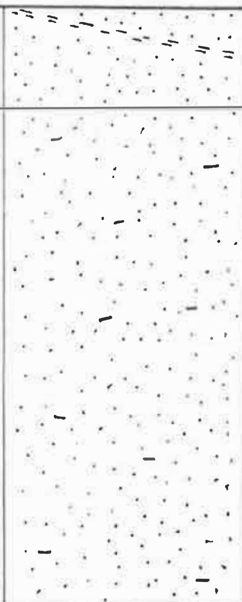
TOTAL THICKNESS	THICKNESS	PROFILE (NOT TO SCALE)	HANDSPECIMEN DESCRIPTION	COMMENTS
metres				
22	3	OPUAK, SEDIMENTS	a) LIGHT ORANGE TO YELLOW. b) FIRM. c) MODERATELY WEATHERED. d) COMPOSITION: CRYSTALS 3% PUMICE: VERY OCCASIONAL, TRACE. CLAY: 96% e) MOSTLY CLAY, SOME FINE SAND. f) WELL SORTED. g) SANDY CLAY STONE	EROSIONAL CONTACT WITH ABOVE. MASSIVE, NO BEDDING. SITE 5. AIR FALL TEPHRA PROBABLY.
19	2	WAITEA RIKI	FAULTED, WEATHERED WAITEARIKI IGNIMBRITE. SIMILAR TO THAT DESCRIBED IN SITE 1.	
17	5		OBSCURED	
12	6	WAIMAKARIRI IGNIMBRITE	a) LIGHT YELLOW. b) CRYSTALS: QUARTZ, FELDSPARS AND MAFICS 10%. c) PUMICE: 35, 18%, 17 [2-40] mm NOT FIBROUS - DENSE - QUITE LENTICULAR. YELLOWISH WHITE. d) LAPILLI COARSE AND FINE TUFF. e) STRONG, PT = 87, UNWEATHERED NOTE: IF SILICA VENEER NOT CHIPPED OFF PT = 100. f) LITHICS: 2% 7 [0.5 - 5] mm g) VITRIC. h) MODERATLY SORTED STRONGLY COLUMNAR JOINTED EVERY 0.75(m). SUB HORIZONTAL JOINTS EVERY 4(m).	ON TOP OF PENSTOCK OUTLETS. BY POWER STATION. WELDED ZONE 22 m THICK. HEAVY SILICA VENEER (20 mm). SAMPLE 515 a WT 23429 SITE 4. SHARP
6	2		a) LIGHT YELLOW ORANGE. b) CRYSTALS: AS ABOVE 15%. c) PUMICE 24, 35% 28 [1 - 52] mm SEMI LENTICULAR, WHITE FIBROUS e) WEAK, PT = 52, SLIGHTLY WEATHERED. d) LAPILLI, COARSE AND FINE TUFF.	CHANGE TO LESS WELDED AREA. STRONG BEDDING APPARENT IN NE/SW DIRECTION. BY TRANSFORMER SAMPLE 514.

Stratigraphic Column: LOWER MANGAPAPA POWER STATION G.R.: U14/778713.

TOTAL THICKNESS	THICKNESS	PROFILE NOT TO SCALE	HANDSPECIMEN DESCRIPTION	COMMENTS
metres		WAIMAKARIRI	f) LITHICS: RHYOLITE, 4% 10[1-3.5]mm g) VITRIC. h) POORLY SORTED.	NOTE THIS IS NOT RELATED TO TEXTURAL CHARACTERISTICS. PROBABLY ACCENTUATED BY WEATHERING. SITE 3
			OBSCURED.	
4.0	0.4	OPUIAKI SEDIMENTS	a) LIGHT ORANGE. b) FIRM. c) MODERATELY WEATHERED. d) COMPOSITION: CRYSTALS: 3%. PUMICE: VERY OCCASIONAL. CLAY = 97%. e) MEDIUM SAND, CLAY. f) WELL SORTED g) FINE SANDY CLAY STONE.	BY LAKE. OCCASIONAL ORANGE LAMINATION. USUALLY MASSIVE. TILTED. SAMPLE 513 WT 23426. GRADITIONAL CONTACT SITE 2
3.6	0.1		a) BRIGHT YELLOW BROWN. b) FIRM. c) MODERATELY WEATHERED. d) COMPOSITION: CRYSTALS 6%, NO PUMICE, SILT 94% e) MEDIUM TO FINE SILT f) WELL SORTED. g) SANDY SILTSTONE	MASSIVE, HAS A MORE GRITTY FEEL THAN THE ABOVE. SHARP EROSIONAL CONTACT.
3.5	0.3		a) LIGHT GREY b) FIRM d) COMPOSITION: CRYSTALS 15% PUMICE: [1-5mm] 5% SILT 80%. c) SLIGHTLY WEATHERED. e) MEDIUM SAND, SILT. f) WELL SORTED g) SANDY SILTSTONE	NORMALLY BEDDED, ALTERNATING COARSE FINE TILTED. SHARP CONTACT
3.2	0.2		a) LIGHT YELLOW. b) FIRM c) SLIGHTLY WEATHERED. d) COMPOSITION: CRYSTALS = 80%, PUMICE = NONE, ROCK FRAGMENTS = 1%, SILT 19%.	HEAVILY Mn STAINED SAMPLE 509 WT 23423 NORMALLY BEDDED SITE 2

e) MEDIUM AND FINE SAND.

Stratigraphic Column : LOWER MANGAPAPA POWER STATION G.R.: U14/778713

TOTAL THICKNESS	THICKNESS		PROFILE NOT TO SCALE	HANDSPECIMEN DESCRIPTION	COMMENTS
metres					
				f) WELL SORTED. g) SILTY SANDSTONE	SITE 2 SAMPLE 509 WT - 23423
3	3 0	WAITEARIKI IGNIMBRITE ↑		a) LIGHT PINK WITH BROWN SPOTS b) CRYSTALS: QUARTZ, FELDSPARS WEATHERED MAFICS 25%. c) NOT SEEN. d) COARSE TO FINE TUFF. e) MODERATELY STRONG PT = 70. f) NOT SEEN g) VITRIC/CLAY. h) WELL SORTED.	CAN CHIP WITH SPADE. BY LAKE SAMPLE 508 WT 23422 SITE 1

THE ABOVE COLUMN IS A DESCRIPTION OF A SIMPLE 'STEP FAULTED' SEQUENCE WHERE THERE IS CONSTANT REPETITION OF THE SAME SEDIMENTS AND IGNIMBRITES, PROBABLY SOON AFTER THE FAULTING OCCURED. THE WAIMAKARIRI FLOWED OVER THE SURFACE. EVIDENCE IS THE ANGLE OF DIP (~40°) OF THE SEDIMENTS WHICH WOULD HAVE BEEN ERODED FAIRLY QUICKLY, UNLESS COVERED.

Stratigraphic Column : TRACK TO OMANAWA FALLS POWER STATION G.R.: U15/ 821682.

TOTAL THICKNESS (metres)	THICKNESS (metres)	PROFILE NOT TO SCALE	HANDSPECIMEN DESCRIPTION	COMMENTS
			MAMAKU OBSCURED BY COLLUVIUM AND ASH. SEE DAIRY FARM COLUMN FOR DESCRIPTION OF MAMAKU IN THIS AREA.	
49	5	MAMAKU IGNIMBRITE	a) GREYISH PINK, ABUNDANT BROWN SPOTS. b) CRYSTALS: QUARTZ FELDSPARS WEATHERED MAFICS. 8%. MEDIUM SIZE. c) PUMICE: 11, 7%, 17[3-60] mm QUITE LENTICULAR, FLOW ALLIGNED IN NW-SE DIRECTION. PARTIALLY DEVITRIFIED THOUGH RELIC FIBROUS TEXTURE APPARENT. d) LAPILLI TO MAINLY COARSE AND FINE TUFF e) MODERATELY STRONG, PT= 68 SLIGHTLY WEATHERED. f) OCCASIONAL RHYOLITE LITHIC 2-3mm) g) VITRIC/CLAY h) MODERATELY SORTED.	STRONGLY COLUMNAR JOINTED EVERY 0.5-0.7m. CAN CHIP WITH SPADE. EXACT CONTACT WITH WAIMAKARIRI DIFFICULT TO ESTABLISH, DUE ALTERATION BY GROUNDWATER. SAMPLE 505 WT 23420 SITE 6.
44	6	WAIMAKARIRI IGNIMBRITE	a) VERY LIGHT GREY. b) CRYSTALS: QUARTZ, FELDSPARS AND MAFICS (SLIGHTLY WEATHERED)), (6%) MEDIUM. c) PUMICE: 32, 10% 15[2-60] mm WHITE, SEMI DEVITRIFIED, NOT LENTICULAR OR ALIGNED d) LAPILLI, COARSE AND FINE TUFF. e) MODERATELY STRONG, PT= 75 SLIGHTLY/MODERATELY WEATHERED. f) OCCASIONAL DARK (ANDESITE?) LITHIC, 0.5% 1-3 mm. g) VITRIC/CLAY, OCCASIONAL OBSIDIAN h) MODERATELY SORTED.	NO SOFT UPPER WAIMAKARIRI, EITHER REMOVED OR NOT DEPOSITED. SEMI VERTICAL COLUMNAR JOINTING. EVERY 0.4-0.7m. SILICA VENEER UP TO 1.5cm THICK SAMPLE 506 WT 23421 SITE 5

Stratigraphic Column ::Track To Omanawa Falls Power Station G.R.: U15/821682

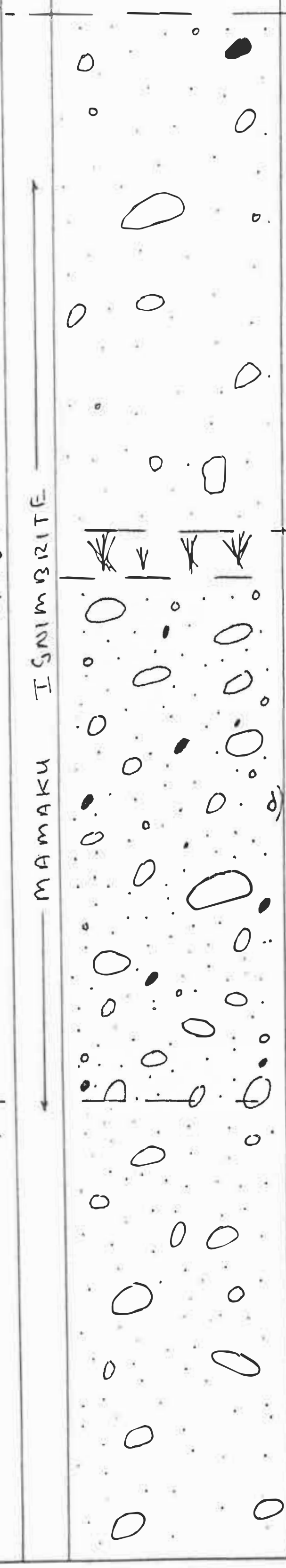
TOTAL THICKNESS	THICKNESS		PROFILE	HANDSPECIMEN DESCRIPTION	COMMENTS
metres					
38	4	WAIMAKARIRI IGNIMBRITE		a) LIGHT BROWNISH GREY b) AS ABOVE 8%. c) PUMICE: 19, 6% 18[3-30]mm GREYISH WHITE , SEMI LENTICULAR, FIBROUS KNOTTY d) LAPILLI, COARSE AND FINE TUFF. e) STRONG , PT = 88 SLIGHTLY WEATHERED. f) LITHICS COMMON, 6% 4[1-15]mm g) VITRIC, OCCASIONAL OBSIDIAN. h) MODERATELY SORTED. SAMPLE 505, WT	BY TUNNEL LEADING TO POWER STATION. SPRING JUST INSIDE DOOR. ABUNDANT VERTICAL COLUMNAR JOINTING EVERY 0.5m. HEAVY SILICA VENEER (10-15mm) JUST CHIP WITH SPADE SITE 4
34	16			TUNNEL LINED, UNABLE TO DESCRIBE IGNIMBRITE	PROBABLY MOST WELDED ZONE IN THIS AREA.
18	7			a) LIGHT GREY b) CRYSTALS: AS ABOVE 18%. c) PUMICE: 17, 8% 14(2-25)mm BROWN GREY, FIBROUS ; LENTICULAR, SEMI ALIGNED d) PYROCLASTIC BRECCIA, TO LAPILLI, COARSE AND FINE TUFF. e) STRONG/MODERATELY STRONG PT = 80 f) LITHICS; COMMON 2% 8[1-13]mm g) VITRIC/LITHIC, CLUMPS OF OBSIDIAN OFTEN SEEN, h) MODERATELY SORTED	COLUMNAR JOINTS EVERY 3-4(m). HALF WAY UP STAIRCASE. CAN CHIP WITH SPADE. SAMPLE 504 WT 23419 SITE 3.
11	10			a) BROWNISH GREY c) PUMICE: 16, 13% 20[3-37]mm DARK GREY, SOLID NOT FIBROUS NO LAYERING, SLIGHTLY LENTICULAR. b) CRYSTALS: AS ABOVE, 4%	BY POWER STATION ROOF. INCIPIENT COLUMNAR JOINTING. SAMPLE 503 WT 23418 SITE 2.

Stratigraphic Column: Track To Omanawa Falls Power Station G.R.: U15/821682

TOTAL THICKNESS (metres)	THICKNESS (metres)		PROFILE	HANDSPECIMEN DESCRIPTION	COMMENTS
		WAIMAKARIRI IGNIMBRITE		d) LAPILLI COARSE AND FINE TUFF. e) MODERATELY STRONG, PT = 68 / SLIGHTLY WEATHERED f) LITHICS: DARK COLOURED. COMMON/ ABUNDANT, 5%, 15[3-20]mm g) VITRIC / LITHIC GROUNDMASS. h) MODERATELY/ POORLY SORTED.	SITE 2 CONTINUED.
1	1			a) BROWNISH GREY. b) CRYSTALS: AS ABOVE 2%. c) PUMICE: 21, 23%, 22[3-75]mm GREY, OCCASIONALLY WHITE, FIBROUS NO BEDDING, ROUNDED d) PYROCLASTIC BRECCIA TO FINE TUFF. e) WEAK, PT = 51, SLIGHTLY WTHD. f) LITHICS: DARK COLOURED, 8%, 18[1-30] g) VITRIC. h) POORLY SORTED.	BY STATION OUTLET. SILICA VENEER INCIPIENT COLUMNAR JOINTING, EVERY 2m SAMPLE 500 WT 23417 SITE 1
	0				

Stratigraphic Column TAURANGA CITY COUNCIL WEIR [T.C.C.]

G.R.: U14/ 857737

TOTAL THICKNESS (metres)	THICKNESS (metres)	PROFILE NOT TO SCALE	HANDSPECIMEN DESCRIPTION	COMMENTS
			OBSCURED.	
90	3		a) PINKISH GREY b) CRYSTALS: QUARTZ, FELDSPARS AND WEATHERED MAFICS 5%. c) PUMICE: 8, 5% 30[2-60]mm GREYISH RED, DEVITRIFIED. d) PYROCLASTIC BRECCIA TO FINE TUFF, MAINLY COARSE TUFF. e) VERY WEAK, PT=23, SLIGHTLY WEATHERED. f) NONE SEEN. g) RELIC VITRIC. h) POORLY SORTED.	EASY TO SPADE. SAMPLE 954 WT 23565 SITE
87	26		OBSCURED.	
61	15		a) PALE YELLOW GREY, BROWN SPOTS. b) CRYSTALS: AS ABOVE 8%. c) PUMICE: 31, 15%, 13[2-90]mm WHITE TO PALE YELLOW. DEVITRIFIED d) PYROCLASTIC BRECCIA TO FINE TUFF, MAINLY LAPILLI AND COARSE TUFF e) MODERATELY STRONG, PT= 76. f) LITHIC CONCENTRATION ZONE 3% 20[1-38]mm. IGNIMBRITE. g) DEVITRIFIED, RELIC VITRIC h) POORLY SORTED.	HARD TO SPADE. VERTICAL JOINTS EVERY ½ m. THIS SITE IS AT BASE OF COLUMNAR JOINTED ZONE. SAMPLE 605 WT 23461 SITE
46	2		a) LIGHT REDDISH BROWN b) CRYSTALS: AS ABOVE, EXCEPT MAFICS ARE FRESH. 6% c) PUMICE: 16, 8%, 30[5-110]mm NOT DEVITRIFIED FRESH, FIBROUS, SEMI LENTICULAR VERY PALE ORANGE. d) PYROCLASTIC BRECCIA TO FINE TUFF, MAINLY LAPILLI TO COARSE TUFF.	SPADES EASILY

Stratigraphic Column : TAURANGA CITY COUNCIL WEIR

G.R.: U14/857 737

TOTAL THICKNESS	THICKNESS	PROFILE (NOT TO SCALE)	HANDSPECIMEN DESCRIPTION	COMMENTS
metres		MAMAKU	e) VERY WEAK, PT = 27, UNWEATHERED. f) NONE SEEN. g) VITRIC h) POORLY SORTED.	SITE SAMPLES 953 WT 23552. CONT
	0.01 to 0.05		COASE PUMICEOUS SAND EROSIONAL UNCONFORMITY	
44	4	WAIMAKARIRI IGNIMBRITE	a) LIGHT GREY b) CRYSTALS: AS ABOVE 5% c) PUMICE: 21, 10%, 27[2-48]mm LIGHT GREY FIBROUS KNOTTY TEXTURE d) LAPILLI TO FINE TUFF, MAINLY COARSE. e) VERY WEAK, PT = 25, UNWEATHERED. f) LITHICS: 1% 3 [0.5 - 14] mm DARK RHYOLITE g) VITRIC h) POORLY SORTED.	EASILY SPADED FROM FACE SAMPLE 607+ WT 23463 SITE
40	27		OBSCURED	
13	2		a) YELLOWISH GREY. b) CRYSTALS: AS ABOVE 4% c) PUMICE: 20, 7%, 32[1-54]mm LIGHT GREY. d) LAPILLI TO FINE TUFF, MOSTLY COARSE. e) WEAK/MODERATELY STRONG, PT = 68 f) LITHICS: NOT SEEN g) VITRIC, h) POORLY SORTED	CAN BE CHIPPED OUT. SAMPLE 950 WT 23549 SITE 4 BASAL ZONE.
11	3		OBSCURED, CONTACT NOT SEEN.	
8.8	2	OPUIAKI SEDIMENTS	a) LIGHT YELLOWISH GREY. b) FIRM IN PLACE, c) MODERATELY WEATHERED. d) CRYSTALS: 4% 0.6-1.2mm PUMICE: YELLOW 5% 5-30mm. NO ROCK FRAGMENTS. 90% VITRIC SILT.	MASSIVE NO BEDDING. SITE 3 CONT'D.

Stratigraphic Column : TAURANGA CITY COUNCIL WEIR

G.R.: U14/ 857737.

TOTAL THICKNESS	THICKNESS	PROFILE NOT TO SCALE	HANDSPECIMEN DESCRIPTION	COMMENTS
metres				
			e) COARSE PEBBLE, COARSE AND MEDIUM SAND, MAINLY FINE SAND TO MEDIUM SILT. f) SANDY SILTSTONE	SAMPLE 601 WT 23457 SITE. 3
6·8	1·5		OBSCURED BY VEGETATION	
5·3	2	OPUIAKI SEDIMENTS	a) PALE YELLOW BROWN. b) FIRM IN PLACE, SLIGHTLY WTH'D c) OCCASIONAL QUARTZ CRYSTAL 1%. NO ROCK OR PUMICE FRAGMENTS 98% VITRIC, SOME OBSIDIAN. d) FINE SAND TO FINE SILT. e) FINE SAND SILTSTONE	NORMALLY BEDDED PARALLEL LAMINATIONS SAMPLE 600 WT 23456 SITE 2 GRADITIONAL CONTACT
3·3	0·3		a) LIGHT YELLOW GREY b) LOOSE, c) UNWEATHERED. d) CRYSTALS: 58% VITRIC: 40% e) VERY COARSE TO FINE SAND AND COARSE SAND TO FINE SILT. f) SILTY SAND STONE.	MASSIVE NO BEDDING. SAMPLE 602 WT 23459 SITE 2
	3		OBSCURED BY VEGETATION.	
0	0	WAITEARIKI IGNIMBRITE	a) LIGHT PINKISH GREY b) CRYSTALS: 25%. c) NO PUMICE SEEN. d) COARSE TO FINE TUFF e) MODERATELY/HIGHLY WEATHERED. PT ≈ 55 IN SOFTER AREAS, PT ≈ 70 IN HARDER PARTS. f) NONE SEEN. g) VITRIC/CLAY GROUNDMASS. h) MODERATELY SORTED	CAN BE CHIPPED WITH A SPADE. SAMPLE 603 SITE 1 WT 23458 IN RIVER BED (WAIORAHI RIVER)

Stratigraphic Column : SCOTTS TRACK [TO PRIVATE POWER STATION]

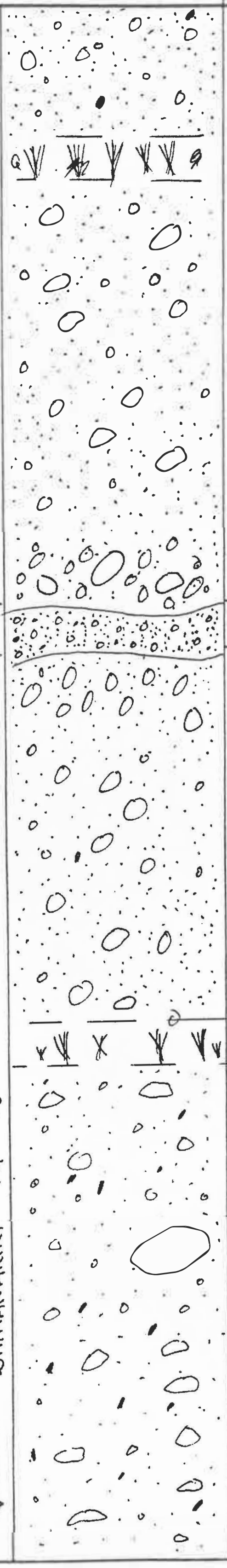
G.R.: 415/777677

PROFILE NOT TO SCALE

TOTAL THICKNESS (metres)	THICKNESS (metres)	UNIT	HANDSPECIMEN DESCRIPTION	COMMENTS
52.	0·2	TEPHRA	BLACK SANDY LOAM. 1-3 mm PUMICE SCATTERED THROUGHOUT.	ROOTS COMMON
51·6	1	TEPHRA	YELLOW BROWN LOAM, ROUNDED GRANULAR STRUCTURE.	OKAREKA ASH.
50·6	0.25	TEPHRA	YELLOW BROWN CLAY, PUMICE RICH AT BASE, THOUGH PUMICE CAN BE FOUND THROUGHOUT	MANGAONI ASH
	0·05	TEPHRA	LIGHT YELLOW TO GREY, SANDY CLAY FIRM IN PLACE. BEDDED GRADATIONAL CONTACT PALE WHITE PUMICE RICH TEPHRA. SMALL [1-3]mm RHYOLITE LITHICS.	ROTOEHU ASH.
50·3	0·3	TEPHRA	PALE WHITE SILT [VITRIC] PALE WHITE SANDY PUMICE	
50	1	TEPHRA	BROWN SANDY CLAY, WELL DEVELOPED AT TOP MASSIVE AT BASE.	HAMILTON ASH
49	12	MAMAKU IGNIMBRITE	WEATHERED MAMAKU a) PINK WITH BLACK/BROWN MOTTLES b) CRYSTALS 8% c) PUMICE: 14, 15% 25[5-38]mm SLIGHTLY LENTICULAR, DARK PINK, DEVITRIFIED. d) LAPILLI TO FINE TUFF, MAINLY COARSE TUFF. e) VERY WEAK, PT=25, f) NO LITHICS SEEN. g) RELIC VITRIC. h) POORLY SORTED	EASILY SPADED SAMPLE 30* WT 23358 SITE
37	6	MAMAKU IGNIMBRITE	a) PALE PINK b) CRYSTALS: 7% c) PUMICE: 53, 23% 8[3-22]mm SEMI LENTICULAR, BROWNISH YELLOW, DEVITRIFIED THOUGH RELIC FIBROUS TEXTURE APPARENT. d) COARSE TO FINE TUFF, e) WEAK/MODERATELY STRONG, PT=65	SAMPLE 33* WT 23361 SITE CONTINUED COLUMNAR JOINTED.

Stratigraphic Column : SCOTTS TRACK

G.R.: U15/777677

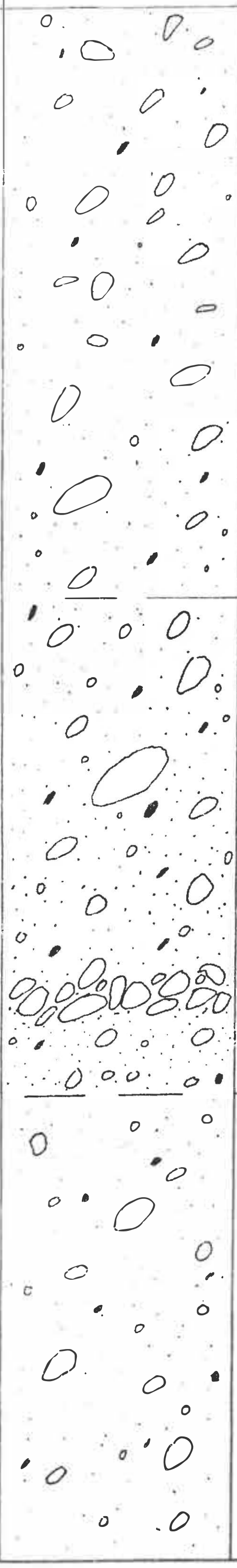


TOTAL THICKNESS	THICKNESS		PROFILE *Not to scale*	HANDSPECIMEN DESCRIPTION	COMMENTS
metres					
		MAMAKU IGNIMBRITE		e) SLIGHTLY WEATHERED f) OCCASIONAL LITHIC [WEATHERED RHYOLITE?] g) RELIC VITRIC. h) POORLY SORTED.	SITE COLUMNAR JOINTED ZONE.
31	15			OBSCURED.	
16	5	MAMAKU IGNIMBRITE		a) PALE REDDISH BROWN. b) CRYSTALS: 10% c) PUMICE 13, 20%, 20 [5-30] mm NOT DEVITRIFIED. PALE YELLOW. FIBROUS. d) LAPILLI TO FINE TUFF. e) VERY WEAK, PT = 35, UNWEATHERED. f) NO LITHICS SEEN g) VITRIC GROUNDMASS. h) POORLY SORTED	FIRM IN PLACE BUT EASILY SPADED. SAMPLE 973 WT23567, SITE 3 BASAL MAMAKU SHARP CONTACT
	0.08			SANDY GRAVEL [PUMICE] LENS	NO BEDDING
11	4			a) ORANGE BROWN. b) CRYSTALS: 8% c) PUMICE 17, 20%, 30 [10-50] mm FIBROUS, PALE GREY. d) AS ABOVE. e) WEAK, PT = 45, UNWEATHERED. f) OCCASIONAL LITHIC g) VITRIC h) AS ABOVE.	SHARP EROSIONAL UNCONFORMITY. NOTICEABLE INCREASE IN PUMICE NUMBERS AND SIZE B/4 CONTACT WITH GRAVELS
7	5			OBSCURED	
2	2	WAIMAKARIRI IGNIMBRITE		a) ORANGE BROWN. b) CRYSTALS: 12%. c) PUMICE 30, 15% 12 [3-110] mm PINKISH BROWN, 'FIBEROUS KNOTTY.' d) PYROCLASTIC BRECCIA TO FINE TUFF e) VERY WEAK, PT = 18, SLIGHTLY WTHD. f) LITHICS COMMON 2%. g) VITRIC h) VERY POORLY SORTED.	BY POWER STATION.
0	0				

Stratigraphic Section: RUAHIHI CANAL. [NORTHERN BANK]

G.R.: U14/783727

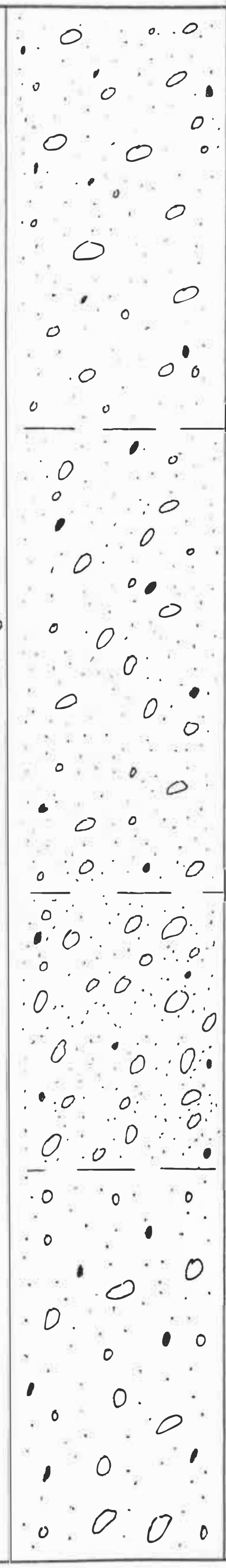
PROFILE NOT TO SCALE.



TOTAL THICKNESS (metres)	THICKNESS (metres)	PROFILE	HANDSPECIMEN DESCRIPTION	COMMENTS
			NOTE: HORIZONTAL PROFILE ALONG NORTHERN BANK. START OF CUTTING.	
	0	WAIMAKARIRI IGNIMBRITE	a) LIGHT YELLOW GREY. b) CRYSTALS QUARTZ, FELDSPARS AND MAFICS 10% c) PUMICE 24, 15%, 22 [2-71] mm. LIGHT GREY, VESICULAR ROPEY. d) PYROCLASTIC BRECCIA TO FINE TUFF. MAINLY LAPILLI AND COARSE TUFF. e) VERY WEAK; PT= 35; UNWEATHERED. f) LITHICS: RHYOLITE? 2 [0.3-4] mm; 3% g) VITRIC: SOME OBSIDIAN. h) POORLY SORTED.	50m FROM START OF CUTTING. EASILY CHIPPED FROM BANK. SILICA VENEER. SAMPLE 627 SITE 1 WT 23482
50	50		a) LIGHT YELLOW GREY b) CRYSTALS: AS ABOVE 8% c) PUMICE: 21, 7%, 30 [2-230] mm PALE GREY, VESICULAR, ROUNDED. d) PYROCLASTIC BRECCIA TO FINE TUFF MAINLY LAPILLI AND COARSE TUFF. e) WEAK, PT= 47, UNWEATHERED. f) LITHICS: DARK RHYOLITE, 3 [0.5-5] mm 2%. g) VITRIC; OCCASIONAL OBSIDIAN. h) VERY POORLY SORTED.	HORIZONTAL PUMICE LENS AT BASE OF TRACK. PUMICE 100 to 150 mm. EASILY CHIPPED FROM OUTCROP. SAMPLE 628 WT 23483 SITE 2.
100	50		a) LIGHT YELLOW GREY. b) CRYSTALS: AS ABOVE 9% c) PUMICE: 28, 8%, 24 [3-50] mm LIGHT GREY, SLIGHTLY VESICULAR d) LAPILLI TO FINE TUFF, MAINLY COARSE TUFF. e) VERY WEAK/WEAK, PT: 41 f) LITHICS: AS ABOVE 2 [0.2-4] 1%. g) VITRIC; OCCASIONAL OBSIDIAN. h) POORLY SORTED	EASILY CHIPPED FROM BANK. SILICA VENEER. SAMPLE 629 WT 23484 SITE 3

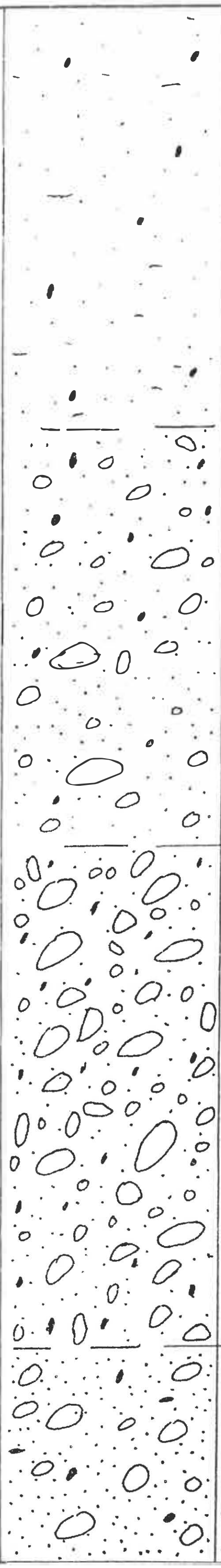
Stratigraphic Section: RUAHIHI CANAL

G.R.: U14/783727

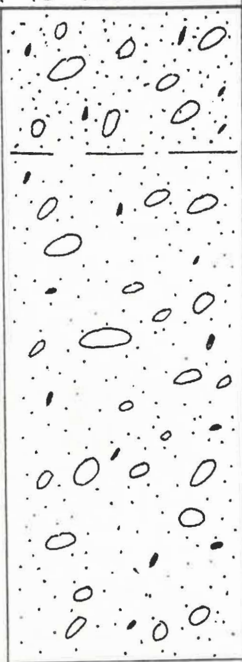


TOTAL THICKNESS (metres)	THICKNESS (metres)	PROFILE *Not to scale*	HANDSPECIMEN DESCRIPTION	COMMENTS
150	50	WAIMAKARIRI IGNIMBRITE	a) LIGHT GREY b) CRYSTALS: 9% c) PUMICE: 24, 7%, 22[3 – 55] mm VERY LIGHT GREY, SLIGHTLY VESICULAR. d) LAPILLI TO MAINLY COARSE AND FINE TUFF. e) VERY WEAK, PT = 37, UNWEATHERED. f) LITHICS: RHYOLITE? 1.5%, 2[0.3 – 6] mm g) VITRIC, OCCASIONAL OBSIDIAN. h) MODERATELY SORTED.	FIRM TO SPADE SILICA VENEER. SAMPLE 630 WT 23485 SITE 4
200	50		a) LIGHT GREY. b) CRYSTALS 7%. c) PUMICE: 22, 9%, 20[2 – 25] mm LIGHT GREY, SLIGHTLY VESICULAR. d) LAPILLI TO FINE TUFF. MAINLY COARSE TUFF. f) LITHICS: RHYOLITE, 1% 3[0.1 – 5] mm e) WEAK/VERY WEAK, PT = 45, UNWEATHERED. g) VITRIC, SOME OBSIDIAN. h) MODERATELY / POORLY SORTED.	AS ABOVE SAMPLE 631 WT 23486 SITE 5.
250	50		a) LIGHT GREY, b) CRYSTALS 8%. c) PUMICE: 26, 18%, 43[5 – 60] mm VERY LIGHT GREY, FIBROUS SLIGHTLY KNOTTY. e) VERY WEAK, PT = 42, UNWEATHERED. f) LITHICS: 1%, 4[0.3 – 7] mm. g) VITRIC h) POORL SORTED.	AS ABOVE SAMPLE 632 WT 23487 SITE 6
300	50		a) LIGHT YELLOW GREY. b) XALS: 10%. c) PUMICE: 24, 7% 17[1 – 32] mm. WHITE SLIGHTLY VESICULAR. d) LAPILLI TO MAINLY COARSE AND FINE TUFF. (e) WEAK, PT = 50, UNWEATHERED. f) LITHICS: 1%, 2[0.3 – 6] mm. g) VITRIC h) MODERATELY SORTED.	'NATURAL' OUTCROP HAS WELL DEVELOPED COLUMNAR JOINTING AND A THICK SILICA VENEER. SAMPLE 633 WT 23489 SITE .

Stratigraphic Column RUAHIHI CANAL G.R.: U14/783727

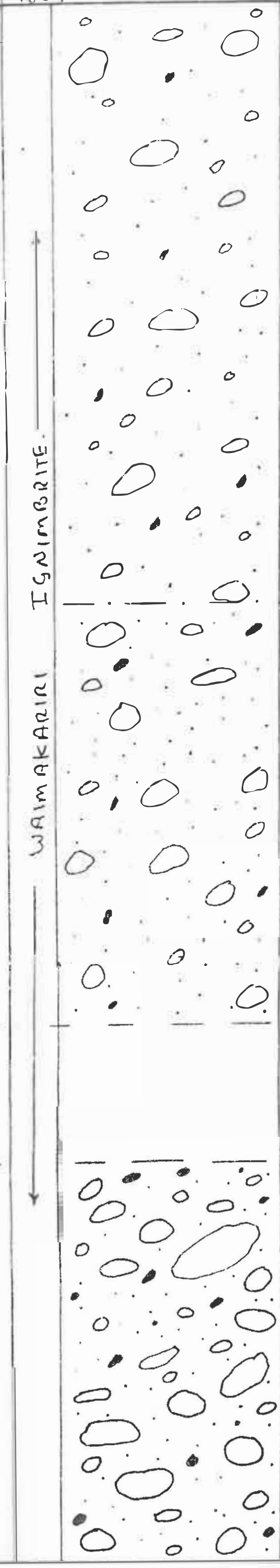
TOTAL THICKNESS (metres)	THICKNESS (metres)		PROFILE NOT TO SCALE	HANDSPECIMEN DESCRIPTION	COMMENTS
32.5	9	WAIMAKARIRI IGNIMBRITE		a) LIGHT YELLOW GREY b) CRYSTALS: QUARTZ, FELDSPARS AND MAFICS [WEATHERED] 10% c) NOT POSSIBLE TO ASSESS, TOO WEATHERED RELIC PUMICE. d) COARSE AND FINE TUFF e) HIGHLY WEATHERED, V. WEAK. f) LITHICS: RHYOLITE ?, 0.5% 2[0.3-4]mm g) CLAY h) WELL SORTED	TOP OF OUTCROP SAMPLE 637 WT 23492 SITE 5 EXPOSURE, HIGHLY WEATHERED, VITRIC MATERIAL TURNED TO CLAY.
23.5	14			a) LIGHT YELLOW, BROWN SPOTS. b) CRYSTALS: 8%, AS ABOVE c) PUMICE: 23, 15% 35[1-90]mm d) PYROCLASTIC BRECCIA TO FINE TUFF MAINLY LAPILLI + COARSE TUFF. e) VERY WEAK, PT=18, MODERATELY WEATHERED. f) LITHICS: RHYOLITE, 1% 2[0.7-3]mm g) VITRIC/CLAY, (h) POORLY SORTED.	EASILY SPADED. SAMPLE 636 WT 23491 SITE 4
9.5	5.3			a) LIGHT GREY b) CRYSTALS 11%. c) PUMICE 1, 50%, 73 [2-90]mm LIGHT YELLOWISH GREY, FIBROUS d) PYROCLASTIC BRECCIA TO FINE TUFF MAINLY LAPILLI + COARSE TUFF. e) VERY WEAK, PT = 25, SLIGHTLY WEATHERED. f) LITHICS: 3% 2 [1 – 6]mm g) VITRIC, CLUMPS OF OBSIDIAN. h) POORLY SORTED	EASILY SPADED. SAMPLE 635 WT 23490 SITE 3 NOTICEABLE INCREASE IN PUMICE SIZE AT THIS SITE.
4.2	2.7			a) LIGHT GREY. b) CRYSTALS: 8%. c) PUMICE: 18, 20%, 37[3-90]mm d) PYROCLASTIC BRECCIA TO FINE TUFF. ⅓ PYROCLASTIC BRECCIA, ⅔ LAPILLI TUFF.	SITE 2 CONT'D. SAMPLE 634. WT 23496

Stratigraphic Column RUAHIHI CANAL G.R.: U14/783727.

TOTAL THICKNESS	THICKNESS	PROFILE NOT TO SCALE		HANDSPECIMEN DESCRIPTION	COMMENTS
metres		WAIMAKARIRI IGNIMBRITE		e) VERY WEAK, PT = 22, UNWTHD f) LITHICS: RHYOLITE 1% 2[0.5-4] mm. g) POORLY SORTED.	SITE 2 SAMPLE 634. WT 23496
1.5	1.5			a) LIGHT YELLOW GREY. b) CRYSTALS: 10%. c) PUMICE: 24, 15% 22[3-71]mm. LIGHT GREY, VESICULAR 'ROPEY'. d) PYROCLASTIC BRECCIA TO FINE TUFF. MAINLY LAPILLI TO COARSE TUFF. e) V WEAK, PT = 38, UN WEATHERED. f) LITHICS, 4% 3[1-5] mm. g) Vitric h) POORLY SORTED	START OF CUTTING READILY CHIPPED FROM FACE. SITE 1 SAMPLE 627 WT 23482 BY ROAD.

Stratigraphic Column: SUN CLUB TRACK

G.R.: U14/827707.

TOTAL THICKNESS (metres)	THICKNESS	PROFILE (NOT TO SCALE)	HANDSPECIMEN DESCRIPTION	COMMENTS
48	6		a) LIGHT BROWN. b) CRYSTALS: QUARTZ, FELDSPARS AND SLIGHTLY WEATHERED MAFICS 7% c) PUMICE: 14, 7% 26[2-30]mm NO BEDDING, LIGHT BROWN, FIBROUS SLIGHTLY LENTICULAR. d) LAPILLI, COARSE AND FINE TUFF e) WEAK, PT=40, MODERATELY WEATHERED. f) LITHICS: 0.5% 3[1-5]mm DARK RHYOLITE? g) VITRIC/CLAY. h) MODERATELY SORTED	TOP OF OUTCROP. NO SOINTING SPADES EASILY SAMPLE 526 WT 23438 SITE 4
42	11		a) VERY LIGHT GREY b) CRYSTALS: AS ABOVE 5% c) PUMICE: 12%, 18, 15 [3-50]mm d) LAPILLI AND COARSE TUFF. SOME FINE. e) WEAK, PT=48, UNWEATHERED f) LITHICS: 1%, 5[1-13]mm DARK RHYOLITE. g) VITRIC [SOME OBSIDIAN] h) POORLY SORTED	SEMI COLUMNAR JOINTED. VERY STRONG SILICA VENEER SAMPLE 525 WT 23437 SITE 3
31	20		MIDDLE WELDED ZONE INACESSIBLE. VERTICAL FACE ABOUT 20 M HIGH.	
11	6		a) PALE WHITE. b) CRYSTALS: AS ABOVE c) PUMICE: 15, 25% 63[2-110]mm SEMI LENTICULAR, FIBROUS d) PYROCLASTIC BRECCIA TO FINE TUFF, MAINLY COARSE TUFF. e) VERY WEAK, PT=30, UNWEATHERED. f) LITHICS: 3% 5[1-30] mm g) VITRIC - SOME OBSIDIAN.	START OF LOWER WELDED ZONE. FIRM TO SPADE. SAMPLE 522 WT 23435 SITE 2. h) POORLY SORTED

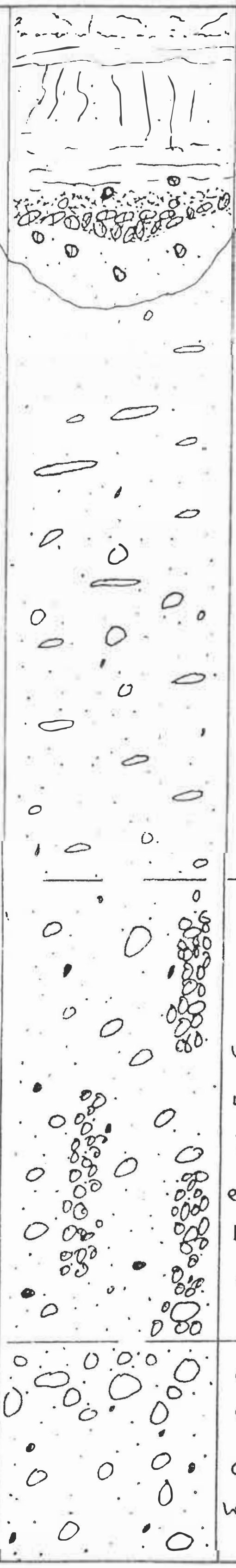
Stratigraphic Column: SUNCLUB TRACK

G.R.: U14/827707

TOTAL THICKNESS (metres)	THICKNESS (metres)		PROFILE *Not to scale*	HANDSPECIMEN DESCRIPTION	COMMENTS
5 0	5 0	← WAMAKARIRI →		a) LIGHT GREY b) CRYSTALS : AS ABOVE 3%. c) PUMICE: 37, 15%, 25[2-62]mm d) PYROCLASTIC BRECCIA TO FINE TUFF, MAINLY COARSE TUFF. e) VERY WEAK, PT ~ 22, UNWEATHERED. f) LITHICS: DARK RHYOLITE? 3% 8[1-37]mm. g) VITRIC, SOME OBSIDIAN.	BASAL ZONE. SAMPLE 521 WT 23434 SITE 1

Stratigraphic Column CARRS TRACK

G.R.: U14/828748.

TOTAL THICKNESS	THICKNESS		PROFILE *Not to scale*	HANDSPECIMEN DESCRIPTION	COMMENTS
metres					
41	7	WAINAKARIRI IGNIMBRITE		5m OF TEPHRA WHICH OVERLIES 2m OF DISTAL [HIGHLY WTHD] SHEET 4 MAMAKU. THIS HAS THE CHARACTERISTIC PUMICE AND GROUNDMASS [FOUND AT THE END OF BELK ROAD.	PUMICE HAS INFILLED TOPOGRAPHIC LOWS.
34	11			a) WHITE TO PALE YELLOW, NUMEROUS BROWN SPOTS. b) CRYSTALS: QUARTZ, FELDSPARS AND WEATHERED MAFICS. 12%. c) PUMICE: 7, 16%, 27 [5 – 57] mm FLOW ALLIGNED, VERY LENTICULAR HIGHLY WEATHERED, PINKISH GREY. d) PYROCLASTIC BRECCIA TO FINE TUFF MAINLY COARSE AND FINE TUFF. e) VERY WEAK, PT = 30, HIGHLY WEATHERED. f) LITHICS 1%, 1–3 mm, RHYOLITE g) CLAY GROUNDMASS – RELIC VITRIC h) MODERATELY SORTED.	SAMPLE 430 WT 23408 SITE NOTE: DUE TO THE ALTERATION OF THE VITRIC MATERIAL TO CLAY, THIS HAS INCREASED RELATIVE STRENGTH, PROBABLY BY CONSOLIDATION.
23	7			a) LIGHT GREY b) CRYSTALS 10%. c) PUMICE: 44, 25%, 11 [2 – 30] mm WHITE, FIBROUS, ROUNDED NOT LENTICULAR. d) LAPILLI TO FINE TUFF. e) VERY WEAK, PT = 23, SLIGHTLY WTHD. f) LITHICS: 2%, 5 [1 – 10] mm. g) VITRIC GROUNDMASS. SOME OBSIDIAN. h) POORLY SORTED.	NOTICEABLE SILICA VENEER 10 mm. EASILY SPADED. SAMPLE 431 WT 23409 SITE. VERTICAL PUMICE RICH LENS COMMON. FINES REMOVED.
16	9			a) WHITISH TAN b) CRYSTALS: 7%. c) PUMICE. 6, 15%, 13 [4 – 24] mm WHITE, FIBROUS, KNOTTY.	THIS SITE IS ABOUT ¼ OF THE WAY THROUGH THE 'WELDED' ZONE. SITE

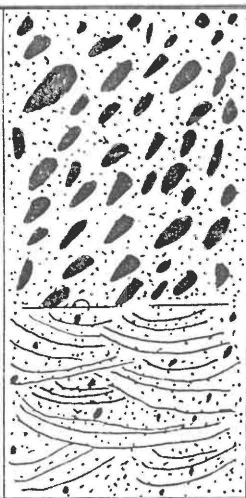
Stratigraphic Column : CARR'S TRACK

G.R.: U14/ 828748

TOTAL THICKNESS	THICKNESS		PROFILE *Not to scale*	HANDSPECIMEN DESCRIPTION	COMMENTS
metres					
		WAIMAKARIRI IGNIMBRITE		d) LAPILLI TO FINE TUFF e) WEAK, PT= 42, UNWEATHERED. f) LITHICS: 1·5% 4[1·0 -10] mm g) VITRIC GROUNDMASS. h) MODERATELY SORTED	NOTE: OVERLYING AND UNDERLYING PUMICE IS NOTICEABLE LARGER SAMPLE
7	3			a) PALE WHITE. b) CRYSTALS 4%. c) PUMICE: 8, 80%, 50[4-270] mm d) MAINLY PYROCLASTIC BRECCIA SOME LAPILLI COARSE AND FINE TUFF. e) UNWEATHERED, VERY WEAK PT = 32. f) LITHICS: 3% 10-20 mm. g) VITRIC GROUNDMASS. h) VERY POORLY SORTED.	SAMPLE 433 WT 23411 SITE BASE OF OUTCROP. PUMICE ANGULAR. SHARP CONTACT
4	2	OPUIAKI SEDIMENTS		a) LIGHT ORANGE BROWN. b) FIRM IN PLACE c) SLIGHTLY WEATHERED d) 99% VITRIC MATERIAL, [OCCASIONAL OBSIDIAN] VERY OCCASIONAL CRYSTAL. 1 PUMICE FRAGMENT. e) FINE SAND TO EDIUM SILT. f) VERY WELL SORTED g) FINE SANDY SILTSTONE	APPEARS BAKED AT CONTACT. SAMPLE 434 WT 23412 SITE VERY FIRM TO SPADE.
	003			RED BROWN SANDY HARD IRON PAN.	SHARP CONTACT WITH OVER AND UNDERLYING SEDIMENTS
2	1			a) DULL YELLOW. b) LOOSE c) CRYSTALS: 0% 0·5[0·1 - 3] mm VITRIC : 10%. OCCASIONAL PUMICE.) COARSE TO FINE SAND) SLIGHTLY WEATHERED. f) WELL SORTED g) SANDSTONE. LENGTH OF CROSS STRATA = 140 mm WIDTH " " " = 30 mm	N4 TYPE CROSS BEDDING. IN E/W DIRECTION IMPLYING A NORTH FLOW DIRECTION. SAMPLE 435 WT 23412 SITE

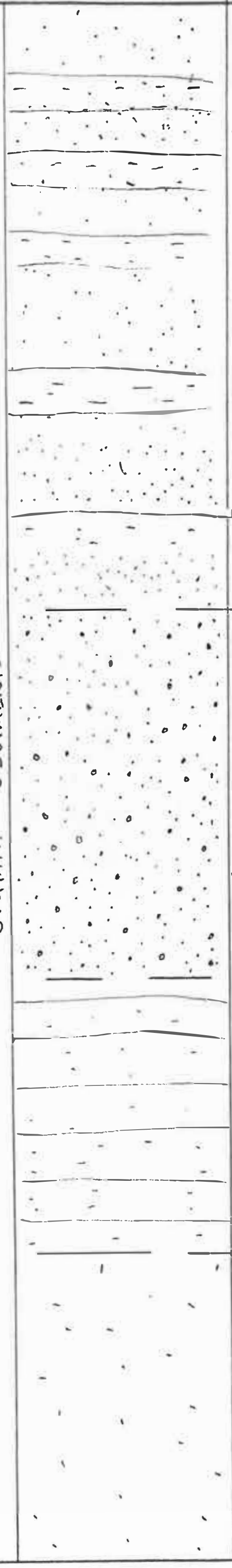
Stratigraphic Column : CARRS TRACK

G.R.: U14/828748.

TOTAL THICKNESS (metres)	THICKNESS (metres)		PROFILE *Not to scale*	HANDSPECIMEN DESCRIPTION	COMMENTS
1.0	0.2	OPUIAKI SEDIMENTS		LENS OF COBBLES, PEBBLES AND SANDS. 30 [0.5 – 80] mm. COMPRISE VESICULAR GREY RHYOLITE AND WAITEARIKI IGNIMBRITE. BOTH ROCKS MODERATELY WEATHERED.	CHANNEL LAG DEPOSIT ?
0.8	0.8			CROSS BEDDED SANDS AND SOME PEBBLES. SAME CHARACTERISTICS AS FOR SAMPLE 435 EXCEPT FOR PEBBLES	
				OUTCROP OBSCURED BELOW THIS POINT. HOWEVER WAITEARIKI OUTCROPS OCCASIONALLY IN THE AREA, PARTICULARLY U14/835744. AND U14/831745.	

Stratigraphic Column: Pozzalana Quarry

G.R.: U14/732 723

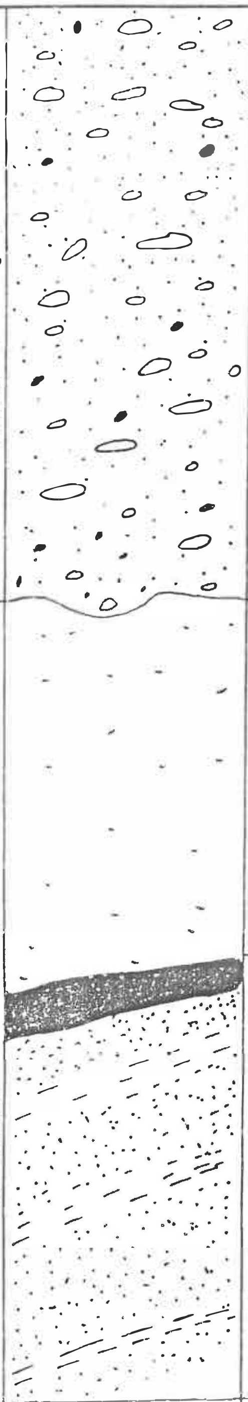


TOTAL THICKNESS (metres)	THICKNESS (metres)	PROFILE (NOT TO SCALE)	HANDSPECIMEN DESCRIPTION	COMMENTS
4.4	1.22		UPPER FINE ZONE. a) WHITE b) FIRM, SLIGHTLY WTHD. c) CRYSTALS 10% VITRIC 90%. d) FINE SAND TO SILT. e) WELL SORTED. f) FINE SANDY SILT STONE. COARSER BASAL ZONE a) WHITE b FIRM IN PLACE. c) UNWEATHERED, 'VERY CLEAN APPARANCE' d) CRYSTALS 40%. VITRIC 60% e) COARSE TO FINE SAND, SOME SILT. f) MODERATELY WELL SORTED g) SILTY SANDSTONE.	DEPOSIT FINES UP AND LAMINATIONS BECOMES DIFFICULT TO DETECT. BASAL ZONE, ALTERNATES BETWEEN NORMALLY BEDDED HORIZONTAL LAMINATIONS OF FINE SAND AND SILT. SAMPLE 747 WT 23520
3.08	0.08		a) YELLOW BROWN. b) LOOSE c) SLIGHTLY WEATHERED. d) CRYSTALS 40%, PUMICE 56% [SEMI ROUNDED, FIRM, 1-3m] 4% ROCK FRAGMENTS [RHYOLITE]. e) COARSE SAND TO FINE SILT. f) MODERATELY SORTED. g) COARSE SANDSTONE.	GRADITIONAL CONTACT. MASSIVE DEPOSIT GRAVEL/SAND LENS SAMPLE 746 WT 23519
3.0	1.2		a) WHITE WITH YELLOW LAMINATIONS b) FIRM IN PLACE. c) UNWEATHERED. d) FINE GRAINED 'VITRIC' APPEARANCE. NO XALS OR ROCK FRAGS. e) SILT. f) V. WELL SORTED g) SILT STONE	SHARP CONTACT. VARVES EVERY 10-20 mm. SAMPLE 745 WT 23518
1.8	1.8		a) WHITE. b) FIRM IN PLACE. c) UNWTHD. d) FINE GRAINED 'VITRIC'. NO CRYSTALS PUMICE OR ROCK FRAGMENTS. e) FINE SILT. f) V. WELL SORTED. g) SILTSTONE	GRADITIONAL CONTACT. NO VARVES. MASSIVE. LIGHT CHALKY FEEL.

OPUIAKI SEDIMENTS

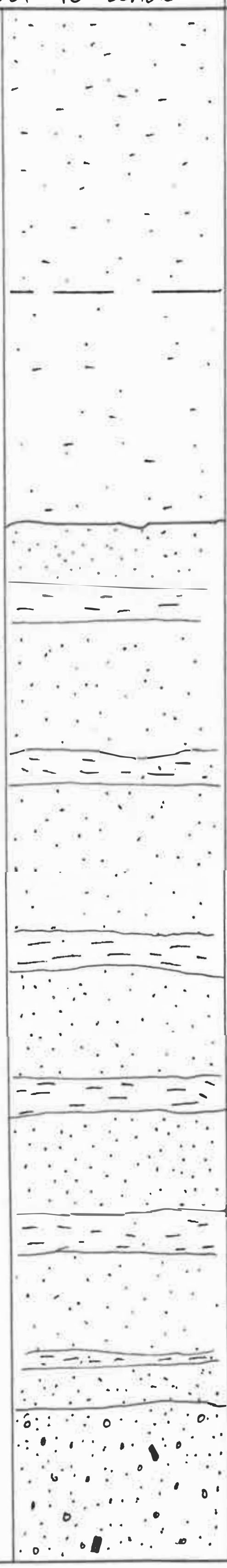
Stratigraphic Column : OPUIAKI RIVER, UPSTREAM OF WEIR G.R.: 415/765 692

NOTE: THIS COLUMN IS ABOUT 2 km DOWNSTREAM OF COLUMN 'B'

TOTAL THICKNESS	THICKNESS		PROFILE *Not to scale*	HANDSPECIMEN DESCRIPTION	COMMENTS
metres					
5	3 (3 METRES EXPOSED HERE, REST OBSCURED.)	WAIMAKARIRI IGNIMBRITE.		a) YELLOWISH GREY b) CRYSTALS 10%. c) PUMICE 18, 20% 18[2-38]mm. LIGHT YELLOW, FIBEROUS, WEATHERED. SEMI FLOW ALIGNED LENTICULAR. d) LAPILLI TO FINE TUFF, MAINLY COARSE AND LAPILLI TUFF. e) WEAK, PT = 41, MODERATELY WEATHERED. f) LITHICS: 3%, DARK RHYOLITE, [1-7] mm g) WEATHERED VITRIC. h) POORLY SORTED.	CAN CHIP WITH SPADE. COLUMNAR JOINTED SHARP CONTACT
2.0	0.7	OPUIAKI SEDIMENTS.		a) LIGHT YELLOW. b) FIRM. d) CRYSTALS: 2%. VITRIC 98% c) SLIGHTLY WEATHERED. e) MEDIUM SAND TO MOSTLY COARSE TO FINE SILT. f) WELL SORTED. g) SANDY SILTSTONE.	DEPOSIT MASSIVE INTERPRETED AS PRE WAIMAKARIRI AIR FALL. SAMPLE 7/6 WT 23503
1.3	0.3			30 mm DARK BROWN LAYER, POSSIBLY OLD PALEOSOL, THOUGH NO STRUCTURE.	
1	1			a) LIGHT YELLOW GREY. b) FIRM c) WEATHERING DECREASES WITH HEIGHT. d) CRYSTALS 50%, VITRIC 50% VITRIC MATERIAL SUPPORTS CRYSTALS. NO PUMICE OR ROCK FRAGMENTS. e) COARSE SAND TO FINE SILT	NORMALLY BEDDED WITH FINE SILTS OVERLYING SANDS SEDIMENTS DIP MARKEDLY OUT OF OUTCROP 45° NW.
0	0				
				SEDIMENTS OBSCURED BY RECENT ALLUVIUM.	

Stratigraphic Column : OPUIAKI RIVER, UPSTREAM OF WEIR. G.R.: U15/753682.

COLUMN 'B'

TOTAL THICKNESS	THICKNESS		PROFILE NOT TO SCALE	HANDSPECIMEN DESCRIPTION	COMMENTS
metres					
5.57	2	OPUIAKI SEDIMENTS		a) LIGHT PINK/GREY WITH BROWN b) FIRM. c) MODERATELY WTHD. d) CRYSTALS 10% 90% VITRIC [RELIC] e) FINE SAND AND SILT. f) MODERATELY WELL SORTED. g) FINE SANDY SILTSTONE	SPOTS. FIRM IN PLACE EASILY CHIPPED WITH SPADE. SAMPLE 713, WT 23500 SITE 5
				a) LIGHT YELLOW. b) FIRM c) MODERATELY WTHD. d) CRYSTALS: 1%. 99% VITRIC [WTHD]. e) SOME SAND MOSTLY SILT. f) WELL SORTED g) SILTSTONE	GRADITIONAL CONTACT WITH ABOVE. MASSIVE NO BEDDING SAMPLE 712. WT23499 SITE 4 SHARP CONTACT.
3.57	1.5			DIRTY SANDSTONE. a) LIGHT YELLOW b) FIRM/LOOSE. c) SLIGHTLY WEATHERED. d) CRYSTALS: 45% [0.2 - 2.1] mm. PUMICE 7% [1 - 3 mm], VITRIC 48% CRYSTALS AND PUMICE SUPPORTED BY VITRIC SILT MATRIX. e) VERY COARSE TO VERY FINE SAND PLUS COARSE TO FINE SILT. f) MODERATELY SORTED. g) SILTY SANDSTONE. SILTY MUDSTONE a) PALE YELLOW GREY. (b) V. FIRM. c) SLIGHTLY WEATHERED. d) NO CRYSTALS OR ROCK FRAGMENTS. 100% SILT AND MUD. e) COARSE TO FINE SILT AND MUD. f) VERY WELL SORTED g) SILTY MUDSTONE.	ALTERNATING LAYERS OF HORIZONTAL, NORMALLY BEDDED SAND AND SILT STONE. SAND STONE DESCRIBED FIRST THEN SILTSTONE. CHANGES BETWEEN SAND AND SILT IS SHARP OVER 1-2 mm. SAMPLES 711 WT 23948. SAND BECOMES NOTICABLY CLEANER TOWARDS BASE SITE 3 SHARP CONTACT
2.07	0.07			a) YELLOWISH GREY b) LOOSE. c) SLIGHTLY/MODERATELY WEATHERED. d) CRYSTALS: 24% QUARTZ,	· SITE 2 CONT'D. SAMPLE 714 WT 23501

Stratigraphic Column OPUIAKI RIVER, UPSTREAM OF WEIR G.R.: U15/753682

COLUMN 'B'

TOTAL THICKNESS (metres)	THICKNESS	PROFILE (NOT TO SCALE)	HANDSPECIMEN DESCRIPTION	COMMENTS
2	2	OPUIAKI SEDIMENTS 	FELSPAR + MAFICS [0.5 - 1.5] mm ROCK FRAGMENTS ; 1% RHYOLITE ANDESITE?. PUMICE: WHITE, ROUNDED, FIBEROUS [0.3 - 3] mm. PEBBLES OF DIATAMOUS SILT STONE. [3 - 20] mm. VITRIC SILT WHICH ACTS AS SUPPORT FOR THE ABOVE MATERIAL. [35%]. e) PEBBLE TO SILT SIZE, MAINLY COARSE TO FINE SAND. f) POORLY SORTED. g) COARSE SANDY SILTSTONE.	OFTEN THIS MATERIAL HAS BEEN ERODED FROM OUTCROP. SAMPLE 714 WT 23501 SITE 2 SHARP CONTACT WITH UNDERLYING SEDS EROSIONAL UNCONFORMITY.
			a) WHITE WITH FINE YELLOW LAMINATIONS b) FIRM IN PLACE. c) UNWEATHERED. d) NO CRYSTALS OR ROCK FRAGMENTS 100% SILT SIZE. e) COARSE TO VERY FINE SILT. f) VERY WELL SORTED. g) DIATOMACEOUS SILT STONE.	VARVES OBVIOUS OCCOUR 1-1.5cm. SAMPLE 710 WT 23497 SITE 1 LIGHT CHALKY FEEL

APPENDIX 3

Modal analysis of the ignimbrites of the northern Mamaku Plateau, total percentage for whole rock.

Mamaku Ignimbrite									
Sample No.	Matrix	Rock Fragments	Total Crystals	Plagioclase	Quartz	Opaques	Pyroxene	Hornblende	Biotite
Ngamanawa (U15/791647)									
303	94.75	-	5	3.25	1	0.5	0.25	-	-
304	93.75	-	6.25	3	1.5	0.25	0.75	-	-
305	87	2.25	10.75	4.75	2.25	0.25	0.5	-	-
306	86.5	1.75	10.75	6	1.25	0.5	-	1	-
307	89.25	-	10.75	6.75	2.75	-	-	-	-
308	85.25	0.25	14	9.25	4	0.5	0.25	-	-
309	84	-	17	9.75	2.75	1.25	0.5	-	-
Belk Road (U14/826712)									
402	90.5	0.25	9.5	4.25	2	1.25	1.25	-	-
404	95.25	-	4.75	2.25	1.75	0.25	-	0.25	-
407	91.5	-	8.5	5.75	2.25	0.25	0.25	-	-
408	91.75	-	8.25	4.25	2.25	0.25	-	0.75	-
Carrs Track (U14/831739, sheet 4)									
430b	95.75	-	10.75	3.25	0.75	0.25	-	-	-
Tramway Tunnel (U14/825711)									
414	88	-	12	9	3	-	-	-	-
416a	87.25	-	12.75	9.5	1.25	0.75	-	-	-
Omanawa Falls (U15/821682, basal welded zone)									
507	90.25	0.25	9.75	4.75	3	0.5	0.5	-	-
Joyce Road (U14/853736, 543 sheet 2, 544 surge, 546 sheet 4)									
543	93.75	-	6.25	2	3	0.5	-	-	-
544	89.65	-	10.26	5.5	3.5	1.26	-	-	-
546	82	-	17.3	14	2	1	0.6	-	-
Mamaku Type Site (U15/887554)									
613	85.25	-	18.5	8.75	3.75	0.25	0.25	-	-
614	85.75	-	14.25	8.5	4.75	-	0.95	-	-
615	86.75	0.25	13	7.25	3.75	1	0.5	-	-
616	85.25	-	13.75	8.5	3.75	0.75	-	-	-
617	85	-	14.5	10.5	3.5	0.25	0.25	-	-
618	89.75	-	10.25	9.25	0.25	0.5	-	-	-
619	87.5	-	12.5	7.5	2.75	1.75	-	-	-
621b	88	-	12	7.25	2.5	1	-	-	-
621c	88.75	-	9.75	3.75	4	1	-	-	-

Sample No.	Matrix	Rock Fragments	Total Crystals	Plagioclase	Quartz	Opaques	Pyroxene	Hornblende	Biotite
Omanawa Falls (U15/821682)									
500	97.75	-	2.25	0.75	1.5	-	-	-	-
503	95.5	-	4.5	2.75	0.5	0.25	1	-	-
504	90.75	-	9.25	7.5	1	0.25	-	-	-
505	89.5	-	9.5	7.75	1.25	-	0.5	-	-
506	91.25	-	8.75	8.25	-	0.25	0.25	-	-
Lower Mangapapa Station (U14/778713, bedded zone)									
514	83	-	16.5	14.5	1.5	0.5	-	-	-
Youth Camp (U14/838743)									
611	95.25	-	4.75	3	0.25	1	0.5	-	-
612	93	0.75	6.75	4.5	1.75	-	0.5	-	-
Ruahihi Canal (U14/783728, following 5 thin-sections from the major cutting)									
43	96.75	-	2.75	1	1.5	-	0.25	-	-
44	95.75	-	3.25	1.5	1.5	-	0.25	-	-
627	91.75	1.5	6.75	6.5	0.25	-	-	-	-
628	90.0	-	10.0	8.25	1	0.25	0.5	-	-
634	89.25	-	10.75	9.25	0.75	0.25	0.5	-	-
(exposed flow units by No. 1 tributary, 951 is overlying flow)									
950	91.5	-	8.5	7.25	0.75	0.25	-	0.25	-
951	89.5	-	11.0	5.25	1	0.75	-	4	-
(Oropi Gorge, U15/877687, Subaqueous Waimakariri flow)									
807	92.0	0.25	8.25	7	0.25	0.25	0.75	-	-
Scotts Track (top of flow, U15/77677)									
972a	94.75	1.0	4.25	4	-	-	0.25	-	-
Waiteariki Ignimbrite									
Ngamuwahine River (U14/752727, densely welded zone)									
24	72.5	-	27.5	18.5	5.25	1	2	0.25	-
100	77.25	-	23.75	19.5	2.5	-	1	0.75	-
(U14/737734, basal zone)									
742	76	-	25	16.75	2.25	1	2.45	2	0.5
(U14/737734, lithics)									
103	75.5	-	23.25	17.75	1.5	0.25	0.75	3	-
743	62.3	-	38.6	32	2.3	-	0.7	-	-
McLarens Falls (U14/783728, 442 is welded pumice)									
40	66.75	-	32.75	25.75	4	0.5	1.75	0.5	-
207	75.75	-	24.75	19.5	2.5	-	0.25	2.5	0.25
411	68.25	-	31.75	25.5	4.25	0.25	0.75	0.75	0.25
442	79.75	-	21.75	17.25	3.5	-	0.25	-	0.5
M.O.W Quarry (U14/752727)									
211	81.75	-	18.25	13.25	2.25	1	-	1.5	-

Sample No.	Matrix	Rock Fragments	Total Crystals	Plagioclase	Quartz	Opaques	Pyroxene	Hornblende	Biotite
Dairy Farm (U15/828681)									
621	95.75	-	4.25	1.75	0.5	1.25	0.25	-	-
622	90.75	2.75	6.5	4.25	0.75	1.25	-	-	-
623	85.75	-	14.25	10.5	1	1.25	-	-	-
626	91.5	-	8.5	3.5	4.25	0.5	-	-	-
Oropi Gorge (U15/877687)									
901	64.75	-	35.5	32	2	0.5	0.75	-	-
903	88.5	-	12	6.75	3.25	0.75	0.5	-	-
904	89.75	-	10.25	8.5	1	0.25	0.25	-	-
906	88	1.5	9.75	6.5	1.5	1	1	-	-
907	91.5	-	9.13	5.25	1.25	0.75	0.75	-	-
911	90.82	-	9.13	8.53	0.3	-	-	-	-
912	93	-	6.5	6	0.5	-	0.5	-	-
T.C.C. Weir (U14/857737, base of flow)									
953a	92.75	-	7.25	5.75	0.75	-	0.75	-	-
Scotts Track (U15/777677, base of flow)									
973a	86.5	1.75	11.75	8.5	1.75	0.25	0.75	-	-

Waimakariri Ignimbrite									
Lloyd Mandeno (U15/786675, base of flow)									
1*	96.5	0.5	2.5	0.75	0.75	-	-	1	-
Soldiers Rd.									
(U14/762709, base of flow)									
215a	93.75	-	6.25	5.5	0.75	-	-	-	-
(U15/752694, welded outcrop)									
216	76.5	-	23	16.5	5.75	0.25	-	0.5	-
(U15/754697, welded outcrop)									
217	72	-	28.5	21.25	6.5	0.25	-	-	-
Kiwifruit Orchard (U14/822722, middle flow unit)									
421	96.25	-	2.75	2	0.5	-	0.25	-	-
Carrs Track (U14/831739)									
430	86.25	-	13.75	11.75	2	-	-	-	-
431	89.25	-	10.75	7.5	2.5	-	-	-	-
432	92	-	8.5	6	1.25	0.25	0.75	-	-
433	96.5	0.25	2.75	1.75	0.75	-	0.25	-	-
Lake Mangapapa (U14/782703, strongly welded zone)									
450	89	1.25	8.75	4.5	3.5	0.25	-	-	-

REFERENCES

Adams, C.J.D; Wadzicki, A.; Weissberg, B.G. (1974) K-Ar dating of hydrothermal alteration at the Tui Mine, Te Aroha, New Zealand. *New Zealand Journal of Science 17*: 193-199.

Attewell, P.B.; Farmer, I.W. (1976) Principles of Engineering Geology. Chapman and Hall, London. 1045p.

Ballance, P.F. (1976) Evolution of the upper Cenozoic magmatic and plate boundary in Northern New Zealand. *Earth and Platenary Science Letters 28*: 356-370.

Berryman, K.; Hull, A. (1984) Guidebook to the North Island scientific excursions. Royal Society Miscellaneous Series: 8, Wellington. 27p.

Braithwaite, R.L. (1980) Petrography of the hydrothermally altered rocks from the Waihi Mines, *New Zealand Geological Survey Report*, M80. 3p.

Briggs, N.D. (1973) Investigations of New Zealand Pyroclastic flow deposits. Unpublished Ph.D. thesis, lodged in the Library, University of Victoria.

Briggs, N.D. (1975) Determination of the cause of thickness variation in ignimbrites *New Zealand Journal of Geology and Geophysics 18*: 105-106

Briggs, N.D. (1976a) Vertical and lateral variations in the Whakamaru Ignimbrite. *Twenty Fifth International Geological Congress Excursion Guide No 55a and 56c:* 30-33.

Birrell, K.S.; Pullar,W.A.; Searle,P.L. (1977) Weathering of Rotoehu Ash in the Bay of Plenty district. *New Zealand Journal of Science 20*: 303-310.

Brothers, R.N. (1984) Subduction regression and oceanward migration of volcanism, North Island, New Zealand. *Nature (309)*: 698-700.

Brown, M.C. (1962) Discussion: Nuées Ardentes and fluidisation. *American Journal of Science 260*: 467-470.

Buck, M.D. (1981) Peralkaline ignimbrite sequences on Mayor Island, New Zealand. Pp 337-345 in: Self, S.; Sparks, R.S.J. (eds.) Tephra Studies, D. Reidel Publishing Co, Dordrecht, Holland.

Buller, A.T. (1973) Distinction among pyroclastic deposits from their grain size frequency distributions. *Journal of Geology 81*: 97-106.

Carryer, S.J. (1974) Report on Ruahini and Intermediate hydro-electric power schemes. Appendix B: Geological Report. *Unpublished Report*.

Carryer, S.J. (1975) Geological report on the detailed investigations for the Ruahihi hydro-electric scheme. *Unpublished Report.*

Chapin, C.E.; Lowell, G.R. (1979) Primary and secondary flow structures in ash flow tuffs of the Gribbles Run Paleovalley, central Colorado. *Geological Society of America Special Paper 180*: 137-154.

Chappell, J. (1975) Upper Quaternary warping and uplift rates in the Bay of Plenty and West Coast, North Island, New Zealand. *New Zealand Journal of Geology and Geophysics 18*: 129-155.

Cole, J.W. (1979) Structure, petrology, and genesis of Cenozoic volcanism, Taupo Volcanic Zone, New Zealand - A Review. *New Zealand Journal of Geology and Geophysics 22*: 631-657.

Cole, J.W. and Lewis, K.B. (1981) Evolution of the Taupo - Hikurangi subduction system. *Tectonophysics 72*: 1-21.

Collins, B.D.; Dunne, T.; Lehre, A.K. (1983) Erosion of tephra covered hillslopes north of Mount St Helens, Washington: May 1980 May 1981. *Zeit schrift fur Geomorphologie Suppl-Bd 46*: 103-121.

Cowbourne, A.J. (1985) Aspects of engineering Geology and Geophysics, Ruahihi, Tauranga. Unpublished M.Sc. thesis, lodged in the Library, University of Auckland.

Cox, A. (1969) A paleomagnetic study of secular variation in New Zealand. *Earth and Planetary Science Letters 6*: 257-267.

Cullen, D.J. (1967) Submarine evidence from New Zealand of a rapid rise in sea level about 11,000 years B.P. *Palaegeography, Paleoclimatology, Paleoecology 3*: 289-298.

Cuthbertson, A.S. (1981) The Hinuera Formation in the Southern Hauraki Lowland, Central North Island. Unpublished M.Sc. thesis, lodged in the Library, University of Waikato.

Davis, B.K. (1985) Structural variations of yellow brown loams, under differing rainfall. Unpublished M.Sc thesis, lodged in the Library, University of Waikato.

Dell, P.M. (1982) The effect of afforestation on the water resources of the Mamaku Plateau region. Unpublished M.Sc thesis, lodged in the Library, University of Waikato.

Enos, P. (1977) Flow regimes in debris flows *Sedimentology 24*: 133-142.

Ewart, A. (1965) Mineralogy and petrogenesis of the Whakamaru Ignimbrite in the Maraetai area of the Taupo Volcanic Zone, New Zealand. *New Zealand Journal of Geology and Geophysics 8*: 611-677.

Fisher, R.V. (1966) Mechanism of deposition from pyroclastic flows *American Journal of Science 264*: 350-363.

Fisher, R.V.J (1971) Features of coarse grained, high concentration fluids and their deposits. *Journal of Sedimentary Petrology 41(4)*: 916-927.

Fisher, R.V. Heiken, G. (1982) Mt Pelee, Martinique: May 8 and 20th, 1902, pyroclastic flows and surges. *Journal of Volcanology and Geothermal Research 13*: 33-371.

Fisher, R.V.; Schmincke, H.U. (1984) Pyroclastic Rocks. Springer-Verlag, Berlin.

Fisher, R.V.; Smith, A.H.; Roobol, J.M. (1980) Destruction of St Pierre, Martinique, by ash cloud surges, May 8 and 20, 1902. *Geology 8*: 472-476.

Fisher, R.V.; Valentine, G.A. (1986) Pyroclastic flows, surges and fluidization. *International Volcanological Congress Abstracts*: 42p.

Foged, N. (1979) Diatoms in New Zealand, the North Island. Bibliotheca Phycologica 47: 130-225.

Fransen, P.J.B. (1982) Geology of the western Mamaku Plateau and variations in the Mamaku Ignimbrite. M.Sc. thesis, lodged in the Library, University of Waikato.

Froggatt, P.C.; Wilson, C.J.N. Walker, G.P.L. (1981) Orientation of logs in the Taupo region, as an indication of flow direction and vent position. *Geology 9*: 109-111.

Grindley, G.W. (1965) The geology, structure, and exploitation of the Wairakei Geothermal Field, Taupo, New Zealand. *New Zealand Geological Survey Bulletin 75.* Government Printer, Wellington, 131p.

Harmsworth, G.R. (1983) Quaternary Stratigraphy of the Tauranga Basin. Unpublished M.Sc. thesis, lodged in the Library, University of Waikato.

Hatch, F.H.; Wells, A.K.; Wells, M.K. (1972) Petrology of the igneous rocks. Thomas Murby and Co, London.

Healy, J. (1955) The Ivy Bridge section, Lower Kaimai. *Unpublished Report*. New Zealand Geological Survey, Rotorua.

Healy, J. (1956) Geological report on the proposed Lower Kaimai hydro development. *Unpublished Report.* New Zealand Geological Survey, Rotorua.

Healy, J. (1957) Geological report on the Omanawa extension to the proposed Lower Kaimai hydro development. *Unpublished Report*. New Zealand Geological Survey, Rotorua.

Healy, J. (1967) Geology of the Kaimai Tunnel section (abs.), *Unpublished Report*. Geological Society of New Zealand Conference.

Healy, J. (1969) Geological report on proposed tunnel line, Kaimai Railway Deviation. *Unpublished Report*. Department of Scientific and Industrial Research.

Healy, J. (1975) Volcanic Lakes in New Zealand. 70p. in: Jolly, V.H. and Brown, J.M.H. (eds.) University of Auckland.

Healy, J. (1982) Central Volcanic Region. Pp. 161-192 in: Soons, J.M. and Selby M.J. (eds.) Landforms of New Zealand. Longman Paul, Auckland.

Healy, J.; Schofield, J.C.; Thompson, B.N. (1964) Sheet 5 Rotorua "Geological Map of New Zealand 1:250,000". Department of Scientific and Industrial Research, Wellington.

Henderson, J. Bartrum, J.A. (1913) The geology of the Aroha Subdivision, Hauraki, Auckland. *New Zealand Geology Survey Bulletin, New Series 16*.

Hildreth, W. (1981) Gradients in silicic magma chambers: Implications for lithospheric magmatism. *Journal of Geophysical Research 86*: 10153-10192.

Hodder, P. (1983) Diapiric replenishment of magma chambers and triggering of volcanism in the Taupo Volcanic Zone, New Zealand. *Chemical Geology 38*: 275-285.

Hogg, A.G.; McCraw, J.D. (1983) Late Quaternary tephras of Coromandel Peninsula, North Island, New Zealand: a mixed peralkaline and calcalkaline tephra sequence. *New Zealand Journal of Geology and Geophysics 18*: 163-187.

Houghton, B.F. and Cuthbertson, A.S. *(in press)* Geological Map of New Zealand, Sheet T4, Kaimai. 1:50 000.

Howorth, R. (1975) New formations of late Pliestocene tephras from the Okataina Volcanic Center, New Zealand. *New Zealand Journal of Geology and Geophysics 18*: 683-712.

Howorth, R.; Froggatt, P.C.; Vucetich, C.G.; Collen, J.D. (1981) Editorial. Pp. 1-4 in Procedings of Tephra Workshop, June 30th-July 1st 1980, Geology Department, University of Victoria, Wellington. Publication 20.

Hsu, K.J. (1975) Catastrophic debris streams, (Sturzstroms) generated by rock falls. *Geological Society of America Bulletin 80*: 129-140.

Hsu, K.J. (1978) Albert Heim: Observations on landslides and relevance to modern interpretations. Pp. 71-93 in Vorght, B. (ed.) Rockslides and Avalanches. Elsevier, Amsterdam.

Irwin, I.W. (1975) Volcanic Lakes in New Zealand. Pp 25-36. in: Jolly, V.H. and Brown, J.M.H. (eds.) University of Auckland.

Kamp, P.J.J. (1984) Neogene and Quaternary extent and geometry of the subducted Pacific Plate beneath North Island, New Zealand: Implications for Kaikoura Tectonics. *Tectonophysics 108*: 241-266.

Kamp, P.J.J. (1985) A structural framework for the Cenozoic tectonic development of New Zealand. Unpublished Ph.D. thesis, lodged in the Library, University of Waikato.

Kennedy, N. (1980) Field recognition of tephric loess. *New Zealand Soil News 28*: 55-58.

Kennedy, N. (1984) Paleo landsurfaces c.140,000-c.14,000 BP on the Mamaku Plateau, North Island, New Zealand. *New Zealand Soil News 32*: 210-211.

Kohn, B.P. (1973) Some studies of New Zealand Quaternary pyroclastic rocks. Upublished Ph.D. thesis, lodged in the Library, University of Victoria.

Kuno, H.; Ishikawa, T. Katsui, Y.; Yagi, Kenzo; Yamasaki, M.; Taneda, S. (1964). Sorting of pumice and lithic fragments as a key to eruptive and emplacement mechanisms. *Japanese Journal of Geology and Geophysics 35.*

Lewis, D.W. (1984) Practical Sedimentology. Hutchinson Ross, Stroudsburg.

Lipman, P.W. (1967) Mineral and chemical variations within an ash-flow sheet from Aso Caldera, South Western Japan. *Contributions to Mineralogy and Petrology 16*: 300-327.

Lipman, P.W.; Christiansen, R.L.; O'Connor, J.T. (1966) A compositionally zoned ash flow sheet in Southern Nevada. *Geological Survey Professional Paper 524-F* 1-46.

Lipman, P.W.; Mullineaux, D.R. (1981) The 1980 eruptions of Mount St. Helens, Washington. *United States Geological Survey, Professional Paper*. 1250.

Lloyd, E.F. (1965) Geological report on the proposed Omanawa Mangapapa Opuiaki hydro-electric scheme. *Unpublished Report*. New Zealand Geological Survey, Rotorua.

Lloyd, E.F. (1968) Third interm report on proposed Mangapapa hydro-electric scheme. *Unpublished Report*. New Zealand Geological Survey, Rotorua.

Lloyd, E.F. (1969) Geological report on proposed dam at Waiorohi stream for extensions to Tauranga City's water supply. *Unpublished Report*. New Zealand Geological Survey, Rotorua.

Lowe, D.R. (1976) Subaqueous liquefied and fluidized sediment flows and their deposits. *Sedimentology 23*: 285-308.

Mahood, G.A. (1983) A discussion of the Rio Caliente Ignimbrite: analysis of a compound intraplinian ignimbrite from a major late Quaternary Mexican eruption by J.V. Wright. *Bulletin Volcanologique 42:* 214-221.

Martin, R.C. (1961) Stratigraphy and structural outline of the Taupo Volcanic Zone. *New Zealand Journal of Geology and Geophysics 4*: 449-478.

Martin, R.C. (1965) Lithology and eruptive history of the Whakamaru Ignimbrites in the Maraetai area of the Taupo Volcanic Zone, New Zealand. *New Zealand Journal of Geology and Geophysics 8*: 680-701.

McBirney, A.R. (1973) Factors governing the intensity of explosive andesitic eruptions. *Bulletin Volcanologique 37*: 443-453.

McCraw, J.D. (1975) Quaternary airfall deposits of New Zealand. *Royal Society of New Zealand Bulletin 13*: 35-64.

McFadgen, B.G.; Sheppard, B.G. (1984) Ruahihi Pa: An investigation. New Zealand Historical Places Trust.

McGlone, M.S.; Howorth, R.; Pullar, W.A. (1984) Late Pleistocene stratigraphy, vegetation and climate of the Bay of Plenty and Gisborne regions, New Zealand. *New Zealand journal of Geology and Geophysics 27*: 327-350.

McTaggart, K.C. (1960) The mobility of Nuées Ardentes. *The American Journal of Science 258*: 369-382.

Mandeno, Chitty and Bell (1975) Ruahihi hydro-electric scheme, report on site investigations and soil testing. *Unpublished report*. Tauranga Joint Generation Committee.

Mitchell, M.T. (1980) Review of soil conditions Ruahihi contract 1053-H2. *Unpublished Report*.

Morgan, L.A. (1986) Tree moulds in densely welded ignimbrites. *International Volcanological Congress Abstracts*: 64p.

Murai, I. (1961) A study of the textural characteristics of pyroclastic flow deposits in Japan. Tokyo University. *Bulletin of the Earthquake Research Institute 39*: 133-248.

Nairn, I.A.; Self, S. (1975) Explosive eruptions and pyroclastic avalanches from Ngauruhoe in February 1975. *Journal of Volcanology and Geothermal Research 3*: 39-60.

Nathan, S. (1975) Notes on the petrology of the Mamaku Ignimbrite and associated rocks. *Unpublished Report*. New Zealand Geological Survey, Rotorua.

Nathan, S. (1976) Geology of the Rotorua District. In Nathan, S. (compiler) 25th International Geological Congress Excursion Guide 55A: 16-19.

Nappi, G.; Martini, M.; Marini, A. (1986) Turbulent pyroclastic flows: specific emplacement characteristics. *International Volcanological Congress Abstracts*: 66p.

Oborn, L.E.; Northey, R.D.; Beetham, R.D.; Brown, I.R. (1974) Engineering geological factors related to collapse of Ruahihi Canal. Engineering Geology Section New Zealad Geological Survey. Submission to Committee to Inquire into Ruahihi Canal Failure. Appendix 3 of M.W.D Committee Report.

Peterson, D.W. (1979) Significance of the flattening of pumice fragments in ash flow tuffs. *Geological Society of America Special Paper 180*: 195-204.

Picard, M.D.; High, L.R. (1972) Criteria for recognising Lacustrine rocks, Pp 108-145. in: Rigby, J.K.; Hamblin, W.K. (eds.) Recognition of ancient sedimentary environments. SEPM, Special publication No. 16.

Prebble, W.M. (1984) Investigations in an active volcanic terrain, in Brown I.R (ed.) Engineering for dams and canals. Proceedings of technical groups, IPENZ, 9: 4(G).

Ragan, D.M.; Sheridan, M.F. (1972) Compaction of the Bishop Tuff, California. *Geological Society of America Bulletin 83*: 95-106.

Reid, F. (1983) Origin of the rhyolitic rocks of the Taupo Volcanic Zone, New Zealand. *Journal of Volcanology and Geothermal Research 15*: 315-338.

Reihle, J.R. (1973) Calculated compaction profiles of rhyolitic ash flow tuffs. *Geological Society of America Bulletin 84*: 2193-2216.

Riddols, B.W. (1971a) Geology of the Mangapapa hydro-electric scheme, progress report No. 1. *Unpublished Report*. New Zealand Geological Survey, Rotorua.

Riddols, B.W. (1971b) Geology of the Mangapapa hydro-electricscheme, progress report No. 2. *Unpublished Report*. New Zealand Geological Survey, Rotorua.

Ross, C.S.; Smith, B.L. (1961) Ash flow tuffs: their origin, geologic relations, and identification. *United States Geological Survey Professional Paper 366*: 1-81.

Rutherford, N.F. (1976) Petrochemistry of ignimbrites from the central North Island and Coromandel, New Zealand. Unpublished Ph.D. thesis, lodged in the Library, University of Auckland.

Rutherford, N.F.; Heming, R.F. (1978) The volatile component of Quarternary ignimbrite magmas from the North Island, New Zealand. *Contributions to Mineralogy and Petrology 65*: 401-411.

Sanders, J.E. (1968) Stratigraphy and primary sedimentary structures of fine grained, well bedded strata, inferred lake deposits, Upper Triassic, Central and Southern Connecticut. Pp. 265-303 in: Klein, G.D. (ed.) Geological Society of America, Special Paper 106.

SAS Institute Inc. (1985) SAS User's Guide: Statistics, Version 5 Edition. Cary, NC: USA.

Schmid, R. (1981) Descriptive nomenclature and classification of pyroclastic rocks and fragments: *Geology 9*: 41-43.

Selby, M.J. (1982) Hillslope materials and processes. Oxford University Press, Oxford. 65, 170p.

Self, S. (1986) Documentation of a high energy proximal to medial pyroclastic flow facies. *International Volcanological Congress Abstracts*: 71p.

Sheridan, M.F. (1971) Particle size characteristics of pyroclastic tuffs *Journal of Geophysical Research 76*: 5627-5634.

Sheridan, M.F. (1979) Emplacement of pyroclastic flows: a review *Geological Society of America Special Paper 180*: 125-135.

Sheridan, M.E.; Ragan, D.M. (1976) Compaction of ash flow tuffs. Pp. 677-717 in: Chilingarian, GV and Wolf, K.H. (eds.) Compaction of coarse grained sediments. Developments in Sedimentology 18B, Elsevier.

Sigurdsson, H.; Carey, S.N.; Espindola, J.M. (1984) The 1982 eruptions of Ele Chichon Volcano Mexico: stratigraphy of pyroclastic deposits *Journal of Volcanology and Geothermal Research 23*: 11-37.

Smith, R.L. (1960a) Ash Flows. *Bulletin of the Geological Society of America 71*: 795-842.

Smith, R.L. (1960b) Zones and zonal variations in welded ash flows. *United States Geological Survey Professional Paper*, 345-F: 149-159.

Smith, R.L.; Bailey, R.A. (1965) The Bandelier Tuff: A study of ash flow eruption cycles. *Bulletin Volcanologique* Tome XXIX: 83-103.

Smith, A.L.; Fisher, R.V.; Roobol, M.J.; Wright, J.V. (1981a) Pyroclastic flows and surges: examples from the lesser Antilles. Pp. 421-425 in: Self, S.; Sparks, R.S.J. (eds.) Tephra Studies. D. Reidel Publishing Co, Dordrecht, Holland.

Smith, A.L.; Roobol, M.J. (1982) Andesitic pyroclastic flows. Pp. 415-433 in R.S. Thorpe (eds.) Andesites. John Wiley and Sons, New York.

Sparks, R.S.J. (1976) Grain size variation in ignimbrites and implications for the transportation of pyroclastic flows. *Sedimentology 23*: 147-188.

Sparks, R.S.J. (1978) Gas release rates from pyroclastic flows: an assessment of the role of fluidization in their emplacement. *Bulletin Volcanologique 41*: 1-9.

Sparks, R.S.J.; Self.S and Walker, G.P.L. (1973) Products of ignimbrite eruptions. *Geology 1*: 115-118.

Sparks, R.S.J.; Walker, G.P.L. (1977) The significance of vitric enriched air fall ashes associated with crystal enriched ignimbrites. *Journal of Volcanology and Geothermal Research 2*: 329-341.

Sparks, R.S.J.; Wilson, L. (1976) A model for the formation of ignimbrites by gravitational column collapse. *Journal of the Geological Society London 132*: 441-451.

Sparks, R.S.J.; Wilson, L.; Hulme, G. (1978) Theoretical modelling of the generation, movement and emplacement of pyroclastic flows by column collapse. *Journal of Geophysical Research 10*: 1727-1739.

Sparks, R.S.J.; Wright, J.V. (1979) Welded air fall tuffs. *Geological Society of America Special Paper 180*: 155-166.

Sparks, R.S.J.; Francis, P.W.; Hamer, R.D.; Pankhurst, R.J.; O'Callaghan, L.O.; Thorpe, R.S.; Page, R. (1985) Ignimbrites of the Cerro Caldera, North West Argentina. *Journal of Volcanology and Geothermal Research 24*: 205-248.

Stokes, E. (1983) Ngamanawa. A study of conflicts in the use of forest land. University of Waikato. 3p.

Suggate, R.P. (1978) The Kaikoura Orogeny. Pp. 627-701 in: Suggate R.P.; Stevens, G.R.; and Te Punga, M.T. (eds.) The Geology of New Zealand. Government Printer, Wellington.

Suzuki, K.; Ui, T. (1983) Factors governing the flow lineation of a large scale pyroclastic flow - an example in the Ata Pyro flow deposit, Japan. *Bulletin Volcanologique 41(1)*: 71-81.

Thompson, B.N. (1953) Pozzalanas at Lower Kaimai, Tauranga. *Unpublished Report*. New Zealand Geological Survey, Rotorua.

Thompson, B.N. (1956) Pozzolan at Lower Kaimai, Tauranga. *Unpublished Report*. New Zealand Geological Survey, Rotorua.

Thompson, B.N. (1958) Dam site on Waiorohi Stream, Tauranga. *Unpublished Report*. New Zealand Geological Survey, Rotorua.

Underwood, E.J.; Filmer,J.F. (1935) The determination of the biologically potent element (cobalt) in limonite. *Australian Veterinary Journal 11*: 84-92.

Valentine, G.A. (1981) *International Volcanological Congress Abstracts*: 85p.

Walker, G.P.L. (1971) Grain size characteristics of pyroclastic deposits. *Journal of Geology 79*: 696-714.

Walker, G.P.L. (1972) Crystal concentration in ignimbrites. *Contributions to Mineralogy and Petrology 36*: 135-146.

Walker, G.P.L. (1981a) New Zealand case histories of pyroclastic studies. Pp 317-330 in: Self, S.; Sparks, R.S.J. (eds.) Tephra Studies. D. Reidel, Dordrecht, Holland.

Walker, G.P.L. (1981) Plinian eruptions and their products. *Bulletin Volcanologique 44*: 223-240.

Walker, G.P.L. (1982) Eruptions of andesitic volcanoes. Pp. 403-413 in: Thorpe, R.S. Wiley, J. (eds.) Andesites: Orogenic andesites and related rocks. Chichester, England.

Walker, G.P.L. (1983) Ignimbrite types and ignimbrite problems. *Journal of Volcanology and Geothermal Research 17*: 65-88.

Walker, G.P.L. (1984) Characteristics of dune bedded pyroclastic surge bedsets. *Journal of Volcanology and Geothermal Research 20*: 281-296.

Walker, G.P.L.; Hemming, R.F.; Wilson, C.J.N. (1980) Low aspect ratio ignimbrites. *Nature 283*: 286-287.

Walker, G.P.L.; Wilson, C.J.N. (1980) Fines depleted ignimbrite in New Zealand - the product of a turbulent pyroclastic flow. *Geology 8*: 245-249.

Walker, G.P.L.; Wilson, C.J.N.; Froggatt (1981) An ignimbrite veneer deposit: the trail marker of a pyroclastic flow. *Journal Volcanology and Geothermal Research 9*: 409-421.

Walker, R.G.; Duke, W.L.; Leckie, D.A. (1983) Hummocky stratification: significance of its variable bedding sequences. Discussion and reply. *Geological Society of America 94*: 1245-1251.

Whitney, J.A; Stormer, J.C. (1985) Mineralogy, petrology and magmatic conditions from the Fish Canyon Tuff, Central San Juan Volcanic Field, Colorado. *Journal of Petrology 26*: 726-762.

Wilson, C.J.N. (1980) The role of fluidization in the emplacement of pyroclastic flows: an experimental approach. *Journal of Volcanology and Geothermal Research 8*: 231-249.

Wilson, C.J.N. (1984) The role of fluidization in the emplacement of pyroclastic flows: experimental results and their interpretation. *Journal of Volcanology and Geothermal Research 20*: 55-58.

Wilson, C.J.N.; Walker, G.P.L. (1981) Violence in pyroclastic flow eruptions. Pp. 441-448 in: Self, S.; Sparks, R.S.J. (eds.) Tephra Studies. D. Reidel, Dordrecht, Holland.

Wilson, C.S.N.; Walker, G.P.L. (1982) Ignimbrite depositional facies: the anatomy of a pyroclastic flow. *Journal Geological Society 139*: 581-592.

Wilson, C.J.N.; Rogan, A.N.; Smith, I.E.M.; Northey, D.J.; Nairn, I.A.; Houghton, B.F. (1984) Caldera volcanoes of the Taupo Volcanic Zone. *Journal of Geophysical Research 89810*: 8463-8484.

Wohletz, K.H. (1979) A model of pyroclastic surge. *Geological Society of America Special Paper 180*: 177-194.

Wolff, J.A.; Storey, M. (1984) Zonation in highly alkaline magma bodies. *Geological Magazine 121*: 563-575.

Wright, J.V. (1981) The Rio Caliente ignimbrite: analysis of a compound intraplinian ignimbrite from a major late Quaternary Mexican eruption. *Bulletin Volcanology 44*: 189-212.

Wright, J.V.; Self, S.; Fisher, R.V. (1981) Towards a facies model for ignimbrite forming eruptions. Pp 433-439 in: Self, S.; Sparks, R.S.J. (eds.) Tephra Studies. D. Reidel, Dordrecht, Holland.

Wright, J.V.; Smith, A.L.; Self, S. (1980) A working terminology of pyroclastic deposits. *Journal of Volcanology and Geothermal Research 8*: 315-336.

Yamazaki, T.; Kato, I.; Muroi, I.; Abe, M. (1973); Textural analysis and flow mechanism of Dunzurbo subaqueous pyroclastic flow deposits. *Bulletin Volcanology 37*: 231-244.

Zlotnicki, S.; Pozzi, S.P.; Boyoon, G.; Morfau, M.G. (1984) A new method for the determination of the setting temperature of pyroclastic deposits (Example of Guadeloupe: French West Indies). *Journal of Volcanology and Geothermal Research 21*: 297-312.