Collection of the Auckland Art Gallery

Watercolour Paintings

by John Barr Clarke Hoyte, 1835-1913

Mt. Tarawera and Lake 1873

JAMES WILLIAM COLE

TARAWERA VOLCANIC COMPLEX

Thesis submitted for the degree of
Doctor of Philosophy
in Geology
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PROLOGUE

"The secret of Tarawera's strength (goes) back to the days of the Arawa canoe. Tamaohoi was an atua, a man-eating ogre who lived on the flanks of the mountain. As the thermal regions were occupied by the growing tribes of Te Arawa, unwary travellers were snatched and devoured by Tamaohoi.

When the news of these ambushes reached Ngatoro, the far-travelled tohunga who had climbed the bare heights of Tongariro and who summoned the fire gods of Hawaiki, he made a special expedition to Tarawera. The atua had no resistance to offer the skilled tohunga of Te Arawa. Ngatoro ascended the mountain and stamped with his foot until a huge chasm was formed. Into this pit he thrust the cannibal demon, covering him with the solid rock of the mountain.

Tamaohoi lay sleeping through the centuries until Tuhoto's prayers* or simply the passage of time woke him from his long slumbers. There came the night when he rose and burst the mountain and laid waste all the land that lay at his feet."

Legends of Rotorua by A.W. Reed

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*Tuhoto was the aged tohunga of Te Wairoa, held responsible by the Maoris for the eruption.

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ABSTRACT

The Tarawera Volcanic Complex is situated on the south eastern side of the Okataina Volcanic Centre, and is an association of rhyolite domes, flows and tephra, and basalt scoria.

Twelve rhyolite domes are described, and using evidence obtained from the good internal sections available, the general structure of volcanic domes is discussed.

Tephra stratigraphy of the Tarawera-Rerewhakaaitu region is described and by relating stratigraphy on the mountain to this tephra, four major eruptions can be recognized. A sequence of events for the Kaharoa eruption in about 1020 A.D. can be postulated. The Tarawera eruption in 1886, however, was observed, and from the eye witness accounts, together with present day field evidence, a detailed account can be written.

All the rocks of the Complex are described petrographically, mineralogically, and in some cases petrochemically. Twelve new full analyses; nine partial analyses of plagioclase, and eight partial analyses of residual glass are given, and the relationship of these is illustrated by variation diagrams.

Finally, the origins of the acid and basic rocks of the Complex are discussed, and a hypothesis for the occurrence of the two lava types is given.

General Acknowledgements

The writer would like to express his sincere thanks to Professor R.H. Clark for suggesting the topic, spending many hours discussing Tarawera and the New Zealand volcanoes in general, and for his guidance in writing the thesis. Thanks are also due to the other members of staff of the Geology Department, Victoria University of Wellington, particularly Professor H.W. Wellman, Professor J. Bradley, Dr. E.D. Ghent and Mr. C.G. Vucetich, for their willingness to discuss problems both in the field and in the laboratory, and to give constructive advice where needed. Each of the above critically read part of the manuscript.

A special note of thanks is given to Dr. A. Ewart, of the New Zealand Geological Survey, who has given the writer great help and encouragement throughout, but particularly in the discussion of rhyolite mineralogy and petrology.

Much help has also been received from Mr. J. Healy and the Staff of the Geological Survey Office, Rotorua, as well as from the many delegates to the International Symposium on Volcanology, 1965, who willingly discussed aspects of the research, and made helpful comments whilst on the mountain.

Finally, the writer would like to thank the University Grants' Committee, especially Mr. E.G. Kedgley, for financial backing in the form of a Commonwealth Scholarship, without which the research could not have been undertaken.

Plate 1. The Tarawera Volcanic Complex looking north east from Te Wairoa, showing the three Late Domes of Wahanga (left), Ruawahia (centre), and Tarawera (right). In front are Northern Lava Flow (left) and North western Lava Flow (right).

GENERAL INTRODUCTION

GENERAL INTRODUCTION

General Setting

Mount Tarawera is a volcanic complex* in the Taupo Volcanic Zone (Healy, 1962, p.2). This zone extends NNE from Ohakune to White Island and includes a number of still active volcanoes (Fig.1). At the north west and south east margins are extensive sheets of ignimbrite, which were probably erupted from the zone early in its volcanic history.

Four centres of activity can be distinguished in the zone (Healy, 1964a; Thompson, 1964):

1. Tongariro Volcanic Centre
2. Taupo Volcanic Centre
3. Maroa Volcanic Centre
4. Okataina Volcanic Centre.

The volcanoes of the Tongariro centre are mainly of andesitic composition, typified by those of Ruapehu, Tongariro and Ngauruhoe, while those of the Taupo, Maroa and Okataina centres are predominantly rhyolite. North of Okataina, more andesite volcanoes occur at Mount Edgecumbe, Whale Island and White Island.

The Tarawera Complex forms the southern part of the Okataina Volcanic Centre (Fig. 2) and is formed by the extrusion of successive

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* The terms 'Volcanic Complex' are used in this paper to describe a series of volcanic features closely associated spatially, but of differing composition and mode of extrusion.

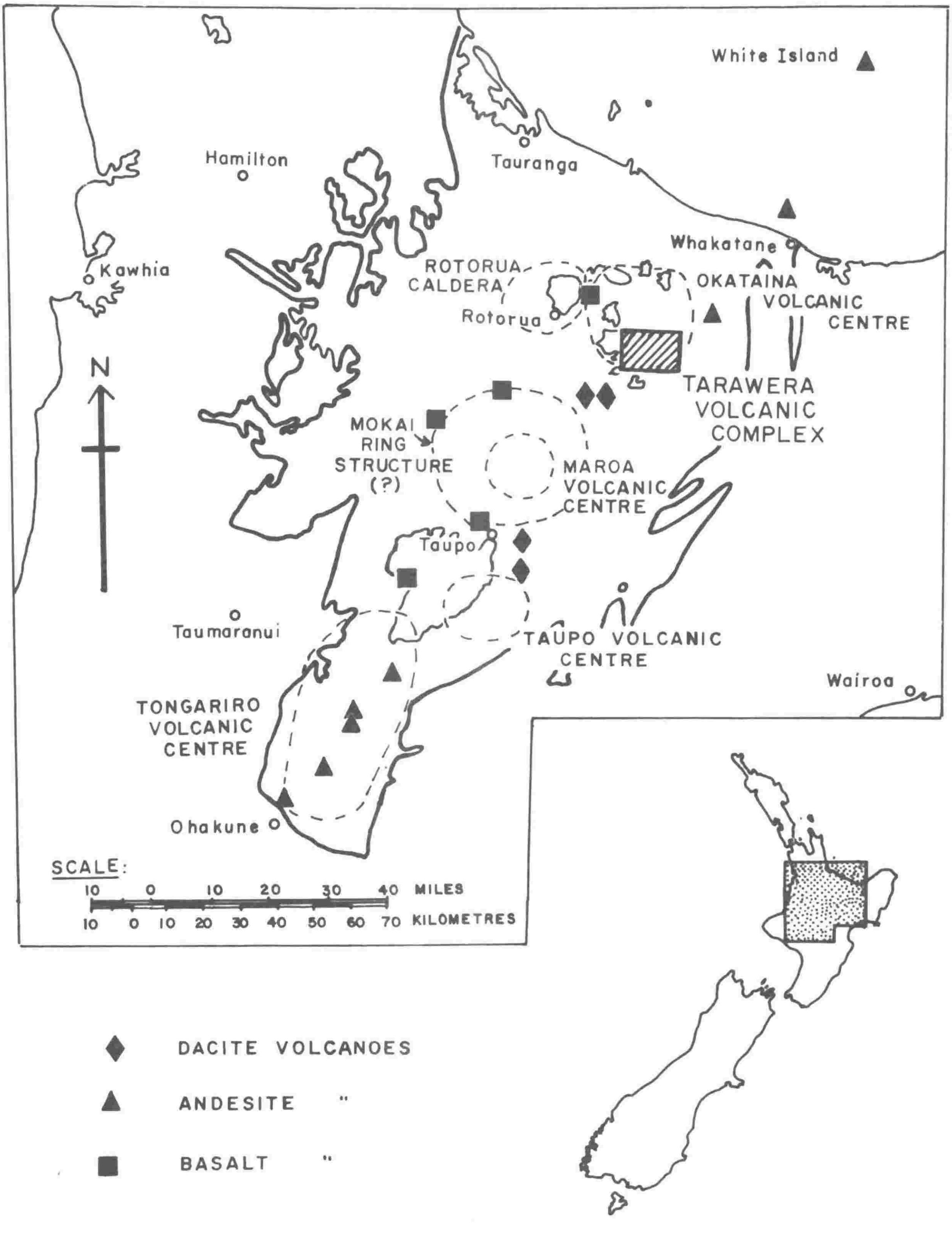
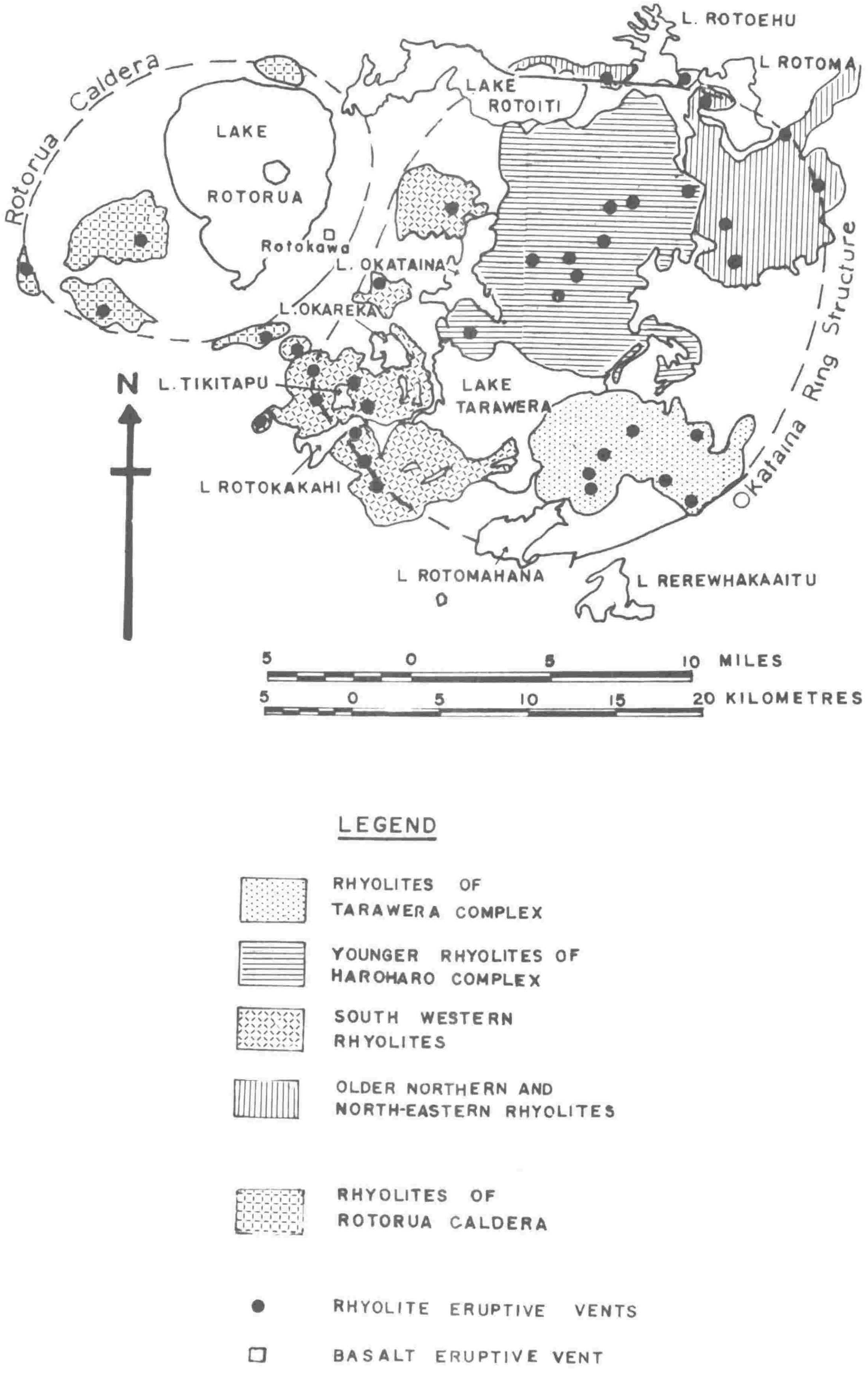


Fig. 1. Location of the Tarawera Volcanic Complex and its relationship to the main Volcanic Centres of the Taupo Zone.

Fig. 2.

Map showing the distribution of the rhyolites of the Rotorua Caldera and the Okataina Volcanic Centre (After Healy, 1965, Fig. H - 2).


L. ROTOEHU
L ROTOMA
LAKE ROTOITI
Rotorua Caldera
LAKE ROTORUA
Rotokawa
L. OKATAINA
L. OKAREKA
L. TIKITAPU
LAKE TARAWERA
L ROTOKAKAHI
L ROTOMAHANA
L REREWHAKAAITU
Okataina Ring Structure
N
5 0 5 10 MILES
5 0 5 10 15 20 KILOMETRES
LEGEND
RHYOLITES OF TARAWERA COMPLEX
YOUNGER RHYOLITES OF HAROHARO COMPLEX
SOUTH WESTERN RHYOLITES
OLDER NORTHERN AND NORTH-EASTERN RHYOLITES
RHYOLITES OF ROTORUA CALDERA
RHYOLITE ERUPTIVE VENTS
BASALT ERUPTIVE VENT

rhyolite domes and flows of the Haparangi Series (Grange, 1937). The last event was the explosive eruption of basalt from a fissure across the mountain in 1886.

Topography

The Complex forms a prominent topographic feature, rising from relatively flat country on three sides and from Lake Tarawera on the fourth. The undulating country to the east is 1300 to 1500 ft. above sea level, and this height is similar to that of the Rerewhakaaitu basin to the south. To the west the surface falls gently to Lake Rotomahana (1098 ft. above sea level), which is only separated by a small rise from Lake Tarawera (980 ft. above sea level).

The edges of Tarawera are in all cases steep, and scarps up to 500 ft. high occur in places. From this level the most recent volcanic extrusions rise steeply to form comparatively flat plateaux over 3000 ft. above sea level. Two topographic units can be distinguished; one to the north west forms Wahanga Peak, and the other, separated from Wahanga by a marked depression, forms Ruawahia and Tarawera Peaks. Ruawahia Trig (3646 ft.) is the highest point of the Complex.

A great fissure extends for four miles across these features. It is more than 500 ft. deep and 1500 ft. wide in parts, and is divided into a number of craters, separated by 'bridges' of solid rock. These provide convenient places to cross the fissure. On the south western edge of Tarawera peak is the Chasm. This is surrounded by cliffs over 200 ft. high on three sides, and forms a distinct feature on the side of the Complex, visible for many miles.

Previous Work

The first European to have visited Tarawera and the immediately surrounding area was a Rev. Chapman, a missionary from Rotorua. He was friendly with the local Maoris, and in June 1841 took Dr. Ernst Dieffenbach on a tour across Lakes Rotomahana and Tarawera. The latter recorded details of the trip in his book "Travels in New Zealand" (Dieffenbach, 1843), and provided the first description of the lakes and the Pink and White Terraces. He also noted that "when we came into the Tera-wera (Tarawera) Lake, the shores became steep and rocky (trachytic). To our right there rose a curious mountain consisting of several truncated cones and exactly resembling a fortification as the upper borders of the cones were fringed all around with perpendicular rocks. This hill is called 'Motonui-Arangi'" (Dieffenbach, 1843, p.384). The description fits Tarawera, hence the name is interesting. Translated it means 'the large island of Rangi', and this would fit with Dieffenbach's theory on the origin of the lakes in the region. He considered that they were the remains of a former arm of the sea which had become closed by uplifting of the land. The name 'Motonui-Arangi' was not used by later authors, and its origin is unknown. It may have been a name given by some local Maoris while others called it 'Tarawera'.

In 1864, Hochstetter referred to Tarawera as an excellent example of a plateau relic with the upper surface of both Tarawera and Horohoro defining "the original level of the district" (Fleming, 1959, translation, p.136). He recorded the presence of obsidian on the mountain and thus was the first person to give a true indication of composition. Hochstetter did not climb the mountain, however, as the Maoris held it 'tapu' (sacred) and no European was allowed to ascend. This 'tapu' was probably upheld until about 1872, when Kirk managed to get to the top and examine the flora. He described the ascent of Ruawahia as difficult "on account of its precipitous character and the danger arising from loose fragments of rock which became detached at the slightest touch" (Kirk, 1873, p.334).

At this period the Pink and White Terraces were causing great interest, and Hutton (1869), Abbay (1878) and others wrote on their morphology and origin, but none mentioned Tarawera. In fact, it was not until 1886, when the Tarawera eruption occurred, that much direct interest was taken in the mountain. Then, between 1886 and 1888 some thirty papers and notes were written on the subject, of which the most comprehensive were by Hector (1886), Hutton (1887), Smith (1886a) and Thomas (1888). They recorded many eye-witness accounts of the eruption, as well as useful descriptions of the mountain beforehand, and changes that took place afterwards. Thomas (1888) also briefly described the internal structure and composition of the rhyolite domes. A full bibliography about the eruption is given in Appendix 2.

After 1886, interest waned, and the majority of papers were of a review nature. Smith (1894) described the state of the country on and around Tarawera once it was again possible to ascend the mountain, but after this the only significant papers for the next thirty years were those of Bell (1906) and Park (1911), and neither added much new information. Grange (1937), in 'The Geology of the Rotorua-Taupo Subdivision' provided the next advance in the study of the Complex. He gave both an excellent general account of the 1886 eruption, and described the structure and composition of the rhyolite domes, noting for the first time the presence of a dome older than those of Wahanga, Ruawahia and Tarawera. Papers written since 1937 which refer to Tarawera have been on more general topics, and include those of Healy, 1947, 1962, 1963a, 1963b, 1964a - General structure and mechanisms of the Taupo Volcanic Zone; Healy, Schofield and Thompson, 1964 - Description of Geological Map of Rotorua District; Modriniak and Studt, 1959 - Structure of the Taupo-Tarawera District; Thompson, 1964 - General description of the Taupo Volcanic Zone; Clark, 1957, 1960a and Steiner, 1958 - Origin of the lavas of Taupo Volcanic Zone; Ewart, 1965b - Rhyolite petrology; Vucetich and Pullar, 1963, 1964 - Ash stratigraphy.

Plate 2. Wahanga Dome from near the top of Ruawahia. The 1886 craters in the foreground are walled by Kaharoa 'Ash' and Tarawera 'Ash'.

SECTION A

GENERAL GEOLOGY, STRUCTURE AND STRATIGRAPHY

A. GENERAL GEOLOGY, STRUCTURE AND STRATIGRAPHY

GENERAL GEOLOGY

NOMENCLATURE

Volcanic Domes:- The nomenclature of volcanic domes has been discussed by Williams (1932a), who concluded that "the term 'dome' be restricted to steep-sided viscous protrusions of lava forming more or less dome-shaped masses around their vents". Cotton (1944) preferred the term 'cumulodome', which Jaggar (1920) had used to distinguish rhyolite extrusions from basaltic 'domes'. This term is more explicit, but in most of the literature becomes abbreviated to 'dome' and loses much of its value. In this account the term 'dome', as defined by Williams, will be used.

Williams (1932a) subdivided domes into three types:

a) Plug domes, which represent upheaved conduit fillings.

b) Endogenous domes, that grow essentially from expansion within.

c) Exogenous domes, built by surface extrusion usually from a central summit crater.

This scheme is of doubtful value for field interpretation as most domes are formed by a combination of processes. It does, however, provide a useful division for a theoretical discussion of the origin and structure of the domes. The term 'plug dome' is extended from Williams' definition to cover any small steep sided rhyolite mass which remains in its eruptive vent and does not flow over the surface. An example of this type of dome probably occurs at Lassen Peak, California (Williams, 1932b, pp.323-6).

When a rhyolite lava flows from a vent, it may move with equal facility in all directions and retain a hemispherical shape. This is the case at Galunggung, Java (Escher, 1920), and results in the formation of a true 'dome'. In most cases, however, a tongue of lava flows more rapidly in one direction, and forms a 'coulée' (Putnam, 1938). An excellent example of such a feature is at Mono Craters, California (Putnam, 1938). Sometimes this lava tongue continues to flow for a considerable distance, and then results in a normal 'lava flow'. All three types occur in the Tarawera Complex.

Internal Structure:- The terminology used in the discussion of internal structure is that used by Balk (1948). In the rhyolite domes, there are two main 'primary' structures (i.e., those considered to have developed during the consolidation of the lava) - 'flow structures', due to movement of the lava from the vent to its final cooling position, and a banding of an 'onion-skin' nature, which will be called 'spheroidal banding' (p.30). Flow structures are either 'linear' or 'platy'. The former occurs where the long axes of crystals are oriented in the same direction, giving 'flow lines'. The latter is where platy minerals occur; where there is a concentration of an elongate mineral in a particular band; or where there is a variation in vesicularity in different layers in pumiceous rhyolite. These form 'flow layers', and they may or may not include flow lines.

Joints can be of several types (Balk, 1948, p.27), of which the most important in the extrusive rhyolites are (1) Cross joints - those perpendicular to primary structures; (2) Longitudinal joints - parallel to primary structures; (3) Diagonal joints - which are at an angle of about 45° to them.

Pyroclastic Rocks:- The nomenclature used in the detailed description of pyroclastic rocks is that proposed by Wentworth and Williams (1932).

Size of ejecta	> 32 mm	Blocks
	32 - 4 mm	Lapilli
	4 - .25 mm	Coarse ash
	< .25 mm	Fine ash.

In each case, juvenile fragments of material (i.e., those that are thought to have come from the magma reservoir) are 'essential'; fragments of previously solidified cognate igneous rocks are 'accessory'; and fragments of non-cognate rocks, usually from an earlier dome or pyroclastic shower are 'accidental'.

The term 'ash' as a general term for pyroclastic rocks is very misleading, as only a small part of the debris is likely to be of ash grade (by Wentworth and Williams' definition). A better term is Thorarinsson's (1954) term, 'tephra', and this will be used where appropriate in this paper. For the description of the ejecta of particular pyroclastic eruptions (e.g., Kaharoa Ash), the term 'Ash' has been firmly embedded in the literature, and hence will be retained.

Ignimbrites:- The terminology of ignimbrites has been confused for many years. Marshall (1935, p.323) defined ignimbrite as "any rock thought to have been deposited from immense clouds or showers of intensely heated, but generally minute fragments of volcanic magma". These 'clouds or showers' he correlated with the 'nuées ardentes' of Lacroix (1903, p.442-3). The term 'ignimbrite' thus covers two important petrographic rock types; 'welded tuff' and 'non-welded tuff or sillar'. Welded tuff refers to tuffs in which "individual fragments have remained plastic enough to be partly or wholly welded" (Mansfield and Ross, 1935, p.308), and sillar to tuffs "in which the induration is primarily the result of recrystallization and for those in which the fragments have little cohesion" (Fenner, 1948, p.883). Both types may occur in the same flow.

'Lahar' may be defined in many ways. It was coined by van Bemmelen (1949, p.191) for "a mudflow containing debris of angular rocks of chiefly volcanic origin", and as such the term covers block flows which sweep down the sides of volcanic domes when loose debris at the edges of domes becomes oversaturated.

Rift:- The term 'rift' was first used by Hector (1886, p.3) for the northern end of "The Great Fissure" and then by Smith (1894) to describe "The Chasm". Since this time it has been the term used most commonly to describe the whole line of craters formed across Mount Tarawera in the 1886 eruption.

'Rift' can be defined in many ways, one of which is "a narrow cleft or fissure in rock" (A.G.I. Glossary, 1960, p.247). However, tension is normally implied. Cotton (1944, p.104, footnote) notes

Fig. 3.

Aerial mozaic map of the Tarawera Volcanic Complex. Rhyolite domes and explosion craters are shown on overlay. All tephra is omitted. (N.B. The map and grid are only accurate to within 1000 ft. on slopes).

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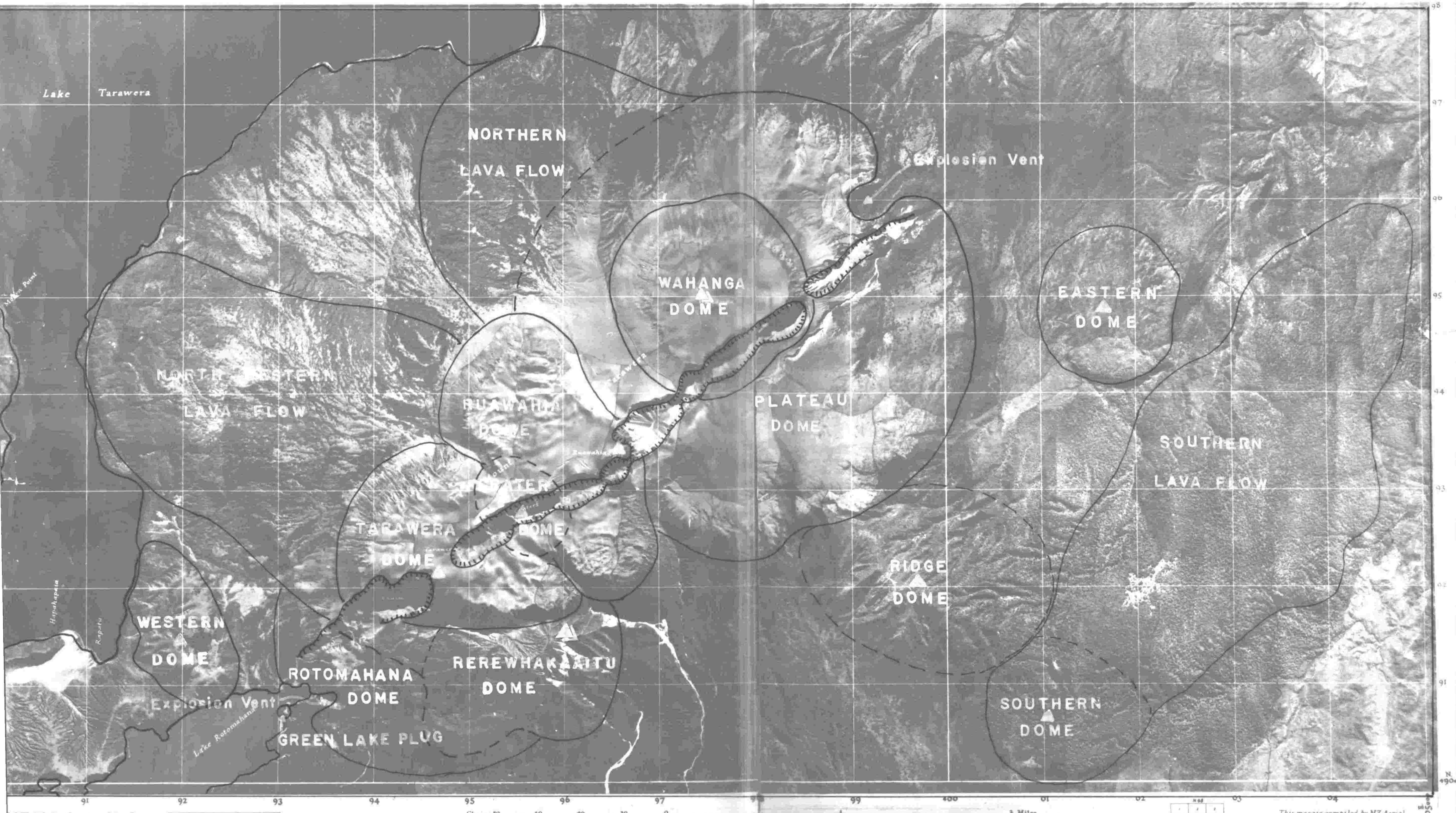

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September 1945 April 1944

Index to Adjacent Sheets

This mosaic compiled by NZ Aerial Mapping Ltd. for Lands and Survey Dept N.Z. Date :- March & April 1950 that "'rift' does not necessarily imply a graben produced by trough faulting. The term is more suitable for an open crack which is the result of tension".

At Tarawera, there is good evidence that fault movement did not take place at the surface during the 1886 eruption, as shower-bedded Kaharoa 'Ash' passes undisturbed across the craters. Furthermore, there is no evidence of tension at the surface. A fault or fissure is indicated at depth by the alignment of the eruptive centres, but the main surface features are the elongated vents from which the basalt lapilli were thrown during the eruption. The deep 'clefts', as between Ruawahia and Tarawera (domes) are a result of explosions which occurred towards the end of the main eruption.

'Rift' is therefore misleading in this context, and the term 'fissure' will be used (as by Smith, 1886a, and Thomas, 1888) to describe the whole feature. The individual centres of basalt eruption and points of explosion will be called 'craters'.

RHYOLITE DOMES

The Tarawera Volcanic Complex consists of twelve rhyolite domes and plugs (Fig. 3) which can be divided on geomorphic and mineralogic evidence into two groups:

(i) Early Domes (in probable order of decreasing age)

Ridge Dome (?)

Western Dome

Rotomahana Dome

Rerewhakaaitu Dome and Flow

Southern Dome and Flow

Plateau Dome and Flow

Eastern Dome

(ii) Late Domes

Crater Dome

Ruawahia Dome

Tarawera Dome

Wahanga Dome

Green Lake Plug.

The domes presumably overlie older rhyolites and ignimbrites of the Okataina centre. It is possible that earlier rhyolites were erupted from Tarawera, but these, if present, are no longer exposed at the surface. A flow which forms the lip of the Tarawera Falls (N77/978012) could represent such a flow, but it is overlain by very similar lava from the Haroharo Complex, and hence it is thought more likely to be associated with this centre than Tarawera, and will not be discussed further.

The positions of vents are always difficult to determine with accuracy. In some cases (e.g., Ruawahia Dome) the lava appears to have flowed from a definite crater, which is thus interpreted as the vent. In perfectly circular domes (e.g., Eastern Dome) it is thought to be in the centre, but in other cases the position is very conjectural. In Fig. 3 the suggested positions of the vents are placed on: general form of the domes; jointing, where this can be seen; and the domes' relationship to pyroclastic deposits, as the latter usually show their source more clearly.

Early Domes and Flows

All domes and flows of the Early group are covered by rhyolitic tephra, and towards the edges of the Complex are further masked by vegetation. These tend to mask the domes and allow few exposures on the tops. Most outcrops are thus found at their margins.

Ridge Dome:- Ridge Dome is the most poorly defined of the domes. Its existence is postulated on the evidence afforded by one exposure. There is some topographic expression, but this could also be produced by a flow from Plateau Dome. There is a difference in mineralogy, however, which makes this unlikely. It is completely covered by thick tephra and vegetation, and the one exposure occurs near the bottom of the deepest gully on the north east side.

Western Dome:- This is a small partly eroded dome (surface area < 1 sq. ml.) lying between Lakes Rotomahana and Tarawera. It could represent a flow from Rotomahana Dome, but like Ridge Dome a differing mineralogy suggests it is a separate intrusion. The western margin is steep, with several cliffs of rhyolite exposed, but the eastern side is completely obscured by later tephra.

Rotomahana (Brecciated) Dome:- This dome is north east of Lake Rotomahana. It is partly covered by later domes, and hence its full extent is unknown. Most of it is covered by thick vegetation and the only good exposures are on the south west side where the edge of the dome forms a marked break of slope (500 ft. high). In a 50 ft. cliff at the end of a pumice wash (N77/961907) two types of rhyolite are exposed, which are intimately mixed together. The significance of this will be discussed later.

Rerewhakaaitu Dome and Flow:- Rerewhakaaitu Dome overlies the eastern side of Rotomahana Dome, and the bulk of the lava from the extrusion apparently flowed nothwards to form the associated Rerewhakaaitu or North Western Lava Flow. There is no marked break of slope at the eastern side of the dome as it is surrounded by a thick sequence of tephra. The western side forms a small lobe or coulée which did not reach the edge of the underlying dome. The Flow, made largely of obsidian, has a steep front (> 100 ft. high), but nearer the source has been covered by tephra and more recent domes. Shallow gullies occur along its length, but debris has washed into these so that no rock exposures are found other than at the northern margin.

Southern Dome and Flow:- This is the most south easterly extrusion of the Complex, probably at the edge of the Okataina Caldera (Fig. 2). There is no topographic separation between the Dome and Flow, and the division is arbitrarily made where the outcrops at the margin change from pumiceous rhyolite to obsidian.

Plateau Dome and Flow:- Plateau Dome is the largest dome in the Complex and has a surface area of over 4 sq. mls. (6 sq. mls. including Flow). The edges of the domes could perhaps be regarded as coulées which moved northwards or southwards from the vent, curved towards the east and partly coalesced together. This is supported by the occurrence of obsidian on the southern and eastern margins of the dome. The main flow (Plateau or Northern Lava Flow) is to the north of the dome and this forms a steep front (200-300 ft. high) at the edge of Lake Tarawera. The centre of the dome is covered by the later Wahanga Dome.

Eastern Dome:- This is a small circular dome to the east of Plateau Dome, with an exceptionally flat top and steep margins. It is covered by tephra and vegetation, and the only exposures are around the southern edge.

Late Domes

The Late Domes are all considered to have been extruded during or after the Kaharoa eruption in approx. 1020 A.D. (see p.58). They are little eroded, and as they were largely covered by thick debris from the 1886 eruption are void of vegetation (plate 1).

Crater Dome:- This dome has no surface expression, as Ruawahia and Tarawera Domes have coalesced around and partly over it, and the remainder of the dome has been covered by the Tarawera Ash and Lapilli. It can only be examined in the deepest of the 1886 craters where a good internal section is exposed.

Ruawahia Dome:- Ruawahia Trig (3646 ft.) forms the highest point on the mountain, and probably marks the site of the vent for the dome. During its extrusion, the lava flowed north west and south to form the well developed coulées. The dome is covered by the Tarawera Ash and Lapilli, but is exposed both at the margins and on top of the coulées. The central area may be studied in the 1886 craters which cut through it.

Tarawera Dome:- This dome was extruded from a vent near the 'Chasm', and the lava flowed to the north west and south east to form two coulées similar to those of Ruawahia. Many exposures of the dome occur around the margin, and there is a good internal section in the Chasm.

Wahanga Dome:- Wahanga Dome covers a total area of about 1½ sq. miles and has been extruded through the Plateau Dome. It appears to have a central vent and to have flowed in three directions. The two southern lobes have been cut by the 1886 craters, and these provide a good section from which to study the structure of the dome (p. 23). The margins of the dome are very steep (800-1000 ft. high) with rugged crags of rhyolite at the top, and large talus slopes below (Plate 2). There are also a few crags on the top of the dome which are not covered by the mantling Tarawera 'Ash.'

Green Lake Plug ('Baby Volcano' of Thomas, 1888, p.49):- This is a small plug which forms a prominent hill at the eastern end of Lake Rotomahana. It has been well exposed by the explosive formation of Green Lake Crater in 1886, which removed half of the plug, and produced an excellent cross section (see Fig. 7). It appears to have pushed through tephra and reached the surface to form a rugged 'boss' 50 ft. high.

EXPLOSION CRATERS

Two explosion craters are located on the edges of domes (Fig. 3). One occurs on the western side of Rotomahana Dome, and the other on the eastern side of Plateau Dome. Both have vertical walls of rhyolite, and were probably formed soon after extrusion of the respective domes. The material which must have been thrown out in each case is not exposed at the surface, however, and hence the exact age of formation is unknown.

The best known explosion craters are those associated with the 1886 eruption, and these will be described in detail in a later section (p.62).

2. INTERNAL STRUCTURE

Introduction

The 1886 fissure cuts across several of the Late rhyolite domes of the Tarawera Complex, and hence the internal structure can be examined in more detail than usually possible. In the Early Domes and Flows, however, the exposures are poor and more or less restricted to the margins. The main features examined in this study were 'primary structures', and jointing. The former could normally be interpreted visually in the field, but in some cases it was found necessary to collect orientated samples of the rock for a more detailed investigation. These were cut into blocks with five or six smooth faces (at varying angles to each other) and after examination with a hand lens the direction of any primary structure noted. The orientation of joint planes was measured at a number of outcrops around the margin of Wahanga Dome, but elsewhere a visual interpretation only was attempted.

Primary Structures

'Flow' structure is best developed in the obsidian lava flows of the Complex, where alternate bands of black and dark grey glass, and the development of lines of spherulites, produce 'platy' flow structure. This is horizontal in the one outcrop visible within a flow (in the Chasm N77/937913) but near the margins of flows it becomes irregular and often forms 'overfolds'. The flow layers always appear to remain parallel to fracture planes. In thin section a microscopic platy flow structure can be seen with alternate bands rich and poor in microlites (each band < 0.5 mm in width).

Feldspars may show a weak lineation in the same direction.

The flow structure in the domes is less well developed, and is only distinct in the more glassy portions of the margin. In the pumiceous rhyolite, which forms the outer 'skins' of the domes, flow lines can sometimes be recognized by alternate bands of solid and pumiceous glass (usually 2-3 mms. wide). This also gives a colour banding, as the former is usually darker than the pumiceous glass. Biotites conform with the banding as their platy surfaces lie parallel to it. Feldspar and quartz crystals show little evidence of lineation.

The 'spheroidal banding' occurs in the centres of some domes, and is normally recognized by elongation of lines of vesicles; preferred orientation of micas, with their flat surfaces parallel to the layering; and colour banding due to alternating layers rich and poor in spherulites. On a larger scale this banding can be seen to be concentric, and where it is possible to get a 3-dimensional interpretation, it appears to be concordant with the 'onion-skin' joint pattern in the domes.

Jointing

Jointing is widespread in the rhyolite domes of the Tarawera Complex. The joints range from small fractures which continue for only two or three feet, to large joints which extend the height of the dome. The surfaces are usually rough, except where they form the walls of the 1886 craters. In the lava flows they are usually smoother than in the rhyolites.

The joints can be broadly divided into two types; straight joints, which bear little common relationship to flow structure; and curved joints, which may or may not be related. The straight joints are normally the shorter and occur particularly around the margins of the domes. They can sometimes be regarded as 'cross joints' or 'diagonal joints', but the type and direction usually varies in any one outcrop. The curved joints occur throughout the domes, and are best developed near the centre.

In the lava flows the pattern is obscure. On a small scale, fractures (3-5 ft. in length) are parallel to the flow structures, but on a larger scale, cross or diagonal joints are probably more common. In a few outcrops at the fronts of the Northern and North Western lava flows, smooth cliffs of obsidian occur, together with large rectangular blocks of the same lava which appear to have fallen from them. This suggests that there may be major joints parallel to the fronts of the flows, which caused their instability. Such joints could correspond to the vertical tension fractures found in the flows associated with the White Hill Dome, Ascension Island (Daly, 1925, p.35).

Domes of the Tarawera Complex

Wahanga Dome

Wahanga Dome is considered from its external form to have been extruded from a central vent and flowed outwards in three lobes. The 1886 fissure has cut across the southern two of these lobes, and the resultant exposure provides the best cross section in the Complex.

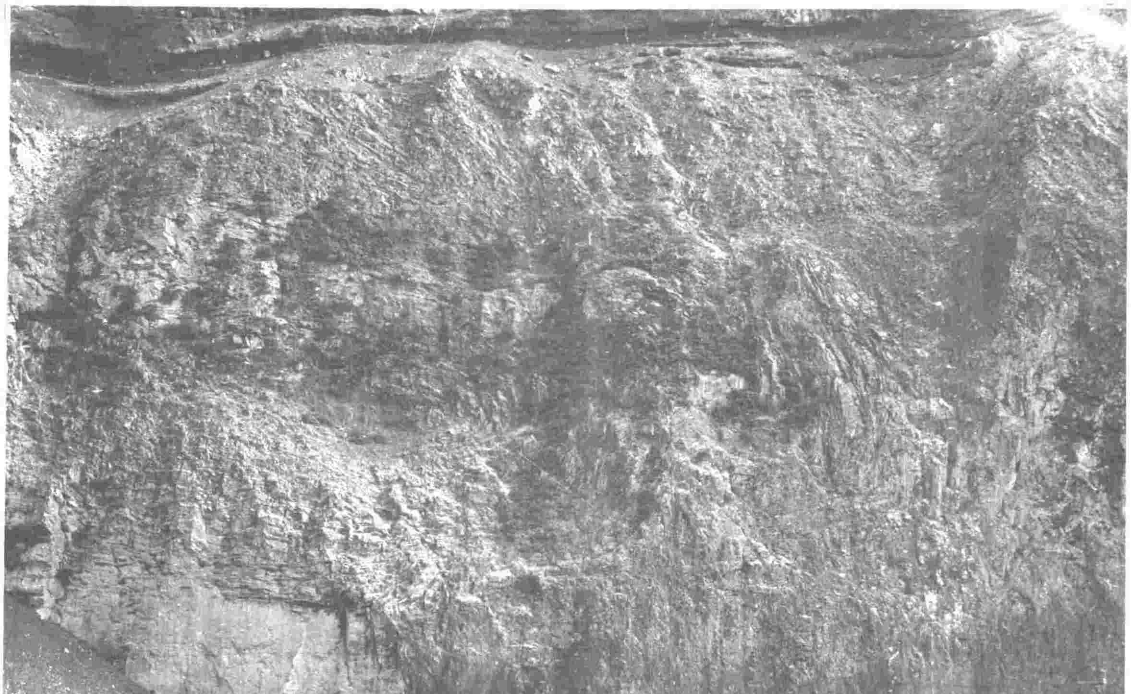
Platy flow structure can be recognised in some of the craggy

Fig. 4.

Crag of pumiceous rhyolite on top of Wahanga Dome (N77/972947) showing flow layers dipping at 80° - 90°.

Fig. 5.

'Onion-skin' structure in Wahanga Dome as seen in the north wall of the 1886 crater on the south side of the dome. Height of section ≈ 300 ft.



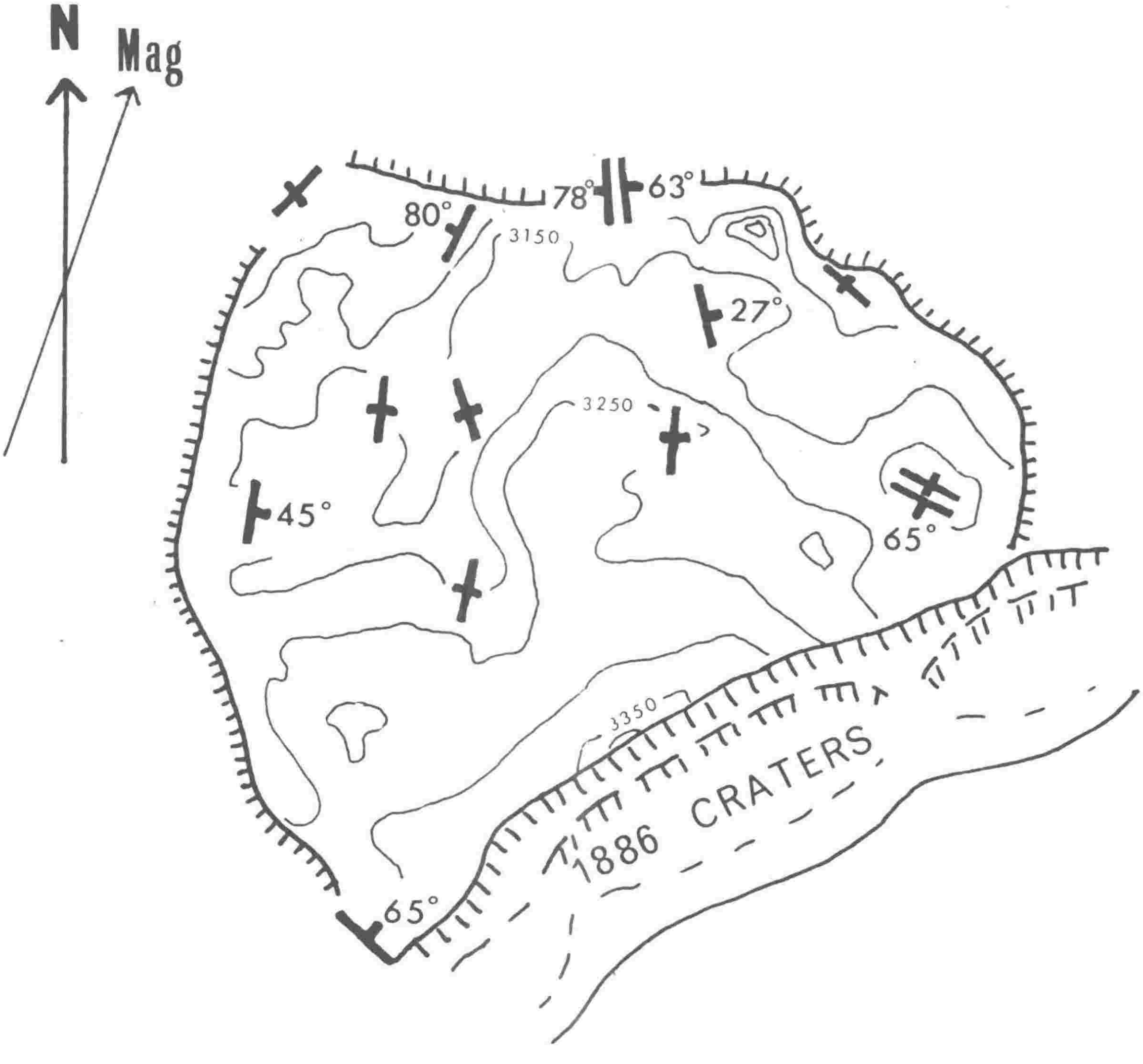


Fig. 6. Orientation of Flow Layers on Wahanga Dome. Note how dip may vary within one outcrop.

outcrops at the margin and on top of the dome (Fig. 4), where the rhyolite is not covered by basalt lapilli. It is usually vertical or dipping steeply into the dome. Fig. 6 shows the average orientation of the flow layers in any one outcrop, and it is apparent from the western part that there is a slight tendency for them to fan outwards. This is comparable to the form of the Main and Breached Domes, Tauhara, described by Lewis (1960, p.22, Fig. 9). There is frequently, however, a tendency for this 'fanning' to occur within individual outcrops (as at the northern margin of the dome) and it is considered that the present orientation of the banding is largely a result of faulting and 'rafting' of the surface blocks of lava on the viscous interior of the dome.

In the exposure formed by the 1886 fissure, the main features are very different. True flow structure (of the type found around the margin) cannot be recognized, and instead spheroidal banding concentric with the circular jointing is found (Fig. 5). By extrapolation, this banding must encircle the vent rather than emerge from it, and thus it must be at right angles to any flow structure. At the base of the dome the rhyolite is brecciated and forms a coarse agglomerate. This is also the case at the outer margins where blocks form a steep breccia front, typical of that associated with rhyolite domes of this type.

Ruawahia Dome

Ruawahia differs from Wahanga Dome in the development of larger coulées. These flow north west and south west from the assumed vent beneath Ruawahia Trig. The pumiceous rhyolite exposed on the top and

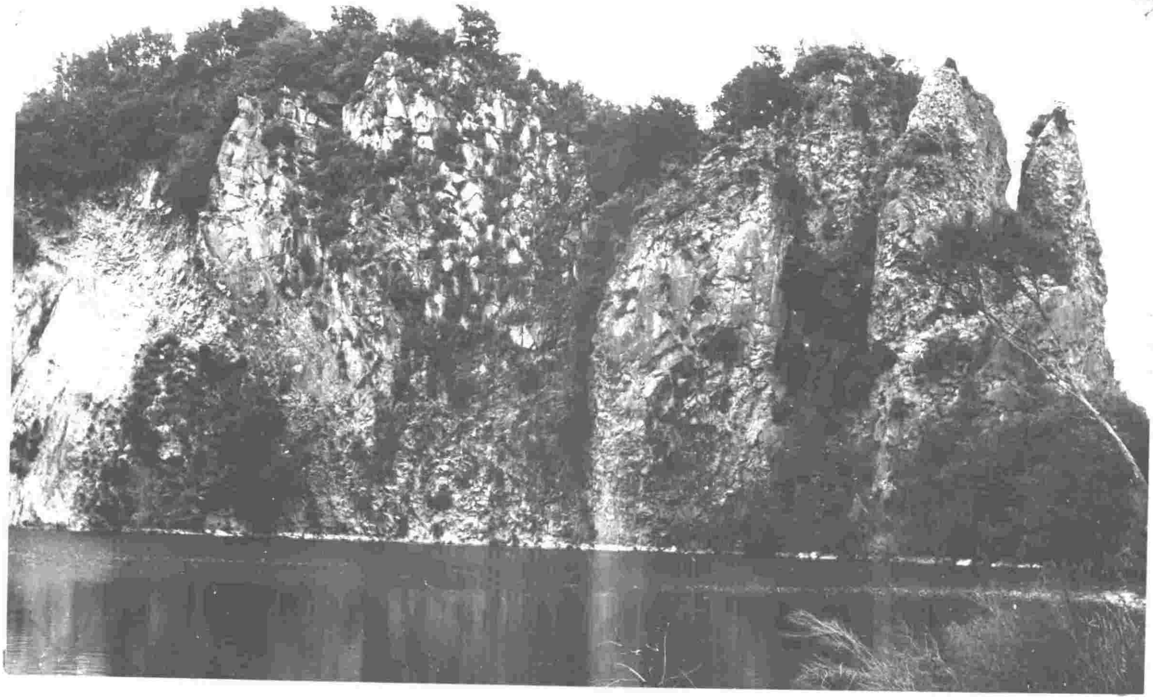


Fig. 7. Green Lake Plug from east side of Green (Crater) Lake. Height of section ≈160 ft.

margin of the dome and coulées resembles that of Wahanga, but from a distance the crags at the margin appear separated by vertical joints. They may thus compare with the Watchman Flow of Crater Lake, Oregon, described by Williams (1942, p.44).

In the section exposed by the 1886 fissure through the centre of the dome the rhyolite is blocky with no apparent consistency of joint directions. In the eastern face of Ruawahia (at the western end of the wide part of the fissure) a slightly later rhyolite dyke cuts vertically through the main lava. It is of the same composition, but can be distinguished by jointing normal to the edges (Plate 3). It appears to reach the surface and form a small 'flow' about 50 ft. long.

Green Lake Plug

This small extrusion is less than 100 yards in diameter and 200 ft. in height. The explosion in 1886, which formed Green (Crater) Lake has destroyed the western half of the plug, but provided a magnificent section through it. The top, like Wahanga and Ruawahia Domes, has blocky crags, but they are agglomeratic, and little consistent flow banding can be measured. The outer margin is steep, the plug having pushed through coarse unwelded ignimbrite of Kaharoa age (Fig. 7). A small talus fan spreads out at the top. Jointing is parallel to the margin, and in the centre there is a small cylindrical 'boss' with a smooth perimeter. This is thought to be comparable to the dyke in Ruawahia in that it represents a late stage intrusion within the plug.

Discussion

Internal Structure

From the previous descriptions of the Tarawera domes, an

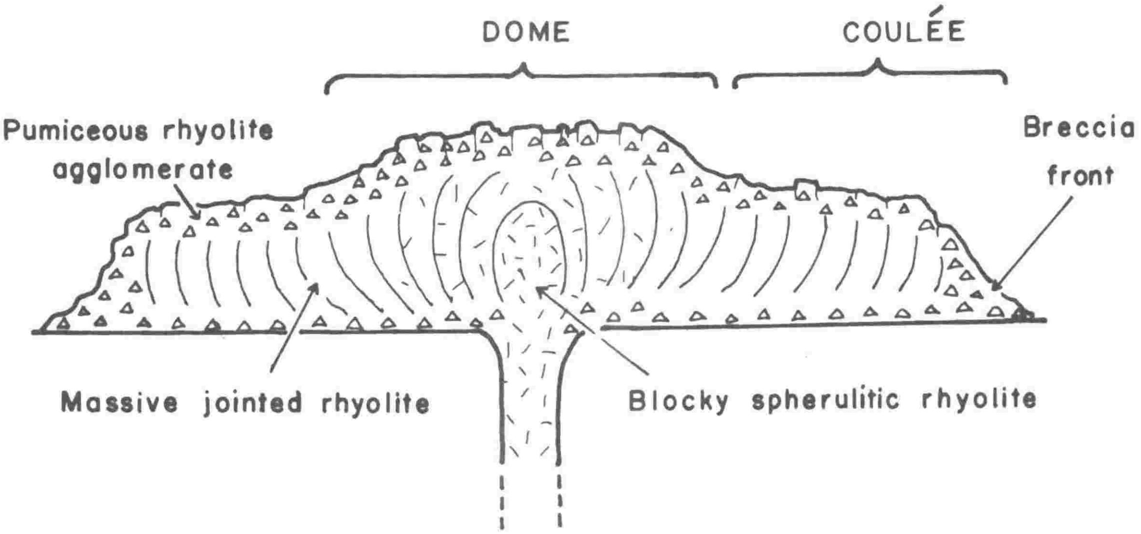
Fig. 8.

A) Diagrammatic cross section of a rhyolite dome and coulée from evidence on Tarawera.

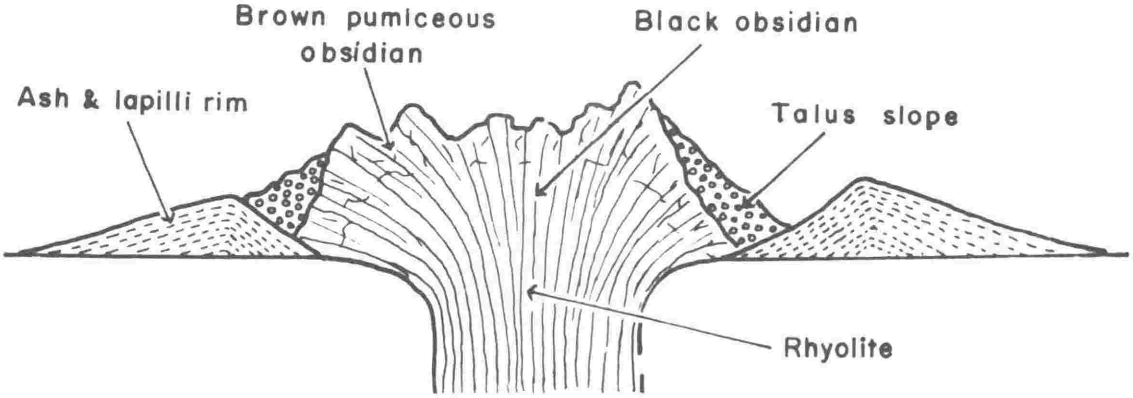
B) Cross section of a dome (Putnam, 1938, Fig.15) from evidence in the Caldera, Mono Craters, California.

C) Colour banding formed in plaster of paris, after it had been extruded through a small aperture (after Reyer, 1888, Fig.84).

A


DOME
COULÉE
Pumiceous rhyolite agglomerate
Breccia front
Massive jointed rhyolite
Blocky spherulitic rhyolite

B


Brown pumiceous obsidian
Black obsidian
Ash & lapilli rim
Talus slope
Rhyolite

C

idealized internal structural model can be produced. Variations from this occur according to size and type of lava within individual domes, but it will serve as a basis for general discussion on the origin and mode of extrusion of rhyolite domes.

The 'spheroidal banding' and concordance 'onion-skin' jointing at the centres of Wahanga and Crater Domes occur in many other parts of the world. The banding has also been produced experimentally by Reyer (1888) who squeezed plaster of paris with various colouring matters in it through a narrow aperture (Judd, 1888, p.125).

At the margins, the joints are irregular, although approximately straight and probably tensional. Primary structures in this position are represented by flow layers 'fanning' out from a centre. The crags of rhyolite (20-30 ft. high) at the tops of the coulees are possibly a result of minor faulting, which produced a series of small 'horsts' and 'grabens' on the extrusions. Such features have also been found by Tanakadate (1917) at Tarumai, Japan.

This model, together with the block fronts developed at the margins of the domes and coulées, is shown in Fig. 8, where it is compared with Reyer's experimental model, and a small generalized obsidian dome, based on one exposed in the Caldera at Mono Craters (Putnam, 1938, p.79, Fig. 15).

Inferred Mode of Growth

Williams (1932a) has summarized the structure and suggested eruptive histories of many domes around the world, and from his account it is apparent that their structure is dependent largely on the composition and viscosity of the lava, and its mode of extrusion.

The formation of most domes is preceded by an explosive phase. This may be of local significance, simply clearing the vent before the main extrusion (e.g., before Crater Dome), or it may be very much more extensive, and produce a widespread ash shower, as occurred before the extrusion of Ruawahia Dome. This phase presumably results from a high volatile content at the top of the magma reservoir. Afterwards less volatile rich magma moves to the surface through the vents produced by the earlier activity.

Once the lava has reached the surface, the two factors previously mentioned decide its history. If the lava is highly viscous, as with most rhyolites, it fills the ash crater to form a plug, or a steep sided dome. In some cases there is sufficient fluidity to form a short coulée, as at the Mono Craters, California (Putnam, 1938, pp.68-82). If the viscosity is lower (e.g., in dacites or trachytes) flows usually form, and these are common in Ascension Island (Daly, 1925) and in the Crater Lake, Oregon region (Williams, 1932a). Composition, and hence viscosity, cannot be the only factors involved, as at Tarawera the domes associated with lava flows, and those without, have similar silica contents. Shaw (1963) has shown that variation in water content affects viscosity, and this could be a controlling factor at Tarawera.

The lava forming the domes may build up in an exogenous or and endogenous manner, and these will each produce a different structure. In the former case the central opening must be maintained and the lava built up layer by layer. This mechanism is envisaged by Lewis (1960, p.30) for the Main and Breached Domes of Tauhara, and is presumably the way in which the small obsidian dome exposed in the Caldera at Mono Craters formed (Putnam, 1938, p.81). At the other extreme, new material extruded pushes earlier material outwards by internal expansion (endogenous growth). This causes strain, normal to the movement of the lava, and results in strain fractures. These promote the formation of spherulites along the length, hence the spheroidal banding. Such a mechanism is most likely to be found in highly viscous lava which is erupted through a very narrow vent, especially if it accumulates under a thin cover of older material. This is thought to have occurred at Divide Peak, Lassen region, California (Williams, 1929, p.293).

In most cases, as Williams (1932a, p.143) pointed out, it is probable that both forms of growth have occurred during the formation of the dome. During the early stage, blocky lava is erupted exogenously, but as this extrusion becomes larger, new lava tends to push this upwards and outwards (i.e., it become endogenous). Fissures develop on the top surface as a result of the expansion, and blocks fall between the others as wedges. If a fissure is particularly large new lava may reach the surface to form a short stubby flow.

The lineation of micas parallel to the spheroidal banding cannot be explained simply by outward expansion, but if any lateral movement of the lava took place during the endogenous growth, the mineral would probably show some orientation. This could occur during cooling, as a certain amount of settling of the dome is thought to take place. Tanakadate (1917, p.97) considered this to be about 5-10 per cent of the total volume. He suggested that the original shape of this type of dome is hemispherical and that the flat top, as on Wahanga Dome, is a result of contraction.

During the periods of growth and cooling, gas accumulates within the dome, and this wherever possible escapes through fissures. If it is unable to do this, pressures will be built up, until the volatile pressure is greater than the strength of the rock, and an explosion will occur. This is the mechanism that probably formed the explosion vents at Tarawera (marked on Fig. 3).

Most of the domes at Tarawera are thought to have formed by the mode of growth described. Wahanga and Crater Domes, with their visible 'onion-skin' structure and Eastern Dome, are the nearest to true endogeneous domes, and as such were presumably extruded through a narrow vent. Ruawahia and Tarawera Domes started in the same manner, but during the formation of the coulées, considerable fracturing of the upper surface must have occurred, and 'dykes' like that visible in Ruawahia Dome would be able to reach the surface.

Plug domes, such as Green Lake Plug, probably have a different mode of origin. The vent is almost the same size as the extrusion, and the lava probably rises in a near solid condition. This produces smooth margins on which striations can now be seen (e.g., Lassen Peak, California; Williams, 1929). In many cases these extrusions congeal under sedimentary deposits at the bottom of craters (as at O-usu, Japan; Tanakadate, 1930, p.697) and become pushed up by the slow continual extrusion of the lava.

Fig. 9.

Tephra columns of the Tarawera - Rerewhakaaitu region.

(in pocket at back of thesis).

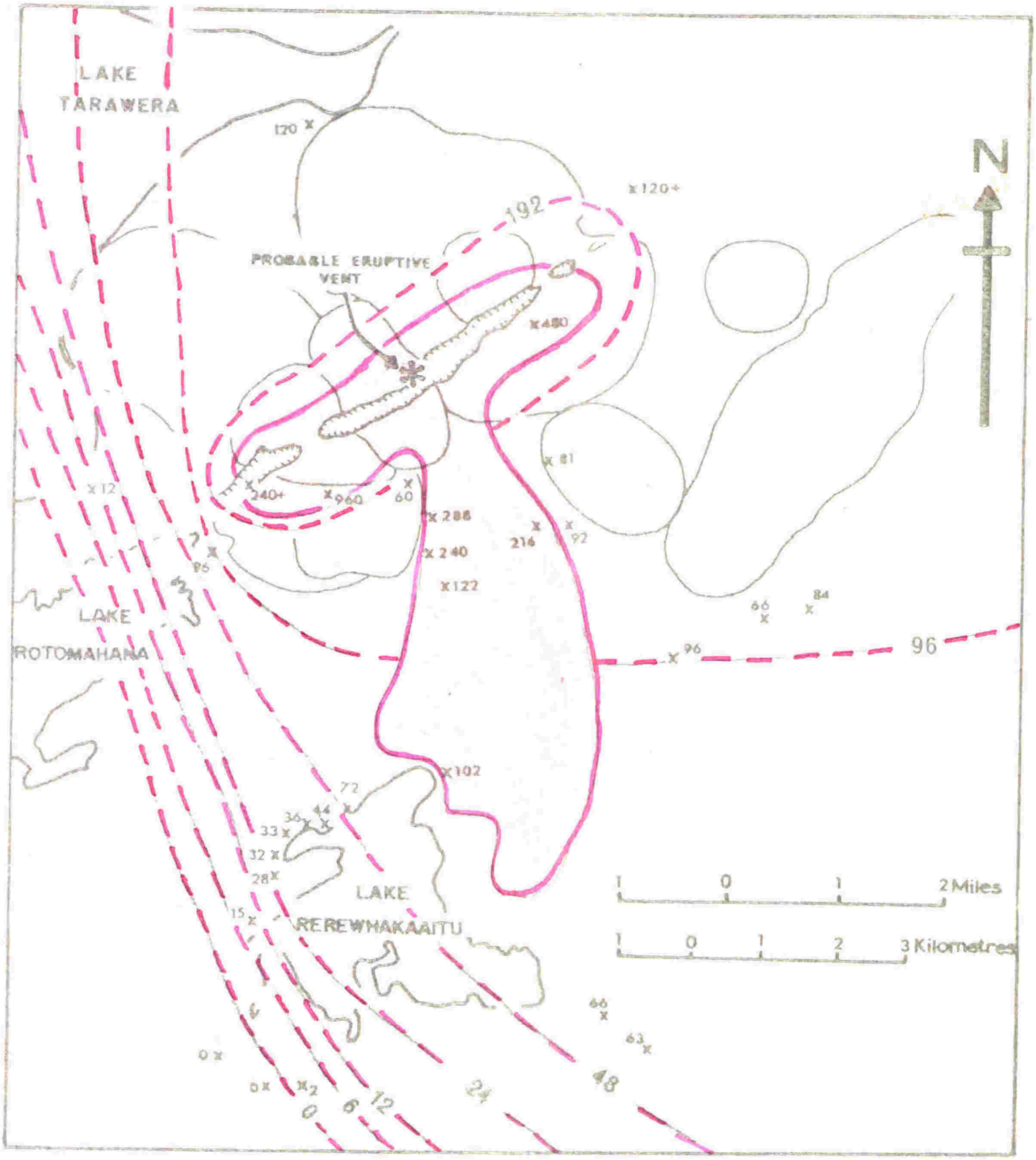


Fig. 10. Generalised Isopach Map showing distribution of the Kaharoa 'Ash' in the Tarawera - Rerewhakaaitu region. X^3 - Thickness of Kaharoa 'Ash' in each section. The shaded area shows the extent of the unwelded ignimbrite deposits. All thicknesses shown in inches.

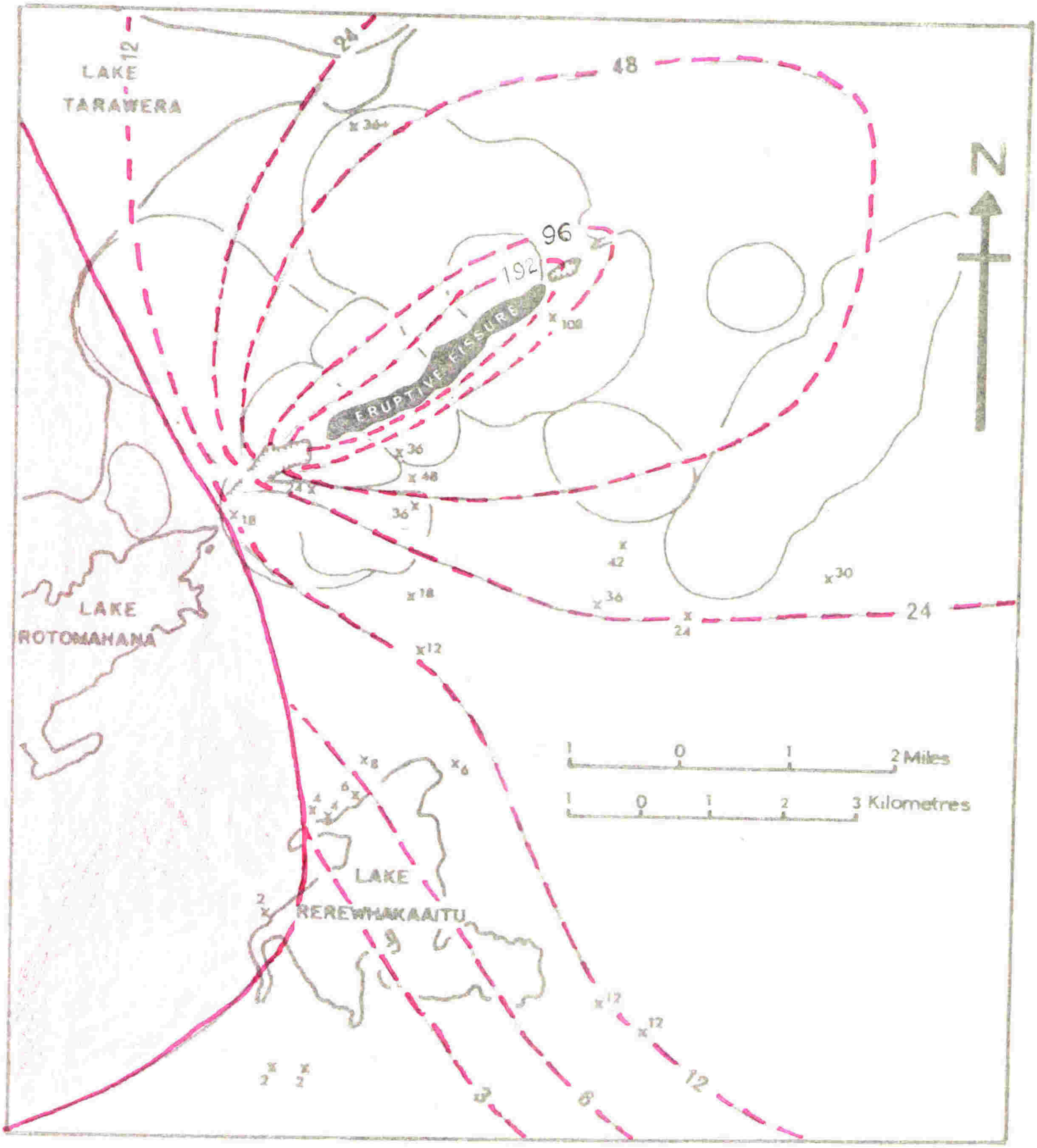


Fig. 11. Generalised Isopach Map showing distribution of the Tarawera 'Ash' in the Tarawera - Rerewhakaaitu region. x^3 - Thickness of Tarawera 'Ash' in each section; Shaded area covered by the Rotomahana Mud. All thicknesses shown in inches.

3. TEPHRA STRATIGRAPHY OF THE TARAWERA-REREWHAKAAITU REGION

INTRODUCTION

The Holocene tephra showers of the Rotorua-Gisborne region have been discussed by Vucetich and Pullar (1964). They have described sections in the region and by their correlation have suggested approximate sources for the deposits. The present study uses their section at Democrat Road, Rerewhakaaitu (Vucetich and Pullar, 1964, pp.66-67) as a standard and by more detailed correlation in the Tarawera-Rerewhakaaitu region (see General Map in pocket at back of thesis), shows local variation in the stratigraphy and structure of the deposits. Four 'Ashes' are regarded as having their source in the Tarawera Volcanic Complex, and these are described in more detail.

Methods of Correlation

The stratigraphic column of tephra in the Tarawera-Rerewhakaaitu region is shown in Table 1, with available 14C dates. Individual sections are shown in Fig. 9 (in pocket at back of thesis) and isopach maps are drawn for the Kaharoa and Tarawera 'Ashes' in Figs.10 and 11.

Individual formations may be recognized by: distinctive lithology; presence or absence of a buried soil; and mineralogy. The lithology changes both with distance from the vent, and, as many air-fall eruptions are directional in their area of deposition, laterally around the vent also. Buried soils are useful in distinguishing older tephra from the Kaharoa 'Ash' particularly near the vent where lithology may be similar.

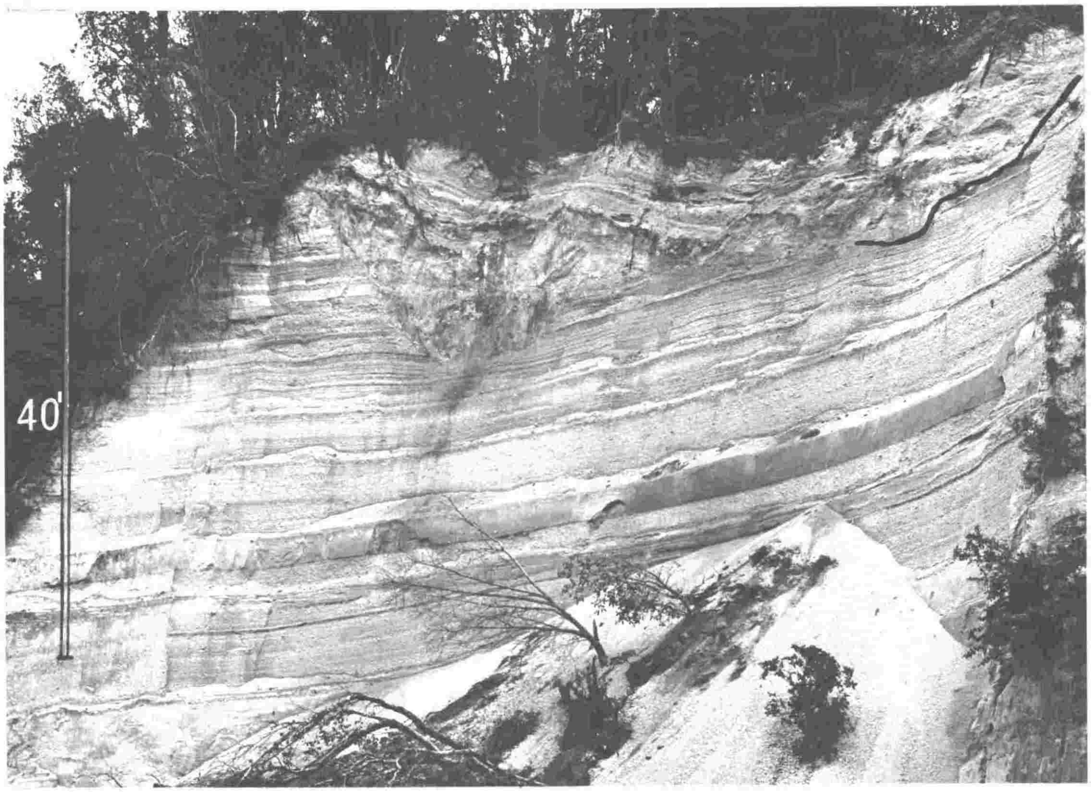
Mineralogy is of limited use in the field but may be the

Fig. 12.

Shower bedded Waiohau 'Ash' in the walls of a pumice wash (N77/964914). Succeeding tephra fills the gully cut into the top of this 'Ash'.

Fig. 13.

'Leach zone' at the top of the Taupo 'Ash' in Gavin Road, Rerewhakaaitu (N86/999825).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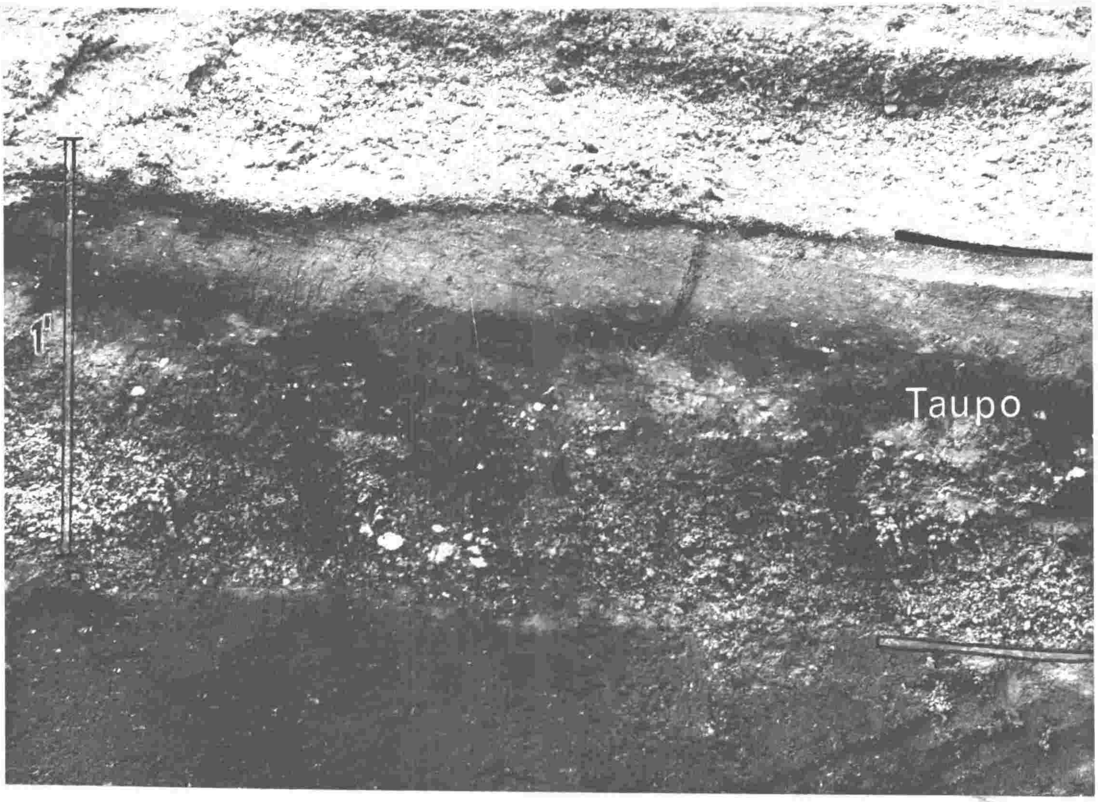

1'
Taupo

deciding factor on later examination in the laboratory. It is particularly useful when only a small section is available with no characteristic lithology and no distinct soil. The Rerewhakaaitu 'Ash' is mineralogically distinctive in that it contains two types of pumice; one rich and the other poor in phenocrysts. Most tephra contains pumice of one type only.

Features of Buried Soils

Buried soils are formed during the time between successive eruptions in which weathering can take place and vegetation grow. The soil may, in some cases, be poorly developed or even absent, and the division between formations now represented only by an erosional break. This occurs particularly at the top of thick tephra deposits where presumably all vegetation has been killed, and sheet erosion can take place. An example in the Tarawera-Rerewhakaaitu region is the Waiohau 'Ash', where frequent depressions cut into the shower bedded tephra. These have become filled with tephra from more recent eruptions (Fig. 12).

Other formations have dark brown soil horizons and many of these contain charcoal within the top 1-2 ins. Such soils are usually followed by a thick sequence of ash, indicating that the falling tephra came from a nearby source. This factor would also be necessary to provide the heat to form the charcoal. An example of this relationship occurs at Gavin Road, Rerewhakaaitu (N86/999825) where the soil of the Rotorua 'Ash' contains charcoal and is followed by a thick succession of Waiohau 'Ash' from a vent on Tarawera.

If only a small amount of cool tephra is deposited from a distant source (e.g., the Rotorua 'Ash' at the above locality) only very low vegetation becomes affected and larger trees survive. This causes the new tephra to become incorporated in the soil of the previous deposit, and it is then difficult to distinguish between the two eruptive units.

About 1 inch below the top of the Upper Taupo Member is a fine grey ash, 3-6 ins. thick in the Rerewhakaaitu region (Fig. 13). This is within the buried soil of the Taupo 'Ash' and has the same mineralogy and age as this 'Ash' (by 14C dating). It is thus regarded as a 'leach' zone where humus has been removed after burial (Vucetich, pers. comm.).

The soil of the Kaharoa 'Ash' is particularly dark, due to small basalt lapilli from the early stages of the Tarawera eruption. These became incorporated in the 'Ash' to give it the appearance of containing much charcoal.

Tephra below Rerewhakaaitu 'Ash'

The sequence of tephra shown in Table 1 mantles different deposits in different places. To the south of Lake Rerewhakaaitu, at Democrat Road (N86/932825) and Gavin Road (86/999825) the Rerewhakaaitu 'Ash' lies on an undifferentiated brown silty ash, which Vucetich and Pullar (1963, p.65) call the 'Pinkish-brown' beds. On the other side of the lake, however, the Rerewhakaaitu 'Ash' lies directly on ignimbrite and the 'Pinkish-brown' beds must have been eroded. Vucetich (pers. comm.) thinks this occurred during a period of colder climate with perhaps higher rainfall.

DESCRIPTION OF TEPHRA ERUPTED FROM THE TARAWERA VOLCANIC COMPLEX

In the descriptions of the tephra, the type or representative sections are taken in the Rerewhakaaitu region as individual 'Ashes', are usually 4-6 ft. thick there. This thickness is convenient for examining vertical variation in lithology and also provides a useful mean for comparing variation in lithology around the vent. Towards the source the thickness increases until complete sections are rare, and this is where mineralogy is most important for correlation.

Rerewhakaaitu 'Ash'

The type section of the Rerewhakaaitu 'Ash' (Vucetich and Pullar, 1964, p.57) is in Democrat Road, Rerewhakaaitu (N86/934824) where the following sequence occurs:

	Thickness (in inches)
Dark brown greasy ash, some pumice fragments 2 cms. diameter (Rotorua 'Ash')	6
Indistinct junction	----------
Light-dark brown ash with pumice fragments up to 5 cms. diameter	6-15
Shower bedded coarse ash, fine ash and lapilli	21-30
Distinct lapilli band	3-5
Shower bedded coarse ash and lapilli	10-15
Undifferentiated 'Pinkish-brown' beds	

In the pumice washes on the south side of Tarawera, the Rerewhakaaitu 'Ash' is very thick (at N77/964914 it is over 200 ft. thick), weakly shower bedded, and contains many blocks of pumice and partially expanded obsidian over 20 cms. in diameter. These blocks occur in a matrix of medium - coarse ash. The top of the 'Ash' is extensively gullied, and this probably took place soon after the eruption. The gullies partially filled with debris from the Rerewhakaaitu 'Ash' and then later became filled with the Waiohau 'Ash'.

The lapilli and blocks are of three types; obsidian, pumice with a high crystal content, and pumice with a low crystal content. This assemblage is most important for correlation near the vent. It also suggests correlation with Rotomahana and Rerewhakaaitu Domes (see p. 93) and it is probable that the Rerewhakaaitu 'Ash' was erupted from the same vent as the Rerewhakaaitu Dome. The increase towards this site, and maximum thickness at N77/964914 tend to confirm this. A few blocks (max. diameter 20 cms.) of hornblende-quartz-dacite are found in the Rerewhakaaitu 'Ash', and these are regarded as most important. Full petrographic and petrogenetic descriptions will be given in the relevant sections.

Waiohau 'Ash'

The Waiohau 'Ash' was named by Vucetich and Pullar (1964 p.55) from the thick deposits in the Waiohau district. The type section is, however, in Democrat Road, Rerewhakaaitu (N86/934824) where the following sequence occurs:

	Thickness (in inches)
Dark brown sandy ash with some charcoal (Taupo 'Ash' Sequence?) grading down into lighter coloured ash with a few pumice lapilli and some obsidian	12 ---------- 9
Shower bedded pumice and obsidian dominant, some rhyolite	12-27
Shower bedded coarse and fine ash	15
Loose pumice lapilli grading up into ash	6-10
Obsidian lapilli band	1
Pumice lapilli	2

Pale yellow 'greasy' ash becoming lighter downwards (Rotorua 'Ash')	24

The Waiohau 'Ash' also thickens towards Tarawera, and in the pumice washes (N77/964914) is over 50 ft. thick (Fig. 12). Shower bedding is ubiquitous. At N77/965915 the base of the Waiohau 'Ash' is in a shallow gully cut into the underlying Rerewhakaaitu 'Ash' and about 6 ins. above the base small charred logs occur. These presumably represent trees that were growing on the Rerewhakaaitu 'Ash' and were destroyed by the Waiohau eruption. One sample has been dated by radiocarbon method as 11,250 ± 250 yrs. before 1960 (Table 1).

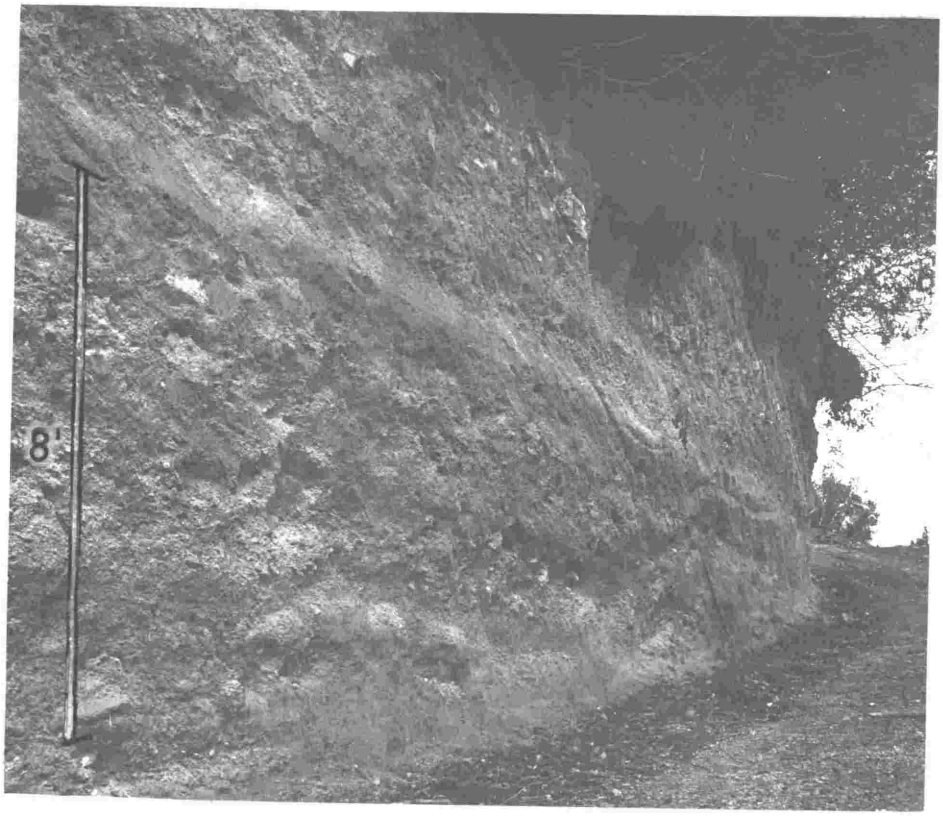
The top of the deposit is always strongly gullied, and in the Rerewhakaaitu basin the depressions are filled by a brown loamy ash which Vucetich and Pullar (1964, p.46) regard as Taupo 'Ash' Sequence Members 16-18. On the southern side of Tarawera where the gullies are larger and deeper the entire succeeding tephra sequence, except for the Kaharoa, may be found in them.

Fig. 14.

Unwelded ignimbrite of 'Waichau' age, exposed by the track up the south side of the mountain (N77/981906).

Fig. 15.

Two unwelded ignimbrite units of 'Kaharoa' age, exposed in the walls of the main pumice wash to the south of the mountain (N86/963898). Length of hammer shaft ≈ 15 ins.


8'

In a large section beside the track from Rerewhakaaitu to the top of the mountain (N77/981906) is an unwelded ignimbrite deposit or sillar which is considered by its position in the tephra sequence to be of Waiohau age. This shows incipient banding with variation both in colour and in grade of the tephra, both shown particularly well when the exposure is wet (Fig. 14). The main feature is the presence of large blocks of obsidian in various stages of expansion, providing a useful index of temperature.

The exact source of the Waiohau 'Ash' is unknown. The thickest sections are in the pumice washes to the south of Tarawera Dome, and it may be that a shallow depression with a tephra rim found on top of Rerewhakaaitu Dome (N77/953914) represents the eroded remains of the original Waiohau 'Ash' cone. However, as this has now been partially filled with Kaharoa and Tarawera deposits this cannot be certain.

Kaharoa 'Ash'

'Kaharoa Shower' is the name given to the parent material of the soil at Kaharoa and north of Rotoiti (Grange, 1929) with the type section taken as Old Tauranga Road, Kaharoa. This has "9 ins. of white pumiceous rhyolite ash (carbonaceous at top) with texture of fine gravelly sand (Kaharoa Shower) overlying 1 ft. of dark brown pumice with basic material (Rotokawau Shower)" (Grange, 1929, p.224). Vucetich and Pullar (1964, p.48) later changed the name to Kaharoa 'Ash'.

Grange's type section is of little use in the present study because of its distance from the source, and a representative section has been taken at Gavin Road, Rerewhakaaitu (N86/999825). The sequence at this locality is:

	Thickness (in inches)
Humus stained sand and ash - few Tarawera lapilli	12-15

Fine ash, yellow brown soil at top	6
Fine and coarse ash alternating with white pumice lapilli, some rhyolite, obsidian and andesite (2 units)	20
Fine ash	2
Shower bedded coarse ash and lapilli, a few thin bands of fine ash	14
Fine and coarse ash alternating with white pumice lapilli, some rhyolite, obsidian, and andesite (3 main units)	22
Fine grey ash	2

Greasy yellow brown sandy ash (Taupo Ash Sequence)	9

The lithology of the Kaharoa 'Ash' changes markedly both around and towards the mountain. The thickness decreases rapidly to the south west, until in the section at N86/934824 it is absent (Fig. 10). Northwards it increases again and at Bretts Road, Rerewhakaaitu (N86/942853) there is the following section:

	Thickness (in inches)
Tarawera lapilli	2

Black ash grading downwards into dark brown ash	4
Coarse ash with thin bands of pumice, rhyolite and obsidian	24
Pumice lapilli	4

Brown greasy ash (Taupo)	> 6

Towards Tarawera the Kaharoa 'Ash' thickens, and several unwelded ignimbrites appear in the sequence. About 18 ft. of Kaharoa 'Ash' is exposed in a section by the track up the mountain from Rerewhakaaitu (N77/981906)

	Thickness (in inches)
Banded coarse and fine basalt lapilli (Tarawera 'Ash')	12-36
Shower bedded ash and lapilli (pumice, obsidian, rhyolite, andesite)	6-24
Fine-coarse pink ash, unsorted, with a few blocks up to 50 mms. diameter. Some current bedding at top, probably due to wind action. One large log of charred wood (Unwelded ignimbrite deposit)	48-72
Coarse lapilli and blocks of pumice, rhyolite, obsidian and andesite	12
Fine-medium unsorted ash (unwelded ignimbrite - as above)	54
Coarse lapilli and blocks up to 75 mms. diameter	12-18
Shower bedded coarse-fine ash of pumice, rhyolite and obsidian (4 main units)	24
Coarse lapilli and blocks, mainly pumice	9-12
Fine-medium ash	9-15
Coarse ash	½
Dark brown ash for top ½ in., then fine grey ash (Taupo)	> 6

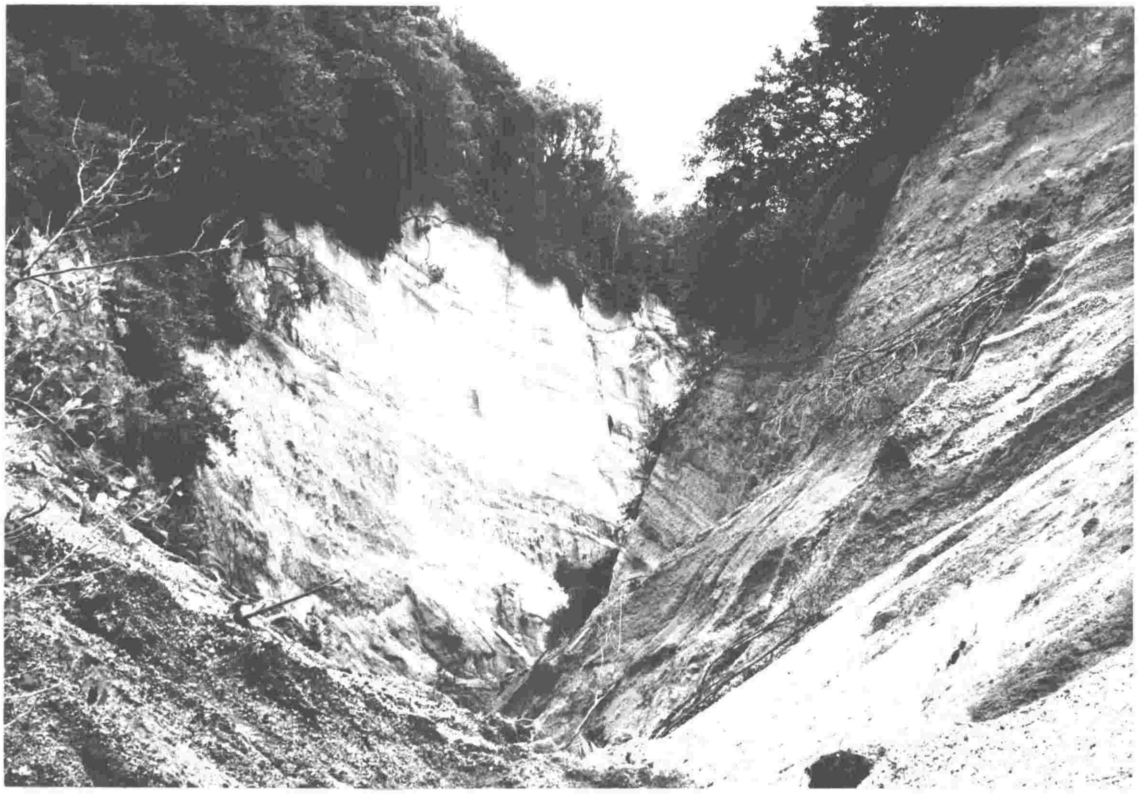
The unwelded ignimbrite deposits (Fig. 15) are of local extent (Fig. 11) and are very similar to those surrounding rhyolite volcanoes in Japan (Aramaki, pers. comm.). They thicken towards Ruawahia Dome, and the site of this dome is considered to be the

Fig. 16.

Lahar breccia of 'Kaharoa' age, with blocks of pumiceous rhyolite probably derived from Ruawahia Dome.

Fig. 17.

Post-Kaharoa 'gully infill' deposit to the right of photograph, and a thick section of Waiohau 'Ash' to the left. Height of latter section $\approx$ 100 ft.



source for the Kaharoa deposits.

To the north east of Lake Rerewhakaaitu there are many loose blocks of rhyolite on the surface, some 1½ metres in diameter. These are entirely pumiceous rhyolite, identical to that of the Late Domes. Where the blocks occur in a breccia (Fig. 16) the matrix is rhyolitic and of ash grade. The origin of these blocks and the unwelded ignimbrites will be discussed in the section on the Kaharoa eruption (p. 62).

After the Kaharoa eruption the thick pumice deposits to the south of the mountain were extensively eroded to form gullies similar to the present day 'pumice washes'. These gullies later became filled with debris derived from the Kaharoa tephra, to form 'gully infill' deposits (Fig. 17). These have made correlation of the tephra very difficult in the region.

The Kaharoa 'Ash' and associated ignimbrites are largely composed of pumice, but there are also blocks and lapilli of obsidian, rhyolite, granodiorite and various basic rocks. The granodiorites resemble rhyolite closely when coated with ash and are difficult to distinguish in situ. Most samples described come from the 'gully infill' deposit. The basic rocks include andesite, pyroxenite and eucrite, and these, with the granodiorite, will be discussed in detail in the section on petrography.

The eruption has been dated by radiocarbon method from a charred log within the Kaharoa 'Ash'. This was found 3 ins. above the base of a section at Northern Boundary Rd., Kaingaroa Forest, and gives an age of 930 ± 70 years before 1950 (N.Z. 170, Grant-Taylor

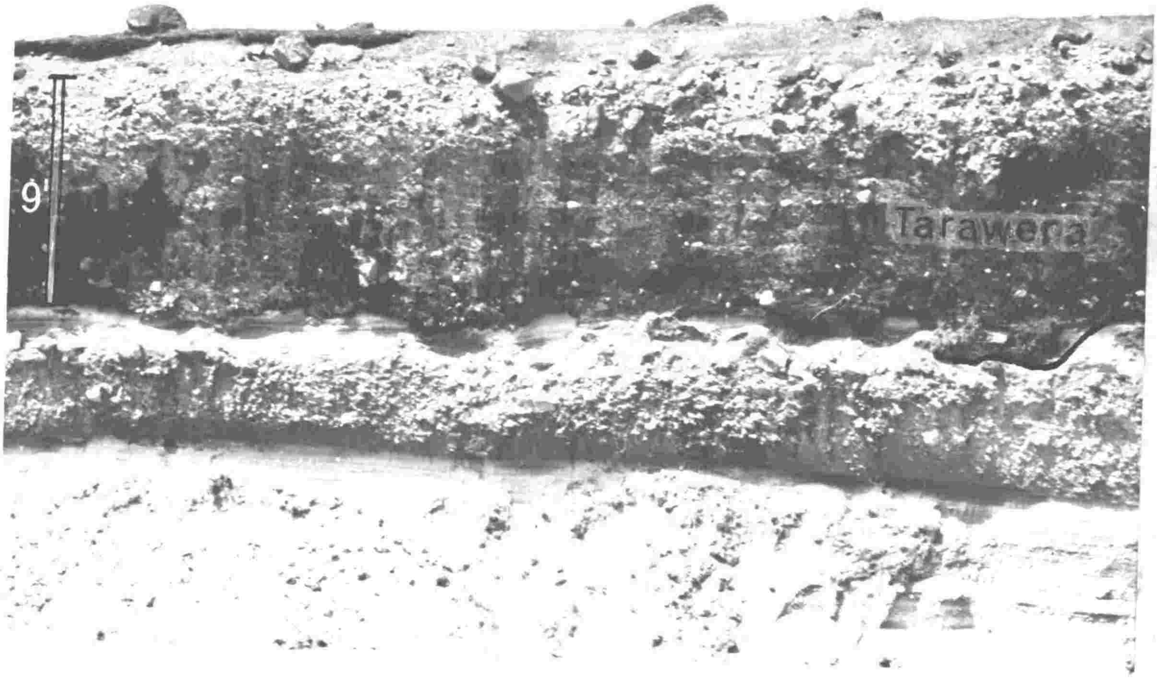
Fig. 18.

Shower bedded Tarawera 'Ash'. Vertical section in gully to south west of Ruawahia Dome (N77/964922). F - fine bands ; C - coarse bands.

Fig. 19.

Tarawera 'Ash' in gully to the south of Wahanga Dome (N77/983941), showing vertical increase in the amount of rhyolite in the sequence.


F
C
F
C
F


9'
Tarawera

and Rafter 1963, p.140).

Tarawera Formation

The Tarawera Formation consists of the Tarawera 'Ash' and the Rotomahana Mud (Vucetich and Pullar, 1964, p.48). The former was erupted from the craters on Tarawera and during the later stages of the eruption, the Rotomahana Mud from Lake Rotomahana.

The Tarawera 'Ash' was deposited in a wide sector from Tauranga in the north west to Tolaga Bay on the east coast (Thomas, 1888, frontispiece) but it can now only be identified in a more restricted area (Vucetich and Pullar, 1964, Fig. 37), providing an example of how detectable limits of tephra decrease with time.

Near its source the Tarawera 'Ash' is shower bedded (Fig. 18) with coarse lapilli units separated by a basaltic ash. The lapilli increase in size towards the mountain until around the craters large blocks of scoria (max. diam. 20 cms.) occur. In the section exposed in a gully to the south of Wahanga Dome, the following sequence occurs:

	Thickness (in inches)
Blocks of pumiceous rhyolite up to 30 cms. with some basalt	36
Basalt with a few blocks of rhyolite	60
Basalt and rhyolite (max. size 10 cms.)	12

Kaharoa 'Ash'

Further from the source, small fragments of rhyolite occur throughout, and are not concentrated in any position in the sequence.

On the north and west side of Lake Rerewhakaaitu, the Tarawera

'Ash' grades up into the Rotomahana Mud with a few basalt lapilli in it (e.g., Bretts Road, N86/942853). Further north west the Tarawera 'Ash' disappears and Rotomahana Mud becomes the only member present (Fig. 11).

TABLE 1 - SUMMARY OF TEPHRA STRATIGRAPHY IN THE TARAWERA-REREWHAKAAITU REGION

FORMATION (Eruption)	MEMBER	14C ages (years before 1960)	REFERENCE
TARAWERA	Rotomahana Mud	Eruption in 1886	
	Tarawera 'Ash'		
KAHAROA		940 ± 70	Vucetich & Pullar (1964, p.45)
TAUPO	Upper Taupo Pumice	1770 ± 80	Healy (1964a p.42)
	Taupo 'Lapilli'		
	Rotongaio 'Ash'		
	'Putty Ash'	1830 (approx.)	" (1964a p.37)
WAIMIHIA		3340 ± 50	Healy (1964a p.36)
WHAKATANE			
MAMAKU			
ROTOMA			
	BREAK		
	Brown greasy ash (tas. 16-18?)	8860 ± 1000	Healy (1964a
WAIOHAU		11,250 ± 250	Unpublished Analysis. N77/542
ROTORUA			
REREWHAKAAITU			

Undifferentiated pinkish-brown ash or loam.

TABLE 2 - SUMMARY OF GEOLOGICAL HISTORY

AGE (^{14}C dates, yrs. before 1960)	ERUPTION	DEPOSIT	PROBABLE VENT SOURCE
Eruption on June 10, 1886	TARAWERA	Rotomahana Mud	Lake Rotomahana
		Tarawera 'Ash and Lapilli'	Fissure from N77/932912-990950
		Green Lake Plug	N77/933905
930 ± 70	KAHAROA	Wahanga Dome	N77/975945
		Ruawahia Dome	N77/965932
		Tarawera Dome	N77/947920
		Kaharoa 'Ash'	N77/965932
		Crater Dome	N77/955915
11,250 ± 250	WAIOHAU	Waiohau 'Ash'	?N77/953914
16,000 (?)	REREWHAKAAITU	Eastern Dome	N77/018945
		Plateau Dome and Flow	?N77/975945
		Southern Dome and Flow	?N77/005912
		Rerewhakaaitu Dome and Flow	N77/955915
		Rerewhakaaitu 'Ash'	
		Rotomahana Dome	N77/955915
		Western Dome	N77/920912
		? Ridge Dome	?N77/992918

4. ERUPTIVE HISTORY

The sequence of events in the history of the Tarawera Volcanic Complex is shown in Table 2. The early events are speculative as key features are often covered by more recent debris, but events in the Kaharoa eruption can be established with more certainty. Good exposures make it easier to establish relative positions of domes and tephra. The Tarawera eruption is well known because of eye-witness accounts, and the possibility of comparing these stories with present field relationships.

For convenience, the eruptive history is divided into three parts; early eruptions, Kaharoa eruption, and Tarawera eruption. These cover all except the formation of Ridge, Western and Rotomahana Domes, the ages of which are earlier than any pyroclastic eruption from the mountain. Ridge Dome is regarded as the earliest dome now exposed in the Complex because of the thick cover of tephra, and lack of topographic expression. Rotomahana Dome underlies the Rerewhakaaitu 'Ash', and must therefore be earlier than the 'Ash'. Western Dome has a similar degree of erosion and petrography to Rotomahana Dome and is regarded of similar age.

EARLY ERUPTIONS

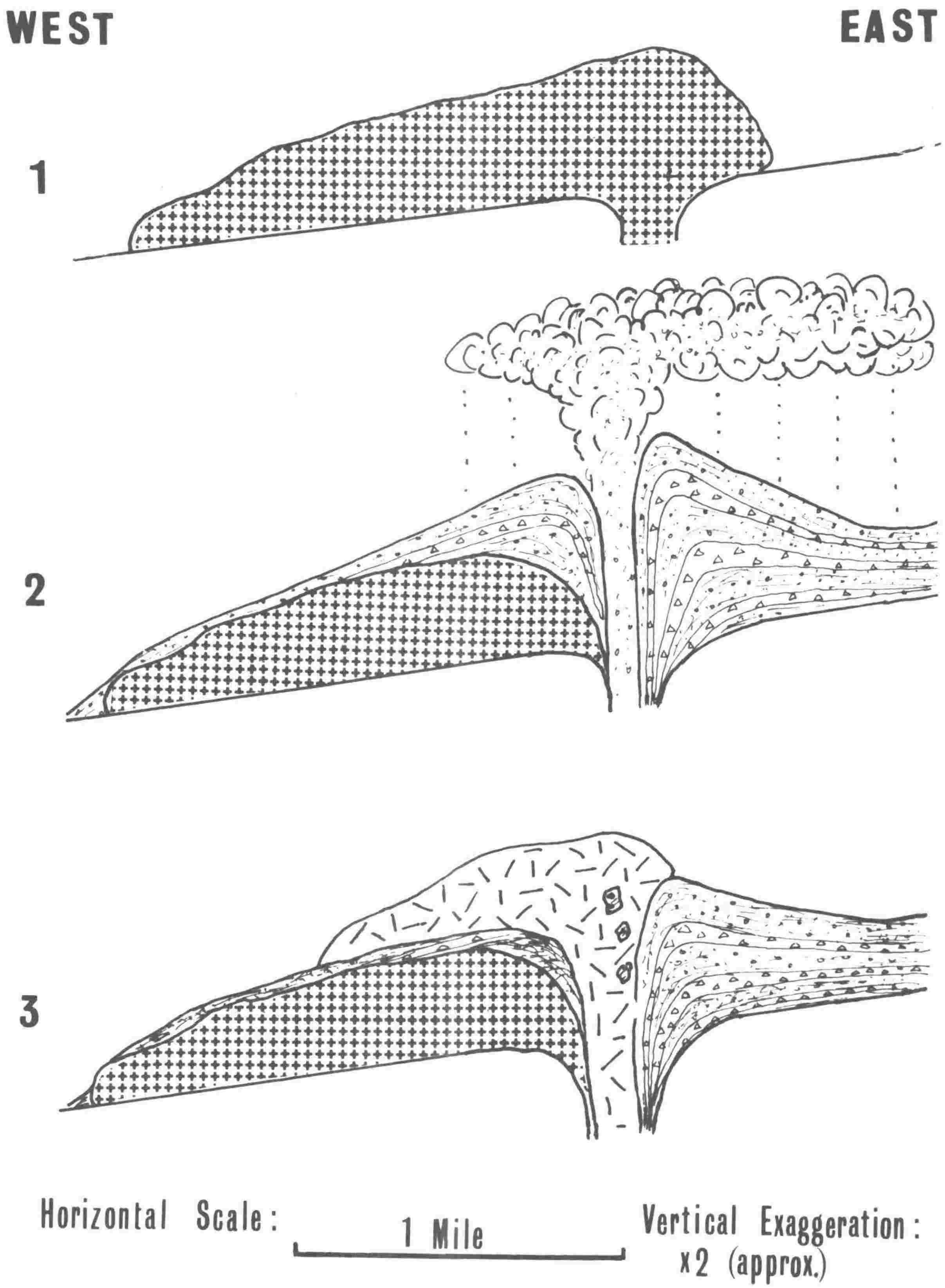
Two pyroclastic eruptions can be distinguished in the early history of Tarawera, and these provide useful reference events for distinguishing relative ages of the rhyolite domes.

1. Eruption of the Rerewhakaaitu 'Ash', accompanied by the formation of Rerewhakaaitu Dome (Rerewhakaaitu Eruption).

Fig. 20.

Diagrammatic cross section of Rotomahana and Rerewhakaaitu Domes, showing probable sequence of events during the Rerewhakaaitu eruption.

1. Extrusion of Rotomahana Dome
2. Explosive eruption of Rerewhakaaitu 'Ash'
3. Extrusion of Rerewhakaaitu Dome (incorporating some of the earlier rhyolite).


WEST
EAST
1
2
3
Horizontal Scale:
1 Mile
Vertical Exaggeration:
x2 (approx.)

2. Eruption of Waichau 'Ash' (Waichau Eruption).

Rerewhakaaitu Eruption

It is not certain how long Rotomahana Dome had been formed before the Rerewhakaaitu 'Ash' was erupted. It may have been thousands of years, or may have been the first event of the Rerewhakaaitu eruption. From its general morphology the former is suspected. However, when the Rerewhakaaitu 'Ash' was erupted, it seems very likely that it was extruded through the same vent as Rotomahana Dome. The 'Ash' is characterized by two distinct types of tephra, one rich in phenocrysts (and comparable to Rotomahana Dome) and the other poor in phenocrysts (like Rerewhakaaitu Dome). It may be that the phenocryst-rich tephra was the earlier dome material, blown out during the eruption, but the high percentage of this tephra in the deposit, and the large blocks of it near the source suggest that the reservoir of the Rotomahana Dome lava was still able to supply ejecta during the Rerewhakaaitu eruption.

This explosive phase was followed by the formation of the Rerewhakaaitu Dome, which flowed in two directions; a small lobe or coulée to the south west, and a larger flow to the north. It perhaps represents the final stage of eruption from the vent. Fig. 20 gives a diagrammatic cross section across this eruptive centre.

The other domes which could be related to the eruption are Southern Dome and Flow, ~~which are~~ similar in composition to Rerewhakaaitu Dome and Flow; Plateau Dome and Flow, and Eastern Dome. It is impossible to relate the domes to one another, as they are all geographically separate. However, Plateau Dome is directly overlain by Waiohau 'Ash' and hence must be between 'Rerewhakaaitu' and 'Waiohau' in age. Eastern Dome is so similar in form and composition to Plateau Dome that it is also regarded as of this age.

Waiohau Eruption

The Waiohau eruption was probably of explosive nature only, as no domes can be directly related to the tephra. The exact site of the vent is unknown, but the most likely position is on Rerewhakaaitu Dome at N77/953914 (see p.45).

KAHAROA ERUPTION

The Kaharoa Eruption occurred about 1020 A.D. (Grant-Taylor and Rafter, 1963, p.140) and produced extensive pyroclastic deposits and the prominent rhyolite domes of Tarawera, Ruawahia and Wahanga (Plate 1). The sequence of events established is comparable to eruptions witnessed in historic times such as that of Mt. Lamington, Papua, in 1951 (Taylor, 1958), and appears to be fairly standard for rhyolite eruptions.

The first event was explosive, producing a 'cone' of coarse blocks around the vent. This breccia is exposed in the moat between Tarawera and Rerewhakaaitu Domes, where it is 20 ft. thick. It is composed mainly of large blocks of devitrified rhyolite, which probably came from the earlier domes. It is thought to represent debris ejected during initial clearing of the vent before the main eruption. This is equivalent to the preliminary explosive phase described elsewhere by Perret (1935), Putnam (1938), and Taylor (1958).

The first lava extrusion was probably the formation of Crater Dome. Evidence of flow structure (p.33) suggests that this dome was extruded quietly, probably without affecting much of the surrounding area, and perhaps just filling the newly formed breccia 'cone'.*

Shortly afterwards, the main pyroclastic eruptions occurred. The tephra came from a vent to the east of Crater Dome and the site of this is now marked by Ruawahia Trig and the wide part of the 1886 fissure immediately to the east (Plate 3). The short time between the two events is indicated by thermal alteration of the tephra directly above the dome, as a result of gases emanating from it. Alternating with the vulcanian type eruptions were nuées ardentes, which flowed to the south, east, and probably the north side of the newly formed 'cone'. These are now exposed in the sections along the track up the south side of the mountain, and in the gully to the south of Wahanga Dome.

This explosive phase was followed by a second series of dome formations, producing Tarawera and Ruawahia Domes. The lava of Ruawahia Dome probably came up the pyrocalstic eruptive vent, and caused hydrothermal alteration of the tephra at the top (Fig. 22). It broke through the side of the 'cone', and flowed in two coulées, to the north west and south west, in a similar manner to the example at Mono Craters (Putnam, 1938). Tarawera Dome must have been extruded at approximately the same time as Ruawahia Dome, as the coulées of the two domes have coalesced around Crater Dome.

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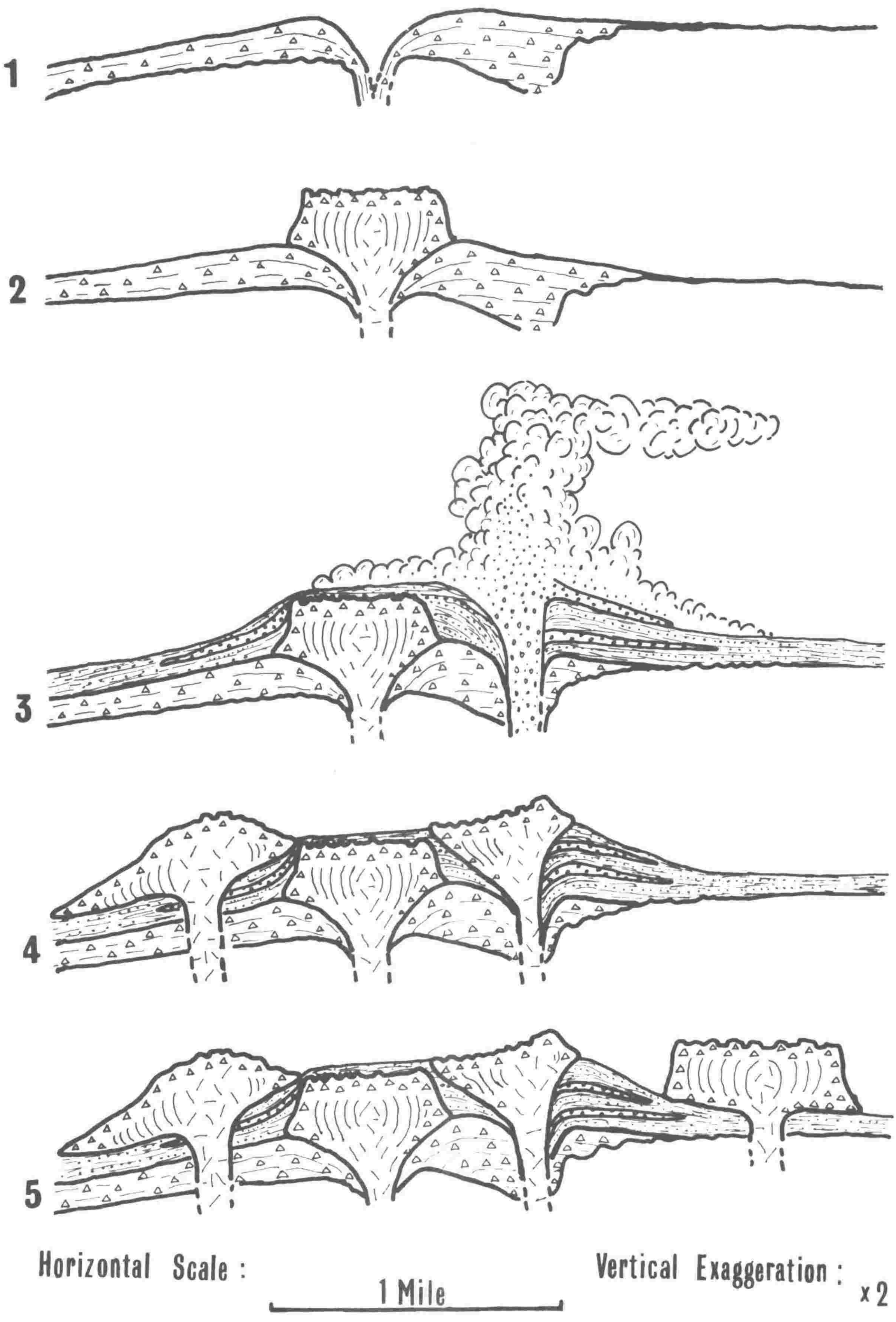
*It would be possible from the occurrence of this dome for it to have been formed late in the sequence of events as an intrusive dome under the Kaharoa 'Ash', but the manner in which Ruawahia and Tarawera Domes coalesce around it and the comparatively localised nature of the thermal alteration in the overlying tephra makes this unlikely.

Fig. 21.

Diagrammatic cross section of Late Domes along the line of the 1886 fissure, to show probable sequence of events during the Kaharoa eruption :

1. Explosive eruption of accidental blocks of rhyolite.
2. Extrusion of Crater Dome.
3. Explosive eruption of Kaharoa 'Ash' (coarse bands represent unwelded ignimbrites).
4. Extrusion of Ruawahia and Tarawera Domes.
5. Extrusion of Wahanga Dome.


1
2
3
4
5
Horizontal Scale :
1 Mile
Vertical Exaggeration :
x 2

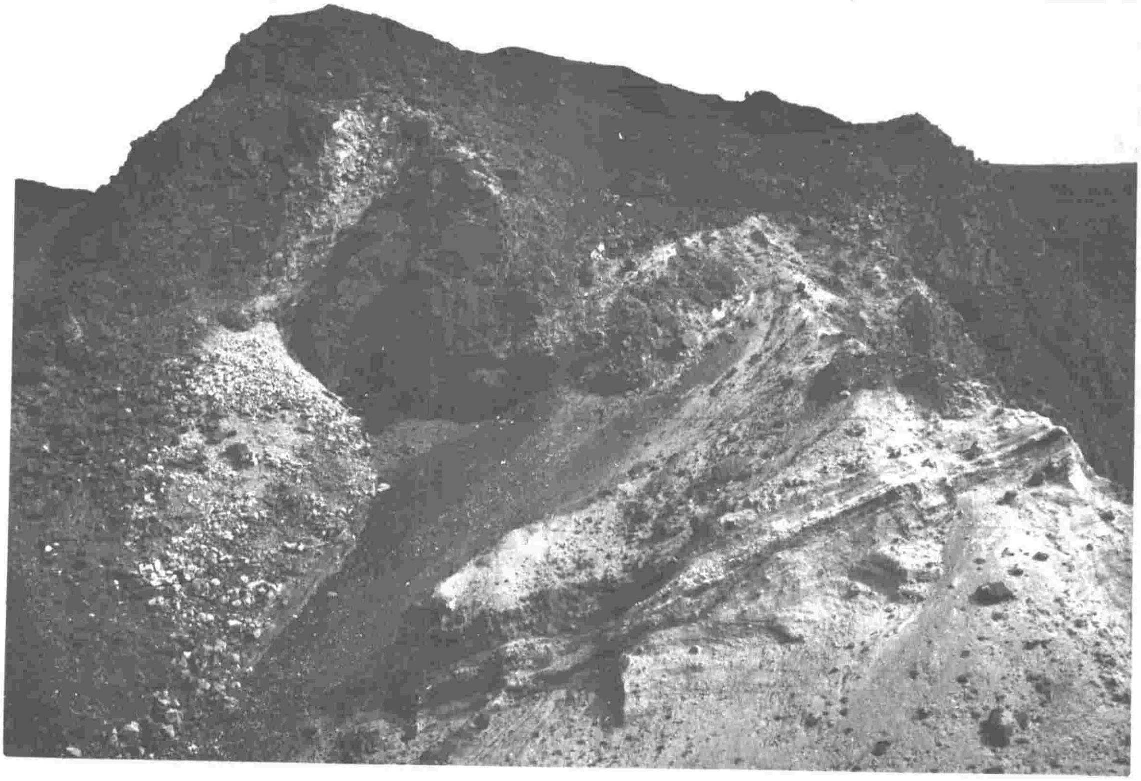


Fig. 22. Rhyolite of Ruawahia Dome filling the earlier Kaharoa 'Ash' vent (N77/965931).

The formation of Ruawahia Dome was accompanied or immediately followed by a lahar pouring down the southern side of the coulée, to flow between the older Plateau and Rerewhakaaitu Domes and spread out into the Rerewhakaaitu basin. It is this deposit which accounts for the large pumiceous rhyolite blocks to the north east of Lake Rerewhakaaitu.

Wahanga Dome may have started to come up before the end of the pyroclastic eruptions as there is some rhyolite beneath the tephra in the 1886 crater on the south side of the dome, and this appears to have flowed as a block bed a short distance (100 yds.) to the south. However, the main development was later, following the pyroclastic eruption. The lava is thought to have ascended quietly, probably through the old vent of the Plateau Dome, and was not accompanied by any air fall tephra.

The main events of the eruption, in the proposed order of development are show diagrammatically in Fig. 21.

TARAWERA ERUPTION

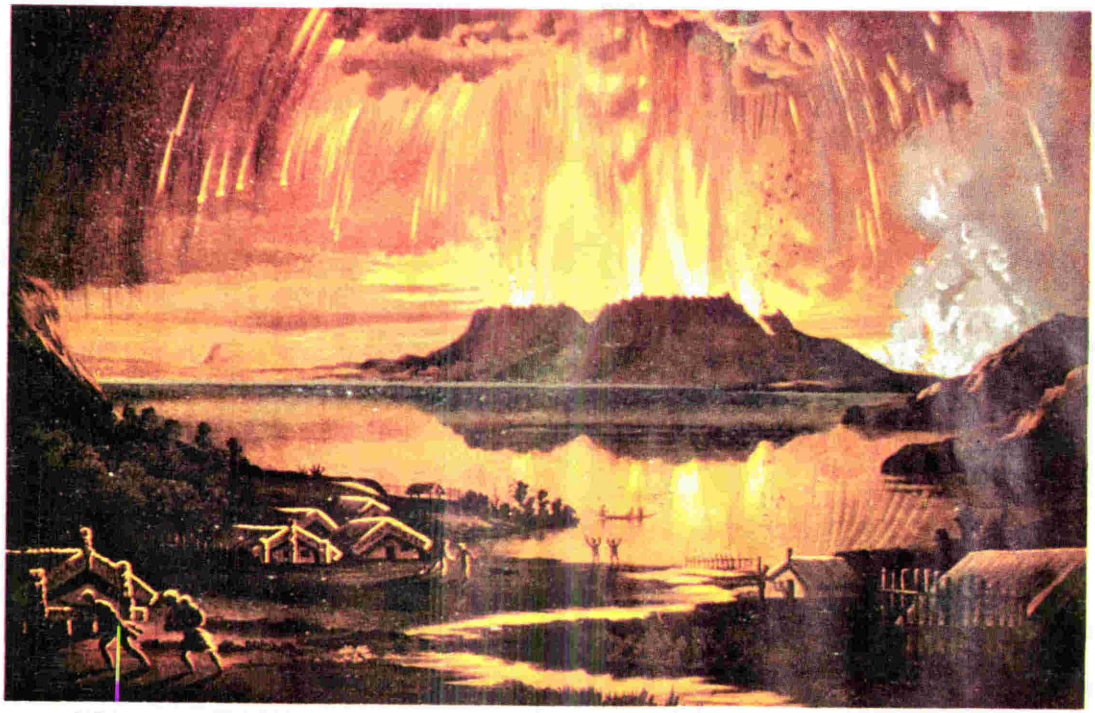
The Tarawera eruption occurred in the early morning of June 10, 1886. It was the first major eruption in New Zealand to be witnessed by Europeans at close hand, and hence created great interest. The hot springs had attracted many people, both European and Maori, to live in the Rotorua region, and the Pink and White Terraces of Lake Rotomahana were visited by many tourists. It was fortunate on this account that the eruption occurred during the winter or there might have been many more fatalities than actually occurred.

Preliminary Indications

Smith (1886a), Hutton (1887) and Thomas (1888) each record many small instances which they regarded as preliminary signs of the eruption. Most are unlikely to be significant, but three features are of interest. It seems probable that there was slightly more activity in Lake Rotomahana during the previous year (although Grange, 1937, disagrees with this) and in November 1885 the White Terrace geyser rose to a height of 150 ft., which was the highest ever recorded (Thomas, 1888, p.28). Smith (1886a, p.20) also records that the hot springs of the Edgecumbe-Te Teko region were more active than usual, and the temperature of the water higher, for some time prior to the eruption. The best substantiated event was a wave or seiche over 1 ft. high on Lake Tarawera on June 1 (Smith, 1886a, p.24, and Thomas, 1888, p.29), recorded at both Te Wairoa and Te Ariki. This was probably caused by an earthquake, although none were recorded on the date. Each of these happenings could be taken as a preliminary indication, but it is unlikely that anyone would have predicted an eruption from them. The apparent lack of earthquakes until just before the eruption seems surprising, but as sensitive equipment was not available at the time, minor earthquakes may have gone unnoticed.

Main Eruption

The first well substantiated indications of activity were at 0030 hrs. on June 10, when a series of earthquakes commenced. These were weak at first but became stronger and culminated in the first eruption, at about 0130 hrs. from Wahanga dome. There is



MOUNT TARAWERA IN ERUPTION, 1886, N.Z.

Fig. 23. Artists impression of Tarawera eruption during the main phase (0230 - 0330 hrs.), as seen from near Te Wairoa.

some disagreement on the time of this first outburst, largely because the nearest surviving observers were at Te Wairoa, 8 miles north west of Tarawera; Rotorua, 14 miles north west; and Galatea, 16 miles south east. Smith (1886a, p.27) and Hector (1886, p.1) record the start as about 0210 hrs., at which time an enormous cloud of smoke and vapour was observed from Te Wairoa. Hutton (1887, p.181) records the eruption as starting at 0115 hrs., and Thomas (1888, p.30) at 0130 hrs., both recording the eruption of Tarawera itself as about 0210 hrs. The latter accounts seem to fit the present day field evidence, and it seems likely that Smith and Hector's sources of information missed the early activity because of the hilly country between Te Wairoa and the mountain.

Hutton (1887, p.181) notes that "only a small cloud was seen, which appears to have subsided and all was again quiet. At 1.45 a.m. (0145 hrs.) the main eruption commenced with a roar from Ruawahia, and a black column glowing with reflections from red hot rocks blew straight upwards. At 2.10 a.m. (0210 hrs.) a violent earthquake occurred and Tarawera dome exploded with a deafening noise, sending up a broad steam column". This column was calculated by Williams (1886, p.380) to be over 6 miles high. By 0230 hrs. the whole length of the fissure was in eruption and Fig. 23 gives an artist's impression of the sight from near Te Wairoa.

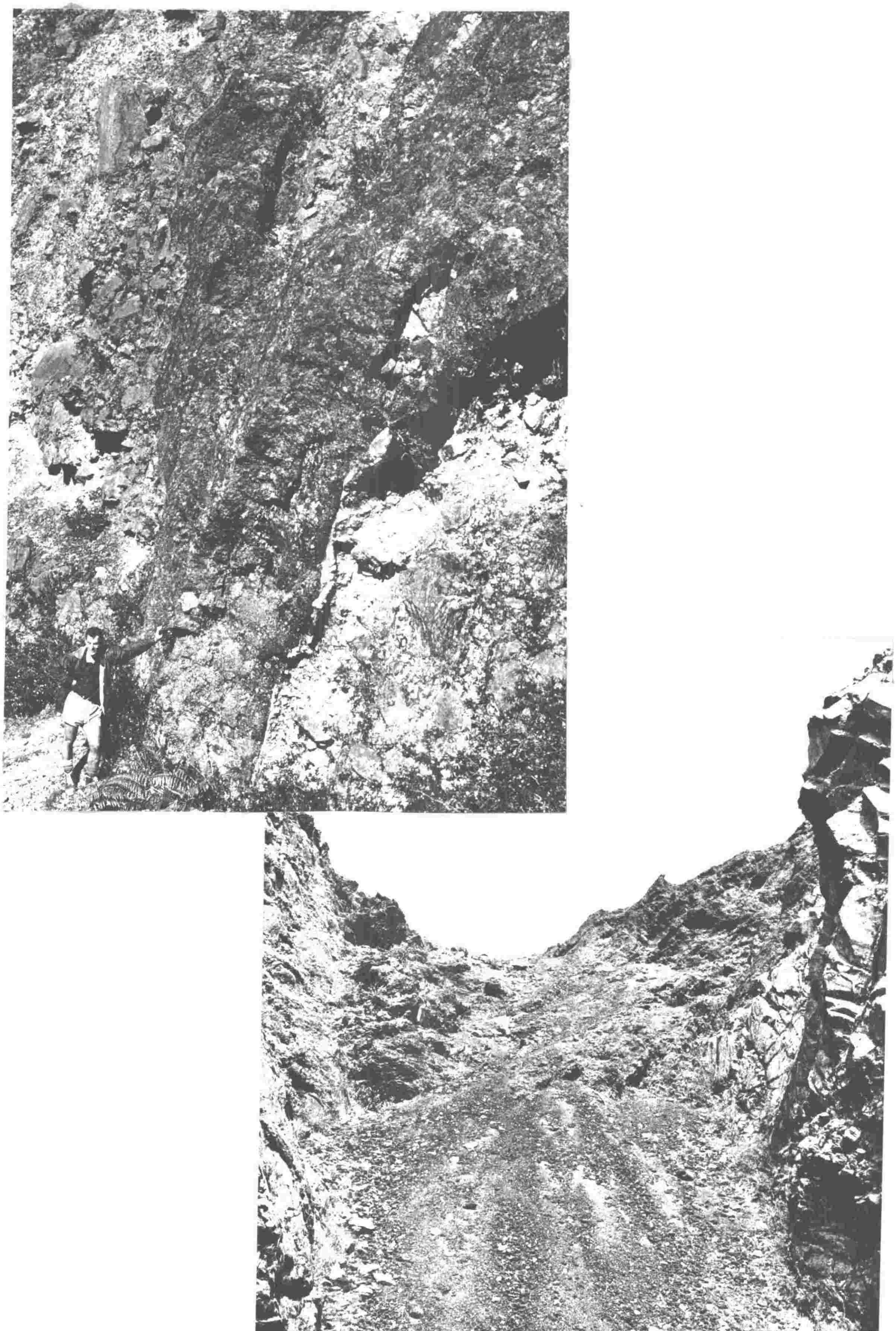
The activity on Wahanga and Ruawahia became more phreatic at about 0330 hrs. and the series of violent earthquakes recorded probably reflect great explosions on the mountain during which large blocks of rhyolite were ejected. At the same time Rotomahana

Fig. 24.

Basalt dyke exposed in the crater on the south side of Wahanga Dome (N77/975942). The rhyolite has been vitrified on each side of the dyke.

Fig. 25.

Basalt dyke cutting through massive rhyolite, exposed in the 'bridge' south west of Ruawahia Trig (N77/963928). Width of dyke ≈ 30 ft.



burst into eruption, throwing out a column of steam higher than that from Tarawera (Hutton, 1887, p.181). It was a phreatic eruption but the explosions were charged with the soft lake sediments of the previous Lakes Rotomahana and Rotomakiriri, as well as volcanic rock which had been intensively altered by earlier thermal activity to form the Rotomahana Mud.

The eruption was largely over by 0530 hrs.

The results of the eruption can be seen today along the eruptive fissure, and in discussing these features it is convenient to divide the eruption into two stages; an early stage from 0130 hrs. to 0330 hrs., and a later stage from 0330 hrs. onwards.

Early Stage

In the crater on the south side of Wahanga Dome there is a small basalt dyke exposed (Fig. 24). It is approximately 3 ft. across, has a chilled margin on either side and probably represents the feeder for the first eruption. A high emplacement temperature is indicated by the large numbers of highly vesiculated and partly molten rhyolite block inclusions. The small initial volume of material ejected relative to the later phase could be related to to the small size of the dyke.

To the south west of Ruawahia Trig, the eruptive fissure was probably about 30 ft. wide, and this can now be seen in a 'bridge' at N77/963928 (Fig. 25). At this place the dyke has a more complex form. The margin has chilled against the rhyolite, and at the same time has melted the rhyolite at the contact to form a glass. Towards the centre a series of 'flows' can be identified, each chilled against the previous one and becoming more scoriaceous towards the centre. This could represent a simple multiple dyke, but as the lava 'blankets' the rhyolite on each side of the fissure above the dyke (see Fig. 24) it seems more likely that the lava reached the top of the fissure and then flowed back into the vent before cooling. This is comparable to eruptions witnessed in Hawaii (Peck, pers. comm.). The increase in width of the fissure compared with that on Wahanga Dome would account for the increased volume of basalt seen to come from Ruawahia.

The explosion from Tarawera Dome is now represented by broad craters at the south western end of the main fissure. The sides of the craters are completely covered by scoria, and a large volume of material appears to have been ejected. The scoria from these explosions must have been very hot when erupted, as it welded together on the sides of the vents and formed small 'flows' which moved a short distance away from the centre of eruption. These can now be seen as solid layers in the lapilli at the sides of the craters, and probably account for the eye-witness descriptions of lava flows coming from the craters during the eruption.

Late Stage

The highly explosive nature of the activity from Wahanga and Ruawahia (which started about 0330 hrs.) is clearly shown by the deep craters on the two domes. These have vertical walls of rhyolite with a few indications of the basalt. It is also reflected in the large numbers of rhyolite boulders (up to 6 ft. in diameter) in the upper part of the Tarawera 'Ash' surrounding the fissure. The Chasm also probably became explosive at this stage of the eruption, as it has similar features to the Wahanga and Ruawahia end of the fissure.

The reason for the change to phreatic activity is unknown. It occurred at the same time as Lake Rotomahana burst into violent phreatic eruption, so the explosions from the Chasm could have been caused by cold water draining from Lake Rotomahana into the eruptive fissure. This source of water cannot be invoked as a cause of the explosions from Wahanga and Ruawahia, however, as activity on Tarawera Dome (which is between the Chasm and Ruawahia) did not become explosive. If the introduction of cold water was also the reason for the change at the north eastern end of the fissure, it must have come from elsewhere (perhaps Lake Tarawera).

Waimangu

Phreatic explosions took place during and after the eruption to the south west, in Waimangu valley. The first occurred at about 0230 hrs. (Grange, 1937, p.82), but the majority took place near the end of the main eruption or shortly afterwards, and the area has continued to be thermally active to the present day. From 1900 to 1904, the spectacular Waimangu Geyser played, in 1903 often reaching a height of 1500 ft.

It is uncertain from eye-witness accounts whether any basalt lava was ejected from the Waimangu area during or after the eruption. Thomas (1888, p.55) thinks not, but there is a surface deposit surrounding Echo Crater which contains blocks of basalt up to 1 inch in diameter (with occasional blocks up to 6 ins.). These contain

Fig. 26.

Steam issuing from the fissure across Tarawera a few months after the eruption of June 10, 1886.

Fig. 27.

Steam vent (marked by arrow), in deep crater between Ruawahia and Tarawera Domes, in 1964 (N77/954925). Note figure at bottom of photograph for scale.

small fragments of cryptocrystalline silica, which were probably originally sinter, strongly suggesting that they came from Waimangu or Rotomahana. Furthermore, the size and distribution of the basalt favours one of these sources. The time at which they were erupted initially is unknown, but it is possible that they came from Black Crater, and were then reworked during later phreatic eruptions.

Length of Eruption.

The main activity on Tarawera had finished by 0530 hrs., making the total time of eruption only 4 hours. Rotomahana remained highly active for several weeks and Waimangu for several months. Earthquakes became weaker after the eruption and had ceased within 24 hours. The only activity on the mountain was then steam, which continued to pour from the walls of the fissure for many months (Fig. 26). Today there are two small steam vents still active in the deep crater between Ruawahia and Tarawera domes (Fig. 27) but they appear to be waning.

Effects of the Eruption

1) Loss of Life

Park (1911) records the number killed during the eruption as: Te Ariki, 52; Moura, 39; Te Wairoa, 14 (including 6 Europeans); Rotomahana, 11 (where Rangiheua and his tribe were staying). This makes a total of 116, but it is very probable that there were more than this number, and fatalities may even have reached 150.

2) Change to Mount Tarawera

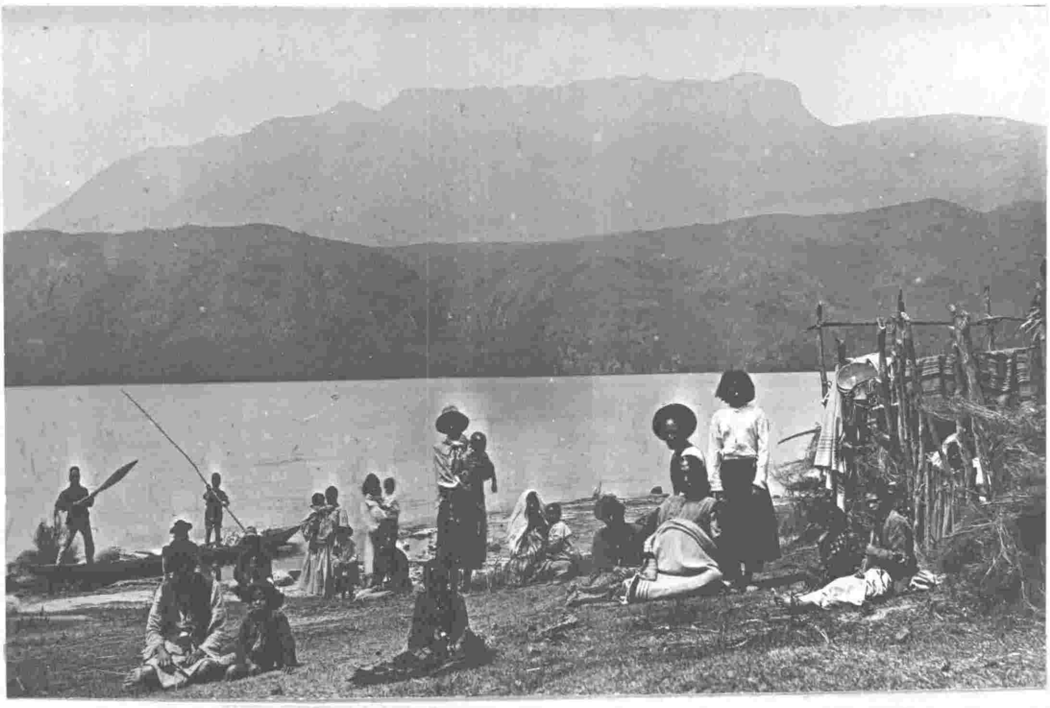
The most spectacular change at Tarawera was the formation of the fissure across the mountain, over 500 ft. deep in places and up

Fig. 28.

A) Tarawera from Te Ariki before 1886.

B) Tarawera from the same position soon after the eruption, showing how little the profile of the mountain changed.

C) Tarawera, from near the site of the previous photo points, in 1964. The level of Lake Tarawera has dropped over 20 ft. during the interim period.



Photographed by G. D. Valentine

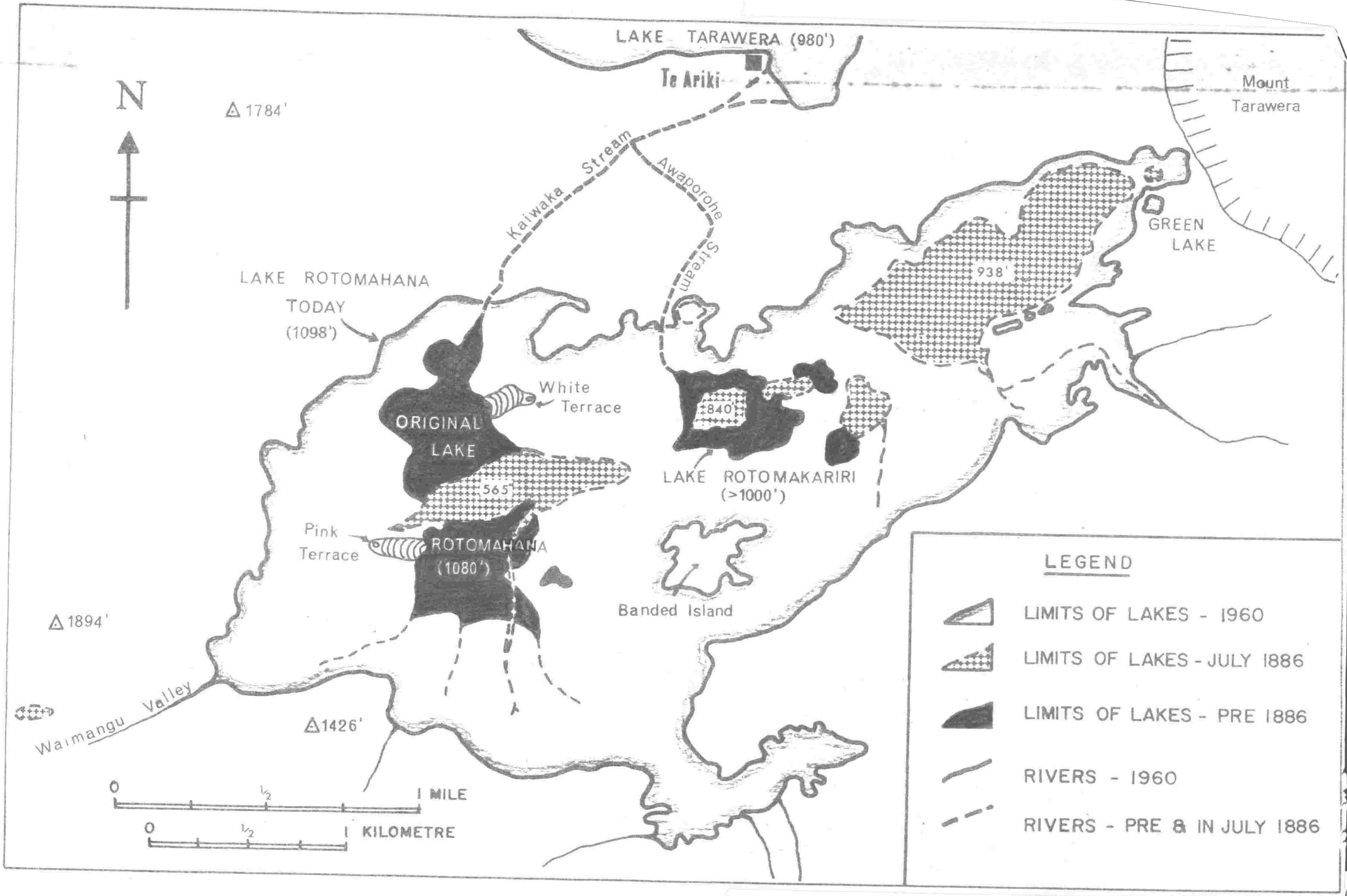


Fig. 29. Changes to Lake Rotomahana caused by the eruption in 1886. Lake level before the eruption is taken from Smith (1886a, p.41); lake level in July, 1886 from Smith (1886b, p.82) and lake level today from Lands and Survey N.Z.M.S. Sheet 152.

to 300 ft. wide. Much slipping has occurred into this fissure, both by small scale rock fall and on a larger scale by great blocks slumping inwards. The latter were probably caused by the numerous cracks from which the gases escaped. Thomas (1888, p.45) records these as "usually parallel to the margins of the craters, although sometimes at right angles..... Some of them are hundreds of yards in length and 10 ft. or more in breadth, with a depth of 5 ft., 10 ft. or more.". At the south west end of the fissure is the Chasm. This is a large scar (900 ft. high approx.) formed by oblique explosions through the side of Tarawera dome (Plate 4).

The thickness of the basalt on the rhyolite resulted in an increase in height on the mountain of between 40 and 100 ft. The height of Ruawahia Trig increased by 40 ft. as the present height is 3646 ft.(Lands and Survey Sheet N77/7), compared with a height of 3606 ft. before 1886. Figs. 28a, b and c, taken from the site of Te Ariki, show the mountain before the eruption, just afterwards, and today, indicating how little topographic features have changed during the period.

3) Changes to Lake Rotomahana

The Rotomahana basin, unlike Mount Tarawera, was well known before the eruption and hence changes can be recorded with more certainty. Hochstetter (1864, Plate 5) drew a map of the basin and this is reproduced with modifications (made from photographs) in Fig. 29. There were two main lakes in the basin, Lake Rotomahana (warm lake) and Lake Rotomakiriri (cold lake). The former was shallow, as a large part of the lake was swamp. It had an outlet,

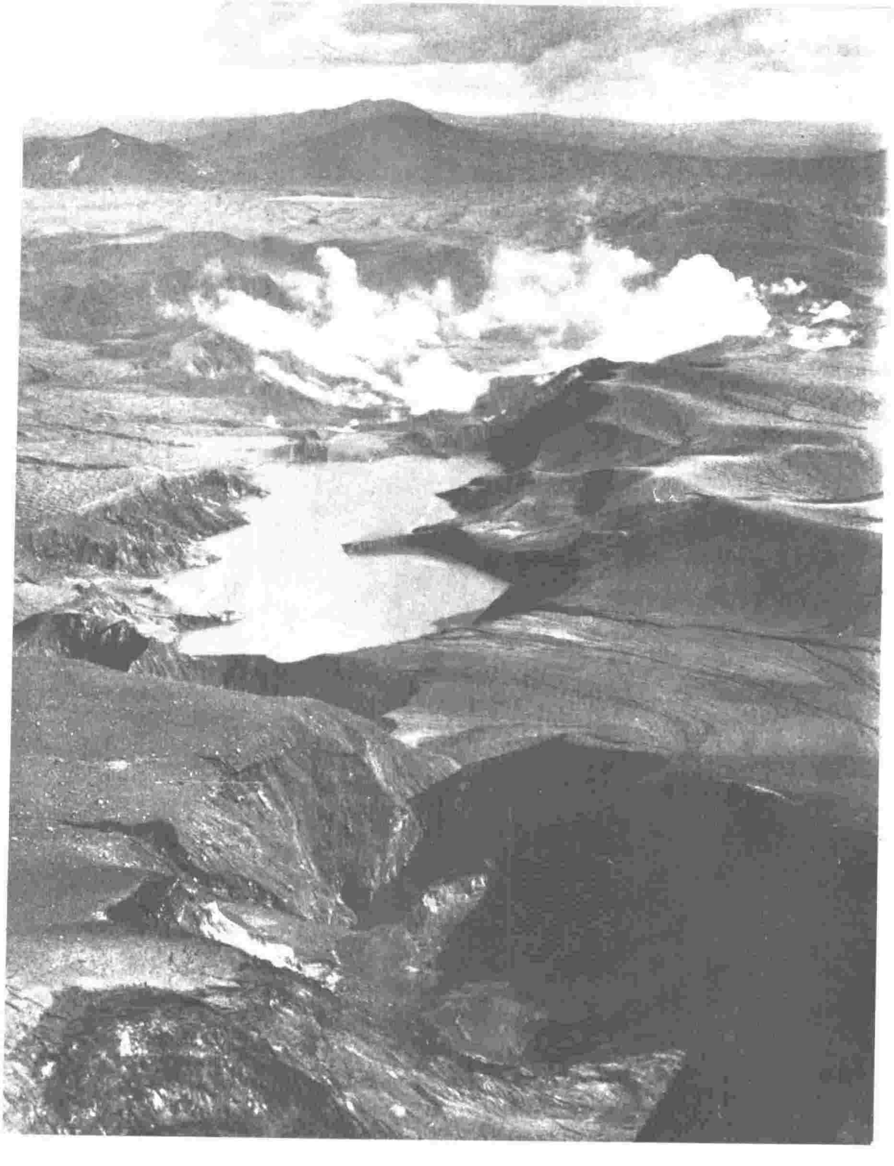


Photo: Burton Bros.

Fig. 30. The Rotomahana basin from Tarawera a few weeks after the eruption. In the middle distance is the new Lake Rotomakiriri and beyond, the steam marks the site of the original Lake Rotomahana.

Fig. 31.

A) Tarawera and Lake Rotomahana from above the Pink Terrace before June 10, 1886.

B) Similar view from a higher level soon after the eruption. The site of the Pink Terrace is probably near the centre of the photograph.

C) View from the north west side of Lake Rotomahana today. Most of the lake is obscured by vegetation or is to the right of the photograph.

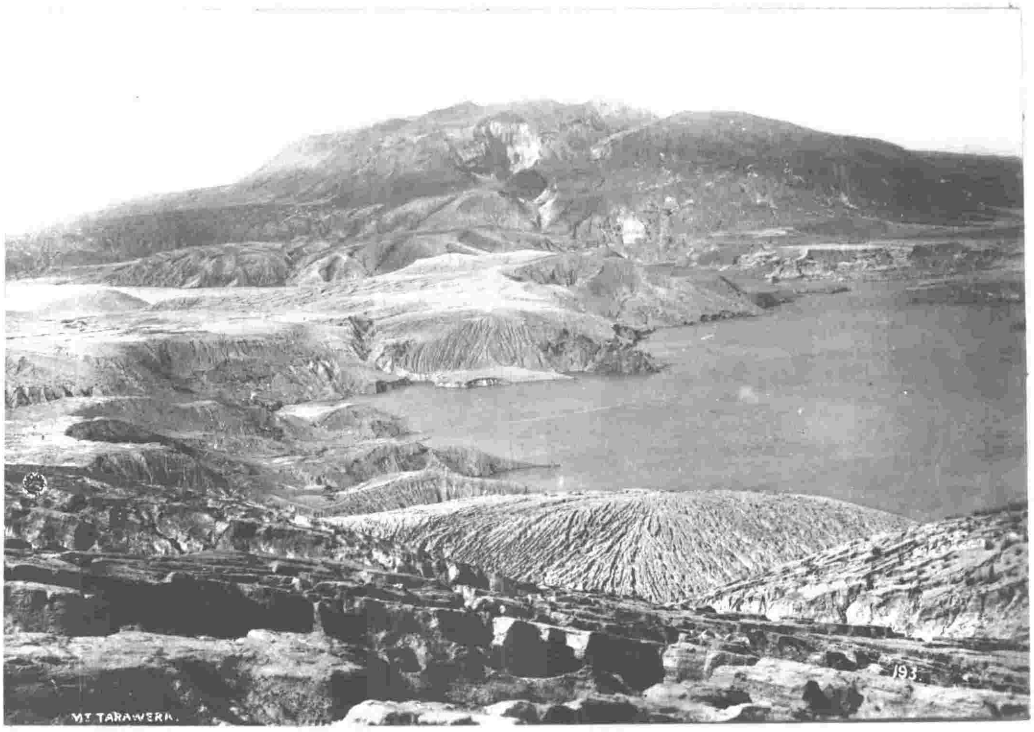


Photo: N. Wells.

the Kiwaka Stream, which flowed into Lake Tarawera. Lake Rotomakiriri was surrounded by numerous small circular 'cones' which Hochstetter regarded as due to the former action of hot springs. The area between Lake Rotomakiriri and Tarawera, Te Waingongongongo, was swampy and must have been the site of a lake at one time as the strata exposed in the craters soon after the eruption contained a succession of Lake beds with lignite (Thomas, 1888, p.26).

During the eruption, both lakes emptied, and a large amount of debris was thrown out of the crater. Within a month a new hot lake had appeared in almost the same position as Rotomahana but about 500 ft. lower (Fig. 29), and a larger lake formed to the north east (Fig. 30). Water level continued to rise until the lake reached its present height of 1098 ft., with Banded Hill becoming an island. Fig. 31 shows the lake viewed from the side of Te Hape-o-toroa before the eruption, in 1889, and today.

At the north east end of the basin was Green Lake Crater, which became incorporated in the new enlarged Lake Rotomahana after the eruption. However, an explosion during the eruption had formed a new crater about $\frac{1}{4}$ mile to the south east, and this, with the rise in water level, formed a crater lake. The water in it was distinctly green from the volcanic gases associated with the crater formation, and hence was named Green Lake by Lands and Survey (Sheet N77/7). This dual use of the name has apparently caused some confusion.

4) Pink and White Terraces

Before 1886, the Pink and White Terraces of Lake Rotomahana were probably the most famous tourist attraction in the region. The White Terrace, or Te Tarata, was over 100 ft. high. At its base were large numbers of cold water basins trickling into one another, and at the top was a geyser which occasionally sent a jet of water up to 150 ft. On the opposite shore of the lake was the Pink Terrace, or Otukapuarangi, which formed a magnificent flight of steps of salmon pink sinter.

It is unlikely that either Terrace survived the eruption. The first party to survey the area after the eruption found large amounts of siliceous sinter distributed far and wide over the mud covered hills. Also Smith (1886b, p.2), in his preliminary report, notes that "the spot where once was situated the.....White Terrace is now, I believe, occupied by a crater forming a sort of horse-shoe bay in the side of the great crater of Rotomahana, and from which a vast column of steam arises". The Pink Terrace could not be seen through the steam cloud at this stage, but as the small hot lake which formed very near the site of this Terrace was 500 ft. lower than the former lake, it seems certain that the Terrace must have been destroyed. It may be significant that the position of the geyser at the head of the White Terrace was very close to that now occupied by the 'Steaming Cliffs' of Lake Rotomahana. These may therefore be a continuation of the original thermal activity.

5) Change to Tarawera Lake and River

Between two and three feet of ash and lapilli were deposited around Lake Tarawera during the eruption. This caused a blockage of the outlet and a corresponding rise in lake level. Much material was carried down the Tarawera River straight after the eruption and Thomas (1888, p.69) notes that "the Tarawera River, which before the eruption had perfectly clear water, has ever since flowed with milk white stream". This deposited much material in low terraces in the Kawerau district. Erosion continued for a number of years allowing base level of the river to fall slowly until in 1904 the ash 'barrier' at the outlet of the lake was broken and the lake drained to a level probably slightly below that before the eruption.

6) Effect of Debris

About 6,000 square miles to the west of the mountain were originally covered by the Tarawera 'Ash' and 'Lapilli', but only about 1,500 square miles were covered sufficiently to remain for any length of time. To the west, Rotomahana Mud fell (see Fig. 31b). This had a different effect on the landscape, and became quickly runnelled to form only poor grazing land, while the Tarawera 'Ash' and 'Lapilli' helped produce good farmland in the Bay of Plenty. The Tarawera deposits also had an effect on the occurrence of bush sickness; areas previously covered by Kaharoa 'Ash' were badly affected, but where Tarawera 'Ash' fell, the incidence was lower (Grange and Taylor, 1932). The bush sickness was later found to be related to the presence of cobalt in the basalt - an element lacking in the earlier Kaharoa 'Ash'.

SECTION B

PETROGRAPHY, MINERALOGY AND PETROCHEMISTRY

B. PETROGRAPHY, MINERALOGY AND PETROCHEMISTRY

1. PETROGRAPHY

TECHNIQUES

All rocks collected from the Tarawera Volcanic Complex were examined in thin section, and representative examples of the rhyolite domes, the basalts, and the xenoliths chosen for more detailed study. These samples were crushed to 230 mesh by a steel roller crusher, and, where required, a representative sample of the total rock was extracted by the cone method for chemical analysis.

A part of each crushed sample was taken for mineral separation, and this was divided into light and heavy fractions by centrifuging the sample in undiluted bromoform. From the light fraction, feldspar + quartz and glass were separated in a mixture of bromoform and acetone, and, where possible, the feldspar and quartz separated by the same method. Each fraction was then purified using the Franz Isodynamic Separator. Often quartz and feldspar could not be completely separated but 90% + purity was usually obtained. The heavy fraction was first divided into biotite + hornblende, or augite, and hypersthene + magnetite, by centrifuging in undiluted methylene iodide. The biotite and hornblende were found to be difficult to separate but reasonably pure fractions were obtained by running the sample down an inclined sheet of paper. As optical measurements only were made of these minerals, this was quite adequate. Augite only occurred in the basic rocks and was never accompanied by biotite or hornblende, so this mineral could be purified directly using the Franz Isodynamic Separator. Magnetite was removed from the hypersthene by a hand magnet and the latter purified in the Franz Separator.

Refractive index measurements were made of all the minerals by the immersion method, and refractive indices of the oils measured on an Abbé refractometer, using sodium light. All measurements are considered accurate to ± 0.002.

Optic angle measurements were made from selected thin sections using a 4-axis Leitz Universal stage. Feldspar determinations were made using the methods described by Slemmons (1962). Direct measurements were made of all minerals where possible, and these are considered to be accurate to ± 2°. In many cases, however, only one optic axis could be measured and this was plotted on a Wulff stereographic net to obtain 2V. These measurements are not considered very accurate, however.

Partial chemical analyses were made of the feldspar and glasses and X-ray determinations were made of some biotites to determine the Fe content.

RHYOLITE DOMES

Rhyolite* is the most voluminous extrusive rock in the Tarawera Volcanic Complex forming over 3.5 cu.miles of lava and tephra.

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* Some authors (e.g., Lewis, 1960. p.65) have justifiably objected to the term 'rhyolite' for the acid effusive rocks of the North Island, because of the low normative alkali feldspar content. If the scheme proposed by Williams, Turner and Gilbert (1958, p.121) is strictly followed, the rocks should be called 'rhyodacites' or in some cases 'dacites'. Because the term 'rhyolite' is firmly embedded in the literature on the region, however, this change would cause considerable confusion and hence 'rhyolite' will be used in this account.

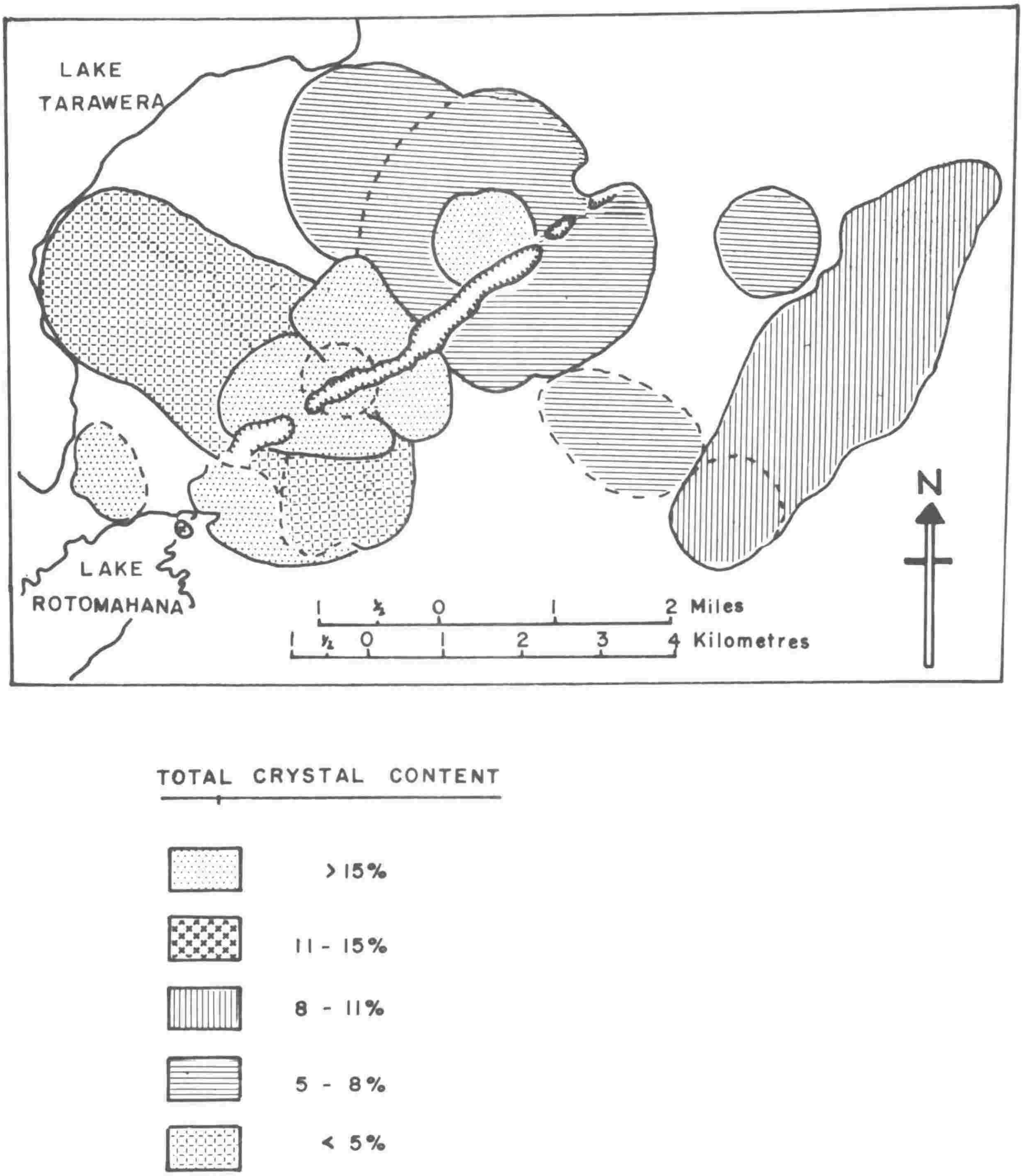

Fig. 32. Total crystal contents of the rhyolite domes of the Tarawera Volcanic Complex (excluding vesicle space).

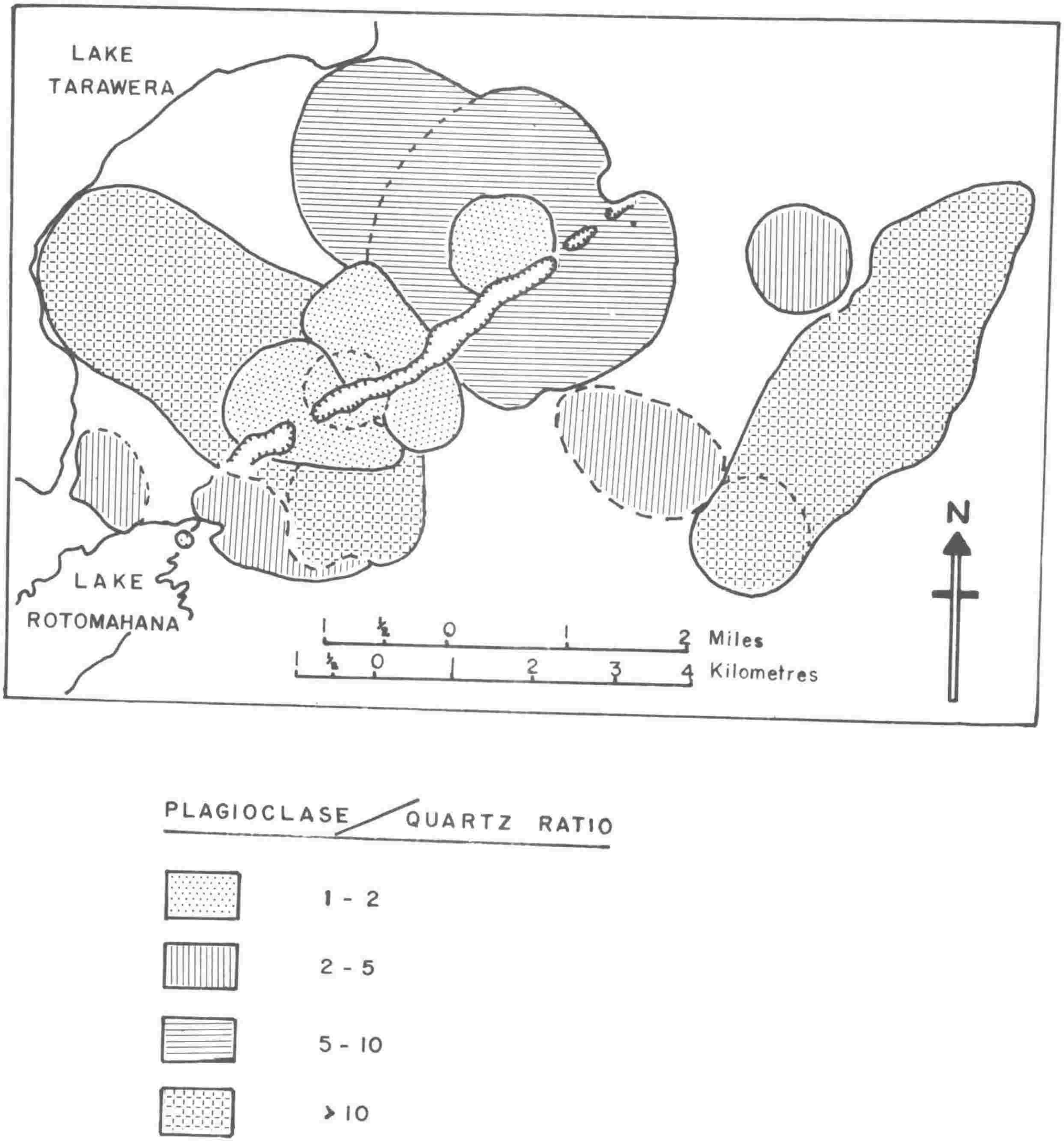

Fig. 33. Plagioclase / Quartz ratio of the rhyolite domes of the Tarawera Volcanic Complex.

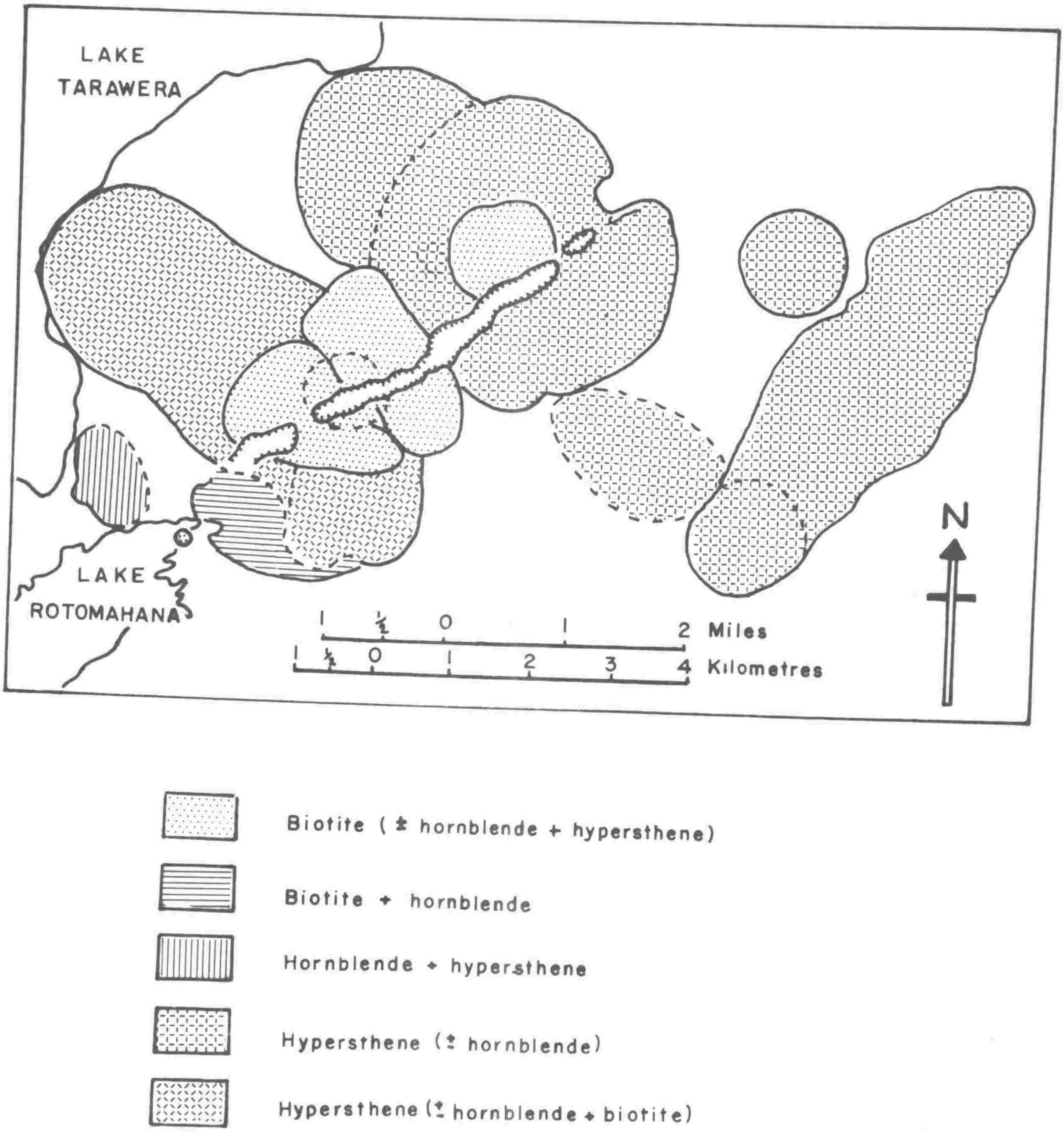

Fig. 34. Ferromagnesian mineral assemblages of the rhyolite domes of the Tarawera Volcanic Complex.

In a previous section (p.14) the domes were divided on geomorphic evidence and hand-specimen mineralogy into Early and Late Domes, and this broad division will be followed in the present section.

Modal analyses of rhyolites are given in Tables 3-5 and from these analyses, the domes can be subdivided for descriptive purposes. In Fig. 32 the total crystal contents of the domes are shown. Most of the Early Domes have a crystal content of less than 11% while all the Late Domes are greater than 15%. Western and Rotomahana Domes are, however, 'Early' in terms of their stratigraphy, but have a crystal content higher than 15%. The plagioclase/quartz ratio in the domes varies from greater than 10:1 in Southern Dome and Flow and Rerewhakaaitu Dome and Flow, to almost equal amounts in the Late Domes (Fig. 33). This ratio is of considerable genetic interest but is not a good method of division for descriptive purposes.

Probably the most satisfactory means of division of the domes is by their ferromagnesian mineral content (Fig. 34). In most of the Early Domes hypersthene is dominant (with a small amount of hornblende, and in the Rerewhakaaitu Dome and Flow some biotite also). Western Dome has an assemblage of hypersthene and hornblende, and Rotomahana Dome, biotite and hornblende in almost equal amounts. All of the Late Domes have biotite as the main ferromagnesian mineral, with small amounts of hornblende ± hypersthene.

For the purposes of discussing the textures and general petrography of the rhyolites, a four-fold stratigraphic-mineralogic division can therefore be made into:

1. Hypersthene-hornblende rhyolite	Early Domes
2. Hornblende-biotite rhyolite	
3. Hypersthene rhyolite	
4. Biotite rhyolite	Late Domes

Hypersthene-hornblende Rhyolite

This type is restricted to the Western Dome, and most samples examined came from the cliffs on the western side. The rock is pink in the hand specimen with many small mafic phenocrysts and larger crystals of quartz and plagioclase. In thin section the crystal content is moderate (av. 20.6%) and the groundmass is spherulitic (spherulites 0.5-1 mm. in diameter).

The phenocrysts are normally large (some plagioclase max. diam. > 3 mm.), and occasionally form glomeroporphyritic aggregates. Quartz and plagioclase are commonly resorbed and may be shattered. Mafic minerals present are basaltic hornblende and hypersthene, and small euhedral grains of magnetite are common.

Specimen 11114[*] was collected from the northern edge of the dome and this has a different texture and mineralogy. The groundmass is glassy with contorted flow bands along which small iron rich microlites are orientated. Medium to large spherulites are present throughout. Quartz, plagioclase and hypersthene phenocrysts are

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[*] All Specimen Numbers refer to rocks and thin sections kept in Geology Dept., Victoria University of Wellington, Collection.

similar to the other samples, although the hypersthene is less oxidised. Hornblende is, however, green-brown, indicating a lower temperature of formation (p.161). This probably indicates that the specimen came from the edge of the dome while the other samples were from nearer the centre.

Biotite-hornblende Rhyolite

This mineral assemblage is found in Rotomahana Dome (and in parts of Tarawera Dome, but this will be described with the Biotite rhyolite; the main assemblage of Tarawera Dome). The rock is usually grey with a high crystal content (> 30%), and in thin section is pumiceous with a few spherulites developed. The phenocrysts are very large, often over 2 mm. in diameter (occasionally 5 mms.). They are usually cracked and the quartz and plagioclase resorbed. The main mafic mineral is biotite but large green or brown hornblende crystals also occur. A small inclusion of hornblende dacite (cognate xenolith) was found in 11087.

The considerable brecciation in Rotomahana Dome suggests it was at least in part extruded in a solid state.

Hypersthene Rhyolite

Hypersthene rhyolite is the most common rock in the Early Domes and is found in Rerewhakaaitu Dome and Flow, Southern Dome and Flow, Plateau Dome and Flow, Eastern Dome and Ridge Dome.

The lava in the dome is predominantly pumiceous with a few small spherulites developed in the glass in places. In the rocks from Eastern Dome granophyric groups (p.142) also occur. The lava flows are obsidian showing complex flow banding with the development of spherulites. The glass contains crystallites (trichites, belonites and margarites) and in Rerewhakaaitu and Plateau Flows, occasional microlites of feldspar. The crystal content is in all cases low with plagioclase the main phenocrysts. This forms moderate-sized crystals (max. size 2.5 mm.). In Southern Dome they are frequently resorbed and some show patchy zoning in the centre (see p. 123). Quartz is rare, especially in Southern and Rerewhakaaitu Domes, and is always resorbed. Hypersthene forms small euhedral crystals (max. diam. 1 mm.) and is usually associated with magnetite. It occasionally occurs in glomeroporphyric aggregates with plagioclase, magnetite and/or hornblende.

On the western side of Rerewhakaaitu Dome the lava has mixed with the earlier Rotomahana Dome. This is visible in hand specimen and is marked in thin section by an increased crystal content, mainly of green hornblende and biotite. These minerals also occur in small amounts in the base of the corresponding Flow, probably indicating assimilation of part of the Rotomahana Dome at the start of the extrusion.

Biotite Rhyolite

Biotite rhyolite occurs in all the domes associated with the Kaharoa eruption. In hand specimen the rock varies from a pink colour to grey or white, but all have a high percentage of phenocrysts. As a type example Wahango Dome may be taken and any difference in the other domes will be described afterwards.

The rocks from Wahanga Dome have a high crystal content (24%)

of quartz, plagioclase and biotite, sometimes in glomeroporphyric aggregates. A few small crystals of hypersthene may occur, but as these are commonly associated with broken feldspar crystals, they may indicate assimilation from earlier domes. Zircon is a common accessory mineral. Brecciation frequently occurs in the dome and this results in highly broken quartz and plagioclase crystals and disintegration of biotite flakes.

Because the 1886 fissure cuts across the south side of the dome, changes in texture and mineralogy from the margin to the centre can be studied in detail. At the margin the rock is pumiceous (maximum vesicularity 30%), and phenocrysts are large but normally broken. Towards the centre, small feldspar microlites appear in the glass and incipient spherulites develop around the phenocrysts. The phenocrysts are cracked but are normally complete. Biotite is highly pleochroic but not oxidised.

The next stage is the increase in spherulite content. Small, poorly developed spherulites occur around phenocrysts and irregularly throughout the glass. The biotite at this stage is becoming reddish brown (ferrian type, see p.127). Further in, individual spherulites become better developed throughout and often reach 0.5 mm. in diameter. These spherulites increase in size towards the centre until in the most central specimen examined from in place (11070) they are over 1.5 mm. in diameter. The area between the spherulites is devitrified and tridymite is often formed in the vesicles. The biotite in the specimen is red-brown.

A specimen (11063) obtained from a fallen block which is considered to have come from the centre of the face goes a stage further. The spherulites are very large and occupy almost the entire rock, and the biotite is partly changed to hypersthene and felospar.

Rocks from Crater Dome and Ruawahia Dome are very similar, but Tarawera Dome is more complex. The margin of this Dome is similar, as it is pumiceous and has a mineral assemblage of quartz, plagioclase and biotite, but the centre is different. Quartz and plagioclase crystals become broken some distance in from the margin, and in addition to the biotite, hypersthene and basaltic hornblende appear. A number of glomeroporphs of small hornblende and plagioclase are also present. Nearer the centre (11102) is a spherulitic obsidian in which there is less brecciation, but the crystal content is very high (30.9%). In the centre of the dome (11104, 11105) quartz, plagioclase, biotite, hypersthene and hornblende all occur, and the hypersthene and hornblende have increased in relative amounts. Both are usually oxidised. In 11105 the rock is slightly brecciated but in 11104 this is extensive and many fragments of plagioclase occur. Possible reasons for this change will be discussed in a later section.

Green Lake Plug also differs from Wahanga Dome in that the crystals (quartz, plagioclase and biotite) are smaller (max. diam. of plagioclase 0.7 mm.), and the glass is full of small microlites of feldspar. Small xenocrysts (< 0.5 mms.) of andesite are common, providing a useful age factor for the dome.

RHYOLITE TEPHRA

Because of the different mode of occurrence of the tephra, different techniques had to be used to establish the mineralogy of the deposits. Near the source they were coarse enough for thin sections to be made from the pumice and modal analyses of these are given in Table 5. Further away, this became impossible and the lapilli had to be crushed and the minerals separated from the glass, using diluted bromoform. It became apparent from this procedure that the tephra eruptions from Tarawera could be distinguished on their mafic mineral content alone, and so no further samples were separated in undiluted bromoform, and the percentage of each mafic mineral estimated visually under the microscope. These were recorded as:

Dominant (d) 50%; Common (c) 25-50%; Rare (r) 10-25% and Present (p) 10%.

The results of this investigation are shown in Table 8, and it is apparent that the Rerewhakaaitu 'Ash' is typified by the minerals hypersthene, hornblende and biotite; the Waiohau 'Ash' by hypersthene (± hornblende); and the Kaharoa 'Ash' by biotite (± hypersthene and hornblende). Variation occurs both horizontally and vertically in the sequence, so that a more detailed modal investigation was of little value.

Horizontal variation in the tephra occurs particularly with distance from the vent, and can probably be attributed to wind conditions during the eruption. A strong wind will, for example, transport biotite for a considerable distance. Vertical variation is mainly from contamination, and samples from the base and top of a deposit are particularly affected. An example of this is in sample 11059/9, from the top of the Waiohau 'Ash', which contains a few grains of augite in addition to the normal assemblage. This mineral is common in the overlying Taupo Ash Sequence and has presumably moved down, perhaps carried by percolating water.

Because of their distinct mineral assemblages, the three rhyolite tephra showers considered to have been erupted from Tarawera (p.41) will be described separately.

Rerewhakaaitu 'Ash'

This deposit contains primary pumice fragments of two types: one poor in phenocrysts (Type A) and the other rich in phenocrysts (Type B). These occur in approximately equal quantities throughout.

Type A: This type has an average total crystal content of 2.9%, which is almost entirely small resorbed crystals of plagioclase (0.5-1 mm. in diameter). Quartz is absent, and the only other mineral present is hypersthene. The glass is pumiceous, with some granophyric groups developed.

Type B: This second type contains a moderate total crystal content (average 19.2%) with plagioclase the dominant mineral. Both plagioclase and quartz are large (max. 3.5 mms.) and are often surrounded by a rim of small feldspar microlites. The quartz is usually strongly resorbed. Mafic minerals are green hornblende and biotite, which are of medium size (< 1 mm.), and are often intergrown together or with plagioclase. The biotite is commonly more strongly pleochroic around the margin than in the centre. The glassy groundmass is full of small laths of feldspar (considered from optical data to be plagioclase) with some small biotite flakes and hornblende crystals.

The two types of pumice in the Rerewhakaaitu 'Ash' resemble the rhyolites of Rerewhakaaitu Dome and Rotomahana Dome respectively, and

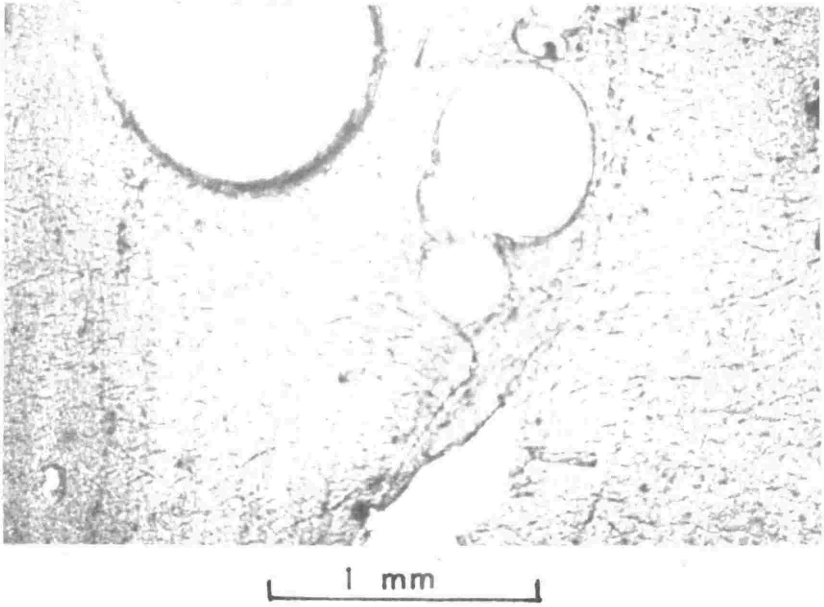


Fig. 35. Expanded obsidian from the Waiohau unwelded ignimbrite (11153) showing how the Flow Structure curves around the vesicles. (Ordinary light).

it is very probable that they were derived from the same magma reservoirs as these domes.

Waiohau 'Ash'.

The Waiohau 'Ash' and associated unwelded ignimbrite deposits have a very low crystal content (av. 4.0%). The deposit has small fragments of quartz and plagioclase, sometimes intergrown with aggregates of hypersthene. A few small hornblende crystals are also present. In 11162, a xenolith (2 mms. in diameter) of quartz and plagioclase shows graphic texture, very similar to that found in the granodiorite blocks associated with the Kaharoa eruption.

The unwelded ignimbrite has the same mineralogy, but the blocks are of obsidian in various stages of expansion. The glass is full of crystallites (typically margarites and trichites) but has no perlitic cracks. Where expansion has begun vesicles distort the flow banding (Fig. 35) showing that expansion occurred while the lava was in a plastic condition.

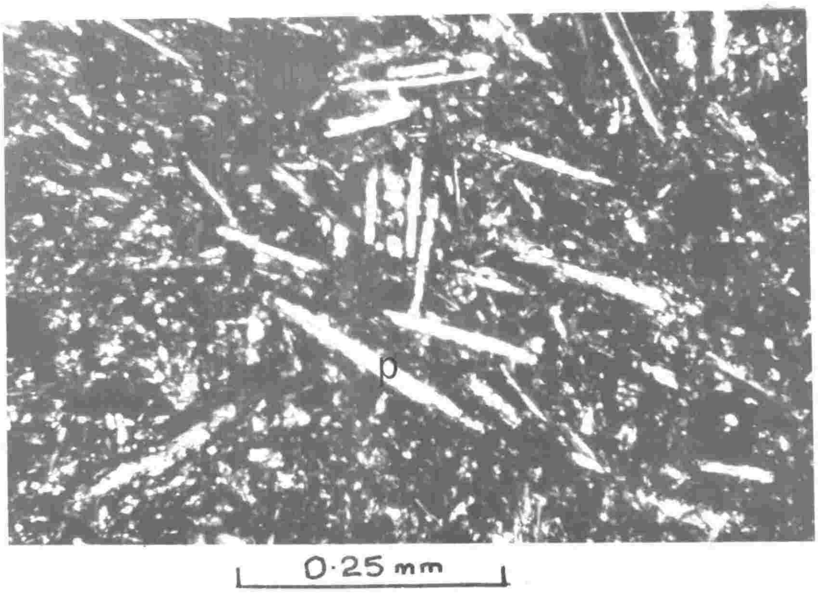
Kaharoa 'Ash'

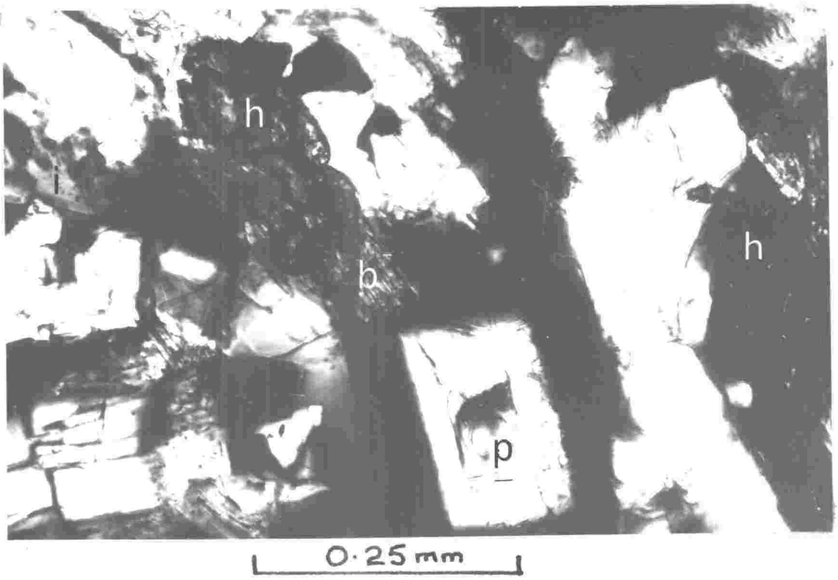
The Kaharoa 'Ash' close to the vent resembles the rhyolite of Ruawahia Dome. Blocks of obsidian and pumiceous rhyolite contain large crystals of quartz, plagioclase and biotite (max. diam. 3 mms.). They are often shattered; the quartz breaking along circular fractures and the plagioclase irregularly or along cleavage planes. Quartz often shows strong resorption. Pumice from Rerewhakaaitu (see p. 46) has a lower total crystal content (Table 5) and the number of small andesitic xenoliths has increased.

Fig. 36. High alumina basalt (11035) : p - plagioclase ; small crystals of olivine and augite in groundmass, (crossed polarisers)

Fig. 37. Hornblende-quartz dacite (11108) : p - plagioclase ; b - biotite h - hornblende ; i - quartz feldspar intergrowth. (crossed polarisers)

Fig. 38. Granodiorite (P29565) : p - plagioclase ; s - sanidine ; q - quartz ; b - biotite. (crossed polarisers).


p
0·25 mm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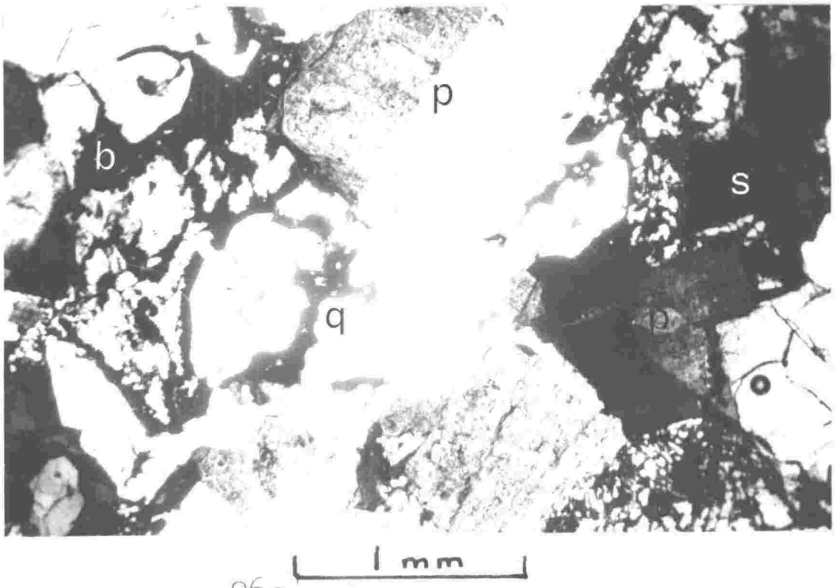
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The unwelded ignimbrites associated with the Kaharoa eruption are composed of the same "primary" rhyolite pumice, but have in addition blocks of ignimbrite, granodiorite and andesite which will be described separately.

HIGH ALUMINA BASALT (11032, 11035, 11045, 11072.)

The high alumina basalt erupted in 1886 (Fig. 36) is considered to be aphyric although it contains a few medium sized crystals of quartz, plagioclase, biotite, augite and olivine, all of which are regarded as "xenocrysts". The major mineral present is plagioclase (av. comp. An_{62}) which usually forms small skeletal laths ($<$ 0.2 mm. long). These are well shown in cross section. Olivine is present in smaller crystals ($<$ 0.15 mm. max. diam.), often euhedral and sometimes showing cleavage. Augite and hypersthene form the smallest identifiable crystals (usually $<$ 0.1 mm.), and with magnetite probably make up most of the groundmass. The xenocrysts are much larger and normally occur in glomeroporphs. Xenocrysts of plagioclase, quartz and biotite are also normally broken. Two modal analyses are given in Table 7.

Various textures are present in the basalt. In the lava at the centre of the eruptive fissure the plagioclase laths show weak orientation, and the rock is slightly scoriaceous. At the margin, however, it is compact and the feldspars show strong orientation parallel to the sides of the fissure. At the edge is a chilled contact and the groundmass has formed a hard black glass. The lava erupted explosively from the fissure is scoriaceous (vesicle space often $>$ 50%), and this may be oxidised to a bright red-brown colour

(11045). Immediately surrounding the vent the scoria has welded together and this is sometimes apparent in thin section, with lapilli or small bombs in a matrix of crushed basalt.

Effect of Basalt on Rhyolite

The effect the basalt has had on the rhyolite depends very much on temperature, and this is largely controlled by the depth at which the lava picked up the included block. If it occurred at or near the surface, the rhyolite glass retains its pumiceous nature, although it may become somewhat expanded. Crystals are little affected, unless at the margin of the rhyolite where they become shattered. Mafic minerals (particularly biotite) become slightly oxidised. If the rhyolite is from greater depths in the vent, the changes become more marked. Such blocks are normally of Early rhyolite, and the glass becomes almost completely devitrified to form a mosaic of cristobalite and alkali feldspar, often with small microspherulites (p.145) Small remnants of glass or spherulite sometimes remain. Any vesicle spaces usually contain tridymite, more of which is normally found in reheated blocks than in unaffected rhyolite. Mafic minerals in these cases are normally highly oxidised and magnetite has a selvage of hematite.

ACCESSORY EJECTA

Two coarser grained rock types have been extruded which are regarded as comagmatic with the rhyolites, and a number of andesites and 'eucrites', which are considered to be related to the basalt. One of the former, a hornblende-quartz dacite, is associated with the Rerewhakaaitu 'Ash', and all the remainder occur in unwelded ignimbrites associated with the Kaharoa eruption. Small xenoliths of these also occur in the lavas of the Late Domes.

a. Hornblende-Quartz Dacite (11108, 11109, 11157)

These boulders occur up to 10 cm. in diameter in the Rerewhakaaitu 'Ash', and resemble the basic inclusions described by other authors (e.g., Lewis, 1960), from the Taupo Volcanic Zone. The dominant mineral is plagioclase which occurs as euhedral crystals up to 0.75 mm. in length and is frequently strongly zoned. In many cases the centres of the crystals have been resorbed and glass and/or small inclusions of mafic minerals are present. Fine grained graphic intergrowths of quartz and feldspar surround some crystals. Quartz also occurs as moderately large anhedral crystals which often seem to form the nuclei for glomeroporphyritic clusters of crystals. Sometimes there is evidence of an original square cross section.

The mafic minerals are variable. A green hornblende is the most common, forming long slender prisms up to 1 mm. in length. Biotite is common in some xenocrysts (e.g., 11157) but less so in others. When both hornblende and biotite occur they are commonly intergrown. Both clinopyroxene and orthopyroxene occur in small amounts but they are invariably surrounded by green hornblende (see Fig. 75). Magnetite is ubiquitous.

The crystals are in a variable amount of pumiceous glass of which the largest amount occurs in 11108. Here vesicles up to 0.25 mms. occur.

b. Biotite Granodiorite (10918, 10920, P29565)

Boulders up to 25 cms. in diameter occur in a post Kaharoa 'gully deposit' immediately to the south of the mountain (N77/964907). Smaller lapilli also occur in the 'Ash' and ignimbrites and it is from these that the debris in the gully is thought to be derived. The rocks are coarse-grained, with euhedral to subhedral plagioclase dominant and some subhedral phenocrysts of sanidine (Fig. 38). Locally poorly developed quartz-sanidine intergrowths occur around the edges of the quartz. The dominant mafic mineral is biotite, and this is found in large flakes usually associated with magnetite and accessory minerals. Small amounts of hypersthene and hornblende also occur, in small irregular masses, and in 10920 epidote is associated with biotite. Minor shearing is very characteristic and results in the displacement of feldspars, recrystallization of quartz, and shattering of biotite flakes.

c) Andesites

The andesites occur as boulders up to 10 cms. in diameter in the Kaharoa ignimbrites and like the granodiorites, as smaller lapilli in the 'Ash' itself. They can be distinguished in hand specimen from the later basalt as the blocks of andesite are coated with a white pumice, whereas the basalt coats this same pumice. Also, green pyroxene crystals are often visible in the andesites, whereas this is never the case in the basalt. Modal analyses of the andesites are given in Table 7. The most common andesite found, and that analysed,[*] is a pyroxene andesite which may or may not contain hornblende in the groundmass. Two other types have also been found, a sodic andesite

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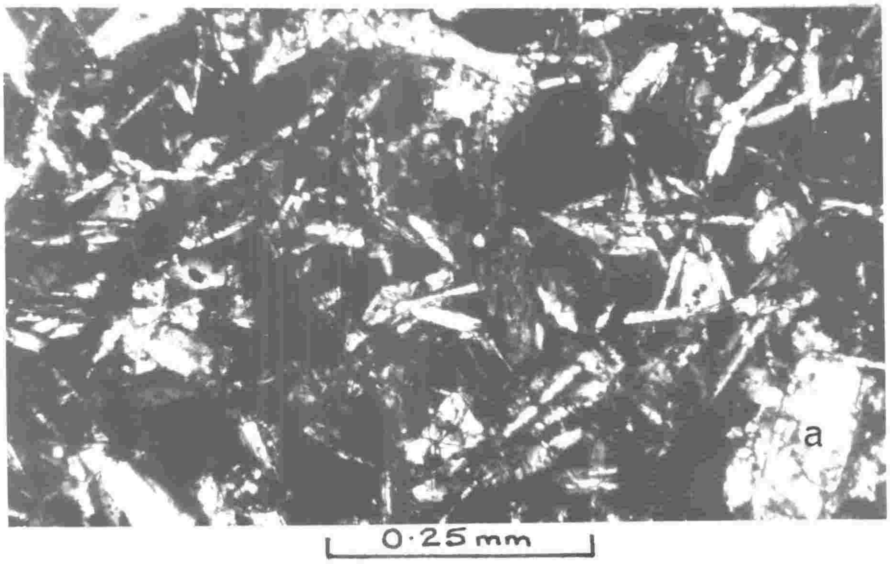
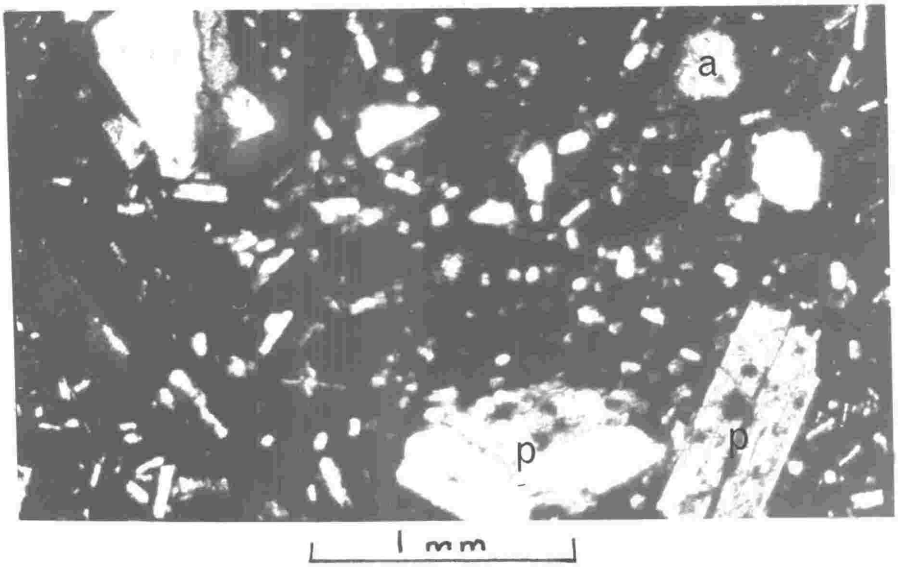
[*] It is from the silica content of the analysed specimen that the name andesite has been given.

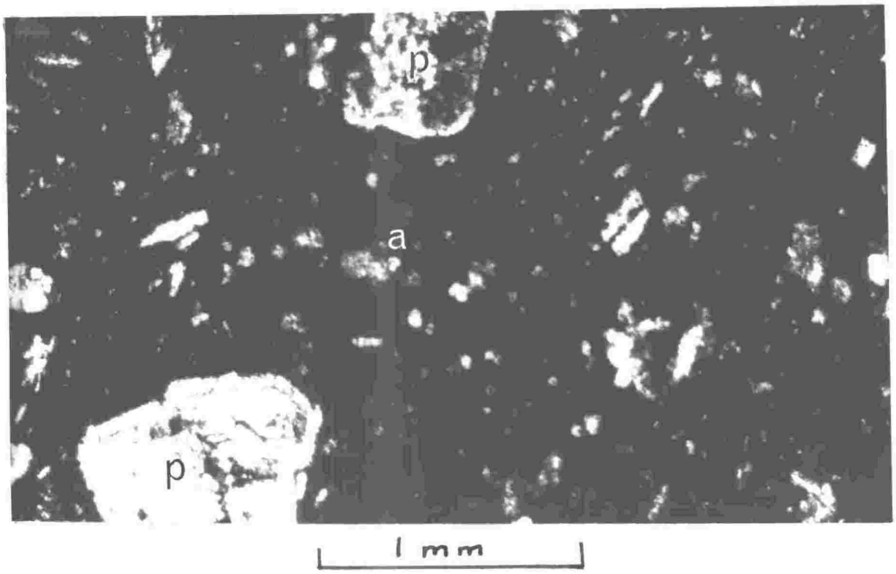
Fig. 39. Pyroxene andesite (11079) : a - augite phenocryst ; laths of plagioclase, augite and olivine in groundmass. (crossed polarisers).

Fig. 40. Bytownite andesite (11083) : p - plagioclase ; a - augite. (crossed polarisers).

Fig. 41. Sodic andesite (11092) : p - plagioclase ; a - augite. (crossed polarisers).


a
0·25 mm


a
p
p
1 mm


p
a
p
1 mm

and a bytownite andesite.

Pyroxene Andesite (11080, 11082, 11158):- This rock (Fig.39) varies in texture from aphyric (11158) to porphyritic (11080). The groundmass is composed of small laths of plagioclase (labradorite) between which are small grains of augite, magnetite and sometimes olivine. The phenocrysts are of augite and olivine (0.5-1.5 mm. diam.) and are very similar to those of the coarse grained ankaramite. The augites are frequently twinned and a few crystals show 'hour-glass' extinction. The olivines, which are normally the larger, are occasionally surrounded by a rim of pyroxene. Hypersthene occurs in most specimens, and this is usually surrounded by an aggregate of augite (see Fig. 76). In some cases the augite has almost replaced the hypersthene to form a fine aggregate of the two minerals. This feature has also been described by Kuno (1950, p.978).

Most of the andesites also contain xenocrysts of plagioclase and quartz. The plagioclase crystals are up to 3 mm. in length and are always partly cloudy. This seems to be related to the lime content, and will be discussed more fully in the section on mineralogy. Quartz, when present, is normally highly resorbed and surrounded by a rim of pyroxene (which appears from optical data to be augite).

A variant of this type is the pyroxene-hornblende andesite (11081, 11099), in which most of the augite of the groundmass is replaced by small prismatic crystals of hornblende (0.05 mm). Larger crystals of augite and olivine, together with quartz and plagioclase xenocrysts, still occur and exhibit the same features.

Bytownite Andesite (11083):- This rock (Fig. 40) resembles the labradorite andesites of National Park described by Clark (1960) except for the composition of the feldspar. The crystals occur in all sizes from 0.1 mm. to 1-1.5 mm. in length, and are usually twinned, having a wide calcic core and narrow zoned margin. The other phenocrysts are augite and olivine similar to those of the pyroxene andesite. The augites are twinned and often appear to be replaced by siderite. The groundmass is a dark glass with feldspar microlites and small augite crystals.

Xenocrysts of quartz, plagioclase and small xenoliths of rhyolite occur in the rock, and the quartz is often surrounded by a rim of small pyroxene crystals ($<$ 0.05 mms.) as in the pyroxene andesites.

Sodic Andesite (11092, 11093):- This rock is most complex in its mineralogy. The essential part of the lava appears to be small feldspar microlites ($<$ 0.06 mms.), apparently of labradorite composition, in a fine dark mesostasis. Small crystals of pyroxene may also be primary. Within this, however, is a wide variety of crystals similar to those described in the pyroxene andesite. These consist of olivine (surrounded by reaction rim), augite, hypersthene (surrounded by augite), sodic feldspar (oligoclase-andesine with a cloudy outer zone), quartz and biotite. (This mineral was not found in the pyroxene-andesite and here is always surrounded by a rim of magnetite.) In addition, numerous inclusions of pyroxene andesites occur (0.5 mm.-20 mm. in diam.), which occasionally have pale hornblende needles developed at their margins (presumably derived from

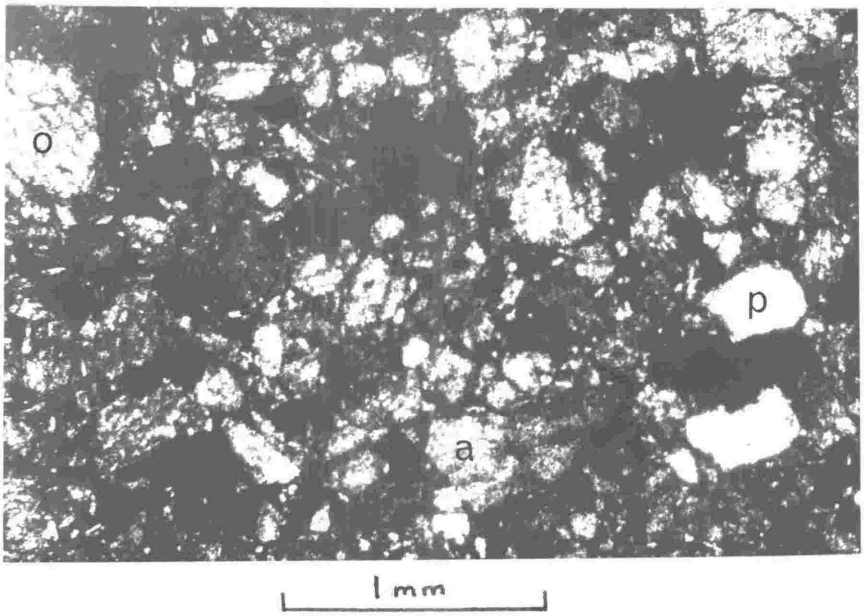


Fig. 42. Ankaramite (11089) : p - plagioclase ; a - augite ; o - olivine. (crossed polarisers).

the pyroxenes). The groundmass varies from cryptocrystalline to glassy.

d) Ankaramite (11089, 11090, 11091)

The dominant mineral in these boulders is augite (Fig. 42) which usually occurs as euhedral-subhedral twinned crystals (max. 1 mm. x 0.5 mm.). Olivine is present in smaller amounts and forms anhedral crystals, often surrounded by a thin oxidised margin. The plagioclase phenocryst content varies; in 11089 it is scarce, but in 11091 it forms about 20% of the crystal content, mostly poikilitcally enclosing augite. The centres of most crystals are unzoned (anorthite-bytownite), but around the margin a number of oscillatory zones may occur which occasionally reach labradorite in composition. Some of the plagioclase crystals in 11089 show marked resorption (see Fig. 48) and in the resorbed areas groundmass occurs.

The groundmass of these rocks is composed of small feldspar laths riddled with minute grains of magnetite, and in 11089 prisms of green hornblende occur. They surround most of the pyroxenes and often appear to be developed from them.

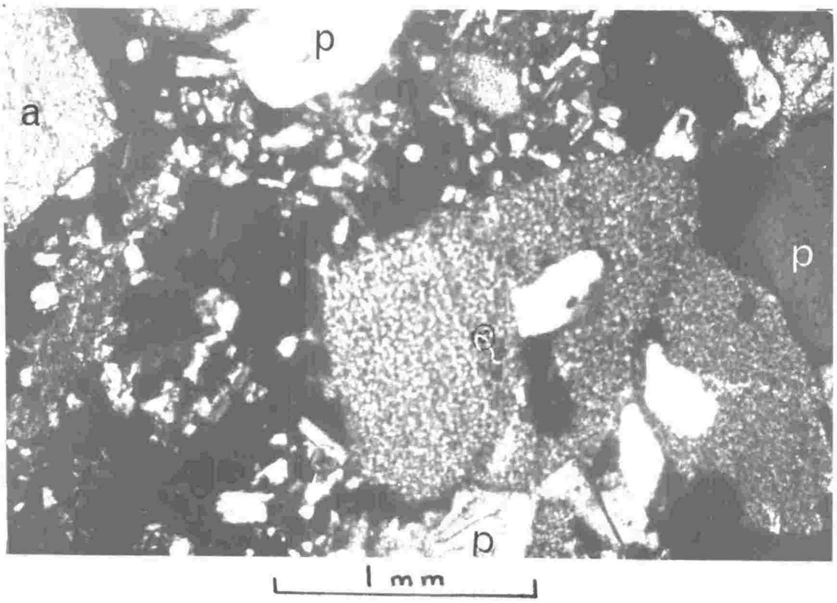
e) 'Eucrites'

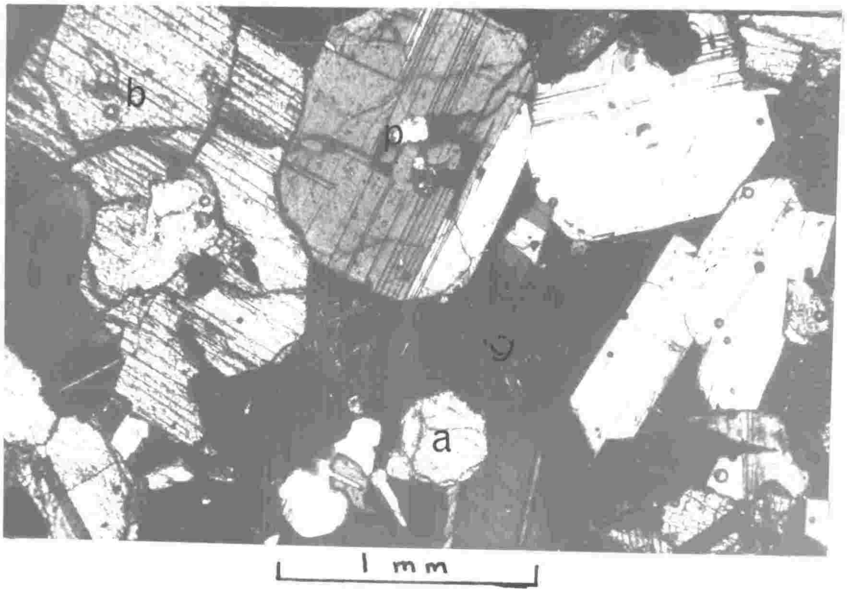
These rocks are coarser grained than the ankaramite, and have a very calcic plagioclase. They have been called 'eucrites' by Williams, Turner and Gilbert's definition (1958, p.52) of a gabbro "characterised by extremely calcic feldspar - namely bytownite or anorthite", despite the presence of a small amount of glass or groundmass. This is to distinguish them from the other lavas in which the groundmass forms the larger portion. The mafic mineral content varies considerably (modal analyses, Table 7), and probably represents a crystallization series.

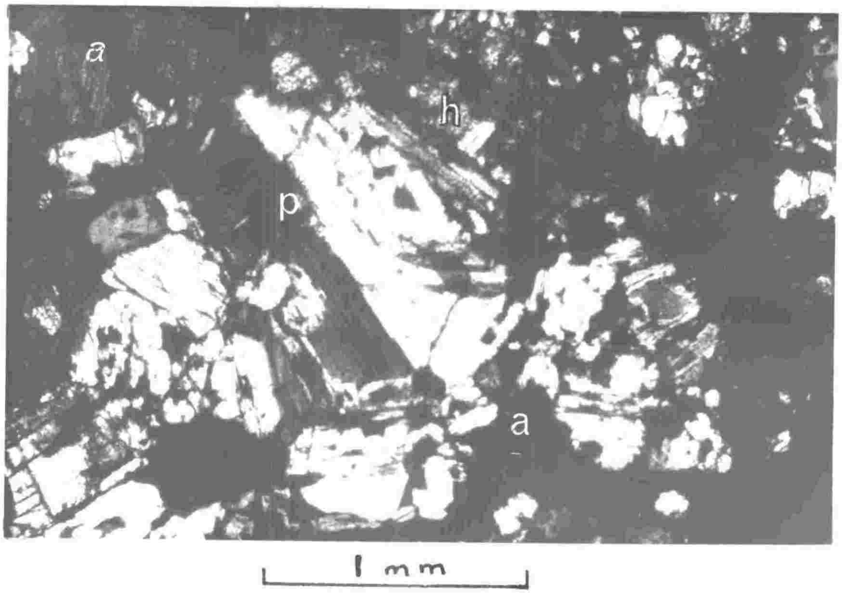
Fig. 43. Olivine eucrite (11176) : p - plagioclase ; a - augite ; o - olivine. (crossed polarisers).

Fig. 44. Bronzite eucrite (11078) : p - plagioclase ; a - augite ; b - bronzite ; g - groundmass. (crossed polarisers).

Fig. 45. Hypersthene eucrite (11077) : p - plagioclase ; a - augite ; h - hypersthene. (crossed polarisers)


p
a
p
a
p
1 mm


b
p
g
a
1 mm


a
h
p
a
1 mm

For convenience, two types can be distinguished.

Olivine Eucrite (11176):- The three main minerals are augite, olivine and plagioclase, as in the ankaramite, but the crystals are larger (max. size 2 mms.), and subhedral-anhedral (Fig. 43). Augite and olivine often show evidence of resorption (particularly olivine) and may include plagioclase. The groundmass is composed of small laths of zoned plagioclase (max. size 0.3 mm.) together with small crystals of augite and magnetite.

Orthopyroxene Eucrites (11077, 11078):- In these rocks the percentage of plagioclase reaches a maximum of 63% and hypersthene or bronzite occur as important mafic minerals. In 11078 (bronzite eucrite) augite and bronzite occur together, and are often partly enclosed in the feldspar (Fig. 44). The bronzite usually encloses small anhedral crystals of olivine indicating perhaps some genetic relationship. Plagioclase is the most important mineral in 11077 (hypersthene eucrite) and olivine is absent; the plagioclase showing resorption and the outer zone (often full of inclusions) much more sodic than the centre (Fig. 45). Hypersthene is often intergrown with the feldspar, and in some cases appears to form large crystals. The groundmass in both 11077 and 11078 is composed of small laths of feldspar probably more sodic than the phenocrysts together with small acicular crystals of hornblende. This is variolitic structure (Hatch, Wells and Wells, 1949, p.301) and is apparently the basic equivalent of spherulitic development in acid rocks. Hornblende also occurs around the margins of pyroxenes, as in the ankaramites.

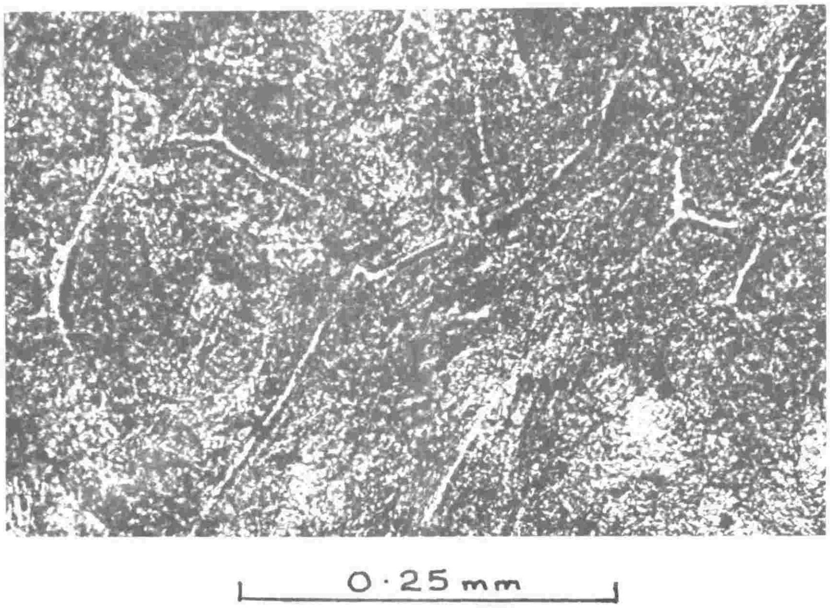


Fig. 46. Ignimbrite (11056) showing Y-shaped shards. (ordinary light).

ACCIDENTAL EJECTA

a) Ignimbrite

A number of small blocks (max. diam. 5 cms.) of ignimbrite have been found in the 'gully infill' deposit and, like the accessory ejecta, are probably derived from the Kaharoa deposits. Three broad types can be recognised:

(i) 11056, 11084, 11085, 11094. These have a moderate crystal content, of which plagioclase (andesine) is the dominant mineral. They are of medium size (max. 2 mm.) and are frequently resorbed around the edge. Some contain inclusions of apatite or zircon and magnetite. Many also show a margin of apparently later crystallisation which is in optical continuity with the crystal, but is more sodic ($2V_\alpha \approx 60^\circ$). Quartz is moderately common and usually resorbed. No mafic minerals are present, but diffuse iron-rich areas could well represent their remains. The glass has good vitroclastic texture (Fig. 46) and is not devitrified. The shards are characteristically Y-shaped, and although they appear to show little flattening, small areas of porous material ($<$ 2 mms.) are present. These presumably represent pumice lapilli.

(ii) 11124, 11125, 11130. This second type has a higher total crystal content and larger crystals (max. diam. plagioclase 4 mms.), particularly of resorbed quartz, are developed (some $>$ 3 mms.). Most crystals are broken, and many small fragments occur throughout the glass. Biotite occurs as small, usually broken, flakes. The glass is devitrified and only in 11130 can shards be distinguished. Large pumice lenticles (5-10 mms. max. diam.) are common and these are now spherulitic.

(iii) 11106. The third type is similar to (i) except it is completely devitrified. Shards can be distinguished and these indicate that little flattening has occurred. A fine grained inclusion present could represent cooked up sediment as no pumice can be distinguished within it. Fragments of spherulites also occur (perhaps from earlier rhyolites).

In addition to the ignimbrites, blocks of tuff occur (11057, 11111, 11112). These usually show no true vitroclastic texture but are full of small pumice, quartz and feldspar fragments (all $<$ 0.5 mms.). Specimen 11057 is full of broken shards, but in this rock no crystals are present.

b) (?) Arkose

One (?) arkose xenolith (11107) was found in the Kaharoa unwelded ignimbrite. This has a sugary appearance in hand specimen with a baked margin. In thin section the major constituent is quartz, which forms large interlocking grains. Numerous cracks cross the mineral and these are often filled with glass, secondary quartz and feldspar. An aggregate of anhedral quartz and feldspar ($<$ 0.25 mms.) is present between some grains. The latter shows albite twinning and is of labradorite composition. In one place there is a fibrous mass of crystals thought to be sillimanite, and if so the rock would compare with those described by Lewis (1960, p.80) from the dacites at Tauhara.

c) Ejecta from Green Lake Crater

Blocks up to 2 metres in diameter were thrown from Green Lake (Explosion) Crater during the eruption in 1886. These consist of various types of ignimbrite and rhyolite, often brecciated, which for the purpose of the present study can be divided into:

Hypersthene-hornblende Ignimbrite (? Rangitikei Ignimbrite)

Biotite Ignimbrite (with lenticulite bands)

Devitrified Rhyolite.

Of particular note is the occurrence of calcite in certain rocks. It appears to replace some of the mafic minerals, although in one case (11126) it occurs in very small veins throughout the rock. The origin of this mineral is unknown, but could possibly be hydrothermal. In 11172 a breccia containing fragments of pumice, spherulitic rhyolite and many crystals of quartz and feldspar is cemented by an iron rich matrix. This is full of small grains (< 0.1 mm.) of carbonate, which further suggests an "invasion" by hydrothermal solutions.

Figs. 47 - 49.

Camera Lucida drawings of phenocrysts showing resorption.

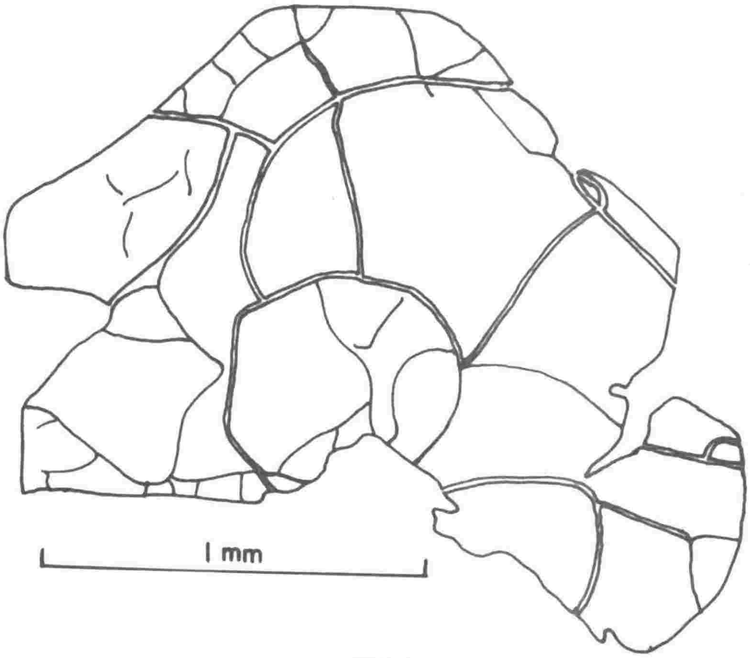


Fig. 47.

Quartz phenocryst from 11073 with preferential resorption along circular cracks.

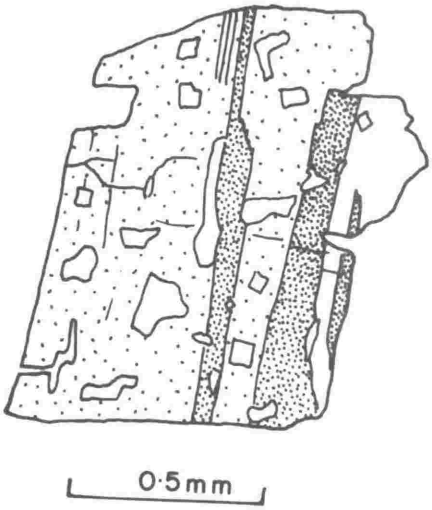


Fig. 48.

Plagioclase phenocryst from 11144.

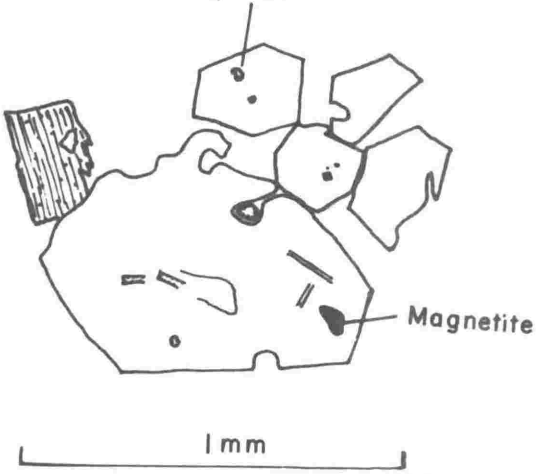


Fig. 49.

Biotite cleavage plates from 11031.

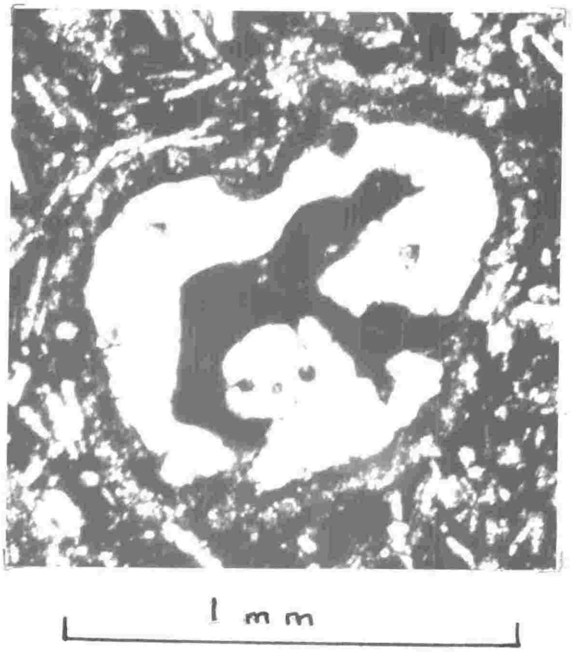


Fig. 50. Highly resorbed quartz crystal from the pyroxene andesite (11080) surrounded by a rim of granular augite (crossed polarisers).

MINERALOGY

SILICA MINERALS

Three silica minerals; quartz, cristobalite and tridymite occur in the rocks of the Tarawera Complex. Quartz is the most common type and the only one forming euhedral phenocrysts. Cristobalite is an important constituent of spherulites and tridymite occurs in many of the rhyolites, particularly where reheating has occurred.

Quartz

Quartz occurs in all the rocks of the Complex, although it is doubtful whether it is of primary origin in the andesites and basalt.

In the rhyolites, quartz phenocrysts vary from < 0.5% of the total rock in some of the lava flows to > 10% in some of the Late domes. The size varies correspondingly, some of the largest occurring in Rotomahana Dome (< 5 mm.). The phenocrysts are usually euhedral to subhedral and are square or hexagonal in cross section. They often contain cracks which may be circular, and continue into the glass as normal perlitic cracking. Frequently embayments occur in the crystals which usually commence along cracks (Fig. 47) and are considered to be a result of resorption.

Quartz crystals are present in very minor amounts in the high alumina basalt and slightly more in the andesites. The crystals resemble those of the rhyolites in their shape and resorption, and in every case they are surrounded by a reaction rim of pyroxene (probably augite) with what appears to be dark glass between the two minerals (Fig. 50).

Fig. 51. Cristobalite in a vesicle within the pyroxene andesite (11158) showing 'roofing structure' (ordinary light)

Fig. 52. Same mineral under crossed polarisers.

Fig. 53. Tridymite crystals in a vesicle within rhyolite (11069). Crystal on right shows pseudo-hexagonal twin (ordinary light).

Fig. 51.

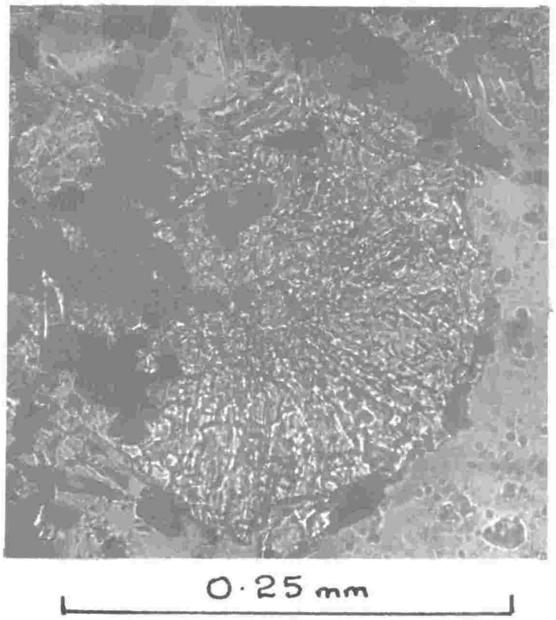
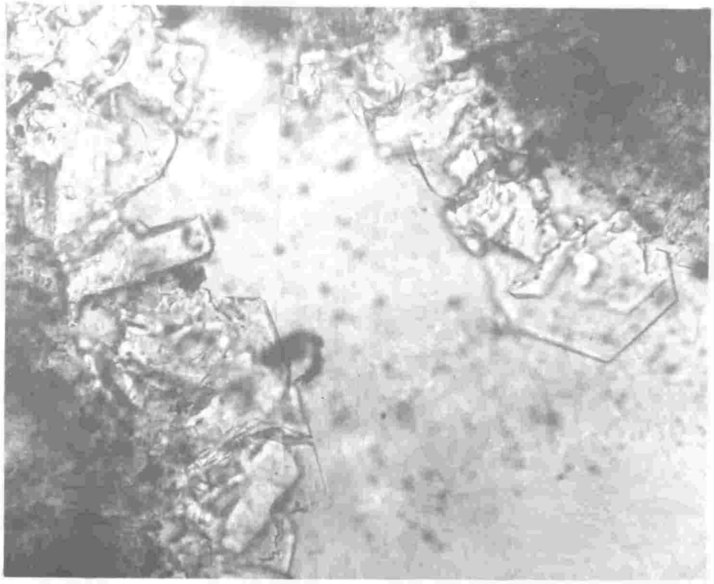


Fig. 52.

Fig. 53.



The quartz of the "cognate" hornblende - quartz dacite, occurs as subhedral grains often intergrown with feldspar and hornblende or biotite. In each case it appears to fill interstices between the other crystals. In the granodiorites it strongly resembles the phenocrysts of the rhyolites. They are large, subhedral to euhedral, and have the typical embayments. In some crystals these appear to be developed parallel to the hexagonal faces of the quartz (Ewart and Cole, in press. Fig. 6).

Cristobalite

Cristobalite is found in spherulites within the rhyolite dome lavas and as these features are very common it is an important occurrence. It is difficult to recognise the mineral optically, but an X-ray diffraction pattern confirmed one spherulite to be cristobalite and sanidine. The mineral is also found in vesicles in a vesicular andesite (11158), where it shows typical twinning and 'roofing' structure (Figs. 51 and 52); and in very small amounts in some specimens of the high alumina basalt.

Tridymite

Tridymite is found lining vesicles in spherulitic rhyolite samples from near the centres of the domes. The small crystals occur as clear euhedral prisms which frequently show wedge-shaped twinning. The refractive index (measured from a crystal in 11069) is 1.478. When a rhyolite has been reheated by inclusion in the basalt, tridymite is more abundant and forms wedge-shaped crystals 0.5 mm. long (Fig. 53). In 11086 the crystals often completely fill the cavities in which they occur.

PLAGIOCLASE

Plagioclase is present in all the rocks of the Tarawera Complex, and in the rhyolite it is nearly always the most abundant phenocryst mineral. Only one example, an obsidian from the Kaharoa 'Ash' (11030) was found to have a higher percentage of quartz than plagioclase. In the high alumina basalt and pyroxene andesites the groundmass, plagioclase accounts for nearly 20% of the total rock, and in the bytownite andesite,phenocrystic plagioclase forms 17% of the rock.

The size of the phenocrysts in the rhyolites vary considerably (< 0.5 mm-5 mm.), both between different domes and in some cases within the same dome. In general, however, rocks with a high total crystal content have larger feldspars than rocks with a small crystal content. Often glomeroporphyritic clusters are formed (max. diam. 8 mm.). Ferromagnesian minerals are sometimes present in these clusters.

The phenocrysts are euhedral-subhedral, but,as they are prone to shattering, in many cases only part of a crystal may remain. Inclusions are common, both of earlier formed minerals (e.g., biotite, hornblende, hypersthene and magnetite) and glass. The latter is probably linked with the common resorption of the mineral (Fig. 48). Zoning and twinning are ubiquitous. The latter may be of albite, combined carlsbad-albite or pericline-albite type. In the rhyolites of Green Lake Plug and in the Rerewhakaaitu 'Ash' small microlites of feldspar occur in the glasses, and these, from X-ray determinations, appear to be plagioclase.

The plagioclase in the groundmass of the basalt and the pyroxene-andesite occur as small laths (< 0.5 mm.), showing carlsbad or albite

...ICAL AND OPTICAL DATA ON PLAGIOCLASE FELDSPARS FROM THE RHYOLITES AND COGNATE XENOLITHS

Spec No.	Na_2O	K_2O	CaO	Composition	2V (±2°) margin - core	R.I. (±0.002)	Comp. Range (±4°/o)
11038 (1P)	4.8	0.36	3.88	$Or_{3.1}Ab_{65.4}An_{31.5}$	63 - 83°	α'_{min} 1.538 γ_{max} 1.555	An_{20} - An_{37}
11137 (2P)	6.04	0.40	6.41	$Or_{2.6}Ab_{60.1}An_{37.3}$	85 - 98°	α'_{min} 1.544 γ'_{max} 1.561	An_{32} - An_{48}
11097 (3P)	6.12	0.40	7.56	$Or_{2.4}Ab_{56.3}An_{41.3}$	70 - 104°	α'_{min} 1.543 γ_{max} 1.563	An_{30} - An_{53}
11129 (4P)	5.24	0.58	5.74	$Or_{4.4}Ab_{58.5}An_{37.3}$	70 - 86°	α'_{min} 1.543 γ'_{max} 1.559	An_{30} - An_{45}
11122 (5P)	4.62	0.60	3.25	$Or_{5.7}Ab_{66.7}An_{27.6}$	64 - 70°	α'_{min} 1.536 γ'_{max} 1.552	An_{16} - An_{31}
11105	-	-	-	-	68 - 86°	α'_{min} 1.540 γ'_{max} 1.557	An_{24} - An_{41}
11144	-	-	-	-	86 - 101°	α'_{min} 1.543 γ'_{max} 1.563	An_{30} - An_{53}
11061/7 (6P)	5.34	0.58	3.31	$Or_{5.2}Ab_{69.6}An_{25.2}$	62 - 72°	α'_{min} 1.536 γ'_{max} 1.552	An_{16} - An_{31}
11170 (7P)	6.24	0.42	6.47	$Or_{2.7}Ab_{60.5}An_{36.8}$	70 - 82°	α'_{min} 1.542 γ'_{max} 1.555	An_{28} - An_{37}
11171 (8P)	6.12	0.54	7.07	$Or_{3.4}Ab_{57.4}An_{39.2}$	a) 72 - 100°+ b) 84 - 98°	α'_{min} 1.543 γ'_{max} 1.562	An_{30} - An_{51}
11108 (10P)	5.84	0.36	8.88	$Or_{2.0}Ab_{51.8}An_{46.2}$	80 - 102°	α'_{min} 1.543 γ'_{max} 1.563	An_{30} - An_{53}
P29565*(11P)	9.2	1.2	3.8	$Or_{6.8}Ab_{75.0}An_{18.2}$	59 - 79°	α'_{min} 1.536 γ'_{max} 1.550	An_{16} - An_{27}

+ The two readings are from the two different pumice types in the Rerewhakaaitu 'Ash'

* Number in collection of the N.Z. Geological Survey, Lower Hutt.

TABLE 10 - OPTICAL DATA ON PLAGIOCLASE FELDSPARS FROM THE BASIC ROCKS

Spec. No.	2V (±2°) margin-core	R.I. ($\pm$0.002)	Approx. Comp. Range (margin-core)
11079 (groundmass)	-	α_{min} 1.560 γ_{max} 1.573	An_{62}-An_{70}
11079 (xenocryst)	87°-84°	α_{min} 1.538 γ_{max} 1.580	An_{86}-An_{20}
11091	103°-83°	α_{min} 1.562 γ_{max} 1.583	An_{86}-An_{92}
11078	84°(?)-81°	α_{min} 1.570 γ_{max} 1.584	An_{88}-An_{94}
11077	95°-81°	α_{min} 1.567 γ_{max} 1.584	An_{78}-An_{94}
11083	91°-80°	α_{min} 1.565 γ_{max} 1.585	An_{74}-An_{96}

Fig. 54.

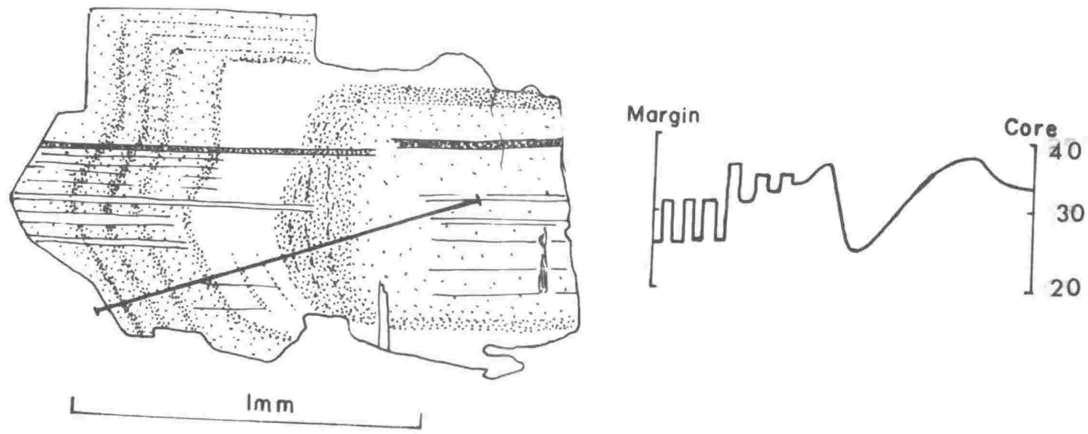
Camera Lucida drawings of plagioclase phenocrysts showing different types of zoning (approximate compositions in % Anorthite).

A) Oscillatory zoning in phenocryst from 11105.

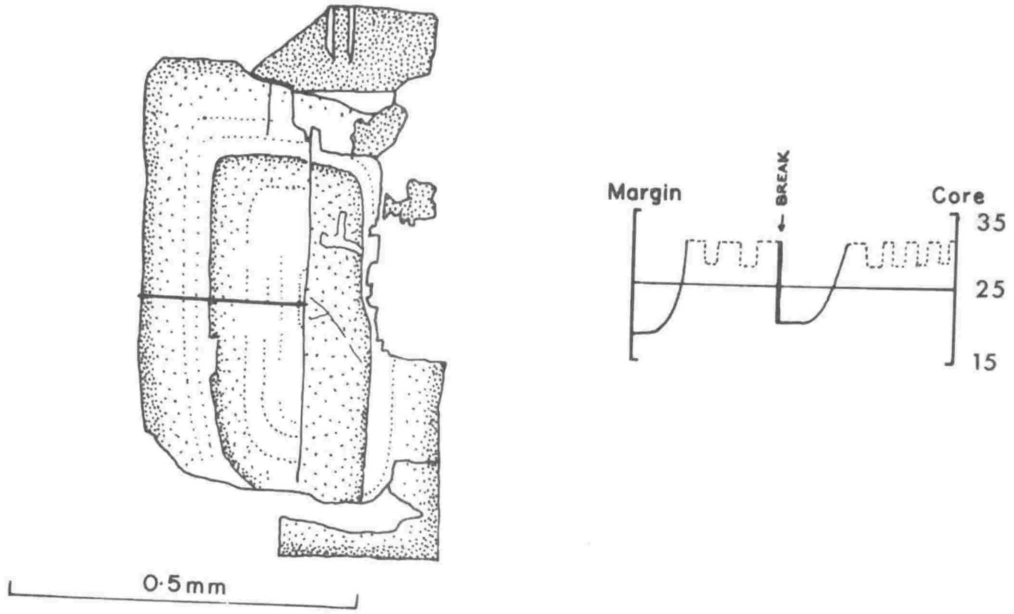
B) Zoning with a break in composition (11071).

C) Zoning with a break in composition, and a patchy core caused by the presence of plagioclase of two compositions and inclusions of glass (11144).

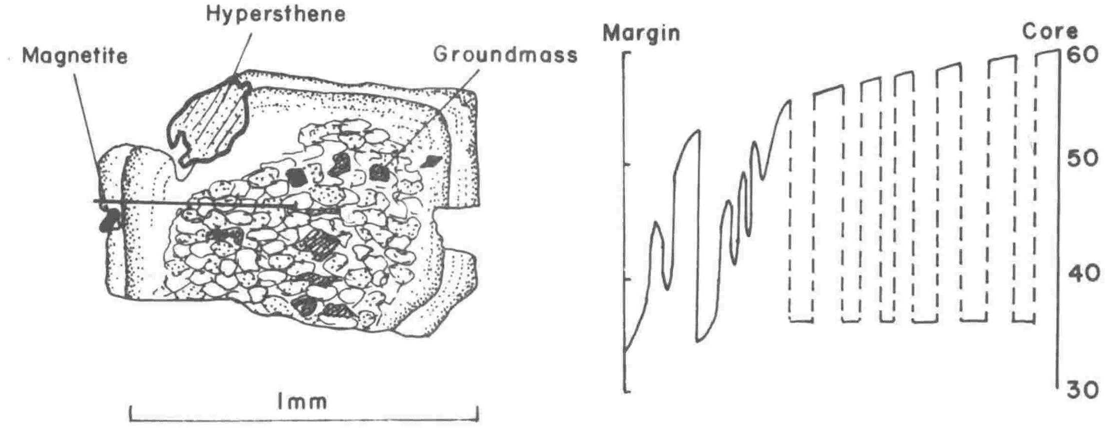
A


Margin
Core
40
30
20
Imm

B


Margin
BREAK
Core
35
25
15
0·5mm

C


Hypersthene
Magnetite
Groundmass
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Core
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Imm

Fig. 55.

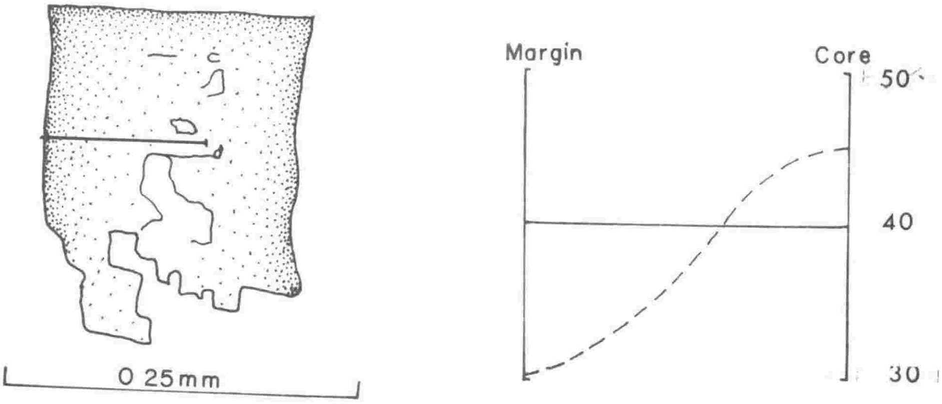
Camera Lucida drawings of plagioclase phenocrysts showing different types of zoning (approximate compositions in % Anorthite).

A) Normal zoning in phenocryst from 11108.

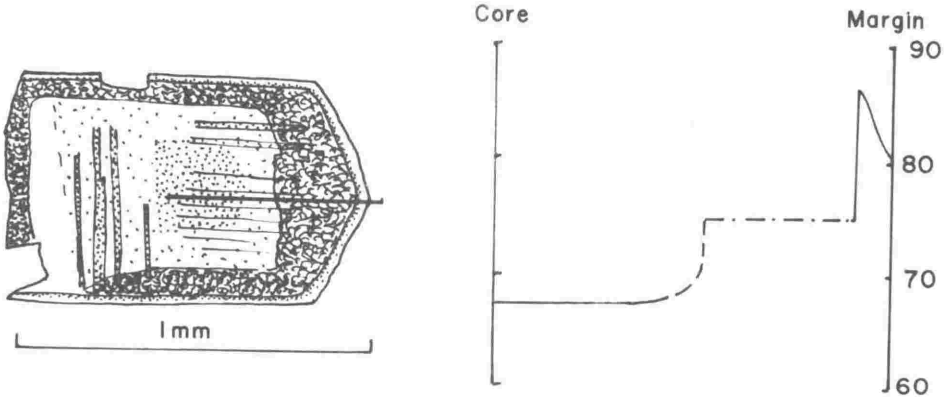
B) Phenocryst from 11099 with sodic core, calcic margin and cloudy zone between.

C) Phenocryst from 11097 with oscillatory zoned core and patchy, resorbed margin.

A


0.25mm
Margin
Core
50
40
30

B


1mm
Core
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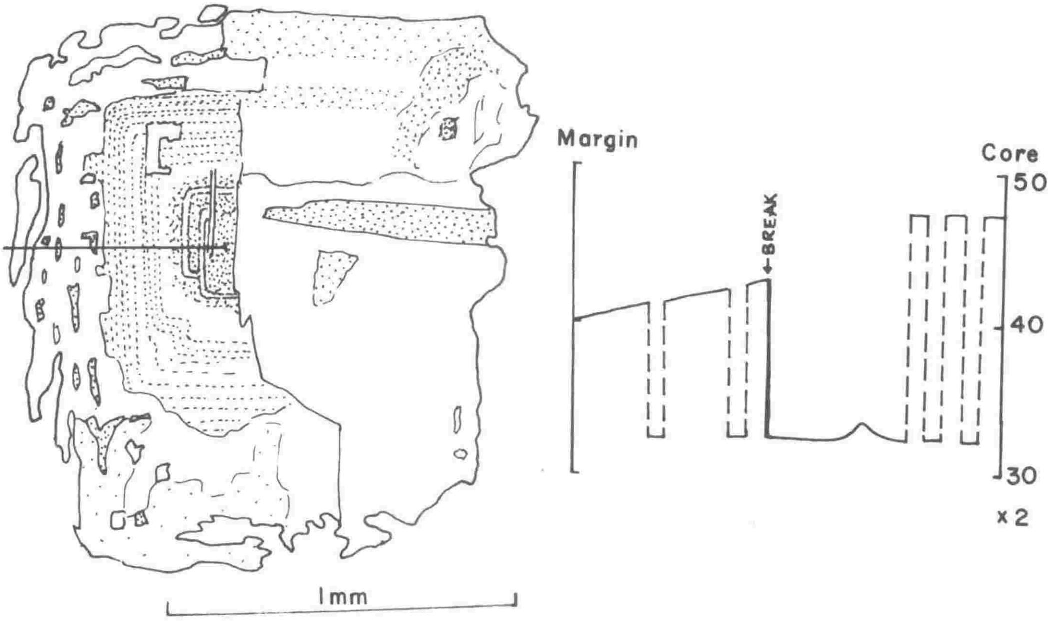
90
80
70
60

C


1mm
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twins. They also frequently form glomeroporphyritic clusters with the ferromagnesian minerals. In the andesites larger crystals occur and in the pyroxene andesites these are euhedral-subhedral, and are partly cloudy. In the 'eucrites' they are subhedral-anhedral, and usually less strongly zoned.

The average compositions of ten plagioclases are shown in Table 9, together with the range of composition determined by measuring refractive indices. Optic angle measurements show the mineral to have a high temperature mineralogy (Deer, Howie and Zussman, 1963, p.134) and this is consistent with the results of Ewart (1963, 1965) who has made X-ray determinations of plagioclases from other acid rocks in the Taupo Volcanic Zone.

The phenocrysts of the rhyolites are andesine-oligoclase in composition, although the core of several crystals are as calcic as labradorite. The composition of crystals in the basic rocks is highly variable. Those in the basalt and in the groundmass of the pyroxene andesite appear to be labradorite (γ max. 1.575, specimen 11072), and those in the eucrites range from anorthite-bytownite (Table 10). The larger crystals in the pyroxene andesites are shown to have a range of composition from bytownite to oligoclase, but in fact the cores are oligoclase and the rims bytownite, with a distinct break between the two compositions.

Zoning

Most of the types of zoning described by Homma (1936) and Larsen (1938) can be found in the Tarawera rocks, and some of these are shown in Figs. 54 and 55. The most common type in the rhyolites is oscillatory zoning (Fig. 54A), which may show breaks between some of the zones (Fig. 54B). Many of the larger phenocrysts have a patchy core in which there is an intimate mixture of plagioclase of two compositions (Fig. 54C) and in the Western and Southern Domes the 'patchy' feature may occur at the margin accompanied by extensive resorption (Fig. 55C). Only one example of reversed zoning is known to have occurred in the rhyolites. This is in Crater Dome and has a core of approximately An_{28} separated from a margin of An_{46} by a distinct break.

In the more basic rocks the groundmass feldspars usually show normaly calcic-sodic zoning (Fig. 55A), but the larger phenocrysts may show one of two types. In the pyroxene andesite they have sodic cores separated from highly calcic rims by a cloudy intermediate zone (Fig. 55B). This intermediate sone appears to be a mixture of the two types, probably with minute inclusions of groundmass. In extreme cases the whole of the core has this cloudy appearance. In the 'eucrites' the cores are highly calcic (An_{92-94}) and these are surrounded by a thin margin of oscillatory or normal zoned plagioclase.

The petrogenetic implications of the type of zones present will be discussed in the section on crystallisation history.

SANIDINE

Sanidine is present only in the granodiorite blocks from the Kaharoa 'Ash'. It occurs as distinct subhedral crystals, and as interstitial material between quartz and plagioclase. It frequently contains dust-like glassy inclusions which give it a cloudy appearance in ordinary light.

The composition and optical properties (from Ewart and Cole, in

TABLE 11 - ~~OPTICAL~~ DATA ON SANIDINE FROM THE GRANODIORITE

Spec. No.	Na_2O	K_2O	CaO	Composition (from partial analyses)	$(\bar{2}01)-(1011)^{(+)}$ Quartz	Comp. from X-ray	$2V_{\alpha}$ ($\pm 2^{\circ}$)	R.I. ($\pm$0.002)
P29565*	4.7	8.6	0.4	$Or_{54.9}Ab_{43.0}An_{2.1}$	0.41 (1.09)	Or_{66} (Or_6)	20 - 30°	α 1.519 γ 1.525
10922	-	-	-	-	0.43 (1.08)	Or_{63} (Or_7)	23 - 33°	α 1.520 γ 1.525

* Number in collection of the N.Z. Geological Survey, Lower Hutt.

(+) X-ray determinations by Dr. A. Ewart. (Subsidiary phase shown in brackets) press) of two specimens are given in Table 11, and these show the mineral to belong to the sanidine-cryptoperthite series (Tuttle, 1952). X-ray powder data show a very strong perthitic development, the sodic phase being almost pure albite.

BIOTITE

Biotite is an important mafic mineral in most of the domes and tephra which have a high crystal content, and also occurs in the granodiorite xenoliths. Of the Early Domes it is only present in the Rotomahana Dome, where it forms up to 3% of the total rock. In the Late Domes it is the most important mafic mineral, usually forming 1-2.5% of the total rock, and occurring in pseudohexagonal plates 0.5-2 mms. in diameter. They are euhedral but frequently show embayments (Fig. 49) and sometimes these are filled by quartz or plagioclase feldspar. Often the biotite includes accessory minerals such as apatite and zircon, and in a few cases it forms intergrowths with other mafic minerals. The most common of these is hornblende (see Fig. 74).

Two types of biotite can be distinguished on optical properties (Table 12):

Type A: The main type found at the margins of the domes and in tephra It is a 'normal' biotite which has a moderate refractive index (γ = 1.658-1.667), high dispersion, and a 2V which varies from 16°-35° measured by the method of Tobi (1956). It is markedly pleochroic; X, pale yellow-light brown; Y, dark brown; Z, dark brown-opaque ($X < Y < Z$). The estimated Fe content of the type is 69-78% (by method of Gower, 1957).

TABLE 12 - OPTICAL AND X-RAY PROPERTIES OF THE BIOTITES

Spec. No.	Location	R.I. (±2°)	Iobs (004) / Iobs (005)	Fe % (±5%)
11129	Rotomahana Dome	a) γ -1.666 b) γ -1.723	- -	- -
11038	Ruawahia Dome	γ-1.658	1.165	69%
11076	Wahanga Dome (core)	γ-1.722	-	-
11071	Wahanga Dome (margin)	γ-1.662 γ-1.722	- -	- -
11177	Tarawera Dome	γ-1.665	1.320	78%
11178	Crater Dome	γ-1.742	0.460	16%
11122	Green Lake Plug	γ-1.662	-	-
11061/7	Kaharoa 'Ash'	γ-1.662	1.270	75%
11171	Rerewhakaaitu 'Ash'	γ-1.663 to 1.667	-	-
P29565	Granodiorite cognate xenolith	γ-1.650	1.250	74%

Type B: This type has a very high refractive index (γ = 1.722-1.742), and is red brown in colour. The pleochroic scheme is X, pale reddish green; Y, red brown; Z, dark red brown. ($X < Y < Z$). 2V is highly variable, a number of plates giving a 2V of $> 50^{\circ}$. It has been recorded in the more basic rocks from the San Juan volcanic rocks, Colorado (Larsen et al., 1937, p.901) and Deer, Howie and Zussman (1963, p.70) note that "among the very few biotites which have refractive indices outside the ranges indicated above (γ = 1.605-1.695) are those with an extremely high content of Fe^{3+} which have γ and δ as high as 1.73 and 0.08 respectively, such minerals are sometimes called ferrian biotites". In the rhyolites at Tarawera ferrian biotite occurs in the centres of domes, and in the centre of Tarawera Dome; it is associated with basaltic hornblende. Winchell (1961, p.376) records that heating biotite to 1000°C raises the refractive index to 1.71 and the observed 2E to 38.4.

HORNBLENDE

Hornblende is present in most of the rhyolites, although in many cases it accounts for < 0.1%. In the andesites it is present in the groundmass particularly surrounding augite crystals, and in 11093 in the reaction rim surrounding an included xenolith. In the hornblende-quartz dacite it forms the major mafic mineral (max. 10%).

Four different types of hornblende can be distinguished and the optical properties of these are listed in Table 13.

Type A. "Pale Hornblende"

This mineral may easily be mistaken at first for hypersthene, but it can be distinguished by the higher extinction angle. It

TABLE 13 - OPTICAL PROPERTIES OF THE HORNBLENDES

TYPE 'A' 'Pale' Hornblende

X	Colourless	
Y	Pale Fawn	$X < Y = Z$
Z	Light brown	

Spec. No.	$\gamma \wedge c$ ±1°	R.I. ±0.002	$2V_\alpha$ ±2°
11038	17°	α 1.656 γ 1.673	80°

TYPE 'B' Green Hornblende

X	Straw yellow	
Y	Olive green	$X < Y < Z$
Z	Dark green	

11108	13°	α 1.662 γ 1.683	74°
11170	13°	γ 1.678	-
11171	15°	γ 1.680	-

TYPE 'C' Brown Hornblende

X	Yellow	
Y	Green brown	$X < Y < Z$
Z	Dark brown	

11145	10°	α 1.667 γ 1.693	-

TYPE 'D' 'Basaltic' Hornblende

X	Pale yellow	
Y	Reddish brown	$X < Y < Z$
Z	Dark red/Opaque	

11097	4°	α 1.669 γ 1.730	high
11129	0°	γ 1.742	-
11105	0°-2°	γ 1.738	-

Figs. 56 - 59.

Camera Lucida drawings of phenocrysts from rhyolites.

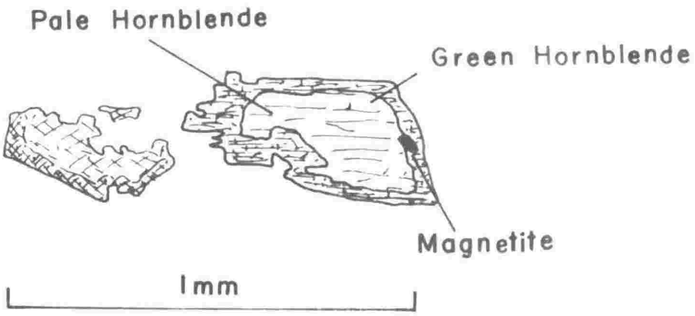


Fig. 56.

Green hornblende separated by a break from pale hornblende (11156).

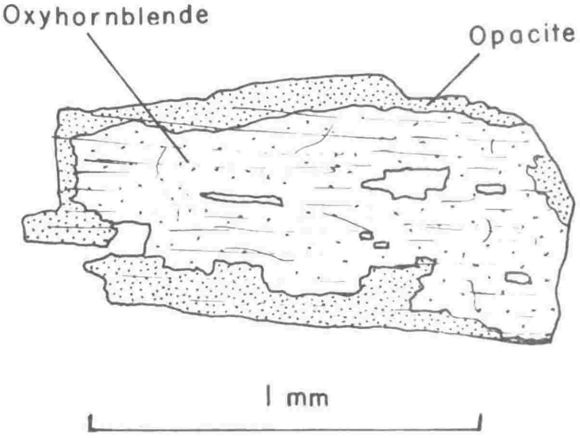


Fig. 57.

Oxyhornblende (= basaltic hornblende) with opacite rim (11098).

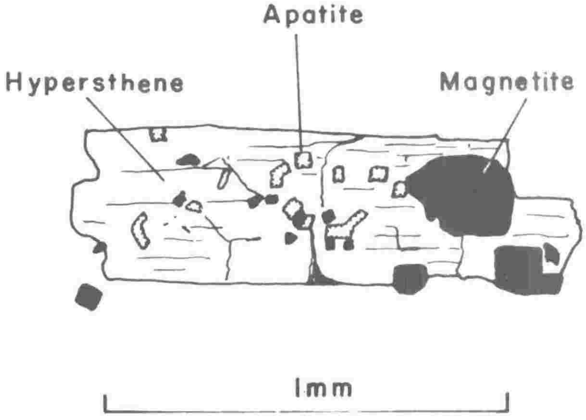


Fig. 58.

Typical hypersthene phenocryst with inclusions of apatite and magnetite (11145).

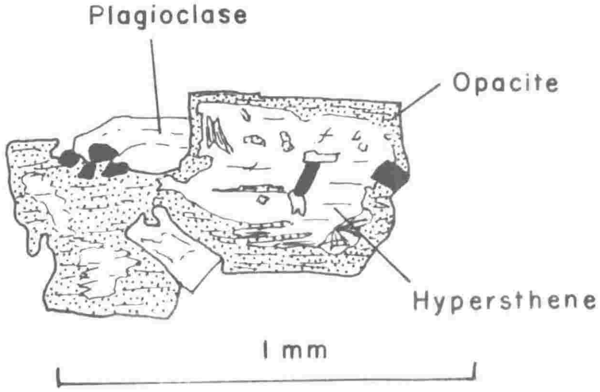


Fig. 59.

Hypersthene phenocryst with opacite rim (11151).

occurs within the Tarawera Complex in small quantities in Ruawahia and Wahanga Domes (< 0.1%) and is present in one crystal from the Rerewhakaaitu 'Ash'. In all cases the crystals are small. Ewart (pers. comm.) has found a similar mineral in the rhyolites of the Haroharo Complex and has shown by analysis that it is cummingtonite. The Tarawera samples have a negative sign, however, and further work would be necessary to decide whether the two minerals are different, or if the optic sign is variable in volcanic cummingtonites. The latter could be the case, as only two other examples of the mineral are known to the writer in volcanic rocks. These are from a dacite tuff, and from the Hakone Volcano, Japan, both described by Kuno (1938, 1950).

Type B. "Green Hornblende"

Green or common hornblende is present in the hornblende-quartz dacite, and in some of the rhyolite domes and tephra. In the andesite it usually forms prismatic crystals with a long axis up to 2 mms. in length, and in the more quartz rich examples, it is often intergrown with biotite.

In 11156, from the Rerewhakaaitu 'Ash', the crystals show zoning, and in one crystal the core is apparently pale hornblende (type A) and the margin green hornblende (Fig. 56); the two minerals separated by a break. This increase in iron towards the margin is comparable with the zoning described by Kuno (1950, p.980) from dacites of Hakone volcano.

Type C. "Brown Hornblende"

Brown hornblende is found in the Southern Dome and Flow, where the crystals are usually small (< 1 mm.) and frequently intergrown with plagioclase and hypersthene. Large crystals of this type occur at the margin of Rotomahana Dome and are particularly well developed in 11127, where one crystal is over 2 mms. in length.

Type D. "Basaltic Hornblende"

This type is found in the rhyolites of Western, Tarawera and Rotomahana Domes. In all cases the enclosing rocks are spherulitic, and in Tarawera Dome it can be clearly demonstrated that the type occurs only in the centre of the dome. In Rotomahana Dome the relationship between basaltic hornblende and brown hornblende is complex, and one type may occur in one outcrop, while the other occurs at the next.

The refractive index of the mineral is very difficult to measure, and the optic angle even more difficult, because of the deep colour and strong dispersion. 2V is, however, in all cases very high (80°-90°?).

Crystals of this type are often surrounded by an opacite rim (Fig. 57) and in a few cases show evidence of resorption and subsequent alteration (p.163).

ORTHOPYROXENES

Hypersthene occurs in most of the rhyolites, but is usually present only in small quantities (< 1% of the total rock). In most of the Early Domes (excluding Western and Rotomahana Dome) and in the Waiohau 'Ash' it forms the major mineral, accompanied by small amounts of hornblende. In the Late Domes it is rare and, where present, may be a result of assimilation of accidental fragments of

TABLE 14 - OPTICAL PROPERTIES OF THE HYPERSTHENES

'Hypersthene' in rhyolite

X Pale pinkish brown
Y Pale pinkish yellow $X \doteqdot Z < Y$
Z Pale green

Spec. No.	R.I. (±0.002)	2V (±2°)	Ca content
11137	α_{min} 1.702 γ_{max} 1.720	54°-56°	0.5%
11097	α_{min} 1.699 γ_{max} 1.712	56°	-
11145	α_{min} 1.700 γ_{max} 1.718	54°-56°	-
11118	γ 1.716	54°	-
11105	γ 1.726	-	-

'Hypersthene' in Eucrite

Spec. No.	R.I. (±0.002)	2V (±2°)	Ca content
11077	α_{min} 1.697 γ_{max} 1.716	59°	-

'Bronzite' in Eucrite

X Pinkish brown
Y Pale yellow $X \doteqdot Z < Y$
Z Pale green

Spec. No.	R.I. (±0.002)	2V (±2°)	Ca content
11078	α_{min} 1.683 γ_{max} 1.697	71°	3.0%

the earlier domes.

In the more basic rocks hypersthene is present in the hornblende-quartz dacite and pyroxene andesites, and in the eucrites both hypersthene and bronzite occur.

The optical properties of the hypersthenes and bronzite are described separately below and in Table 14.

Hypersthene

In the rhyolite, hypersthene forms small euhedral to subhedral crystals ($<$ 0.5 mms.) which may be cracked, but rarely show resorption. They usually have numerous inclusions of magnetite and some also contain apatite (Fig. 58). In the centres of the domes they are surrounded by a rim of opacite (Fig. 59) but there does not appear to be any difference in composition between these crystals and those without the rim, as found by Lewis (1960, p.45).

The hypersthene in the hypersthene eucrite (11077) is similar in optical properties to that in the rhyolite, except that 2V is higher (see Table 14). The crystals, however, are more anhedral and resemble those of the bronzite, to which they are probably genetically related.

Bronzite

This occurs as subhedral to anhedral crystals in sample 11078 (bronzite eucrite). The crystals are large and usually contain small inclusions of olivine (see Fig. 44). Augite and plagioclase may also be partly enclosed by the mineral.

CLINOPYROXENES

The only clinopyroxene present in the Tarawera rocks is augite, which forms the dominant mafic mineral in the ankaramite, eucrites, basalt, and in the andesites.

In the ankaramite and eucrites, euhedral to subhedral crystals (max. diam. < 1 mm.) are very pale green and non-pleochroic. They are sometimes enclosed poikilitically in feldspar. Twinning is common and is often multiple, parallel to 100. The composition based on optical properties shows some variation in relative Fe and Mg content, but calcium is more or less constant. Optics are as follows:

$\beta = 1.691-1.701$ (± 0.002), 2V 53° ($\pm 2^\circ$), $Z \wedge c$ 41 (± 1)°.
Average estimated composition (after Hess 1949) $Ca_{44}Fe_{19}Mg_{37}$.

Many of the phenocrysts are rimmed by prismatic crystals of pleochroic green hornblende which appears to be orientated in the same crystallographic direction as the main crystal.

In the andesites the phenocrysts occur with the same optic properties as those of the ankaramite, and are considered to be comagmatic. There are also smaller crystals (< 0.3 mm.) of clinopyroxene in the groundmass, some of which rim the olivine and quartz 'xenocrysts' in the rock.

In the basalt a few 'phenocrysts' of augite and some glomeroporphyric aggregates of augite and feldspar occur. Both are the same as found in the andesites and are presumably derived from them. Minute crystals of clinopyroxene (< 0.1 mm.), probably augite, occur in the groundmass, but no interference figure could be obtained.

OLIVINE

Forsteritic olivine occurs as euhedral to subhedral crystals in the ankaramite blocks of the Kaharoa 'Ash'. It is clear and can be distinguished from the accompanying augite by the general lack of cleavage and twinning. A thin oxidation rim often occurs around the margin. In the andesites olivine has the same optical properties as in the ankaramites, but the crystals are usually anhedral. They are sometimes surrounded by a rim of pyroxene and magnetite similar to that found around the quartz. In the olivine eucrite the mineral is large, and sometimes resorbed, but in the bronzite eucrite it occurs only as inclusions in the orthopyroxene.

In the Tarawera basalt crystals are very small (< 0.2 mm.) and frequently have 'hollows' at either end of the long axis. This feature was also found by Kuno (1950, p.970) in the Hakone Volcano, and he illustrates a complete gradation between these crystals and normal olivine crystals, suggesting the crystals to be the first stage in the growth of the olivine.

ACCESSORY MINERALS

Magnetite

Magnetite is ubiquitous in all the rocks of the Tarawera Complex. In the rhyolite and granodiorites it forms small euhedral to subhedral crystals (< 1 mm.) and inclusions (0.1-0.3 mm.) in many mafic minerals. At the margins of the domes it is steel-grey in reflected light, but towards the centres of the domes it is oxidised, and develops a red lustre. In rocks where hydrothermal alteration has occurred, leucoxene is often present. This is distinguished by its white colour in reflected light, and probably indicated that the original magnetite had a moderately high TiO_2 content.

In the more basic rocks magnetite forms a high percentage of the groundmass. In the basalt it forms minute (< 0.05 mm.) anhedral crystals in the glass and in the andesite it is usually slightly larger (< 0.1 mm.) and often euhedral with a square cross section.

Apatite

Apatite is a rare accessory in a few of the rhyolites, and occurs as small prismatic crystals, usually enclosed in biotite. In one crystal the centre appears to be hollow.

Zircon

This is common as inclusions in biotite crystals, where it normally forms small prismatic crystals (< 0.1 mm.), particularly when the biotite is in an aggregate with other minerals. A few examples show well developed geniculate twinning (e.g., 11064).

Epidote

An iron rich epidote is present in one of the granodiorite blocks examined (10920). It occurs in small crystals (max. 0.5 mm.), which are pleochroic from pale yellow to yellow green, and are closely associated with biotite (Ewart and Cole, in press).

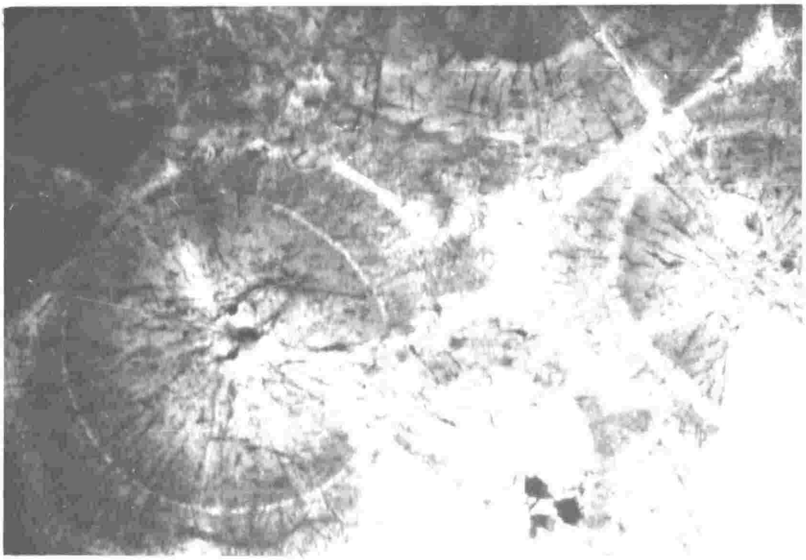
Carbonates

Calcite occurs in the matrix of a breccia from Green Lake Crater. It forms small anhedral crystals surrounded by hematite and is probably from a hydrothermal source.

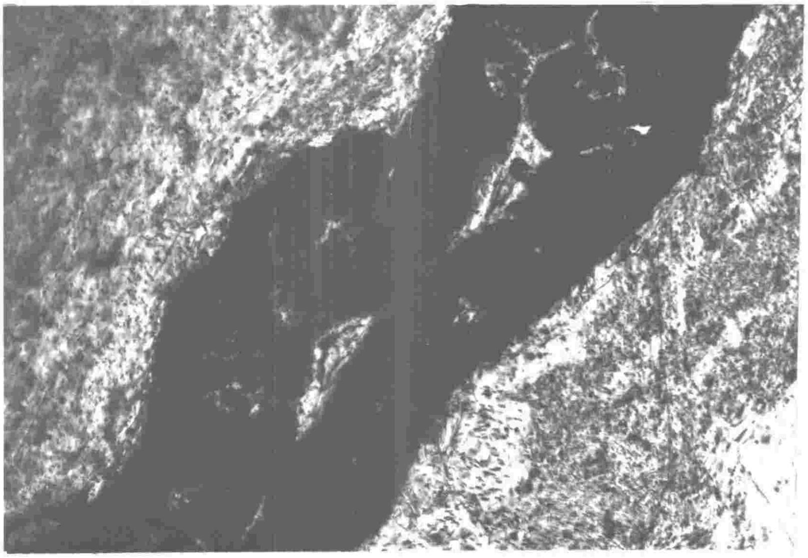
In another rock from the same location siderite is present. This forms large euhedral to subhedral crystals which were probably originally pyroxene. It also occurs in some rocks as spherulites with alternating bands rich and poor in iron. The source of the siderite is, like the calcite, probably hydrothermal.

Fig. 60. Simple spherulite developed in rhyolite (11179) showing several concentric bands (ordinary light).

Fig. 61. Composite spherulite in 11120, formed by coalescing of many spherulites along a fracture plane (ordinary light).



0·5 mm



0·25 mm

3. SPHERULITES AND ASSOCIATED FEATURES

The term 'spherulite' has been defined by Holmes (1928, p.214) as "a radiating and often concentrically arranged aggregation of one or more minerals, in outward form approximating to a spheroid, and due to the radial growth of prismatic or acicular crystals in a viscous magma of rigid glass about a common centre or inclusion". Bryan (1940, p.41) points out, however, that difficulty may be met in using such a strict definition, for many features associated with spherulites are not determined by the growth in the way the definition demands. Such bodies, he suggests, should be called "spheruloids". Spherulites and some associated spheruloids are common in acid extrusives, and in the Tarawera complex three types can be identified.

1. Spherulites (sensu stricto).
2. Granophyric groups.
3. Micro-spherulites.

Each type is probably formed by a similar process, but during a different period in the history of the lava.

Spherulites (sensu stricto)

The form and structure of the true spherulite has been described by Bryan (1940) and he divides them into simple and composite structures. Both types may be found in the rhyolites and obsidian at Tarawera (Figs. 60 and 61).

The composition of the spherulites was the subject of much discussion at the end of the last century. Harker (1909, p.275) suggested that they were entirely feldspar fibres. Others said they were both feldspar and quartz. It was not until Hurlbut (1936) did an X-ray analysis that the minerals were confirmed to be cristobalite and perthitic feldspar or sanidine, and an X-ray analysis of a spherulite from Tarawera conforms with this interpretation. Their origin was considered by Harker (1909) to be "a result of rapid crystallisation in a highly supersaturated solution", but he notes that in glassy rocks, flow lines seem to pass uninterrupted through the spherulites. This suggests that they developed when the lava had ceased moving and this is supported in the Tarawera rocks as perlitic cracks frequently pass through the spherulites. Marshall (1961, p.1513) has calculated that devitrification of glass at low temperatures ($< 20^{\circ}C$) is no more than 4-5μ in 100 m.yrs. and hence spherulite development must take place before cooling is complete. Water is probably a critical factor as Marshall has found that devitrification in the presence of water requires only a short time at temperatures of no more than 300°C. Thus it seems likely that most spherulites form during the final stages of cooling of a rhyolite dome.

In volcanic domes the size of spherulites increases towards the centre, where cooling is presumably slower. The 'trapped' water content inside the dome would presumably lower the viscosity, also aiding spherulite development. It appears that a seed must be present, and in the centres of the domes it is normally a phenocryst. Often the spherulite develops from a number of points on the 'seed' and an elongate or composite spherulite forms. Growth must be irregular as evident from the many concentric zones within some crystals (Fig. 60). Hydrothermal diffusion may play an important role in this feature.

In the obsidian lava flows development is less uniform, and

Fig. 62. Granophyric group of Type A. Single microlite of feldspar from which quartz and feldspar form a graphic intergrowth (crossed polarisers).

Fig. 63. Granophyric group of Type B. Two granophyric groups of type A intergrown (crossed polarisers).

Fig. 64. Granophyric group of Type C. Individual fibres radiate from a centre (crossed polarisers).

Fig. 62.

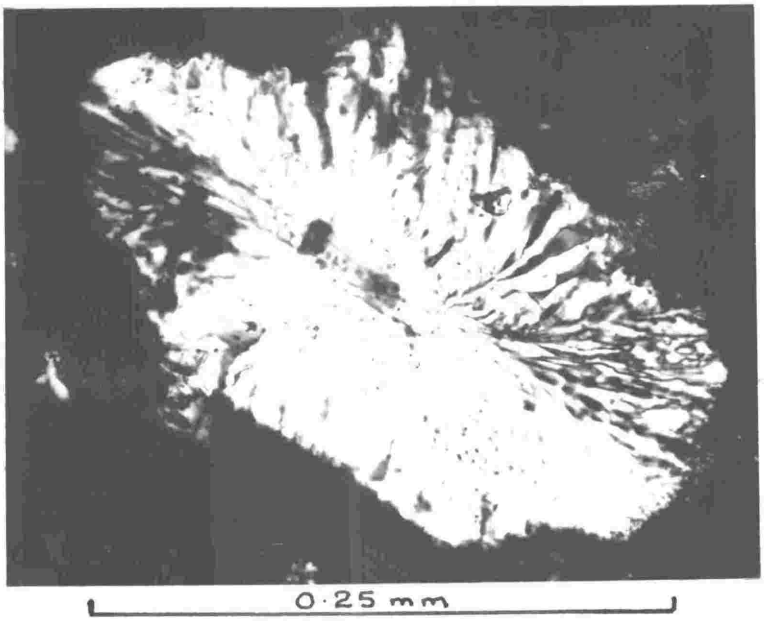


Fig. 63.

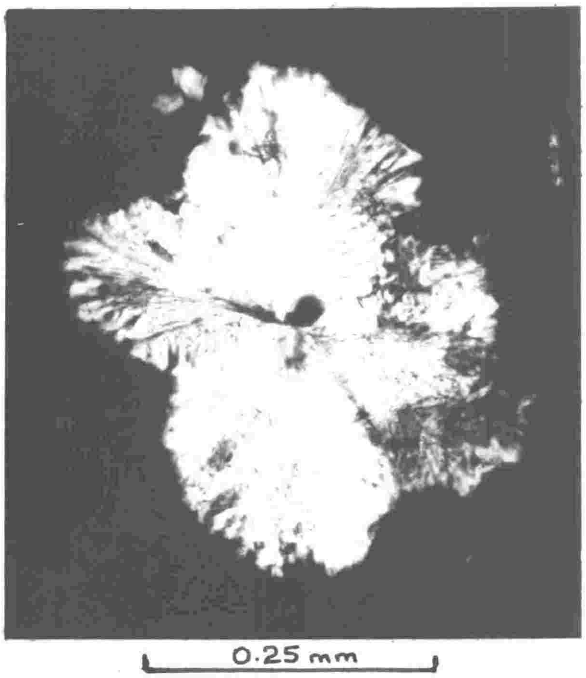
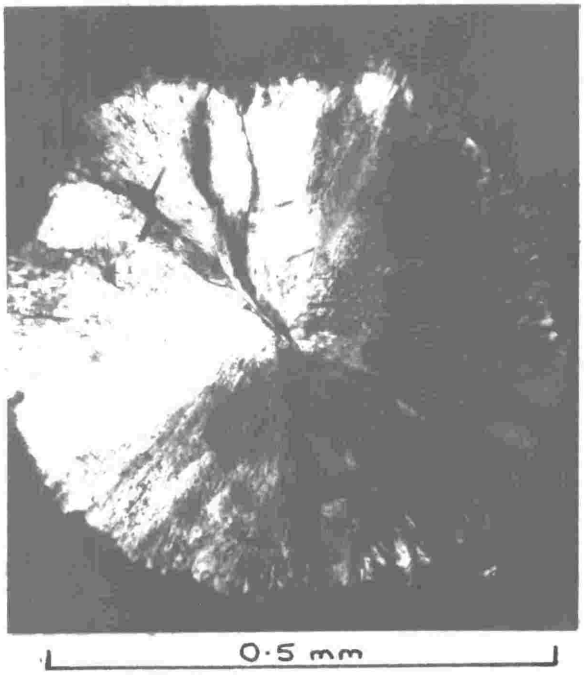


Fig. 64.



simple forms predominate. A critical factor seems to be strain, as spherulites frequently occur along cracks developed parallel to the flow banding (Fig. 61), and even simple spherulites tend to develop where the flow banding is most contorted. This feature may also play an important part in the centres of domes, as bands of spherulites are often found parallel to the circular joint planes. The reason for this is probably that such breaks in the glass act as 'seeds' in the same way as phenocrysts, and permit the start of growth of the spherulites.

Granophyric Groups

These are found in pumiceous rhyolite at the outer margin of some of the earlier domes and in some of the earlier tephra. They are generally small (< 1 mm. in diam.) and three different types can be distinguished:

1. The base of the group is a single crystal of feldspar (thought from refractive index and approximate optic axis measurements to be anorthoclase). Within this, small inclusions of quartz occur which produce the granophyric intergrowths (Fig. 62).

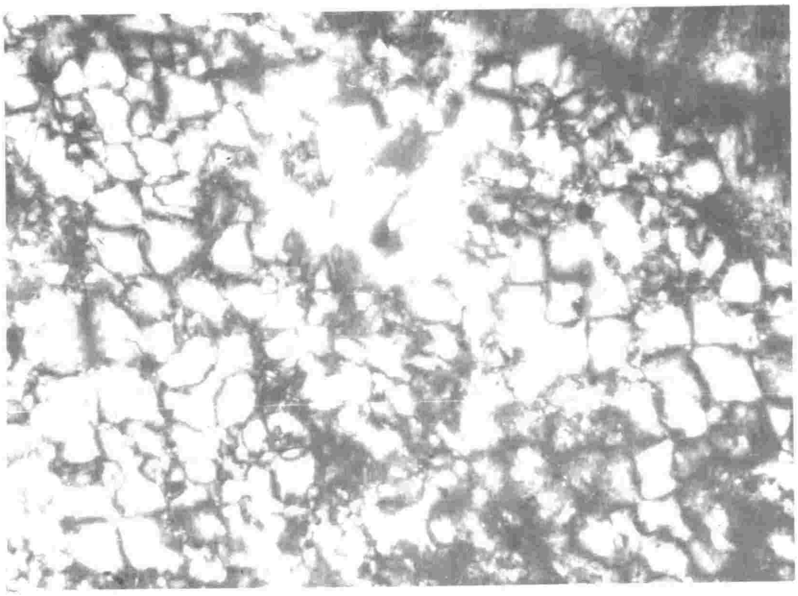
2. This type is formed by two or more of the first type intergrown to produce the granophyric groups described by Iddings (1888). The granophyric intergrowth is less distinct than the first type, but can still be identified (Fig. 63).

3. In the third type individual fibres radiate from a centre in the same way as a spherulite. Each fibre is distinct, but a granophyric intergrowth of type 1 cannot be recognized (Fig. 64).

The origin of these groups is regarded by Teall (1888) to be due to crystallization at eutectic conditions, but, as Harker (1909)

Fig. 65. Microspherulites in 11033 from a block of rhyolite reheated during the 1886 eruption. Some 'spherules' show a 'pseudo-isogyre' effect (crossed polarisers).

Fig. 66. Enlarged photograph of microspherulites from same rock (11033) showing 'peudo-isogyre' effect (crossed polarisers).



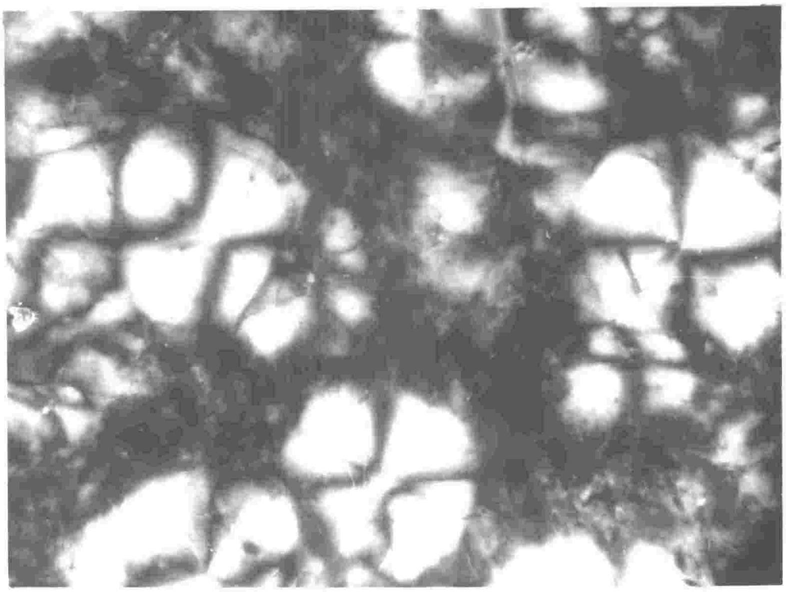


Fig. 67.

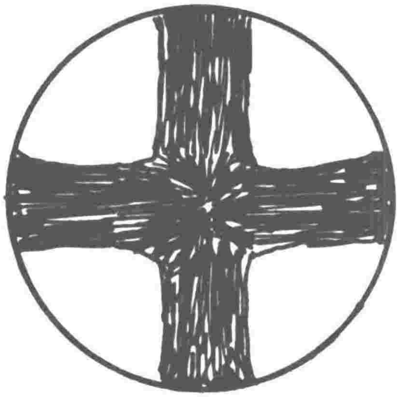
Microspherulites:

A) Normal NS / EW extinction cross.

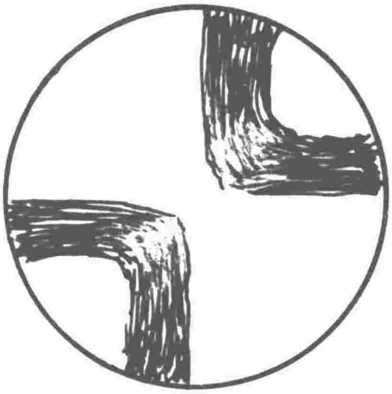
B) Rotation through 45° to give 'pseudo-isogyres'.

C) Small microlite with straight extinction in centre of microspherulite, providing possible explanation for feature B.

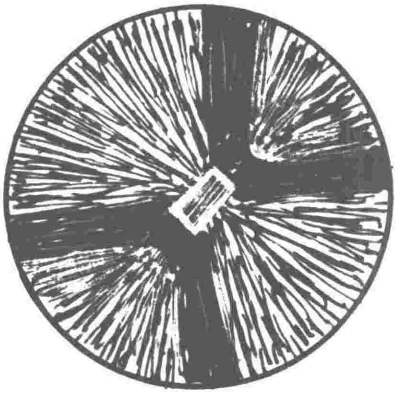
D) Section cut through the basal section of microlite - the extinction cross will not 'break up' on rotation.



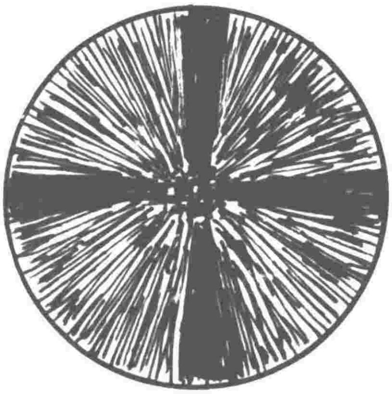
A



B



C



D

points out, a spherulite does not crystallise at one point of time but grows over a period of time from a centre outwards. Iddings (1888, p.276) regards the spherulites as having "crystallised before the lava came to rest", and this is supported in 11131 by the small crystallites of the groundmass, which flow around the groups. Normal spherulites are also sometimes developed around them.

The reason for the granophyric groups' presence in the outer zones of the older domes and tephra only is more difficult to interpret. Many authors, including Ewart and Cole (in press), have suggested a correlation between graphic intergrowths and a high volatile content, and this may be a controlling factor in the formation of granophyric groups. It would be consistent with their occurrence only in the pumiceous rhyolite, and the presence of anorthoclase rather than plagioclase in the crystals (see Ewart and Cole, in press). The complete absence of the groups in the Kaharoa 'Ash' and associated Late Domes cannot be explained, unless the lack of crystallites in the glass meant that nuclei were not available to seed their formation.

Microspherulites

The third type of spherulitic development is very small (< 0.2 mm.) and usually clear in ordinary light. It can thus only be distinguished under crossed nicols (Fig. 65). A single microspherulite appears circular and has a well-defined extinction cross within it (Figs. 66 and 67A). This is in all cases NS/EW showing the constituent fibres to have straight extinction. On rotation through 45°, the extinction cross often splits up into two 'pseudo-isogyres' as shown in Figs. 66 and 67B. This may be explained if the structure resembles the granophyric groups, with a microlite in the centre and the fibres radiating from this. If the section is cut along the microlite, 'pseudo-isogyres' will develop (Fig. 67C), but if the section is cut across the microlite, the normal extinction cross will remain at all positions of rotation (Fig. 67D). All intermediate sections will occur between the two.

In flow banded rocks the microspherulites tend to occur parallel to the flow planes, and in some places they coalesce to form continuous chains.

Microspherulites are considered to grade from the normal sanidine/cristobalite assemblage to a single mineral, as in some cases the fibrous nature can only be identified by the extinction cross. The refractive index is still less than Canada balsam (1.54) and X-ray determination suggests that it is an alkali feldspar, presumably sanidine. It is significant in this context that between groups of these microspherulites patches of quartz are usually present, and they may therefore result from a separation of the two minerals.

These spherulites are found both in small xenoliths of earlier rhyolite included in later extrusions, and in boulders thrown up during the 1886 eruption, both of which involve reheating of the rock. Coombs (1952, p.205) regards similar features as a result of potash and silica metasomatism of glassy rhyolite, and this could be applicable in the Tarawera rocks.

4. PETROCHEMISTRY

General

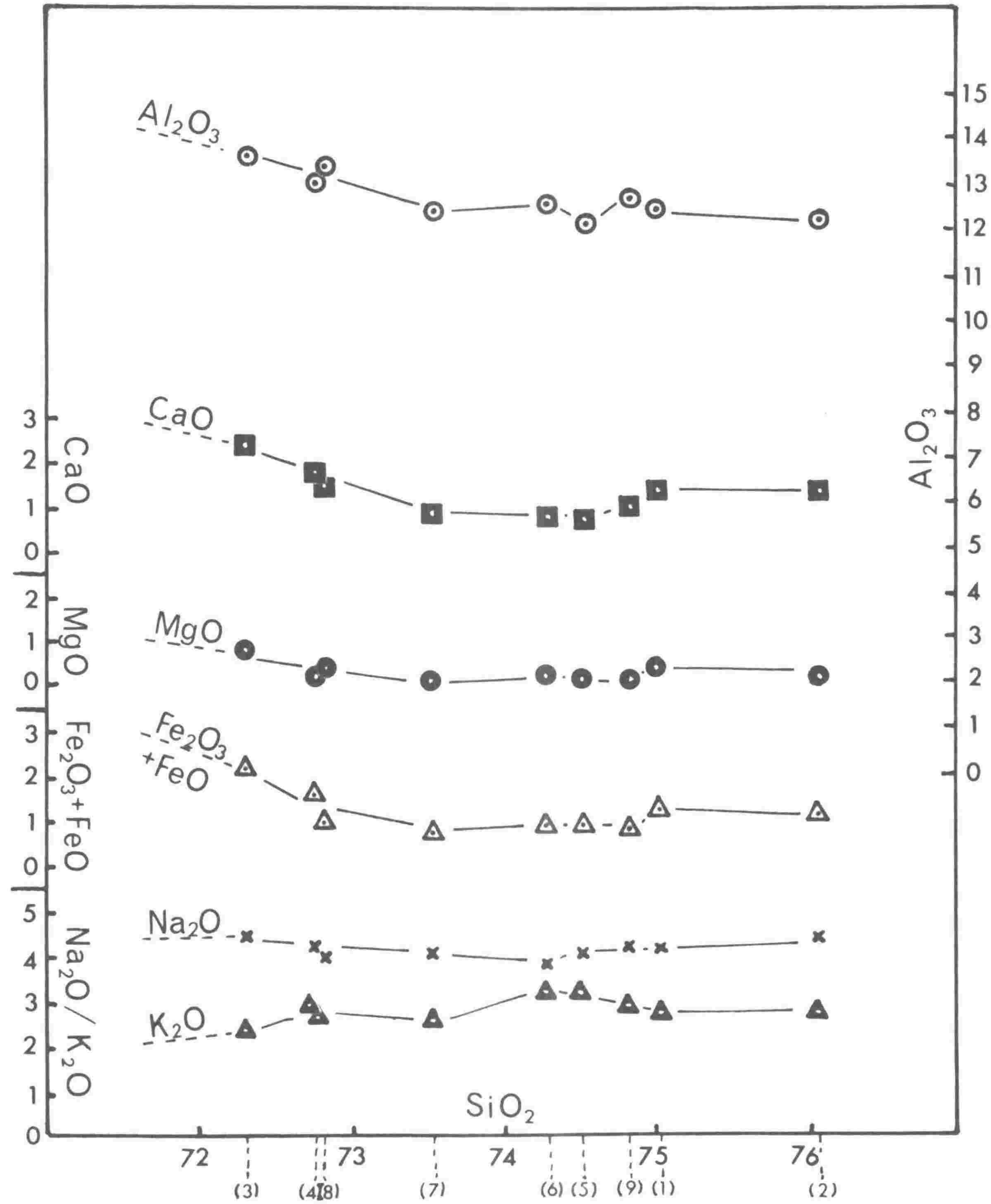
Twelve new chemical analyses have been made of total rock samples from the Tarawera Complex, using the methods of Ritchie (1962). Five of the samples are from rhyolite domes, four from rhyolite tephra, and one each of the hornblende-quartz dacite, pyroxene andesite and high alumina basalt. The results of these are given, together with their equivalent norms, in Tables 15-19. Analyses of the granodiorite (Ewart and Cole, in press) and the basalt scoria (Grange, 1937, p. 79) are also given. Average rhyolite dome and total rhyolite (dome + tephra) analyses of the Tarawera Complex are given in Tables 15 and 16 for comparison with average analyses of the Taupo Volcanic Zone, younger rhyolites of the Okataina, Rotorua and Mokai Complexes (Ewart, 1965b) and the calc-alkaline rhyolite of Nockolds (1954, p.1012). In Table 19 analyses of the Rotoatua, K Trig, Orakeikorako basalts, average 'central' type basalt of Nockolds (1954, p.1021) and average high alumina basalt of Kuno (1960) are shown for comparison with the high alumina basalt.

The only consistent normative variation in the rhyolites is in the anorthite, which decreases with time. This can be correlated with the change in composition of the feldspars (see Fig. 84). The presence of normative corundum or diopside seems to be related to the mafic mineral content - normative diopside indicating hornblende bearing rocks. Analysis 5 has an abnormally high normative diopside content, however, and this is probably due to the many small inclusions of the pyroxene andesite seen in thin section. Of the oxides, the main anomaly is the high Fe_2O_3 in 3. It should be noted,

Fig. 68.

Variation diagram of the rhyolites from the Tarawera Volcanic Complex

(Numbers in this and succeeding figures correspond to analyses
in Tables 15 - 19).


Al_2O_3
CaO
MgO
Fe_2O_3 +FeO
Na_2O
K_2O
SiO_2
CaO
MgO
Fe_2O_3+FeO
Na_2O / K_2O
Al_2O_3
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
72 73 74 75 76
(3) (4) (8) (7) (6) (5) (9) (1) (2)

however, that this was located near the centre of the dome, whereas all the other samples were collected from the margins of the domes.

The modal content of the granodiorites (Table 17) suggests that their composition is very similar to the rhyolites of Tarawera, but the analysis is more basic. Because of this discrepancy, a second, partial analysis was made (P29565) and this differed from the original, but corresponded to the modal analysis. A repeat of the alkalis was made on the original sample (10918) but this just confirmed the original analysis. It is therefore considered likely that the part of 10918 analysed previously, contained a vein of epidote, which is common in several of the granodiorite specimens examined from Tarawera (Ewart and Cole, in press).

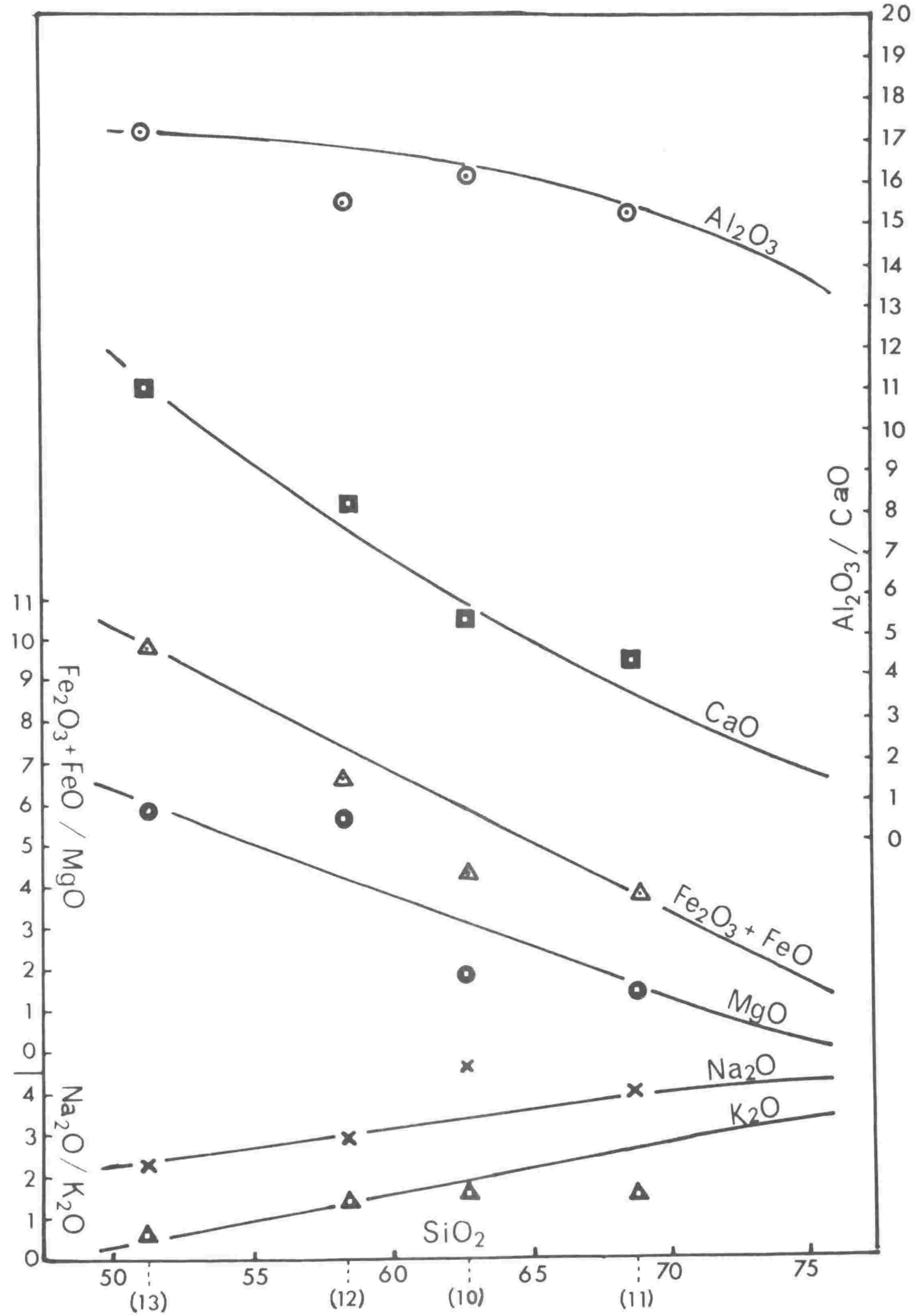
In the basalts the variations in norm between 13 and Grange's (1937) analysis are largely due to the former sample being partially oxidized. This affects the normative magnetite, hypersthene, diopside and quartz.

Comparison of the Chemistry of the Tarawera Rocks with Others in the Taupo Volcanic Zone

The range of the main oxides in the Tarawera rhyolites (Fig. 68) and their normative components are comparable to the other rhyolites in the region, and the average 'Tarawera dome' analysis is very similar to the average 'young rhyolite' analysis of Ewart (1965b). The tephra likewise compares closely with the dome rhyolites, as would be expected, for most was erupted at the same time as the domes formed. The water content is higher in the tephra, except for Sample 9 - an unwelded ignimbrite deposit (p. 45) full of blocks of expanded pumice. Water presumably escaped from this sample during the process of expansion (as in Perlite manufacture) and thus only a small amount of

Fig. 69.

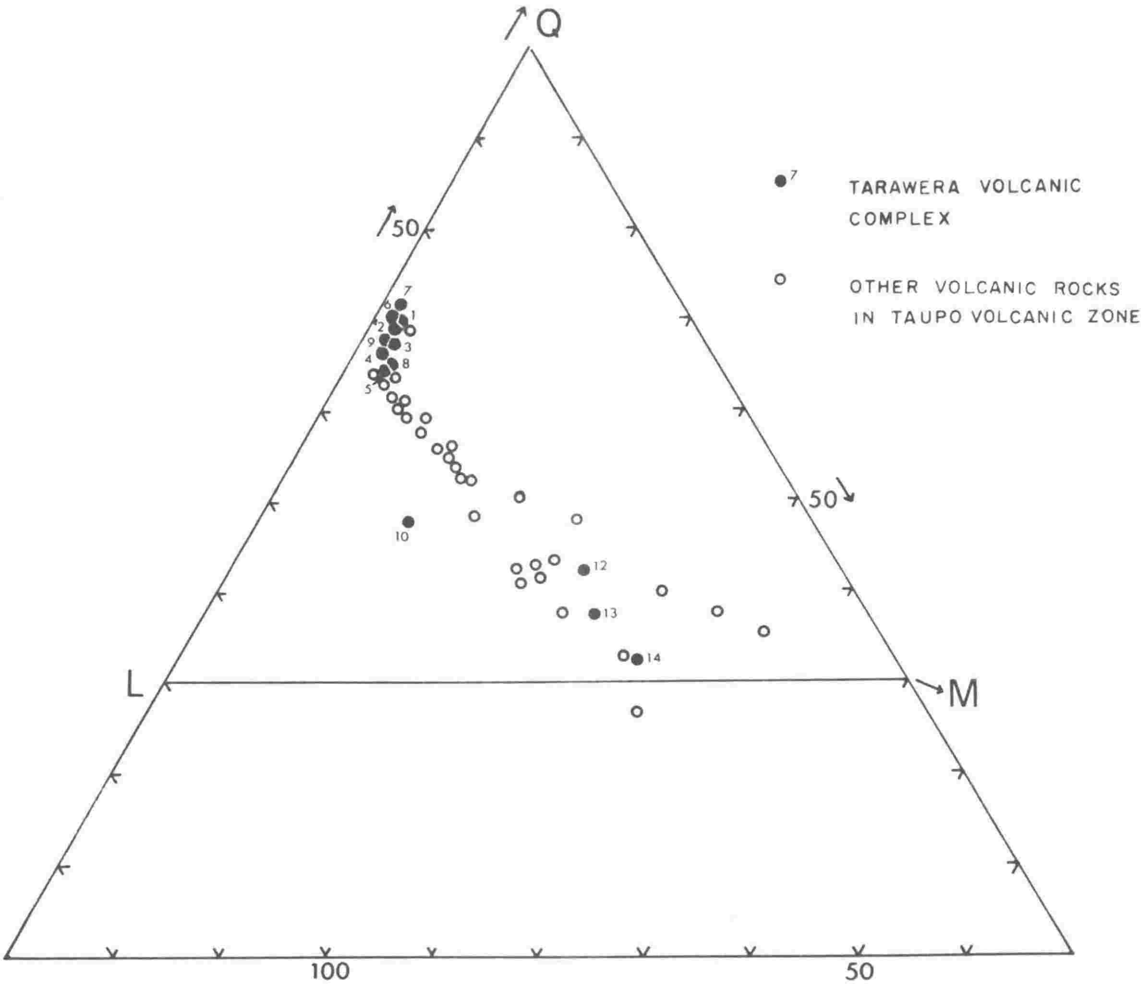
Variation diagram showing the relationship between the Tarawera basalt, andesite, hornblende-quartz dacite and granodiorite, and the main trends of the Taupo Volcanic Zone (after Lewis, 1960).



Al_2O_3
CaO
$Fe_2O_3 + FeO$
MgO
Na_2O
K_2O
SiO_2
Al_2O_3 / CaO
$Fe_2O_3 + FeO$ / MgO
Na_2O / K_2O
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
50
55
60
65
70
75
(13)
(12)
(10)
(11)

Fig. 70.

Enlarged section of von Wolff diagram (after Clark, 1960b, Fig. 16), showing relationship of Tarawera rocks to others in the Taupo Volcanic Zone.


Q
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7
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1
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9
3
4
8
5
10
12
13
14
50
L
M
100
50
TARAWERA VOLCANIC COMPLEX
OTHER VOLCANIC ROCKS IN TAUPO VOLCANIC ZONE

Fig. 71.

A F M digram showing relationship of the Tarawera rocks to others of the Taupo Volcanic Zone.

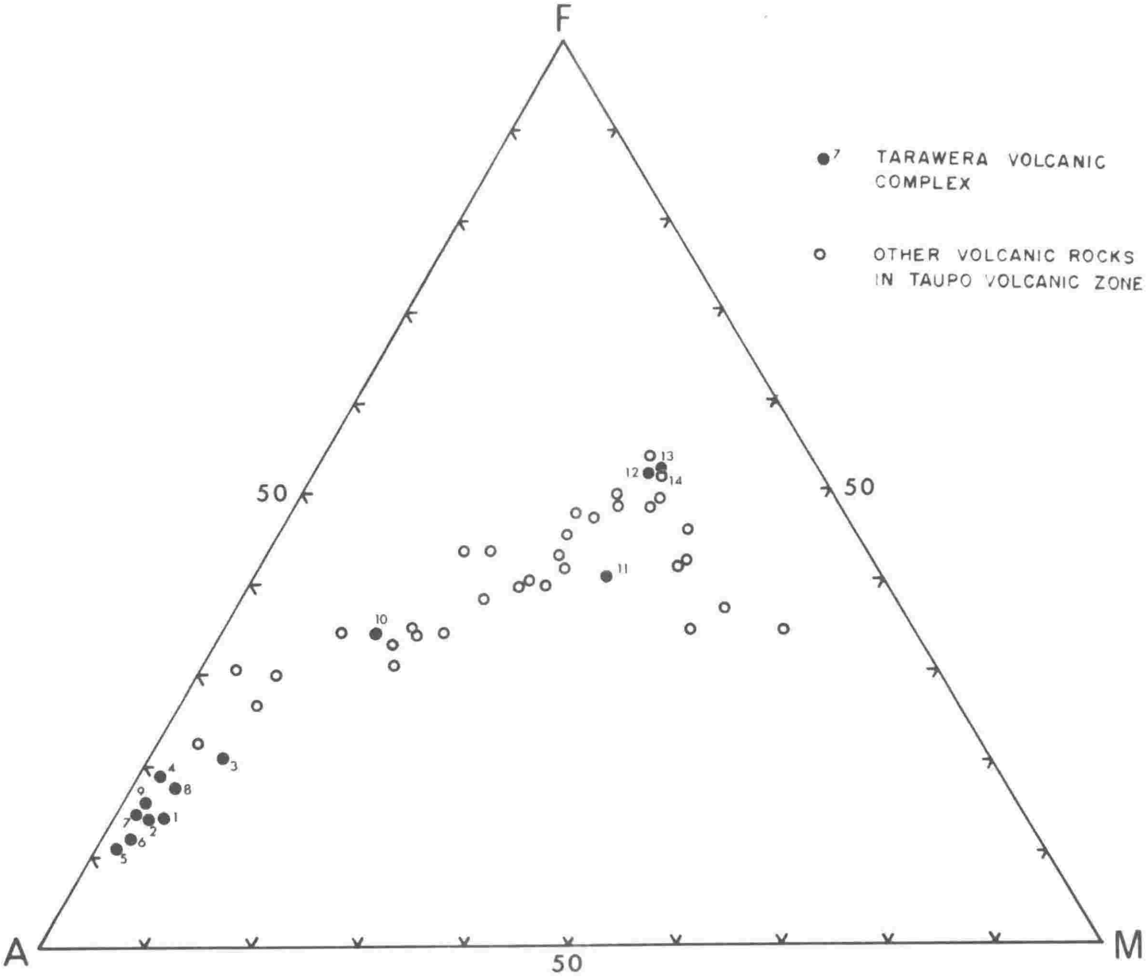
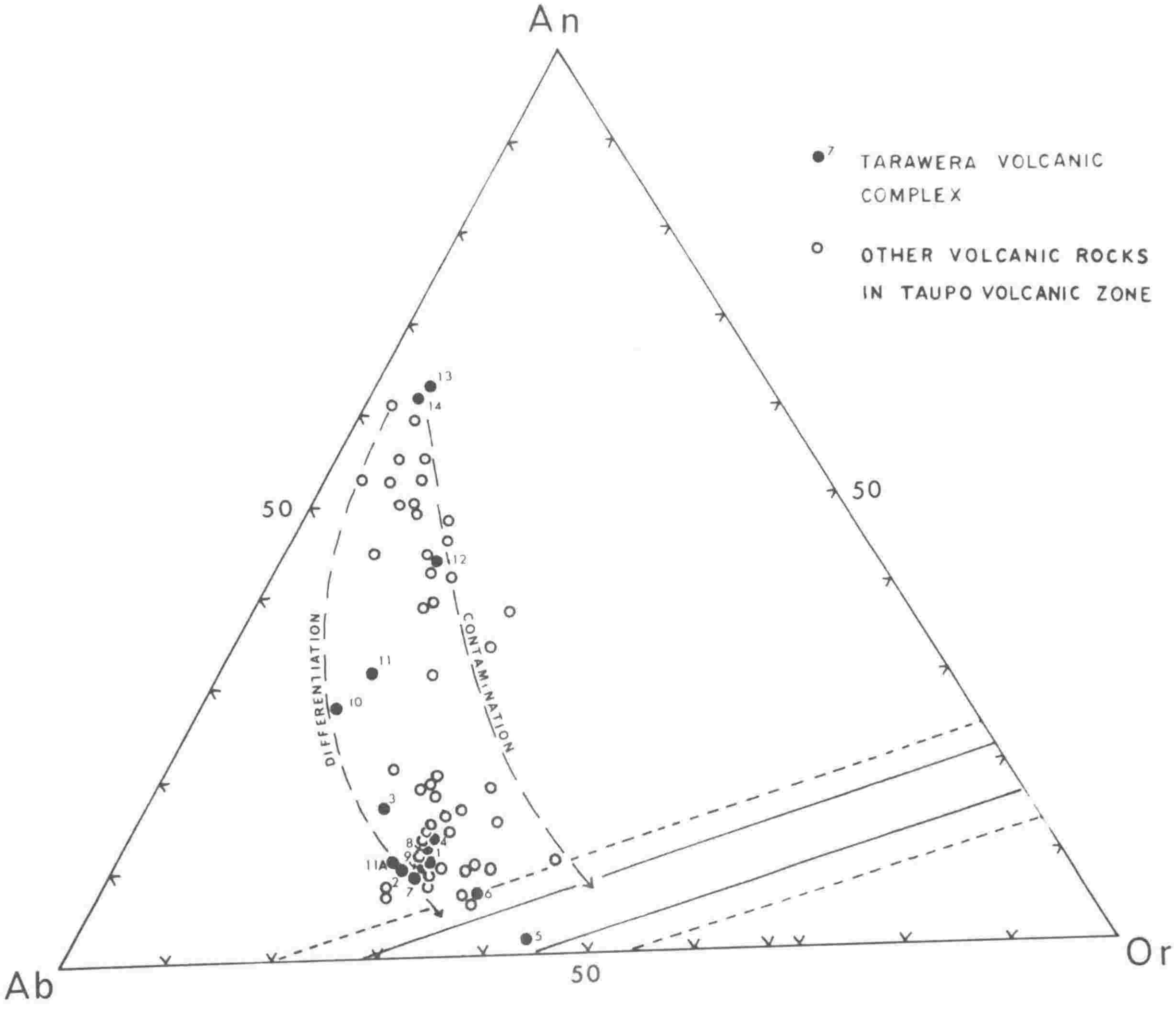

F
A
M
50
50
50
● TARAWERA VOLCANIC COMPLEX
○ OTHER VOLCANIC ROCKS IN TAUPO VOLCANIC ZONE
1
2
3
4
5
6
7
8
9
10
11
12
13
14

Fig. 72.

Volcanic rocks from the Taupo Volcanic Zone plotted in the ternary system Ab - An - Or (after Ewart, 1965c, Fig. B - 9). The differentiation trend is from the Thingmuli province, Iceland, and the contamination trend from the San Juan province, Colorado (Carmichael, 1963). Dashed and solid lines near base of diagram represent the low temperature trough of Kleeman, 1965.



An
Ab
Or
50
50
50
●⁷ TARAWERA VOLCANIC COMPLEX
○ OTHER VOLCANIC ROCKS IN TAUPO VOLCANIC ZONE
DIFFERENTIATION
CONTAMINATION
13
14
12
11
10
3
8
4
1
9
11A
2
7
6
5

water would be expected to remain.

The granodiorite analysis from Tarawera is similar to an analysis of an equivalent rock from Huka (Ewart and Cole, in press) but the possible epidote in the Tarawera specimen makes direct comparison difficult. The more basic rocks are also difficult to correlate. The hornblende-quartz dacite has a high Na_2O, but low MgO and FeO compared with other rocks of the region with a similar silica percentage (Fig. 69), and this probably reflects the high modal plagioclase. The pyroxene andesite (Table 18) has a high MgO and CaO but a low Al_2O_3, which is presumably due to a high percentage of pyroxene.

The high alumina basalt compares closely with those of K Trig, in the Maroa Complex (Grange, 1937, p. 75) and Rotoatua, in the Okataina Volcanic Centre (Steiner, 1958, p. 330). The basalt from Orakeikorako (Lloyd, in press) is more alkaline, and has a correspondingly lower silica content. All can, however, be classed as high alumina basalts.

All the analyses from the Tarawera Complex are plotted on a von Wolff diagram in Fig. 70; an AFM diagram in Fig. 71, and an Ab-An-Or ternary diagram in Fig. 72 for general comparison with other rocks of the Taupo Volcanic Zone. The petrogenetic significance of these will be discussed in the next section.

Comparison of the Tarawera Rocks with Other Calc-alkaline Rocks

The average rhyolite of Tarawera is comparable to the average calc-alkaline rhyolite of Nockolds (1954, p. 1012) except for the Na_2O/K_2O ratio, (Table 15). In most calc alkaline rocks $K_2O > Na_2O$, but in the Tarawera rocks, as in almost all acid rocks in the Taupo Volcanic Zone $Na_2O > K_2O$. This feature is most important in considering genesis of the rocks. Ferric iron is slightly lower in the Tarawera rocks, but this may be because most samples were taken from the unoxidised margins of the domes. Analysis 3 (from the centre of Western Dome) has slightly higher Fe_2O_3 than Nockolds average.

The Tarawera basalt is a typical high alumina basalt, and is very similar to the averages given by Nockolds (1954, p.1021)* and Kuno (1960, p.141). The only difference is that the Tarawera basalt has a slightly lower Al_2O_3 content and correspondingly higher CaO content. This is reflected in the higher normative diopside and lower hypersthene (Table 19). The andesite is very different, however, from Nockolds (1954, p.1019) average andesite (Table 18). It is more basic, yet has a lower Al_2O_3 and total iron content, and a correspondingly higher CaO content. These proportions are similar to the high alumina basalt and may reflect the rock's hybrid origin.

Strontium Ratios in Tarawera Rocks

Dr. S.R. Taylor (Clark, pers. comm.) has analysed five rocks from the Tarawera Volcanic Complex to find Sr^{87}/Sr^{86} ratios. The results are listed below:

		Sr^{87}/Sr^{86} ratio
NZ-A	High alumina basalt	0.7037
NZ-B	High alumina basalt	0.7039
NZ-C	Pyroxene andesite	0.7043
NZ-D	Spherulitic rhyolite	0.7045
NZ-E	Pumiceous rhyolite	0.7049

The significance of these results will be mentioned in the section on origin of the Tarawera rocks.

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*Nockolds' (1954, p.1021) average 'central' basalt, however, differs petrographically from the high alumina basalt, and hence cannot directly be compared.

Plate 4. Lake Rotomahana and Tarawera from Waimangu Valley. On the left of the mountain is Tarawera Dome and on the right, Rotomahana and Rerewhakaaitu Domes. The 'scar' on Tarawera Dome is the Chasm.

SECTION C

PETROGENESIS

Figs. 73 - 76.

Camera Lucida drawings showing relationships between minerals.

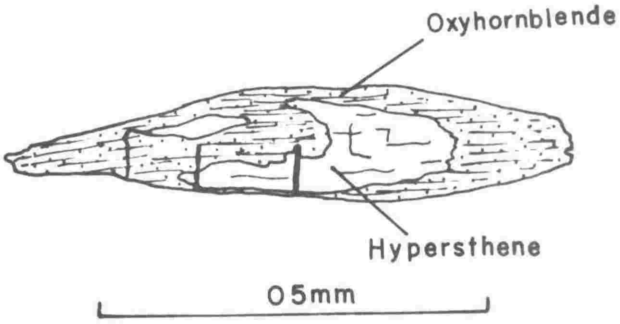


Fig. 73.

Hypersthene surrounded by oxyhornblende (=basaltic hornblende) in 11097.

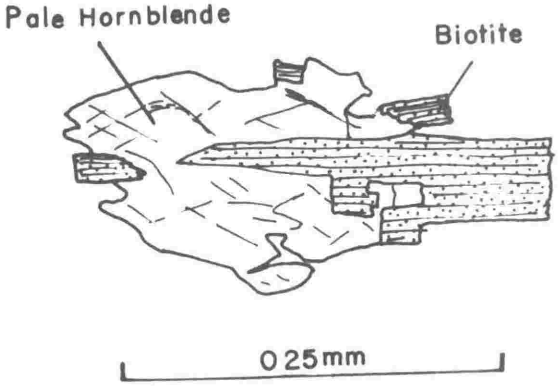


Fig. 74.

Intergrowth of biotite and pale hornblende (11036).

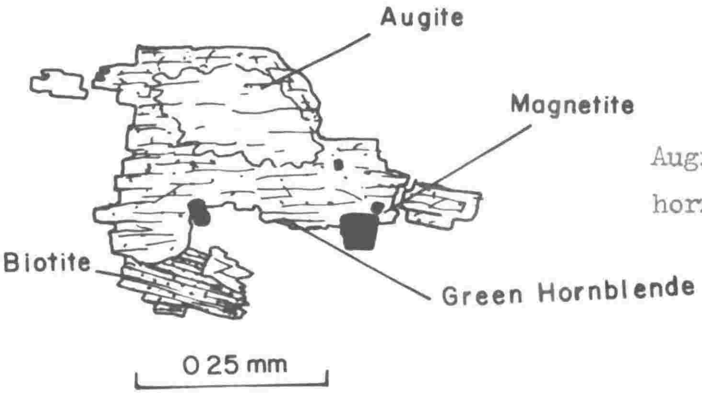


Fig. 75.

Augite surrounded by green hornblende and biotite in 11110.

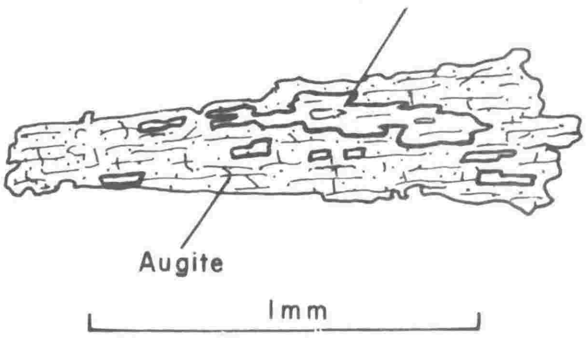


Fig. 76.

Hypersthene surrounded by augite (11082).

C. PETROGENESIS

1. CRYSTALLIZATION OF MINERALS IN ACID ROCKS

FERROMAGNESIAN MINERALS

The ferromagnesian minerals present in the rhyolites of the Tarawera Complex are hypersthene, hornblende and biotite. Hornblende occurs in most domes, but hypersthene and biotite are not usually found together as primary minerals in the same rock.

It is difficult to establish the crystallisation history of the ferromagnesian minerals accurately because of the complex nature of the lavas. The accessary minerals were presumably first to crystallise, followed by pyroxenes, and then hornblende and/or biotite. In the rhyolites, hypersthene often occurs in the centres of crystals, surrounded by hornblende (Fig. 73); and in the hornblende-quartz dacite, augite may be surrounded by hornblende in a similar way (Fig. 75). In each case the hornblende may be intergrown with biotite, showing that the two minerals crystallised together (Fig. 74). Throughout the crystallisation of the ferromagnesian minerals, plagioclase appears to have been forming, as the mineral is often found as inclusions, or in glomeroporphyritic aggregates with biotite and hornblende. The plagioclase phenocrysts often show resorption and zoning (p.122), illustrating the complex crystallisation history of the magma, and during this period the ferromagnesian minerals must also have been affected. In some cases two rhyolite magmas may have been mixed, providing two different mineral assemblages. This is known to have occurred in the Rerewhakaaitu 'Ash' and could account for the hypersthene in Tarawera Dome.

The compositions (Mg, Fe, determined optically, Ca, chemically)

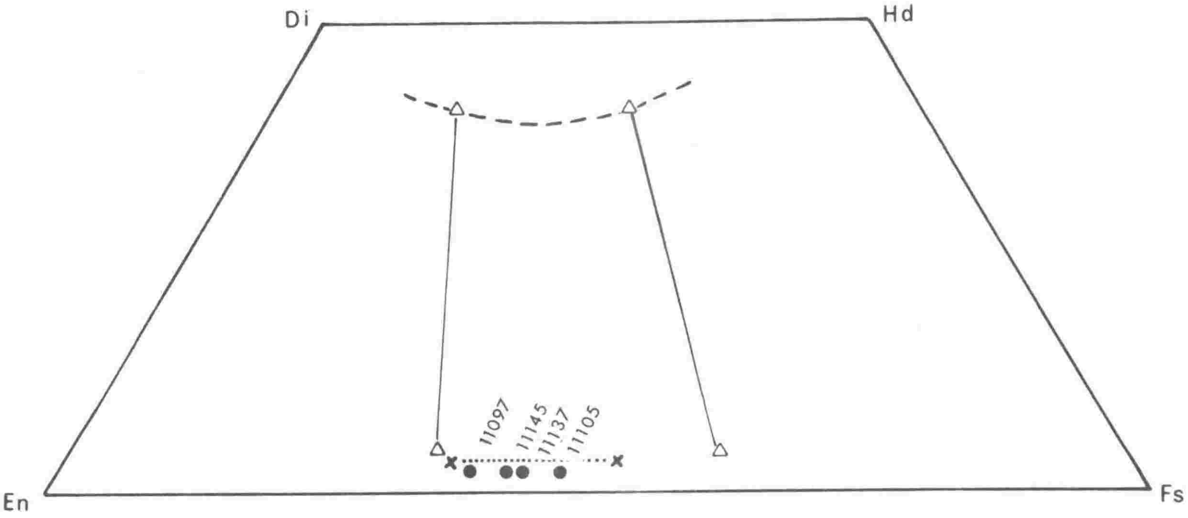


Fig. 77. Crystallization trends of hypersthenes from the rhyolites of the Tarawera Volcanic Complex : △–△ Two pyroxene pairs from the Thulean Volcanic Province (Carmichael, 1960), X···X Range of compositions from the Taupo pumices (Ewart, 1963) for comparison.

of four hypersthenes from Tarawera are plotted in terms of Mg, Fe and Ca in Fig. 77. The range of compositions of the hypersthenes from pumice deposits of the Taupo Sub-Group (Ewart, 1963), and two co-existing clino- and orthopyroxenes from acid rocks of the Thulean-Icelandic province (Carmichael, 1960), are plotted for comparison. The Tarawera minerals are similar in composition to the Mg-rich members of these examples, and this is consistent with the frequent inclusions of magnetite in the crystals. Carmichael (1963) has shown that the early separation of magnetite from the liquid will impoverish this liquid in iron, and this will result in the formation of iron-poor pyroxenes. Ewart (1965a, p.685) has further noted that as the pyroxenes crystallize the reverse effect should take place and the liquid become enriched in iron. This would result in zoning of the crystals, which is a common feature of orthopyroxenes. Kuno (1954, p.30) states that he has "never seen unzoned pyroxenes from volcanic rocks". However, in the acid rocks of the Taupo Volcanic Zone zoned orthopyroxenes have not been found (Ewart, pers. comm.). This may perhaps be due to the small size of the crystals, allowing the mineral to remain in equilibrium with the liquid. In the Tarawera rocks, the hypersthenes are not zoned, but become more iron rich with successive eruptions, a feature consistent with the above scheme.

The reason for the crystallization of hornblende and biotite rather than clinopyroxene has been discussed by Larsen et al. (1937, p.893) and Ewart (1963, 1965a). Larsen et al., considered that mineralizers were the critical factors, and Ewart (1965a, p.659) attributed the hypersthene-hornblende assemblage to a lower temperature and higher volatile content than the augite-hypersthene assemblage. The volatile content at the time of eruption was unlikely to be high at Tarawera as the greatest volume of material is in the form of rhyolite domes, and these presumably formed under non-explosive conditions. A more critical factor in determining which mineral crystallized may be temperature. The temperature within the domes immediately after extrusion was probably 700°-800°C, and this is below the temperature (900°-1000°C) at which pargasite reacts in the presence of quartz to form diopside + enstatite + plagioclase (Boyd, 1956).

Another factor considered by Ewart (1965a, p.619) to be important is the concentration of K_2O in the crystallising liquid, and it may be significant in this context that biotite always occurs at Tarawera in rock with a high crystal content. This suggests that the formation of plagioclase may have impoverished the liquid in Na and Ca, leaving it enriched in K, which could thus go into forming biotite.

Kuno (1954, p.980) has suggested that there is a solid solution series within the amphiboles from cummingtonite-green hornblende-basaltic hornblende. Sundius (1933) and Watters (1959), however, put a miscibility gap between the cummingtonite and green hornblende. This would be consistent with the evidence at Tarawera (if the pale hornblende proves to have a low calcium content) as a distinct break occurs between the two minerals described from a zoned crystal in 11156.

The formation of basaltic hornblende from common hornblende

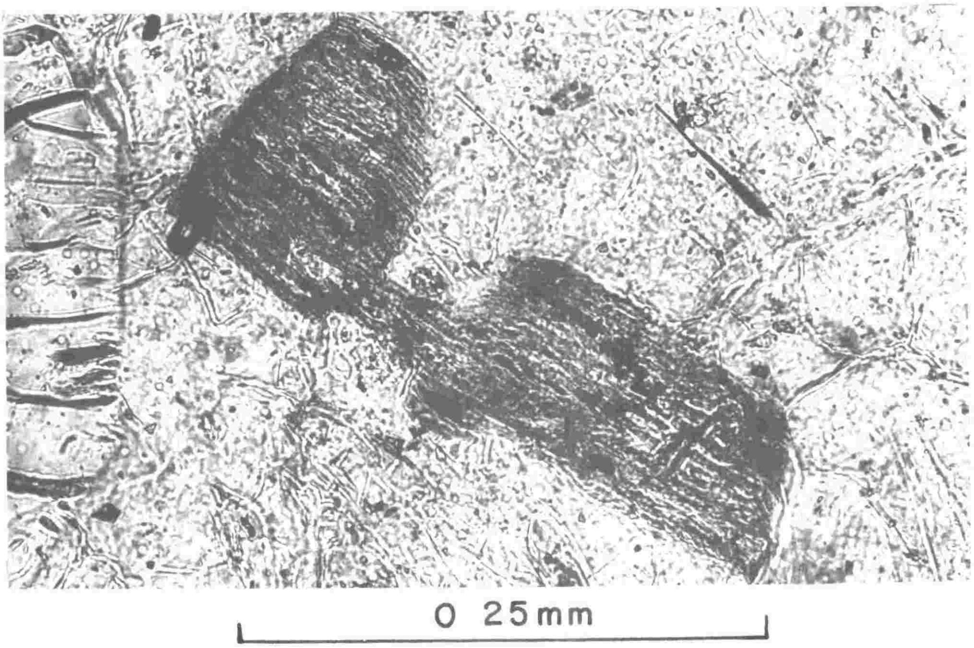


Fig. 78. Biotite showing alteration (11039), probably to vermiculite (ordinary light).

has been shown by Kozu, Yoshiki and Kani (1927) to take place at 750°C by oxidation of iron and subsequent loss of water. At Tarawera it only occurs in the centres of domes where presumably cooling was slower and devitrification could take place. It thus produces a useful temperature indicator for the domes. The formation of ferrian biotite is presumably analogous with the process forming basaltic hornblende. This agrees with the data of Hellner and Euler (1957) and Kozu and Yoshiki (1929) who found that on heating biotite gradually from 500°C - 800°C the γ refractive index changed from 1.655-1.703 and from 650°C the 2V began to enlarge.

Alteration of Biotite and Hornblende.

Biotite and hornblende are very prone to alteration when subjected to moderate temperatures and pressures or hydrothermal solutions. Two forms of alteration can be distinguished at Tarawera, one a result of leaching and the other oxidation.

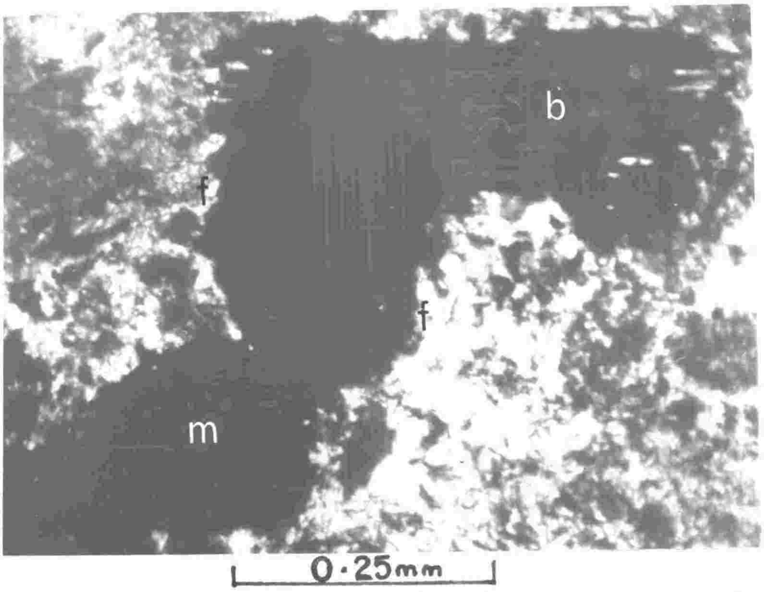
Leaching: At the tops of some domes, biotite becomes totally devoid of colour (Fig. 78) and the relief lower (< 1.54). Under crossed nicols, basal sections are opaque, but other sections show slight birefringence. This suggests vermiculite, but because of the small quantity and difficulty of separation this mineral could not be confirmed by X-ray.

Schwartz (1958) notes that iron, magnesium, and/or potassium can be leached from the biotite, and Walker (1949) has suggested that if potassium only is removed by weathering or hydrothermal alteration, vermiculite is formed. The processes causing the

Fig. 79. Biotite from 11150 showing alteration to magnetite and feldspar (ordinary light).

Fig. 80. Biotite from 11034 showing alteration to magnetite, feldspar and orthopyroxene (ordinary light).

Fig. 81. Hornblende showing oxidation to magnetite, feldspar and orthopyroxene (ordinary light).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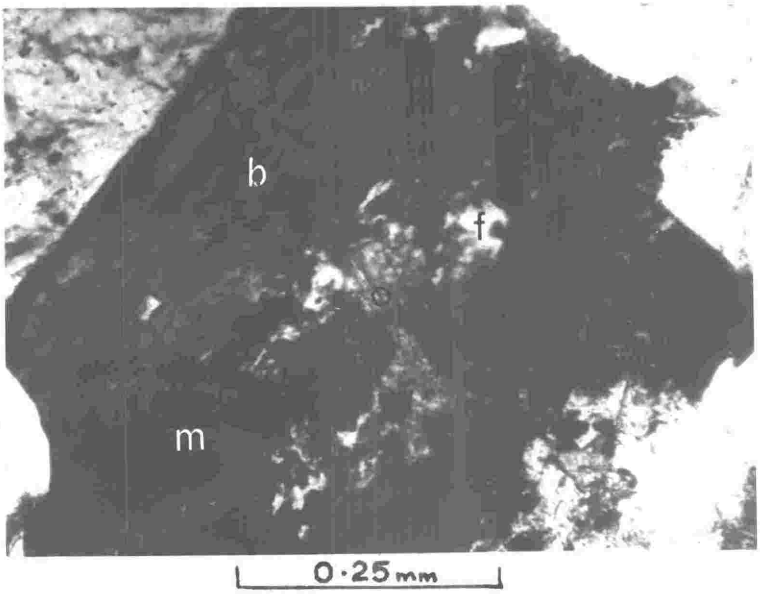
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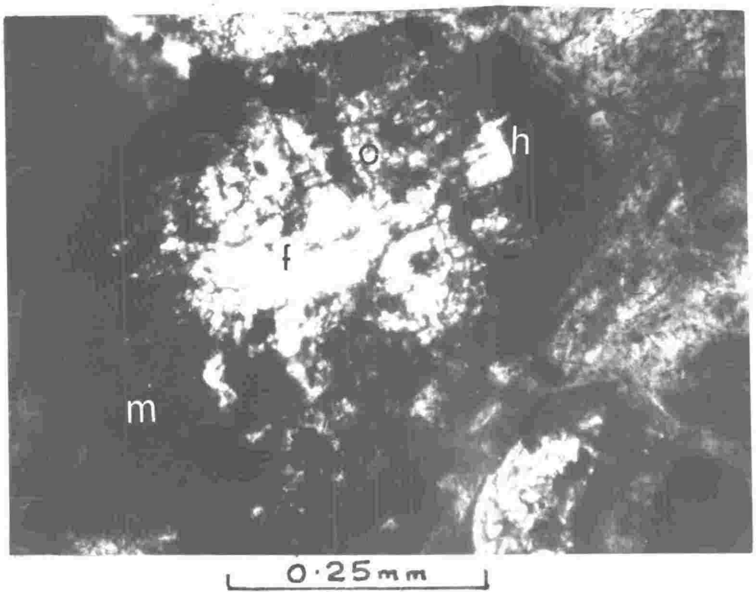
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leaching at Tarawera are unknown, but as the plagioclase crystals in the rock are also altered, hydrothermal activity is probably the most likely.

Oxidation: The origin of iron rich biotites (ferrian biotites) and hornblendes (basaltic hornblendes) has already been discussed. Oxidation can take place in another way, however, and cause resorption and subsequent recrystallisation of the mineral to give iron oxide, feldspar and/or pyroxene. Larsen et al., (1937) have inferred this process from San Juan, Colorado where they recognize three stages of development in biotite. Firstly, "pyroxene or a reddish alteration product....are concentrated next to the border....On further resorption an outer zone of the biotite is replaced by fine grained feldspar, red and black ore and pyroxene....Finally all evidence of the original biotite is destroyed" (Larsen et al, 1937, p.900). The three stages are difficult to recognize at Tarawera, but examples with magnetite and fine grained feldspar (Fig. 79) and magnetite + feldspar + pyroxene (Fig. 80) are common. Hornblende shows a similar type of alteration, often with distinct crystals of hypersthene, alkali feldspar and magnetite as in Fig. 81.

It is generally considered that this type of alteration took place after the lavas were erupted (Larsen et al., 1937, p.890; Lewis, 1960, p.57) as the alteration has not occurred in the same lava where it has a glassy groundmass. The products of the alteration are not disseminated throughout the rock. Zavaritskii and Sobolev (1964) note that biotite dissociates above 850°C, but both 'normal' and ferrian biotite, and basaltic and brown hornblende show this alteration, so it seems unlikely that temperature is the only factor. Eugster and Wones (1962, p.117) have shown that annite will break down to potash feldspar and magnetite between 400°C and 825°C, depending on fO_2 (oxygen fugacity). Breakdown will occur if temperature is decreased while fO_2 is constant, or if fO_2 is increased while temperature is constant. The latter could occur during the cooling of rhyolite domes, the increase in fO_2 probably resulting from a loss of hydrogen (and water) during devitrification.

The presence of quartz in the rock has little influence on the reaction at high values of fO_2, but with low to moderate values the field of stability of annite is reduced and the minerals break down to form sanidine + fayalite + vapour. The presence of magnesium in the biotite changes the reaction to:

biotite + quartz = sanidine + pyroxene + vapour

and this could presumably account for the pyroxene within the oxidised biotite at Tarawera. The value of fO_2 and temperature at which this change occurs is not yet known.

It seems, therefore, that this oxidation may take place at the same time as the production of ferrian biotite and basaltic hornblende, probably during devitrification, but due to local differences in fO_2 and temperature within the domes.

FELDSPARS

It is not known whether plagioclase or quartz was the first salic mineral to crystallize in the Tarawera rhyolites and granodiorites, but the two minerals closely followed one another. Sanidine was much later, occurring as a separate phase only in the holocrystalline granodiorite.

Fig. 82.

Normative components of total rocks and their residual glasses from the Tarawera Volcanic Complex, plotted in the system Ab - Or - Q - (H_2O). The boundary curves have been plotted for four water vapour pressures (in kg / cms^2). ++++ Positions of the minima on the boundary curves (after Tuttle and Bowen, 1958).

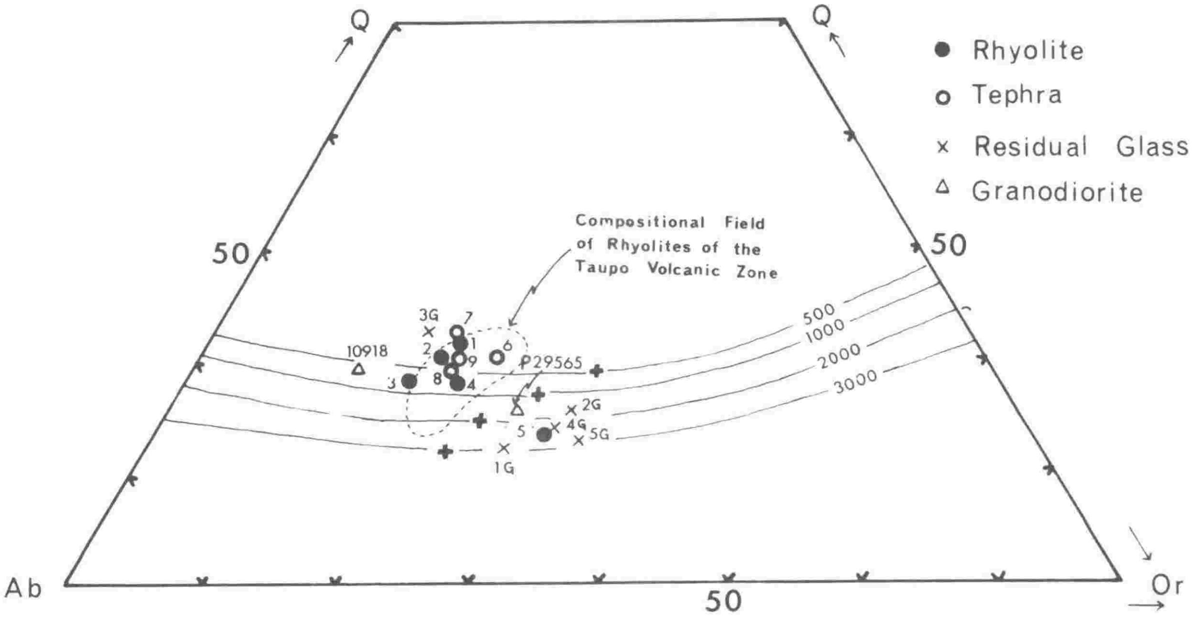
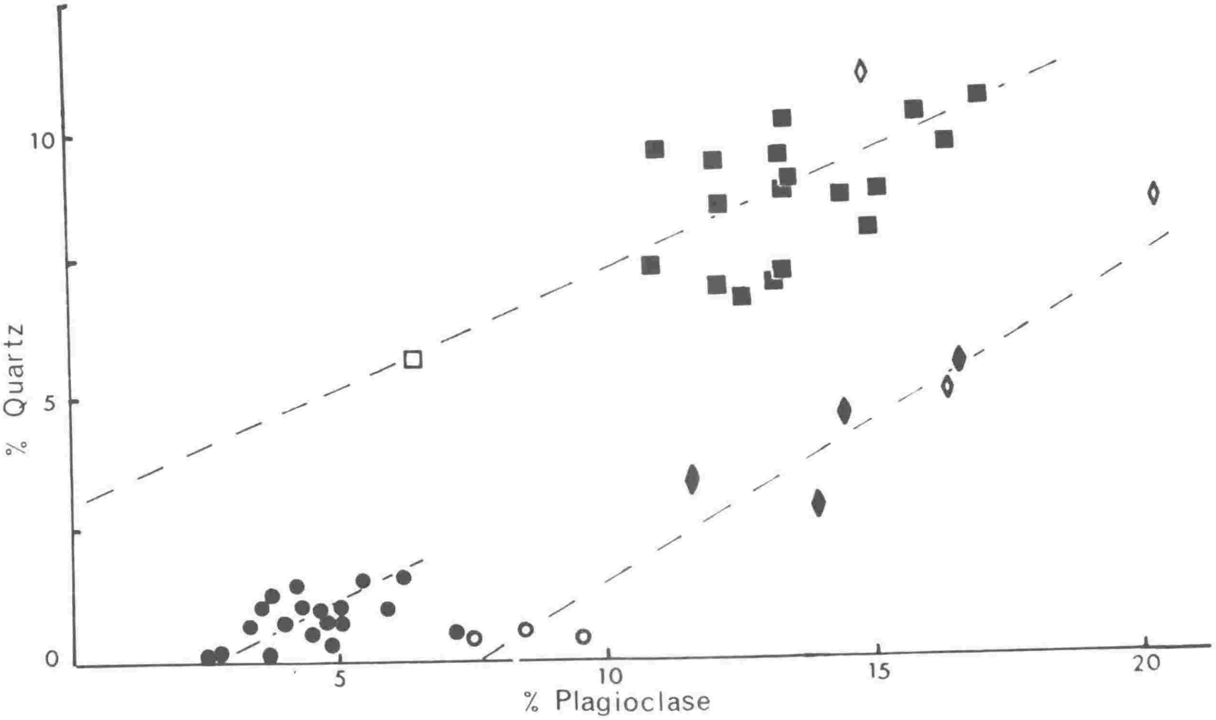

Q
Q
● Rhyolite
o Tephra
× Residual Glass
△ Granodiorite
Compositional Field of Rhyolites of the Taupo Volcanic Zone
50
50
500
1000
2000
3000
3G
7
1
2
6
9
10918
P29565
3
8
4
2G
5
4G
5G
1G
Ab
50
Or

Fig. 83.

Modal quartz to plagioclase ratios of the rhyolite domes of the Tarawera Volcanic Complex. ● Early Domes and Flows; ○ Southern Dome and Flow; ♦ Western Dome; ◊ Rotomahana Dome; ■ Late Domes; □ Green Lake Plug.

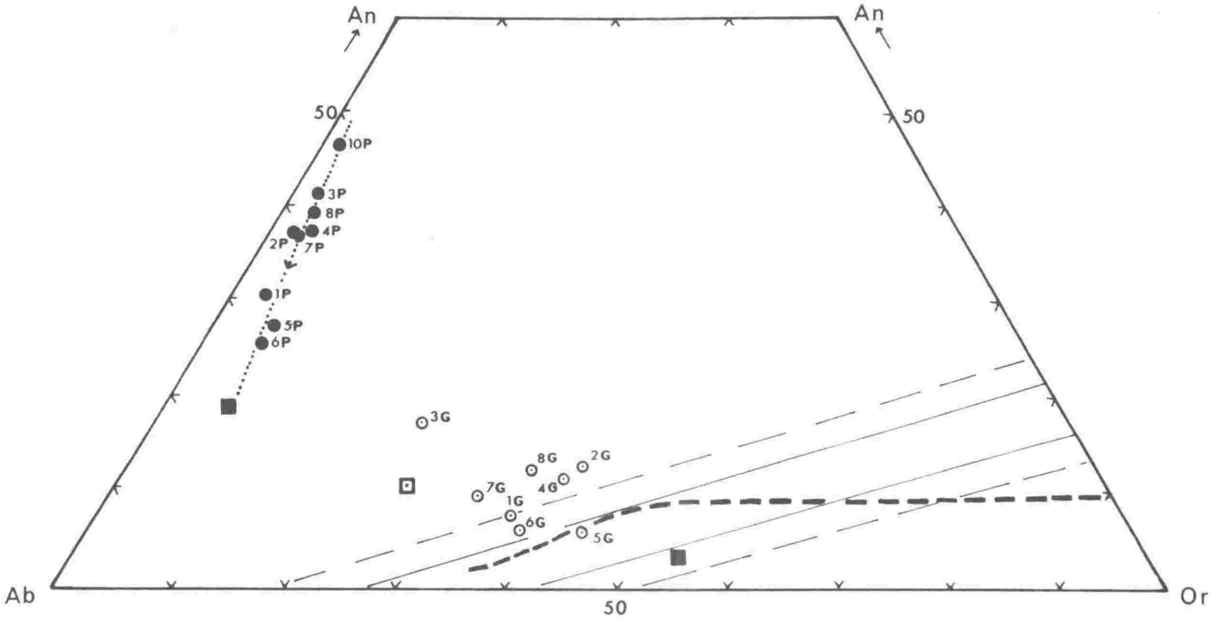

% Quartz
10
5
0
5
10
15
20
% Plagioclase

If the normative components of the total rock analyses are plotted in the system Ab-Or-Q-(H_2O) (Fig. 82), most of them fall within the main compositional field of the rhyolites of the Taupo Volcanic Zone, and most are on the quartz side of the quartz-feldspar boundary curve. This suggests that quartz would be the first mineral to crystallize (Carmichael, 1963a, p.110). Ewart (1965a, p.656) has pointed out, however, that "the quartz-feldspar boundary slopes back towards the quartz apex of the tetrahedron as the boundary moves away from the Ab-Or-Q plane. Thus a composition relatively rich in anorthite, which lies near but not on the feldspar side of the boundary will actually project on to the Ab-Or-Q face on the quartz side of the boundary curve".

There is good correlation in the Tarawera rocks between the projected positions of the total rock compositions plotted in the Ab-Or-Q-(H_2O) diagram and the positions of the points on a graph showing modal plagioclase/quartz ratio (Fig. 83). Western and Rotomahana Domes (3 and 4) plot almost on the 1000 bar cotectic in the Ab-Or-Q-(H_2O) diagram and if a mean line is drawn through the equivalent points in the plagioclase/quartz diagram it projects back to cut the plagioclase baseline. This suggests that plagioclase crystallised first. Ruawahia Dome (1) is the most quartz rich of the domes in the ternary diagram, and in the plagioclase/quartz diagram the mean line of the Late Domes projects back to cut the quartz baseline, suggesting that quartz crystallised first. Plateau Dome (2) (representing the Early Domes) is intermediate in both diagrams and in age. Thus the boundary between the quartz and feldspar field in the Tarawera rocks (with some anorthite

Fig. 84.

Normative plagioclase (P) and residual glass (G) components plotted in the system Ab - An - Or. ■ ⊡ ■ Coexisting plagioclase - sanidine - residual glass assemblage of granodiorite P29565 (Ewart and Cole, in press). – – – Two feldspar boundary surface of Carmichael, 1963. ¦¦ ¦¦ Low temperature trough of Kleeman, 1965.


An
An
50
50
10P
3P
8P
4P
2P
7P
1P
5P
6P
3G
8G
2G
7G
4G
1G
6G
5G
Ab
50
Or

present) is probably nearer the quartz apex than apparent on the Ab-Or-Q face.

Plagioclase

If the normative components of the plagioclase feldspars are plotted in the system An-Ab-Or (Fig. 84) they form a well-defined trend from An_{45}-An_{20} (approx.). Normative Or increases correspondingly from 2% to almost 7%. The most calcic member is from the hornblende-quartz dacite blocks of the Rerewhakaaitu 'Ash' (10P), and the most sodic, the corresponding granodiorite blocks of the Kaharoa 'Ash' (11AP). The plagioclase from the rhyolites range between these, with the oldest (3P) the most calcic, and the Kaharoa 'Ash' (6P) the most sodic. The only anomaly is that 5P, which is the youngest extrusion, is slightly more calcic than the preceding Kaharoa 'Ash'. The range of composition (determined optically, Table 9) is, however, the same, and hence it is probable that the difference is a result of differing proportions of early and late formed zones in the phenocrysts. This increase in sodium during crystallisation of the plagioclase has also been noted by Ewart (pers. comm.) in other parts of the Taupo Volcanic Zone.

The crystallization history of individual phenocrysts is complex, as shown by their zoning and resorption features. The phenocrysts of some of the domes have "patchy" cores surrounded by oscillatory zones, normally without resorption, which are similar to those described by Vance (1965, p.645) from plutonic rocks. These he regards as having formed at depth, risen to a higher level in the crust, become resorbed and then finally crystallized a more sodic feldspar in the resorption bays and around the margin.

The Tarawera phenocrysts have a number of important differences, however, from those described by Vance. For example, his distinction between a calcic oscillatory zoned core and normal zoned rim cannot be made. The usual arrangement in the Tarawera phenocrysts is a patchy core surrounded by an oscillatory zoned rim which extends to the margin. The composition of the sodic member of the core often corresponds to the outermost zone of the margin (see Fig. 54C), suggesting that the formation of the patchy core was very late in the development of the crystal. At Tarawera, such phenocrysts all occur in domes, which presumably had a lower volatile pressure at the time of eruption than the tephra which is often erupted just before them (p.122). This would suggest a drop in vapour pressure at the top of the magma reservoir shortly before extrusion of the domes. Vance (1962, p.754) notes that "rapidly decreasing pressure will cause resorption of earlier crystals in a melt under-saturated in volatiles", and this may therefore account for the patchy cores.

A problem with this explanation is that if the formation of the patchy core was a direct result of movement of the magma to the surface on extrusion, all crystals should show the feature. In fact, in the domes that they occur, less than 20% of the plagioclase phenocrysts have them. Even allowing for some of the sections not passing through the centres of crystals, this is very low. The form of the oscillatory zoned margin also varies between adjacent crystals in some instances this has also been found by Greenwood and McTaggart (1957) to be the general case in volcanic rocks. It thus seems that the phenocrysts with the patchy core and complex zoning have probably undergone a different crystallization history to the remainder, and this may either be due to mixing of two magmas, or to differing physical conditions within any one large magma reservoir.

Sanidine

Sanidine has only crystallised as a separate mineral in the granodiorites from the Kaharoa deposits. It probably did not start to appear until at least 50% of the rock had crystallised (Ewart and Cole, in press), by which time the plagioclase phenocrysts may have ceased to form. The reason for its not occurring as phenocrysts in the rhyolites is presumably that the composition of the liquid had not reached the Ab-Or cotectic before extrusion, and this is probably related to the high Na_2O content of the Tarawera rhyolites. Biotite, whose appearance is closely linked with that of sanidine elsewhere (Ewart, 1965a, p.659), crystallised earlier than, or contemporaneously with, the plagioclase at Tarawera, and thus it cannot require such a high enrichment in K_2O before crystallisation commences.

Residual Glass

If the norms of the residual glasses of the rhyolites are plotted in the system Ab-An-Or they fall, with one exception, above the two feldspar cotectic of Carmichael (1963d) and Ewart (1965a) or the low temperature trough of Kleeman (1965). This exception is 5G (from Green Lake Plug) which falls just below the cotectic. From this it would be expected that potash feldspar should have begun to crystallise in the rock, but neither optical nor X-ray measurements detected this. Ewart (1965a, p.652) also found that sanidine did not occur in some rocks whose glasses plotted along the cotectic, while in others it did occur. He suggested that there was a vapour pressure control in the crystallisation of the mineral and this could perhaps explain the lack of sanidine in the Green Lake Plug rhyolite.

Western Dome (3G) plots some distance towards the Ab-An sideline. This rock is certainly more basic than the others, but the low normative Or could also be due to sampling. The rock is highly spherulitic, and Ewart (pers. comm.) has noted that spherulites are usually enriched in sodium at the expense of the glass.

SILICA MINERALS

Quartz

Quartz usually forms square or hexagonal crystals which are typical of high temperature or β quartz (Foster, 1960, p.892) and these are frequently resorbed. Rittmann (1962) and Steiner (1963) have attributed this feature to a xenocrystic origin, but the constant ratio of the quartz to plagioclase throughout a particular dome (Table 15) makes this unlikely. Ewart (1965a p.656) has shown that the resorption can also be explained by changes in water pressure during crystallisation of the magma. This mechanism has already been invoked to explain some of the resorption in the plagioclase feldspars at Tarawera (p.172) and hence could well have caused the resorption of the quartz.

Cristobalite

This mineral occurs in the rhyolites only in spherulites and, as such, is presumably a late product of crystallisation formed by devitrification of the glass.

Tridymite

Wedge-shaped crystals of tridymite occur in gas vesicles of some spherulitic rhyolites and are presumably even later than cristobalite to form. They probably form by vapour phase deposition in the same way that Ross and Smith (1961) regard the mineral as forming in ignimbrites. The amount of tridymite is small in the rhyolite, but increases if the rock has been reheated (e.g., by inclusion in the basalt of the 1886 eruption), so that it may also form after solidification, as suggested by Rogers (1928), by pneumatolytic metamorphism.

2. CRYSTALLIZATION HISTORY OF MINERALS IN THE BASIC ROCKS

Information on the crystallisation history of the minerals in the basic rocks is meagre, as high alumina basalt is the only rock which reached the surface in a liquid state; the andesites, ankaramite and eucrites occurring only as blocks in the Kaharoa deposits. In many cases, as a further complication, the rocks appear to have been modified during their rise to the surface.

FERROMAGNESIAN MINERALS

The main ferromagnesian minerals are olivine and augite, with hornblende or orthopyroxene present in some of the rocks. The size of the minerals is variable; in the eucrites the crystals are comparatively large (max. 2 mms.) while in the basalts and andesites most are much smaller ($<$ 0.2 mms.). A few larger crystals occur ($<$ 1 mm.) and these form the major constituents of the ankaramite.

In the olivine eucrite there is little evidence indicating which mineral started to crystallise first, and it is probable that during most of their development olivine and augite crystallized together. The common resorption of the olivine suggests, however, that as the composition of the liquid changed, olivine ceased crystallising and, with further change, started to become resorbed. This is supported by the lack of any olivine in the groundmass.

In specimen 11078 the percentage of olivine is greatly reduced and orthopyroxene (bronzite) occurs. This mineral frequently encloses anhedral inclusions of olivine, suggesting that it is derived from it. This agrees with the views of Kuno (1950, p.991) who notes that a "reaction relationship between magnesian olivine

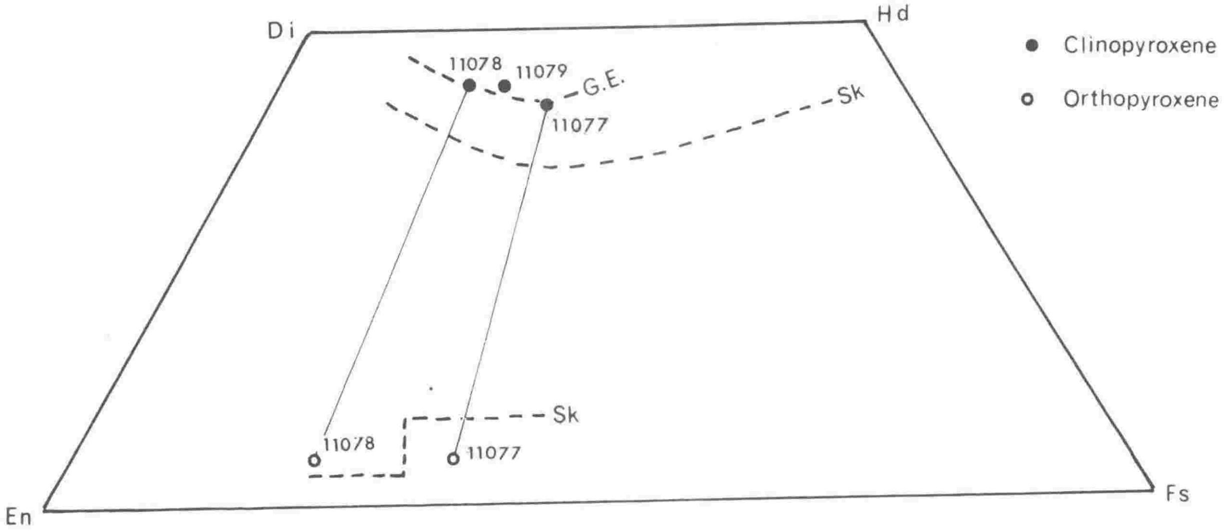


Fig. 85. Crystallization trends of coexisting hypersthene and augite from the eucrites of the Tarawera Volcanic Complex, with an augite from the pyroxene andesite plotted for comparison (11079). Two trends are also plotted for comparison : G.E. Garbh Eilean Sill, Shiant Isles ; Sk. Skaergaard Intrusion (Deer, Howie and Zussman, 1963).

(Positions on diagram plotted from optical data).

and hypersthene is (also) suggested by the antipathetic relation between porphyritic olivine and hypersthene in the rocks". In specimen 11077 olivine is absent, and the orthopyroxene is more iron rich (Fig. 85). Augite also increases in iron content, and this increase has been found by many authors to occur during differentiation of tholeiite and alkali basalt magmas (e.g., Poldervaart and Hess, 1951; Muir, 1951; Wilkinson, 1956). In the Tarawera rocks, however, the enrichment of the orthopyroxenes appears extreme (beyond the inversion point to pigeonite postulated by Muir (1951) in the Skaergaard intrusion), and it seems probable that it is a result of assimilation of acidic material. The hypersthene crystals present in the pyroxene andesite are nearly always surrounded by a rim of granular augite (see Fig. 76), suggesting that they also are out of equilibrium with the melt. They may thus be 'xenocrystic', but whether from an earlier basalt or from an acid rock is unknown.

Hornblende occurs only in the groundmass of the rocks, where it often forms long acicular crystals surrounding augite or hypersthene. This suggests that it may be a secondary alteration product of the pyroxene during the final stages of crystallization - perhaps due to an increased water pressure.

FELDSPARS

The crystallization history of the feldspars differs in the various types of basic rock. The small laths of plagioclase in the basalt and pyroxene andesite are labradorite in composition (Table 10) and show well developed zoning. They are probably a result of direct crystallisation during cooling of the magma (possibly en route to the surface).

The larger plagioclase crystals are of two types. In the pyroxene andesites they have a sodic core surrounded by a cloudy zone and a thin calcic rim. The cores of these crystals are completely out of equilibrium with the composition of the host magma, but are very similar to those of the rhyolite. It is therefore most probable that they have been derived from the rhyolites by a process of assimilation. Larsen et al., (1938, p.255) have come to the same conclusions to explain similar crystals in the San Juan lavas of Colorado.

The other type of crystals occur in the eucrites, ankaramite and bytownite andesite. These have an almost unzoned core of anorthite or bytownite surrounded by narrow zones, that become successively more sodic towards the margin, and may reach labradorite in composition. They resemble the plagioclase crystals in some of the rocks of the Hakone volcano (Kuno, 1950, p.963) which are considered to represent early segregations in the basaltic magma. In 11077, which is the most feldspar rich of the eucrites, there is a break between the calcic core of the crystal and the more sodic margin, which includes much variolitic glass. As these crystals occur in the same rock as the unusually iron rich hypersthenes (p.133), it is thought that the change may have been caused by assimilation of acid material, which would alter the composition of the liquid.

SILICA MINERALS

Quartz

Quartz crystals occur in most of the pyroxene andesites and occasionally in the basalt. In both cases they are surrounded by a reaction rim of pyroxene. As the host rocks also contain small crystals of olivine, the quartz must be out of equilibrium with the melt, and this is further indicated by the common resorption of the mineral. The crystals are thus probably derived from the rhyolites in the same way as the sodic cores of the plagioclase feldspars.

Cristobalite

This mineral occurs in the gas cavities of one of the andesites (p. 116) and in very small amounts in some samples of the basalt. In both cases it was formed at a very late stage in the crystallization history of the rock, and probably resulted from gas transfer after solidification of the groundmass, in the same way as Larsen et al., (1936) considered it to form in the lavas of the San Juan region, Colorado.

Fig. 86. Fault scarp to south of Lake Rotomahana which is thought to represent the southern margin of the Okataina Ring Structure. Outcrops at left edge of photograph are of ignimbrite.

3. ORIGIN OF ACID ROCKS

The Tarawera Volcanic Complex lies within the Okataina Volcanic Centre, which is regarded by Healy (1964) as bounded by a ring structure. This interpretation is based largely on topographic expression of the volcanic domes, but can in part also be substantiated by studying the fault pattern. To the south of Lake Rotomahana there is a well developed fault scarp, which is almost at right angles to the regional trend (Fig. 86). It probably continues to the south of Tarawera, but it cannot be identified there because of thick tephra deposits masking it. The fault can again be inferred to the south east of the Southern Lava Flow, and followed for a distance of about one mile before becoming obscured by further tephra. At the second locality, beds of older tephra, e.g., the Rotoiti Pumice Breccia (Vucetich, pers. comm.) occur directly to the south east of the structure. These are block faulted and tilted, and from the estimated age of the Rotoiti Pumice Breccia movement is indicated within the last 36,000 years (Thompson; Vucetich, pers. comm.). In the Tarawera Complex (to the north west of the fault and inside the proposed ring structure) the lowest bed identified is the Rerewhakaaitu 'Ash', which is much younger. This suggests that the earlier beds, if present, must have been downfaulted to a lower level within the structure.

During the earlier history of the Okataina Volcanic Centre, ignimbrite sheets (e.g., the Matahina and Kaingaroa Ignimbrites) were erupted (Bailey, 1965; Healy et al., 1964). These were followed by eruptions of 'ash-flow' pumices (e.g., Rotoiti Pumice Breccia) and, finally, extrusion of rhyolite domes and flows accompanied by explosive eruptions of 'air-fall' tephra. This type of activity has continued until the present day (Healy, 1965, p.10).

The origin of the acid lava has caused much argument. Battey (1965) has suggested that the rocks are derived from a sub-crustal source, and compares the Taupo Volcanic Zone with Iceland, where the concept of acid material being produced from the mantle, in conjunction with basaltic volcanism, is widely accepted. Most New Zealand petrologists, however, favour an origin within the crust (Clark, 1957, 1960a; Steiner, 1958; Ewart, 1964, 1965a). The main argument in favour of a crustal origin is the large volume of acid lava in the Taupo Volcanic Zone, probably about 4,000 cubic miles (Healy, 1962). Clark (1960a, p.128) has calculated that about ten cubic miles of basalt are required to 'differentiate' one cubic mile of acid lava, so that for Healy's estimated volume 40,000 cubic miles of basalt would be required. If this had happened in New Zealand it would seem logical to expect more than the one cubic mile of basalt erupted. A further argument against a 'differentiation' origin is the lack of a complimentary ultrabasic fraction. A few blocks of ankaramite have been ejected at Tarawera, but no large quantities of peridotite or other ultrabasic rocks are known or indicated by geophysical methods.

The sialic material which could produce the magma is equally speculative. Steiner (1958) has suggested that it is gneiss, but as there must be a large volume of greywacke faulted under the region this is also a possibility (Clark, 1960a). The high Na_2O/K_2O ratio of the New Zealand greywackes, and the comparable high Na_2O/K_2O ratio in the acid volcanic rocks makes it a very reasonable choice. Ewart (1965a) has plotted the normative Ab-An-Q in a ternary diagram, and finds that, by combination of greywacke and argillite, a rock of very similar composition to the acid volcanics can be produced.

The rhyolites of the Tarawera Complex form well defined trends if their compositions are plotted on von Wolff or AFM diagrams (Figs. 70 and 71). This suggests that they have probably originated from the same magma source. Variation within individual domes, however, suggests that the lava may have risen to separate reservoirs before eruption, and crystallized under slightly different conditions. At times the magma from more than one reservoir may have been erupted at the same time and this could account for the variation in mineralogy present, for example, in Tarawera Dome. It is possible that in some examples the variation could be due to differences within an original large magma reservoir. In the Rerewhakaaitu 'Ash', however, about equal quantities of two types of pumice were erupted simultaneously, and the lack of any intermediate types makes this unlikely.

The hornblende-quartz dacite and granodiorite are both considered comagmatic with the rocks with which they were erupted. The granodiorite blocks in particular show evidence of having crystallized high in the crust (p.100) and probably represent the plutonic rock which would have resulted had the magma completely crystallized without eruption. This interpretation is consistent with the usual occurrence of granite or granodiorite plutons in older ring structures, e.g., Central Ring Complex of the Isle of Arran (King, 1954) and those of Northern Nigeria (Jacobson, McLeod and Black, 1958). The granite in many of these plutons also exhibit the granophyric intergrowths found in the Tarawera rocks.

The accidental ejecta of the Kaharoa eruption (ignimbrite, etc.) have presumably been caught up by the rhyolite lava en route to the surface, and from petrographic correlation of these ignimbrites with those of the Rerewhakaaitu region further confirmation of downthrow in the ring structure can be obtained.

4. ORIGIN OF BASIC ROCKS

The most voluminous basic rock at Tarawera is the high alumina basalt erupted in 1886, which is typical of the basalt lava erupted in the circum-Pacific region (Kuno, 1960). There is little doubt that its origin is from within the mantle, but the reason for the high alumina content is debatable. Kuno (1960) regards the high alumina basalt in Japan as a primary magma intermediate between tholeiite and alkali basalt, and produced by partial melting of the mantle at a depth of 200 kms. Yoder and Tilley (1962) show, however, that basalt with a high alumina content can form important members of both the tholeiite and olivine basalt groups. He attributes the high alumina content to the large amount of plagioclase present, possibly by removal of olivine. O'Hara (1965, p.34) suggests that it is the way the magma reaches the surface that is important. He considers that high alumina basalt forms by interruption of the ascent of the magma in a low pressure region (presumably within the crust) where fractionation occurs and a liquid rich in normative plagioclase results.

The Tarawera basalt must have either contained a moderate - high percentage of water, or absorbed water en route to the surface, for the lava vesiculated and became highly explosive. This produced small basalt lapilli and these were probably the only eruptive product, any apparent coherent lava having formed by a welding together of these lapilli.

The origin of the andesites is debatable. The blocks could have come from an andesite volcano extruded before the earliest visible dome at Tarawera. However, their complete absence in domes and tephra until the Kaharoa eruption makes this unlikely. A general aeromagnetic survey (see Appendix 1) has shown a slight positive magnetic anomaly over the region, but this could also be explained by basalt near the surface, and this seems far more likely.

Pyroxene andesite is probably the nearest chemically to high alumina basalt, especially the aphyric andesite, and the samples with only a few phenocrysts of augite and olivine. Quartz and plagioclase, present in most specimens, are presumably derived from acid rocks, and these could be the cause of the high silica content of the analysed sample (and hence the name 'andesite'). If this is the reason, however, the original rock must have had a relatively low alumina content, for in spite of the feldspar xenocrysts the content of Al_2O_3 is lower than that of the basalt. As the lava must have been intruded at least 1000 years before the 1886 eruption (i.e., before the Kaharoa eruption) this is consistent with O'Hara's explanation for the origin of high alumina basalt.

The andesite intrusion is considered to have followed the same fissure as the basalt, for the latter contains many small inclusions of andesite. Also the general lack of rhyolitic material in the basalt, except for blocks picked up near the surface, suggests that the vent pipe was probably largely through basic rocks. The variation in texture in the andesite from compact to vesicular, and the occurrence of black glass in some samples (e.g., 11158), suggests that the intrusion almost reached the surface. (Macdonald, 1963, p.1076 regards the maximum depth that vesicles form in the Hawaiian magmas to be 2000 ft. below the contemporaneous surface.) No trace of this dyke can now be found, but as the event must have occurred pre-Kaharoa eruption, it would presumably now be buried under the domes or destroyed by the 1886 eruption.

The ankaramite which is formed almost entirely of augite and olivine phenocrysts is thought to be an accumulative rock, formed by sinking of phenocrysts in the 'andesite' intrusion. This would account for the gradation from aphyric to porphyritic samples.

The most problematic of the basic rocks are the eucrites. These are usually regarded as early formed segregations within a basaltic reservoir (Kuno, 1950) and this is probably the case at Tarawera. Their coarse grained nature suggests that they are comparatively deep seated; they could represent a marginal facies of an early deep magma reservoir. The olivine eucrite, from its petrography, would seem the nearest to the composition of a basalt, and from features in the hypersthene eucrite (e.g., the formation of the orthopyroxene from the olivine; the presence of sodic margins to the plagioclase and the even more sodic feldspars in the groundmass) some assimilation of acid material is suggested. Thomas (in Richey and Thomas, 1930, p.295) considered the eucrites of Ardnamurchan to be a mixing product, but in this case the assimilation went further to produce a suite of biotite and alkali feldspar bearing eucrites. The lack of these minerals at Tarawera may be due to the materials assimilated having a low potash content (e.g., greywacke or granodiorite). It is likely that, during emplacement of the pyroxene andesite, blocks of eucrite were rafted into the intrusion, as the blocks of eucrite brought to the surface are always coated with some andesite.

5. SUGGESTED EXPLANATION FOR TWO LAVA TYPES AT TARAWERA

It has already been stated that vast amounts of acid lava have been erupted from the Okataina Volcanic Centre. Most of this has been in the form of ignimbrite, which flows for many miles away from the centre of eruption. The Matahina Ignimbrite, for example, flowed as far east as the front of the Ikawhenua Range; in the Rangitikei Gorge, 10 miles east of the proposed ring structure, it is still 350 ft. thick. These large outpourings of material must have affected the stability of the crust in the area, and are likely to have caused collapse of the material overlying the partially emptied magma reservoir (Williams, 1941; Smith et al., 1961), to produce a caldera. The widespread distribution of the ignimbrite is also likely to lower the load pressure in the immediate source area, and to compensate for this, denser basalt from within the mantle could move up into the crust.

This combination of 'roof collapse' and intrusion of basalt would tend to cause any magma left in the reservoir (now probably under a lower volatile pressure) to move towards the surface through fractures developed in the collapsed roof, or around the margin of the caldera. This stage is well seen at Valles Caldera, New Mexico, and results in a ring of domes near the margin (Smith, et al., 1961, Fig. 340.1). In the Okataina Volcanic Centre this stage is represented by the alignment of domes (see Fig. 2) in the centre of the structure and in the semi-circular arrangement around the north eastern edge.

Once basalt moved into the crust, it could be affected by the 'differentiation' process suggested by O'Hara (1965). The first material to solidify, presumably at the edges of the basic intrusion, would tend to be low in alumina, and during its rise through the crust would be likely to assimilate some of the rhyolite 'magma'. The varying degree to which this assimilation occurs could reflect the variation in the andesites at Tarawera from pyroxene andesite to sodic andesite. Once the original basic intrusion had crystallised it would provide a 'sheath' for any later basalt upwelling (as in 1886) and retard further assimilation. Thus the later eruptives would be nearer to the parental composition.

An argument against this hypothesis is that no andesites are found at the surface in association with other basalts in the Taupo Zone. It should be remembered, however, that the only reason for the presence of the andesite blocks at Tarawera is the intervening Kaharoa eruption. Had it not been for this event, the lava would presumably still be in place within the crust. At the other basalt eruptive centres, there have been no explosive acid eruptions to eject blocks of earlier intrusions, and insufficient work has been done on the basalts themselves to check for small xenoliths. A final supporting point is the occurrence of andesites at Wairakei (Grindley, 1965). These occur in fissures at the intersections of faults, and form small lava flows which thin rapidly away from the vents. They differ from the Tarawera andesites in having no quartz phenocrysts, and their feldspars are of andesine composition. However, the close association with faulting is very similar to the proposed occurrence at Tarawera.

The NE-SW alignment of the basalt eruptive vents in the Taupo Volcanic Zone is very striking. It occurs at K Trig (unpublished observation) and at Tarawera. Hunt (pers. comm.) has also suggested from magnetic evidence that there is a second dyke at Tarawera of similar orientation and thickness to the main fissure, but several hundred yards to the south east (see Appendix 1). This does not reach the surface. It could thus be that once in the crust, further movement of the lava is controlled by the NE-SW faults common throughout the Zone. It has been suggested that before the Kaharoa eruption at Tarawera a basic dyke occurred; a second dyke is thought to occur now a small distance to the south east, and so it does not seem unreasonable to suggest that other NE-SW fractures may contain basalt at depth. If so, there could be the beginnings of a dyke swarm comparable to that formed in the final stages of eruption in the Thulean volcanic province of Scotland and Iceland.

SUMMARY

1. Tarawera Volcanic Complex consists of twelve rhyolite domes and flows, which fall into Early and Late suites.

2. Wahanga and Crater Domes are most nearly endogenous in origin, while the rest are substantially exogenous.

3. Tarawera was the source of four tephra deposits which form essential datums for consideration of the stratigraphy on the mountain.

4. During the Kaharoa eruption 'air-fall' tephra was erupted, nuées ardentes swept down the southern and eastern sides of the mountain, and Crater, Ruawahia, Tarawera and Wahanga Domes were extruded. Finally Green Lake Plug was emplaced.

5. In the Tarawera eruption of June 10, 1886, the first activity was from a fissure on Wahanga Dome at about 0115 hrs. This was followed by activity from the extension of the same fissure first on Ruawahia Dome, then on Tarawera Dome. At 0330 hrs. activity became phreatic, and large 'accidental' blocks of rhyolite were torn from the walls and ejected, leaving the present deep craters. The main activity had ceased by 0530 hrs.

6. About 500 ft. thickness of debris was blown out of the centre of Rotomahana basin, and both the Pink and White Terraces were probably destroyed.

7. Petrologically the rhyolites can be divided into four types: hypersthene-hornblende rhyolite, ~~hypersthene~~ hornblende-biotite rhyolite, hypersthene rhyolite, biotite rhyolite.

8. Discrete blocks of hornblende-quartz dacite, granodiorite, andesite, ankaramite and eucrite were ejected with the rhyolite tephra during the Kaharoa eruption.

9. Chemically, the Tarawera rhyolites and basalt are comparable to similar rocks from other centres in the Taupo Volcanic Zone and to the averages of calc-alkaline rocks of other provinces. The andesites are, however, more comparable to the average of high alumina basalts than to the average andesite.

10. The rhyolites formed by melting of crustal rocks, possibly graywacke, and the hornblende-quartz dacite and granodiorite formed at the sides of the magma 'reservoir'.

11. The high alumina basalt is thought to be nearest in composition to the parent basic magma, and the andesites probably originated by deep seated assimilation of acid material by this basic magma. The ankaramite and the eucrites probably resulted from variation in the original intrusion.

12. The presence of two lava types at Tarawera resulted from the vast outpourings of ignimbrite and rhyolite and consequent crustal readjustment. The reduced load pressure caused by these eruptions allowed basalt magma to move from the mantle into the crust. At first the magma could mix with acid rhyolite to produce 'andesite', then later basalt magma could rise through the andesite without contamination from rhyolite. Such a process would adequately account for the basalt erupted in 1886.

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APPENDIX 1

MAGNETIC SURVEYS OF THE TARAWERA VOLCANIC COMPLEX

APPENDIX 1 - MAGNETIC SURVEYS OF THE TARAWERA VOLCANIC COMPLEX

Introduction

The Tarawera Volcanic Complex is an ideal location for magnetic investigations because of the inter-relationship of rhyolite and basalt. Rhyolite from the area has a remnant magnetism of about 400×10^{-6} cgs. units while basalt has been measured at about $30,000 \times 10^{-6}$ cgs. units (Hunt, pers. comm.). It is thus easy to locate basalt within rhyolite even where the former has not reached the surface.

Investigation

The first investigation of magnetic variation at Tarawera was made in 1936 by Watson-Munro (1938). He traversed the 1886 fissure in three places (Fig. 87A - in pocket at back of thesis) using a Schmidt Vertical Variometer, and made random measurements elsewhere. In his paper, Watson-Munro has drawn a sketch map of the area, and has shown data from two traverses. A third traverse is indicated on the map by a small arrow, and the data given in a profile in his Figure 1.

In 1951, an airborne magnetometer survey was carried out over the whole Rotorua-Taupo thermal area (Gerard and Lawrie, 1955). Two flight lines crossed Tarawera, but no major variation was measured.

The most recent survey was carried out by Hunt*, who in 1964 made three further ground traverses across the 1886 fissure (Fig. 87A) also using a Schmidt Vertical Variometer. He also re-measured the

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*This was a project undertaken by T.M. Hunt for a B.Sc.(Hons.) degree at Victoria University of Wellington, and much of the information in this Appendix comes from his unpublished thesis, held in the Geology Department Library at Victoria University of Wellington.

remnant magnetism of the two major rock types at Tarawera.

Results

The results of the six ground traverses made across the fissure are shown in Fig. 87B. Profile A records no major anomaly; the slight variation probably a result of topography. Profile B, which crosses near the centre of the line of the craters, shows a marked anomaly (maximum 5679 gammas). The size and shape of this suggests that the basalt is very near the surface in the craters, and as a dyke, 30 ft. wide, outcrops in the bridge between craters 1000 ft. (approx.) to the south east, this is reasonable. A similar anomaly can be recognized in each profile to the south west, as far as Lake Rotomahana, showing the continuous nature of the dyke.

A second anomaly is shown in profiles B, C and D (Fig. 87B) to the south east of the main fissure. This is considered by Hunt to be a dyke vertically parallel to the main dyke, but which does not reach the surface. The smaller anomaly in profile C, compared with profiles B and D, may reflect variation in the maximum height reached by the second dyke. It does not appear to extend further south west than profile E.

Summary

1. A basalt dyke exists beneath the length of the 1886 craters across Tarawera.

2. This dyke does not continue north east of the mountain.

3. There is probably a second dyke, of similar trend, about 1500 ft. south east of the main dyke, which does not reach the surface.

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APPENDIX 2

BIBLIOGRAPHY OF PAPERS WRITTEN ABOUT THE TARAWERA ERUPTION OF 10th JUNE, 1886

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APPENDIX 3

MODAL ANALYSES OF ROCKS IN
TARAWERA VOLCANIC COMPLEX

Localities of all samples are shown on map in pocket at back of thesis.

TABLE 3A - MODAL ANALYSES OF THE EARLY RHYOLITE DOMES

	1	2	3	4	5	6	7	8
Thin Section No.	11135	11113	11095	11096	11097	11087	11127	11129
Glass or Groundmass	94.4	82.1	75.9	78.0	80.5	69.0	71.1	75.2
Quartz	1.0	3.6	5.5	4.5	2.8	8.3	11.9	5.0
Plagioclase	4.3	11.6	16.7	14.4	14.0	20.4	15.0	16.5
Biotite	-	-	-	-	-	1.9	1.3	1.9
Hypersthene	0.1	0.9	0.6	1.8	1.2	-	-	-
Hornblende	-	1.2	0.6	1.0	0.7	0.3	0.4	1.1
Magnetite	0.2	0.6	0.7	0.3	0.8	0.1	0.3	0.3
Total Crystal Content	5.6	17.9	24.1	22.0	19.5	31.0	28.9	24.8
Plagioclase/Quartz ratio	4.30	3.22	3.02	3.20	4.82	2.46	1.26	3.20
Vesicular (V) or Spherulitic (S)	V	V	S	S	S	V	V	V

1	Ridge Dome
2-5	Western Dome
6-8	Rotomahana Dome

TABLE 3B - MODAL ANALYSES OF THE EARLY RHYOLITE DOMES

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Thin Section No:	11161	11163	11088*	11115	11116	11117	11110	11144	11145	11146	11138	11133	11134	11142	11119	11120	11062	11136
Glass or Groundmass	97.3	95.8	94.0	97.0	94.3	94.8	94.7	90.3	88.8	91.0	93.0	95.4	94.9	94.3	93.7	94.8	93.9	93.6
Quartz	0.1	0.1	0.6	0.1	0.2	1.1	0.6	0.4	0.3	0.3	1.5	1.0	0.6	0.6	0.9	0.4	1.4	1.0
Plagioclase	2.4	3.9	3.1	2.8	4.9	3.6	4.6	8.3	9.5	7.4	5.3	3.4	4.2	5.0	5.9	4.5	4.1	5.0
Biotite	-	-	0.2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Hypersthene	0.1	0.1	0.3	-	0.5	0.2	0.1	0.8	0.7	0.7	0.1	0.1	0.2	0.1	0.2	0.1	0.5	0.2
Hornblende	-	-	0.3	0.1	-	0.1	-	0.1	0.4	0.2	-	-	-	-	0.1	-	-	-
Magnetite	0.1	0.1	1.5+	-	0.1	0.2	-	0.1	0.3	0.4	0.1	0.1	0.1	0.1	0.2	0.2	0.1	0.2
Total crystal content	2.7	4.2	6.0	3.0	5.7	5.2	5.3	9.7	11.2	9.0	7.0	4.6	5.1	5.7	7.3	5.2	6.1	6.4
Plagioclase/Quartz ratio	24.0	39.0	5.16	28.0	24.5	3.27	7.66	20.75	31.6	24.5	3.52	3.40	7.0	8.32	6.54	11.25	2.92	5.0
Vesicular (V) or Spherulitic (S)	V	V	V	V	S	S		V	V	S	V	V	S	-	V	S	S	V

1-3 Rerewhakaaitu Dome
4-7 North Western Lava Flow
8 Southern Dome
9-10 Southern Lava Flow
11-14 Plateau Dome
15-16 Northern Lava Flow
17-18 Eastern Dome

* Contains crystals from Rotomahana Dome

\+ Total iron oxide

TABLE 4 - MODAL ANALYSES OF THE LATE RHYOLITE DOMES

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Thin Section No:	11149	11150	11151	11046	11037	11036	11075	11101	11102	11040	11044	11147	11066	11067	11068	11069	11070	11123
Glass or Groundmass	71.1	80.9	75.6	75.5	76.6	72.8	72.3	76.0	69.1	77.8	74.6	78.7	75.8	75.2	76.3	75.1	74.4	86.7
Quartz	9.7	7.3	8.7	7.2	8.5	8.7	10.3	7.2	10.5	7.0	7.9	6.8	9.4	9.6	9.3	10.1	8.7	5.7
Plagioclase	16.6	10.9	13.5	13.3	12.2	15.1	15.8	13.2	17.1	12.2	15.0	12.6	13.2	11.0	12.1	13.2	14.5	6.3
Biotite	2.3	0.7	1.8	2.5	2.2	3.0	1.3	3.1	1.7	3.0	2.5	1.7	1.4	4.2	2.3	1.2	2.2	0.9
Hypersthene	-	-	0.3	-	-	-	-	-	0.3	+	-	0.1	-	-	-	-	-	0.3
Hornblende	-	-	-	-	0.1+	-	-	0.1	0.5	-	-	-	-	-	-	-	-	-
Magnetite	0.3	0.2	0.1	1.5	0.4	0.4	0.3	0.4	0.8	-	-	0.1	0.2	-	-	0.3	0.2	0.1
Total crystal content	28.9	19.1	24.4	24.5	23.4	27.2	27.7	34.0	30.9	22.2	25.4	21.3	24.2	24.8	23.7	24.9	25.6	13.3
Plagioclase/Quartz ratio	1.71	1.49	1.55	1.87	1.44	1.75	1.53	1.83	1.63	1.78	1.90	1.85	1.41	1.15	1.30	1.31	1.64	1.10
Vesicular (V) or Spherulitic (S)	S	S	S	S	V	V	S	V	S	S	V	V	V	S	S	S	S	V

1-3	Crater Dome
4-7	Ruawahia Dome
8-9	Tarawera Dome
10-17	Wahanga Dome
(13-17	- series from margin to core)
18	Green Lake Plug

+ Cummingtonite

TABLE 5 - MODAL ANALYSES OF RHYOLITE TEPHRA BLOCKS

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Thin Section No:	11116	11160	11165 (1)	11165 (2)	11159	11156	11152	11153/4	11153/7	11169	11142	11030	11064	11065
Glass or Groundmass	98.3	97.5	96.7	80.5	81.2	82.0	98.1	94.0	95.7	94.7	83.3	66.6	62.5	68.0
Quartz	-	-	-	3.8	2.8	2.8	0.3	1.6	1.2	1.3	4.6	13.5	13.5	9.3
Plagioclase	1.3	2.5	3.2	12.0	13.5	13.1	1.5	3.6	2.6	3.1	9.5	16.3	19.4	21.0
Biotite	-	-	-	3.0	2.0	1.2	-	-	-	0.3	2.2	3.6	4.2	1.6
Hypersthene	0.3	-	-	0.1	0.2	-	0.1	0.7	0.4	0.3	-	-	-	-
Hornblende	-	-	-	0.1	0.2	0.7	-	-	-	-	0.2	-	-	-
Magnetite	0.1	-	0.1	0.5	0.2	0.2	-	0.1	0.1	0.1	0.2	-	0.4	0.1
Xenoliths	-	-	-	-	-	-	-	-	-	0.2	-	-	-	-
Total Crystal Content	1.7	2.5	3.3	19.5	18.9	18.0	1.9	6.0	4.3	5.4	16.7	33.4	37.5	32.0
Plagioclase/Quartz Ratio	∞	∞	∞	3.1	4.8	4.7	5.0	2.3	2.16	2.4	2.06	1.21	1.44	2.26
Vesicular (V) or Spherulitic (S)	S	V	V	V	-	V	V	-	-	V	V	-	V	V

1-3	Rerewhakaaitu 'Ash' (pumice of Type A)
4-6	Rerewhakaaitu 'Ash' (pumice of Type B)
7	Waiohau 'Ash'
8-9	Unwelded ignimbrite of Waiohau age
10-14	Kaharoa 'Ash'

TABLE 6 - MODAL ANALYSES OF COGNATE XENOLITHS FROM TARAWERA

	1	2	3	4
Thin Section No.	11109	11143	10918	P29565*
Glass or Groundmass	32.5	24.1	-	-
Quartz	3.7	11.5	34.2	35.6
Plagioclase	48.6	53.2	41.3	36.5
Sanidine	-	-	20.9	24.4
Biotite	-	5.8	3.3	3.0
Hypersthene	0.7	-	< 0.1	< 0.1
Hornblende	10.2	4.7	0.1	< 0.1
Magnetite	1.4	0.7	0.2	0.5
Graphic Intergrowths	2.8	-	-	-
Total Crystal Content	67.5	75.9	100	100

1. Hornblende-quartz-dacite
2. Rhyodacite

3-4 Granodiorite

*Specimen held in N.Z. Geol. Survey Colln., Lower Hutt.

TABLE 7 - MODAL ANALYSES OF THE BASIC ROCKS

	1	2	3	4	5
Thin Section No:	11032	11074	11082	11158	110
Groundmass:					
General	77.6	79.8	-	-	65.
Feldspar	17.1	15.6	73.7	59.7	9.
Olivine	5.3	4.6	-	1.0	-
Pyroxene	g	g	21.5	36.4	2.
Amphibole	-	-	-	-	-
Magnetite	g	g	0.9	3.0	g
Phenocrysts:					
Plagioclase	-	-	-	-	19.
Olivine	-	-	1.7	-	-
Augite	-	-	2.0	-	2.
Hypersthene	-	-	-	-	-
Xenocrysts:					
Plagioclase	0.7	1.5	8.7	-	-
Quartz	-	-	0.2	-	-
Biotite	-	-	-	-	-
Xenoliths:					
Rhyolite	-	-	-	-	4.0
Andesite	-	0.8	-	-	-
Vesicular (V)	V	-	V	V	V

1-2 High alumina basalt
3-4 Pyroxene andesite
5 Bytownite andesite
6 Sodic andesite
7-8 Ankaramite
9 Olivine eucrite
10 Bronzite eucrite
11 Hypersthene eucrite

TABLE 8 - MAFIC MINERAL CONTENT OF THE RHYOLITE TEPHRA

1. REREWHAKAAITU 'ASH'

Spec. No.	Hypersthene	Pale Hornblende	Green Hornblende	Biotite	Posn. in section
11060/1	r	-	c	d	(Base)
11060/3	c	-	c	c	↓
11060/5	c	-	c	c	↓
11060/7	c	P	r	d	(Top)
11152/1	d	-	r	r	(Base)
11152/2	d	-	r	r	↓
11152/3	d	P	r	r	(Top)
11051	c	-	c	p	(Base)
11052	c	-	c	p	↓
11053	c	-	r	d	↓
11054	c	-	c	c	(Top)
11164/1	d	-	r	r	(Base)

2. WAIOHAU 'ASH'

Spec. No.	Hypersthene	Pale Hornblende	Green Hornblende	Biotite	Posn. in section
11059/1	d	-	c	p	(Base)
11059/2	d	-	p	-	↓
11059/5	d	-	p	-	↓
11059/7	d*	-	p	-	↓
11059/9	d*	-	p	-	(Top)
11048/4	d	-	p	-	
11152/4	d	p	r	-	(Base)
11152/6	c	-	c$^+$	-	↓
11152/8	d	-	c$^+$	p	↓
11152/9	c	p	c$^+$	p	

Spec. No.	Hypersthene	Pale Hornblende	Green Hornblende	Biotite	Posn. in section
11152/10	d	-	r	-	↓
11152/11	d	-	-	-	
11152/12	d	-	-	-	(Nr. Top)
11152/13	d	-	p	p	?
11152/14	d	p	r	p	?
11152/15	d	-	p	-	?
11055	d	-	p	p	
11154/2	d	-	p	-	
11154/3	d	-	p	-	
11164/2	d	p	p	-	
11139	d	-	-	-	(Base)
11140	d	-	r	-	(Nr. Top)
11153/1	d	-	r	-	(Base)
11153/3	d	-	r	-	↓
11153/7	d	-	r	-	
11153/11	d	-	r	-	(Top)
11173	d	-	p	-	
11175	d	-	r	-	

3) KAHAROA 'ASH'

Spec.No.	Hypers-thene	Pale Hornblende	Green Hornblende	Biotite	Olivine	Augite	Posn.in section
11061/1	r	-	p	c	r	r	(Base)
11061/3	p	-	-	d	p	p	↓
11061/6	p	-	p	d	?p	p	(Top)
11142/6	r	p	p	d	-	p	
11043	p	-	p	d	-	p	
11132	r	p*	p	c	-	r	
11050	r	p	r	d	-	r	
11121	p	p	p	d	p	p	
11168/1	r	p*	p	d	-	r	
11168/2	r	-	p	d	-	p	
11167	p	p	p	d	-	-	

Key to Symbols:

d - dominant (> 50%)
c - common (25-50%)
r - rare (10-25%)
p - present (< 10%)
+ - brown hornblende present
* - augite present.

Localities:

11060	Type section - Democrat Road (N86/934823)
11152	Near head of large pumice wash (N77/964908)
11051-5	Head of small pumice wash (N77/936914)
11164	'Moat' between Tarawera and Rerewhakaaitu Domes (N77/949914)
11059	Type section - Democrat Road (N86/934824)
11048	Bretts Road (N86/946861)
11144	East of fissure (N77/994952)
11139-42	Gully S.E. of Wahanga (N77/985942)
11153	Track up mountain (N77/981906)
11173-5	West side Rotomahana Dome (N86/955899)
11061	Type section - Gavin Road (N86/993831)
11043	South side Ruawahia coulée (N77/969927)
11132	East shore Lake Rotomahana (N77/930903)
11050	South end pumice washes (N86/963887)
11121	On Northern Lava Flow (N77/957973)
11168	Top of Tikitere Hill (N76/829134)
11167	North end gully between Ruawahia and Wahanga Domes (N77/965950)

APPENDIX 4

CHEMICAL ANALYSES OF ROCKS IN TARAWERA VOLCANIC COMPLEX

TABLE 15 - CHEMICAL ANALYSES OF THE RHYOLITE DOMES (and averages for comparison)

	1	2	3	4	5	A	B	C	D	E
SiO_2	75.03	76.05	72.36	72.80	74.76	74.20	74.95	74.05	74.22	73.66
TiO_2	0.17	0.23	0.35	0.31	0.21	0.25	0.25	0.32	0.28	0.22
Al_2O_3	12.50	12.26	13.68	13.02	12.10	12.71	13.07	12.70	13.27	13.45
Fe_2O_3	0.47	0.48	1.03	0.94	0.23	0.63	0.75	0.58	0.88	1.25
FeO	0.83	0.75	0.87	0.77	0.69	0.78	0.88	0.77	0.92	0.75
MnO	0.10	0.05	0.09	0.10	0.09	0.08	0.06	0.06	0.05	0.03
MgO	0.40	0.29	0.72	0.23	0.22	0.37	0.25	0.30	0.28	0.32
CaO	1.38	1.31	2.32	1.74	0.76	1.50	1.45	1.29	1.59	1.13
Na_2O	4.12	4.40	4.40	4.22	4.12	4.25	4.51	4.16	4.24	2.99
K_2O	2.82	2.84	2.36	3.00	3.57	2.92	3.04	2.97	3.18	5.35
H_2O+	0.68	0.23	0.37	1.50	2.13	0.98	0.81	1.47	0.80	0.78
H_2O-	0.12	0.07	0.09	0.08	0.13	0.10	0.17	0.27	0.23	-
P_2O_5	0.13	0.01	0.09	0.04	0.01	0.06	0.05	0.05	0.05	0.07
Li_2O	All < than 0.05									
NORMS										
Qz	36.74	36.54	31.98	32.70	31.50	33.89	33.56	34.90	33.45	33.2
Or	16.68	16.68	13.90	17.79	27.24	18.46	17.97	18.13	18.81	31.7
Ab	34.58	37.20	37.20	35.63	34.58	35.84	38.12	35.08	35.86	25.1
An	6.12	5.56	10.56	7.51	1.11	6.17	6.45	5.73	7.54	5.0
C	0.51	-	-	-	-	0.10	-	0.47	0.09	0.9
Hy	2.06	0.81	2.20	0.68	0.36	1.22	1.75	1.28	0.48	0.8
Di	-	0.70	-	0.91	2.32	0.32	0.30	0.16	-	-
Mt	0.70	0.70	1.39	1.39	0.23	0.88	1.25	0.85	1.27	1.9
Il	0.30	0.46	0.61	0.30	0.46	0.43	0.53	0.42	0.53	0.5
Ap	0.34	-	0.34	-	-	0.14	0.14	0.07	0.13	0.2

TABLE 16 - CHEMICAL ANALYSES OF THE RHYOLITIC TEPHRA (and their average)

	6	7	8	9	F
SiO_2	74.33	73.59	72.80	74.86	74.05
TiO_2	0.26	0.22	0.11	0.23	0.21
Al_2O_3	12.52	12.35	13.40	12.48	12.70
Fe_2O_3	0.41	0.49	0.57	0.65	0.58
FeO	0.59	0.70	1.00	0.74	0.77
MnO	0.02	0.04	0.04	0.07	0.04
MgO	0.25	0.17	0.37	0.18	0.30
CaO	0.82	0.96	1.42	1.09	1.29
Na_2O	3.92	4.04	4.06	4.22	4.16
K_2O	3.48	2.72	2.92	2.92	2.97
H_2O+	2.19	2.80	2.01	0.82	1.47
H_2O-	0.49	0.70	0.43	0.14	0.27
P_2O_5	-	0.03	0.01	0.03	0.02
Li_2O		All $<$ than 0.05			
NORMS					
Qz	36.24	37.26	33.78	36.30	35.90
Or	20.57	16.12	17.24	17.24	17.79
Ab	33.01	34.06	34.58	35.63	34.32
An	3.89	4.73	6.95	5.56	5.28
C	0.92	1.12	0.92	0.41	0.84
Hy	0.80	0.73	0.80	1.03	1.34
Di	-	-	-	-	-
Mt	0.70	0.70	0.93	0.93	0.82
Il	0.54	0.46	0.15	0.46	0.40
Ap	-	-	-	-	-

TABLE 17 - CHEMICAL ANALYSES OF THE COGNATE XENOLITHS

	10	11	11a
SiO_2	62.74	68.8	
TiO_2	0.84	0.42	
Al_2O_3	16.21	15.2	
Fe_2O_3	1.89	1.3	
FeO	2.38	2.45	
MnO	0.12	0.06	
MgO	1.77	1.3	
CaO	5.44	4.5	1.3
Na_2O	4.78	3.9	4.6
K_2O	1.42	1.45	2.7
H_2O+	1.28	0.45	
H_2O-	0.18	0.15	
P_2O_5	0.16	0.08	
Li_2O	< 0.05		

NORMS

Qz	16.44	27.06
Or	8.34	8.90
Ab	40.35	33.01
An	18.63	19.46
Hy	3.02	5.28
Di	6.54	1.61
Mt	2.78	1.86
Il	1.52	0.76
Ap	0.34	0.34

TABLE 18 - CHEMICAL ANALYSIS OF THE PYROXENE ANDESITE (and comparison with an average andesite)

	12	G
SiO_2	58.49	54.20
TiO_2	0.48	1.31
Al_2O_3	15.50	17.17
Fe_2O_3	1.97	3.48
FeO	4.67	5.49
MnO	0.11	0.15
MgO	5.43	4.36
CaO	8.30	7.92
Na_2O	2.84	3.67
K_2O	1.36	1.11
H_2O+	0.53	0.86
H_2O-	0.21	-
P_2O_5	0.15	0.28
Li_2O	$<$ 0.05	-
NORMS		
Qz	11.28	5.7
Or	8.34	6.7
Ab	24.10	30.9
An	25.30	27.2
Hy	13.76	12.0
Di	12.55	8.4
Mt	3.02	5.1
Il	0.91	2.4
Ap	0.34	0.7

TABLE 19 - CHEMICAL ANALYSES OF THE HIGH ALUMINA BASALT
(with others from the Taupo Volcanic Zone, and average analyses for comparison)

	13	14	H	I	J	K	L
SiO_2	51.24	51.16	51.46	49.52	49.1	51.33	50.19
TiO_2	0.77	0.80	0.81	1.15	1.40	1.10	0.75
Al_2O_3	17.28	17.12	17.07	17.32	17.0	18.04	17.58
Fe_2O_3	5.25	2.40	2.05	3.81	2.45	3.04	2.84
FeO	4.32	7.25	6.82	7.03	6.95	5.70	7.19
MnO	0.15	0.18	0.18	0.19	0.17	0.16	0.25
MgO	5.82	6.12	6.04	6.01	6.8	6.01	7.39
CaO	11.08	11.41	11.43	11.41	10.4	10.07	10.50
Na_2O	2.20	2.28	2.40	2.50	3.15	2.76	2.75
K_2O	0.60	0.54	0.64	0.33	0.40	0.82	0.40
H_2O+	0.16	0.27	0.56	0.25	0.72	0.45	-
H_2O-	0.12	0.15	0.17	0.26	0.34	-	-
P_2O_5	0.20	0.13	0.10	0.19	-	0.16	0.14
NORMS							
Qz	7.26	2.40				2.2	-
Or	3.34	2.78				5.0	2.22
Ab	18.34	19.39				23.6	23.58
An	35.86	35.03				33.9	34.47
Hy	10.28	17.20				14.7	15.54
Di	14.48	17.46				12.8	14.16
Fo	-	-				-	2.66
Fa	-	-				-	1.63
Mt	7.66	3.48				4.9	4.18
Il	1.52	1.52				2.1	1.52
Ap	0.34	0.34				0.3	0.34

TABLE 20 - CHEMICAL ANALYSES OF GLASSES FROM RHYOLITE DOMES AND TEPHRA

	1G	2G	3G	4G	5G	6G	7G	8G
SiO_2	75.13	75.88	75.82	73.99	74.66			
FeO	0.61	0.35	0.27	0.61	0.56			
Fe_2O_3	0.07	0.15	0.03	0.55	0.19			
MgO	0.14	0.16	0.11	0.14	0.11			
Na_2O	4.4	3.76	4.16	3.76	3.82	4.10	3.90	3.84
K_2O	4.24	4.80	2.42	4.52	5.04	4.12	3.60	4.00
CaO	1.02	1.68	2.07	1.48	0.75	0.82	1.08	1.54
Or	37.6	41.3	24.1	40.6	45.2	39.0	35.4	37.2
Ab	55.0	46.3	58.5	48.2	49.1	54.8	55.3	50.7
An	7.4	12.4	17.4	11.2	5.7	6.2	9.3	12.1
Or	27.2	30.2	16.6	29.8	32.0			
Ab	40.1	33.8	40.3	35.4	34.5			
Q	32.7	36.0	43.1	34.8	33.5			

TABLE 21 - CO-ORDINATES IN THE SYSTEMS Or - Ab - An AND Ab - Or - Q - (H_2O) FROM THE TARAWERA VOLCANIC COMPLEX

(Calculated to 100%)

	Or	Ab	An	Ab	Or	Q
1.	29.1	60.2	10.7	39.3	19.0	41.7
2.	28.0	62.6	9.4	41.2	18.5	40.3
3.	22.6	60.3	17.1	44.8	16.7	38.5
4.	29.2	58.5	12.3	41.4	20.6	38.0
5.	43.2	55.0	1.8	37.0	29.3	33.7
6.	35.7	57.5	6.8	36.7	22.9	40.4
7.	29.4	62.0	8.6	39.0	18.4	42.6
8.	29.4	58.8	11.8	41.2	19.8	39.0
9.	29.3	60.3	9.4	40.0	19.3	40.7
10.	12.4	59.9	27.7	61.9	12.8	25.3
11.	14.5	53.8	31.7	47.7	12.9	39.4
11A.	21.2	38.9	9.0	-	-	-
12.	14.4	41.8	43.8	-	-	-
13.	5.8	31.9	62.3	-	-	-
14.	4.9	33.9	61.2	-	-	-

TABLE 22 - A-F-M AND VON WOLFF (L-M-Q) CO-ORDINATES FROM THE TARAWERA VOLCANIC COMPLEX

(Calculated to 100%)

	A	F	M	L	M	Q
1.	81.3	14.0	4.7	57.06	3.04	39.90
2.	82.7	14.0	3.3	57.80	2.48	39.72
3.	72.0	20.3	7.7	60.62	4.46	34.92
4.	78.8	18.7	2.5	60.60	2.98	36.42
5.	87.1	10.4	2.5	61.74	3.52	34.54
6.	85.5	11.6	2.9	57.75	1.86	40.36
7.	83.2	14.7	2.1	56.22	1.88	41.90
8.	78.3	17.6	4.1	59.14	3.08	37.78
9.	82.0	15.9	2.1	57.94	2.12	39.94
10.	50.7	34.8	14.5	67.20	14.40	18.40
11.						
12.	25.8	40.8	33.4	54.70	33.22	12.08
13.	15.4	52.6	32.0	55.75	36.32	7.93
14.	15.2	52.0	32.8	54.20	43.22	2.65

KEY TO ANALYSES IN TABLES 15-22 AND FIGURES 68-72, 82, 84

No.	Spec. No.	Location	Reference
1.	11038	Ruawahia Dome, Tarawera	Unpublished
2.	11137	Plateau Dome, "	"
3.	11097	Western Dome, "	"
4.	11129	Rotomahana Dome, "	"
5.	11122	Green Lake Plug, "	"
6.	11061/7	Kaharoa 'Ash', Gavin Road, Rerewhakaaitu	"
7.	11170	Waiohau 'Ash', Democrat Road, Rerewhakaaitu	"
8.	11171	Rerewhakaaitu 'Ash', Democrat Road, Rerewhakaaitu	"
9.	11155/4	Waiohau 'Ash' Nuee deposit, N77/981906	"
10.	11108	Hornblende-quartz-dacite. Xenolith in Kaharoa Tephra, N77/964913	"
11.	10918	Granodiorite. Xenolith in Kaharoa Tephra, N77/964913	Ewart and Cole (in press)
11A.	P29565	"	"
12.	11079	Pyroxene andesite. Xenolith in Kaharoa Tephra N77/964913	Unpublished
13.	11072	High alumina basalt. Fissure to the S.W. of Ruawahia Trig.	"
14.	-	Basalt scoria, Tarawera	Grange, 1937 p.79
A.	-	Average Tarawera dome (average of 5 analyses)	Unpublished
B.	-	Average Young Rhyolite Dome. (average 11 analyses)	Ewart, 1965, p.14.

No.	Spec. No.	Location	Reference
C.	-	Average Tarawera rhyolite (dome + ash) (average of 9 analyses)	Unpublished
D.	-	Average Rhyolite of Taupo Volcanic Zone (average of 25 analyses)	Ewart, 1965 p. 14.
E.	-	Average Calc-alkaline rhyolite	Nockolds, 1954 p.1012.
F.	-	Average Tarawera Tephra (average of 4 analyses)	Unpublished
G.	-	Average 'andesite'	Nockolds, 1954 p.1019
H.	-	Basalt scoria, Rotoatua	Steiner, 1958 p.330
I.	-	Basalt, K Trig	Grange, 1937 p.75
J.	-	Basalt, Orakeikorako	Lloyd, in press
K.	-	Average 'Central' type basalt	Nockolds, 1954 p.1021
L.	-	Average 'high alumina' basalt	Kuno, 1960 p.141.

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14, H, I	F.T. Seelye