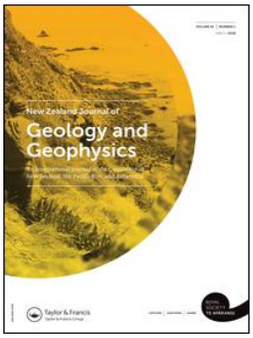

New Zealand Journal of Geology and Geophysics

ISSN: 0028-8306 (Print) 1175-8791 (Online) Journal homepage: https://www.tandfonline.com/loi/tnzg20

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To cite this article: Anthony J. Gow (1968) Petrographic and petrochemical studies of MT Egmont andesites, New Zealand Journal of Geology and Geophysics, 11:1, 166-190, DOI: 10.1080/00288306.1968.10423683

To link to this article: https://doi.org/10.1080/00288306.1968.10423683

Published online: 16 Jan 2012.

PETROGRAPHIC AND PETROCHEMICAL STUDIES OF MT EGMONT ANDESITES

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(Received for publication 16 August 1966)

ABSTRACT

Thin section studies of pebbles and boulders from the Rapanui Formation near Hawera have been made in an attempt to ascertain the principal trends of petrographic variation in Mt Egmont andesites. In addition to the commonly acknowledged hornblende andesites several other varieties of andesite identified included augite andesites completely devoid of hornblende and basaltic andesites containing up to 7% modal olivine. Hypersthene andesites of the type dominating volcanic rocks in the Tongariro National Park area are conspicuously absent. Petrographic and petrochemical relationships of andesites of Mt Egmont indicate that these rocks were formed either by contamination of basaltic magma with sialic materials or by fusion of crustal rocks of dioritic composition. The latter process of origin of andesitic magma is favoured.

INTRODUCTION

Andesitic volcanism in Taranaki during the Pleistocene was concentrated at three principal centres, Kaitake, Pouakai, and Mt Egmont. Kaitake and Pouakai are now both extinct but Mt Egmont, the highest (8,260 ft) and least dissected of the three volcanoes, is believed to have been active as recently as 400 years ago (Grant-Taylor, 1964). According to Grant-Taylor, Mt Egmont was either active before the final extinction of Pouakai or it grew to its present size in a relatively short time. In any event the bulk of its lavas are not exposed at the present day and if petrographic details of these older lavas are to be obtained at all then the only alternative is to study the detritus derived during the growth of Mt Egmont and now entombed, in part at least, in the Rapanui Formation near Hawera.

In the present study an attempt is made to trace out the major trends of petrographic variation in Mt Egmont andesites from an examination of thin sections of pebbles and boulders from various levels in the Rapanui Formation. To supplement these studies the writer has drawn upon the two principal sources of chemical analyses of Mt Egmont andesites in order to discuss the petrochemical relations of these rocks.

PREVIOUS STUDIES

Igneous rocks in Taranaki early claimed the attention of Hutton (1889), who described hornblende, augite, and olivine andesites from Mt Egmont.

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Marshall (1908) reporting on rocks from the same area referred to them as hornblende-augite andesites, and he further noted that hornblende may be completely resorbed in some andesites. Marshall identified olivine in some of the andesites from Mt Egmont and he also described augite-free hornblende andesites from both the Kaitake and Pouakai Ranges. Clarke (1912) recognised only hornblende and augite andesites in the agglomerates near New Plymouth, but he did note the occurrence of hypersthene in some specimens. Morgan and Gibson (1927) observed that augite was common to all andesites from Mt Egmont and that hornblende never exceeded augite and was absent from some andesites. They also described hornblende andesites with some biotite, and hornblende andesites without augite from the Pouakai Range. Morgan and Gibson also drew attention to the frequent occurrence of inclusions of other rocks in the Taranaki andesites, particularly other types of andesites and segregations of diorite and gabbro. Inclusions of sedimentary rocks were identified mainly as altered greywacke.

LOCATION OF SAMPLES

Samples used in the present study were collected from beach deposits, and from various conglomerates, gravels, and breccias in the Rapanui Formation near Hawera. For comparative purposes two small collections were made on Mt Egmont itself; one at Dawson Fall and the other from the bed of Ngatoro Stream near North Egmont House. Locations of samples are given in Fig. 1.

GENERAL PROPERTIES OF MT EGMONT ANDESITES

All rocks examined here can be classified as andesites, though several merit the title andesitic basalt. Texturally they range from black vesicular rocks to hard fine-grained holocrystalline andesites. Pumiceous andesites were also observed. Most andesites are extremely porphyritic and contain a high proportion of phenocrysts (*see* Table 1).

In most of the rocks phenocrysts of feldspar, hornblende, and augite can be readily observed with the naked eye. Phenocrysts often show strongly developed flow structure, and thin section studies also revealed marked alignment of feldspar microlites in the groundmasses of many andesites. Pilotaxitic or hyalopilitic textures are typical.

The following classification based on the relative abundance of ferromagnesian phenocrysts was adopted:

Augite andesite—devoid of hornblende;

Augite-hornblende andesite (i)—augite exceeds hornblende;

Augite-hornblende andesite (ii)—both ferromagnesian minerals are present in about equal amounts;

Augite-hornblende andesite (iii)—hornblende occurs in excess of augite;

Augite-olivine andesite—contains significant amounts of olivine.

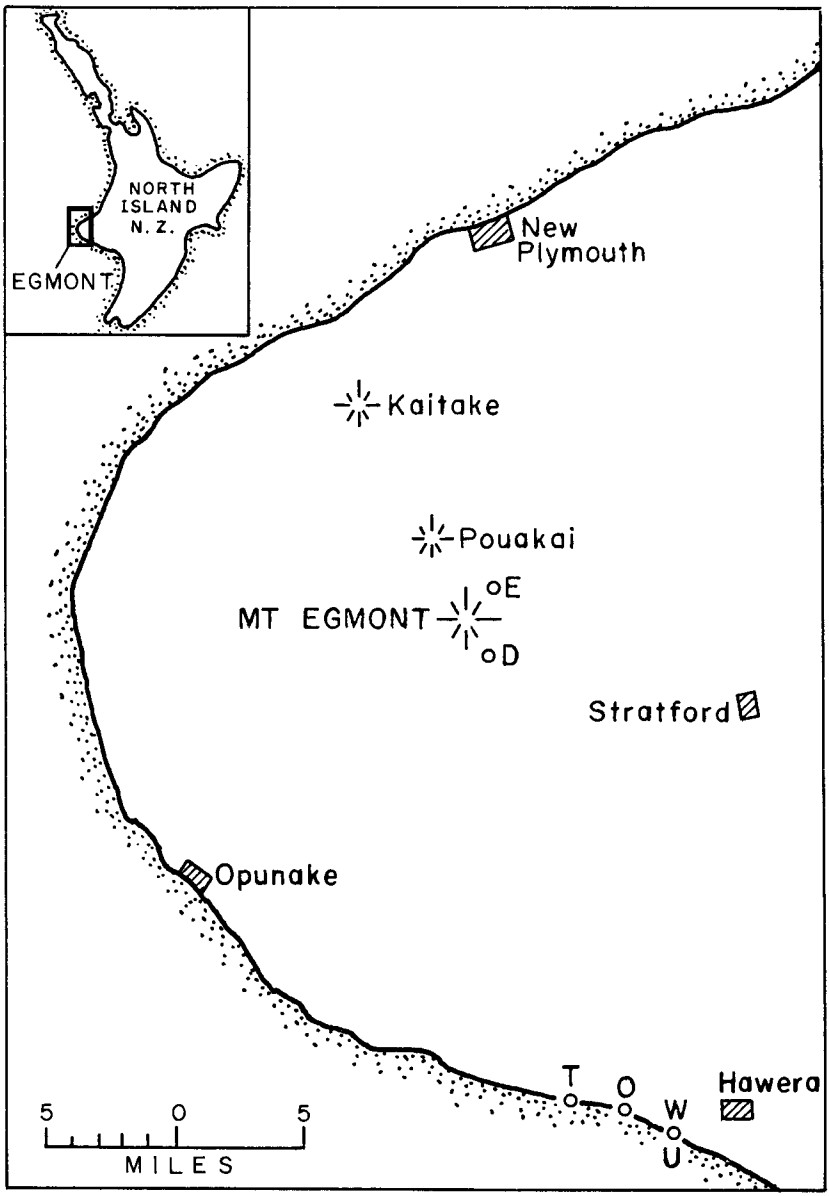

FIG. 1—Locations of andesite samples: W, Rapanui Formation, Waihi Beach; U, Basal conglomerate, Rapanui Marine Sand, Waihi Beach; O, Rapanui Formation, Ohawe Beach; T, Beach debris between Inaha and Kapuni Streams; D, Pebbles and boulders, Dawson Fall, Mt Egmont; E, Pebbles and boulders, Ngatoro Stream, Mt Egmont.

The various types of andesite more or less grade one into the other, but augite-hornblende andesites (i) are by far the most abundant. Augite andesites invariably contain small amounts of olivine (up to 1% in the mode) and microphenocrystic hypersthene is usually found in the same andesites too. Rare crystals of olivine and hypersthene were also observed in some augite hornblende andesites (i), but hypersthene andesites comparable with those of the National Park (O'Shea, 1959; Clark, 1960) were not observed. The rocks classified here as augite-olivine andesites contain up to 7% modal olivine, and they can all be reasonably referred to as basaltic andesites. The basaltic andesites of Mt Egmont possess typically andesitic groundmass textures, not the ophitic texture of basalts. Furthermore, the clinopyroxene of these basaltic andesites is diopsidic augite, not the common brown augite found in the true basalts.

Igneous inclusions were found in many pebbles and boulders. These include fragments of other types of andesites, basic hornfelses, clusters of hornblende crystals, and aggregates of plagioclase-augite and/or hornblende that texturally resemble diorites.

TABLE 1—Modal Analyses of Mt Egmont Andesites
(Volume Percentages)

	Augite-olivine Andesites				Augite Andesites			
	T7	T8	W15	U5	W17	U3	U10	D7
Plagioclase	34·3	23·1	32·0	29·5	39·7	34·0	29·1	23·9
Augite	28·6	21·4	21·1	18·8	11·0	15·2	15·0	7·7
Olivine	7·1	2·3	4·9	0·8				
Magnetite	2·9	2·0	1·8	4·3	2·0	3·8	4·9	1·1
Groundmass	27·1	51·2	40·2	46·6	47·3	47·0	51·0	67·3

	Augite-hornblende Andesites (ii)					Augite-hornblende Andesites (iii)
	W4	W5	D8	T4	U11	O5
Plagioclase	22·1	39·2	7·9	22·8	39·2	25·6
Augite	13·9	16·5	19·6	16·8	9·4	7·8
Hornblende	7·7	10·8	6·5	7·0	7·6	12·5
Magnetite	1·8	5·0	3·6	10·4	4·2	4·4
Groundmass	54·5	28·5	62·4	43·0	39·6	49·7

	Augite-hornblende Andesites (ii)				Diorite Inclusions	
	W2	W3	E1	O11	W1	W10
Plagioclase	43·3	37·7	31·7	28·1	50·0	59·3
Augite	18·2	12·8	10·3	9·9	17·2	13·3
Hornblende	19·4	13·6	9·7	10·2	27·0	21·2
Magnetite	4·4	4·8	3·6	4·4	5·8	6·2
Groundmass	14·7	31·1	44·7	47·4	—	—

PETROGRAPHIC METHODS

Approximately 60 thin sections were prepared for petrographic studies. From these a representative group of andesites was selected for modal analysis and results of these analyses are given in Table 1. Optic orientations of augite were measured on a four-axis universal stage using Turner's variation of the Nemoto method to determine $Z \wedge c$ and 2V for crystals twinned on (100). Extinction angles and 2V for hornblendes were also measured, as well as some 2V values for both hypersthene and olivine.

MINERALS PRESENT IN THE ANDESITES

Feldspar

Plagioclase feldspar is the dominant phenocryst in most andesites and it occurs in a variety of forms including prisms, tabular crystals, and laths. Symmetrically illuminated albite twins, and sections perpendicular to *a* were used to determine composition. Plagioclase of sodic labradorite composition (An_{55}) is typical but in zoned phenocrysts, abundant in most andesites, a range from basic labradorite (An_{65}) to acid andesine (An_{35}) was observed. The majority of zoned phenocrysts were of the normal type but reverse zoned phenocrysts were also observed. Inclusions are common and in zoned phenocrysts these inclusions, especially bubbles, tend to be concentrated in those zones nearest the core. The largest phenocryst may exceed 3–4 mm in length. In a typical augite-hornblende andesite (i) average-sized phenocrysts measure about 0·85 mm × 0·25 mm. Groundmass crystals and microlites rarely exceed 0·05 mm in length and are generally very much smaller. Measurements of extinction angles of microlites indicate compositions as sodic as acid andesine (An_{35}).

Diopsidic Augite

Diopsidic augite was found in all andesites and is usually the predominant ferromagnesian mineral. Crystals possess a distinctive green colour, and pale green-yellow pleochroism was detected in many. Idiomorphic outlines are typical, but glomeroporphyritic aggregates were observed, especially with plagioclase and magnetite. Augite crystals are frequently twinned on (100) and zoning was observed in some phenocrysts (*see* Figs. 2 and 3). Augite phenocrysts as large as 20 mm in length were observed in a single specimen of augite andesite, but in a typical augite-hornblende andesite (i) the phenocrysts average around 0·7 mm in diameter. Inclusions of magnetite are particularly common. No trace of exsolution lamellae was observed in any of the augite phenocrysts.

Hornblende

Two varieties of hornblende were recognised, common green-brown hornblende and red-brown hornblende (lamprobolite). Green-brown hornblende occurs much more abundantly than lamprobolite but it only rarely occurs in excess of augite. Large phenocrysts (up to 10 mm long) are not

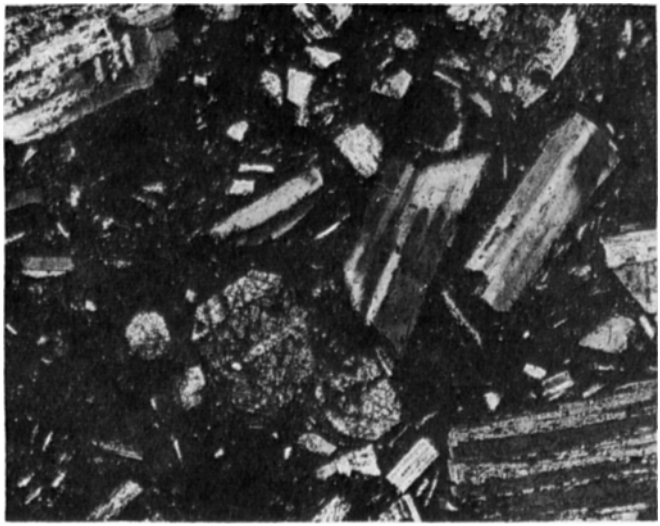

FIG. 2—Augite andesite from Rapanui Formation, Waihi Beach. Twinned augite and plagioclase. Crossed polars × 30. Section W17.

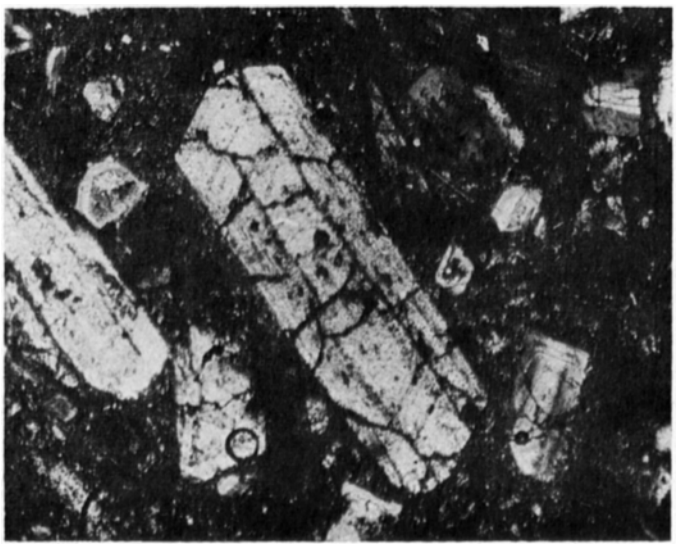

FIG. 3—Augite-hornblende andesite (i) from Rapanui Formation. Ohawe Beach. Zoned augite and moderately resorbed hornblende. Crossed polars × 40. Section O12A.

uncommon and prismatic and lozenge shaped crystals are typical. In contrast to augite fresh hornblende rarely contains inclusions of magnetite but resorption is notable, ranging from a mere peppering of crystal margins with magnetite to the development of thick rims of opacite. Unresorbed hornblende was found in a few andesites only. In others only skeletal outlines enclosing opaque material remain. The various stages in this resorption process are illustrated in Figs. 4 to 6. An example of uralitised augite is demonstrated in Fig. 7. Red-brown hornblende is usually found in the unresorbed state, but in some andesites cores of intensely opacitised green-brown hornblende have been oxidised to lamprobolite.

Olivine

Olivine occurs as rounded grains in the groundmass of all augite andesites and in some hornblende-bearing andesites (*see* Fig. 8). Euhedral phenocrysts up to 2·5 mm in length are restricted to the more basic andesites. Cores of olivine were observed in some augite phenocrysts and occasional inclusions of olivine were also noted in augite.

Hypersthene

Hypersthene occurs only rarely as phenocrysts, occasionally as cores in augite crystals, and more typically as prismatic euhedra in the groundmasses of augite andesites.

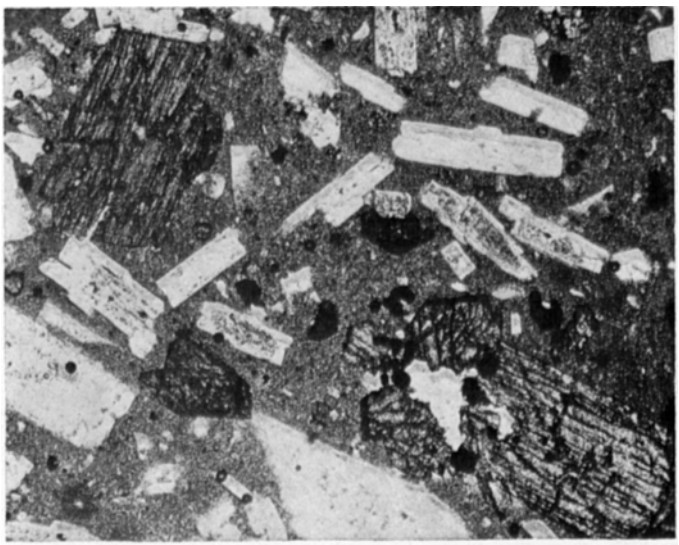

FIG. 4—Augite-hornblende andesite (ii) beach pebble, Ohawe Beach. Contains unresorbed green-brown hornblende. Ordinary light, × 35. Section O7.

FIG. 5—Augite-hornblende andesite (iii) from Rapanui Formation, Ohawe Beach. Features lightly to moderately resorbed hornblende. Crossed polars × 35. Section O12.

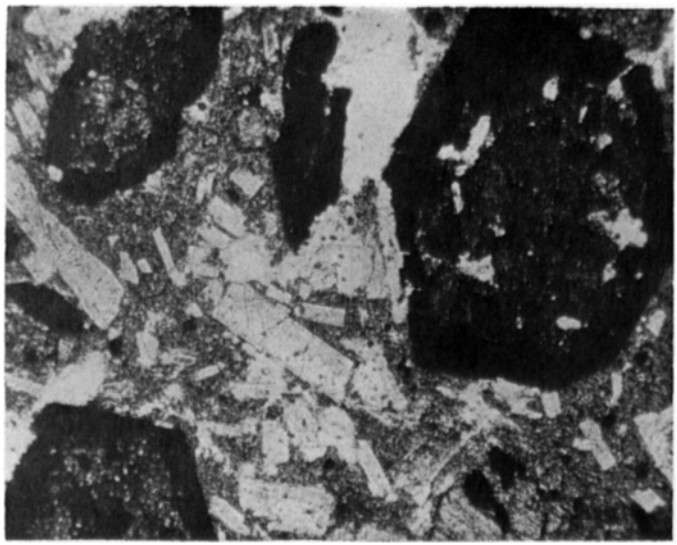

FIG. 6—Augite-hornblende andesite (iii) beach pebble from near mouth of Kapuni Stream. Features strongly resorbed hornblende. Ordinary light × 35. Section T4.

Magnetite

Titaniferous magnetite is fairly abundant in most andesites and commonly occurs as early-formed phenocrysts. Large grains are sometimes associated with augite and olivine in glomerophenocrysts. Inclusions in augite are particularly common and considerable amounts of magnetite have been liberated during resorption of hornblende. Most andesites contain abundant magnetite in the groundmass.

PETROGRAPHIC DESCRIPTIONS OF SOME MT EGMONT ANDESITES

The following descriptions are based upon an examination of a group of representative thin sections.

Slide W5—Augite-hornblende andesite (i)

A coarsely porphyritic andesite with minimal glassy groundmass, and containing approximately equal amounts of plagioclase and ferromagnesian minerals. Phenocrysts of labradorite and hornblende generally larger than augite phenocrysts. Augite occurs more abundantly than hornblende. The optical properties of hornblende were as follows: $Z \wedge c$ 45°; 2V + 58°.

Green-brown hornblendes feature moderately opacitised margins and possess the following optical properties: *X* yellow-green; *Y* green; *Z* brownish green; $Z \wedge c$ 22°; 2V − 81°.

The groundmass consists of devitrified glass in which plagioclase microlites, and small grains of augite, hornblende, and magnetite are embedded.

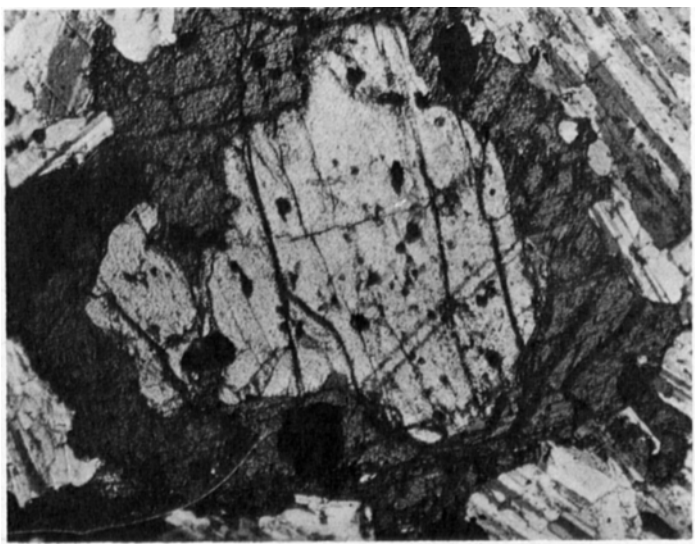

FIG. 7—Dioritic inclusion in andesite pebble from Rapanui Formation, Waihi Beach. Features uralitised augite. Crossed polars × 30. Section W1.

Slide W3—Augite-hornblende andesite (i)

A strongly porphyritic andesite containing abundant phenocrysts of labradorite and approximately equal amounts of augite and hornblende. The following optical properties were observed for augite: $Z \wedge c$ 45°; 2V + 60°.

Phenocrysts of green-brown hornblende feature embayed outlines but are not opacitised. Instead the corroded phenocrysts are rimmed with reaction products, principally augite and magnetite. In some hornblendes complete replacement has occurred. This type of reaction might be attributed to a small rise in the temperature of the magma, followed by relatively slow cooling. The wholly crystalline nature of the groundmass would also indicate that relatively slow cooling of the magma had occurred. Optical properties of hornblende are as follows: *X* yellow; *Y* green; *Z* greenish brown; $Z \wedge c$ 22°; 2V − 80°.

Small phenocrysts of magnetite are common. The groundmass contains abundant microlites of plagioclase interspersed with small crystals of augite, hornblende, and magnetite.

Slide W4—Augite-hornblende andesite (ii)

A dark vesicular rock, containing much smaller phenocrysts than the more compact non-vesicular andesites. Phenocrysts of labradorite are prismatic, but groundmass crystals are characteristically needle shaped. Diopsidic augite occurs in excess of hornblende, and is occasionally associated with the latter in multicrystalline clusters. Hornblende phenocrysts exhibit strong

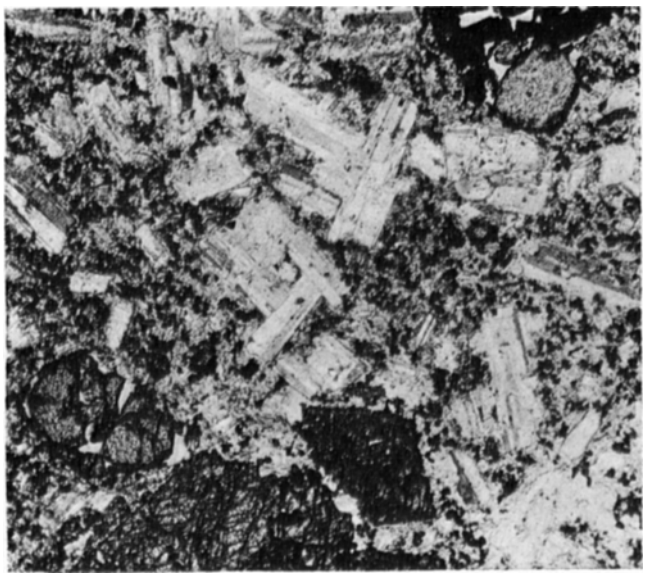

FIG. 8—Augite-olivine andesite from Rapanui Formation, Waihi Beach. Crossed polars × 35 Section W15.

body colour and yellow-brown pleochroism. Lack of resorption is a distinctive feature of these hornblendes. Optical properties of augite are as follows: $Z \wedge c$ 44°; 2V + 58°. Optical properties of hornblende are as follows: X yellow; Y brown; Z dark brown; $Z \wedge c$ 21°; 2V − 78°.

Magnetite occurs abundantly in the groundmass.

Slide W15—Augite-olivine andesite (Fig. 8).

This rock is characterised by abundant phenocrysts of labradorite and augite in a crystalline and predominantly feldspathic groundmass. Although phenocrysts of euhedral olivine were also observed, rounded and obviously corroded phenocrysts were more typical. Olivine occasionally occurs as inclusions in augite. The groundmass contained considerable quantities of magnetite.

Optical properties of augite were: $Z \wedge c$ 44°; 2V × 59°. Optical properties of olivine were: 2V − 88° to +86°.

Slide W17—Augite andesite (Fig. 2)

A hyalopilitic andesite in which labradorite is the predominant porphyritic constituent. Ferromagnesian minerals included numerous small phenocrysts of augite, frequently twinned, skeletal crystals of common green hornblende, and occasionaly microphenocrysts of hypersthene. The glassy partly devitrified groundmass contained numerous needles and microlites of feldspar, granular magnetite and augite, and some hypersthene.

Slide O5—Augite-hornblende andesite (iii)

Characterised by an abundance of phenocrysts in a cryptofelsic groundmass, and approaching a porphyrite in texture. Phenocrysts of labradorite predominate. Prismatic and tabulate forms are typical, and many phenocrysts have a fragmented appearance. This might indicate that the phenocrysts had been subjected to considerable stress before consolidation of the magma. Hornblende occurs more abundantly than augite, and is moderately resorbed. The following optical properties were observed for hornblende: absorption $X < Y < Z$; X green; Y dark green; Z dark brown; $Z \wedge c$ 21°; 2V − 82°.

Phenocrysts of augite are generally smaller than associated hornblende and are frequently twinned. Optical properties are: $Z \wedge c$ 44°; 2V + 60°.

Magetite occurs as phenocrysts and in granular clusters, but it is notably scarce in the groundmass. The latter consists largely of microlites of andesine and cryptofelsic material (not observably glassy), enclosing small crystals of augite and hornblende.

Slide O7—Augite-hornblende andesite (ii) (Fig. 4)

Characterised by the growth of only moderate sized phenocrysts in a predominantly glassy groundmass. Unresorbed hornblende and augite were present in approximately equal amounts. The groundmass contained minor quantities of plagioclase and magnetite only.

Slide U5—Augite-olivine andesite

In thin section this rock revealed numerous phenocrysts of plagioclase and augite in a crystalline groundmass of predominantly microlitic feldspar, prismoidal augite, olivine, magnetite, and hypersthene. Labradorite phenocrysts though more abundant than augite are generally smaller. Zoned phenocrysts with abundant inclusions occur commonly. Augite phenocrysts are often riddled with granules of magnetite. Optical properties are: $Z \wedge c$ 44°; 2V + 60°.

Occasional phenocrysts of olivine were also observed but they represented less than 1% of the modal composition of the rock.

Slide U11—Augite-hornblende andesite (ii)

A notably feldspathic andesite with marked flow structure. The groundmass contains abundant plagioclase microlites (andesine), small crystals of augite and hornblende, and granular magnetite. Zoned phenocrysts of plagioclase generally contain cores of basic labradorite and rims of acid andesine. Oscillatory zoning was observed in some phenocrysts. Pale green augite occurs slightly more abundantly than hornblende. Optical properties of augite are as follows: $Z \wedge c$ 44°; 2V + 59°.

Phenocrysts of hornblende exhibit a distinctive yellow-brown pleochroism and possess moderately "peppered" margins, with X yellow-green; Y green-brown; Z brown; $Z \wedge c$ 22°; 2V − 80°.

Olivines were occasionally found in glomeroporphyritic association with clinopyroxenes. Small grains of olivine and idiomorphic hypersthene were observed in the groundmass. Magnetite occurs abundantly in the groundmass.

Slides T7 and T8—Augite-olivine andesites

Both these andesites are very similar to specimen W15 in texture and mineralogical composition. However, T7 is appreciably richer in olivine (*see* Table 1).

Slide E1—Augite-hornblende andesite (ii)

A typical andesite of hyalopilitic texture containing very abundant phenocrysts of sodic labradorite, and approximately equal proportions of clinopyroxene and hornblende. Twinned augite occurs fairly commonly and yields the following optical data: $Z \wedge c$ 45°; 2V + 58°.

Phenocrysts of hornblende are only slightly resorbed. Optical properties are as follows: X yellow; Y brown; Z deep brown; absorption $X < Y < Z$; $Z \wedge c$ 21°.

Magnetite occurs abundantly in the groundmass, and occasionally as large irregular grains in glomerophenocrysts of augite and hornblende.

Slide D8—Augite-hornblende andesite (i)

In this rock phenocrysts of augite occur in excess of labradorite. However, andesine microlites are particularly abundant in the groundmass. The pyroxene is diopsidic augite with the following optical properties: $Z \wedge c$ 45°; 2V + 58°.

Olivine occurs sporadically in the groundmass and occasionally as phenocrysts. Inclusions of olivine were found near the margins of several of the larger augite phenocrysts. These inclusions were apparently absorbed at some late stage in the growth of the augite phenocrysts. Hornblende was highly resorbed. Only relict patches of deep green hornblende enclosed in opaque granular material remain. In addition to copious microlitic feldspar the groundmass contained widespread magnetite dust, but only small amounts of granular augite and olivine.

Slide D7—Augite andesite

A glassy andesite with relatively few phenocrysts. Phenocrysts of labradorite typically tabular; groundmass feldspars microlitic and needle shaped. This andesite contains fewer augite phenocrysts than other augite andesites (*see* Table 1 of modal analyses). The following optical properties were observed for several twinned augites: $Z \wedge c$ 44°; $2\bar{V} + 59°$.

The groundmass contained considerable glass in which were suspended needles and microlites of plagioclase feldspar, and a few small grains of augite. Olivine and hypersthene were not observed but opaque dust was widely distributed.

IGNEOUS INCLUSIONS

Pebbles and boulders of andesite near Hawera abound in igneous inclusions varying in size from a few millimetres to more than 10 cm across. The smallest inclusions of the order of 1–2 mm only, are generally composed of clusters of plagioclase, augite, and/or hornblende and magnetite, and these inclusions could properly be termed glomerophenocrysts. Among the larger intrusions several types varying both in mineralogy and texture were observed. These include fragments of other types of andesite that have undergone little or no alteration since their enclosure and clusters of lamprobolitic hornblende, individual crystals of which measure as much as 3–4 cm in length. Of somewhat greater interest, however, are (*a*) fragments of thermally metamorphosed andesite that now possess granoblastic textures typical of basic hornfelses, (*b*) coarse-grained holocrystalline inclusions of thoroughly dioritic aspect composed of plagioclase, augite, and/or hornblende and magnetite.

Among the rocks containing hornfelsic inclusions is a feldspar-rich augite andesite enclosing a fragment of thermally metamorphosed andesite composed of plagioclase, augite, and magnetite. Relict zoning and twinning were observed in a number of plagioclase crystals. All three major minerals are distributed fairly uniformly throughout the section. The inclusion also contains sporadic crystals of hypersthene. Augite crystals average 0·2 mm in diameter. Plagioclase and grains of magnetite average around 0·1 mm. This recrystallised andesite featuring a well formed granoblastic texture can probably best be described as a diopside-plagioclase-magnetite hornfels. In another example the host lava is a hyalopilitic augite andesite enclosing a fragment of basic hornfels that differ from other varieties of hornfels in that it is somewhat coarser grained, and also contains an

appreciable amount of hornblende. Crystals of plagioclase, augite, and hornblende average around 0·2 mm in length. The whole section is charged with grains of magnetite of average diameter of about 0·1 mm.

Dioritic inclusions composed of augite (invariably rimmed with, and occasionally entirely replaced by hornblende), plagioclase feldspar, and magnetite were found to have crystallised in two principal types of texture, hypidiomorphic granular and the poikilitic.

Slide W1

This is a coarse-grained diorite consisting of subhedral crystals of twinned plagioclase (basic andesine), diopsidic augite, and magnetite (Fig. 7). The augite is usually rimmed with hornblende and in some instances almost total replacement of augite by hornblende has occurred. Plagioclase crystals are remarkably clean and inclusion free. The optical properties of augite and hornblende are as follows: Augite, $Z \wedge c$ 45°; 2V + 60°; hornblende, X yellow-green; Y green; Z dark green; $Z \wedge c$ 19°.

Since the colour index of this inclusion exceeds 40% (*see* Table 1) it could be referred to as a meladiorite.

Slide T5

A poikilitic hornblende diorite completely devoid of augite. The plagioclase of basic labradorite composition encloses hornblende which is of the green-brown variety with an extinction angle of 21°.

PETROCHEMCAL RELATIONS OF MT EGMONT ANDESITES

None of the andesites used in the present study were analysed chemically. However, a number of andesites from Mt Egmont have already been analysed and for the purposes of this present discussion two major sources of analyses were consulted. Morgan and Gibson (1927) published 20 analyses of andesites from their Pouakai Series in Taranaki including a group of 16 that can be assigned to sources on Mt Egmont. However, a number of the specimens were incompletely analysed and only 10 of the original 16 analyses are reproduced here (Table 2.) Twelve additional analyses (unpublished) were obtained through the courtesy of Dr J. J. Reed of the New Zealand Geological Survey. These analyses (Table 3) were performed by Mr F. T. Seelye of the D.S.I.R., but the exact location on Mt Egmont of the specimens is not known nor are petrographic details or thin sections of these andesites available. The analyses of Morgan and Gibson are accompanied by very brief petrographic descriptions only.

A variation diagram of the major oxides versus silica is presented in Fig. 9 and the average compositions of andesites from Mt Egmont (Table 3) and the Tongariro subdivision (Clark, 1960) together with Nockolds' world average andesite (Nockolds, 1954) are given in Table 4.

The oxide plots show an appreciable spread of values though those of Table 3 depart somewhat less from smooth curves than the analyses in Table 2. According to Bowen (1928) only those rocks belonging to, or

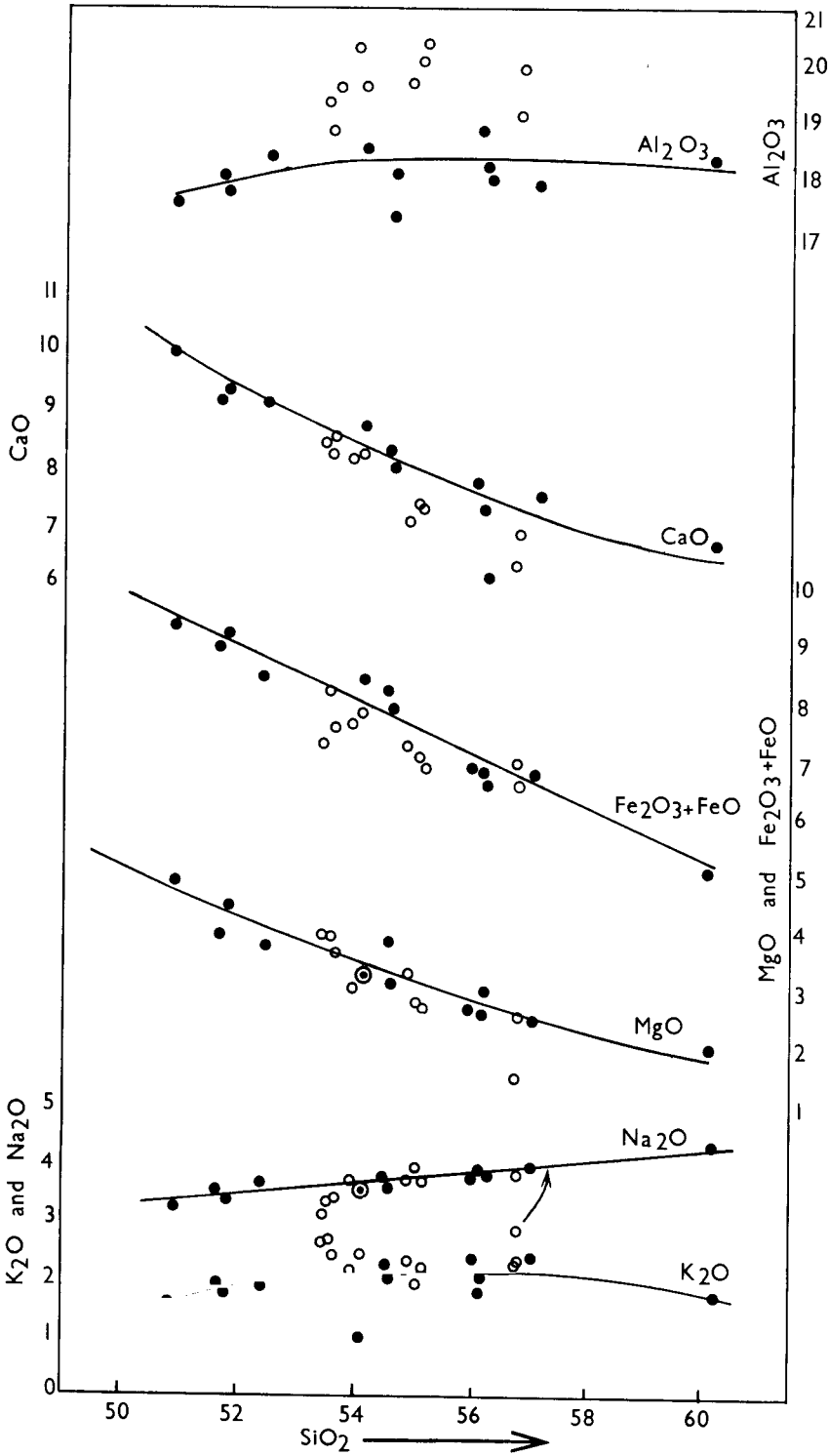

FIG. 9—Variation diagram of Mt Egmont andesites. All curves are drawn to fit data from Table 3 (solid circles). Table 2 analyses are plotted as open circles.

TABLE 2—Chemical Analyses (Main Oxides) of Mt Egmont Andesites (from Morgan and Gibson, 1927)

	F453	F454	F455	F456	F459	F460	F465	F467	F468	F483
SiO_2	56·85	54·95	53·62	54·15	53·50	53·70	53·98	55·22	55·12	56·82
Al_2O_3	19·91	19·74	18·80	19·59	19·35	19·54	20·26	20·36	20·02	19·08
Fe_2O_3	4·00	3·72	5·67	4·06	2·64	2·56	3·36	3·12	3·40	4·88
FeO	2·48	3·49	2·45	3·67	4·58	4·93	4·18	3·67	3·60	2·02
MgO	2·58	3·28	3·91	3·25	3·92	3·60	3·01	2·70	2·79	1·48
CaO	6·87	7·06	8·22	8·18	8·40	8·50	8·10	7·28	7·35	6·30
Na_2O	3·81	3·71	3·34	3·49	3·08	3·39	3·68	3·68	3·94	2·95
K_2O	2·36	2·32	2·70	2·41	2·59	2·39	2·14	2·20	1·92	2·26
TiO_2	0·83	0·95	1·04	1·10	1·00	0·94	0·97	0·89	0·95	0·80
MnO	0·18	0·18	0·21	0·18	0·14	0·14	0·12	0·15	0·15	0·16

TABLE 3—Unpublished Chemical Analyses (Main Oxides) of Mt Egmont Andesites (obtained through courtesy of New Zealand Geological Survey)

	1	2	3	4	5	6	7	8	9	10	11	12
SiO_2	57·10	56·09	52·48	54·70	51·84	51·75	56·31	54·63	60·16	54·17	50·94	56·25
Al_2O_3	17·91	18·77	18·38	18·12	17·79	18·00	18·02	17·33	18·30	18·41	17·59	18·22
Fe_2O_3	3·42	3·62	3·68	3·99	3·92	4·75	3·90	3·88	2·88	4·87	4·27	3·62
FeO	3·28	3·24	4·73	3·81	5·13	4·19	2·71	4·25	2·13	3·42	5·03	3·11
MgO	2·52	2·65	3·75	3·13	4·41	3·96	2·99	3·79	1·95	3·20	4·82	2·63
CaO	7·53	7·73	9·08	8·08	9·28	9·13	6·15	8·25	6·74	8·75	9·98	7·29
Na_2O	3·92	3·81	3·58	3·62	3·34	3·48	3·87	3·70	4·28	3·52	3·30	3·86
K_2O	2·40	2·26	1·81	2·02	1·82	1·88	2·02	2·19	1·78	1·00	1·57	1·78
TiO_2	0·81	0·84	1·01	0·95	1·10	0·54	0·70	1·00	0·56	0·85	1·07	0·75
MnO	0·15	0·17	0·16	0·18	0·19	0·18	0·15	0·17	0·14	0·16	0·15	0·16

closely approximating to, the liquid line of descent can be expected to yield smooth curves when the oxides are plotted against silica. Since this condition is best realised with glassy or aphanitic rocks it would be unreasonable to expect the Mt Egmont andesites with their typically coarsely porphyritic textures to display anything but a considerable scatter of points in variation diagrams. Nevertheless all lines drawn to obtain the best fit with data from Table 3, with the exception of those of total iron and soda, do show small but distinctive curvature, indicative perhaps of some degree of fractional crystallisation. The range of silica percentages is quite small—from 51% to 60%. The analyses indicate a trend towards basalts at the lower silica percentages and dacites at the upper end.

A noteworthy difference between analyses in Table 2 and Table 3 lies in the alumina percentage which is significantly higher in the andesites of Table 2. In three of these andesites alumina exceeds 20%, but in Table 3 not a single analysis contains more than 19% alumina. These latter analyses performed by Mr Seelye are probably much more reliable than the older analyses in Table 2 but even these more recent analyses indicate that Mt Egmont andesites contain appreciably more alumina than do most andesites, especially those from the Tongariro National Park area.

It is clear from Table 4 that in terms of their overall chemical composition the Mt Egmont andesites compare much more closely with Nockolds' world average rock than do the andesites of the Tongariro subdivision. The Mt Egmont rocks contain appreciably more alumina and potash than Nockolds' world average, but they are somewhat poorer in total iron and titania and they are markedly deficient in magnesia. The Tongariro andesites on the other hand contain even more magnesia than Nockolds' average andesite and they are somewhat more siliceous. However, they are notably deficient in alumina compared with the Mt Egmont andesites and they also contain appreciably less soda and potash. Furthermore the state of oxidation of iron is much greater in the Mt Egmont andesites than it is in the Tonga-

TABLE 4—Comparison of Chemical Compositions of Andesites

	A	B	C
SiO_2	54·70	54·20	57·33
Al_2O_3	18·07	17·17	15·55
Fe_2O_3	3·90	3·48	1·59
FeO	3·75	5·49	5·86
MgO	3·32	4·36	6·11
CaO	8·17	7·92	8·06
Na_2O	3·69	3·67	2·74
K_2O	1·88	1·11	1·19
TiO_2	0·85	1·31	0·68
MnO	0·16	0·15	0·15

(A) Average composition of Mt Egmont andesites (Table 3).

(B) World average andesite (Nockolds, 1954).

(C) Average composition of andesites of Tongariro subdivision (after Clark, 1960).

riro andesites. These dissimilarities of chemical composition probably reflect significant differences in the sources of magma of the Mt Egmont and Tongariro andesites.

The bulk chemical relationships of Mt Egmont andesites can be conveniently demonstrated in terms of the relevant L, M, and Q values of the von Wolff norms plotted in Figs. 10 and 11. Von Wolff norms are characterised by unusually high contents of orthoclase and quartz. In Table 3, for example, only one of the analyses was found to be undersaturated in quartz. Most contain several percent of quartz and one of the andesites (No. 9) contains 13·8% normative quartz. In several analysed andesites normative orthoclase exceeds 10% and on this basis alone some authorities, e.g., Williams, Turner, and Gilbert (1954) would be inclined to classify such rock as trachyandesites (latites). However, most other authorities would agree that latites should contain modal orthoclase at least in the form of sanidine microlites. In spite of the relatively high potash in some of the analysed andesites no such rocks were observed in the present study.

From Fig. 11 it can be seen that the andesites of Mt Egmont are all disposed well to the leucocratic side of the Tongariro trend with the curve linking Nockolds' world averages situated more or less in between. The Mt Egmont and Nockolds' curves run almost parallel to one another and if the Mt Egmont trend is extended downwards from just below the silica

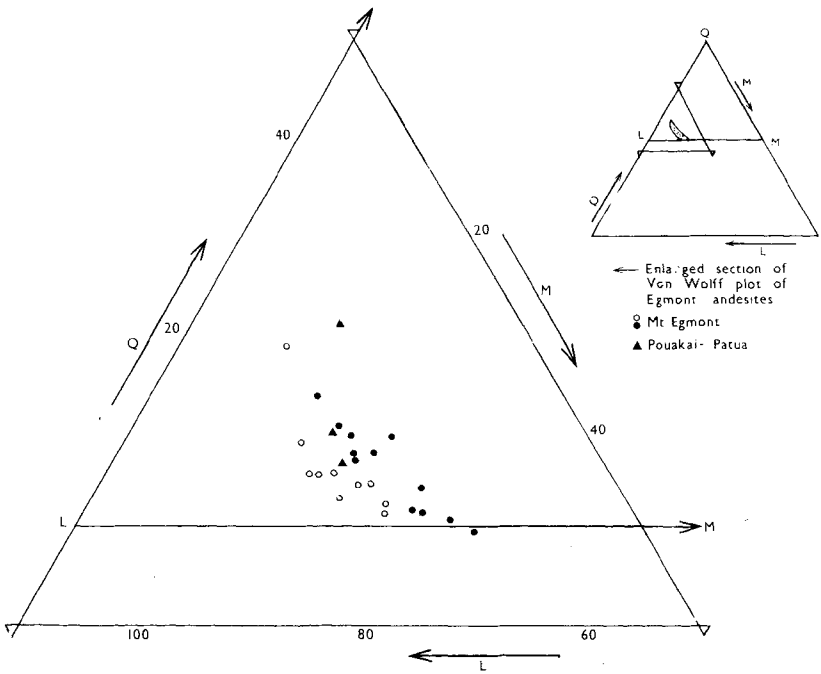

FIG. 10—Section of von Wolff plot of Egmont andesites. Solid circles are for analyses from Table 2 and the open circles are from data from Table 3. Wording accompanying last symbol should read: Pouakai–Kaitake.

saturation line it would pass very close to the point occupied by Nockolds' world average hornblende + augite diorite. From these relationships it would appear that the Mt Egmont volcanic rocks are appreciably more feldspathic than other andesites, and that they trend towards dacites rather than latites at the acid end and towards rocks of dioritic rather than basaltic composition at the basic end.

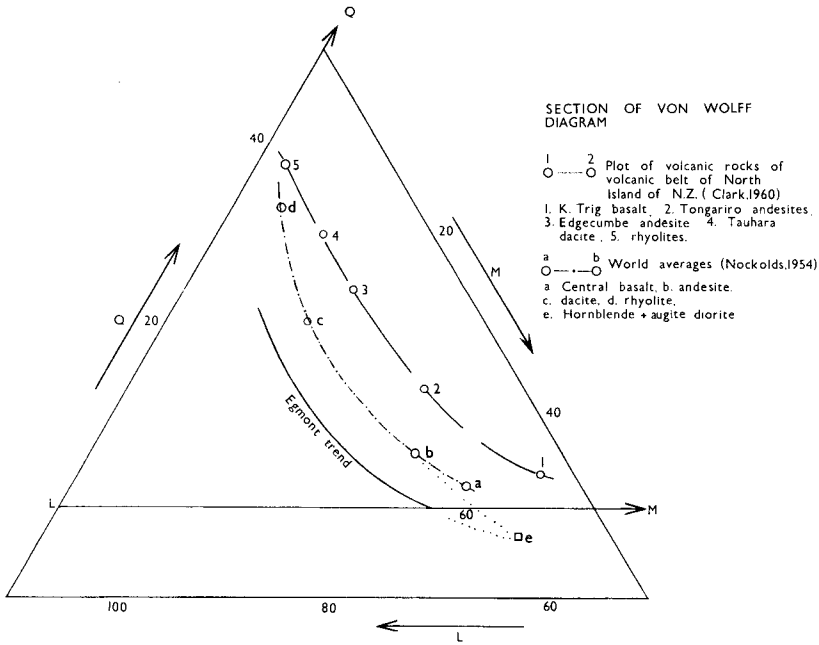

FIG. 11—Enlarged section of von Wolff diagram comparing the Egmont trend with those for the volcanic rocks of the Tongariro subdivision, North Island, New Zealand, and Nockolds' World Averages.

CRYSTALLISATION OF PRINCIPAL MINERALS

Feldspar

Plagioclases are the dominant constituents of virtually all andesites examined, both as phenocrysts and as microlites in the groundmass. The occurrence of labradorite rather than andesine can be ascribed most probably to the high lime and alumina contents of these andesites. Some andesites show a more or less gradual transition in size from phenocrysts to groundmass crystals, but in the vast majority of the rocks a gross change in the size of phenocrysts and microlites can readily be discerned in thin sections. This variation, of quite large order of magnitude in some andesites, would indicate that the magma had undergone considerable crystallisation immedi-

ately before its eruption. The growth of large phenocrysts in which zoning and resorption is abundantly developed, together with the generally coarsely porphyritc textures would also imply that the plagioclases of Mt Egmont andesites have passed through a protracted period of crystallisation during which changes in the composition, temperature, and pressure of the magma have all been effective.

Orthopyroxene

Hypersthene is found only in trifling amounts in the more basic andesites. Since it is generally confined to the groundmass most hypersthene would appear to have crystallised late.

Clinopyroxene

Diopsidic augite is the dominant mineral among ferromagnesian phenocrysts in Mt Egmont andesites. It is also an abundant constituent of the groundmass in the majority of andesites so that its history of crystallisation probably parallels that of plagioclase very closely. Phenocrysts are characteristically idiomorphic and since resorbed or corroded crystals are exceptionally rare it would appear that unlike plagioclase and hornblende, augite has remained stable over a considerable range of magmatic temperatures.

The diopsidic augite of most Mt Egmont andesites is noteworthy in that when crystals twinned on (100) are oriented on the universal stage both halves of the twin tend to extinguish simultaneously, i.e., the X vibration direction of one half of the twin must coincide with the Z vibration direction of the other. This in itself would indicate a highly symmetrical indicatrix in which 2V+ is close to 60° and $Z \wedge c$ is approximately 45°. Measurements on numerous twinned crystals from a large number of andesites show a range from 56° to 60° for 2V+ and 44° to 45° for $Z \wedge c$. These data are consistent with lime rich (diopsidic) augite, and the rather small variation in the optical properties probably reflects only minimal changes in the composition of augite from one andesite to another.

Olivine

Although phenocrysts of olivine are generally confined to the more basic andesites, groundmass crystals are of fairly widespread occurrence in other types of andesite. This would tend to indicate that olivine has formed at both early and late stages of the crystallisation of Mt Egmont andesites. Universal stage measurements of 2V of a number of olivine crystals from several andesites indicated a range of composition of from $Fo_{80}Fa_{20}$–$Fo_{65}Fa_{35}$. It would appear that olivine is a more widespread constituent of Mt Egmont andesites than was previously thought; it occurs much more abundantly than hypersthene.

Magnetite

Magnetite is of widespread occurrence in most andesites and it has obviously crystallised at all stages in the cooling history of the Mt Egmont

magmas. It occurs commonly as phenocrysts and as inclusions in augite, and it is also a major constituent of the groundmass of practically all andesites. Secondary magnetite also occurs as one of the principal by-products of the resorption of hornblende phenocrysts.

Amphiboles

These are a most important phenocrystic constituent of many andesites of Mt Egmont. Both green-brown hornblende and lamprobolite were readily identified. Widespread resorption of the amphiboles indicates that hornblende is much more sensitive to changes in the pressure and temperature of the magma than augite. All stages of resorption were observed but the great majority of andesites only contained hornblende in a particular state of resorption, and common green-brown hornblende was only occasionally found in the same andesite as lamprobolite.

Most petrologists are now agreed that amphiboles are the products of crystallisation of so-called "wet" magmas. For example, Larsen (1938) has deduced from very detailed studies of the Tertiary lavas of the San Juan Region, Colorado, that the abundance of mineralisers, i.e., volatiles in the magma, and not the composition of the magma, is the dominant factor in the crystallisation of hornblende. In a later discussion of the latite-andesite sequence of rocks from the same area Larsen and Cross (1956) concluded that in most if not all these lavas, including the pyroxene andesites, the greater part of the pyroxene was formed by the resorption of hornblende or of hornblende and biotite. In the Mt Egmont andesites, however, there is little if any petrographic evidence to show that augite was ever derived from pre-existing hornblende. If such had been the case then we could reasonably expect to find some hornblende andesite with little or no augite. No such rocks were observed. In addition, hornblende only occasionally occurs in excess of augite in Mt Egmont andesites, and furthermore some andesites are completely devoid of hornblende. In practically all andesites containing hornblende phenocrysts, crystals of hornblende as well as augite could be observed in the groundmass, indicating that in these lavas at least, augite and hornblende had crystallised simultaneously during the latter stages of consolidation of the magma.

If the formation of hornblende can be attributed to the attainment of some critical concentration of volatiles in the magma, then the subsequent resorption of hornblende can almost certainly be attributed to changes in the temperature and pressure of the magma. These changes are most likely to be caused by the escape of volatile constituents near the surface. The periodic eruption of volcanic ash from Mt Egmont, as evidenced by its widespread occurrence in the Rapanui Formation and younger sediments near Hawera, would attest to such explosive emissions of volatile rich magma. These ashes invariably contain appreciable quantities of hornblende, too.

Although lamprobolite is not usually associated with common hornblende there is no direct evidence in the andesites themselves that the two varieties of hornblende have crystallised independently of one another. According to Kozu, Yoshiki, and Kani (1927) common hornblende can be converted to lamprobolite by heating to 750°C. They attribute this change to the

expulsion of water and the oxidation of iron. In the case of lamprobolite in Mt Egmont andesites it would appear that though the rise in magmatic temperatures was great enough to convert common hornblende directly to lamprobolite it was of sufficiently short duration to prevent resorption. The observation that lamprobolite is usually restricted to those andesites with a glassy to cryptocrystalline groundmass would also tend to indicate that the magmas giving rise to these lavas had cooled rapidly after oxidation of the hornblende.

Apparently, resorption (opacitisation) occurs at temperatures somewhat lower than that needed to convert common hornblende to lamprobolite so that the extent of the resorption could be expected to depend on the actual duration of dis-equilibrium conditions in the magma. This, in fact, tends to be borne out by the groundmass textures associated with a particular state of resorption. The least resorbed hornblendes tend to be restricted to andesites with either a glassy or fine-grained groundmass, whereas the magmatically corroded and the more thoroughly opacitised hornblendes are invariably associated with holocrystalline (and presumably more slowly congealed) andesites. Only the occasional phenocryst of hornblende shows renewed growth upon a previously resorbed border, indicating that in most andesites resorption occurred late and continued to the end of consolidation of the lava.

The widespread occurrence of segregation of hornblende crystals can be ascribed most probably to the tapping of deep-seated magma in which early formed crystals of hornblende had settled. Possibly some of the phenocrystic hornblendes of the andesites themselves have been introduced in this way. Alternatively, mixing of an augite andesite magma with a hornblende andesite magma could conceivably account for the formation of an augite-hornblende andesite (*i*). The only problem with postulating an independent source of hornblende andesite magma is that andesites corresponding to such a magma have not been observed on Mt Egmont, i.e., hornblende andesites with little or no augite.

PETROGENESIS OF THE MT EGMONT ANDESITES

In attempting to ascertain the magmatic origins of the Mt Egmont andesites the following petrographic and petrochemical properties of these rocks must be taken into account. Chemically they can be classified as calc-alkalic aluminous andesites. Some analysed andesites approach dacites in composition but the latite trend is not apparent in spite of a fairly high potash content. The more basic andesites apear to trend towards diorites rather than basalts. The Mt Egmont andesites chemically resemble Nockolds' world average andesites much more closely than do the andesites of the Tongariro subdivision.

Petrographically the Mt Egmont andesites are characterised by strongly porphyritic textures. Crystallisation has been dominated by simultaneous precipitation of plagioclase and augite. Hornblende also occurs abundantly as phenocrysts. Olivine is fairly common in augite andesites, but hypersthene is a relatively rare constituent and as far as I am aware not a single specimen of hypersthene andesite has ever been reported from Mt Egmont.

Despite the relative abundance of olivine in some augite andesites, basalts as such have not been positively identified on Mt Egmont. This lack of basaltic lavas coupled also with the apparent absence of acid differentiates, i.e., rhyodacites and rhyolites, would tend to imply that the Mt Egmont andesites have not been derived directly from basaltic magma by simple crystal differentiation. This view is in accord with those of Tilley (1950) and Waters (1955), who both believe that it would be very difficult if not quite impossible to derive andesitic magma by simple crystal differentiation of basaltic magma. According to Dickinson (1962) in his discussion of the petrogenesis of the Jurassic andesites of the Pacific coast of North America this judgment should apply equally well to all basalts whether they be high alumina basalt, or tholeiitic, or alkaline basalts.

It would seem, then, that if basaltic magma is involved in the formation of andesitic magma beneath Mt Egmont then some contamination by sialic materials is also necessary. If tholeiitic basalt is parental to the Mt Egmont andesites, then in view of the relatively high alumina and potash contents of the latter it would be necessary to invoke some process of alumina-potash enrichment in the tholeiitic magma. This could be most conveniently achieved by incorporation of argillaceous rocks. However, assimilation of alumina should, according to Bowen (1922), cause the separation of hypersthene which would be entirely inconsistent with the petrographic characteristics of Mt Egmont andesites. They are practically devoid of phenocrystic hypersthene. Under strongly hydrous conditions, however, hornblende could have possibly crystallised in lieu of hypersthene. According to Waters (1955) there is some evidence that this has actually occurred in some of the lavas of the High Cascades of North America. However, there is little if any evidence that the bulk of the hornblende of the Mt Egmont andesites ever originated in this way.

A major problem here of course is to even attempt to use a subordinate rock type (in this case basalt) to explain the origin of rocks that are almost entirely andesitic. Derivation from basaltic magmas seems possible only if the original magma had undergone complete modification to andesitic magma as a result of contamination by sialic materials before it ascended into the magma chamber. In this way the basalt magma would be prevented from reaching the surface as basalt. Much the same restrictions apply to the mixing of basaltic and rhyolitic magmas as has been suggested by Clark (1960) as a possible mode of origin of andesitic magma of the Tongariro subdivision.

Alternatively, the andesites of Mt Egmont could well be derived from a primary andesitic magma formed by the fusion of a crustal layer of dioritic composition. That such a source of magma does conceivably exist seems to be indicated by the widespread occurrence in the andesites of dioritic inclusions. These inclusions are composed of unzoned plagioclase, augite, and/or hornblende, possess hypidiomorphic granular textures and appear to be thoroughly plutonic. They could of course have been derived from pockets of andesitic magma that had cooled slowly enough to form rocks closely simulating diorites in texture and mineralogic composition. Whether they represent fragments of undigested diorite or not, the relative abundance of such inclusions would indicate strongly the existence beneath Mt Egmont of appreciable quantities of raw andesitic magma.

Considering all the available information on the petrochemical and petrographic characteristics of Mt Egmont andesites I would favour fusion of dioritic rocks rather than contamination of basalt by sial as the most likely source of the Mt Egmont magma. According to Byers (1961) there is increasing evidence to show that the lavas of Mt Rainier of the High Cascades were formed by partial fusion of underlying dioritic rocks.

The advantage of a primary andesitic magma formed by fusion of dioritic rocks is that it represents a simple and essentially uniform source of magma. The widespread occurrence of early formed magnetite in most andesites would also tend to indicate that the magma was generated under conditions of high water pressure. This is also suggested by the co-existence of hornblende and augite in many andesites.

In most of the andesites examined in thin section the composition of plagioclase, augite, and hornblende appeared to remain fairly constant, indicating perhaps that variations in chemical analyses may be due largely to differences in the proportions of principal minerals, rather than to any significant changes in the composition of the feldspathic and ferromagnesian minerals themselves. Such a process would be best accomplished by crystallisation from a uniform magma in a chamber that is periodically replenished with new magma replacing partially crystallised magma that has moved towards the surface. The existence of several magma chambers would favour occasional mingling of magmas and perhaps permit explanation in part of some of the disequilibrium phenomena observed in the Mt Egmont andesites. Segregations of hornblende were probably formed as a result of fractionation, but the very slight curvature evident in the variation diagram and the von Wolff curve would tend to indicate that fractional crystallisation has played little part in the genesis of Mt Egmont andesites.

ACKNOWLEDGMENTS

I would like to thank Professor R. H. Clark and Professor J. Bradley of the Geology Department of Victoria University of Wellington for valuable help and criticism.

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