The Volcanic Geology of the Western Tauranga Basin

A thesis

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by

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Abstract

The western Tauranga basin is bounded to the north by the Tauranga Harbour and to the west by the Kaimai Range. It contains rhyolitic domes, ignimbrites, fluvial deposits and tephras.

The oldest units are the Minden Rhyolites which are hypersthene, hornblende and biotite rhyolites. These form the dome complexes Minden Peak, Manawata and Kaikaikaroro. These domes are surrounded by the overlying Waitearíki Ignimbrite which is a dacitic ignimbrite made up of three flow units and contains co-eruptive lithics within its basal unit. The Te Puna Ignimbrite is a rhyolitic ignimbrite which is found in the coastal cliffs around westerm Tauranga Harbour. Fluvial material which is prodominantly of volcanic origin lies unconformably below and on top of the Te Puna Ignimbrite. A number of tephras overlie the rhyolites and ignimbrites in the area. These are: Pahoia Tephras, Hamilton Ash, Rotoehu Ash, Mangaone, Oruanui, Okareka, Mamaku, Taupo and Kaharoa Tephras.

Whole rock geochemistry shows that western Tauranga basin rocks are calc-alkaline, and have resulted from arc volcanism. The rocks have formed predominantly from crystal fractionation, with the rhyolites also resulting from crustal melting.

The Te Puna Ignimbrite contains pumice that ranges in SiO2 content which indicates that the magma chamber was zoned. Upon eruption the magma chamber under went simple inversion which is seen when comparing element composition and stratigraphic height. This eruption may have caused a caldera which is located east of Katikati.

The Tauranga basin lies between the Coromandel Volcanic Zone and the Taupo Volcanic Zone, and is a transitional zone in terms of age and geochemistry, shown by transitional incompatible trace element ratios.

Acknowledgements

I would like to take this opportunity to thank the many people who helped in the production of this thesis.

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Finally I wish to thank my husband Alton, who **now** knows all there is to know about the Tauranga basin, and who gave me support and understanding when I needed it.

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1.1 Introduction

The western Tauranga basin has never been studied to find out the local stratigraphy and geology. The current geological map which contains the area has become out-dated and the need for a new geological map has been realised. This lack of detailed local stratigraphy has lead to geological mapping of the Tauranga basin in cooperation with the Bay of Plenty Regional Council (BOPRC) and previous MSc students.

1.2 Locality

The Tauranga basin is at the southern extent of the Hauraki Volcanic Region, which extends in a NNW direction from Poor Knights Island to beyond Tauranga. The Hauraki Volcanic Region consists of predominantly andesite-dacite volcanism in the mid-Miocene and rhyolite and ignimbrite volcanism more dominant in the late Miocene and Pliocene (Skinner 1986).

The Tauranga basin contains volcanic, fluvial and estuarine deposits. The basin is bounded by the Kaimai Range and Whakamarama Plateau in the west and the Papamoa Hills and the Mamaku Plateau to the south (fig 1.1).

1.3 Delineation of Field Area

The area studied consists of 115 km^2 of farmland, bush, horticulture, and residential areas. It is bounded to the north by the Tauranga Harbour, to the east by the Wairoa River and State Highway 29, and to the south by Ngamuwahine Road (fig 1.2).

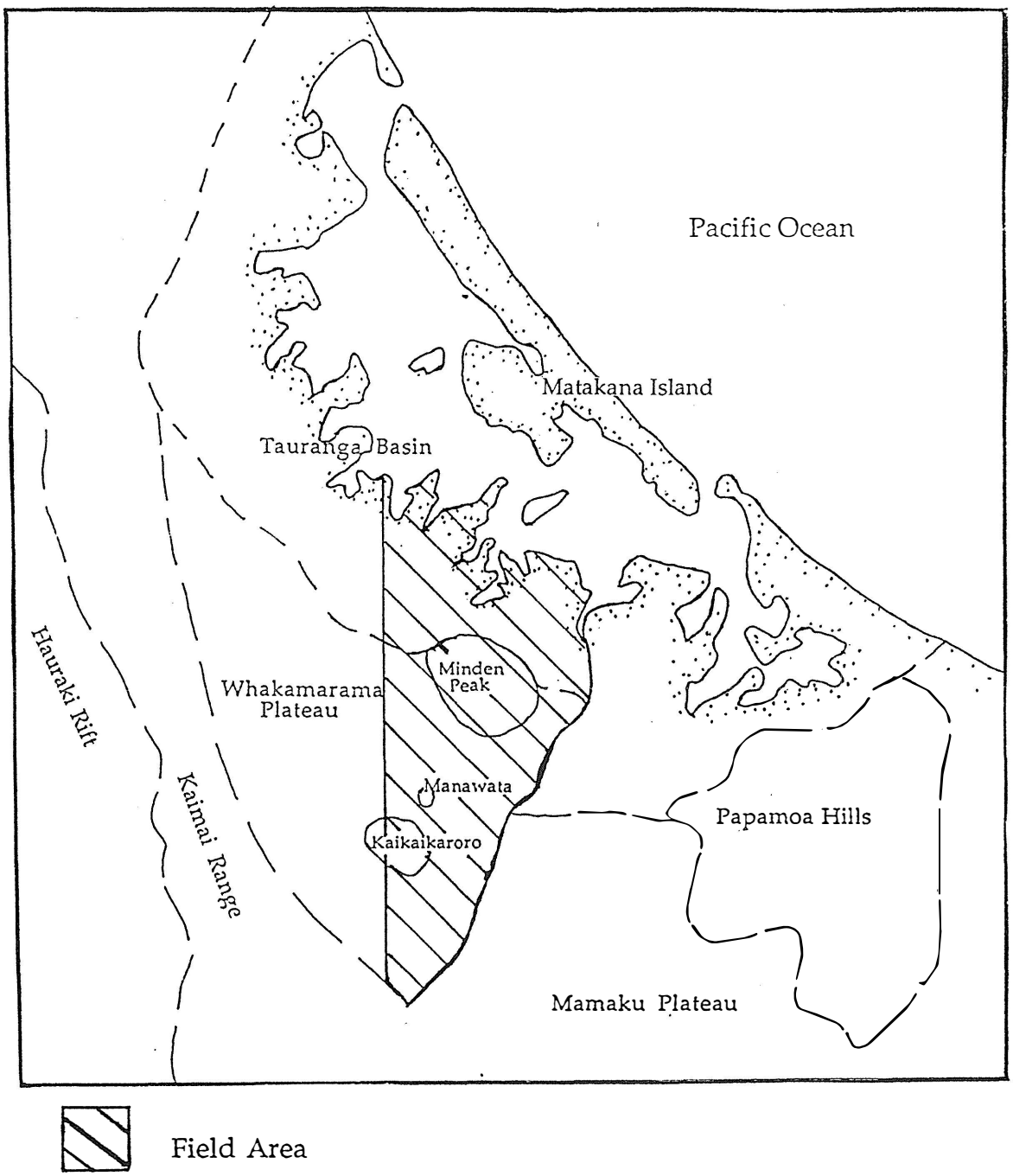


Fig 1.1 Major physiography features of the study area.

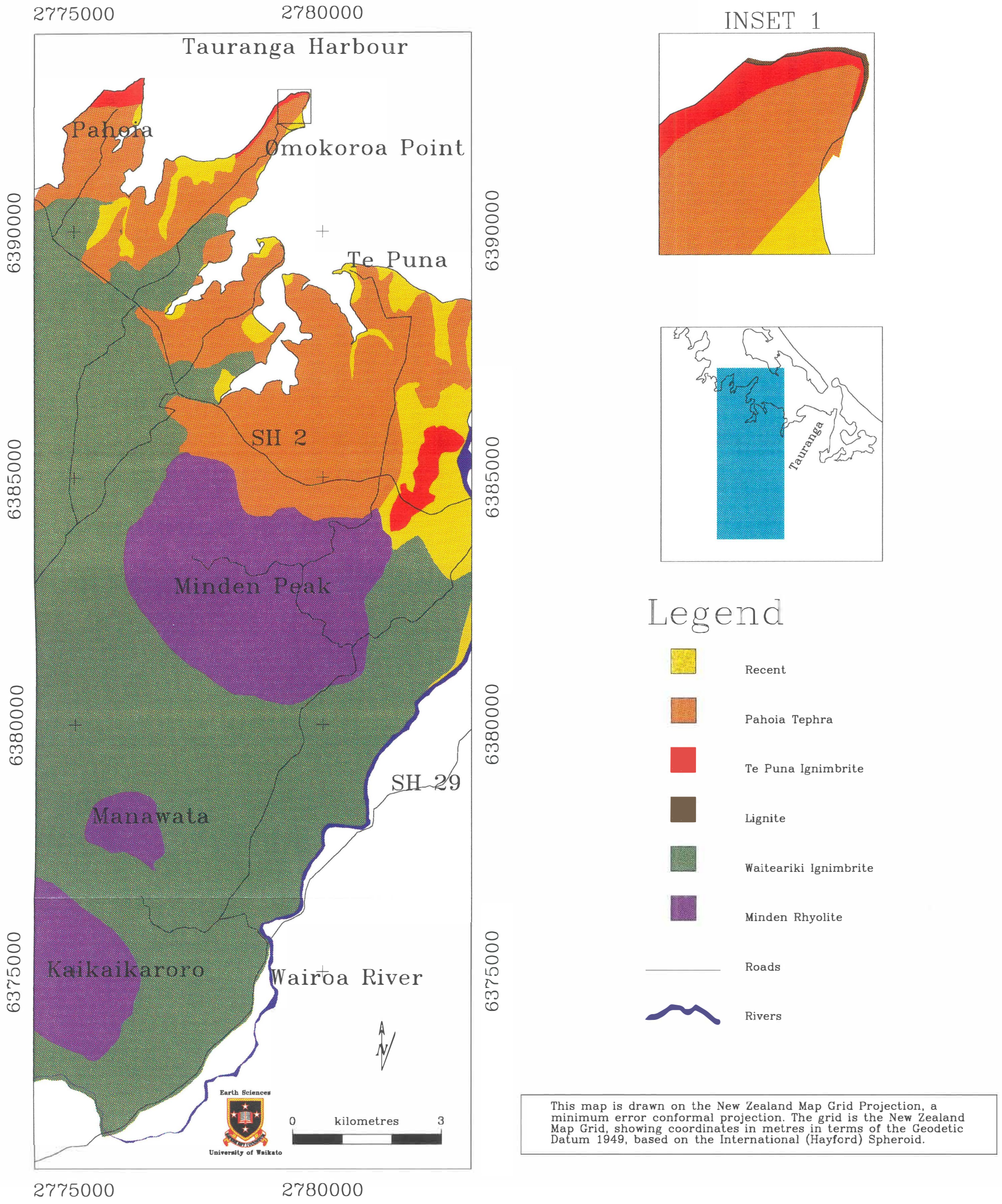


Fig 1.2 Location and Geology of Field Area.

1.4 Physiography of the Area

The dominant physiographic landform in the field area is the Whakamarama Plateau which dips 8-14°NE into the Tauranga basin (Harmsworth 1983). The plateau consists of the Waiteariki Ignimbrite which flowed around Minden Peak. The Waiteariki Ignimbrite becomes increasingly incised northeastward. It may once have extended further into the Tauranga Harbour, but over time it has been eroded back, forming the north-east trending peninsulas along the coastline.

The other major features are northeasterly aligned rhyolite domes, Kaikaikaroro, Manawata and Minden peak (fig 1.2). Kaikaikaroro (U14 746750) is a bush covered dome with a height of 444 m at the southern extent of the field area. The vegetation and rugged relief make access difficult and outcrops are confined to stream beds. To the northeast, Manawata (U14 762782) is a 317m dome which is covered by forest and farmland. Outcrops are highly weathered and confined to stream beds or as fallen boulders. Minden peak (U14 786832) at a height of 286m, is a flat topped rhyolite dome with lava flows. In places the rhyolite is weathered and has become highly unstable resulting in landslides, more recently in December 1983 and January 1986.

To the north of Minden peak, peninsulas which extend into the harbour, are covered by tephras up to 20m thick. The predominant unit is the Pahoia Tephra which contains thin pyroclastic flow deposits which are intercalated with white pumiceous fluvial sediments (Harmsworth 1983). The Pahoia Tephras are exposed around most of the coastline and are highly weathered. The weathering of the tephras to clay has resulted in a landslip at Omokoroa in 1979.

1.5 Previous Literature

The Hauraki Volcanic Region was first studied in the mid 19th Century due to an interest in mining in the region. The first geological and detailed investigations into the region was commissioned by the Geological Survey Branch of the Department of Mines. This resulted in the publication of bulletins which outlined the geology and economic value of the region (Fraser & Adams 1907, Fraser 1910, Henderson & Bartrum 1913, Morgan 1924).

Henderson and Bartrum (1913) studied the Aroha subdivision, which included the Tauranga basin. They produced a geological map of the area, and divided the rock types into series dependent on lithological and petrographic criteria. This also included a detailed study of the sediments in the area, mainly the Tauranga beds.
The Tauranga beds consist of conglomerates, sandstones and clays. Towards the base of the series there are seams of lignite which are at their thickest at Omokoroa, being measured at 4.27 m. They concluded that the coal-forming vegetation accumulated in place in elongated estuary-like depressions.

In 1963 geological investigations in the Kaimai Range resulted in the selection of an area for a tunnel linking Waharoa in the Hauraki Depression with Apata in the Tauranga basin. Healy (1967) produced a detailed study of the volcanic rocks of the area as part of a report investigating the proposed Kaimai Tunnel. Healy found that on the eastern side of the range, andesites where overlain by a series of younger ignimbrite sheets, pumice breccias, tuffs and interlayered sediments which slope down into the Tauranga basin (Ministry of Works and Development 1976).

Healy et al. (1964) mapped the geology of the Rotorua area which includes the Tauranga basin. They divided their rock types further based on lithology and composition. They separated the Waiteariki Ignimbrite from the dacites and likened it to the Papamoa Ignimbrite of similar age and composition.

Geophysical data of the Tauranga basin is presented in map form by Woodward and Ferry (1973) on the Isostatic Vertical Gradient Anomalies, Bouguer Anomalies and Isostatic Anomalies, and by Hunt and Whiteford (1979) on Magnetic Anomalies.

Stability investigations at Omokoroa and Minden Peak areas has been undertaken by Tonkin and Taylor (1991). Detailed investigation on the slope stability of Minden Peak found that the weathered rhyolite was prone to instability.

Known ages of the rocks within the Tauranga basin are limited. Stipp (1968) were determined potassium-argon ages of two andesites 2.95 Ma and 2.54 Ma for Beesons Island Volcanics in the Papamoa Hills. Kohn (1973) determined by Fission Track methods ages on the Waiteariki Ignimbrite at 0.84 ± 0.11 Ma and the Aongatete Ignimbrite at 0.86 ± 0.14 Ma. Rutherford (1978) determined an age of 4.34 ± 0.3 by fission track methods at Mt

Maunganui. Kamp and Turner (pers com 1994) examined the magnetism of the Te Puna Ignimbrite and found that it was reversely magnetised and that is likely to be Matuyama reversed which indicates that it is older than 0.78 Ma.

Houghton and Cuthbertson (1989) produced a detailed geological map of the Kaimai Range which is adjacent to the area studied. This included a detailed description of rock units which are also present in the field area. A new subgroup was established, the Kaimai Subgroup which previously included the Beeson Island Volcanics, Waitawheta Dacites and Omahia Andesites. The petrographic subdivision into a dacitic and an andesitic formation was not sustainable as both lithologies occurred throughout the stratigraphic sequences.
They also established the Whakamarama Group, which are mid Pleistocene ignimbrites forming the Whakamarama plateau. This new group includes the Aongatete and Waitеariki Ignimbrites. The Te Puna Ignimbrite should now be included as it is a mid-Pleistocene ignimbrite which is at the northern end of the Whakamarama plateau.

Recently, detailed investigations of the geology of the region have been researched by MSc students. Morgan (1986) studied the geology of the Northern Mamaku Plateau. This was extended northwards by Hughes (1993) whose area included the Papamoa Ranges and eastern Tauranga Basin. Harmsworth (1983) studied the Quaternary stratigraphy of the Tauranga Basin. Bird (1981) studied the nature and causes of coastal landsliding on the Maungatapu peninsula within Tauranga.

1.6 Objectives of Thesis

1 To produce a geological map and ascertain the stratigraphic relations of the rocks in the Minden area, western Tauranga basin.

2 Study the field relationships and physical volcanology of local eruptives and investigate their possible source, emplacement processes, and relationship to each other.

3 Use laboratory methods to characterise the petrography, mineral chemistry, and whole-rock major and trace element geochemistry of the rocks in the Minden area.

4 To describe the nature and chemistry of the Te Puna Ignimbrite in detail.

5 To examine how the Tauranga basin relates to the Taupo Volcanic Zone and Coromandel Volcanic Zone.

1.7 Regional Geology

The Tauranga basin is located at the southern extent of the Hauraki Volcanic Region. It is also within the Central Volcanic Region (CVZ) based on maps of the New Zealand Geological Survey (NZ Geo. Surv. 1972,1973) which includes all Quaternary rhyolites within the region. The basin represents a transitional zone where rock types show characteristics of both the Hauraki Volcanic Region and the Taupo Volcanic Zone and where andesite ages indicate an apparent southeast migration with time (Stern 1986).

The NNW trending peninsula of the HVR is the result of the horst-graben nature of the basement rocks which have been overlain by Neogene arc volcanism. These NNW-striking faults are cross cut by NE-striking faults all along the Hauraki Volcanic Zone (Skinner 1986).

Northeasterly faults were mapped in the Tauranga basin between Tauranga and Te Puke by Healy et al. (1964) which are thought to link up to offshore faults. The NE-striking faults are almost all downthrown to the south progressively, lowering the Jurassic basement (Skinner 1986). This has resulted in no surface expression of the Jurassic basement in the Tauranga basin.

1.8 Regional Stratigraphy and Petrography

The Coromandel Volcanic Zone consists of the Coromandel and Kaimai Ranges. The CVZ varies in composition from basaltic to rhyolitic with a basement of late Jurassic Marine sedimentary rocks (Manaia Hill Group) (Fig 1.3) (Skinner 1986).
The stratigraphy within the Tauranga Basin is summarised in Table 1, and includes ages of dated units.

Coromandel Group

The Coromandel Group ranges in composition from basic andesite to rhyodacite (Skinner 1986). Within the Tauranga basin, near the Papamoa range, the Beeson Island Volcanics outcrops as flows and centres. The Beeson Island Volcanics belong to the Kuaotunu Subgroup of the Coromandel Group. They are mid-Miocene to late Miocene with K-Ar ages of 16-7 Ma (Rutherford 1978, Cole 1979, Skinner 1986, 1993). These rocks are andesitic-dacitic in composition, characterised by hornblende - hypersthene ± augite ± biotite.

Whitianga Group

The Whitianga Group includes the Minden Rhyolite Subgroup. This subgroup includes all hypersthene, hornblende and biotite rhyolites within the Coromandel-Bay of Plenty area, north of the Taupo Volcanic Zone (Houghton et al. 1989). Minden rhyolite outcrops as domes and flows within the Tauranga basin.

Whakamarama Group

The Whakamarama Group is defined by Houghton and Cuthbertson (1989) as mid Pleistocene ignimbrites forming the Whakamarama plateau. It includes the Aongatete and Waiteariki Ignimbrite which are dacitic to andesitic. The Te Puna Ignimbrite should now be classed within the Whakamarama group as it is of mid-Pleistocene age of >0.78 Ma (Kamp and Turner; pers com 1994) and it is at the northern extent of the Whakamarama plateau.

The Aongatete is a crystal poor ignimbrite with a high abundance of crystal-poor dacitic pumice. The crystals are andesine/labradorite-hypersthene-augite (Houghton and Cuthbertson 1989). It exceeds 490m thickness beneath the Tauranga basin.
The Waiteariki Ignimbrite overlies the Aongatete Ignimbrite. It is crystal-rich with plagioclase-hornblende-hypersthene-quartz-biotite-zircon. It has dacitic pumice which are cream, or black within the lenticular zone.

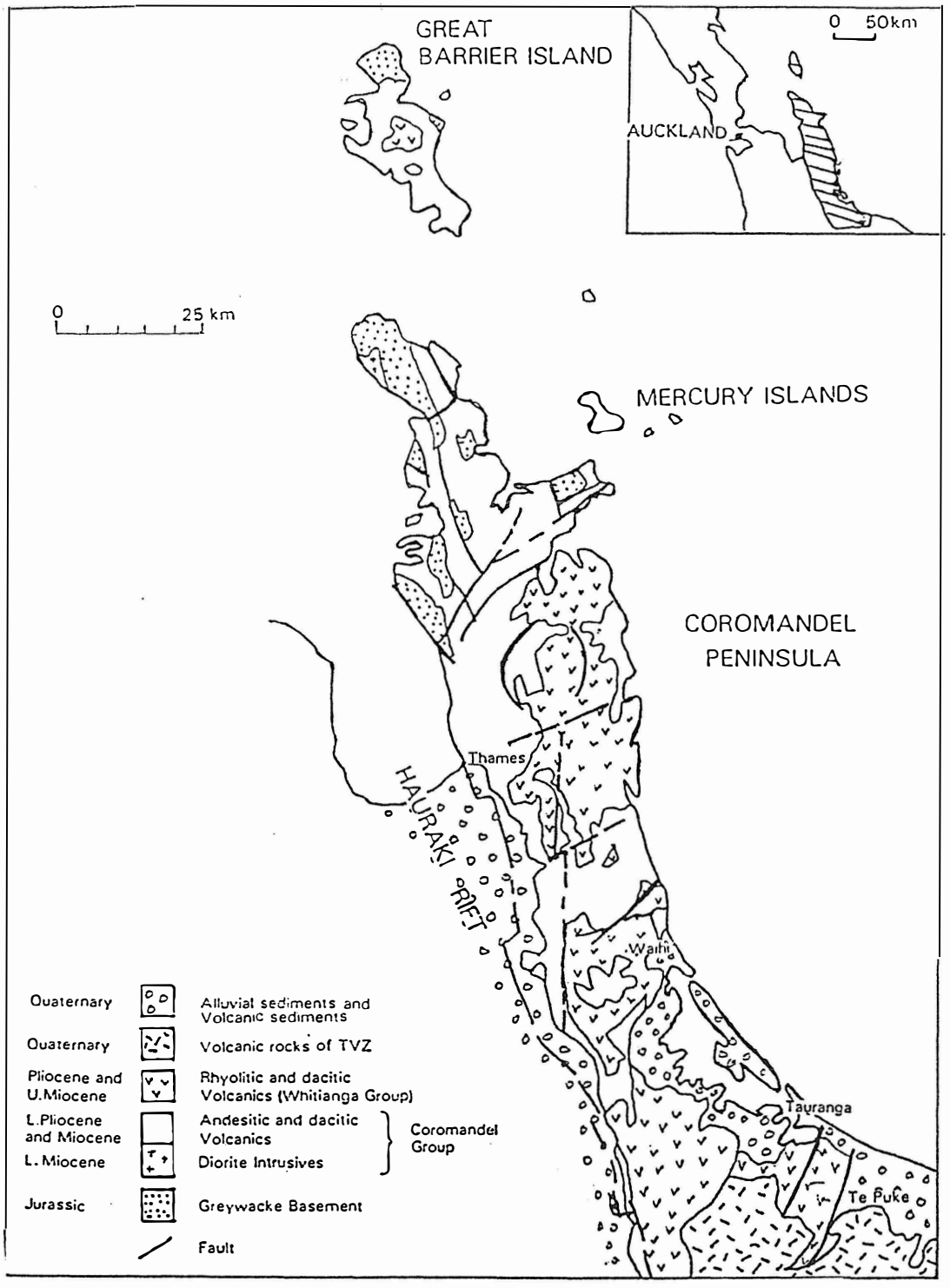


Fig 1.3 Generalised geology of the Coromandel Volcanic Zone (after Skinner 1986, Brathwaite 1989).

The Papamoa Ignimbrite is an informal member of the Whakamarama Group as it is of similar age to the Waitearikí Ignimbrite and also of dacitic composition (Houghton et al. 1989). It outcrops in the north-eastern sector of the Tauranga basin and consists of an lower layer which has a brown to yellow-tan matrix with protruding pumice of varying colours and mineralogy and an upper dense cream to grey rock with small white angular pumice (Hughes 1993).

Tauranga Group

The Tauranga Group includes late Cenozoic deposits found in the Bay of Plenty, Hauraki lowland, Hamilton lowland, Lower Waikato and Manukau Harbour. It is made up of mainly pumiceous, terrestrial, estuarine and marine sediments (Kear and Schofield, 1978)

These units belong to the Matua Subgroup within the Tauranga Basin. It includes all Pleistocene sediments that overlie the Waitearikí Ignimbrite, which includes fluvial, estuarine strata, ignimbrites and airfall tephra (Harmsworth 1983).

The ignimbrites within the Tauranga basin are the Wairoa, Te Ranga, Waimakariri, Ohauiti, Kopurereroa and Merrick Ignimbrites (Harmsworth 1983, Hughes 1993). These ignimbrites are generally not found outside of the Tauranga basin.

Table 1.1 Summarised stratigraphy and ages of the Tauranga Basin after Healy et al. (1964), Stipp (1968), Kohn (1973), Rutherford (1978), Murphy and Seward (1981), Fransen (1982), Harmsworth (1983), Houghton and Cuthbertson (1989) Kohn et al. (1992), Hughes (1993), Kamp and Turner (pers com 1994).

Group Subgroup	Formation	Age	Comments
Rotorua	TVZ Tephras		Widespread, thick deposits
	Mamaku Ig.	0.14± 0.08Ma	Thick, mantle deposit
	Merrick Ig.		
Tauranga Group	Waimakariri Ig.	0.18 Ma	Large pumice, crystal rich
Matua	Hamilton Ash	0.35 ±0.04 Ma	
	Pahoia Tephras		Highly weathered tephras and paleosols
	Kopurereroa Ig.		nonwelded
	Te Ranga Ig.		Sandy, nonwelded
	Ohauiti Ig.		nonwelded
	Wairoa Ig.		nonwelded
	Fluvial		gravels and sands
Whakamarama	Te Puna Ig.	>0.78 Ma	non to partially welded
	Waitereriki Ig.	0.84 ± 0.11 Ma	Dacitic, crystal rich
	Papamoa Ig.		Southern area of basin only
	Aongatete Ig.	0.86 ± 0.14 Ma	Breccia
		0.94 ± 0.13 Ma	Dacitic Tuff
Coromandel	Andesites	2.54 + 2.95 Ma	Flows and Strato Volcanoes
Coromandel Dacites	Dacites		Domes and Flows
Whitianga Minden Rhyolite	All Rhyolites in Coromandel Volcanic Zone	4.34 ± 0.38 Ma	Spherulitic domes and flows

Chapter Two

Stratigraphy

Chapter Two

Stratigraphy

2.1 Introduction

The Western Tauranga basin is confined to the west of the Kaimai Range which is made up of rhyolitic, dacitic, and andesitic rocks. Within the basin the oldest exposed rocks are rhyolites which form dome complexes. These have been surrounded by the Aongatete and the Waiteariki Ignimbrites, of which only the Waiteariki is aerially exposed within the field area. These two ignimbrites are believed to have originated from the Kaimai Range.

After a period of time and erosion another ignimbrite was deposited, the Te Puna Ignimbrite. This was then followed by the deposition of the Pahoia Tephras, and late Pleistocene tephras which were derived form the Taupo Volcanic Zone.

Summarised stratigraphy of the western Tauranga basin is shown in Table 2.1.

2.2 Minden Rhyolite

Minden Rhyolite includes all hypersthene, hornblende and biotite rhyolites within the Coromandel-Bay of Plenty area, north of the Taupo Volcanic Zone (Houghton et al 1989). Rhyolitic volcanism is mainly attributed to single explosive centres and is usually associated to caldera formation, so grouping all rhyolites that occur in the Bay of Plenty and Coromandel together is not considered appropriate. Therefore rhyolites will be referred to by their apparent source as proposed by Hughes (1993). Rhyolites within the field area will be referred to as Minden Peak, Manawata and Kaikaikaroro.

Age

Manawata, Kaikaikaroro and Minden Peak are older than the overlying Whakamarama Group.

Table 2.1 Stratigraphy of the western Tauranga basin. Ages from Stipp (1968), Pullar et al. (1972), Kohn (1973) Rutherford (1978),Froggatt and Lowe (1990), Kohn et al. (1992), Kamp and Turner (pers com 1994).

Group	Unit	Age	Lithology
	Recent		Fluvial sediments and volcanic gravels and sands
	Taupo Tephra	1819 ± 17 yrs BP	Rhyolitic
	Mamaku Tephra	7250 ±20	Rhyolitic
	Rotorua Tephra	12000	Rhyolitic
	Okareka Tephra	18000	
	Oruanui Tephra	19850 ± 310 yrs BP	Rhyolitic
	Mangaone Tephra	27730± 350	
	Rotoehu Ash	41700 ± 3500 yrs BP	Rhyolitic
	Hamilton Ash	35000 ± 0.04 yrs	
	Pahoia Tephras	300000 yrs	Rhyolitic
Tauranga Group -Matua subgroup	Fluvial sediments		Sediments containing volcanic gravels, sands and ash.
	Lignite	<0.78 Ma	Contains visible plant structures.
Whakamarama Group	Te Puna Ignimbrite	> 0.78 Ma	Crystal-rich rhyolitic ignimbrite with white and grey pumice.
	Waitearíki Ignimbrite	0.84 ± 0.11 Ma	Crystal-rich dacitic ignimbrite with cream and black pumice.
	Aongatete Ignimbrite	0.86 ± 0.14 Ma 0.94 ± 0.13 Ma	Crystal-poor dacitic ignimbrite with crystal poor dacitic pumice.
Whitianga Group -Minden Rhyolite	Manawata Kaikaikaroro Minden Peak		Grey spherulitic rhyolites with visible plagioclase, hornblende and quartz.

Source and distribution

Within the Tauranga basin these rhyolites outcrop as dome and flow complexes. The domes have a linear relationship in a north-northeasterly direction, which suggests that their locations are fault related, possibly within the basement rocks.
The domes are steep sided complexes with few exposures which are limited to road cuttings and the Te Puna Quarry (U14 788842) in Minden Peak. The degree of weathering ranges from unweathered in places to highly weathered. No unweathered outcrops were found on Manawata.

Lithology

Minden Peak Rhyolite is predominantly grey but also varies from cream to pink. Visible hornblende, biotite, quartz and plagioclase can be seen in hand specimen, and grain size is less than 2 mm. The rhyolite is spherulitic, and upon weathering the rock structure disintegrates. Flow banding can be seen on Minden Road, indicating flowage down the side of the dome.

Manawata Dome is a steep sided dome complex with a flat top (Fig 2.1). It is surrounded by the Waitearíki Ignimbrite, which suggests that it is older than the ignimbrite which flowed around it. Also where streams have incised the Waitearíki Ignimbrite around the dome, Manawata Rhyolite is exposed. The Manawata Rhyolite is also light grey and contains phenocrysts of quartz, plagioclase, hornblende and biotite within a spherulitic groundmass.

Kaikaikaroro Dome is thought to be older than the Waitearíki Ignimbrite (0.84 ± 0.11 Ma)(Kohn 1973) which overlies it. Kaikaikaroro (U14 746750) is a steep sided volcano and is surrounded by the Waitearíki Ignimbrite. Access is difficult due to the rugged terrain and bush cover (Fig 2.2). It is light grey and contains phenocrysts of quartz, plagioclase (up to 7 mm), hypersthene and hornblende (up to 5mm), surrounded by a spherulitic groundmass containing Fe-Ti oxide and zircon.

Fig 2.1 The Manawata Rhyolite dome (covered in pine trees) viewed from the east, surrounded by undulating hills underlain by the Waitearíki Ignimbrite.

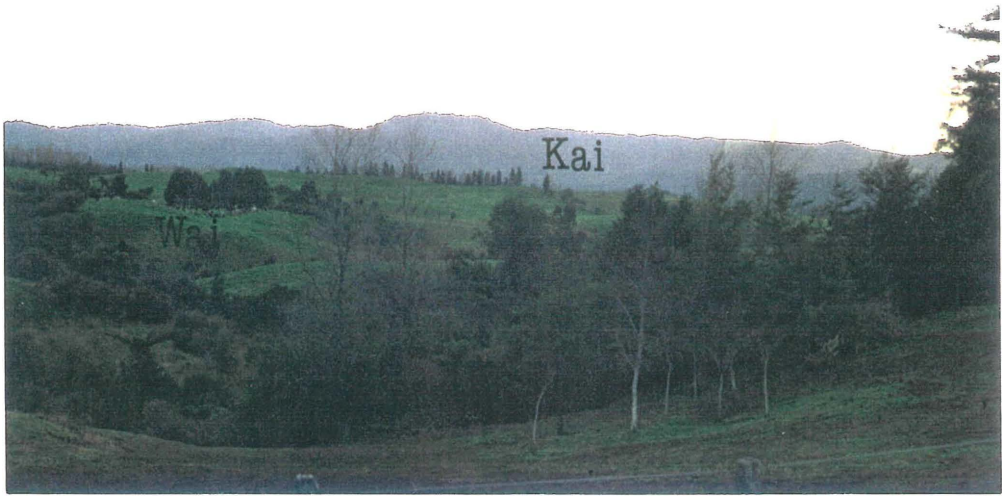


Fig 2.2 View to the north, showing bush covered Kaikaikaroro Rhyolite(Kai) dome surrounded by Waitearíki Ignimbrite(Wai).

2.3 Waitearikí Ignimbrite

The Waitearikí Ignimbrite was first named by Healy et al. (1964). It belongs to the Whakamarama Group, which includes all mid-Pleistocene ignimbrites forming the Whakamarama plateau (Houghton and Cuthberton 1989).

Age

The Waitearikí Ignimbrite is reversely magnetised (Cox 1969) and has a fission track age of 0.84 ± 0.11 Ma (Kohn 1973).

Distribution

The Waitearikí Ignimbrite is an extensive unit. It forms the dipping Whakamarama Plateau and underlies the Tauranga basin to depths of 50-100m. It was deposited prior to the uplift of the Kaimai Range as it is displaced by the Hauraki and Okauia faults into the Hauraki plains where it has been located in drill holes at a depth of 55m (Davidge 1982).

Lithology

The Waitearikí Ignimbrite is 220m thick at its type section (T14 641797), where it can be divided into three flow units:

1 a soft non-welded to welded top between 50 and 70 m thick with extensive vapour phase alteration of pumice to cristobalite and alkali feldspar;
2 up to 150m of welded material containing alternatively moderately densely welded and very densely welded glassy lenticular zones;
3 a 3 to 5m thick nonwelded base consisting of pumiceous tuff breccia and ash (Houghton et al. 1989).

The Waitearikí Ignimbrite is a light grey-brown ignimbrite with 20% pumice which varies from lenticular cream pumice to black fiamme. It is densely welded with columnar jointing seen in outcrops (Fig 2.3). The Waitearikí Ignimbrite is unusually crystal rich with 30% crystals of plagioclase, quartz, hornblende, hypersthene and biotite.

Fig 2.3 The middle flow unit of the Waitearikí Ignimbrite at McLaren Falls showing columnar jointing.

Fig 2.4 Dacite lithic within the lower flow unit of the Waitearikí Ignimbrite at Ngamuwahine Road (U14 733737).

Lithics within the unit are dacitic. These lithics at Ngamuwahine Road (U14 736732) are large, up to 30 cm, indicating proximity to source (Fig 2.4).
In the basal part of the unit, co-eruptive lithics or lithics from the previous flow unit, can be found within the flow. This may suggest that an earlier flow unit may have been deposited before the main unit. This could have resulted in the incorporation of the lithic into the following flow

Welding

The Waitearíki Ignimbrite becomes increasingly welded to the south. This results in a change in appearance from a soft pinky brown nonwelded ignimbrite in the north, to a dark brown welded ignimbrite in the south.

In the southern region of the field area, the Waitearíki Ignimbrite shows higher degrees of welding and post-eruptive devitrification. Samples at McLaren Falls contain spherulites which are thought to occur as the result of devitrification (Lofgren 1970). Where welding is greatest, the ignimbrite has a eutaxitic texture defined by fiamme.

2.4 Matua Subgroup

Lignite

Lignite is within the Matua Subgroup which includes all Pleistocene sediments which overlie the Waitearíki Ignimbrite within the Tauranga Basin (Harmsworth 1983). The lignite is exposed within the field area at Omokoroa Point and Te Puna estuary. It is also found at Matakana Island and Motuhoa Island. It underlies the Te Puna Ignimbrite at Omokoroa Point (Fig 2.5) and therefore is thought to be older than the Te Puna Ignimbrite (>0.78 Ma) (Kamp and Turner, pers com 1994). The lignite is black with plant structures, such as branches and logs still visible. At Omokoroa Point large ring like structures up to 3m in diameter may represent residual tree stumps.

The significance of the lignite is that it is a potential paleoenvironmental indicator. Hull (1977) suggests that the swamp from which the lignite formed grew at temperatures 3°C lower than at present with annual precipitation 800 to 900 mm higher than the present 1348mm per year.

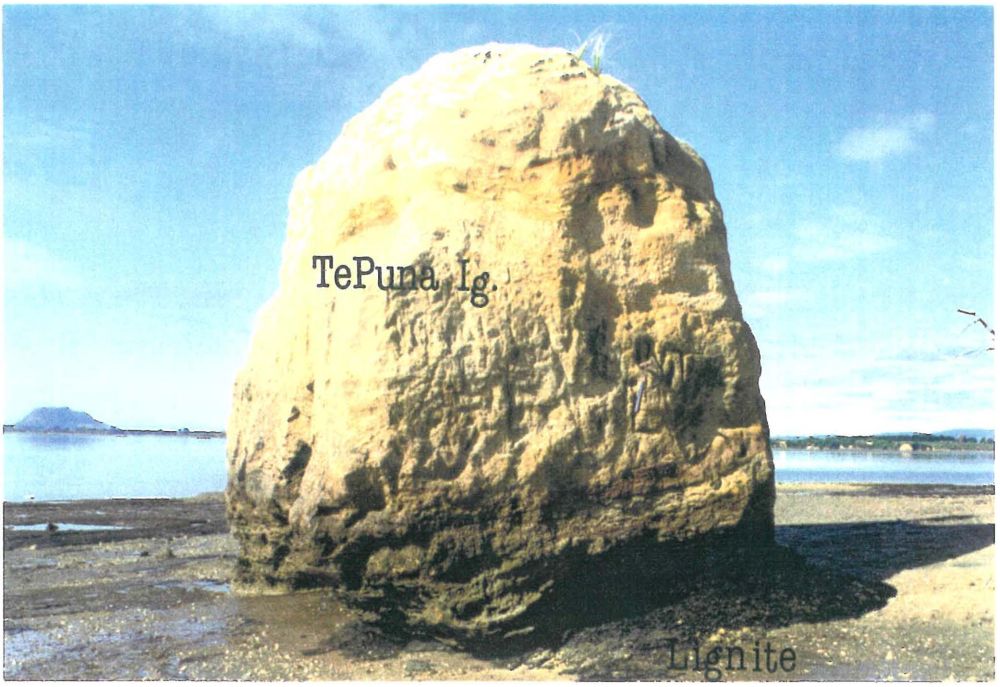


Fig 2.5 Te Puna Ignimbrite at Omokoroa Point overlying Lignite.

Fluvial Sediments

Fluvial Sediments within the western Tauranga basin are predominantly pumiceous clays, sands and gravels. These fluvial beds are moderately to well sorted and commonly show cross-bedding.
The source of this material is from a volcanic terrain which has been eroded into the Tauranga basin. The clasts are mainly derived from previous pyroclastic flows, the Te Ranga Ignimbrite, Waimakariri Ignimbrite and Te Puna Ignimbrite, and airfall material mainly the Pahoia tephras (Harmsworth 1983).

2.5 Te Puna Ignimbrite

The Te Puna Ignimbrite was first described by Harmsworth (1983). It is exposed on Clarke Road (U14 825855) and in coastal sections at Omokoroa, at Pahoia Point where it forms the coastal cliffs, and also on Matakana Island.

Age

The Te Puna Ignimbrite has not been radiometrically dated. Primary magnetisation within the ignimbrite is reversed which means that it is likely to be Matuyama reversed, and is therefore older than 0.78 Ma (Kamp and Turner pers com).

Lithology

The Te Puna Ignimbrite is a nonwelded to partially welded buff brown ignimbrite. It contains 15-20% white to grey pumice which contains glomeroporphyritic plagioclase and quartz. The matrix of the ignimbrite is crystal-rich (25%) with visible plagioclase, quartz and hornblende.
Lithic abundance is poor (1-2%) and lithic types consist of grey, red, and green rhyolites. Also present is charcoal and the occasional lithic of obsidian.

The Te Puna Ignimbrite varies in thickness from >16 m at Clarke Road to 2 m at Omokoroa Point to 10 m at Pahoia Point. This variation in thickness is due to the undulating nature of the pre-existing topography and subsequent erosion.

At Omokoroa (U14 797928), the unit overlies lignite and fluvial pumice beds, which suggests that the ignimbrite flowed into a swamp or estuarine environment (Fig 2.6). The fluvial pumice beds may have resulted from plinian eruptions which occurred before the main ignimbrite forming eruption. The presence of chalazoidites and elutriation channels within the ignimbrite indicate that the eruption was high in water content. On Matakana Island lake sediments overlie the Te Puna Ignimbrite. These lake sediments may represent an intracaldera lake which formed after the eruption of the ignimbrite which caused the caldera collapse.

The Te Puna Ignimbrite contains a lithic-rich layer of rhyolite lithics up to 40mm in length and Te Puna Ignimbrite lithics (Fig 2.7, 2.8). The ignimbrite lithics are subrounded and up to 105 mm in length (Fig 2.9). The presence of Te Puna Ignimbrite lithics at the boundary between the two flow units, indicates two phases in the eruption, where the second pyroclastic flow incorporated ripped up ignimbrite lithics from the previous flow. Transportation of these reworked clasts resulted in their subrounded nature. The increase in rhyolite lithics at the flow unit boundary may represent a widening of the vent by

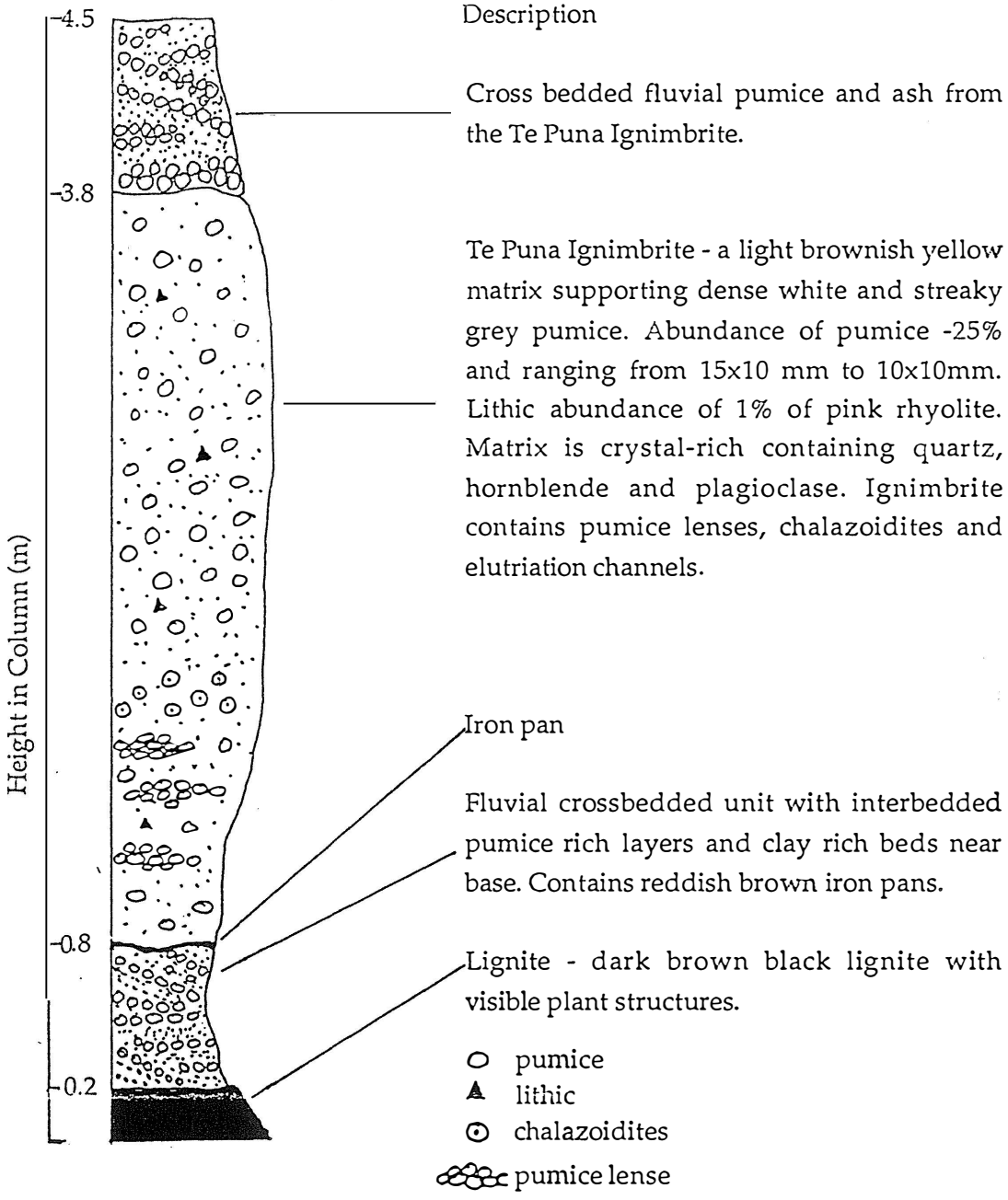


Fig 2. 6 Stratigraphic column of Te Puna Ignimbrite overlying lignite and fluvial material of the Tauranga Group, Omokoroa Point (U14 798928).

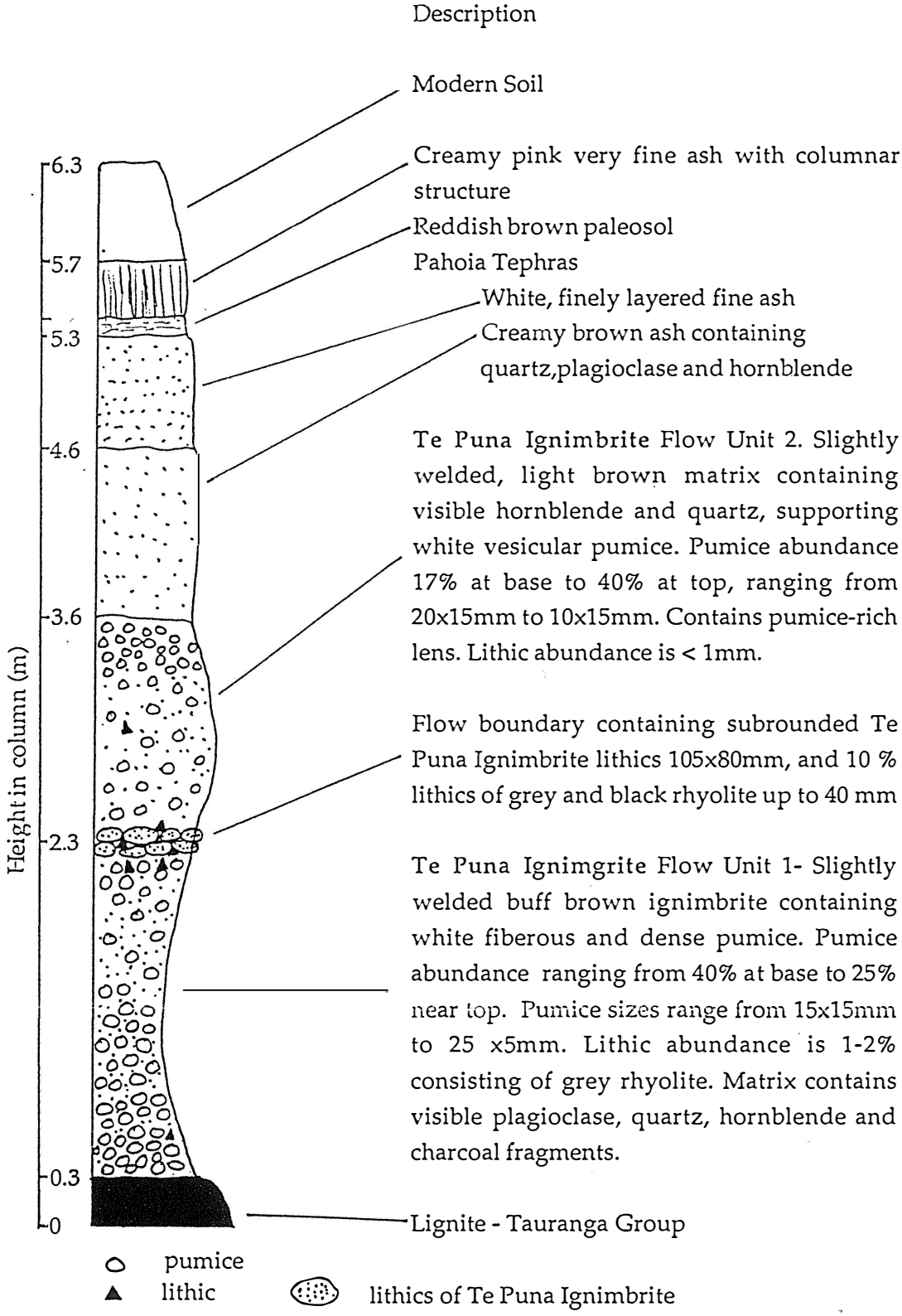


Fig 2.7 Stratigraphic column of Te Puna Ignimbrite and overlying ash beds at Omokoroa Point, U14 798927.

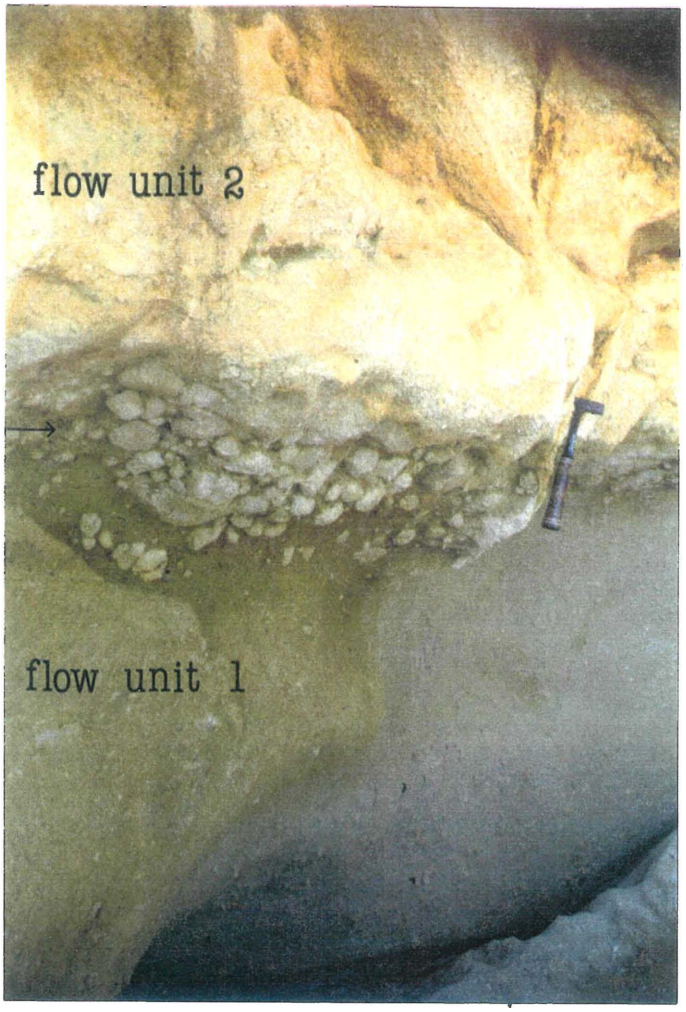


Fig 2.8 Te Puna ignimbrite lithics within the Te Puna Ignimbrite.

Fig 2.9 Subrounded Te Puna Ignimbrite lithics and Rhyolite lithics within the Te Puna Ignimbrite.

erosion. This increase in lithic abundance in the stratigraphic column can also indicate the time at which caldera collapse occurred.

2.6 Tephras

Within the field area a number of tephra layers can be recognised. The thickest and most distinctive is the Pahoia Tephras which underlies the Rotoehu and Hamilton Ash. Pullar et al (1973) also identified other less distinctive Holocene tephras at Pahoia. They are; Mangaone Tephra, Oruanui Tephra, Okareka Tephra, Rotorua Tephra, Mamaku Tephra, Taupo Tephra, and Kaharoa Tephra.

Pahoia Tephras

The Pahoia Tephras are strongly weathered white and olive coloured tephras which range in average thickness from 10-20 m. The Pahoia Tephras unconformably overlie the Te Puna Ignimbrite at Clarkes Road, Omokoroa and Pahoia Point. Pullar et al. (1973) suggested an age range of 125 000 to 300 000 yr BP .

The Pahoia Tephras are rhyolitic, normally graded, show shower bedding, and also contain thin (< 2m) ignimbrites and interbedded paleosols. At Omokoroa Point 14 beds are informally named with upper contacts defined by colour and slight textural changes or by pale brown clay rich paleosols (2 to 15 cm thick) (Harmsworth 1983).

Hamilton Ash

The Hamilton Ash Formation in the Tauranga Basin forms a thick (> 0.9m) yellow brown to dark reddish brown deeply weathered sequence in which paleosols are developed. At Omokoroa this sequence is 2.5 m thick while at Te Puna it is < 1.2 m (Harmsworth 1983). It can also be seen on the Whakamarama Plateau, in road cuttings, lying above the Waitekariki Ignimbrite. It has an age of 75000-150000 yrs BP (Pullar et al. 1973).

Rotoehu Ash

The Rotoehu Ash was first named by Healy et al. (1964). The tephra was erupted from the Okataina centre and is associated with the Rotoiti Breccia. It has an age of 64 ± 4 ka (Wilson et al. 1992) and is at the base of the Quaternary tephra column. The bed shows prominent shower bedding and it is crystal rich with a calc-alkaline phenocryst assemblage.

Chapter Three

Petrography and Mineralogy

Chapter Three

Petrology and Mineralogy

3.1 Introduction

Petrography of the western Tauranga Basin was studied from 68 representative rock samples taken from the field area. Modal data was obtained from representative thin sections by point counting methods (Table 3.1). Polished sections were prepared for eleven selected samples of which the mineral chemistry was investigated by microprobing at the Department of Geology, University of Auckland. Representative chemical analyses of minerals are in Table 3.2, 3.3, 3.4, 3.5.

3.2 Rhyolites

There are three rhyolite domes, Minden Peak, Kaikaikaroro and Manawata, within the field area. Petrographically they are very similar, with phenocrysts of quartz, plagioclase, orthopyroxene, amphiboles, and biotite.

3.2.1 Minden Peak

Minden Peak rhyolite is a grey to pink hypocrystalline rock with medium (1-2mm) grain size. It has phenocrysts of plagioclase, quartz, hornblende and biotite set in a spherulitic groundmass (Fig 3.1), where spherulites have diameters of 1-2mm. Flow banding, where present, is defined by a variation of the matrix from pink to grey.

With weathering the rock varies in colour from cream to pink to grey. Weathering of the rhyolite between the spherulites can cause the spherulites to become detached and result in the disintegration of the structure of the rock.

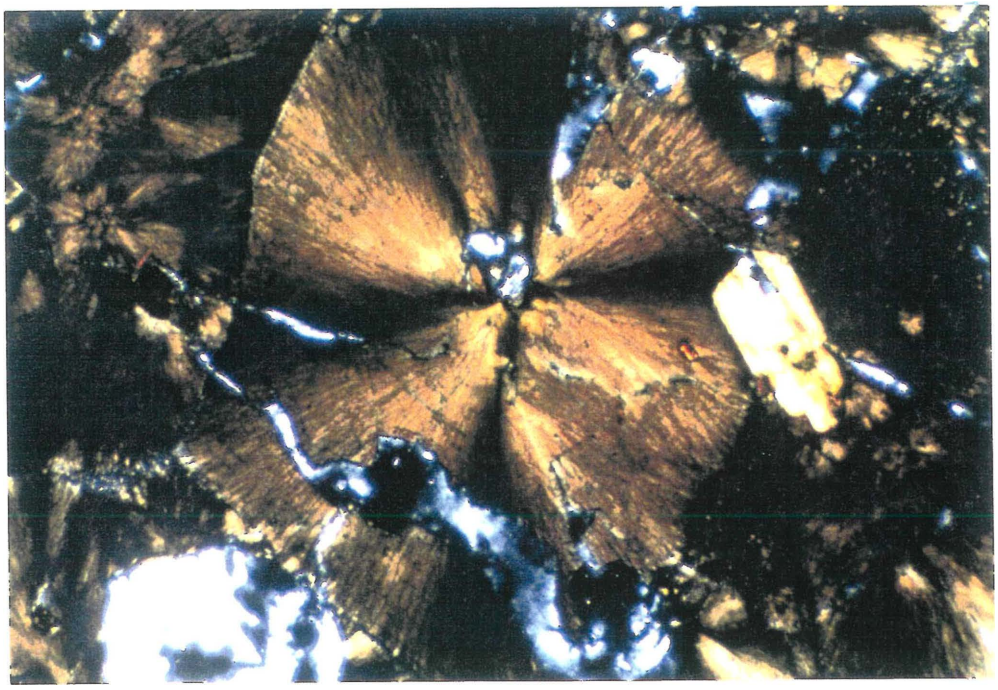


Fig. 3.1 Photomicrograph of Minden Peak rhyolite showing spherulites radiating out from a quartz grain and interstitial to hornblende, X40 magnification, crossed polarised light.

Table 3.1 Modal analyses of whole rock samples from the Western Tauranga Basin

Unit	Rock type	Sample No	matrix %	Plag. %	Quartz %	Hrnblde %	Biotite %	Hyper. %	Opaques %	Zircon %	Pumice %	Sec.Min %	Lithics %
Minden	rhyolite	6	81.2	11.2	4.8	1	1.4	0	0.2	0	0	0	0
Minden	rhyolite	7	89	8	0.2	1.2	1.6	0	0	0	0	0	0
Kaikaikaroro	rhyolite	13	60	26.2	7.2	4	0	1.4	0.8	0.4	0	0	0
Kaikaikaroro	rhyolite	14	59.2	31.8	1	3.6	0.2	2.8	1.2	0.2	0	0	0
Manawata	rhyolite	15	86	9	0.4	2.4	1.4	0	0.8	0	0	0	0
Manawata	rhyolite	16	91.2	4.4	1	0.8	2.2	0	0.4	0	0	0	0
Te Puna	ignim.	24	57	15.2	0.8	0.6	0	0	0	0	23	0.6	0.4
Te Puna	ignim.	26	55.2	23	0.6	1.8	0	0.2	0.4	0	13	1.4	4.8
Te Puna	ignim.	28	54.8	19.6	2.8	0.4	0	0	0.2	0	18.2	0.4	3.6
Waitearíki	ignim.	32	69.8	20.6	2.8	0.2	0	1.8	1	0.2	3.4	0	0.2
Waitearíki	ignim.	32	57.8	18.4	0.4	0.4	0	2.8	0.2	0	17.8	0	0.2
Minden	rhyolite	33	77.6	19	0.2	0.6	0.8	1.6	0.4	0	0	0	0
Minden	rhyolite	35	86.4	10.4	0.4	1.6	0	0.6	0.6	0	0	0	0
Minden	rhyolite	36	82.8	12.6	2	1	0.2	0.4	0.4	0	0	0	0
Minden	rhyolite	41	84.6	11.2	0.4	2.4	0.2	0.8	0.4	0	0	0	0
Kaimai	rhyolite	53	89.2	7	1	1.8	0.2	2	0.6	0	0	0	0
Waitearíki	ignim.	62	58	34	1.2	1.2	0.6	4	0.6	0	0	0	0
Waitearíki	lithic	22	67.8	24.2	0.8	2	0.4	3.8	0.6	0	0	0	0.2
Waitearíki	lithic	23	65.6	27	1	3.6	0.2	2	0.6	0	0	0	0

Table 3.2 Representative microprobe analyses for plagioclase phenocrysts of the Western Tauranga Basin. Kia (Kaikaikaroro Rhyolite), Min (Minden Peak Rhyolite), Wai (Waitearíki Ignimbrite), TeP (Te Puna Ignimbrite).

Sample	Kia 13	Kia 13	Min 7	Min 41	Min 41	Wai 12	Wai 51	Wai 51	Wai 62	Wai 62	TeP 28	TeP 28
	Plag	Plag	Plag	Plag Core	Plag Rim	Plag	Plag Rim	Plag Core	Plag Rim	Plag Core	Plag Core	Plag Core
SiO2	57.89	58.23	59.55	58.05	59.35	60.24	57.89	57.81	56.95	57	59.93	57.98
TiO2	0.1	0.05	0.09	0	0.05	0.01	0.05	0.02	0.11	0.11	0.06	0.06
Al2O3	26.21	25.78	25.13	26.12	24.91	23.95	25.92	26.63	26.62	25.7	24.17	26.54
FeO	0.34	0.3	0.12	0.26	0.11	0.12	0.27	0.28	0.16	0.12	0.1	0.2
MnO	0.21	0.09	0.08	0.18	0.04	0.13	0.03	0.02	0.04	0.07	0.05	0.02
MgO	0.1	0.02	0.08	0.03	0.12	0.06	0.1	0.06	0.1	0.18	0.08	0.09
CaO	8.02	7.63	6.46	7.91	6.65	5.63	7.83	8.23	8.79	8.03	6.09	8.12
K2O	0.35	0.43	0.61	0.41	0.54	0.67	0.37	0.38	0.37	0.38	0.53	0.36
Na2O	6.54	6.78	7.39	6.63	7.05	7.5	6.65	6.29	5.98	6.28	7.45	6.62
P2O5	0.06	0.05	0.26	0.15	0.14	0.25	0.12	0.23	0.01	0.09	0.18	0.02
Total	99.55	99.15	99.14	99.37	98.49	97.98	98.92	99.61	98.7	97.38	98.97	99.61
Albite	58.4	60.1	65	58.8	63.6	67.9	59.3	56.7	54	57.3	66.7	58.4
Anorthite	39.6	37.4	31.4	38.8	33.2	28.2	38.6	41	43.8	40.5	30.1	39.6
Orthoclase	2.1	2.5	3.5	2.4	3.2	4	2.2	2.3	2.2	2.3	3.1	2.1

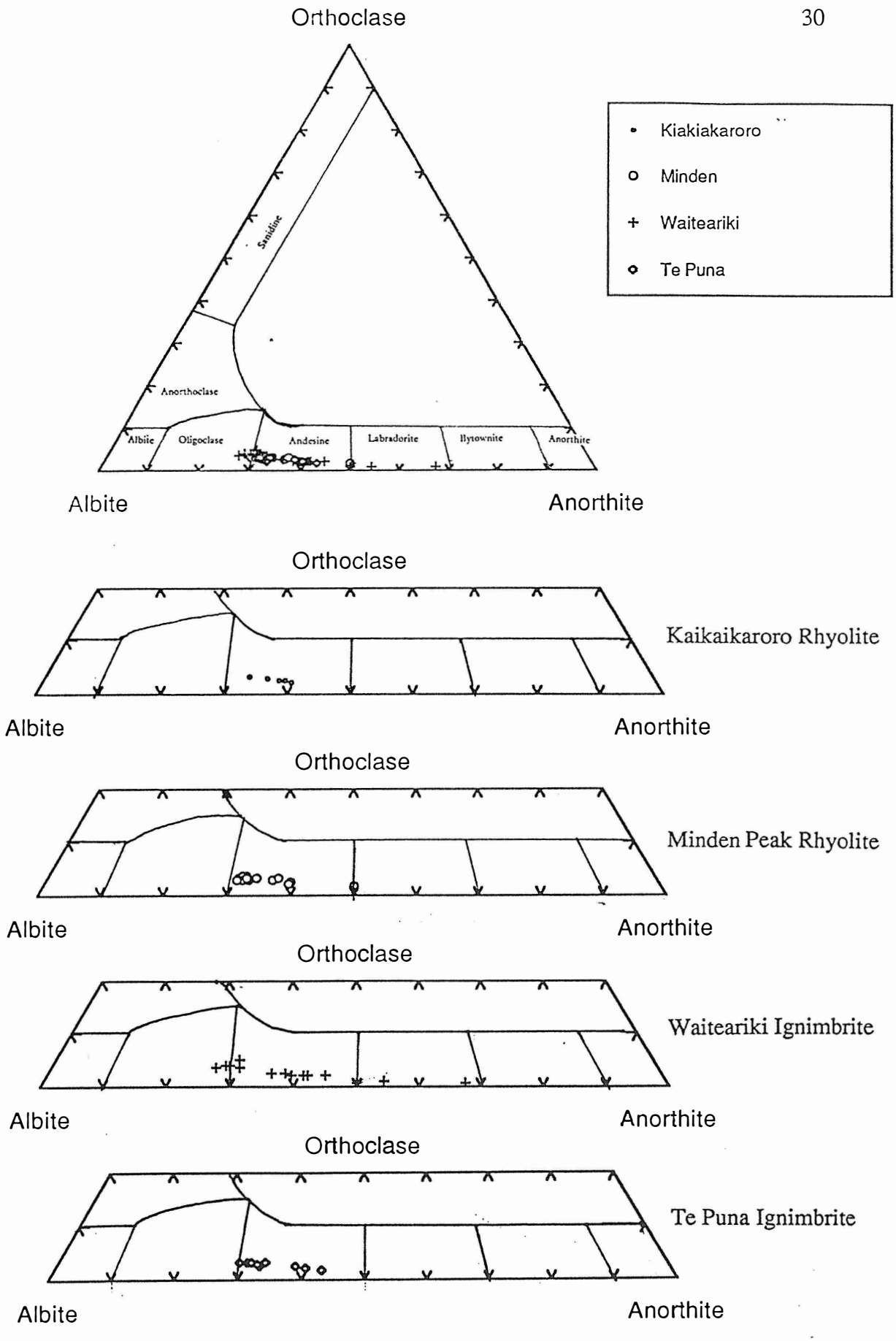


Fig 3.2 An-Ab-Or classification diagram for plagioclase feldspars of the Western Tauranga Basin.

Table 3.3 Representative microprobe analyses for amphibole phenocrysts of the Western Tauranga Basin. Kia (Kaikaikaroro Rhyolite), Min (Minden Peak Rhyolite), Wai (Waitearíki Ignimbrite), TeP (Te Puna Ignimbrite).

Sample	Kaikai 13	Kaikai 13	Min 7	Wai 12	Te P 28	Te P 28	Min 41	Wai 51	Min 33	Wai 62
SiO2	46.24	41.83	46.18	43.54	46.36	44.81	45.19	41.7	45.22	44.06
TiO2	1.38	2.59	1.19	19.4	1.3	1.54	0.98	2.02	1.34	1.8
Al2O3	8.21	10.8	6.73	8.41	6.75	7.08	7.3	8.88	7.52	8.14
FeO	14.57	19.66	19.89	19.49	19.97	18.37	21.91	20.59	20.07	18.82
MnO	0.34	0.35	0.74	0.5	0.5	0.45	0.78	0.28	0.55	0.29
MgO	14.02	9.86	11.03	10.38	11.89	11.6	9.81	8.82	10.51	10.57
CaO	11.04	10.55	10.42	10.69	10.12	10.6	10.33	10.26	9.96	10.97
K2O	0.27	0.44	0.41	0.51	0.47	0.35	0.57	0.46	0.53	0.52
Na2O	1.45	2.09	1.03	1.83	1.37	1.66	1.1	1.58	0.93	1.67
P2O5	0.19	0.2	0.02	0.02	0.05	0.09	0.04	0.08	0.04	0.06
Total	97.54	98.18	97.61	97.28	98.73	96.15	97.88	94.6	96.62	98.24

Table 3.4 Representative microprobe analyses for biotite phenocrysts of the Western Tauranga Basin. Man (ManawataRhyolite), Min (Minden Peak Rhyolite), Wai (Waitearíki Ignimbrite).

Sample	Min 7	Man 15	Man 15	Min 41	Min 41	Wai 51
SiO2	45.86	35.13	34.64	35.55	36.27	34.99
TiO2	1.21	4.1	5.2	4.74	4.9	4.98
Al2O3	7.22	15.73	13.33	13.76	14.1	16.63
FeO	18.15	21.98	25.07	20.85	21.16	24.23
MnO	0.46	0.29	0.22	0.09	0.06	0.03
MgO	12.03	8.28	8.36	11.46	11.65	9.06
CaO	10.23	0.15	0.03	0.13	0	0.09
K2O	0.36	7.96	8.56	8.66	8.72	8.47
Na2O	1.278	0.41	0.54	0.08	0.69	0.6
P2O5	0.08	0	0.11	0.23	0.01	0.11
Total	96.79	94.02	95.69	95.83	97.49	95.96

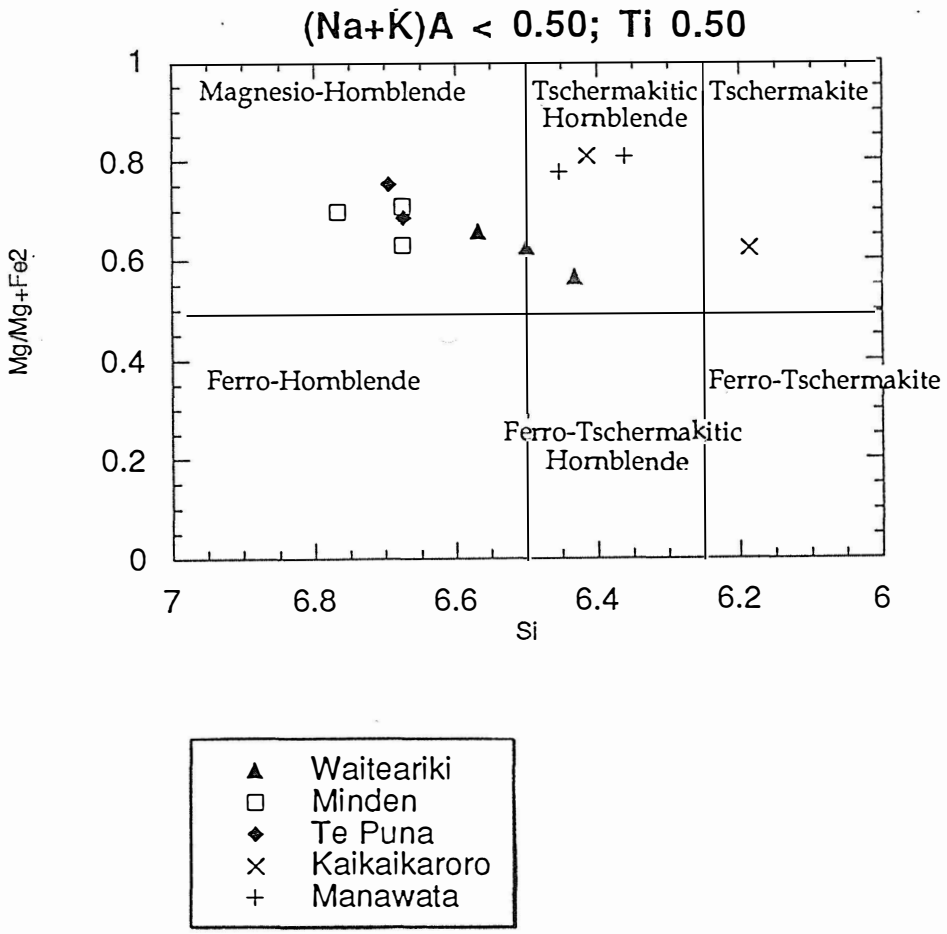


Fig 3.3 Amphibole compositions within the Western Tauranga Basin, classified according to Leake (1978).

Table 3.5 Representative microprobe analyses for orthopyroxene phenocrysts of the Western Tauranga Basin. Kai (Kaikaikaroro Rhyolite), Min (Minden Peak Rhyolite), Wai (Waitearíki Ignimbrite).

Sample	Kia 13	Kia 13	Kia 13	Min 7	Wai 12	Wai 12	Min 41	Min 41	Wai 51	Wai 51	Min 33	Min 33	Wai 62	Wai 62
SiO2	46.24	44.29	41.83	49.77	49.54	49.5	48.39	50.31	50.14	49.41	50.7	50.06	50.84	51.74
TiO2	1.38	1.76	2.59	0.07	0.14	0.05	0.05	0.11	0.18	0.23	0.3	0.06	0.23	0.52
Al2O3	8.21	9.34	10.8	0.67	0.49	0.53	14.73	0.6	1.08	0.99	0.65	0.27	0.8	1.56
FeO	14.57	15.86	19.66	31.3	33.55	33.92	26.08	30.88	30.63	32.9	30.35	32.26	28.02	22.65
MnO	0.34	0.37	0.35	1.53	1.15	1.67	0.98	1.57	0.87	0.93	1.46	1.49	0.45	0.49
MgO	14.02	13.13	9.86	15.6	14.66	13.47	15.64	16.15	15.44	14.76	16.68	15.63	18.12	21.78
CaO	11.04	11.07	10.55	0.71	1.18	1.36	0.73	0.84	1.57	0.94	0.76	0.7	1.1	1.87
K2O	0.27	0.19	0.44	0.05	0.12	0.03	0.03	0.02	0.01	0.1	0.05	0.05	0.01	0.02
Na2O	1.45	1.64	2.09	0.01	0.07	0.03	0.14	0	0.02	0.08	0.07	0.15	0.01	0.06
P2O5	0.19	0.05	0.2	0.18	0.18	0.04	0.02	0.22	0.03	0.21	0.1	0.17	0.09	0.18
Total	97.54	97.66	98.18	99.59	101.04	100.45	106.56	100.35	99.73	100.15	100.6	100.41	99.57	100.6
En	46.5	43.8	34.7	48.1	45.2	41.8	50.8	49.1	46.5	45.3	50.1	47.8	53.4	62.8
Fs	27.1	29.7	38.6	50.4	52.2	55.2	47.5	49	50.1	52.6	48.2	50.6	44.3	33.3
Wo	26.3	26.5	26.7	1.6	2.6	3	1.7	1.8	3.4	2.1	1.6	1.5	2.3	3.9

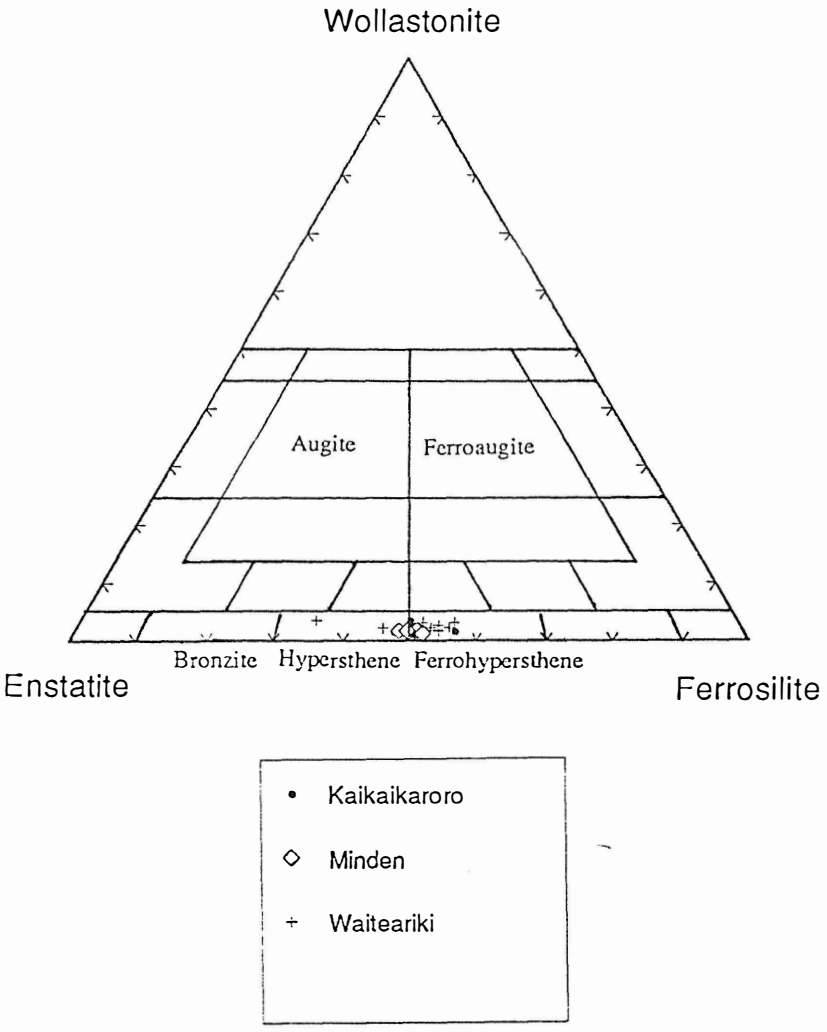


Fig 3.4 Wo-En-Fs ternary classification diagram for pyroxenes (after Morimoto, 1988) of the Western Tauranga Basin.

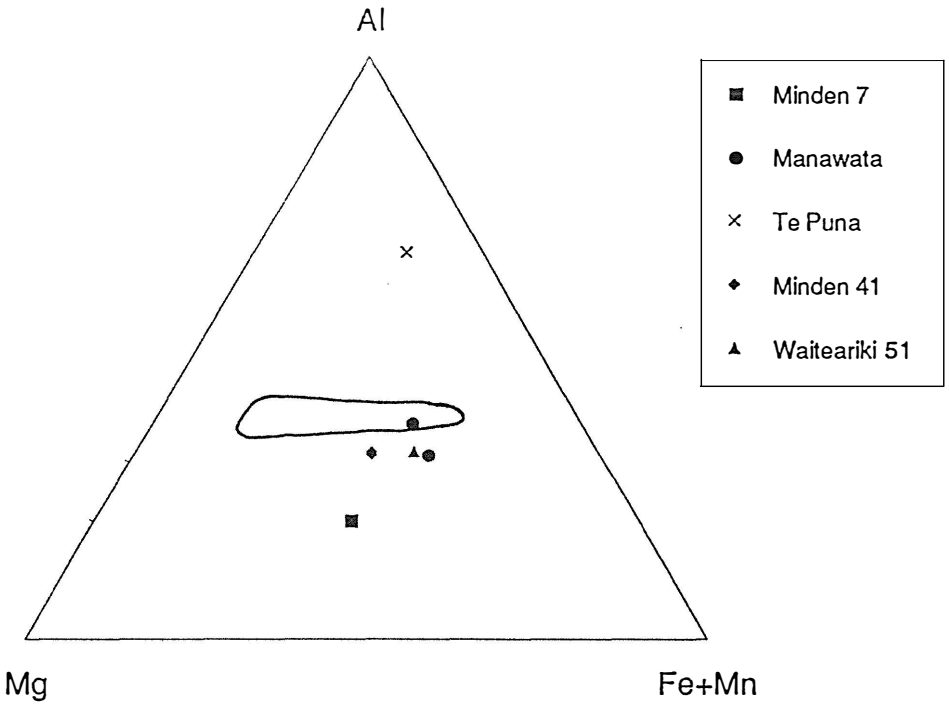


Fig 3.5 Al-Mg-Fe+Mn ternary diagram for biotite of the Western Tauranga Basin. Field is also plotted for TVZ biotite rhyolite (solid) after Ewart (1979).

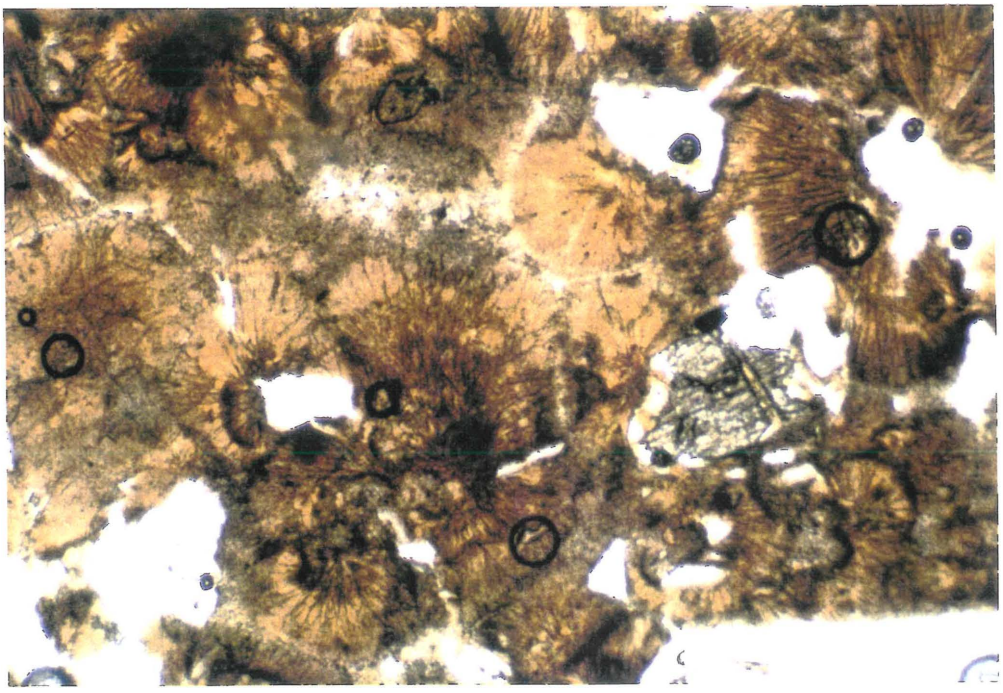


Fig. 3.6. Photomicrograph of spherulitic rhyolite from Kaikaikaroro showing hypersthene and hornblende within a spherulitic groundmass. X 40 magnification, plane polarised light.

Plagioclase

Plagioclase phenocryst compositions for the rhyolites are presented on the An-Ab-Or feldspar ternary classification diagram (Fig 3.2) and representative analyses are presented in Table 3.2. Plagioclase phenocryst composition is classed within the andesine (An 35-50) range.
Plagioclase within the rhyolite occurs as medium grained (1-4mm) euhedral to subhedral phenocrysts, up to 12.6%. The plagioclase phenocrysts show polysynthetic twinning and occasional zoning (An 33-38). Some grains are glomeroporphyritic or have inclusions of biotite or zircon.

Quartz

Quartz occurs as euhedral to anhedral phenocrysts up to 2 mm in length. Quartz occurs in all rocks but it is low in abundance at 0.2%. Phenocrysts are frequently embayed indicating that they are not in equilibrium with the surrounding material.

Amphibole

Calcic amphibole occurs at 0.6 modal percent and is magnesio hornblende using parameters by Mogessie *et.al.* (1988) and classified according to Leake (1978) (Fig 3.3).

Phenocrysts occur up to 2 mm in length and are generally anhedral to euhedral (Fig 3.1). Crystals occasionally show simple twinning and vary in shades of green to green-brown pleochroism. Embayment of the amphiboles can be seen in a number of crystals.

Orthopyroxene

The orthopyroxene phenocryst compositions for the rhyolites are presented on the Wo-En-Fs pyroxene ternary classification diagram (Fig 3.4) and representative analyses are presented in Table 3.5.

The orthopyroxenes present are hypersthene (En 80-50) and ferrohypersthene (En 50-12). Minden Peak contains both hypersthene and ferrohypersthene as En (51-41). Phenocrysts are generally anhedral to subhedral and have a maximum size of 2 mm. Pleochroism within the crystal is from pink to green to varying intensities.

Biotite

Biotite is not a dominant mineral within Minden Peak rhyolite and constitutes only 0.2 modal percent. Phenocrysts are generally subhedral to euhedral and reach 1mm in length. Opaque inclusions within the phenocrysts are common. Phenocryst compositions are presented on the Al-Mg-Fe+Mn ternary diagram (Fig 3.5) and are compared to Taupo Volcanic Zone (TVZ) biotite rhyolites of Ewart (1979). Minden rhyolite biotite shows a lower Al content than the TVZ rhyolites. Representative analyses are presented in Table 3.4.

Fe--Ti Oxides

Titanomagnetite occurs as anhedral grains, which commonly have zircon inclusions. Titanomagnetite also occurs with maghemite, haematite or with ilmenite lamellae. Ilmenite generally occurs as euhedral grains but some grains show embayment.

3.2.2 Kaikaikaroro

Kaikaikaroro rhyolite is a grey hypocrystalline rhyolite with medium to coarse grained (1->5mm) crystals. It is crystal-rich (40%) with visible euhedral hornblende to lengths of 5mm, plagioclase to lengths of 7mm, and quartz. The texture in thin section is spherulitic, which is embedded within a felsitic groundmass.

Plagioclase

Plagioclase phenocryst compositions are presented on the An-Ab-Or feldspar ternary classification diagram (Fig 3.2) and representative analyses are presented in Table 3.2. Phenocryst compositions are classified as andesine. Plagioclase (An 57-58) occurs as subhedral coarse grained (up to 7mm) phenocrysts and constitute up to 31.8% of the whole rock. Phenocrysts show zonation and polysynthetic twinning.

Quartz

Quartz occurs as medium grained (up to 2mm) subhedral phenocrysts and are frequently embayed. Their abundance is 7.2 % of the whole rock.

Amphibole

Calcic amphibole occurs in Kaikaikaroro as tschermakitic hornblende, using parameters by Mogessie et al. (1988) and classified according to Leake (1978) (Fig 3.3).
Phenocryts are medium grained, up to 5mm in length, are generally euhedral, and show pleochroism from brown to green. Phenocryst abundance is up to 3.6% at Kaikaikaroro.

Biotite

Biotite is low in abundance at 0.2% of the whole rock. It occurs as fine grained, less than 1mm, euhedral phenocrysts.

Orthopyroxene

Hypersthene and ferrohypersthene (En 42-51) are present (Fig 3.4). They occur as fine grained, less than 1mm, subhedral to anhedral phenocrysts with tabular and prismatic forms and make up 2.4% of the whole rock (Fig3.6). Phenocrysts contain occasional inclusions of opaques.

Fe-Ti Oxides

Fe-Ti oxides are euhedral ilmenite and anhedral titanomagnetite and make up 1.2% of the whole rock. Titanomagnetite grains can show exsolution and replacement by ilmenite lamellae. Magnetite and ilmenite commonly contain zircon inclusions.

3.2.3 Manawata

Manawata rhyolite is a light grey to pink hypocrystalline rock. It is phaneritic with medium grained (1-3mm) phenocrysts of quartz, plagioclase and hornblende within a spherulitic groundmass. Manawata rhyolite shows flow banding which is distinguishable due to colour changes in the bands from light grey to pink and by the alignment of hornblende crystals.
It weathers to a light grey to white soft rock with a pocky nature due to the weathering out of plagioclase.

Plagioclase

Plagioclase phenocryst compositions for the rhyolites are presented on the An-Ab-Or feldspar ternary classification diagram (Fig 3.2) and representative analyses are presented in Table 3.2. Phenocryst compositions fall within the andesine (An 35-50) range.

Plagioclase within the rhyolite occurs as medium grained (1-4mm) euhedral to subhedral phenocrysts, constituting 4.4% of the rock. The plagioclase phenocrysts show polysynthetic twinning and occasional normal zoning (An 33-38).

Quartz

Quartz occurs as euhedral to anhedral phenocrysts up to 2 mm in length and up to 1 modal percent. Phenocrysts are frequently embayed indicating that they are not in equilibrium with the surrounding material.

Amphibole

Calcic amphibole abundance is 2.4% at Manawata. Manawata contains tschermakitic hornblende, using parameters by Mogessie *et al.* (1988) and classified according to Leake (1978) (Fig 3.3).
Phenocrysts occur up to 2 mm in length, are generally anhedral to euhedral (Fig 3.3), and have green-brown pleochroism. Some crystals show simple twinning.

Orthopyroxene

In Manawata Rhyolite the hypersthene has been weathered, leaving only a remnant of the original crystal.

Biotite

Biotite occurs in abundance from 1.4-2.2%, is generally subhedral to euhedral, and reaches 1mm in length. Opaque inclusions within the phenocrysts are common.
Phenocryst compositions are presented on the Al-Mg-Fe+Mn ternary diagram (Fig 3.5) and compared to Taupo Volcanic Zone (TVZ) biotite Rhyolites of Ewart (1979). Manawata rhyolite biotite is more similar chemically to the TVZ

rhyolites. Representative analyses of the western Tauranga biotites are presented in Table 3.4.

Fe--Ti Oxides

Titanomagnetite occurs as anhedral grains, which commonly have zircon inclusions. Titanomagnetite also occurs with maghemite, haematite or with ilmenite lamellae. Ilmenite occurs as euhedral grains to subhedral grains .

3.3 Waitearíki Ignimbrite

The Waitearíki Ignimbrite is a crystal-rich (22.2 - 41.6%) ignimbrite with 20% pumice up to 400 mm in length. It varies in appearance from cream pumice within a creamy brown matrix to collapsed pumice forming dense, black, glassy fiamme within a light brown matrix. Visible crystals of plagioclase (5mm), hornblende and hypersthene can be seen in hand specimen. Lithics within the ignimbrite have been found up to 300 mm.

Plagioclase

Plagioclase phenocryst compositions are presented on the An-Ab-Or feldspar ternary classification diagram (Fig 3.2) and representative analyses are presented in Table 3.2. Phenocrysts are classed as oligoclase, andesine and labradorite.

Plagioclase (An 28-70) occurs as medium grained (3mm) euhedral to subhedral phenocrysts and crystals which are commonly fragmented, characteristic of a high energy eruption. Phenocrysts show polysynthetic twinning and normal zoning (An 41-49). It is the most abundant phenocryst and comprises 18.4 - 34% of the total rock.

Quartz

Quartz abundance is low (<2.8%) and is present as fine grained (<1mm) anhedral crystals which are generally embayed.

Orthopyroxene

Both hypersthene and ferrohypersthene (see Fig 3.4 and Table 3.3) are present with compositions ranging from En 45-62. They occur as subhedral to anhedral phenocrysts with tabular and prismatic form, and make up 2.8-4% of the rock. Phenocrysts show pink-brown pleochroism and are less than 1mm. Opaque inclusions are common.

Amphibole

The calcic amphiboles, magnesio hornblende and tschermakitic hornblende are found within the Waitеariki Ignimbrite as classified by Leake (1978) (Fig3.3). Amphibole analyses are given in Table 3.3.
They are pleochroic from brown to green and occur as subhedral tabular crystals with 120/60^{o} cleavage cross-sections. Phenocrysts have occasional opaque inclusions. It comprises 1.2% of the rock with crystals less than 1mm in length.

Biotite

Biotite is only found in the upper layer of the ignimbrite and is absent elsewhere. It is found at McLaren Falls where the biotite comprises 0.6% of the rock and occurs as euhedral laths with reaction rims.
Only one biotite phenocryst was microprobed and its chemical composition (Table 3.4) is plotted on the Al-Mg-Fe+Mn ternary diagram (Fig 3.5) .

Zircon

Zircon within the rock generally occurs associated with opaques. They occur as prismatic grains and have straight extinction. Their size is generally less than 0.1mm but have been found up to 0.5mm in length.

Fe-Ti Oxides

Fe-Ti oxides are subhedral tabular ilmenite and anhedral titanomagnetite and make up to 1% of the total rock. Titanomagnetite is also found with ilmenite lamellae and occasionally contain marcasite inclusions.

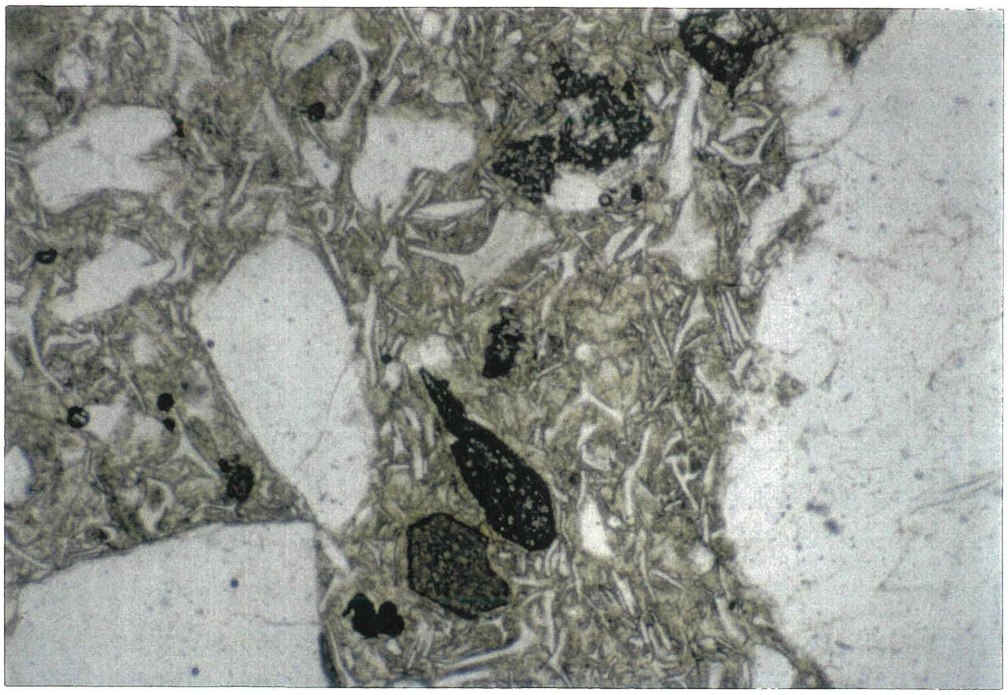


Fig 3.7 Photomicrograph of Waitearikí Ignimbrite with cuspate and Y-shaped glass shards and hornblende and zircon crystals in the lower centre. X 40 magnification, plane polarised light.

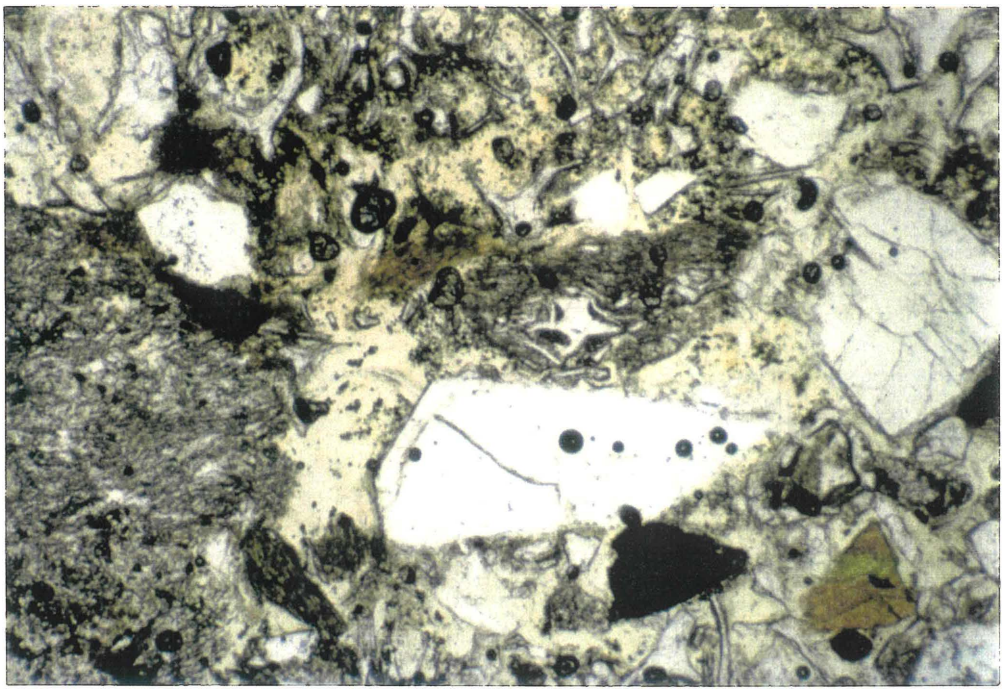


Fig. 3.8 Photomicrograph of Te Puna Ignimbrite with mica, hornblende, plagioclase, and vesicular pumice within a glass shard matrix. X4 objective, plane polarised light.

Pumice

Pumice within the Waiteariki Ignimbrite is fibrous and reaches 30cm in length. It varies in colour from cream to black, and in texture from fibrous to dense, due to the degree of welding and devitrification. Pumice is generally lenticular and shows fiamme characteristics at McLaren Falls. Where the pumice is highly devitrified, spherulites are present.

Groundmass

The groundmass is made up of cuspate and Y-shaped glass shards (Fig 3.7). Preferential devitrification occurs from the inside of the shards. Devitrification is greatest at McLaren Falls where it is also densely welded.
Lithics within the ignimbrite are andesitic, rhyolitic and dacitic, and comprise up to 3.6% of the total rock. Andesite lithics, up to 1 mm, contain aligned plagioclase laths in an interstitial groundmass. Rhyolitic lithics, up to 1 mm, are of brown spherulites with phenocrysts of plagioclase and titanomagnetite.
Dacitic lithics up to 30 cm are mineralogically similar to the Waiteariki Ignimbrite. They contain biotite, subhedral to anhedral hornblende, subhedral to anhedral hypersthene, subhedral plagioclase, embayed quartz, Fe-Ti oxides, and zircons in a glassy flow-banded groundmass. These lithics may represent earlier lava flows from the same source.

3.4 Te Puna Ignimbrite

The Te Puna Ignimbrite is holocrystalline nonwelded to partially welded ignimbrite. It contains 23% of white pumice within a buff brown matrix. It is crystal rich with 27% crystals, with visible plagioclase, quartz and hornblende. Lithic abundance is low (1-2%) and lithic types consist of banded and nonbanded rhyolite, and dacite.

Quartz

Quartz abundance within the ignimbrite is 2.8%, and occurs as subhedral to anhedral crystals, which are commonly embayed.

Plagioclase

Plagioclase phenocryst compositions are presented on the An-Ab-Or feldspar ternary classification diagram (Fig 3.2), with samples lying within the andesine range; representative analyses are presented in Table 3.2.
Plagioclase (An 30-39) is the dominant phenocryst and it occurs as medium grained (2mm) euhedral to subhedral crystals that are often fragmented. The crystals show polysynthetic twinning and normal zoning (An 32-37) with occasional inclusions of hornblende, hypersthene and Fe-Ti oxides. Plagioclase abundance is up to 19% of the whole rock.

Orthopyroxene

Hypersthene occurs as subhedral prismatic phenocrysts up to 1mm in length with ragged terminations and occasional opaque inclusions. It constitutes up to 0.4% of the whole rock.

Amphibole

Calcic amphibole occurs as magnesio hornblende within the Te Puna Ignimbrite as classified by Leake (1978) (Fig 3.3). It occurs as medium grained (2mm) prismatic subhedral phenocrysts with poorly developed terminations, or as six sided cross-sections showing 120/60º cleavage. Phenocrysts are pleochroic from dark green to brown and commonly show simple twinning.

Secondary minerals

A Secondary mineral within the Te Puna Ignimbrite may be the result of weathering of biotite within the ignimbrite. The mineral is golden in hand specimen, and light brown in thin section (Fig 3.8). Abundances range from 0.4-1.4% with the length of the crystals reaching 1mm. The compositions are in Table 3.4 and plotted with western Tauranga biotites on the Al-Mg-Fe+Mn ternary diagram (Fig 3.5). The mineral shows a high proportion of Al which has occurred due to weathering.

Groundmass

The groundmass consists of cuspate, lunate and Y-shaped glass shards in a yellow matrix and contains accessory lithics.

Brown rhyolite lithics, are up to 2 mm and contain plagioclase phenocrysts and zircon within a spherulitic groundmass. Waitearíki Ignimbrite also occurs up to 2 mm and contains hypersthene, plagioclase, and hornblende in a glass shard groundmass.

Pumice

The pumice is fibrous and makes up to 25% of the ignimbrite. It has a glomeroporphyritic texture and contains euhedral plagioclase, euhedral hornblende, subhedral hypersthene, quartz, biotite and Fe-Ti oxides (Fig 3.9).

Fe-Ti Oxides

Titanomagnetite and ilmenite are the most common opaques. Ilmenite grains occasionally have inclusions of apatite and marcasite.

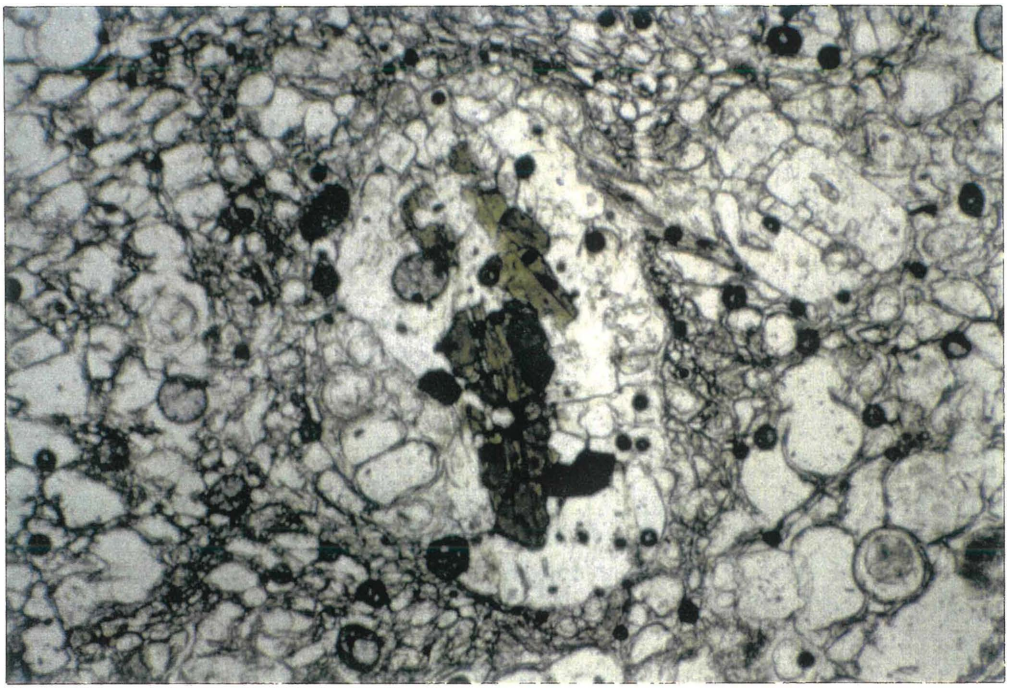


Fig 3.9 A Photomicrograph of glomeroporphyritic plagioclase and hornblende within the Te Puna Ignimbrite, X 40 magnification, plane polarised light.

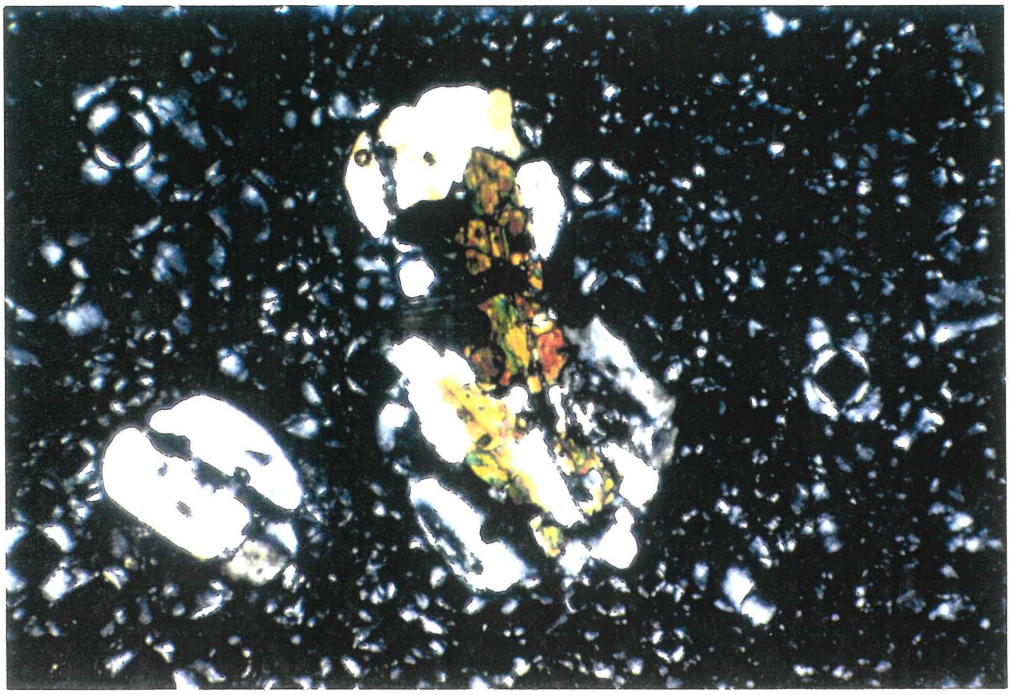


Fig. 3.9B Photomicrograph of glomeroporphyritic plagioclase and hornblende within the Te Puna Ignimbrite, X 40 magnification, crossed polarised light.

Chapter Four

Petrochemistry

Chapter Four

Petrochemistry

4.1 Introduction

Twenty four major and trace element analyses were determined on rocks in the western Tauranga Basin by X-ray fluorescence (XRF), and data are presented in Tables 4.1 and 4.2. Analyses were carried out at the Analytical Facility, Victoria University, Wellington.
The following discussion on petrochemistry involves determining if there is any significant chemical relationships between the rocks in the studied area. Also a comparison of the rocks in Coromandel (Adams 1992), Eastern Tauranga basin (Hughes 1992), Motiti Island (Henry 1991) and White Island (Graham and Cole 1989) is undertaken, using primitive mantle-normalised trace element plots.

4.2 Classification

Several geochemical variation diagrams can be used to classify the rock types. Peccerillo and Taylor (1976) classified rock types based on the relationship between SiO2 and K2O content. Their classification defines basalts as <52% SiO2, basaltic andesites 53-56% SiO2, andesites 56-63% SiO2, dacites 63-70% SiO2, and rhyolites >70% SiO2. K2O divisions mark the boundaries between arc tholeiite calc-alkaline, high-K calc-alkaline and shoshonite series.
Gill (1981) further divided andesites into high-K, medium-K and low-K andesites, whereas Le Maitre (1984) used SiO2 vs Na2O+K2O%.

Using the Peccerillo and Taylor (1976) SiO2 vs K2O (Fig 4.1) and the Le Maitre (1984) SiO2 vs Na2O+K2O (Fig 4.2) classification diagrams it is seen that Waitearikiki Ignimbrite is dacitic to rhyolitic, Kaikaikaroro, Manawata and Minden Peak are rhyolitic, and Te Puna Ignimbrite is rhyolitic with pumice ranging from rhyolite to high silica rhyolite.

The Western Tauranga basin rocks are subalkaline in nature as classified according to Irvine and Baragar (1971) (Fig 4.3).

Table 4.1 Major (normalised to 100% volatile free) and trace element XRF analyses of the Western Tauranga basin volcanics. Min=Minden Peak Rhy, Kai=Kaikaikaroro Rhy, Man= Manawata Rhy, TeP=Te Puna Ign, Wai=Waitekariki Ig.

Sample	Min 6 rhyolite	Min 7 rhyolite	Kai 13 rhyolite	Man 15 rhyolite	Man15 rhyolite	Te P 28 ignim.	Wai 32 ignim.	Min 33 rhyolite	Min 35 rhyolite	Min 36 rhyolite	Min 41 rhyolite	Min 43 rhyolite
SiO2	75.98	75.73	70.92	74.44	76.25	70.52	70.07	74.68	75.36	75.51	75.5	74.56
TiO2	0.2	0.2	0.4	0.26	0.22	0.36	0.4	0.22	0.22	0.2	0.2	0.23
Al2O3	13.82	13.77	15.54	15.92	15.3	17.28	15.91	14.86	14.17	13.56	13.92	15.12
Fe2O3	0.37	0.36	0.69	0.41	0.4	0.59	0.75	0.41	0.39	0.35	0.35	0.41
FeO	1.33	1.3	2.5	1.48	1.44	2.11	2.68	1.46	1.4	1.28	1.28	1.48
MnO	0.03	0.04	0.06	0.03	0.02	0.09	0.09	0.04	0.03	0.03	0.02	0.05
MgO	0.24	0.23	0.73	0.25	0.13	0.36	0.46	0.26	0.27	0.16	0.2	0.22
CaO	1.06	1.21	2.57	1	0.56	2.31	2.6	1.31	1.2	1.51	1.36	1.32
Na2O	3.15	3.4	3.71	2.93	2.08	3.79	4.42	3.47	3.29	3.81	3.5	3.3
K2O	3.8	3.73	2.83	3.24	3.57	2.58	2.59	3.26	3.65	3.55	3.64	3.28
P2O5	0.02	0.02	0.05	0.02	0.01	0.02	0.02	0.02	0.03	0.03	0.02	0.05
LOI	1.98	1.68	2.27	3.4	4.22	4.78	2.78	1.66	1.49	0.69	1.3	2.06
Total	100	100	100	100	100	100	100	100	100	100	100	100
Sc	4	3	9	4	2	7	9	4	4	4	5	5
V	16	15	44	15	11	25	28	14	16	15	15	18
Cr	2	1	5	2	1	2	3	2	1	2	2	3
Ni	1	2	2	3	2	2	4	1	1	1	3	2
Cu	4	4	7	5	5	4	6	3	3	4	3	4
Zn	28	29	54	41	33	58	64	32	28	30	33	29
Ga	14	14	16	15	16	17	17	15	14	14	14	15
As	3	4	4	4	3	4	4	5	4	4	4	4
Rb	133	131	99	120	126	91	82	77	126	127	123	87
Sr	90	92	154	96	57	171	194	99	95	114	99	100
Y	12	14	28	32	16	28	45	17	30	16	80	19
Zr	133	132	158	193	156	209	209	150	142	134	138	148
Nb	8	8	6	7	8	9	8	9	7	7	6	8
Ba	789	794	786	786	681	727	717	820	800	796	771	798
La	18	21	32	89	25	24	52	26	26	23	50	22
Ce	36	39	45	64	46	68	93	38	35	42	40	48
Pb	17	15	15	16	14	18	12	14	15	15	15	18
Th	15	14	10	12	13	12	8	14	13	13	13	15
U	4	4	2	4	3	3	3	3	4	3	4	3

Table 4.2 Continued Major (normalised to 100% volatile free) and trace element XRF analyses of the Western Tauranga basin volcanics. Wai=Waitearíki Ignimbrite, TePp=Te Puna Pumice

Sample	Wai 62	TePp 82	TePp 83	TePp 84	TePp 85	TePp 86	TePp 87	TePp 88	TePp 89	TePp90	TePp91
rhyolite	ignim.	pumice	pumice	pumice	pumice	pumice	pumice	pumice	pumice	pumice	pumice
SiO2	67.54	73.88	75.67	75.09	73.51	75.17	74.41	73.96	73.52	72.58	73.13
TiO2	0.54	0.26	0.19	0.2	0.31	0.24	0.27	0.3	0.27	0.24	0.25
Al2O3	16.84	14.31	13.58	13.83	14.23	13.6	14.07	14.05	14.53	16.1	15.92
Fe2O3	0.95	0.44	0.35	0.38	0.53	0.39	0.46	0.51	0.47	0.44	0.47
FeO	3.41	1.59	1.25	1.35	1.92	1.4	1.65	1.85	1.68	1.6	1.69
MnO	0.01	0.07	0.06	0.06	0.08	0.05	0.06	0.16	0.08	0.09	0.12
MgO	0.67	0.33	0.25	0.3	0.43	0.35	0.39	0.41	0.38	0.29	0.32
CaO	3.76	2	1.55	1.68	1.96	1.6	1.66	1.77	2.02	1.88	1.55
Na2O	3.91	3.55	2.92	3.04	3.46	3.57	3.24	3.3	3.55	3.46	3.28
K2O	2.15	3.54	4.18	4.06	3.57	3.62	3.78	3.67	3.5	3.31	3.26
P2O5	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.01
LOI	2.28	3.18	3.57	3.66	3.47	2.93	3.35	3.7	3.08	4.41	4.24
Total	100	100	100	100	100	100	100	100	100	100	100
Sc	14	5	4	5	6	4	5	8	7	6	6
V	55	18	12	13	21	14	17	23	17	17	15
Cr	8	2	2	3	4	2	2	4	3	3	3
Ni	5	1	2	2	1	2	2	2	2	2	3
Cu	8	2	3	3	3	3	3	4	4	4	4
Zn	62	46	40	40	52	42	48	54	46	45	46
Ga	17	14	13	15	15	14	16	15	15	17	16
As	3	5	5	4	5	5	5	5	5	4	5
Rb	73	113	132	130	113	122	126	116	110	106	113
Sr	232	150	111	120	140	116	118	122	145	132	106
Y	53	25	23	24	25	23	27	39	27	31	34
Zr	170	174	133	140	209	167	177	209	190	174	173
Nb	7	8	8	7	8	8	8	10	9	8	9
Ba	680	744	793	771	756	739	652	890	777	787	790
La	30	23	25	24	25	27	22	55	30	33	36
Ce	48	49	49	47	50	43	48	94	54	64	75
Pb	12	14	14	14	14	13	13	21	15	19	20
Th	8	11	13	14	12	13	12	12	10	13	16
U	2	2	3	4	3	3	3	3	3	3	3

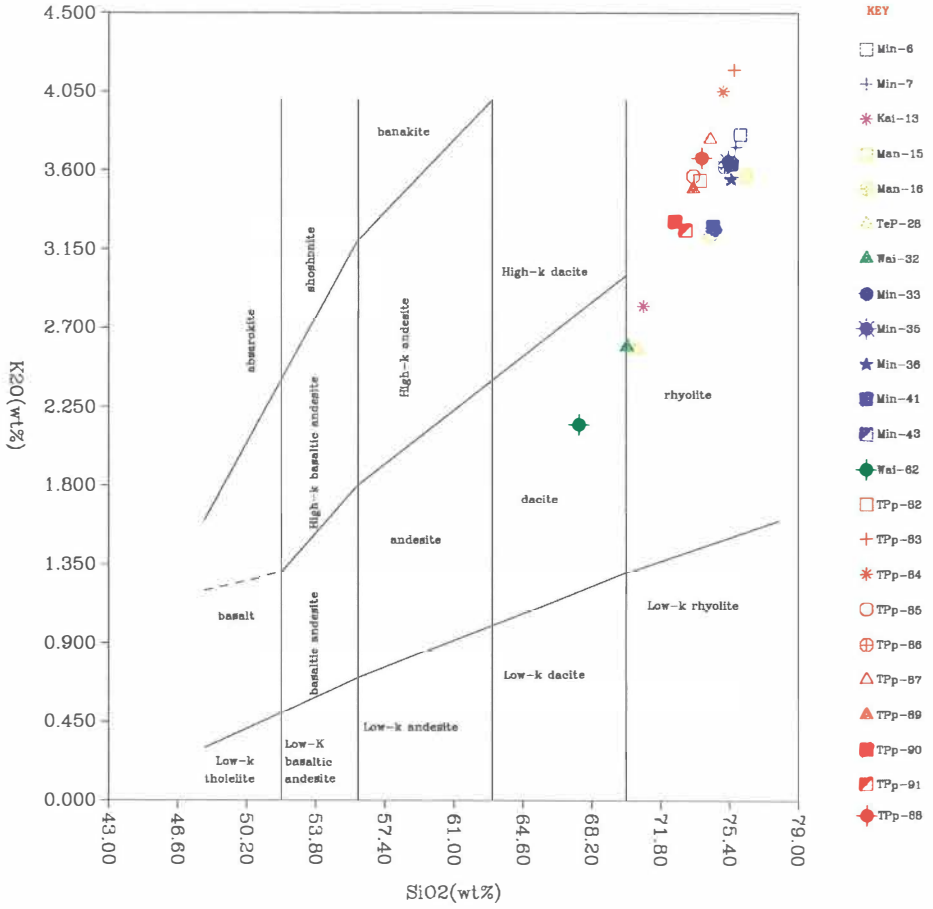


Fig 4.1 Classification of Western Tauranga basin Volcanic rocks using the K20 vs Si02 diagram of Peccerillo and Taylor (1976).

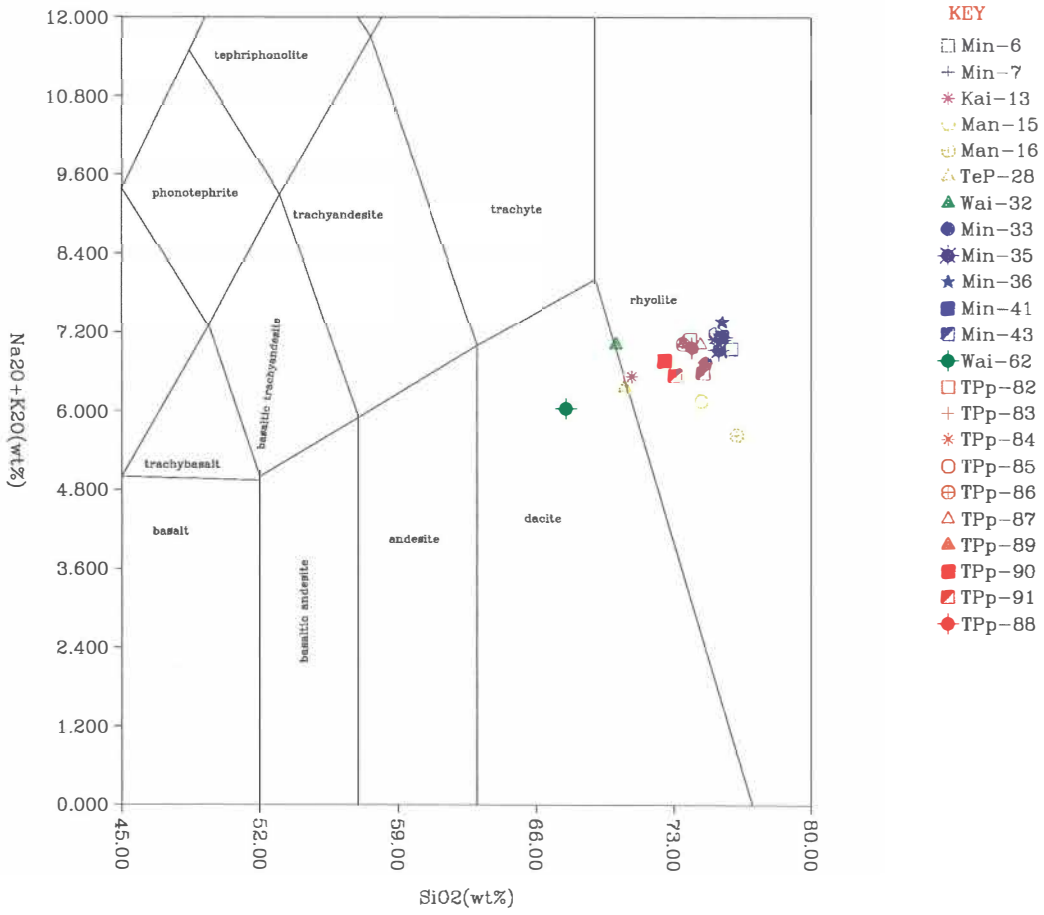


Fig 4.2 Na2O + N2O vs SiO2 diagram of Western Tauranga basin rocks (after Le Maitre 1984).

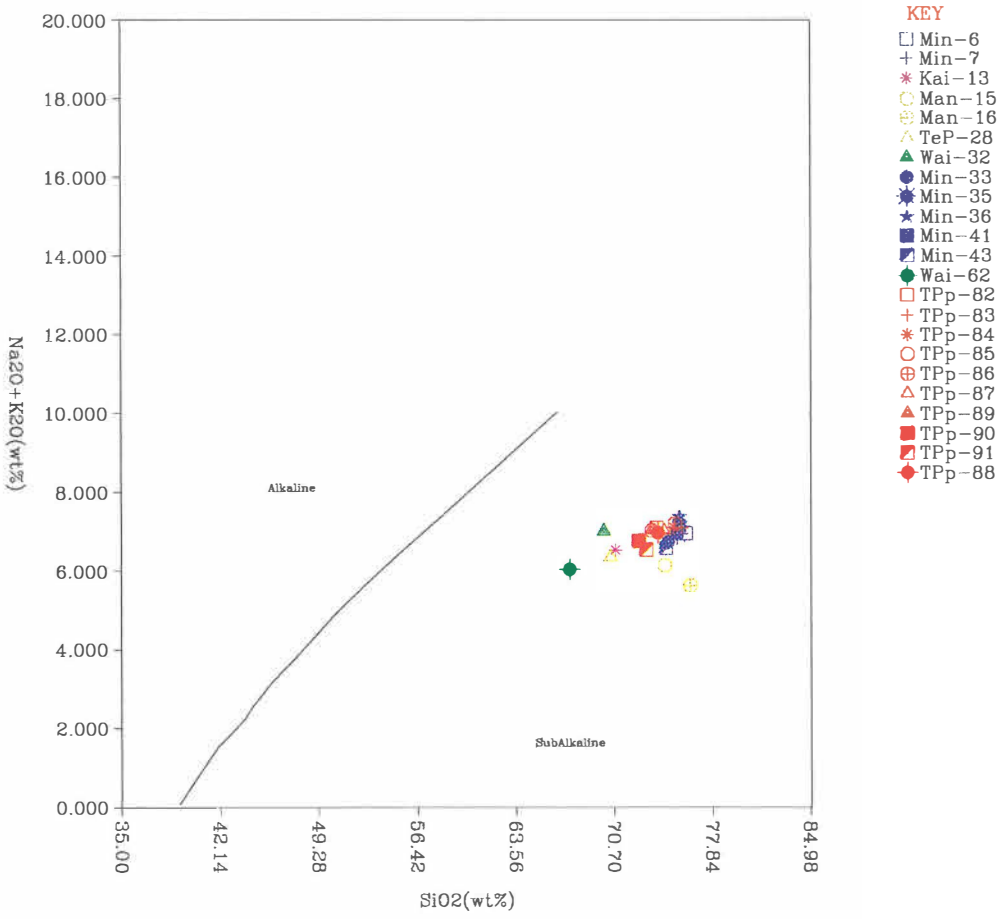


Fig 4.3 Total alkali vs silica plots of Western Tauranga basin rocks. The distinction between alkaline and subalkaline is after Irvine and Barager (1971).

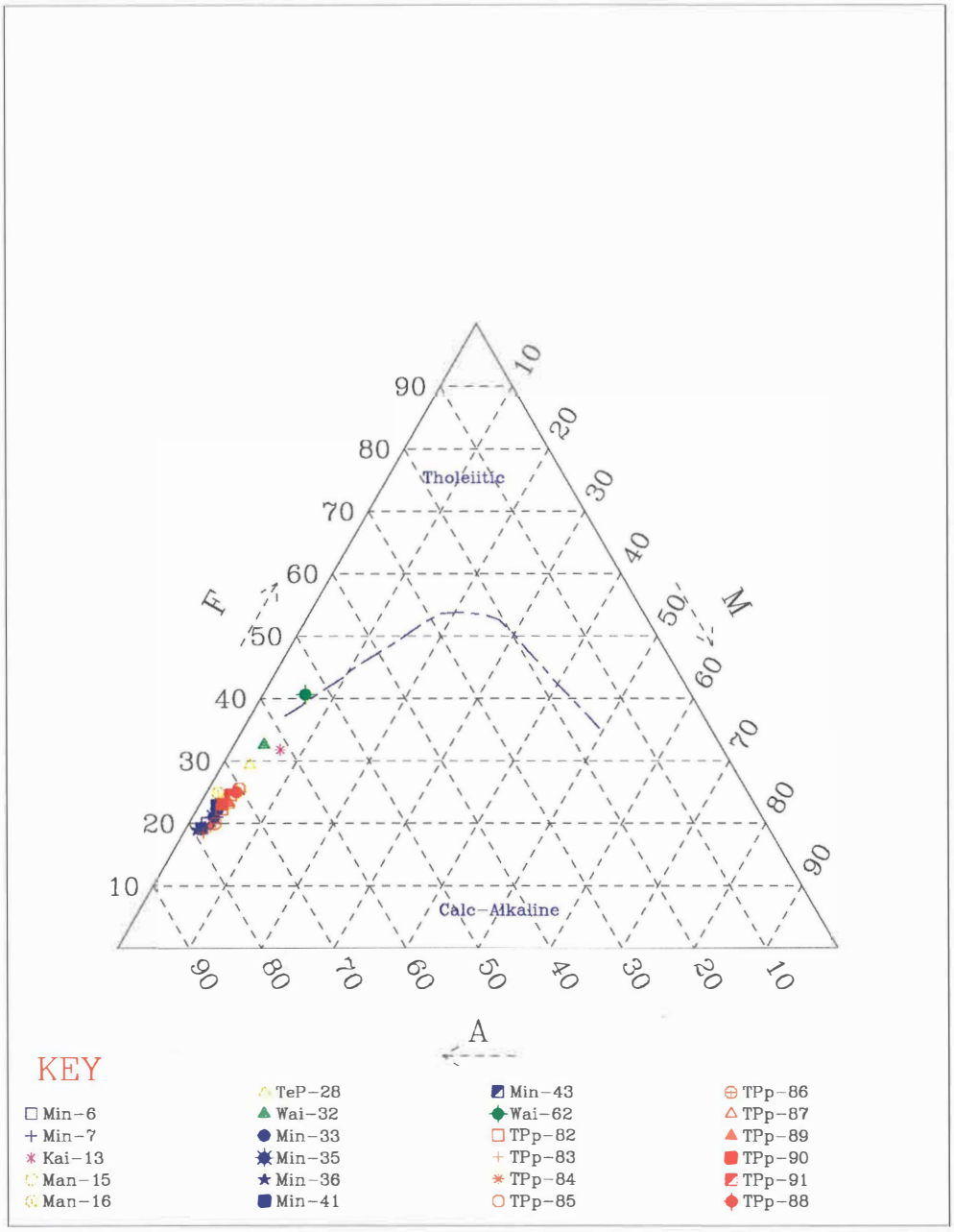


Fig 4.4 AFM diagram of Western Tauranga basin volcanic rocks compared to other North Island rocks (after Irvine and Baragar 1971).
1=White Island(Cole & Graham 1989), 2=Motiti Island(Henry 1991)
3=Coromandel(Adams 1992), 4=Eastern Tauranga basin(Hughes 1993)

To define the magmatic series involved, the AFM (A= Na2O + K2O, F= FeO + 0.8998 Fe2O3, M=MgO) diagram of Irvine and Baragar (1971) has been used which chemically classifies the volcanic rocks into tholeiitic and calc-alkaline suites. These suites are distinguished on the basis of iron enrichment, with tholeiitic rocks containing more iron, and calc-alkaline showing iron depletion. Fig 4.4 shows samples from the western Tauranga basin are calc-alkaline, except for the Waitearíki Ignimbrite (sample 62) which is tholeiitic. Samples show an increase in iron enrichment with a reduction in silica content. The more rhyolitic rocks have less iron enrichment than the dacitic rocks.

Also plotted are data from other areas, White Island, Motiti Island, Coromandel and eastern Tauranga. The western Tauranga rocks show a similar plot to eastern Tauranga basin and Coromandel rocks except for the lower MgO contents in the andesites.

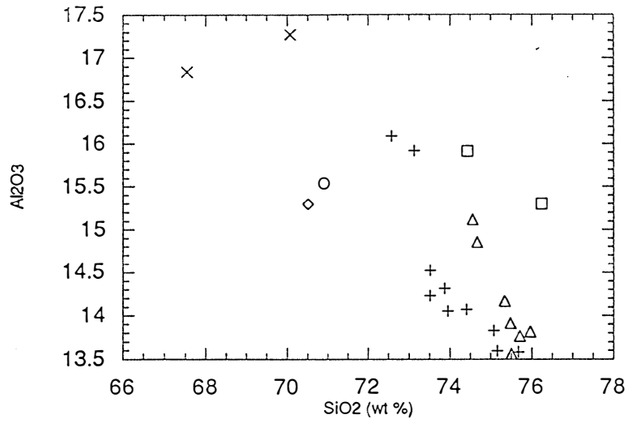
4.3 Major Element Chemistry

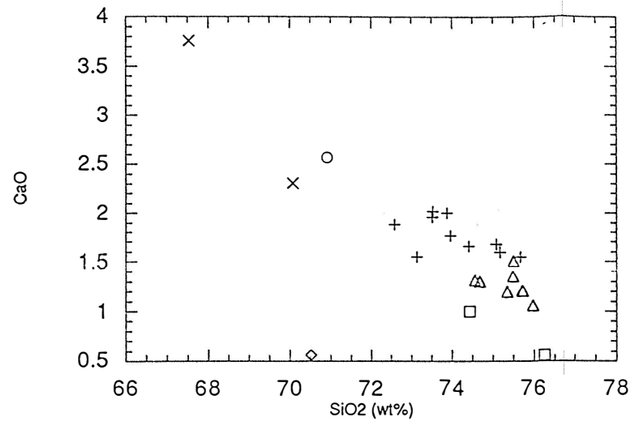
Harker diagrams are used to present data in a form where trends may represent the course of chemical evolution of a magma. Major element trends are easily seen using Harker variation diagrams, plotting SiO_2 wt % against other major element oxides (Fig 4.5). Silica content provides a convenient relative abscissa to show graphically the variation in concentration of other oxides, and silica correlates positively and significantly with measures of differentiation (Gill 1981).

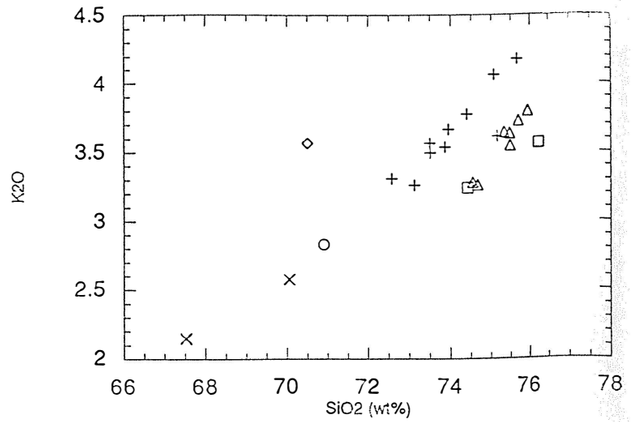
In general, for suites of cogenetic igneous rocks, pairs of oxides are strongly correlated, either positively or negatively. Such correlations or trends may be generated as a consequence of partial melting, fractional crystallisation, magma mixing or crustal contamination, either individually or in combination (Wilson 1989).

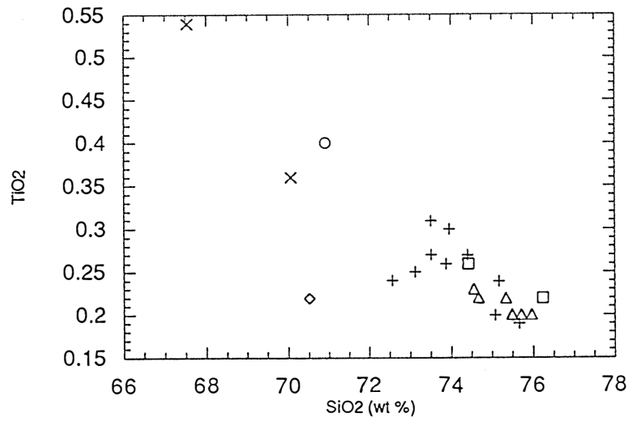
4.3.1 Rhyolites

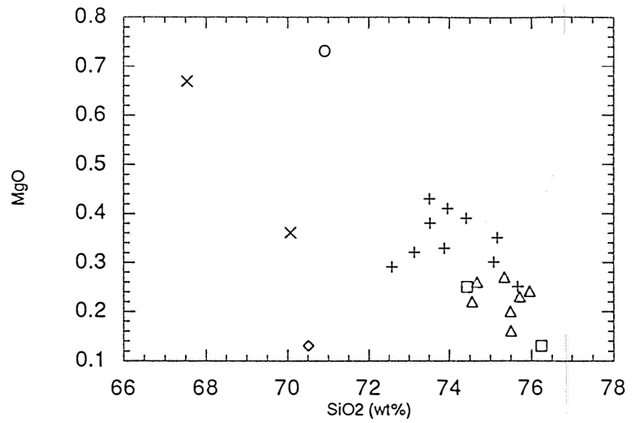
Minden Peak rhyolite and Manawata rhyolite show similar major element plots. Their data cluster together for MgO, CaO, Fe2O3, FeO, K2O and TiO2. This may indicate a similar magmatic source.

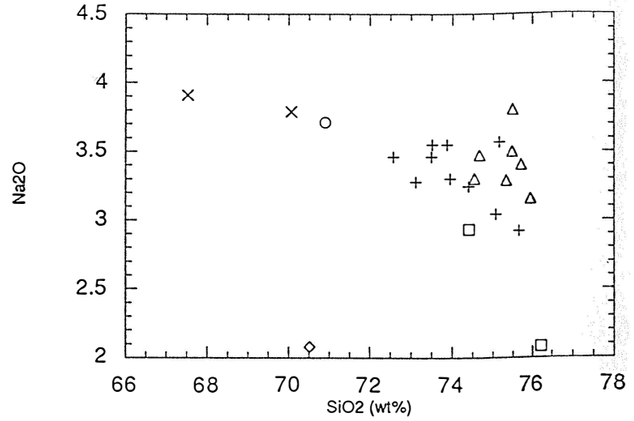


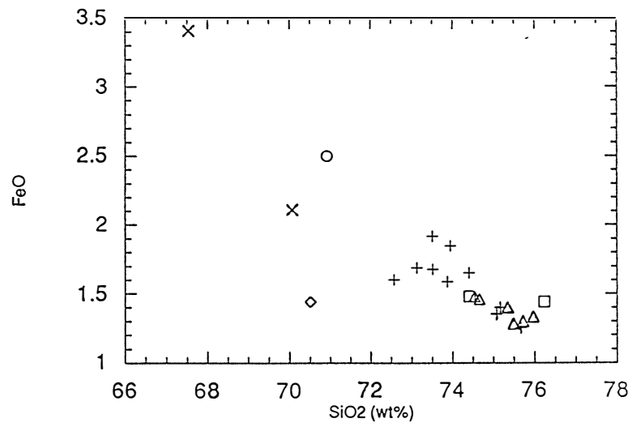


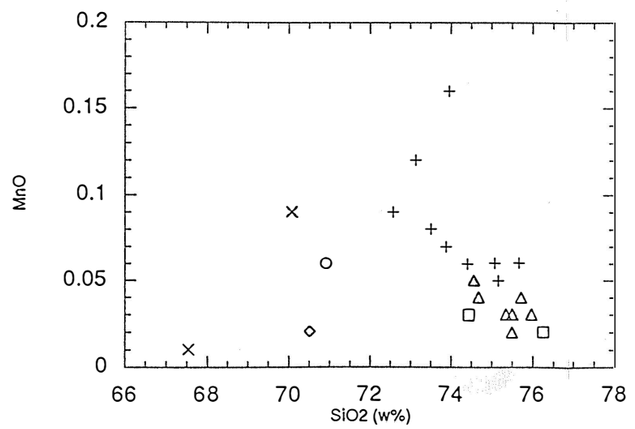












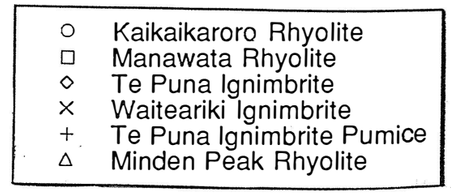


Fig 4.5 Major element Harker diagrams of western Tauranga basin volcanics. Values expressed in wt %.

Kaikaikaroro rhyolite has a lower SiO2 content than Manawata and Minden Peak. Kaikaikaroro has higher Fe2O3, CaO, MgO, FeO and TiO2 values and lower K2O values than the other rhyolites.

4.3.2 Waitearíki Ignimbrite

Samples were taken from two different flow units within the Waitearíki Ignimbrite which vary in SiO2 content. The lower unit contains cream pumice which has a fibrous texture and has a SiO2 content of 70.07%. The second flow unit is moderately to densely welded with lenticular black pumice and has a SiO2 content of 67.54%. The dacitic sample has higher FeO, MgO, CaO, Na2O, FeO3 and TiO2 values. The more rhyolitic unit has higher K2O and Al2O3 values. The differences in the oxide contents may be due to differentiation, or zonation in the magma chamber resulting in the two flows having different compositions. If there was zonation in the magma chamber the deeper more dacitic layer may have been tapped first, or an injection of dacitic magma may have erupted through a more rhyolitic magma chamber.

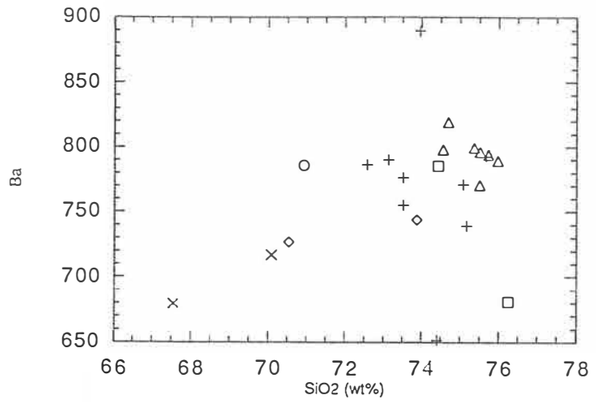
4.3.3 Te Puna Ignimbrite

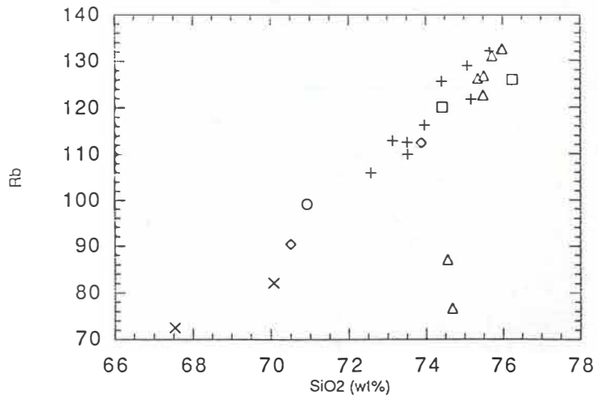
Pumices from the Te Puna Ignimbrite samples have different SiO2 values, and range from 72.58 - 75.17% SiO2. The most SiO2-rich sample has lower K_2O and higher TiO2, FeO, Na2O, CaO, K2O, Al2O3 and Fe2O3 values. The lower SiO2 content sample has lower K2O and higher TiO2, Al2O3, CaO and Na2O values

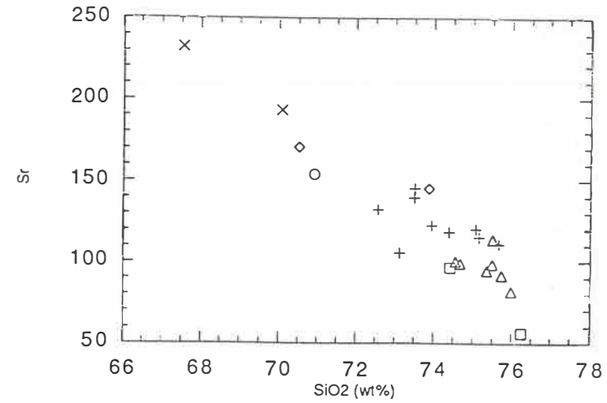
There is a strong negative correlation in FeO, CaO, Al2O3 and TiO2 values and positive correlation in K2O. The negative correlation indicates that as the magma chamber becomes more SiO2-rich, a depletion in these oxides due to crystallisation of the phenocrysts. The phenocrysts are plagioclase (andesine), quartz, calcic amphibole (magnesio hornblende), hypersthene, zircon, magnetite and ilmenite.

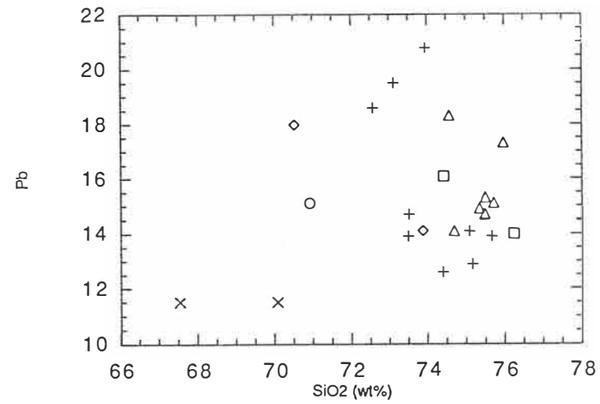
4.4 Trace Element Chemistry

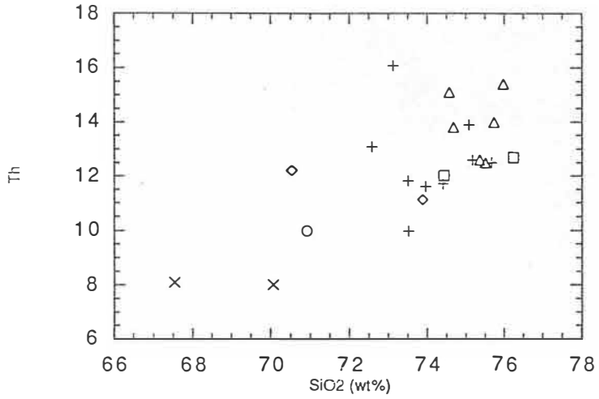
A trace element is an element which is present in rocks in concentrations of up to a few thousand parts per million. Different minerals may incorporate or exclude trace elements. Their analyses can lead to constraints on the nature and

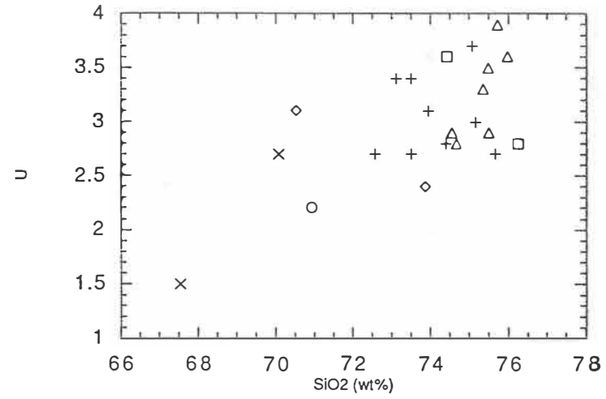


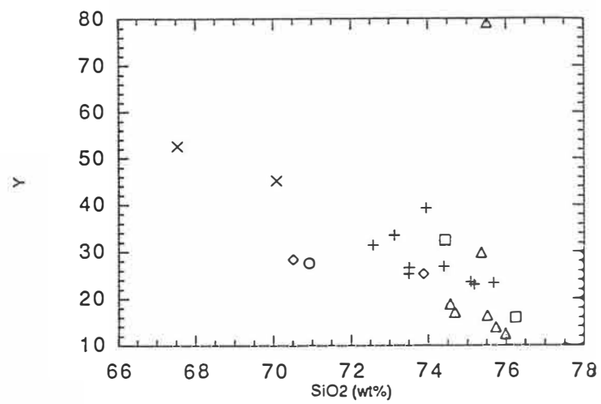


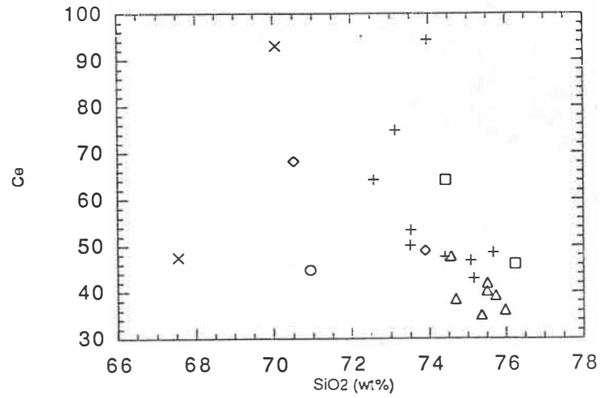












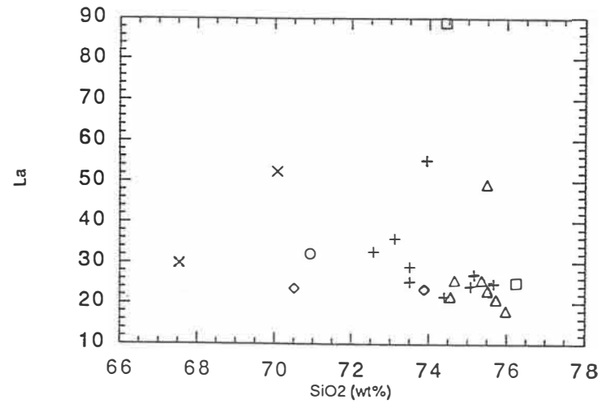
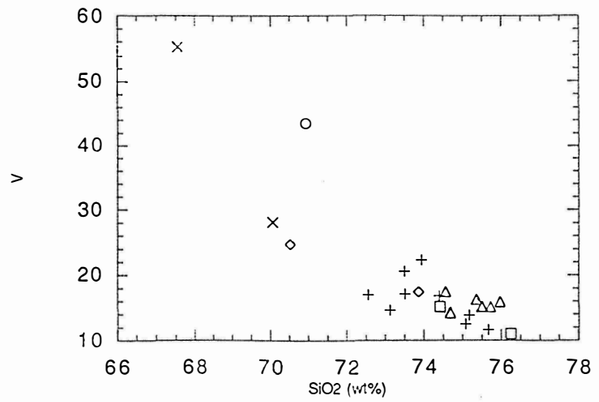
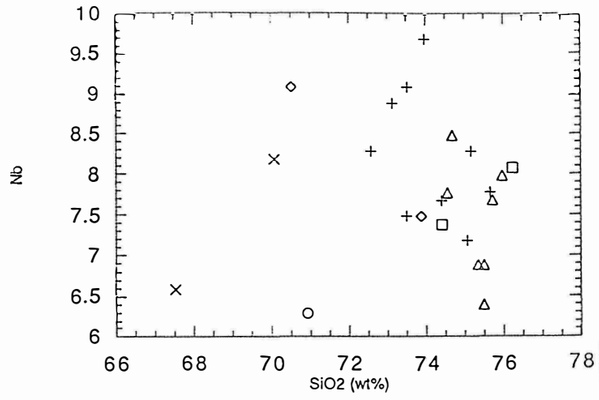
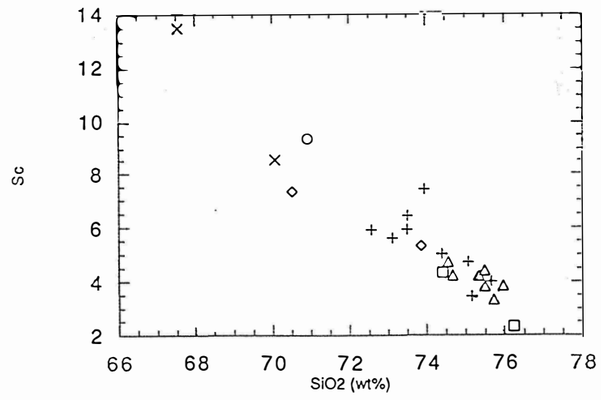
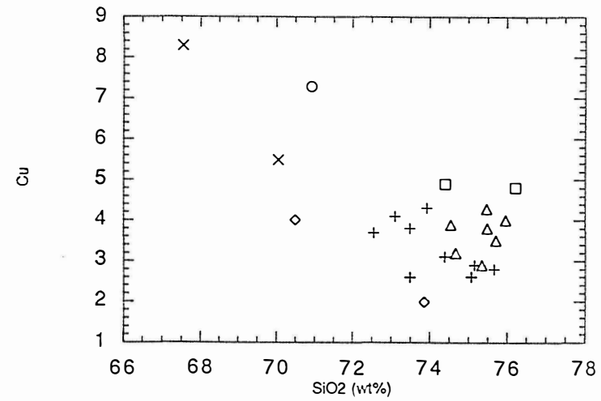


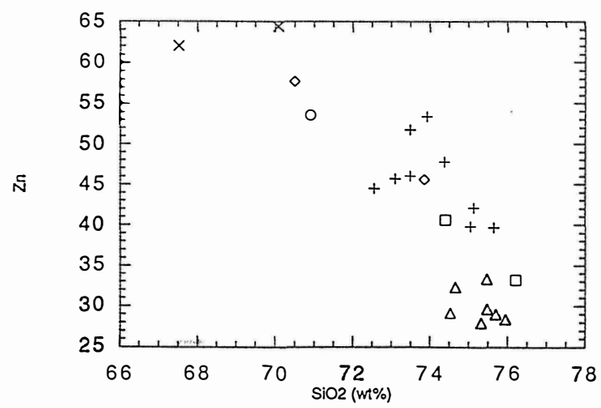
Fig 4.6 Trace element Harker diagrams of western Tauranga basin volcanics. Values expressed in SiO2 wt% and ppm.

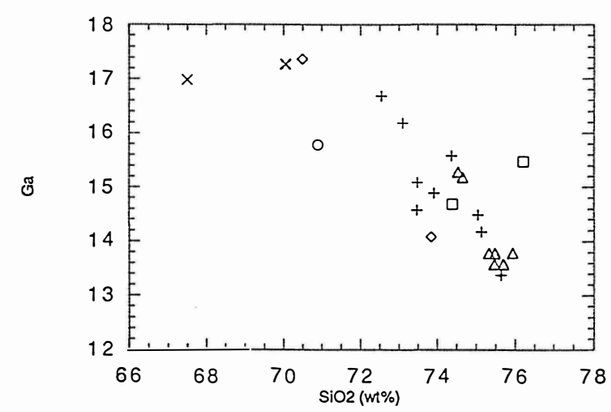












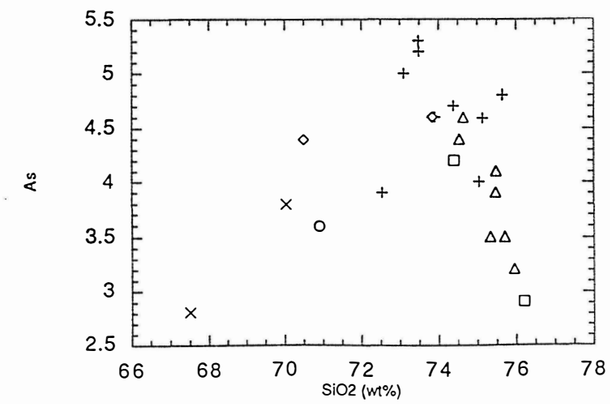


Fig 4.6 continued.

composition of the mineral assemblages with which a magma may have previously equilibrated (Cole 1979). Trace elements plotted against SiO2 are shown in Fig 4.6.

Sc, Cr and V show negative correlation as these elements are compatible. Compatible elements are preferentially incorporated into crystallising solid phases and therefore their abundance reduces with increasing SiO2 content. These elements tend to be concentrated in ferromagnesian minerals, than in the co-existing melt. The feromagnesiam minerals within the rocks are hypersthene, ferrohypersthene, biotite and hornblende.

Sr has a negative correlation, which is a similar trend to CaO, which is due to the fractionation of plagioclase.

Cu and Zn have negative correlation as they are compatible with ferromagnesian minerals and therefore incorporated into hypersthene, hornblende and biotite.

Rb, Th and U have positive correlations as they are incompatible elements and are not incorporated into minerals. This results in an increase in element content with increasing SiO2.

Ni is compatible and usually shows negative correlation as it is concentrated in ferromagnesian minerals.

The rare earth group (REE), La and Ce, have no correlation to SiO2 and show a large degree of scatter. A few samples from La, Ce and Y having anomalously high concentrations. Ewart (1979; 1982), Reid and Cole (1983) and Graham and Hackett (1987) indicate that the maximum values for La and Y is about 30ppm, and about 50ppm for Ce. Anomalously high concentrations are found in Manawata Rhyolite with La at 89 ppm, Te Puna Ignimbrite pumice (88) and Waiteariki Ignimbrite (32) have Ce values of 93 ppm, and Minden Peak Rhyolite (41) having a Y concentration of 79 ppm.

REE enrichment, to higher degrees (eg La= 458 ppm, Y=300 ppm) have also been noted in the Kiwitiahi volcanics (Kuschel and Smith 1990; Dunbar 1991; Black et al. 1992) and in Coromandel rocks (Briggs and Fulton 1990, Hunt 1991). These rocks show no mobility in other trace elements and are not petrographically discernible from other rocks in the area. Kuschel and Smith (1990), Dunbar (1991) and Black et al. (1992) have identified submicroscopic

secondary minerals. Black et al. (1992) identified, through SEM backscattered electron imagery, localised REE and Y-enriched silicate minerals on grains of plagioclase. These secondary minerals are thought to be products of weathering or late-stage localised hydrothermal alteration (Fodor et al. 1992).

The major and trace element chemistry of the western Tauranga basin rocks show no distinct variations between the rock units. Concentrations in elements tend to suggest that the units are genetically related as no distinct compositional groups can be seen on the Harker variation diagrams. The main process which can be seen in the geochemistry of the rocks is fractional crystallisation. Several major elements and compatible trace elements show negative correlations with SiO2, which is indicative of fractional crystallisation. The major fractionating minerals are plagioclase, biotite, orthopyroxenes and hornblende. Plagioclase fractionation is shown by a negative correlation in Al2O3, CaO and Sr with SiO2. Biotite, orthopyroxenes and hornblende fractionation is shown by strong negative correlations in CaO, MgO, FeO, Sc, Cr, V, Cu, and Zn with SiO2. A correlation between SiO2 and TiO2 indicates the fractionation of titanomagnetite and ilmenite from the melt.

4.5 Spider Diagrams

Spider diagrams are plotted to show the pattern of trace elements within a rock. These diagrams can be used to compare elemental abundances between rock samples.
The abundances of a range of incompatible trace elements are normalised to estimates of their abundances in the primordial Earth. The elements plotted all behave incompatibly (D<1) during most partial melting and fractional crystallisation processes. The main exceptions to this are Sr, which may be compatible with plagioclase, and Ti with magnetite.

Trace elements are normalised using chondrite and primitive mantle data (Taylor and McLennan 1985) which allows comparison between rock samples. A selection of primitive mantle and chondrite normalised spider diagrams from representative Western Tauranga basin rocks are shown in Fig 4.7.

The primitive mantle plot (Fig 4.7a) shows that Ba, Rb, Th, U and K values for the different rock types increase with increasing SiO2 content. This is due to the incompatible nature of these elements during differentiation which excludes them during crystal growth. Trace elements on the right hand side of the

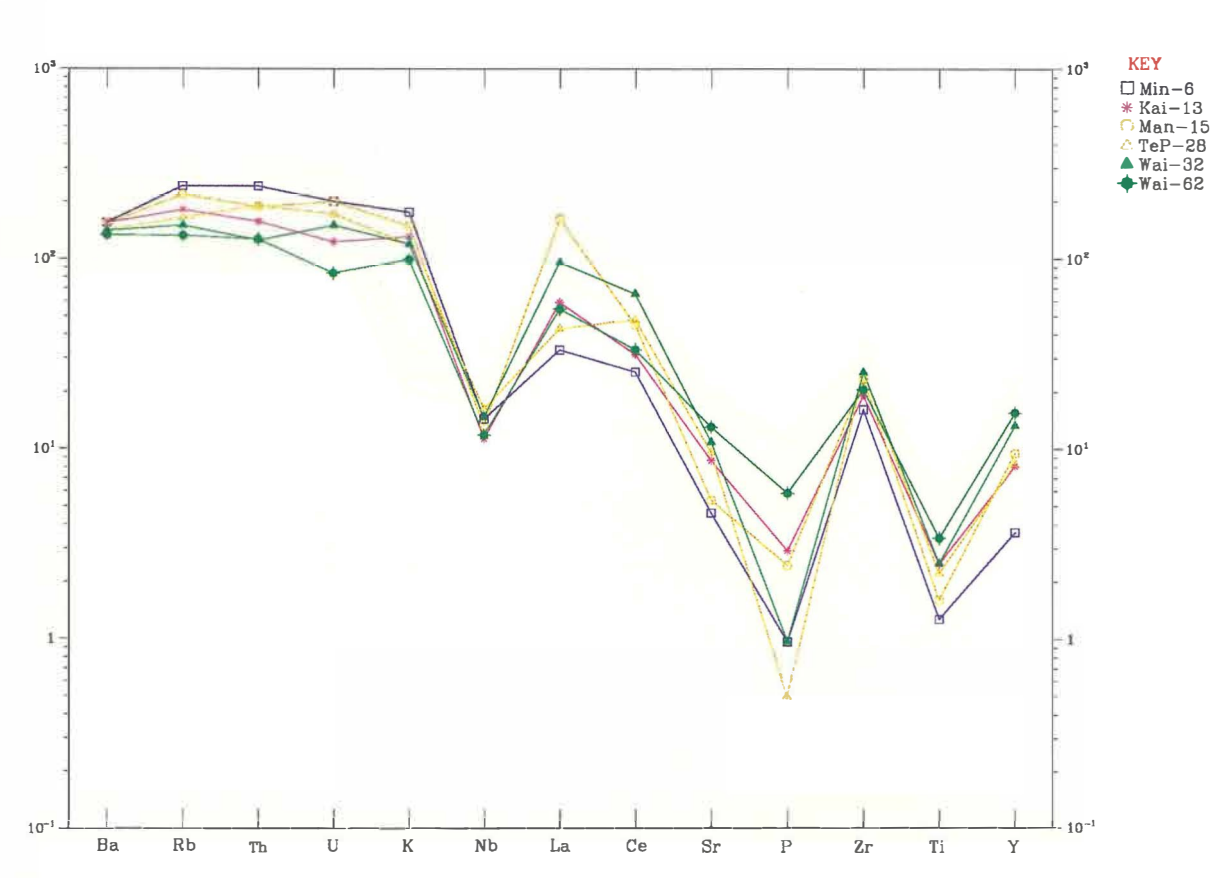


Fig 4.7a Spider diagram of trace element concentration normalised to Primative mantle for selected Western Tauranga rocks. Values for primative mantle are after Taylor and McLennan (1985).

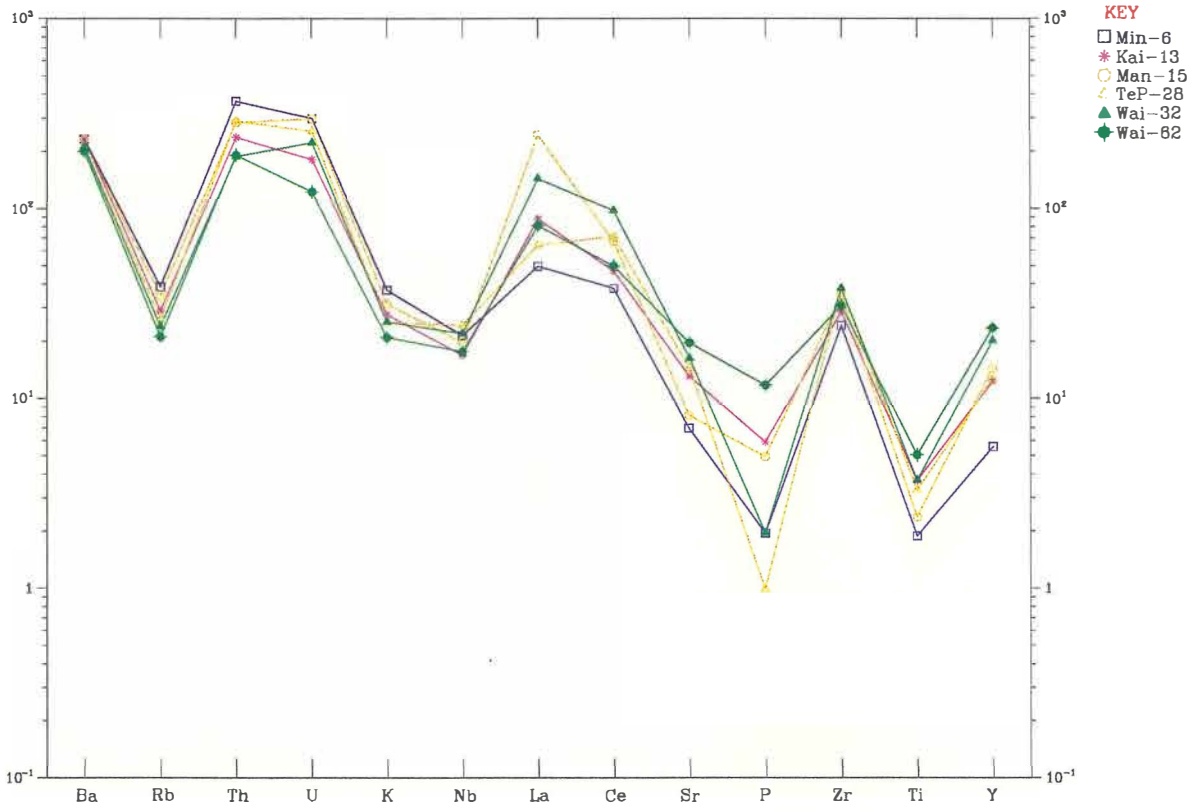


Fig 4.7b Spider diagram of trace element concentrations normalised to chrondrite for selected Western Tauranga rocks. Values for chrondrite are after Taylor and McLennan (1985).

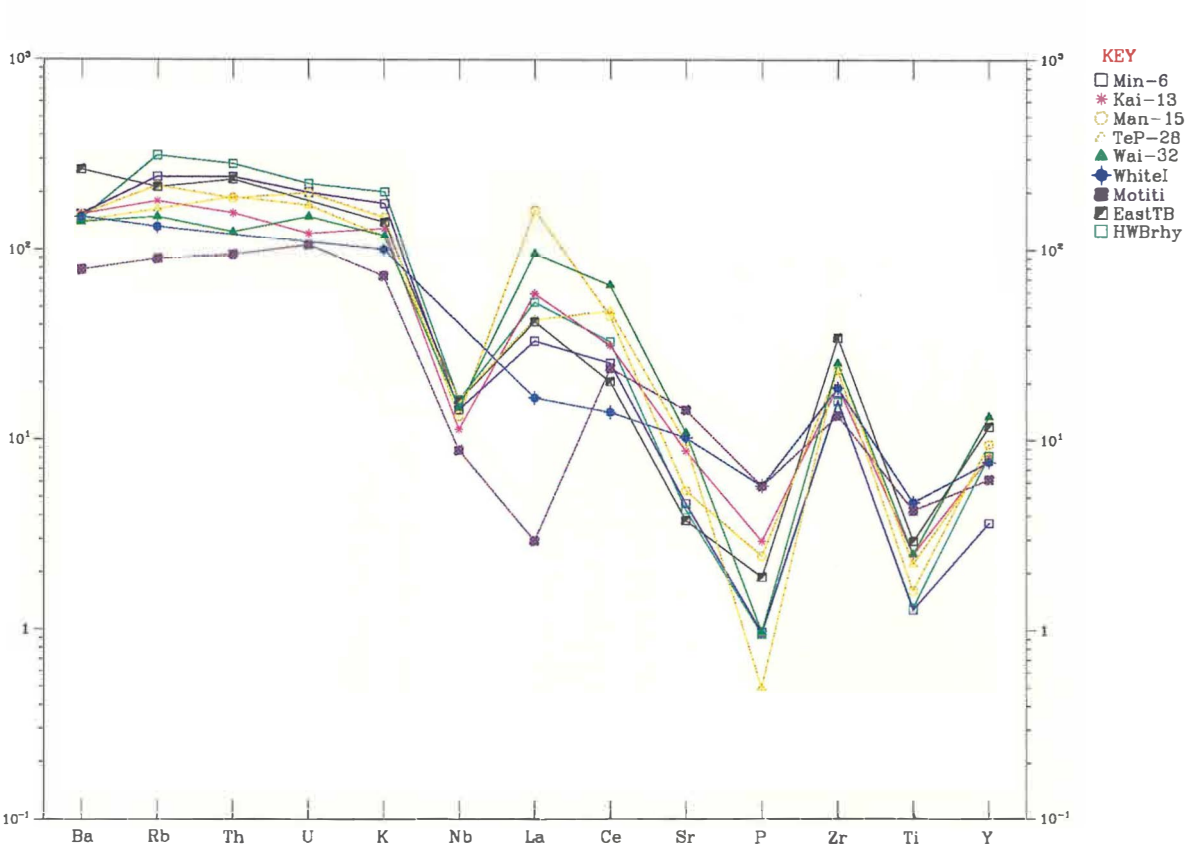


Fig 4.7c Western Tauranga rocks compared to White Island (Graham & Cole 1989), Motiti Island (Henry 1991), Coromandel (HWB) (Adams 1992), and Eastern Tauranga basin (EastTB) (Hughes 1993), normalised to primative mantle using values of Taylor & McLennan (1985).

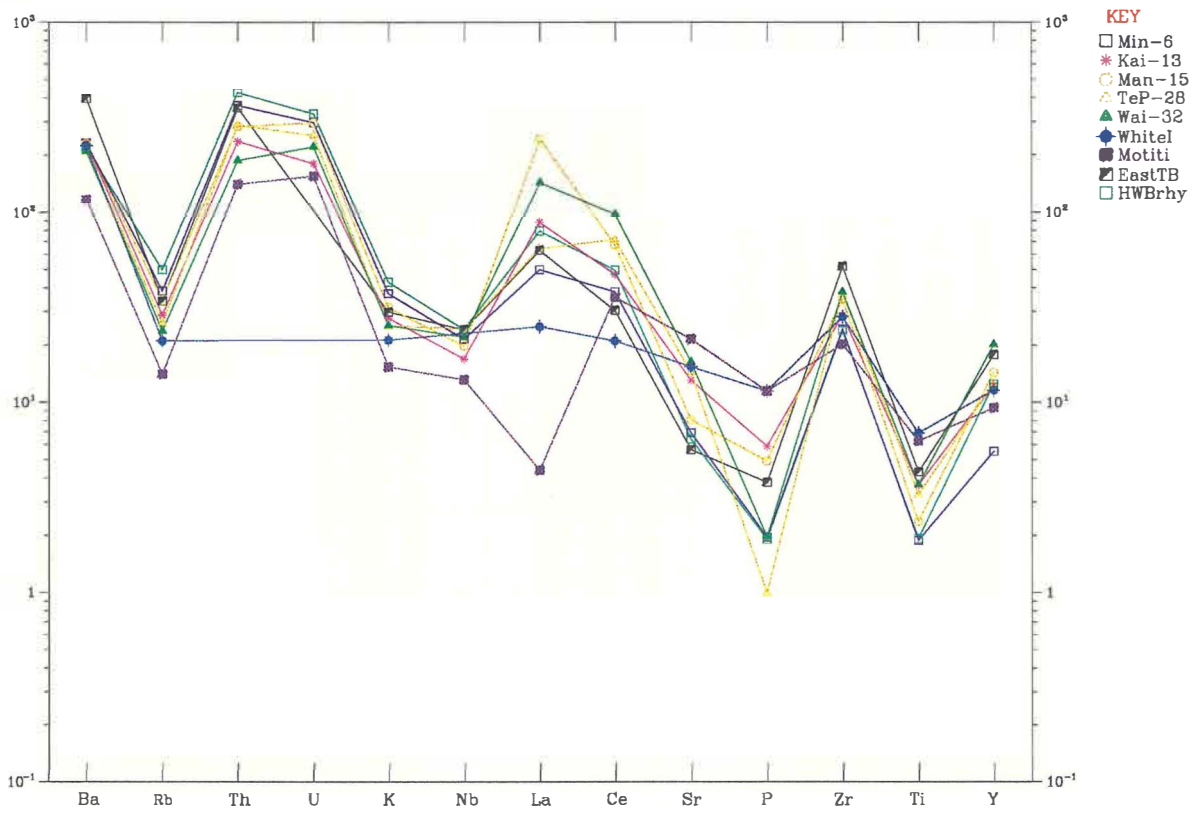


Fig 4.7d Western Tauranga basin rocks compared with White Island (Graham & Cole 1989), Motiti Island (Henry 1991), Coromandel (HWBrhy) (Adams 1992), and Eastern Tauranga basin (EastTB) (Hughes 1993) normalised to chrondrite values of Taylor and McLennan (1985).

diagram are less incompatible and therefore are depleted during partial melting.

The large abundance of Zr is a characteristic, and expressed in the petrography of the rocks by the ubiquitous presence of zircon as an accessary mineral. This is also a feature of rocks in other areas, for example the Tauranga basin (Hughes 1993) and CVZ (Adams 1992) and TVZ rocks.

The depletion of Nb and Ti in both the primitive and chondrite normalised spider diagrams (Fig 4.7 a,b) is characteristic of subducted rocks. Rocks at convergent plate boundaries have lower TiO2 contents than in volcanic rocks from intra-plate localities. This depletion of arc magmas in all the Ti-group elements is used to distinguish arc-derived rocks (Gill 1981).Samples form Western Tauranga basin are compared to Coromandel (Adams 1992), Eastern Tauranga basin (Hughes 1993), Motiti Island (Henry 1991) and White Island (Graham and Cole 1989) using primitive mantle and chondrite normalised trace element plots (Fig 4.7 c,d).

Motiti and White Island show different patterns to the other samples. This may be due to them being andesitic in composition compared to the more rhyolitic nature of the other rocks. Motiti Island has a depletion in La whereas the other rocks have a higher value.

Coromandel (HWB rhy) has higher incompatible elements and lower amounts of lesser incompatible elements. This may suggest that more partial melting or fractionation has occurred in these rocks.
Rhyolites from eastern Tauranga basin (East TB) plot with similar patterns to the rhyolites from within the field area. These same patterns may indicate that the rocks originated from the same magmatic source.

4.6 Fe-Ti Geothermometry

The temperature and oxygen fugacity of equilibrium between coexisting magnetite-ulvospinel (spinel phase) and ilmenite-haematite solid solution (rhombohedral phase) can be obtained from the compositions of the two phases. The Computer program of Stormer (1983) was used to calculate possible temperatures of the rocks within the western Tauranga area. The program uses the model of Spencer and Lindsley (1981) and calculates the mole

fractions of ilmenite and ulvospinel using the Anderson (1968), Carmichael (1967), Lindsley and Spencer (1982), and Stormer (1983) schemes.

Temperatures of the western Tauranga basin rocks can be seen in Table 4.3. The rhyolites vary in temperature from 795-839°C. Other rhyolites within New Zealand which also contain plagioclase, quartz, hornblende, biotite and hypersthene have temperatures of 720-765°C. Their lower temperatures of crystallisation may be due to a slightly higher water content (Ewart 1979). Waiteariki Ignimbrite (805°C) and Te Puna Ignimbrite (765-780°C) have similar crystallisation temperatures to other plagioclase, quartz, hornblende and hypersthene rocks in New Zealand and Japan (Ewart 1979).

Table 4.3 Temperatures of Western Tauranga basin rocks (after Stormer 1983.

Sample	Model			
	Stormer	Anderson	Carmichael	Lindsley
	T °C	T °C	T °C	T °C
Minden Rhyolite	795	791	815	785
Kaikaikaroro Rhyolite	838	835	838	829
	839	836	839	830
Manawata Rhyolite	809	803	809	796
Waiteariki Ignimbrite	805	810	799	797
Te Puna Ignimbrite	765	770	770	761
	780	784	801	774

Chapter Five

Te Puna Ignimbrite

Chapter Five
Te Puna Ignimbrite

5.1 Introduction

The Te Puna Ignimbrite was first described by Harmsworth (1983) as a nonwelded to partially welded buff brown ignimbrite containing white to grey pumice. His work concentrated on the stratigraphy of this unit, and no work was undertaken on the geochemistry. This chapter examines in more detail the geochemistry of the Te Puna Ignimbrite.

5.2 Distribution

The Te Puna Ignimbrite is exposed at Clarke Road, Omokoroa Point, Pahoia Point, Motuhoa Island and Matakana Island. It varies in thickness from >17m at Clarke Road to 2 m at Omokoroa Point. The variation in thickness is due to the nature of the undulating pre-existing topography and suggests a low energy flow. The Te Puna Ignimbrite stratigraphically overlies lignite and underlies the Pahoia Tephras.

5.3 Mineralogy

The Te Puna Ignimbrite is a buff brown nonwelded to partially welded ignimbrite containing white to grey pumice within a crystal-rich (27%) matrix. Plagioclase phenocrysts are euhedral to subhedral and are andesine in composition with normal zoning (An 32-37). Hypersthene is subhedral and constitutes up to 0.4% of the rock. Amphiboles are calcic and occur as magnesio hornblende. The subhedral grains show 120/60° cleavage in cross section and are pleochroic from dark green to brown. Quartz is subhedral to anhedral and constitutes 2.8% of the rock. Fe-Ti oxides occur as titanomagnetite and ilmenite. Ilmenite contains occasional inclusions of apatite and marcasite.

Lithic abundance within the ignimbrite is low (1-2%) and consist of spherulitic grey, red, and green rhyolites, the basal flow unit of the Waiteariki Ignimbrite,

obsidian and charcoal. The red and grey rhyolite lithics have the same mineralogy as the rhyolite domes within the field area. Any of these domes may have been the source of the lithics.

5.4 Stratigraphic Section

A measured stratigraphic section (Fig 5.1) was selected at Clarke Road (U14 828859) on the basis of suitable vertical exposure and where the pumice was as fresh as possible for geochemical analysis.

The base of the Te Puna Ignimbrite at this location is not seen indicating that the ignimbrite is > 17 m. The ignimbrite is buff brown to light grey brown and contains white and grey vesicular pumice which has visible phenocrysts of quartz, plagioclase and hornblende. Pumice abundance varies form 20 % at the base , to 12 % at the top of the unit. Flattening ratios of the pumice are also greatest at the base of the unit.

Lithics within the section vary from 1-2 % and consist of obsidian, grey rhyolite, red brown rhyolite, black rhyolite, green-grey rhyolite, and orange hornblende dacite.

The top of Te Puna Ignimbrite is deeply eroded and overlain by 3.8 m of colluvium, tephras and Maori middens.

5.5 Geochemistry

Samples of pumice at 1 m intervals were taken from the stratigraphic section on Clarke Road, except where samples were inaccessible between 10-15m. These samples were analysed using XRF at Victoria University. Major and trace element geochemical data of the representative pumice samples in the Te Puna Ignimbrite are presented in Table 5.1.

Plots of geochemical data versus SiO2 in Figs 5.2 and 5.3 and geochemical data versus height are shown in Figs 5.4 and 5.5.

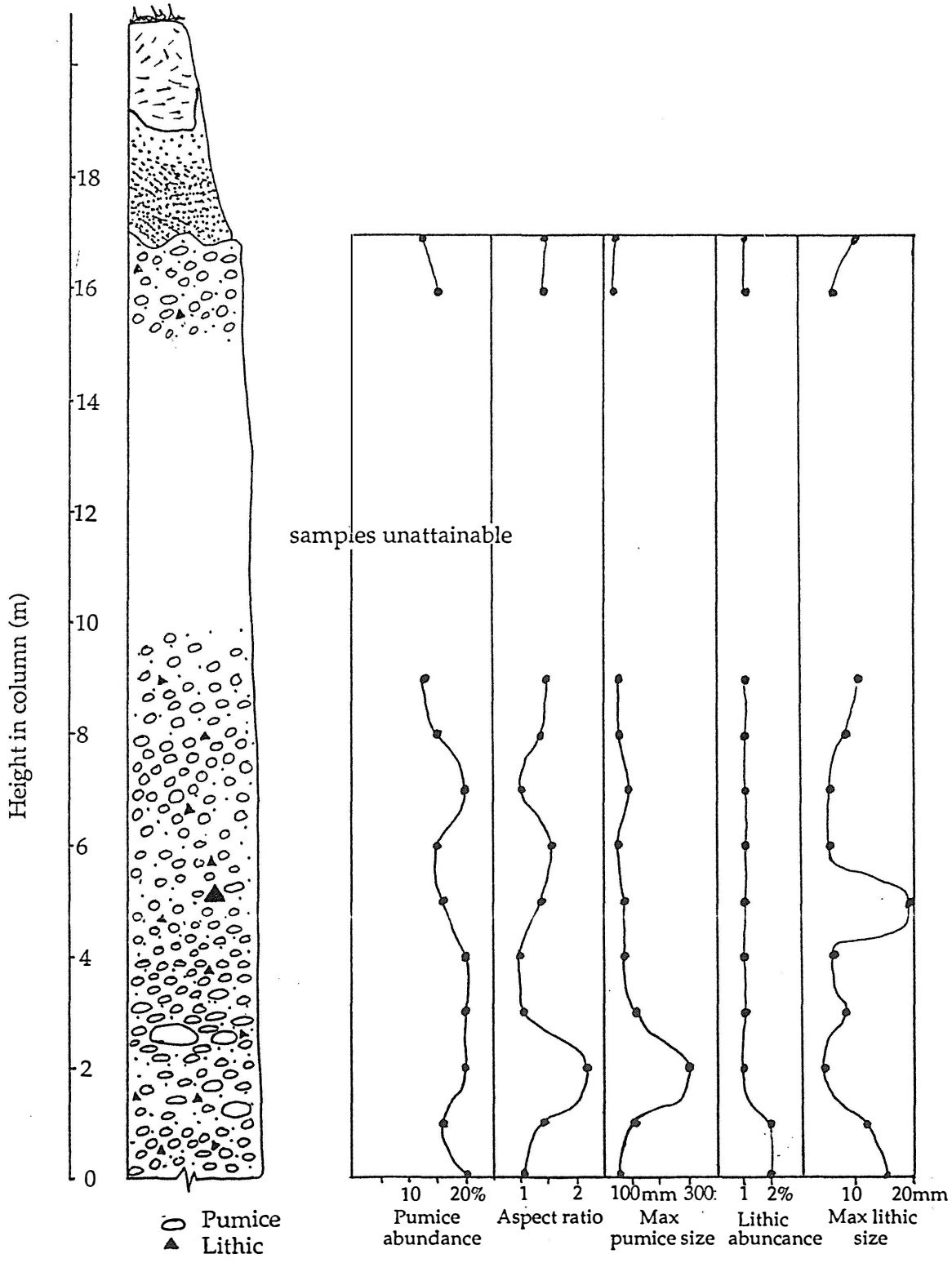


Fig 5.1 Stratigraphic Section of Te Puna Ignimbrite showing pumice and lithic abundances, Clarke Road (U14 828859)

Table 5.1 Major (wt%) and trace element (ppm) XRF compositions of pumices in the Te Puna Ignimbrite.

Sample	82	83	84	85	86	87	88	89	90	91
Height(m)	0.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	9.0	16.0
SiO2	73.87	75.67	75.09	73.51	75.17	74.41	73.96	73.52	72.58	73.13
TiO2	0.26	0.19	0.20	0.31	0.24	0.27	0.30	0.27	0.24	0.25
Al2O3	14.31	13.58	13.83	14.23	13.60	14.07	14.05	14.53	16.10	15.92
Fe2O3	0.44	0.35	0.38	0.53	0.39	0.46	0.51	0.47	0.44	0.47
FeO	1.59	1.25	1.35	1.92	1.4	1.65	1.85	1.68	1.60	1.69
MnO	0.07	0.06	0.06	0.08	0.05	0.06	0.16	0.08	0.09	0.12
MgO	0.33	0.25	0.30	0.43	0.35	0.39	0.41	0.38	0.29	0.32
CaO	2.00	1.55	1.68	1.96	1.60	1.66	1.77	2.02	1.88	1.55
Na2O	3.55	2.92	3.04	3.46	3.57	3.24	3.30	3.55	3.46	3.28
K2O	3.54	4.18	4.06	3.57	3.62	3.78	3.67	3.50	3.31	3.26
P2O5	0.02	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.01
LOI#	3.18	3.57	3.66	3.47	2.93	3.35	3.70	3.08	4.41	4.24
Total	100	100	100	100	100	100	100	100	100	100
Sc	5	4	5	6	4	5	8	7	6	6
V	18	12	13	21	14	17	23	17	17	15
Cr	2	2	3	4	2	2	4	3	3	3
Ni	1	2	2	1	2	2	2	2	2	3
Cu	2	3	3	3	3	3	4	4	4	4
Zn	46	40	40	52	42	48	54	46	45	46
Ga	14	13	15	15	14	16	15	15	17	16
As	5	5	4	5	5	5	5	5	4	5
Rb	113	132	129	113	122	126	116	110	106	113
Sr	145	111	120	139	115	118	122	145	132	106
Y	25	23	24	25	23	27	40	27	31	34
Zr	174	133	140	209	167	177	209	190	174	173
Nb	8	8	7	8	8	8	10	9	8	9
Ba	744	793	771	756	739	652	890	777	787	790
La	23	25	24	25	27	22	55	30	33	36
Ce	49	49	47	50	43	48	94	54	64	75
Pb	14	14	14	14	18	18	21	15	19	20
Th	11	13	14	12	13	12	12	10	13	16
U	2	3	4	3	3	3	3	3	3	3

#Original values

5.5.1 Pumice geochemistry

The chemistry of the pumice ranges from low to high silica rhyolite (72.6-75.7% SiO_2) which may indicate a zonation in the magma chamber due to the large range in the SiO2 content.

Positive correlation of incompatible elements and negative correlation of compatible elements indicates that differentiation has occurred (Gill 1991). Positive correlation for Al2O3 and CaO may signify plagioclase fractionation.

A positive correlation for K2O implies that it behaves as an incompatible element, resulting in higher concentrations in more siliceous rocks. This is consistent with the petrography as there is no biotite or major K-bearing phase.

A negative Fe2O3 correlation and a slightly negative correlation for TiO2 could reflect the fractionation of titanomagnetite and ilmenite.

Sc and V show negative correlation indicating these elements are compatible. Compatible elements are preferentially incorporated into crystallising solid phases and therefore their abundance reduces with increasing SiO2 content. These elements tend to be concentrated in ferromagnesian minerals, rather than in the co-existing melt. The ferromagnesian minerals within the Te Puna Ignimbrite are hornblende and hypersthene.

Sr has a slightly negative correlation, which is a similar trend to CaO, which is probably due to the fractionation of plagioclase.

Rb has a positive correlation indicating that it is an incompatible element and it is not significantly incorporated into any of the phenocrysts in the Te Puna pumice. This results in an increase in element content with increasing SiO2.

Zr has a slightly negative correlation which is due to the crystallisation of zircon which is an accessory mineral. As differentiation occurs the concentration of Zr left in the melt reduces.

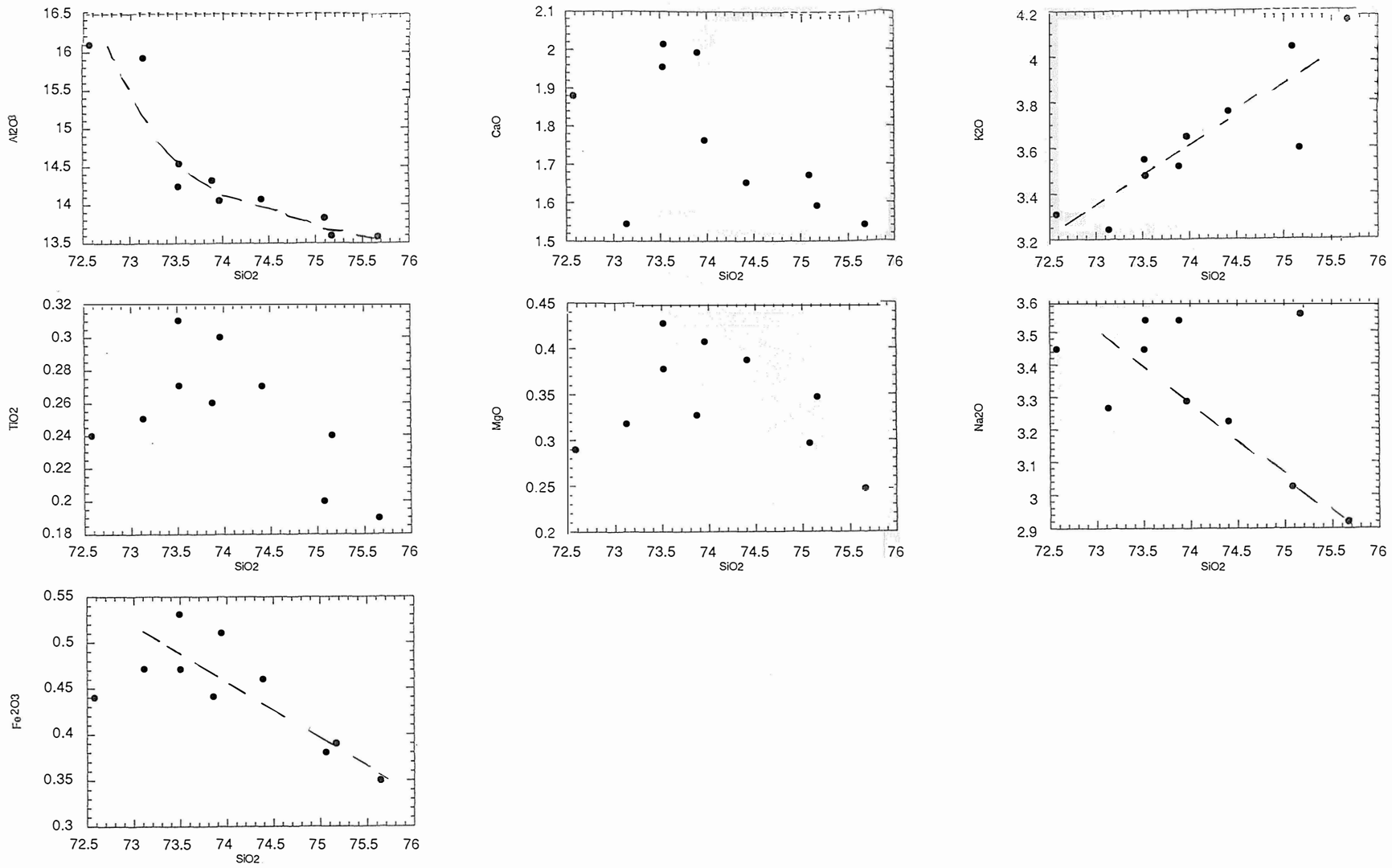


Fig 5.2 Major element concentrations (wt%) of Te Puna pumice plotted against SiO2 content.

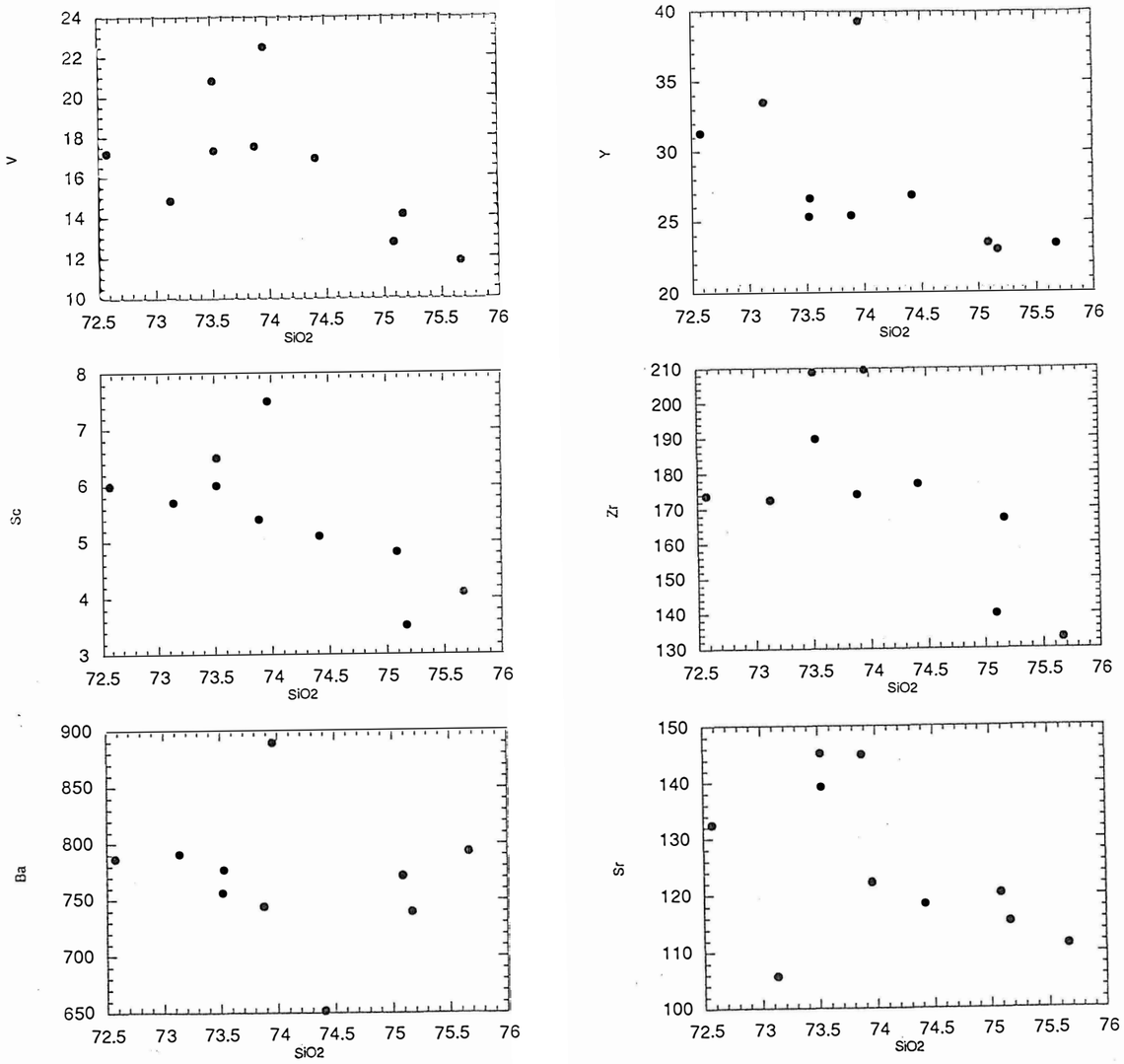


Fig 5.3 Trace element concentrations (ppm) of Te Puna pumice plotted against SiO2 content.

5.5.2 Pumice geochemistry related to stratigraphic height

When examining the chemistry of the pumices in relation with their stratigraphic height there are a number of correlations both for major and minor elements. These correlations may be due to a zoned magma chamber.

In the major elements SiO2 and K2O decrease with an increase in height, while Fe2O3 increases with an increase in height. Trace elements which increase with height are Cu, La, Nb, Ga, Ce and Y, while Rb decreases with stratigraphic height.
Samples at 0.0m and 16.0m are commonly inconsistent with the trends. This may be due to mixing of the magma as they tend to plot away from the trend in the major element vs SiO2 plots.

The sample at 6.0m has anomalously high abundances of Y (40 ppm), Ce (94 ppm), and La (55 ppm), however it's Al2O3 content is normal. Weathering or vapour-phase alteration may have caused the high abundances of the elements even though the samples look petrographically fresh. Black et al. (1992) found that samples which had anomalously high abundances of REE and Y, which petrographically looked fresh, contained secondary minerals when observed using the SEM backscattered election imagery.

Theory number 1 - *crystal settling in a non-convecting magma chamber*

A liquid magma chamber cools with heat loss being greater towards the top of the chamber. This results in more crystallisation occurring at the top than elsewhere, so that the residual liquid composition must take on a vertical zonation. The more evolved liquid lying at the top of the chamber and the less evolved below. This results in the existence of a vertical temperature gradient in the chamber which produces higher temperature (more basic) crystals at lower levels than exist at the same time at higher levels (Cox et al. 1979).

Theory number 2- *Convection and mixing in magma chamber*

Magma chambers are multi component systems which are controlled by the size and shape of the chamber, the density and viscosity of the magma and by processes which operate at the boundaries of the chamber(Wilson 1989).

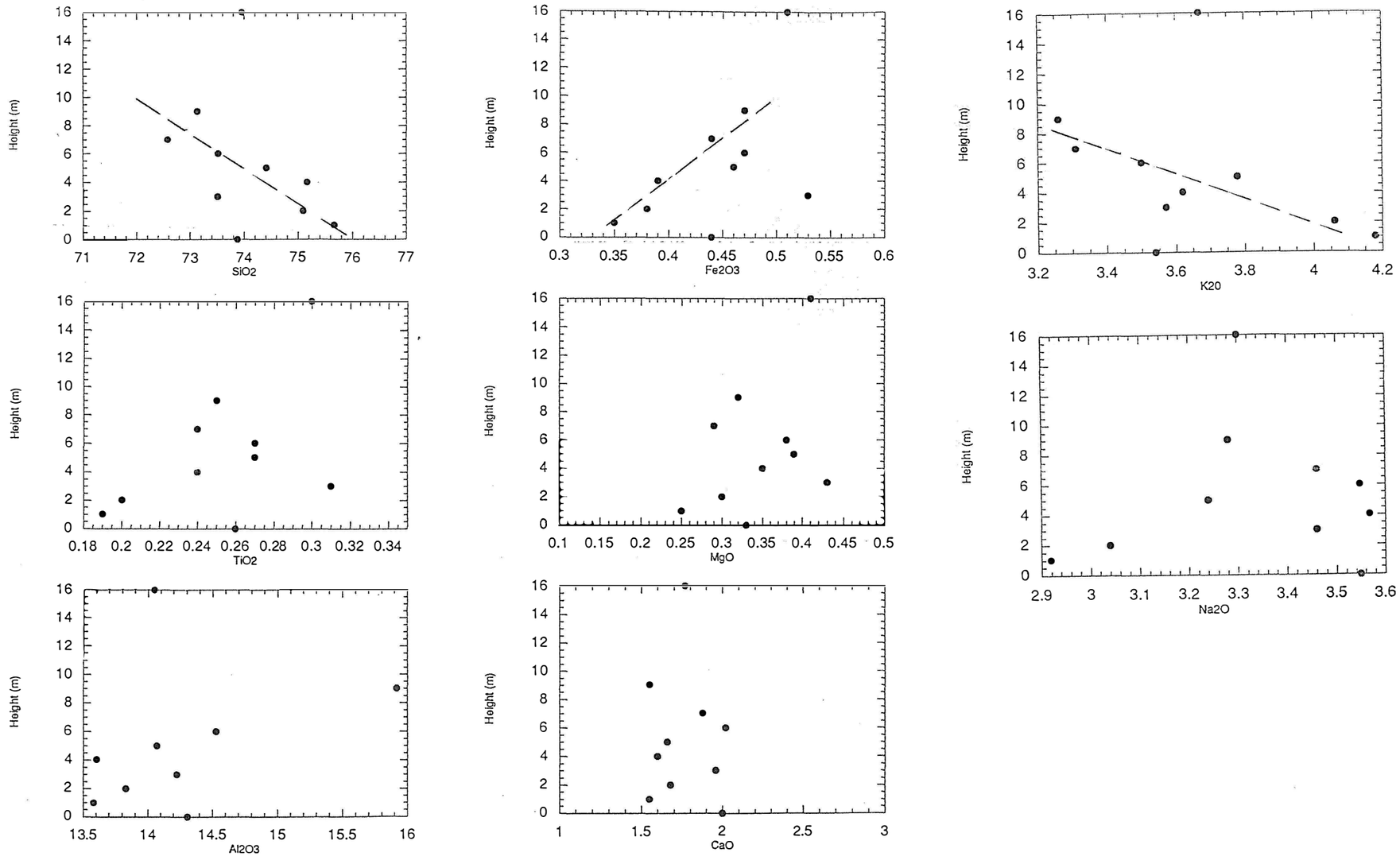


Fig 5.4 Major element concentrations of Te Puna pumice plotted against stratigraphic height. Major elements in wt %.

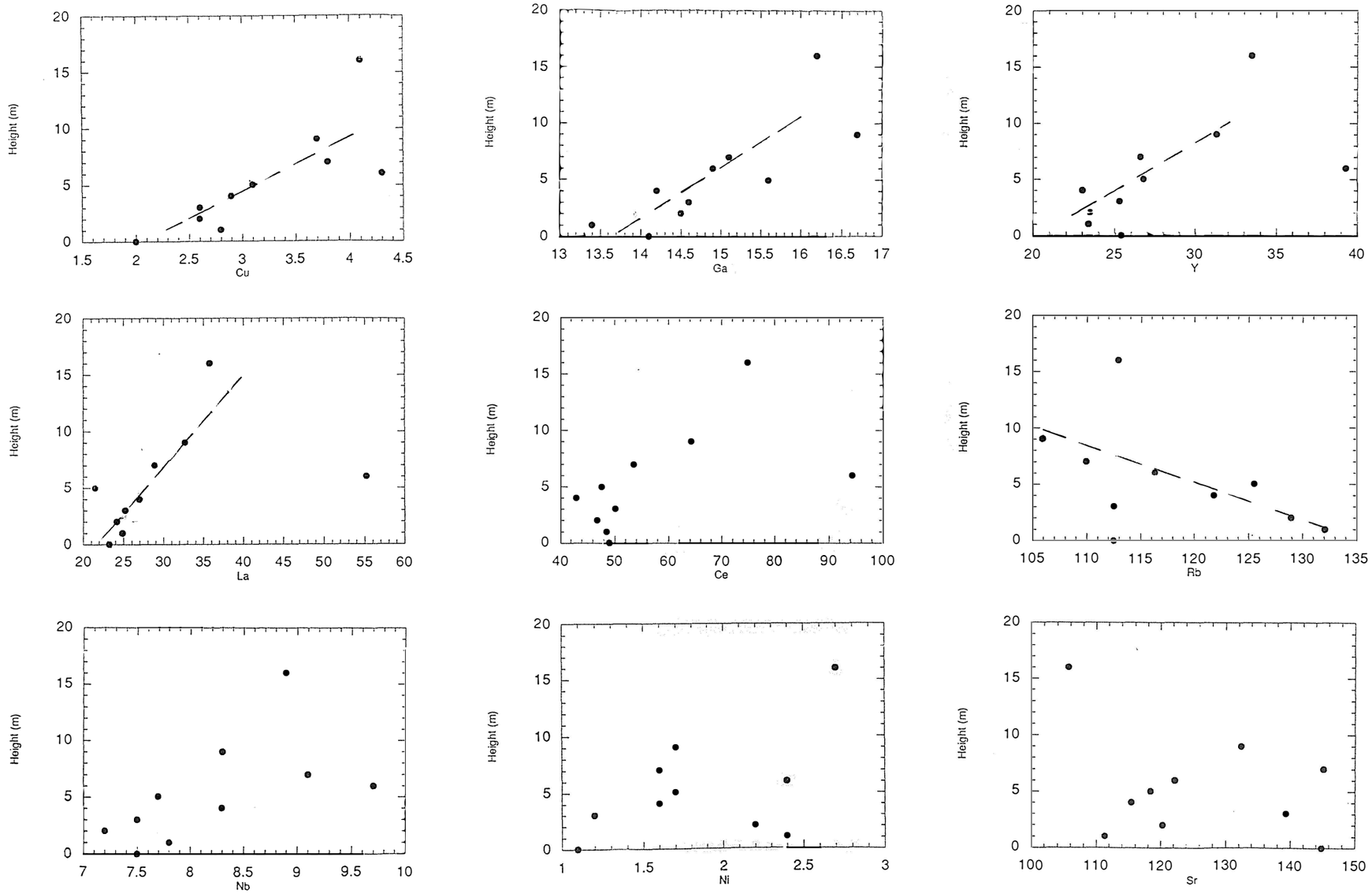


Fig 5.5 Selected trace element concentrations (ppm) of Te Puna pumice plotted against stratigraphic height.

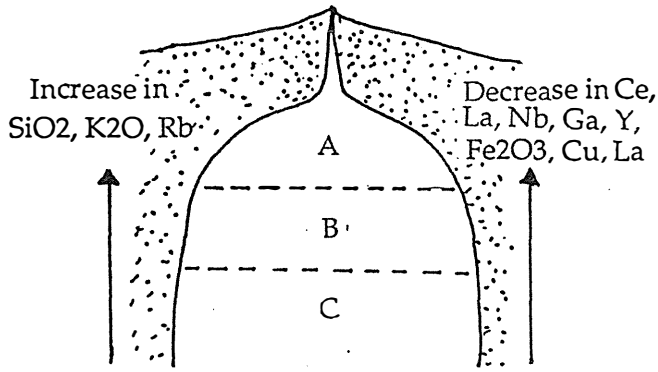
When crystallisation occurs in a magma the fluid next to the growing crystals may become either enriched or depleted in heavy components, depending upon the minerals crystallising. The density of this layer will therefore be different from that of the main chamber magma. As a result, the liquid will convect away from the crystal faces. Fluids may become vertically stratified with respect to density, composition and temperature (Wilson 1989).

5.6 Inversion of the Magma Chamber

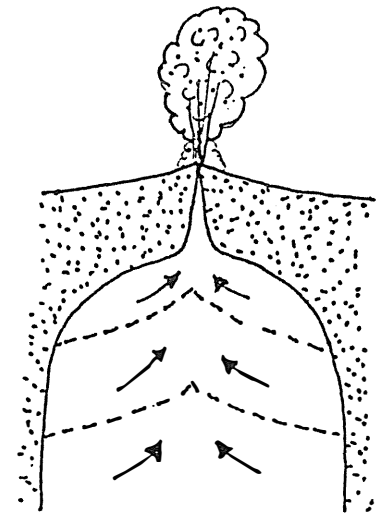
Upon eruption the magma chamber may be inverted within the ignimbrite (Fig 5.6). In the magma chamber where SiO2 increases near the top it increases towards the base of the ignimbrite. This occurs as magma is withdrawn from the top of the magma chamber first. However during the eruption the zoned magma chamber may be disrupted and mixing of the layers may occur.

Blake and Ivey (1986) through modelling found that the liquid being sampled from a draining reservoir of density-stratified fluid, such as an erupting zoned magma chamber, is derived from a relatively thin withdrawal layer adjacent to the level of the chamber outlet. This is a consequence of the buoyancy force associated with the density gradient inhibiting vertical motion so that the opportunity for widely separate density levels to be tapped and mingled syneruptively is suppressed. If the caldera collapse distance is much greater than the withdrawal layer then the selective withdrawal process leads to successive levels of the chamber being skimmed. This allows the compositional stratigraphy of the chamber to be inverted by the eruptive processes, with little opportunity for syneruptive mixing between diverse magma compositions.

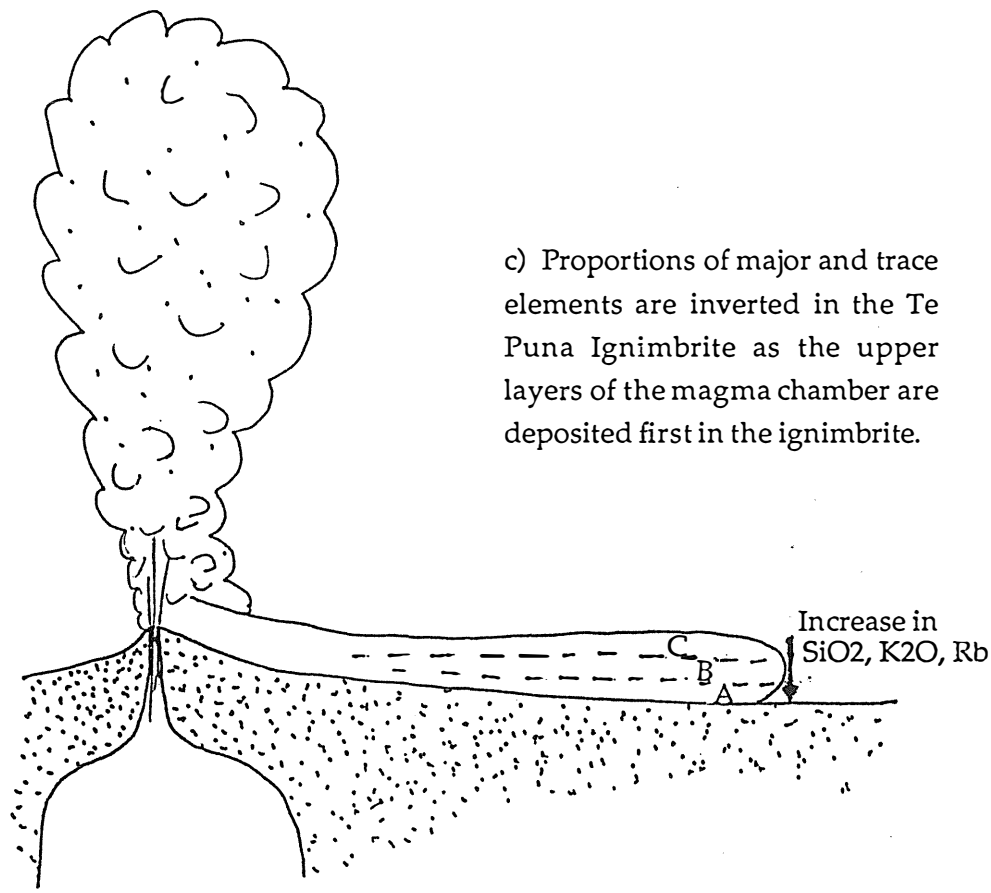
The sample at 0.0m has a lower SiO2 content than the expected trend. This may be due to an injection of material into the magma chamber which has caused less SiO2 rich magma to be erupted first. The sample at 16.0m also does not follow the trend. This layer may have been at the end of the eruption where the magma within the magma chamber has become highly disrupted and more SiO2 magma than expected is erupted.



a) Zonation of the major and trace elements within the magma chamber



b) Upon eruption, magma is tapped from the top layers and progressively taken from greater depths.



c) Proportions of major and trace elements are inverted in the Te Puna Ignimbrite as the upper layers of the magma chamber are deposited first in the ignimbrite.

Fig 5.2 Invertion of a zoned magma chamber within the erupted Te Puna Ignimbrite.

5.7 Previous studies into zoned magma chambers

Zonation in magma chambers, particularly from acidic ignimbrites have been described by Smith and Bailey (1965) in the Bandelier Tuff, Lipman (1967) from the Aso caldera, Schuraytz et al. (1989) in the Topopah Spring Tuff in southwest Nevada, and Vogel et al. (1989) in the Black Mountain Volcanic Centre.

Within New Zealand very few ignimbrites derived from zoned magma chambers have been identified. Ewart (1965) found that in the Whakamaru ignimbrite there was a reversal of the magma chamber in the two ignimbrite sheets, with mineral abundances and elemental abundances altering with height.

Blake et al. (1992) suggests a three-layered stratified chamber from andesite at the base to rhyodacite to rhyolite at the top as the source of the Waimihi eruption from Taupo. The zonation occurred due to the injection of andesite into a rhyolite chamber and mixing to form a rhyodacite layer. The eruption tapped the magma chamber which preferentially withdrew the layers of lowest density. The extent to which the dense layers are tapped being governed by the thickness of overlying layers and the withdrawal rate. A chamber with a thin cap and high discharge rate favoured the lower layers being tapped.

Briggs et al. (1993) investigated the mineralogy, geochemistry and isotopic composition of the pumice clasts in ignimbrites from the Mangakino volcanic centre. They found that the magma chamber was originally zoned, shown by trends in major and trace elements, but the zonation was disrupted during eruption of the ignimbrites when mixing occur.

5.8 Discussion

The Te Puna Ignimbrite is one of only a few known ignimbrites which have originated from a zoned magma chamber in New Zealand in which the magma erupted by simple inversion of the magma chamber from the top down. The major and trace element chemistry show zonation as their abundances vary with stratigraphic height. The ignimbrite represents a simple inversion of the magma chamber as mixing does not occur to any large extent.

Chapter Six

Summary

Chapter Six

Conclusions

The Western Tauranga basin is an area which is bounded to the west by the Kaimai Range and to the south by the Whakamarama Plateau which dips into the basin. The major features within the area are three rhyolitic domes. These domes are surrounded and lapped on to by the Waitearíki Ignimbrite which becomes progressively eroded in a northerly direction. To the north, peninsulas extend out into the Tauranga Harbour which contain the Te Puna Ignimbrite, volcanic fluvial material from the Matua subgroup, which are overlain by the Pahoia tephras, Hamilton Ash and tephras from the Taupo Volcanic Zone.

The oldest unit consists of three rhyolite domes which are aligned in a north-northeasterly direction which suggests that their alignment may be fault controlled. The rhyolites, Minden Peak, Manawata and Kaikaikaroro and form complexes of domes and lavas.

Minden Peak Rhyolite contains plagioclase (within the andesine range), quartz, calcic amphibole (magnesio hornblende), orthopyroxene (hypersthene and ferrohypersthene), biotite, titanomagnetite, ilmenite and zircon. Kaikaikaroro Rhyolite consists of andesine, quartz, tschermakitic hornblende, biotite, hypersthene and ferrohypersthene, titanomagnetite, ilmenite and zircon. Manawata Rhyolite contains andesine, quartz, tschermakitic hornblende, hypersthene, biotite, titanomagnetite, ilmenite and zircon.

Minden Peak and Manawata rhyolite are similar in chemical composition with Kaikaikaroro contains higher amounts of Fe2O3*, CaO, MgO, TiO2 and lower SiO2.

Waitearíki Ignimbrite is younger than the rhyolites and has a fission track age of 0.84 ± 0.11 Ma (Kohn 1973). The Waitearíki Ignimbrite forms the dipping Whakamarama plateau and surrounds and laps onto the rhyolite domes. The ignimbrite is crystal-rich (30%) and is divided into three flow units which have different degrees of welding. Within the field area the lower flow unit of the Waitearíki Ignimbrite is light grey-brown with 20% lenticular cream pumice. Flow unit two is densely welded and contains black lenticular pumice. It contains crystals of plagioclase (varying from oligoclase to labradorite), quartz,

orthopyroxene (hypersthene and ferrohypersthene), calcic amphibole (magnesio hornblende and tschermakitic hornblende), biotite, zircon, titanomagnetite and ilmenite.
Samples from the two different flow units from within the Waitearíki Ignimbrite vary in geochemistry. The lower sample stratigraphically, is higher in SiO2 content (70.1%) than the younger flow unit with 67.5% SiO2. This may indicate that the magma chamber was zoned and that inversion of the magma chamber occurred on eruption resulting in a more rhyolitic flow overlain by a dacitic flow.

The Matua Subgroup overlies the Waitearíki Ignimbrite and contains lignite and fluvial sediments. The fluvial sediments are predominantly volcanic in origin and comprise of pumice and ash.

The Te Puna Ignimbrite is a nonwelded to partially welded buff brown ignimbrite. It contains 15-20% white to grey pumice in a crystal-rich (27%) matrix. The ignimbrite was deposited into a swamp or estuarine environment as it overlies fluvial material and lignite from the Matua subgroup. The crystals within the ignimbrite are plagioclase (An 30-39.5), quartz, hypersthene, calcic amphibole (magnesio hornblende), titanomagnetite, ilmenite and zircon.

Pumices from within the Te Puna Ignimbrite have different SiO2 contents (72.58-75.67%), which vary stratigraphically, tending to decrease with stratigraphic height. This indicates that the magma chamber was zoned and therefore varied in SiO2 composition with more silicous magma near the top of the chamber. Upon eruption magma was withdrawn from the top of the magma chamber and inverted in to the ignimbrite. This resulted in more SiO2 rich pumice at the base of the stratigraphic column, compared to the top.

The rocks within the western Tauranga basin are calc-alkaline in composition except for the middle flow unit in the Waitearíki Ignimbrite which is tholeiitic. The rocks distribution on the AFM diagram (Irvine and Baragar, 1971) plot in a similar manner to rocks from Coromandel and eastern Tauranga basin, this shows that the rocks have similar amounts of iron and MgO. On chondrite and primitive mantle normalised spiderdiagrams, the rocks from western Tauranga basin have similar incompatible trace element contents to those of eastern Tauranga rocks, but higher incompatible trace elements contents than the Coromandel rocks. This suggests that the eastern and western Tauranga basin rocks are likely to have formed from the same processes. Their similar

proportion of incompatible elements are likely to be due to similar amounts of differentiation of the magma or partial melting of the crust.

6.1 Tectonic Setting

New Zealand is an active continental margin where oceanic crust (Pacific Plate) is subducted beneath continental crust (Australian Plate). As the subducted plate melts, magma rises which may cause partial melting of the continental crust. This causes continental margin magmas to be more silica-rich than those in island arcs (which contain no continental crust). In any destructive plate margin environment the nature and distribution of magmatic activity in the overriding plate is directly linked to the geometry of the subducted slab, which is a function of the convergence rate of the lithospheric plates and the age of the subducted lithosphere (Wilson 1989).

Within the North Island the present volcanic arc is expressed in the Taupo Volcanic Zone which extends from Mt Ruaephu to White Island. This volcanic arc is thought to have migrated with time as the ages of the rocks tend to become younger from Whangarei to Taupo (Kear 1959, Brothers 1984, Ballance 1986). Migration of the volcanic front in the North Island is suggest to be the result of plate rotation and migration southward and south westward in the last 25 Ma. With an increase in plate motion the direction of the volcanic front has become more easterly with time (Kamp 1992).

Kear (1959) noted an apparent south-eastward migration of volcanism with time across the northern and central North Island based on K/Ar ages of rocks with low-K andesite character. Brothers (1984) using additional ages constructed time lines which represent the oldest dated rocks, and thus the initiation of volcanism at each volcanic centre throughout the northern North Island. This gave western Tauranga basin rocks an approximate age of 3 Ma. He proposed that the steepening of the subducting plate from the Miocene resulted in the migration of calc-alkaline volcanism from Tokatoka and Whangarei to Taupo in a NE-SW orientation.

Ballance (1976) and Ballance et al. (1982) define six spatially separated magmatic arcs since 20 Ma when the Australian-Pacific plate boundary spread through the North Island. Stern (1987) suggests that the movement of the active volcanic front is not just migrating at 20 mm/y but also a rotation of 30° has occurred over the last 4 Ma (Fig 6.1).

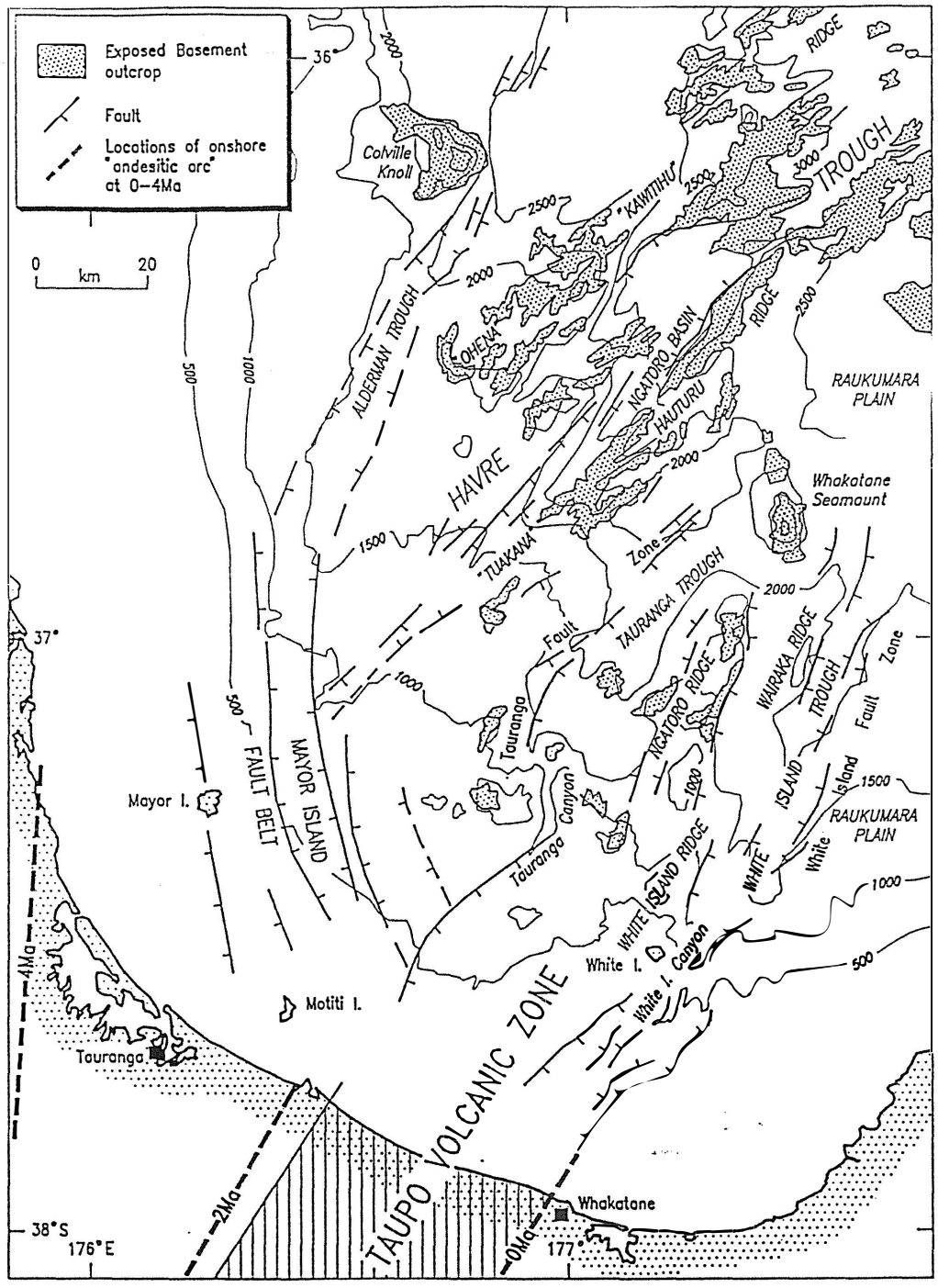


Fig 6.1 Synoptic bathymetry and structure of southern Havre Trough-Bay of Plenty (Wright et al.,1990). Location of onshore 'andesitic arc' since 4 Ma from Stern (1987).

Kamp (1984) used the K2O-h parameter of depth of magma generation together with age distribution of andesites to define the geometry of the subducting slab. However, using the K2O-h relationship may not be correct (Reynors 1990) as the K2O abundance in basalts and andesites is also controlled by other magmatic processes other than depth. These processes may be partial melting, crystal fractionation or crustal contamination.

Ballance et al. (1985) and Ballance (1988) challenged Brothers and Kamp's isochons as some of the ages used for isochons did not represent the initial eruptions from the areas. Also within the Coromandel Peninsula the dates may not be correct due to hydrothermal alteration which alters the age of the rock.

Karig (1970) suggested that the Tonga, Kermadec and Taupo arcs formed part of a single arc system and the arc continued directly into the North Island, into the Taupo Volcanic Zone. However, Cole (1978) considered that the arcs were separate and that the Havre Trough, an active intraoceanic back-arc basin, extended south-westward into the Ngatoro Basin intersecting the coast of New Zealand at Tauranga and not the Taupo Volcanic Zone (Fig 6.1).

Feden et al. (1976) suggests that the Havre Trough developed at about 5 Ma and this resulted in tensional graben structures and active marginal basins, initially on the eastern side of Coromandel, later (2-3Ma) forming the volcanism in the Tauranga area, and finally the Taupo Volcanic Zone.

In offshore Bay of Plenty, the basement structure is comprised of a series of parallel basement ridges and basins aligned in a NE-SW direction (Wright 1992) (Fig 6.1). Within the field area in the western Tauranga basin the alignment of the rhyolite domes is in a north-northeasterly direction. The domes alignment may be due to faulting in the basement rock which may represent an onshore continuation of the Ngatoro Basin.

Wright et al. (1990) found through a side-scan sonar survey in the Bay of Plenty, that the Havre Trough tectonism and volcanism relates to a series of laterally discontinuous, multiple spreading rifts which terminate southward at the 3 km deep Ngatoro Basin. A 45 km sinistral offset, attributed to en echelon synthetic shearing, separates the basin from the actively spreading Taupo Volcanic Zone. Before plate movement and rotation caused the en echelon synthetic shearing the volcanic front would have been centred in the Tauranga area. With plate movement and rotation the volcanic front would of migrated southward into the present day Taupo Volcanic Zone.

6.2 Comparison of the Tauranga basin to other Volcanic Zones

The Tauranga basin includes the western and eastern Tauranga basin which was studied by Hughes (1993). The Tauranga basin is cited between the Coromandel Volcanic Zone (CVZ) and the Taupo Volcanic Zone (TVZ) and may represent the migration of the volcanic front from north to south. The CVZ ranges in age from 18 Ma at its northern extent to 3 Ma to the south (Skinner 1986). Within this zone the ages of the rocks become progressive younger towards the south. The Tauranga basin has relatively few ages and some may be unreliable as fission track analyses were undertaken on volcanic glass. Volcanic glass may give incorrect ages if devitrification of the glass has occurred. The estimated age is between 2-4 Ma. Currently the Institute of Geological and Nuclear Science is dating rhyolites and ignimbrites from within the Tauranga basin and Kaimai Range by Ar/Ar dating, which will give a better age restraint on the zone. The TVZ is younger than the Tauranga basin with an age of < 1.6 Ma (Pringle 1992).

The mineralogy of the rhyolites varies within the three zones . Coromandel rhyolites (Adams 1992) contains plagioclase (oligoclase-labradorite), rare sanidine, calcic amphibole, hypersthene, augite, biotite, quartz and zircon. Western Tauranga rhyolites contain andesine, magnesio-hornblende, tschermakitic-hornblende, hypersthene-ferrohypersthene, biotite, quartz and zircon.
Rhyolites of the TVZ (Ewart 1979) contain plagioclase (labradorite to oligoclase), rare sanidine, hypersthene-ferrohypersthene, augite, cummingtonite, hornblende, biotite, quartz and zircon.

The CVZ and TVZ range is composition from basalt to rhyolite with numerous ignimbrites. Tauranga basin has andesite to rhyolite and numerous ignimbrites with basaltic andesite pumice found within the Papamoa Ignimbrite (Hughes 1993).

Within the three areas the trace element chemistry ratios of Ba/La, Ba/Nb, K/Rb and Rb/Sr show that the Tauranga basin dacites are in between the values for the CVZ and the TVZ (Table 6.1). This shows that the Tauranga basin has features of both zones which was also noted by Hughes (1993). The rhyolite ratios are generally within the range of both the CVZ and TVZ.

Table 6.2 Comparison of incompatible trace element ratios for the CVZ, Tauranga basin and TVZ after Hughes (1993). Data for CVZ adapted from Briggs and Fulton (1990), Eastern Tauranga Basin from Hughes (1993), and TVZ from Cole and Graham (1989), Reid and Cole (1983) and Ewart (1979). *=K/Ar ages from Skinner (1986), # = Ar/Ar ages from Pringle et al. (1992).

	Coromandel Volcanic Zone	Tauranga basin		Taupo Volcanic Zone
		Western Tauranga basin	Eastern Tauranga basin	
Age Range	3-18 My*		2-3 My*	0-1.6 My#
Dacites				
Ba/La	11-19	22	34-51	63-84
Ba/Nb	107-123	97	62-88	62-70
K/Rb	226-230	244	227-341	223-576
Rb/Sr	0.41-0.43	0.31	0.27-0.42	0.05-0.46
Rhyolites				
Ba/La	20-34	24-48	14-52	25-33
Ba/Nb	88-99	85-131	92-155	110-152
K/Rb	228-237	224-312	160-240	186-244
Rb/Sr	1.89-4.44	0.64-2.21	0.56-3.24	0.98-2.89

6.3 Caldera Identification

The Coromandel Volcanic Zone and the Taupo Volcanic Zone are dominated by silicic volcanism and contain several calderas. Within the Tauranga basin the presence of rhyolite domes and flows and ignimbrites suggest that caldera formation is likely to have occurred. Rhyolite calderas can be recognised by a number of features, including:

a Geophysically defined subcircular basement depressions indicated by gravity anomalies,

b Late-stage rhyolite domes and flows which lie within or at the margins of the caldera, forming intracaldera complexes or arcs of domes along ring fractures,

c Hydrothermal systems including epithermal mineral deposits,

d A variety of caldera-fill or moat deposits eg lake sediments, fluvial epiclastic sediments, caldera-collapse or post-collapse breccias,

e Circular or arcuate structures observed by remote sensing techniques

f Thick intracaldera ignimbrites and co-ignimbrite breccias, and thin outflow sheets (Cas and Wright 1987).

Hughes (1993) proposed a possible caldera which linked rhyolite domes, faults and hydrothermal systems in the eastern Tauranga basin.

6.4 Evidence for the Katikati Caldera

The western Tauranga basin shows no surface expressions of a caldera. Nevertheless, the Te Puna Ignimbrite which outcrops in the area is likely to be the result of caldera collapse, and there is some evidence for a caldera based on the above features.

Geophysical data from gravity maps of the Tauranga area (Woodward and Ferry 1973) show a large negative isostatic vertical gradient anomaly east of Katikati in the Tauranga Harbour (Fig 6.2), and isostatic and Bouguer anomaly maps show low values also east of Katikati. A negative anomaly can indicate a caldera as it gives a lower value than expected due to the low density nature of the pyroclastic material which infills the caldera. The anomaly is <-40 Eotvos which is the same value as over the Okataina, Reporoa and Mangakino calderas. This large negative anomaly may therefore be indicative of a caldera.

On Matakana Island there are very finely layered lake sediments, indicating that fine material settled out of still water as apposed to a stream or river. These sediments overlie the Te Puna Ignimbrite. The lake sediments may represent moat deposits within the caldera. These occur due to formation of the caldera, resulting in a depression, from which water can not drain and therefore a lake forms.

A dacitic dome occurs at U14 788952 just southwest off Matakana Island. This dome may represent a late-stage dacite dome which lies within or at the margins of the caldera.

The thin outflow sheet which is associated with the caldera may be the Te Puna Ignimbrite. At its thickest point it is >16m and 2m at its thinnest.

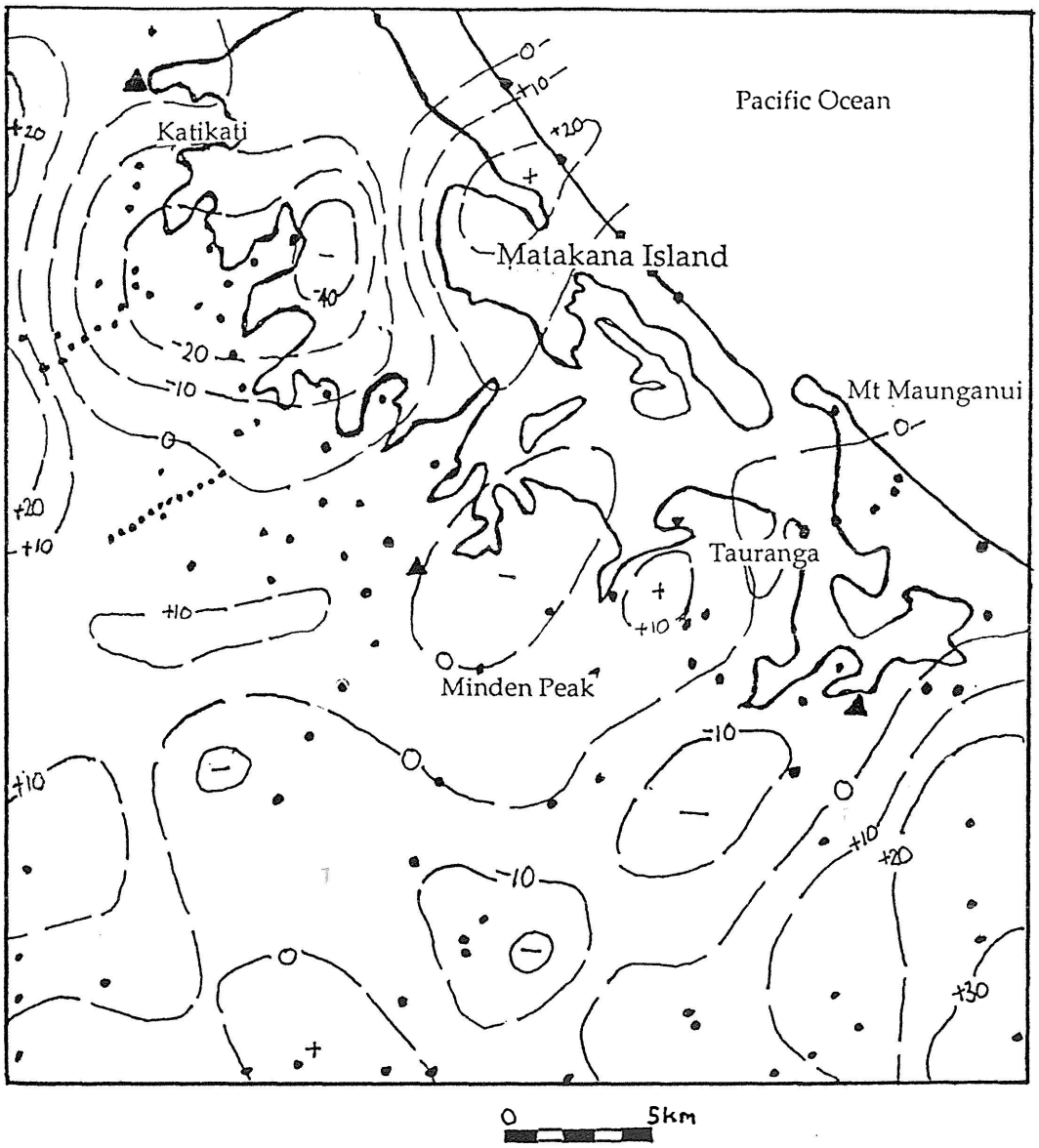


Fig 6.2 Isostatic vertical gradient anomalies in the Tauranga area, (after Woodward and Ferry 1973) units in Eotvos(10^{-9} N/kgm)

- Gravity station
- Gravity station of NZ Primary gravity network

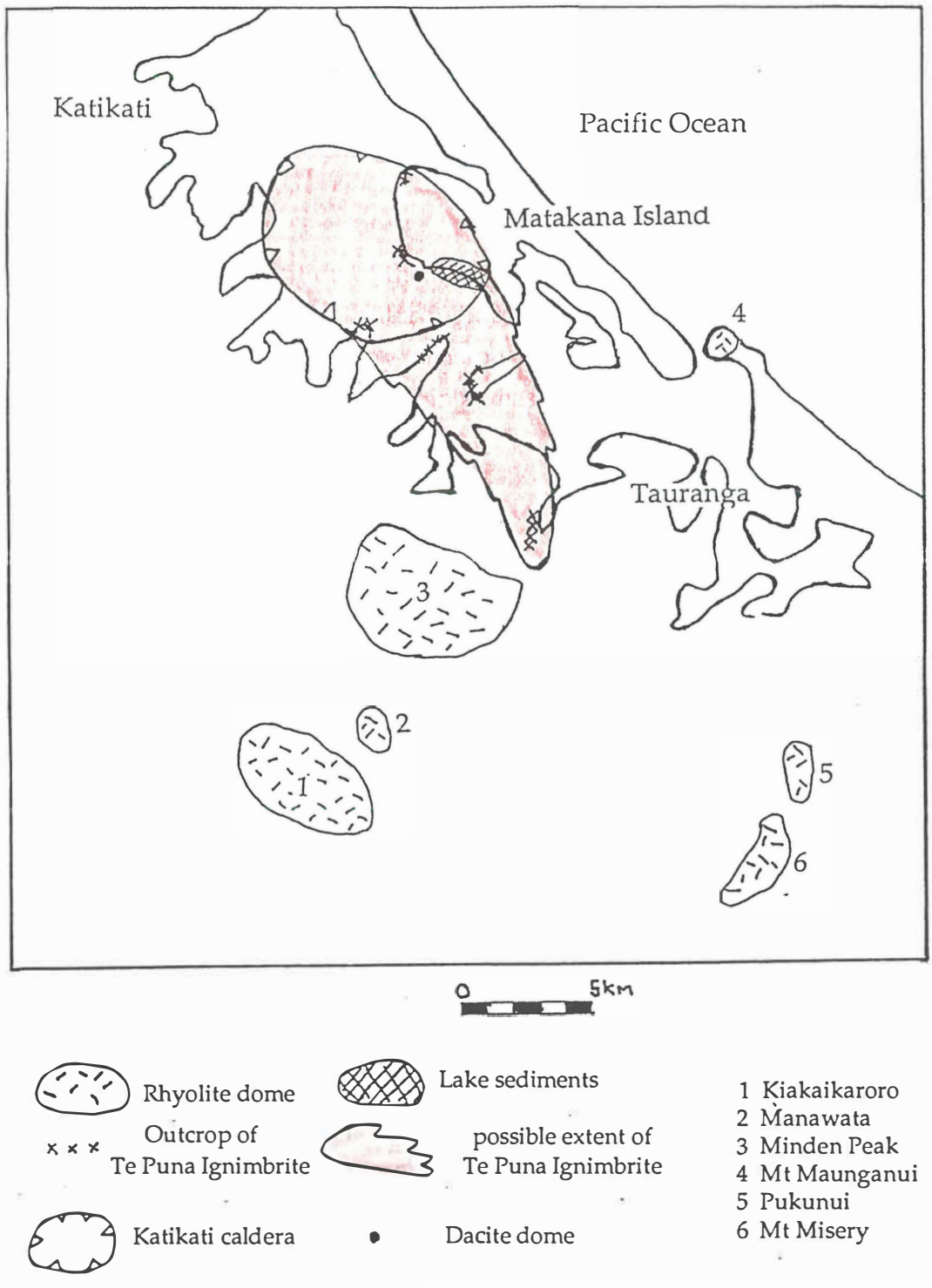


Fig 6.3 Position of the proposed Katikati caldera within the Tauranga basin. Te Puna Ignimbrite assumed to be associated with caldera formation.

The evidence given above suggests that there could be a caldera within the Tauranga basin. The proposed position of the caldera is given in Fig 6.3 based mainly on the location of the negative gravity anomaly. The boundary of the negative anomaly is based on contouring of the values between each gravity station. The eastern boundary of the anomaly at Matakana Island is not precise enough to indicate the caldera boundary as contouring occurs between fewer gravity stations.

It is also based on the position of the lake sediments which would lie within the caldera. Te Puna Ignimbrite outcrops are indicated as well as a suggested original distribution before any erosion of the ignimbrite occurred. This indicates a possible direction of flow in an easterly direction.

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Appendix - 1

Catalogue of rock samples

Samples are referred to in the text by their field number, but are calalogued inthe University of Waikato Earth Sciences Department rock store under a differnt number (W number). 'W' numbers are prefixed by the year e.g 94, and consequently read as follows: W9401.

Grid references refer to NZMS 260 U14 Tauranga Edition 1 (1:50000).

TS - thin section, XRF - X-ray fluoresence, MA - modal analysis, MP - microprobe analyses.

Catalogue No	Sample No	Rock Name	Location	Application
W94320	1	Alluvium	829844	TS
W94321	3	Waitearki	827824	TS
W94322	6	Minden	807818	TS,XRF,MA
W94323	7	Minden	807815	TS,XRF,MP,MA
W94324	8	Waiteariki	791790	TS
W94325	9	Waiteariki	795805	TS
W94326	12	Waiteariki	804788	TS,MP
W94327	13	Kaikaikaroro	742754	TS,XRF,MP,MA
W94328	14	Kaikaikaroro	742754	TS,MA
W94329	15	Manawata	762780	TS,XRF,MP,MA
W94330	16	Manawata	762780	TS,XRF,MA
W94331	22	Waiteariki lithic	736732	TS,MA
W94331	23	Waiteariki lithic	736732	TS,MA
W94332	24	Te Puna Ig	798928	TS,MA
W94333	25	Te Puna Ig	798928	TS,MA
W94334	26	Te Puna Ig	798928	TS,MA
W94335	28	Te Puna Ig	798928	TS,XRF,MP,MA
W94336	31	unknown	787757	TS
W94337	32	Waiteariki Ig	795795	TS,XRF,MA
W94338	33	Minden	788740	TS,XRF,MP,MA
W94339	34	Minden	788740	TS,
W94340	35	Minden	788740	TS,XRF,MA
W94341	36	Minden	788740	TS,XRF,MA
W94342	37	Minden	788740	TS
W94343	41	Minden	797823	TS,XRF,MP,MA

Catalogue No	Sample No	Rock Name	Location	Application
W94344	43	Minden	804841	TS,XRF,
W94345	50	Minden	787840	TS
W94346	51	Waitearikí Ig	750720	TS,MP
W94347	53	Kaimai	summit	TS,XRF,MP,MA
W94348	60	Te Puna Ig	827855	TS
W94349	61	Te Puna Ig	827855	TS
W94350	62	Waitearikí Ig	783729	TS,XRF,MP,MA
W94351	64	Waitearikí Ig	785758	TS
W94352	65	Waitearikí Ig	788756	TS
W94353	71	Te Puna	798928	TS
W94354	72	Te Puna	798928	TS
W94355	74	Te Puna	760928	TS
W94356	75	Te Puna	786920	TS
W94357	76	Te Puna	786920	TS
W94358	77	Te Puna	789925	TS
W94359	78	Te Puna	789924	TS
W94360	79	Te Puna	827855	TS
W94361	80	Te Puna	828856	TS
W94362	81	Te Puna	828856	TS
W94363	82	Te Puna	828856	TS,XRF
W94364	83	Te Puna	828856	TS,XRF
W94365	84	Te Puna	828856	TS,XRF
W94366	85	Te Puna	828856	TS,XRF
W94367	86	Te Puna	828856	TS,XRF
W94368	87	Te Puna	828856	TS,XRF
W94369	88	Te Puna	828856	TS,XRF
W94370	89	Te Puna	828856	TS,XRF
W94371	90	Te Puna	828856	TS,XRF
W94372	91	Te Puna	828856	TS,XRF

Appendix - 2

Microprobe analyses data

Tables of microprobe data for representative phenocrysts of the Western Tauranga basin volcanic rocks are presented below. Samples were prepared using standard techniques to produce polished and carbon coated thin sections which were analysed on the electron microprobe at the University of Auckland.

Plagioclase

Unit	Kaikaikaroro	Kaikaikaroro	Kaikaikaroro	Kaikaikaroro	Kaikaikaroro	Minden	Minden	Minden	Minden
Sample	13	13	13	13	13	7	7	7	7
SiO2	57.89	58.23	57.86	58.86	59.85	58.35	59.52	59.55	54.41
TiO2	0.1	0.05	0.14	0.02	0.09	0.05	0.06	0.09	0.12
Al2O3	26.21	25.78	25.98	25.51	25.12	25	24.77	25.13	27.72
FeO	0.34	0.3	0.24	0.09	0.26	0.06	0.33	0.12	0.3
Fe203	0	0	0	0	0	0	0	0	0
MnO	0.21	0.09	0.03	0.07	0.04	0.05	0.02	0.08	0.01
MgO	0.1	0.02	0.03	0.06	0	0.04	0.06	0.08	0.17
CaO	8.02	7.63	7.78	7.14	6.6	7.13	6.08	6.46	10.03
K2O	0.35	0.43	0.45	0.46	0.56	0.47	0.55	0.61	0.31
Na2O	6.54	6.78	6.6	6.85	7.26	6.76	7.43	7.39	5.57
P2O5	0.06	0.05	0.2	0.17	0.2	0.16	0.16	0.26	0.26
Total	99.55	99.15	98.91	98.83	99.62	97.71	98.68	99.14	98.34
Albite	58.38	60.11	58.95	61.72	64.39	61.40	66.63	65.05	49.22
Anorthite	39.56	37.38	38.40	35.55	32.35	35.79	30.13	31.42	48.98
Orthoclase	2.06	2.51	2.65	2.73	3.27	2.81	3.25	3.53	1.80

Unit	Minden	Minden	Waitearíki	Waitearíki	Waitearíki	Waitearíki	Waitearíki	Te Puna	Te Puna
Sample	7	7	12	12	12	12	12	28 Plag Rim	28 Plag Core
SiO2	59.16	58.47	60.24	59.07	59.79	60.65	59.35	59.98	59.93
TiO2	0.05	0.12	0.01	0.1	0.03	0.04	0.06	0.04	0.06
Al2O3	25.27	25.07	23.95	24.19	23.49	23.79	24.42	24.47	24.17
FeO	0.15	0.24	0.12	0.4	0.23	0.08	0.18	0.08	0.1
Fe203	0	0	0	0	0	0	0	0	0
MnO	0.05	0.05	0.13	0.11	0.12	0.04	0.07	0.13	0.05
MgO	0.05	0	0.06	0.07	0.1	0.07	0.07	0.1	0.08
CaO	6.64	7.14	5.63	5.96	5.46	5.41	5.97	6.67	6.09
K2O	0.52	0.52	0.67	0.62	0.69	0.66	0.89	0.41	0.53
Na2O	7.48	6.55	7.5	7.41	7.61	8.08	7.47	7.43	7.45
P2O5	0.22	0.27	0.25	0.02	0.15	0.1	0.26	0.11	0.18
Total	99.06	97.75	97.98	97.65	97.04	98.59	97.8	98.97	98.97
Albite	65.09	60.44	67.86	66.69	68.68	70.24	65.79	65.26	66.73
Anorthite	31.93	36.41	28.15	29.64	27.23	25.99	29.06	32.37	30.15
Orthoclase	2.98	3.16	3.99	3.67	4.10	3.78	5.16	2.37	3.12

Unit	Minden	Waitearíki	Waitearíki	Waitearíki	Waitearíki	Waitearíki	Waitearíki	Waitearíki	Minden
Sample	41 Plag	51 Plag Core	51 Plag Rim	51 Plag core	51 Plag Rim	A51 Plag Cor	51 Plag Rim	51 Plag Core	33 Plag Rim
SiO2	60.2	53.81	58.68	57.15	57.89	57.81	54.4	50.1	59.25
TiO2	0.05	0.13	0.08	0.05	0.05	0.02	0	0.06	0.16
Al2O3	24.55	28.76	25.59	26.17	25.92	26.63	28.1	31.5	25.12
FeO	0.14	0.23	0.31	0.28	0.27	0.28	0.21	0.37	0.19
Fe203	0	0	0	0	0	0	0	0	0
MnO	0	0.12	0.7	0.3	0.03	0.02	0.03	0.02	0.1
MgO	0.08	0.05	0.1	0.1	0.1	0.06	0.01	0.07	0.06
CaO	6.29	10.91	7.2	8.16	7.83	8.23	9.84	13.73	6.46
K2O	0.65	0.16	0.44	0.38	0.37	0.38	0.15	0.12	0.49
Na2O	7.48	5.05	7	6.41	6.65	6.29	5.43	3.64	7.59
P2O5	0.19	0.16	0.02	0.24	0.12	0.23	0.08	0.21	0.12
Total	99.18	98.68	99.21	98.54	98.92	99.61	97.92	99.46	98.91
Albite	65.71	45.15	62.12	57.39	59.27	56.73	49.52	32.20	66.10
Anorthite	30.53	53.91	35.31	40.37	38.56	41.02	49.59	67.11	31.09
Orthoclase	3.76	0.94	2.57	2.24	2.17	2.26	0.90	0.70	2.81

Unit	Te Puna	Te Puna	Te Puna	Te Puna	Te Puna	Te Puna	Te Puna	Minden	Minden
Sample	28 Plag Core	28 Plag Rim	28 Plag Core	28 Plag Rim	28	28 Plag Core	28 Plag Rim	41 Plag Core	41 Plag Rim
SiO2	57.98	56.52	58.66	59.67	59.04	58.56	57.93	58.05	59.35
TiO2	0.06	0.02	0.05	0.15	0.14	0.15	0.06	0	0.05
Al2O3	26.54	26.48	24.86	24.43	24.38	24.62	25.53	26.12	24.91
FeO	0.2	0.09	0.17	0.17	0.37	0.06	0.3	0.26	0.11
Fe203	0	0	0	0	0	0	0	0	0
MnO	0.02	0.09	0.1	0.05	0.15	0	0.02	0.18	0.04
MgO	0.09	0.01	0.07	0.01	0.12	0.15	0.01	0.03	0.12
CaO	8.12	8.4	6.65	5.77	6.39	6.55	7.66	7.91	6.65
K2O	0.36	0.32	0.54	0.52	0.54	0.55	0.44	0.41	0.54
Na2O	6.62	6.14	7.57	7.53	7.66	7.09	6.69	6.63	7.05
P2O5	0.02	0.32	0.23	0.03	0.1	0.03	0.04	0.15	0.14
Total	99.61	97.87	98.27	97.93	98.38	97.37	98.54	99.37	98.49
Albite	58.36	55.86	65.26	68.08	66.34	64.04	59.67	58.82	63.63
Anorthite	39.56	42.23	31.68	28.83	30.58	32.69	37.75	38.78	33.17
Orthoclase	2.09	1.92	3.06	3.09	3.08	3.27	2.58	2.39	3.21

Unit	Minden	Minden	Minden	Kaimai	Kaimai	Kaimai	Kaimai	Kaimai	Kaimai
Sample	33 Plag core	33	33	A53 Plag Rim	53 Plag Core	53 Plag Rim	53 Plag Core	53 Plag Rim	53Plag Core
SiO2	59.83	57.17	59.14	56.62	56.9	57.12	55.86	55.36	55.66
TiO2	0.1	0.16	0.06	0.07	0.02	0.04	0.14	0.08	0.02
Al2O3	24.58	25.84	24.69	26.58	26.23	26.17	26.19	27.35	27.78
FeO	0.17	0.16	0.25	0.13	0.25	0.36	0.1	0.44	0.23
Fe203	0	0	0	0	0	0	0	0	0
MnO	0.02	0.04	0.1	0.04	0.06	0.04	0.14	0.1	0.1
MgO	0.05	0.02	0.03	0.05	0.08	0.07	0.06	0.15	0.11
CaO	6.24	8.02	6.52	8.72	8.19	8.08	8.77	9.53	9.56
K2O	0.52	0.4	0.59	0.43	0.37	0.39	0.45	0.35	0.26
Na2O	7.64	6.76	7.44	6.12	6.46	6.57	6.23	5.9	5.89
P2O5	0.03	0.19	0.27	0	0	0.19	0.15	0.09	0.07
Total	98.81	98.19	98.62	98.47	98.39	98.69	97.5	98.92	99.13
Albite	66.84	59.01	65.09	54.54	57.53	58.19	54.78	51.77	51.92
Anorthite	30.17	38.69	31.52	42.94	40.30	39.54	42.62	46.21	46.57
Orthoclase	2.99	2.30	3.40	2.52	2.17	2.27	2.60	2.02	1.51

Unit	Kaimai	Kaimai	Waitearíki	Waitearíki	Waitearíki
Sample	53	53	62 Plag Rim	62 Plag Core	62
SiO2	59.18	56.58	56.95	57	57.85
TiO2	0.02	0.04	0.11	0.11	0.02
Al2O3	24.84	26.24	26.62	25.7	25.25
FeO	0.11	0.06	0.16	0.12	0.21
Fe203	0	0	0	0	0
MnO	0.03	0.05	0.04	0.07	0
MgO	0.08	0.01	0.1	0.18	0.03
CaO	7.04	8.06	8.79	8.03	7.53
K2O	0.54	0.4	0.37	0.38	0.4
Na2O	7.2	5.79	5.98	6.28	6.67
P2O5	0.14	0.08	0.01	0.09	0
Total	98.8	97.07	98.7	97.38	97.7
Albite	62.91	55.11	53.97	57.26	60.12
Anorthite	33.99	42.39	43.84	40.46	37.51
Orthoclase	3.10	2.51	2.20	2.28	2.37

Orthopyroxene

Unit	Kaikaikaroro	Minden	Waitearíki	Waitearíki	Waitearíki	Minden	Minden	Minden	Waitearíki
Sample No	13	7	12	12	12	41	41	41	51
Mineral	PX	PX	PX	PX	PX	PX	PX	PX	PX
SiO2	50.2	49.77	49.54	49.5	49.19	48.39	50.31	50.23	50.14
TiO2	0.18	0.07	0.14	0.05	0.22	0.05	0.11	0.04	0.18
Al2O3	1.31	0.67	0.49	0.53	0.34	14.73	0.6	0.83	1.08
FeO	30.46	31.3	33.55	33.92	33.12	26.08	30.88	30.62	30.63
MnO	0.6	1.53	1.15	1.67	1.54	0.98	1.57	1.42	0.87
MgO	16.16	15.6	14.66	13.47	13.75	15.64	16.15	16.08	15.44
CaO	1.7	0.71	1.18	1.36	1.07	0.73	0.84	0.78	1.57
K2O	0.05	0.05	0.12	0.03	0.3	0.03	0.02	0.05	0.01
Na2O	0.12	0.01	0.07	0.03	0.6	0.14	0	0.22	0.02
P205	0.05	0.18	0.18	0.04	0.16	0.02	0.22	0.21	0.03
Total	100.43	99.59	101.04	100.45	99.24	106.56	100.35	99.96	99.73
Enstatite	48.474	48.051	45.188	41.795	43.35	50.788	49.123	48.993	46.489
Ferrosilite	47.861	50.377	52.198	55.172	54.225	47.509	49.04	49.299	50.114
Wollastonite	3.665	1.572	2.614	3.033	2.424	1.704	1.836	1.708	3.397

Unit	Waitearíki	Waitearíki	Minden	Minden	Kaimai	Waitearíki	Waitearíki
Sample No	51	51	33	33	53	62	62
Mineral	PX	PX	PX	PX	PX	PX	PX
SiO2	49.89	49.41	50.7	50.06	50.61	50.84	51.74
TiO2	0.11	0.23	0.3	0.06	0.12	0.23	0.52
Al2O3	0.73	0.99	0.65	0.27	1.04	0.8	1.56
FeO	32.57	32.9	30.35	32.26	27.33	28.02	22.65
MnO	1.04	0.93	1.46	1.49	1.37	0.45	0.49
MgO	15.05	14.76	16.68	15.63	17.57	18.12	21.78
CaO	1.07	0.94	0.76	0.7	0.72	1.1	1.87
K2O	0	0.1	0.05	0.05	0	0.01	0.02
Na2O	0.11	0.08	0.07	0.15	0.25	0.01	0.06
P205	0.04	0.21	0.1	0.17	0.15	0.09	0.18
Total	100.35	100.15	100.6	100.41	98.64	99.57	100.6
Enstatite	45.703	45.332	50.173	47.831	52.873	53.379	62.846
Ferrosilite	51.962	52.593	48.184	50.629	45.57	44.292	33.276
Wollastonite	2.335	2.075	1.643	1.54	1.557	2.329	3.878

Amphibole

Unit	Minden	Minden	Waitearikl	Waitearikl	Minden	Minden	Minden	Minden	Kaimai	Waitearikl	Waitearikl
Sample No	41	41	51	51	33	33	33	33	53	62	62
mineral	AM	AM	AM	AM	AM	AM	AM	AM	AM	AM	AM
SiO2	45.19	45.52	41.7	1.75	45.22	45.65	45.73	46.03	46.2	44.74	44.06
TiO2	0.98	1.28	2.02	7.84	1.34	1.22	1.29	1.31	1.21	1.64	1.8
Al2O3	7.3	8.07	8.88	18.88	7.52	7.31	7.23	7.55	6.89	7.97	8.14
FeO	21.91	21.18	20.59	0	20.07	19.91	18.47	18.27	18.09	20.08	18.82
Fe203	0	0	0	0	0	0	0	0	0	0	0
MnO	0.78	0.52	0.28	0.28	0.55	0.43	0.35	0.53	0.51	0.28	0.29
MgO	9.81	9.89	8.82	10.91	10.51	10.87	12.41	11.93	11.94	10.86	10.57
CaO	10.33	10.58	10.26	10.78	9.96	10.25	10.09	10.18	10.44	10.7	10.97
K2O	0.57	0.66	0.46	0.42	0.53	0.52	0.35	0.36	0.46	0.4	0.52
Na2O	1.1	1.33	1.58	1.62	0.93	1.17	1.27	1015	1.02	1.57	1.67
P205	0.04	0.08	0.08	0.12	0.04	0.18	0.03	0.06	0.01	0.06	0.16
Total	97.88	99.02	94.6	97.28	96.62	97.33	97.19	97.31	96.77	98.24	96.85

Unit	Kaikaikaroro	Kaikaikaroro	Kaikaikaroro	Minden	Manawata	Waitearikl	Waitearikl	Waitearikl	Te Puna	Te Puna	Te Puna
Sample No	13	13	13	7	15	12	12	12	28	28	28
mineral	AM	AM	AM	AM	AM	AM	AM	AM	AM	AM	AM
SiO2	44.29	41.83	43.74	46.18	44.76	59.03	43.54	44.12	46.36	44.81	46.15
TiO2	1.76	2.59	1.91	1.19	1.95	0	1.94	1.74	1.3	1.54	1.29
Al2O3	9.34	10.8	9.05	6.73	8.96	24.37	8.41	7.46	6.75	7.08	6.85
FeO	15.86	19.66	19.02	19.89	14.83	0.27	19.49	20.46	19.97	18.37	19.32
Fe203	0	0	0	0	0	0	0	0	0	0	0
MnO	0.37	0.35	0.25	0.74	0.41	0.01	0.5	0.39	0.5	0.45	0.52
MgO	13.13	9.86	11.35	11.03	13.05	0.01	10.38	10.29	11.89	11.6	11.57
CaO	11.07	10.55	10.82	10.42	10.9	6.13	10.69	10.59	10.12	10.6	10.24
K2O	0.19	0.44	0.45	0.41	0.4	0.59	0.51	0.64	0.47	0.35	0.38
Na2O	1.64	2.09	1.79	1.03	1.62	7.22	1.83	1.79	1.37	1.66	1.13
P205	0.05	0.2	0.05	0.02	0	0.13	0.02	0.17	0.05	0.09	0.04
Total	97.66	98.18	98.36	97.61	96.9	97.61	97.28	97.44	98.73	96.15	97.46