GEOLOGY AND PETROLOGY
OF RUAPEHU VOLCANO AND RELATED VENTS

by
William Robert Hackett

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ABSTRACT

Ruapehu Volcano is an active, multiple-vent, andesite composite volcano at the southern terminus of the Taupo Volcanic Zone, central North Island, New Zealand. The present-day volume of Ruapehu is estimated at 110 km^3 , and construction of the massif probably occurred during the past 0.5 m.y. Geologic mapping and stratigraphic studies have led to the recognition of four periods of cone construction, each occurring over 10^4 – 10^5 year time intervals. On the basis of lithologic/petrographic differences, and conspicuous unconformities which separate the deposits of each cone-building period, four new formations are defined, comprising the Ruapehu Group. Te Herenga Formation (new formation name) comprises the oldest deposits of Ruapehu (upper lavas ca. 0.23 Ma) and is exposed as planeze surfaces and arêtes on N and NW Ruapehu. The formation includes lava flows, tuff breccias, and small intrusive bodies surrounded by zones of hydrothermal alteration. There is little petrographic and compositional diversity; most lavas are porphyritic titanomagnetite-augite-hypersthene-plagioclase basic andesites. Wahianoe Formation (new formation name) is younger than Te Herenga Fm., but of unknown age. It is well exposed on SE Ruapehu, and comprises mostly lava flows and tuff breccias. The lavas comprise acid and basic andesites. Mangawhero Formation (new formation name) is well exposed everywhere except SE Ruapehu, and the upper lavas and pyroclastics (ca. 0.02 Ma) form the present high peaks and main cone of Ruapehu. The lavas are petrographically and geochemically diverse, ranging from basalt to dacite in bulk composition. Some of the lower lavas are olivine-bearing andesites of hybrid origin. Whakapapa Formation (new formation name; ca. 15,000 years to present) comprises conspicuously young lava flows, tuff breccias, airfall pyroclastics and minor pyroclastic flows of acid- and basic andesite. The deposits of these post-glacial summit and flank eruptions are subdivided into the Iwikau, Rangataua, Tama and Crater Lake Members. 'Related vents' produced Heuhungatahi Andesite Fm. ($> 0.5 \text{ Ma}$?), and Holocene deposits of basalt and basic andesite at isolated, monogenetic centres comprising Ohakune Andesite Fm., Pukeonake Andesite Fm., and Waimarino Basalt Fm. (new formation name).

Most Ruapehu lavas are medium-K acid and basic andesites (mean of 144 bulk rock analyses is 57.8 wt % SiO_2), but rare basalt and minor dacite are present. Nearly all lavas are porphyritic in plagioclase, augite and hypersthene $\pm$ olivine, with titanomagnetite microphenocrysts, and contain abundant metamorphic and igneous rock inclusions.

Petrography, mineral chemistry and bulk rock chemistry indicate fractional crystallization series from parental basalts (52–53 % SiO_2 , Q-normative, low-alumina) to medium-K basic- and acid andesites (58–59 % SiO_2). Early fractionating minerals are olivine and clinopyroxene with minor chrome spinel and plagioclase, followed by plagioclase, orthopyroxene, clinopyroxene and minor titanomagnetite in later stages of differentiation. Thus, basalt differentiation to produce andesites involves 'POAM-type' (Gill, 1981) fractional crystallization.

Three second-order differentiation processes operate concurrently with fractional crystallization: (1) Crystal accumulation involves addition of co-genetic plutonic rock fragments and crystals derived from them. These inclusions are common and few rocks represent liquid compositions. (2) Magma mixing involves mingling of magmas in repeatedly-occupied conduits. End members are as diverse as basalt and dacite, yielding petrographically and chemically distinctive high-Mg andesites of the upper cone complex and parasitic centres. (3) Selective crustal assimilation is suggested by partially fused metamorphic inclusions, positive correlation of $^{87}\text{Sr}/^{86}\text{Sr}$ with SiO_2 , and failure of simple 'POAM' fractionation to explain dacites (63-65 % SiO_2).

Petrogenesis of Ruapehu andesites takes place under open-system conditions, involving production of parental Q-normative basalts in the mantle wedge, concurrent fractional crystallization and crustal contamination, entrainment of co-genetic plutonic rocks, and mixing of magmas in common conduits.

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CONTENTS**page****Part I: GEOLOGY OF RUAPEHU VOLCANO AND RELATED VENTS**

1. GENERAL INTRODUCTION	1
1.1 Regional Setting	1
1.2 Previous Work	5
1.3 Nature and Scope of This Study	12
1.4 Nomenclature	12
2. GEOLOGY OF RUAPEHU MASSIF	27
2.1 Introduction	27
2.2 Use of "Formation" for Volcanic Rock Units	27
2.3 Use of "Facies" for Volcanic Rock Associations	30
2.4 Te Herenga Formation (new formation name)	33
2.5 Wahianoa Formation (new formation name)	54
2.6 Mangawhero Formation (new formation name)	82
2.7 Whakapapa Formation (new formation name)	98
2.8 The Origin of Lahar Mounds Deposits, NW Ruapehu	116
2.9 Glacial Features of Ruapehu Massif	120
2.10 Faulting	123
2.11 Implications for Volcanic Hazard Assessment at Ruapehu	125
3. GEOLOGY OF RELATED VENTS	129
3.1 Introduction	129
3.2 Geology of the Pukeonake Vents	129
3.3 Geology of Hauhungatahi	133
3.4 Geology of the Ohakune Vents (a published manuscript)	138
4. SUMMARY OF GEOLOGIC HISTORY	139
5. GEOLOGY OF WAIMARINO BASALT (new formation name)	143

PART II: PETROLOGY AND GEOCHEMISTRY

1. GENERAL INTRODUCTION	145
1.1 Previous Work	145
1.2 Nature and Scope of This Study	146
1.3 Results	148
2. PETROGRAPHY	149
2.1 Te Herenga Formation	149
2.2 Wahianoa Formation	152
2.3 Mangawhero Formation	156
2.4 Whakapapa Formation	163
2.5 Lavas From Sources Other Than Ruapehu	167
2.6 Igneous Nodules	173
2.7 Metamorphic Xenoliths	180
3. SURVEY OF MINERAL CHEMISTRY IN LAVAS	187
3.1 Olivine	187
3.2 Pyroxenes	190
3.3 Feldspars	192
3.4 Oxides	194
3.5 Amphibole	201
3.6 Apatite	201
3.7 Other Minerals	202
4. SUMMARY OF MINERALOGY AND PETROGRAPHY	202
5. IMPLICATIONS OF MINERAL ASSEMBLAGES AND COMPOSITIONS FOR PETROGENESIS	205

CONTENTS, continued**page**

6. BULK ROCK MAJOR AND TRACE ELEMENT COMPOSITION	207
6.1 Introduction	207
6.2 Classification	209
6.3 Major Elements	211
6.4 Trace Elements	217

PART III: PETROGENESIS

1. INTRODUCTION	222
1.1 General Statement	222
1.2 Nature of the North Island Plate Boundary	223
1.3 Previous Work on Petrogenesis of TVZ Eruptives	225
2. THE ROLE OF THE MANTLE WEDGE	232
2.1 Primitive Nature of Waimarino Basalt	233
2.2 Production of Quartz Normative Magmas in the Upper Mantle	236
2.3 Composition of Ruapehu Basalt and Relationship to Waimarino Basalt	239
2.4 Comparison of Waimarino Basalt with Other Basalt Magma Types	240
2.5 Ultramafic Nodules as Possible Samples of Upper Mantle	245
3. THE ROLE OF BASALT FRACTIONATION	247
3.1 Criteria for Choice of Samples Representing Liquid Compositions	247
3.2 Discussion of Least Squares Modelling	248
4. THE ROLE OF CRYSTAL ACCUMULATION	257
4.1 Introduction	257
4.2 Effects of Accumulation	258
4.3 Summary of Major Points Concerning the Role of Accumulation	263
5. THE ROLE OF MAGMA MIXING	264
5.1 Introduction	264
5.2 Mineralogical Effects of Magma Mixing	265
5.3 Discussion of Least Squares Modelling, and Geochemical Effects of Magma Mixing	267
6. THE ROLE AND NATURE OF THE CRUST	274
6.1 Introduction	274
6.2 Metamorphic Conditions in the Crust	275
6.3 Xenolith Bulk Compositions	278
6.4 Role of the Crust in Petrogenesis of Ruapehu Lavas	285
7. MAGMA EVOLUTION IN TIME AND SPACE: A RETURN TO THE STRATIGRAPHIC CONTEXT	294
8. EPILOGUE	298

REFERENCES CITED	303
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APPENDICES:

I. Stratigraphic Descriptions of Measured Sections	I-1
II. Bulk Rock Chemical Analyses	II-1
III. Mineral Analyses from Lavas and Pyroclastics	III-1
IV. Mineral Analyses from Igneous Nodules	IV-1
V. Mineral Analyses from Metamorphic Xenoliths	V-1
VI. Least Squares Mixing Calculations	VI-1

LIST OF FIGURES

Caption (many captions are abbreviated)	Page
Fig 1. Volcanic centres of the Taupo Volcanic Zone, central North Island	2
Fig 2. Andesite massifs and cones of the Tongariro Volcanic Centre	4
Fig 3. Grain size limits of pyroclastic fragments, after Fisher (1961)	15
Fig 4. Lithologic types, after Fisher (1966)	15
Fig 5. Summary diagram for Genetic Classification	17
Fig 6. Stratigraphic summary for Ruapehu massif	28
Fig 7. Generalized geologic map of Ruapehu and related vents	29
Fig 8. Scheme of volcanic facies for a composite volcano	32
Fig 9. Aerial view of the northwest slopes, Ruapehu	34
Fig 10. Aerial photograph of the northern slopes, showing megascopic features of the Te Herenga Formation exposed at upper Pinnacle Ridge	37
Fig 11. Outcrop photographs of Te Herenga Formation, central facies, upper Pinnacle Ridge	38
Fig 12. Proximal facies of Te Herenga Formation at Pinnacle Ridge	40
Fig 13. Te Herenga and Whakapapa Fms exposed in Whakapapanui Valley, northwest Ruapehu	41
Fig 14. Ruapehu Section 1. 145 m of Te Herenga Fm exposed in Whakapapanui Gorge, northwest Ruapehu	42
Fig 15. Ruapehu Section 2. 80 m of Te Herenga Fm exposed at Te Herenga Ridge, northwest Ruapehu	43
Fig 16. Ruapehu section 12. 73 m of Te Herenga and Mangawhero Fms exposed in Whakapapaiti Valley, west Ruapehu	44
Fig 17. Outcrop photograph of proximal facies lithologies of the Te Herenga Formation, upper Pinnacle Ridge	46
Fig 18. NRM vectors for two heterolithologic tuff breccias from the proximal facies of Te Herenga Formation	51
Fig 19. Colluvial deposits of Te Herenga Fm proximal facies, Pinnacle Ridge	52
Fig 20. North-trending dyke of Te Herenga Fm, Pinnacle Ridge	52
Fig 21. Geologic map of Pinnacle Ridge, northwest Ruapehu	53
Fig 22. Aerial photograph of southeastern slopes of Ruapehu. Wahianoa Fm is exposed in headwaters of Wahianoa and Whangaehu Rivers	55
Fig 23. Geology of the southwest face, Girdlestone Peak. The unconformable contact of Wahianoa and Mangawhero Formations is exposed here.	57
Fig 24. Central facies of Wahianoa Fm exposed in headwaters of Whangaehu River, southeastern summit region of Ruapehu	59
Fig 25. Wahianoa Fm exposed in Whangaehu Gorge, southeast Ruapehu	61
Fig 26. Wahianoa Fm exposed in Wahianoa Valley, southeast Ruapehu	62
Fig 27. Ruapehu Section 3. 223.5 m of Wahianoa Fm exposed in Whangaehu Gorge, southeast Ruapehu	63
Fig 28. Ruapehu Section 4. 13.5 m of Wahianoa Fm exposed in the Whangaehu Gorge, southeast Ruapehu	64
Fig 29. Ruapehu Section 5. 64.4 m of Wahianoa Fm exposed in Whangaehu Gorge, eastern Ruapehu	65
Fig 30. Ruapehu Section 8. 37.5 m of Wahianoa Fm exposed in an unnamed stream valley of north Ruapehu	66
Fig 31. Ruapehu Section 7. 26 m of Wahianoa Fm exposed at Girdlestone Peak	67
Fig 32. Ruapehu Section 6. 192 m of Wahianoa Fm exposed in Wahianoa Valley, southeast Ruapehu	68
Fig 33. Internal blocky jointing developed in Wahianoa Fm lava flow	69
Fig 34. Basal platy jointing and underlying autobreccia of Wahianoa Fm lava flow	69
Fig 35. Flow banding near base of Wahianoa Fm lava flow	69

LIST OF FIGURES, continued

Page

Fig 36. Transition from lava flow to autobreccia in Wahianoa Fm	71
Fig 37. Lenses of welded, incipient autobreccia in Wahianoa Fm lava flow	71
Fig 38. (Omitted)	
Fig 39. Unwelded bomb bed, 30 m interval of RS 3	72
Fig 40. Mantle- bedded airfall lapilli and ash, 20 m interval of RS 3	72
Fig 41. Framework- supported, reversely graded heterolithic tuff breccia; 10.9- 11.9 m interval of RS 4	75
Fig 42. Matrix- supported, reversely graded heterolithic tuff breccia; 22.6- 26.6 m interval of RS 3	75
Fig 43. Photograph of "Type C" TBh unit, near the 170- 180 m interval of RS 3	76
Fig 44. Breadcrusted bombs in "Type C" TBh unit	76
Fig 45. Internally shattered, breadcrusted bomb in "Type C" TBh unit	76
Fig 46. NRM vectors for "Type C" heterolithic tuff breccia	78
Fig 47. Cross- bedded sand filling interstices of coarse breccia; 19.2- 19.8 m interval of RS 3	81
Fig 48. Cross- bedded sand in coarse breccia, Wahianoa Fm	81
Fig 49. A. Aerial photograph of southwestern slopes of Ruapehu, showing tabular lava flows and autobreccias of Mangawhero Fm B. Northeastern slopes, showing main cone of Mangawhero and Whakapapa Fms	83
Fig 50. Ruapehu Section 9. 76 m of Mangawhero Fm exposed at Girdlestone Peak, southeastern summit region of Ruapehu	85
Fig 51. Ruapehu Section 10. 42.5 m of Mangawhero Fm exposed beneath Taurangi, southern summit region of Ruapehu	86
Fig 52. Ruapehu Section 11. 117 m of Mangawhero Fm exposed in Mangaturuturu River Valley of southwest Ruapehu	87
Fig 53. Ruapehu Section 13. 117 m of Mangawhero Fm exposed in an unnamed stream valley of northeast Ruapehu	88
Fig 54. Chaotic association of lava flows and autoclastic breccias, lower 16 m of RS 11	90
Fig 55. SG deposits of Mangawhero Fm; 41.5- 42.5 m interval of RS 10	92
Fig 56. SG deposits of Mangawhero Fm; 16- 20 m interval of RS 11	92
Fig 57. Bedded tuffs and lapilli tuffs of Mangawhero Fm; 14.8- 16.8 m and 41.5 m intervals of RS 10	93
Fig 58. Dykes of Mangawhero Fm at Girdlestone Peak	95
Fig 59. Glacial unconformities developed in Mangawhero Fm beneath Taurangi	96
Fig 60. Cathedral Rocks, western summit region of Ruapehu	97
Fig 61. Feeder dyke for northern flank eruptions of Mangawhero Fm	97
Fig 62. Aerial photograph of the southern slopes of Ruapehu. Vent region for the Rangataua Member is enclosed in box outline	100
Fig 63. Ruapehu Section 14. 12.5 m of Rangataua Member (Whakapapa Fm) exposed in a stream valley to the east of the vent region, south Ruapehu	100
Fig 64. Aerial photographs of the northern slopes. Block lava flows of Tama Mbr	103
Fig 65. Coarse pyroclastics at the vent region for lower lava field of Tama Mbr	103
Fig 66. Airfall ash and lapilli of the Tama Member, north Ruapehu	103
Fig 67. Oblique aerial photograph of the northwestern slopes of Ruapehu	104
Fig 68. Ruapehu Sections 15 A,B,C. Welded airfall tuff of Pinnacle Ridge Mbr, Whakapapa Fm	105
Fig 69. Welded airfall tuff of Pinnacle Ridge Mbr, at locality for RS 15B	106
Fig 70. Eutaxitic texture developed in welded airfall tuff, Pinnacle Ridge Mbr	106
Fig 71. Lithic blocks of underlying Te Herenga Fm in densely welded airfall tuff, Pinnacle Ridge Member of Whakapapa Fm	106
Fig 72. Internal stratification in welded airfall tuff, Pinnacle Ridge Member	107

LIST OF FIGURES, continued

Page

Fig 73. Thick, densely welded airfall tuff near the vent region for Pinnacle Ridge Mbr	107
Fig 74. Block lava flows and autoclastic breccias of Iwikau Member	111
Fig 75. Autobrecciation of block lava flows of Iwikau Mbr, exposed at Whakapapa skifield and along Bruce Road, northwest Ruapehu	112
Fig 76. Crater Lake basin, photographed from Ruapehu summit	113
Fig 77. Mantle-bedded pyroclastics and subordinate lava flows of Pyramid Peak	113
Fig 78. Map of 'lahar mounds' deposits, their inferred source regions, and probable paths of the debris flows	117
Fig 79. Photograph and drawing of lahar mound exposed along SH 48	119
Fig 80. Glacial moraines of Ruapehu massif	121
Fig 81. Aerial photographs of Ruapehu glacial features	122
Fig 82. Ground photographs of Whakapapanui Valley, northwest Ruapehu	122
Fig 83. Ground photographs of glacial features in upper Whakapapaiti Valley	122
Fig 84. Fault traces on Ruapehu massif	124
Fig 85. Aerial photograph of Whangaehu lahar fan, eastern ring plain of Ruapehu	127
Fig 86. Distribution of Pukeonake Andesite Formation	131
Fig 87. Aerial photograph of Hauhungatahi, a deeply eroded volcano to the west of Ruapehu	134
Fig 88. Geologic cross-section of Hauhungatahi	134
Fig 89. Pyroclastics beneath upper sequence of lava flows, Hauhungatahi	136
Fig 90. Schematic drawings of Ruapehu history, viewed from the west	141
Fig 91. Photomicrographs from Te Herenga Formation	150
Fig 92. Photomicrographs from Wahianoa Formation	154
Fig 93. Photomicrographs from Mangawhero Formation	158
Fig 94. Photomicrographs from Whakapapa Formation	164
Fig 95. Photomicrographs of non-Ruapehu lavas	170
Fig 96. Photomicrographs of igneous nodules	175
Fig 97. Photomicrographs of crustal xenoliths	184
Fig 98. Compositions of coexisting pyroxenes and olivines	188
Fig 99. Plagioclase compositions	193
Fig 100. Oxide mineral compositions from Waimarino Basalt	196
Fig 101. Oxide mineral compositions from basalt of Mangawhero Fm., Ruapehu	197
Fig 102. Oxide mineral compositions from two basic andesites	198
Fig 103. Composite diagram of all oxide mineral compositions	199
Fig 104. Composition diagram for Fe-Ti oxides	200
Fig 105. MgO and SiO ₂ histograms for 144 bulk rocks from Ruapehu and other vents	208
Fig 106. Silica-potash diagram for 144 bulk rocks	210
Fig 107. Silica variation diagrams for 144 bulk rocks	212
Fig 108. Trends of iron enrichment for bulk rocks	213
Fig 109. Rubidium variation diagrams for 144 bulk rocks	218
Fig 110. Tectonic elements of the Taupo-Hikurangi arc-trench system	224
Fig 111. Geophysical interpretation of the North Island plate boundary	226
Fig 112. Pyrolite melting grid	238
Fig 113. Major and trace element characteristics of 'boninite series' and IAT	242
Fig 114. MORB-normalized plot of Waimarino Basalt and IAT	243
Fig 115. Comparison of calculated and observed mineral proportions during fractional crystallization	249
Fig 116. Phenocryst mineral proportions for accumulative and non-accumulative lavas	261
Fig 117. Some effects of accumulation on bulk rock compositions	262
Fig 118. Mineral zonation patterns in two hybrid lavas	266
Fig 119. Variation diagrams comparing hybrid lavas with those of fractional crystallization series	273
Fig 120. Summary of metamorphic conditions inferred from xenolith mineralogy	276

LIST OF FIGURES , continuedPage

Fig 121. Major element compositional variation of xenoliths	279
Fig 122. Physical evidence for assimilation of crustal material	287
Fig 123. Strontium isotopic data from metamorphic xenoliths and lavas	289
Fig 124. K/Rb variation in lavas	291
Fig 125. Compositional diversity of lavas and pyroclastics	295

<u>LIST OF TABLES</u> (captions are abbreviated)	<u>Page</u>
Table 1. Modal data from Te Herenga Formation	151a
Table 2. Modal data from Wahianoa Formation	155a
Table 3. Modal data from Mangawhero Formation	162a
Table 4. Modal data from Whakapapa Formation	166a
Table 5. Modal data from non-Ruapehu lavas	172a
Table 6. Modal data from igneous nodules	179a
Table 7. Basalt analyses of the present study, with comparative data from other sources	234
Table 8. Summary of least-squares mixing calculations for fractional crystallization of Ruapehu basalt	251
Table 9. Summary of least-squares mixing calculations for fractional crystallization of Waimarino Basalt	254
Table 10. Least-squares mixing calculations for hybrid magmas	268
Table 11. Representative bulk rock analyses of hybrid lavas	272
Table 12. Representative bulk rock analyses of metamorphic xenoliths	280

PART I : GEOLOGY OF RUAPEHU VOLCANO AND RELATED VENTS

1. GENERAL INTRODUCTION

1.1 REGIONAL SETTING

The Taupo Volcanic Zone (Healy, 1962) is a region of Pliocene to Recent tectonic activity and volcanism which extends northeastward across the central portion of the North Island (Fig.1). The depression is a structural and topographic low which extends from Ruapehu to White Island, and may merge northwards with the submarine Havre Trough. The volcanic and structural features described by Healy (1962, 1964), Healy *et al.* (1964), Grindley (1960), Gregg (1960, 1961), and Modriniak and Studt (1959) lead to the conclusion that the Taupo Volcanic Zone (TVZ) is a volcano-tectonic depression, the central portion of which has been infilled to a depth of several kilometres by silicic ignimbrites, lavas and volcano-genic sediments.

Structural elements of the central North Island have been outlined and interpreted in the context of convergent tectonics (Cole and Lewis, 1981). The TVZ is interpreted by these authors as a NNE-trending, Plio-Pleistocene to Recent marginal basin. Recent andesitic to dacitic volcanism along the eastern side of the TVZ is interpreted as a volcanic arc which extends from the Tongariro Volcanic Centre in the south to White Island in the north. Most of these vents erupted olivine-bearing andesite and low-silica andesite, with minor low-alumina basalts; all of the olivine-bearing lavas are considered to be less than about 50,000 years old (Cole, 1979).

Four large rhyolitic volcanic centres -- Taupo, Maroa, Rotorua, and Okataina -- occupy the central part of the TVZ. Healy (1962) estimated 16,400 km³ of silicic lavas and ignimbrites from these centres were spread over an area exceeding 45,000 km², constructing extensive plateaux which extend beyond the depression itself. Minor amounts (2 km³; Cole, 1979) of high-alumina basalt occur at isolated localities

FIG. 1. Volcanic centres of the Taupo Volcanic Zone, central North Island, New Zealand (from: Cole, 1979).

where NNE-trending regional faults cross caldera structures (Cole, 1972). Intermediate volcanics occur at the northern and southern extremities of the TVZ and have an aggregate volume of 265 km^3 (Cole, 1979). At the southern end, five composite volcanoes -- Ruapehu, Ngauruhoe, Tongariro, Pihanga and Kakaramea-Tihia -- comprise the Tongariro Volcanic Centre (Fig. 2). Cole (1978) has identified two structural trends in the Tongariro Volcanic Centre: An older, northwest-trending line of vents defined by Pihanga, Kakaramea-Tihia, and the old Tongariro vents of Mathews (1967), and a NNE-trending lineament which parallels the present-day regional fabric and is defined by the younger multiple vents of Tongariro and Ruapehu. Many recently active NNE-trending normal faults traverse the Tongariro region, and vent locations of at least the last 30,000 years have been controlled by these deep-seated basement structures.

Ruapehu is the largest edifice of the Tongariro Volcanic Centre, and represents about 40 percent of the total volume of TVZ intermediate volcanics. The summit reaches 2797 metres and is the apex of the North Island. The massif has a basal diameter of about 19 km and covers some 285 km^2 . Numerous vents were active during its history, and constructed a multiple composite cone with a present-day volume of 110 km^3 (J.H. Latter, pers. comm. 1981) which is currently active. Ruapehu is thus of nearly identical size to Vesuvius, and about one fifth to one eighth the volume of such other large and well-known cones as Fujiyama, Etna, Rainier and Shasta. Below the 1400 metre level, it is surrounded by an extensive ring plain of laharic debris and airfall tephra. To the north, the volcanic deposits of Ruapehu merge with those of Tongariro and Ngauruhoe. To the south and west, they unconformably overlie block-faulted Tertiary marine sediments of the Wanganui Basin. To the east, the ring plain deposits abut Mesozoic metagreywacke of the Kaimanawa Range. It is deduced that Ruapehu was constructed on a dissected and faulted terrain of Tertiary marine sediments and underlying Mesozoic greywacke. Judging from distal exposures of the

FIG. 2. Andesite massifs and cones of the Tongariro Volcanic Centre (from: Cole, 1978). Lahar formations are those of Grindley (1960).

southern and western Ruapehu ring plain, the top of the marine sediments there occurs at about 1,000 metres above sea level. Seismic evidence (Latter, 1981) suggests that the top of the marine sequence beneath the centre of Ruapehu occurs approximately at sea level, which is indicative of significant basement downfaulting beneath the massif.

1.2 PREVIOUS WORK

Gregg (1960) gives a detailed outline of early observations in the Tongariro area, commencing with Bidwill's ascent of Ngauruhoe in 1839. Geologic observations were rudimentary until the late 1880's, when James Park (1887) climbed Ruapehu and described the summit region. In the next few decades, Ruapehu was climbed by numerous geologists; most described only the activity of the Crater Lake. Speight (1908) gave an account of the general geology of the Tongariro National Park, which had been established in 1894 through a gift of Maori land to the New Zealand Government. In a number of papers published between 1910 and 1926, James Park described supposed glacial features around Ruapehu. These were replied to by several authors, notably Grange (1931). After Grange's account, there was little doubt that Park's glacial features were in fact the products of lahars.

Grange and his co-workers are to be credited with the first mapping of the Tongariro region (Grange and Hurst, 1929; Grange and Williamson, 1930, 1933). The four 1:63,360 geological maps resulting from these surveys were later included in New Zealand Geological Survey Bulletin 40, The Geology of Tongariro Subdivision (Gregg, 1960). This was the first major compilation of field data for the area and included the age, lithology, faunas and distribution of the surrounding sedimentary deposits, as well as descriptions of the volcanoes themselves. The early surveys were necessarily of a reconnaissance nature, but the following contributions to the volcanic geology of Ruapehu and related vents were made:

"The western plateau, which occupies more than three-fourths of the district, is here formed of Tertiary beds lying horizontal or dipping gently westward and overlain with volcanic debris. From it rise the volcanic piles of Ruapehu, Ngauruhoe, and Tongariro and dominate the landscape."

(Grange and Williamson, 1933, p.18).

"Following a period of faulting and erosion in Pleistocene times, volcanic eruptions commenced and still continue. Ruapehu and Tongariro, more particularly the latter, have complex histories. "Ancient Ruapehu" was built up of grey andesites probably to a height a little greater than it is today. Its top down to about the 7,000 foot level was removed by collapse or by explosions, but later lava-flows have almost restored the mountain to its former shape and size. Three grey andesite ridges extend up to about the 7,000 foot level, the most prominent being that on which are situated the needle-like rocks called the Pinnacles. The latest lava-flows from Ruapehu, extending far down the valleys, are dark coloured and have a rough surface similar to the "aa" of Hawaii."

(Grange and Hurst, 1929, p.6).

"Some seven miles west-north-west from Ruapehu is Hauhungatahi, a small crescent shaped mesa, two miles and a half long and rather more than a mile wide, surmounted on its eastern edge by a small volcano, 4,983 feet high. ...

Farther north, 3½ miles from Ngauruhoe, Pukeonake, a small cone 4,018 feet high stands out from Tongariro.

Raetihi, a small basaltic cone, rises to 2,923 feet a few miles north of Ohakune."

(Grange and Williamson, 1933, p.20).

This early reconnaissance mapping is highly significant in several respects. Grange and his co-workers recognized that Ruapehu is a multiple cone with a complex history, as seen from their references to the grey andesites of "ancient

Ruapehu" and to the conspicuously young, dark lava flows of northwest Ruapehu. They mapped Hauhungatahi as an eroded volcano, and the parasitic centres at Pukeonake and Ohakune ("Raetihi") were recognized. They also identified "alluvium" and "conglomerate" deposits of several ages, formed during periods of degradation on Ruapehu.

Fleming and Steiner (1950) found no volcanogenic components in the lower Pliocene marine sediments beneath Ruapehu, and inferred that volcanism in the Taupo area must have commenced later than lower Pliocene time. Fleming (1953) identified hypersthene andesite pebbles in Nukumaruan (lower Pleistocene) conglomerates of the Wanganui Basin, which provides a minimum age of about 1.5 Ma for the beginning of volcanism in the Taupo district.

Grindley (1960) distinguished several lava flow and lahar formations at Ruapehu:

"The history of Ruapehu Andesite volcano is similar to Tongariro but less advanced. The volcano was built to maximum size with a well preserved ring plain (Waimarino Lahars) and is active. Younger flows from Ruapehu (ru_1 , ru_3) and from a parasitic cone on the north flank (ru_2) are mapped. Two lahar terraces in the Wangaehu Valley (Hautapu Lahars, Murimotu Lahars) are correlated with waxing of the Ruapehu ice-cap during Stadials of the last Glaciation. Recent lahars (fl) are mapped in the Wangaehu Valley and still occur as shown by the Tangiwai disaster of 1953."

With the benefit of vertical aerial photographs, Grindley built upon the earlier observations of Grange, et al. and constructed a geologic map of greater detail. He identified several periods of eruptive activity at Ruapehu and associated some of the laharic deposits with episodes of glaciation. The influence of NNE-trending normal faults on Tongariro vent locations was also identified.

In a later map, Grindley and Mathews (1965) listed two andesite formations on Ruapehu, the earlier from the time of "Last Glaciation" and the younger as "post-Glacial". In the accompanying text (Grindley, 1965), the multiple nature of Ruapehu is again referenced:

"Ruapehu is much younger than Tongariro, and in shape and general appearance resembles Mt Egmont in Taranaki, which is probably of comparable age. In distant views, Ruapehu shows faint indications of a two-stage development; the basal section up to 5,000 feet is more deeply dissected, slopes are smoother, and a pronounced break in slope suggests a discontinuity in growth. The youngest extensive flows are those in Whakapapanui Valley, extending from the summit to the Chateau."

To this point, a crude relative chronology had been constructed for Ruapehu massif and its ring plain deposits, largely based on relative degrees of dissection. Stipp (1968) made a significant contribution to Ruapehu geology by providing three whole rock K-Ar ages from the mountain. These showed that the oldest subaerially exposed lavas from Ruapehu (as defined in this study) were erupted about a quarter of a million years ago. Younger flows from the southern slopes of Ruapehu returned ages of about 36,000 and 24,000 years.

Hay (1967) mapped lahar deposits from Ruapehu, and Hauhungatahi Andesite to the west of the mountain.

Studies of physical volcanology at Ruapehu include Healy (1965), who made observations on the lahar mounds below the Chateau, and Parsons (1967, 1969). Parsons' (1967) abstract outlines geologic observations on Ruapehu:

"Ruapehu volcano is a compound, andesitic stratovolcano in the Taupo Volcanic Zone of the central North Island, New Zealand. The cone is built largely of thin, massive

andesite flows and is surrounded by a ring plain of laharic breccias and andesitic conglomerates. The last important cone building period occurred during late Pleistocene time, although a few post-glacial flows have been emplaced. Most flows are plagioclase or plagioclase-pyroxene andesites. Recent mapping indicates the presence of an older, partially buried cone on the north side of the volcano. This cone is composed largely of volcanic breccias, in contrast to the flows of the younger main cone. An approximate age of 225,000 years is indicated by potassium-argon (preliminary) dating. A small, complex intrusive plug of fine-grained diorite with an aureole of alteration is present on Pinnacle Ridge. The extrusives are pyroxene andesites similar to the younger flows. ..."

Parsons also left an undated, unpublished, pencilled map of the Pinnacle Ridge area in the files of the New Zealand Geological Survey, Rotorua (B.F. Houghton, pers. comm., 1981). He mapped a "Pinnacle Series" with dykes, an intrusive plug, altered and unaltered breccias, and moraines. A younger "Whakapapanui Series" was mapped to the west of Pinnacle Ridge, and a "post-Pinnacle, pre-Whakapapanui Series" on lower Pinnacle Ridge was mapped as ignimbrite.

Parsons' (1969) review of criteria for the recognition of volcanic breccias includes several illustrated examples from the Tongariro volcanoes. In Plate 1 and the accompanying text (p.271), he describes "eruption debris mixed with brecciated lava flow material" at an undefined locality on Ruapehu. The present writer's observations indicate that this is probably a Pinnacle Ridge deposit. Plate 2 (Parsons, 1969) includes a view of Pukeonake Cinder Cone deposits. Plate 3 and the discussion of page 286 to 287 include descriptions of the lahar mounds deposits on the northern slopes of Ruapehu below the Chateau.

Topping and his co-workers made several contributions to the Holocene tephra chronology and stratigraphy in the Tongariro region (Topping, 1973, 1974; Topping and Kohn, 1973). Topping (1974) has applied the tephra chronology to Ruapehu and related vents; Pukeonake Scoria Cone, Hauhungatahi, and numerous small craters in the vicinity of Ohakune were all shown to have been active prior to 20,000 years ago. The geology of Pukeonake tephra and lava flows was discussed in detail by Topping (1974). Most tephra erupted from Ruapehu between about 10,000 to 14,000 years ago were strongly wind-controlled and were deposited to the east or, less frequently, to the north. These Ruapehu tephra comprise most of Topping's (1973) Okupata Tephra Formation, which has a volume exceeding 0.2 km^3 . He considered the youthful lava fields above the Chateau and on the lower northern flank of Ruapehu to have been erupted between 5,000 and 10,000 years ago, on the basis of their tephra cover. Relatively little tephra were being emitted from Ruapehu between 2,500 and 10,000 years ago. Tephra erupted since 2,500 years ago were probably from the currently-active Crater Lake vent, with most of the activity from this vent having occurred after the Taupo eruption of 1819 years ago. The post-Taupo Ngauruhoe Tephra Formation (Topping, 1973) has a total volume of 1.3 km^3 and its major source was Ruapehu.

Cole and Nairn (1975) outlined the form, structure and geological history of Ruapehu, and addressed the origin of Ruapehu's summit topography:

"The present authors can see no evidence for caldera collapse, and consider that the large number of lahars originating from Ruapehu more than account for material removed from the summit. It is thus considered that the (summit) craters largely represent explosive eruption vents which have been later modified by erosion."

(Cole and Nairn, 1975, p.100).

In summarizing previous geological work, it is clear that the multiple-vent composite nature of Ruapehu was recognized during the 1920's and 1930's by Grange and his co-workers. Although Grindley (1960) mapped post-Glacial flows on Ruapehu, he did not distinguish the older "grey andesite ridges" which had been noted earlier by Grange, et al. Yet during the mid-1960's, both Parsons (1967, and unpublished map in NZGS Rotorua files) and Stipp (1968) recognized the Pinnacle Ridge and Te Herenga Ridge deposits as segments of an older, deeply eroded Ruapehu cone. Stipp's (1968) contribution of nine K-Ar dates from Tongariro Volcanic Centre demonstrated that the oldest subaerially exposed lava flows were erupted about a quarter of a million years ago. Furthermore, the ages from "old Tongariro" and "Old Ruapehu" are nearly comparable within the limits of error. This, along with physiographic evidence, is at odds with Grindley's (1965) statement that Ruapehu is much younger than Tongariro. Both massifs probably commenced activity at about the same time, as judged from both radiometric dating and the comparable degree of dissection of the oldest deposits.

The time of inception of activity at Tongariro Volcanic Centre remains poorly defined. The oldest dated subaerially exposed lavas on the massifs are about a quarter of a million years old, but Fleming (1953) has reported hypersthene andesite pebbles of central North Island provenance in Nukumaruan (about 1.5 Ma) conglomerates of the Wanganui Basin, and Grindley (1960) reports that the oldest Tongariro flows are exposed in the channel of the Tongariro River. These flows have not yet been dated.

Topping's (1973, 1974) Holocene tephra chronology has contributed substantially to knowledge of the volumes and distribution of distal airfall tephra from Ruapehu, as well as enabling datation of some of the younger eruptives on the mountain.

Cole and Nairn's (1975) work was largely of a review nature, but an additional contribution was made by them in recognizing the origin of Ruapehu summit topography as the result of multiple explosive vents and subsequent erosion, a conclusion with which this writer agrees.

A synthesis of all previous work leads to the conclusion that no detailed geologic studies had been performed on Ruapehu prior to this writing, although general geologic relations had been ascertained.

1.3 NATURE AND SCOPE OF THIS STUDY

The primary goal of this section is documentation of the prehistoric geology at Ruapehu volcano and its parasitic vents. Although the cone is surrounded by an extensive ring plain of erosional debris, detailed study has been performed only on the massif - that portion of the cone which is approximately above the 1,000 metre level, which is well exposed, and largely free of bush. Between April 1979 and March 1982, the massif was mapped by ground traverse as to the distribution, relative chronology, structure, and lithology of volcanic deposits. Where significant vertical exposure was present, measured stratigraphic sections were obtained, and these provided a third dimension to complement the ground surveys.

Concurrently with the mapping and stratigraphic studies, specimens of lava flows, pyroclastics, and enclaves were collected for petrographic and chemical studies. These results are reported in later sections.

1.4 NOMENCLATURE

1.4.1 Stratigraphic Nomenclature

A detailed stratigraphy for Ruapehu and related vents is given below, with formal stratigraphic designations. Several terms are defined here, following usage in the 1962 edition of the AGI Dictionary of Geological Terms:

Facies. This term is used in both a petrographic and stratigraphic sense. Petrog.: "Part of a rock body as differentiated from other parts by appearance or composition; a type of rock distinguished from other more or less related types". Stratig.: "A lateral subdivision of a stratigraphic unit, as in lithofacies".

Formation. "The primary unit in lithostratigraphy consisting of a succession of strata useful for mapping or description. Most formations possess certain distinctive lithologic features that may indicate genetic relationships. Ordinarily, the upper and lower boundaries of a formation are determined lithologically, but they may be unconformities... The age or time value of a formation is not necessarily the same wherever it is recognized".

Group. "Lithostratigraphic unit consisting of two or more formations".

1.4.2 Lithologic Classification

The nomenclature used here is largely that of Wright, et al., 1980, who have proposed a dual classification:

"No unique classification for pyroclastic rocks can be made and at least two systems are required: (1) a genetic classification, to interpret the genesis of a deposit, and (2) a lithological classification which may be solely descriptive, but which also may be used to discriminate on a lithological basis the mechanisms which produced a particular pyroclastic deposit. ...

... Genetic classification schemes are presented for various types of fall, flow and surge deposits. A lithological classification is given based on grain size limits and distribution, constituent fragments, and degree and type of welding." (from the Abstract).

The grain size limits used here for pyroclastic fragments (Fig. 3) are those of Fisher (1961). Lithologic types (Fig. 4), based on grain size limits and distribution of

Grain size (mm)	Pyroclastic fragments	
256 64 2 1/16	coarse	blocks and bombs
	fine	
	lapilli	
	coarse	ash
	fine	

FIG. 3. Grain size limits of pyroclastic fragments, after Fisher (1961).

FIG. 4. Lithologic types, after Fisher (1966). Percentage boundaries for the mixtures are purposely omitted, to allow application in the absence of quantitative grain size data.

pyroclastic fragments, are those of Fisher (1966). The term tuff breccia is used following Wentworth and Williams (1932, p.46): "*volcanic breccias of pyroclastic origin with abundant tuff matrix*". In this writer's opinion, the general use of the term tuff for all consolidated deposits of pyroclastic origin (as used by Wright, et al., 1980), while it simplifies terminology, does not adequately convey grain size information. The term tuff breccia is retained here because it adequately describes the wide range of grain sizes which are present in many Ruapehu deposits.

A lithological classification will be used in this study, and when genetic interpretations are possible, these will be discussed separately from the lithological descriptions.

1.4.3 Genetic Classification

For the genetic classification of fragmental volcanic deposits, Fisher (1961, 1966) emphasizes the process of breaking, and secondly the size of the fragments:

"Genetic categories are autoclastic, pyroclastic, and epiclastic (to which hyaloclastic should be added), thereby placing the emphasis on the manner of fragmentation. It is important to distinguish between fragments that are produced instantly such as the pyroclasts, and those that are produced over a longer period of time by the weathering of volcanic rocks Pyroclastic deposits may be dispersed and deposited by streams, but such dispersal does not alter the fact that the fragments are pyroclastic in origin. Thus there may be "primary" (unreworked) as well as "secondary" (reworked) pyroclastic deposits."

(Fisher, 1966, p.296).

It is emphasized that, on the massif, true epiclastic deposits (i.e., fragmented by weathering) are considered to be of very minor abundance, relative to secondary pyroclastic and autoclastic deposits. In practice, Fisher's

(1966) distinction of these two genetic types has limited application on composite volcanoes. Parsons (1969, p.287) has stated this situation succinctly: *"While the resulting breccias are of epigene nature, the actual fragmentation was mainly the result of the volcanic processes"*.

Parsons (1969) reviewed criteria for the recognition of volcanic breccias, which include (1) structural features (stratification, interbedding with lava flows and sediments, mantle bedding, graded bedding), character of the fragments (size, shape and texture of fragments; degree of sorting; angularity or roundness; vesicularity and percentage of glassy fragments; proportions of essential, accessory, and accidental fragments), and (2) composition and texture of the groundmass (amount of glassy versus crystalline material; porosity; proportion of groundmass to fragments; amount and type of alteration). These criteria will be incorporated here in discussions of genesis.

Genetic classification is based not only on the internal lithologies of units, but also on relationships with other lithologies and on morphology and distribution of the deposits. A summary diagram of genetic types is presented as Figure 5.

1.4.4 Summary of Lithologic and Genetic Types

Synthesis of all lithologic information from Ruapehu and related vents, as obtained from ground traverses and measured stratigraphic sections, leads to the recognition of seven lithologic types. To simplify presentation of the stratigraphic data, the measured sections are presented as figures, and lithologic types are noted on the columns with abbreviated labels. Full lithologic descriptions for the measured sections are given in Appendix 1. A general discussion of the lithologic types and their genesis is given below, as a prelude to the more detailed discussions which will occur under the individual Formation headings.

FIG. 5: Summary diagram for Genetic Classification.

Type of Deposit: Intrusive Igneous Bodies.

Notation: I

Lithology: Both porphyritic-aphanitic and finely holocrystalline textures are observed. The rocks are usually dense and non-vesicular. Magma bodies occur as vertical, jointed dykes with similar petrography to lava flows, and irregular intrusive plugs which are often highly shattered and jointed. Dyke-like masses of monolithologic tuff breccia are also present.

Relationship to Other Lithologies: Intrusive bodies exhibit cross-cutting relationships with all other deposits. Few concordant intrusives have been identified, but ^{it} is recognized that these could be confused with lava flows. Near exhumed vent regions, where hypabyssal plugs are closely spaced, hydrothermal alteration pervades both the intrusive bodies and the host cone.

Genesis: These are shallow magma bodies intruded into fragmental deposits and lava flows of the host cone. Local hydrothermal alteration is produced where multiple intrusions have supplied enough heat to drive circulation of phreatic water through the permeable deposits of the host cone. Intrusive breccias originate by the subterranean fragmentation of viscous magma.

Type of Deposit: Lava Flow.

Notation: L

Lithology: Thicknesses of lava flows vary from one metre to tens of metres, but most are of the order 5 to 10 metres in thickness. They are tabular lithosomes and tend to follow pre-existing drainage channels on the slopes of the edifice. Where exposures are extensive, individual flows can often be traced subaerially or in the subsurface for distances of several kilometres. Flow interiors are transected by a network of irregular fracture surfaces, producing a characteristic blocky jointing. The degree of fracturing is highly variable, but generally equant, angular, metre-sized blocks are produced. A second, non-pervasive type of jointing is nearly always present: subparallel, anastomosing planar

fractures are developed, commonly parallel to and within a few metres of the bases of flows. This platy jointing is highly characteristic of Ruapehu lava flows. Columnar jointing is sometimes developed in glassy flows, but is not a general phenomenon. Flow banding is commonly developed as contorted laminae in flow interiors, and tabular plagioclase microphenocrysts often exhibit preferred orientation. The banding is usually evident only on weathered surfaces, and is not conspicuous on fresh surfaces or under the microscope. This suggests that the banding is a result of subtle differences in the degrees of groundmass crystallinities.

Lava flows are nearly always phenocryst-rich, containing ten to forty or more volume percent of individual crystals and glomero-phenocrysts. Groundmasses are seldom notably vesicular or glassy, although a dense, microvesicular texture is very common. Centimetre-sized enclaves are ubiquitous in lava flows, and two varieties predominate: White, saccharoidal quartzite, and gray, microcrystalline feldspathic rock.

Relationship to Other Lithologies: Lava flows often grade into coarse, monolithologic tuff breccias of welded and unwelded character (see: TBm below). Lava flows are interbedded with all other lithologies at the scale of an outcrop.

Genesis: The lava flows were produced during relatively mild effusions of viscous, de-gassed magma, and were emplaced subaerially as tabular bodies with primary dips between about fifteen and thirty-five degrees. A high viscosity for the magmas is inferred from two commonly observed characteristics; the tendency to brecciate under the influence of gravity, and to develop internal shear planes (platy jointing).

Type of Deposit: Monolithologic Tuff Breccia.

Notation: TBm, TBmw.

Lithology: These deposits are coarse, unbedded, unsorted tuff breccias with a single clast petrography. The clasts have a porphyritic-aphanitic texture which is identical to that of lava flows. Individual dense, microvesicular clasts are usually angular to subangular and nearly always constitute a

clast-supported deposit, although matrix-supported varieties are present. The degree of clast rounding is coincident with the degree of matrix-supported character. A complete size gradation exists, from metre-sized angular blocks to fine ash matrix, although the proportion of ash-sized material is always minor. The fine material consists of rock fragments and crystals; no pumice or glass shards are present. The matrix and outer rinds of blocks are characteristically oxidised to a brick-red colour. These deposits are subdivided into unwelded (TBm) and welded (TBmw) varieties.

Relationship to Other Lithologies: These fragmental deposits grade laterally and vertically into coherent lava flows, the transition usually occurring over distances of less than 0.5 metres. They are commonly interbedded with, and are sometimes gradational into heterolithologic tuff breccias (TBh).

Genesis: TBm and TBmw are not consistent with airfall origin, due to their poor sorting and absence of internal stratification. The lithologic characteristics and common association with lava flows are consistent with an interpretation as autoclastic breccias, produced by the fragmentation of actively growing lava flows through gravitational collapse on steep slopes. Fiske, et al., (1963, p.74) have described similar deposits on the upper slopes of Mt Rainier:

"Interstratified with these lavas high on the mountain are breccias formed by explosive shattering of the lava flows. They contain fragments of porous or compact glassy lava, ranging from small chips to blocks as much as ten feet across, in a matrix of sand- and silt-sized glass particles and crystals. The blocks in these breccias are not a varied assemblage of different kinds of lava, such as might be torn by explosions from the walls of a conduit, but are glassy and scoriaceous equivalents of the adjacent partly crystalline lava into which they grade. The blocks have rough, slaggy surfaces, many of which are reddened by oxidation, or they are covered by agglutinatelike crusts. The breccia commonly grades up through pods and lenses of slaggy, brecciated

and agglutinated lava into less shattered and reddened lava, and finally into massive lava forming a definite flow. Other breccias are on the tops of flows, and grade downward into them. Still other breccias do not visibly grade into flows, but they enclose small to large roughly concordant streaks, pods and tongues of slaggy lava."

The coincidence of rounded clasts and matrix-supported character is strong evidence that the matrix is derived by attrition of originally angular clasts. Attrition can occur when blocks are spalled off the noses of actively growing flows, while the active flows override and crush their own debris, or during secondary transport long after effusion has ceased. The ubiquity and great volume of this type of tuff breccia on Ruapehu, and its association with heterolithic tuff breccias, suggest that the process of auto-brecciation produces a major proportion of the fragmental deposits on Ruapehu massif.

Type of Deposit: Heterolithic Tuff Breccia.

Notation: TBh.

Lithology: These poorly sorted tuff breccias contain two or more clast petrographic types and are commonly matrix-supported, in contrast to TBm. Individual clasts can occur up to metre size, and range from angular to subrounded. The degree of rounding and alteration is coincident with increasing vesicularity of clasts, which can range from dense to pumiceous in a single deposit. Clasts can exhibit breadcrusted outer surfaces and intense internal fracturing, while maintaining coherence as individual fragments. Clasts are present exhibiting varying degrees of alteration and oxidation. Very poor sorting is characteristic and complete gradation down to ash grade is common. Matrices are generally reddish brown to pale buff or gray in colour, consist of rock fragments and crystal fragments, and are usually indurated but not welded. Crude internal stratification is sometimes evident in subtle vertical changes of average grain size, or in laterally

continuous zones of slightly better sorted material.

Stratification commonly occurs between depositional units.

Relationship to Other Lithologies: TBh are interbedded with all other lithologies. Gradational contacts occur only with TBm and with SG.

Genesis: Genetic interpretations for these deposits must rely not only on lithology, but also on proximity to the inferred vent regions. Explosive eruptions can produce pyroclastic flow deposits with many of the above characteristics; extremely chaotic deposits with no internal stratification and very poor sorting, and containing fragments of previously consolidated and altered rocks, as well as juvenile magmatic fragments. Airfall origin is precluded by the poor sorting, lack of well developed internal stratification, and absence of impact structures beneath large clasts.

Major question arises as to the role of secondary deposition. On the massif, these deposits occur within four kilometres of the inferred vent regions, and can be traced into the vent regions without notable changes in lithology (aside from post-depositional hydrothermal alteration). Thus, the fragments clearly derive directly from active volcanism, and pyroclastic flow mechanisms involving the collapse of eruption columns seem viable. However, the crude internal stratification and the presence of subrounded clasts in many of these deposits suggest some degree of secondary transport. This leads to the question of when to cease labelling deposits as unwelded pyroclastic flows and to begin calling them lahars or debris flows. On Ruapehu massif, lithologic criteria alone are insufficient for deducing the role of secondary transport.

Genetically, all TBh are subaerially emplaced mass flows, probably ranging from cold lahars which were fluidized by water, to relatively dry debris flows, to hot pyroclastic flows which were fluidized by gas. The distinction between "wet" lahars and "dry" debris flows is not easily made. Neither is "hot" emplacement easily demonstrated, and requires

lithologic evidence (pervasive high temperature oxidation and/or welding; breadcrusted clasts present) as well as paleomagnetic evidence (non-random magnetic vectors for the clast population), in order to postulate high emplacement temperatures.

Type of Deposit: Bedded sand and gravel.

Notation: SG

Lithology: These moderately- to well sorted deposits are heterolithologic and usually matrix-supported. Nearly all clasts are of gravel size or smaller, and show some degree of rounding. Thicknesses of deposits are several metres or less. Internal planar and high angle cross stratification are well developed on a centimetre to decimetre scale.

Relationship to Other Lithologies: SG are nearly always interbedded with TBh and are sometimes gradational into TBh, but comprise a minor component of the overall stratigraphy.

Genesis: The sedimentary structures and sorting suggest fluvial origins by redeposition of fine pyroclastic/auto-clastic material. Sheet wash, leading to the generation of small, water-laden "lahars" under conditions of heavy rainfall, is a viable mechanism. This process has been observed by the author during field studies.

Type of Deposit: Well sorted, mantle bedded breccia (bombs and blocks) or tuff (lapilli and ash) deposits; Bw and Tw are welded equivalents.

Notation: B,T; Bw,Tw

Lithology: Well sorted, monolithologic, mantle bedded deposits consisting of angular cognate lithic blocks, rounded vesicular bombs, and subordinate accessory lithic blocks. Well developed internal stratification, shower bedding, good sorting, presence of distinguishable fall units and, where sufficient exposure exists, a systematic decrease in thickness and grain size away from source are characteristic features. Impact structures are present beneath large clasts. Ash grade material is crystal-vitric tuff or vitric-crystal tuff.

Complete gradation exists between the extremes of unwelded and densely welded lithologies. The welded varieties

(Bw and Tw) also exhibit good sorting when individual clasts can be recognized, and are internally stratified. Lateral and vertical changes in the degree of welding are well developed, and the deposits are most densely welded where the thickness is the greatest. Bw and Tw are often interstratified with massive, dense, lava-like deposits which seldom exceed a few metres in thickness and may or may not be laterally continuous at the scale of an outcrop. Conspicuous flow banding is developed in some of these dense layers.

Relationship to Other Lithologies: Unwelded B and T are rare on the massif but are associated with all other lithologies. Contacts with lithologies other than Bw and Tw are abrupt.

Genesis: All lithologic characteristics are consistent with airfall origin. Unwelded airfall breccias and tuffs are rare on the massif and are largely restricted to the Holocene. These poorly consolidated deposits apparently have a low preservation potential and were rapidly removed from the steep slopes by fluvial and mass wasting processes. Fine airfall material probably comprises a significant proportion of the matrices in secondary mass flow deposits (lahars and debris flows) of the ring plain.

Bw and Tw are interpreted as welded airfall deposits. Welded airfall tuffs have been described by Sparks and Wright (1979) and by Wright (1980). In contrast to ignimbrites, which exhibit regular zones of internal welding produced by compaction of plastic pumice fragments, welded airfall tuffs show significant vertical and lateral fluctuations in flattening of clasts, porosity and density. Sparks and Wright (1979) have attributed these fluctuations to the heterogeneous nature of the stratified airfall ejecta. These authors consider that rapid accumulation is critical toward producing welding in airfall deposits.

Some of the thin, dense, flow banded deposits intercalated with Bw and Tw are probably rheomorphic welded tuffs:

"Rheomorphism ("flow change") of a welded tuff is the secondary mass flowage of the tuff as a coherent viscous fluid. Rheomorphic welded tuffs are characterized by stretched fiamme which define a lineation parallel to the flowage direction. Flowage is capable of producing folding and other internal flow structures similar to those found in salic lava extrusions."
(Wright, et al., 1980, p.332).

1.4.5 Field Petrographic Nomenclature

Ruapehu lavas fit a broad petrographic definition of andesite: Mesocratic porphyritic-aphanitic rocks which lack quartz, K-feldspar, and feldspathoids. Hand specimen terminology for Ruapehu lava flows and fragmental deposits is straightforward since nearly all the eruptives contain phenocrysts of plagioclase (plag), augite (cpx) and orthopyroxene (opx). Abundant conspicuous plagioclase phenocrysts are present, generally with lesser amounts of two pyroxenes in approximately equal proportions (i.e., $\text{plag} \approx \text{cpx} + \text{opx}$, and $\text{cpx} \approx \text{opx}$). Accessory amounts (less than about one volume percent) of opaque oxide microphenocrysts are present in many lavas, but are inconspicuous in hand specimens. Accessory olivine (ol) is common, but amphibole (am) is rare.

For purposes of geologic discussion, mineral prefixes to the rock names follow the order of modal abundance in hand specimens. Thus, a lava with plagioclase phenocrysts dominant over pyroxenes is termed a plag-cpx-opx andesite. It is usually not possible to accurately judge the relative proportions of cpx and opx in hand specimens. If a lava contains accessory olivine, it is termed "ol-bearing". It is emphasized that hand specimen petrography is insufficient for predicting the silica contents of rocks in the field. Andesites and dacites are usually petrographically identical, and conspicuously olivine-bearing lavas range from basalt to andesite in bulk composition. "Andesite" may be replaced by

other rock names when the silica content is known from quantitative bulk rock analysis. "Basalt" has less than 53 wt % silica, "basic- or low-silica andesite" (used interchangeably by this writer) has between 53 and 57 wt % silica, "acid andesite" contains 57 to 63 wt % silica, and "dacite" has greater than 63 wt % silica. This is a generalization of the chemical terminology of Gill (1981), which will be used in later sections on petrology. The use of these rock names is intended to convey an idea of the compositional variation during geologic discussion. Detailed petrography and major element chemistry is given in Part II.

2. GEOLOGY OF RUAPEHU MASSIF

2.1 INTRODUCTION

New formation names proposed for the Ruapehu Group are given in the general stratigraphy, Figure 6, and the subaerial distribution of these formations is given in the generalized geologic map, Figure 7. A detailed geologic map at 1:25,000 scale is present inside the back cover of this volume. It is emphasized that formations are distinguished on the basis of lithologic and petrographic characteristics, in conjunction with conspicuous unconformable relations which define the formation boundaries.

Measured vertical sections are presented, and type areas are designated for each of the formations.

2.2 USE OF 'FORMATION' FOR VOLCANIC ROCK UNITS

Although the formations have been established following formal stratigraphic convention, i.e., they are small lithostratigraphic units useful for mapping and description, the nature of volcanic deposits demands a concise definition of this basic stratigraphic unit.

Stratovolcanoes such as Ruapehu are typically among the most complex of volcanic terrains. The distal airfall products of stratovolcano eruptions obey the usual stratigraphic axioms of superposition and, to a lesser extent, lateral continuity. In distal regions, it is often possible to recognize single airfall units or groups of temporally related airfall units, and to formally define these as stratigraphic members or formations. Such a stratigraphy was accomplished by Topping (1973), who defined numerous andesitic

tephra formations as comprising the Tongariro Subgroup, a sequence of largely airfall deposits which spans the past 14,000 years. Individual airfall units, sometimes

FIG. 6. Stratigraphic summary for Ruapehu massif.

Conspicuously young. Block lava flows, autoclastic breccias, local airfall pyroclastics, and minor pyroclastic flows, erupted from six vents.

Includes Rangataua flows of S. Ruapehu, Whakapapa flows, Taranaki Falls flow, Tama flows, and Pinnacle Ridge tuff of N and NW Ruapehu, and Crater Lake eruptives.

Andesites with subordinate low-silica andesite.

EXTENSIVE UNCONFORMITY, LARGELY FLUVIAL.

Upper lavas and pyroclastics form present high peaks and main cone. Well exposed everywhere, except SE Ruapehu.

Eruptions occurred at several vents, producing mainly lava flows and autoclastic breccias.

Many local unconformities.

Variable from basalt to dacite. Lower lavas commonly olivine-bearing.

UNCONFORMITY AT GIRDLESTONE PEAK AND N. RUAPEHU.

Extensively exposed at SE Ruapehu. Consists of lava flows, autoclastic breccias, and lahars.

Andesites dominant, low-silica andesites subordinate. Rarely olivine-bearing.

MAJOR GLACIAL UNCONFORMITY AT NW RUAPEHU.

Exposed as planeze surfaces and arêtes on N and NW Ruapehu: Pinnacle Ridge, Te Herenga Ridge, N side Whakapapa Valley.

Includes intrusive plugs, surrounded by zone of hydrothermal alteration developed in host tuff breccias. Upper cone complex is lava flows and autoclastic breccias, with numerous dykes.

Uniform low-silica andesites.

FIG. 7. Generalized geologic map of Ruapehu and related vents. Note the northeasterly alignment of young vents, which parallels the regional trend of normal faults.

mapped as formations, probably represent several hours or days of activity. Groups of temporally-related airfall units, also mapped as formations, generally represent 10^2 to 10^3 years of deposition. Formations can also be defined as the products of each individual monogenetic parasitic vent, probably representing months to years of activity.

By contrast, stratocones themselves are regions of persistent volcanism and intense erosion, with concurrent deposition of tabular, valley-confined lava flows, pyroclastic flows, and lahars, as well as more widely dispersed airfall deposits. Local unconformities are common, and the lengths of time they represent are not easily deduced. The observed stratigraphy not only reflects the character of eruptions, but also the potential for preservation. Thus, as will be shown below, poorly consolidated airfall material is rare in the prehistoric record at Ruapehu massif. Rapid lateral changes in lithology occur, and local observations of apparent superposition can lead to erroneous conclusions. In such terrains, a working definition of "Formation" is the smallest lithostratigraphic unit mappable over a large area. At conventional scales of mapping, i.e., 1:25,000 to 1:100,000, the most clearly recognizable subdivision is to group as formations all the products of each discrete cone-building episode. The time scale of such units is probably of the order 10^4 to 10^5 years, as opposed to 10^0 to 10^3 years for the deposition of related airfall formations in distal regions.

2.3 USE OF 'FACIES' FOR VOLCANIC ROCK ASSOCIATIONS

The recognition of volcanic facies has proved valuable during the volcano-stratigraphic study of Ruapehu and related vents, and follows the treatment of Williams and McBirney (1979, p.311-312):

"Certain features are diagnostic of rocks laid down close to eruptive vents; others are more typical of the outer slopes, and still others are more likely to be found at greater distances from the locus of volcanism. In such terms, volcanic rocks of any age can be grouped into volcanic facies, not unlike the depositional facies of sediments or the mineralogic facies of metamorphic rocks.

A single outcrop may have no unique significance, but taken together the rocks of various spatial zones have distinctive characteristics. They can be divided into three broad volcanic settings, sometimes referred to as central, proximal and distal zones. Each of these zones can be recognized from one or more lithologic features that is typical of that particular environment of deposition."

Figure 8 is a generalized scheme of these volcanic facies. At Ruapehu, the central facies occurs within about 0.5 km of the central vent regions. This association is characterized by (1) thin lava flows which are often volumetrically subordinate to fragmental deposits, (2) coarse, poorly sorted breccias and tuff breccias, (3) steep primary dips which are radial to the central vent, (4) dykes which are usually, but not always, radially oriented, (5) small, irregular intrusive bodies which have deformed the deposits of the host cone, and (6) pervasive hydrothermal alteration with steep lateral gradients.

Deposits of the slopes and outer flanks of the cone complex comprise the proximal facies, which includes (1) voluminous and extensive lava flows with associated autoclastic breccias, (2) laharic tuff breccias with angular to subrounded clasts up to several metres in size, (3) volcanoclastic debris which has been reworked by water, and (4) subordinate airfall tephra layers with grain sizes mainly in the lapilli to coarse ash range.

FIG. 8. Scheme of volcanic facies for a composite volcano.
Modified after Williams and McBirney (1979, p.313).

The distal facies of Ruapehu has not been extensively studied here. This facies encompasses deposits which are collectively referred to as the 'ring plain', and includes (1) lahars with subrounded clasts and abundant sand- to mud-sized matrix, (2) finely layered tephra with grain sizes largely in the ash range, (3) interlayered soils and organic matter, and (4) lava flows largely restricted to isolated vents and to local, valley-filling flows.

2.4 TE HERENGA FORMATION (New Formation Name) DISTRIBUTION, THICKNESS AND VOLUME

The Te Herenga Formation is named from Te Herenga Ridge, a prominent topographic feature of the northern slopes of Ruapehu at about 1,550 metre elevation. The Te Herenga Formation is not exposed over large areas of the mountain, and is restricted to arêtes and planeze surfaces on the northern and northwestern slopes (Fig. 9). The best exposures occur at Pinnacle Ridge, Te Herenga Ridge, and the unnamed ridge and planeze surface to the north of the upper Whakapapaiti Stream. The formation includes lava flows, tuff breccias, and intrusive bodies which occupy these areas and are unconformably overlain by younger deposits. The greatest thickness, about 300 metres is exposed in the Whakapapanui valley, north Ruapehu. The volume of the formation cannot be estimated with precision owing to the extensive cover by younger formations, and subsequent erosion. Assuming a simple cone-like geometry and allowing for material removed by erosion, the original volume was probably of the order 65 km³.

TYPE AREAS: Pinnacle Ridge, Te Herenga Ridge

FORMATION BOUNDARIES

The base of the Te Herenga Formation is not exposed, and at depth these deposits probably rest unconformably on Tertiary marine sediments of the subvolcanic basement. A conspicuous unconformity, largely of glacial origin, separates the eroded remnants of the Te Herenga cone from younger formations. At

FIG. 9. Aerial view of the northwest slopes, Ruapehu. Te Herenga Formation is indicated by the shaded pattern. Intrusive bodies and a surrounding zone of hydrothermal alteration comprise the central facies of upper Pinnacle Ridge. Lower Pinnacle Ridge, Te Herenga Ridge, and the unnamed ridge at the lower right consist of proximal facies deposits. The unnamed ridge is an arête capped by lateral moraine, and glaciated surfaces are present at "G" (see Fig. 83). Lava flows of the Whakapapa Formation now occupy the broad glacial valley which was developed in the Te Herenga cone.

most localities, the Te Herenga Formation is unconformably overlain by lava flows of the post-glacial Whakapapa Formation, and the contact relations are particularly well displayed in the upper Whakapapanui Gorge beneath Mead's Wall, and along the northern side of the unnamed ridge which lies to the north of the Whakapapaiti Stream. Te Herenga Formation is unconformably overlain by Mangawhero Formation in the headwaters of the Whakapapaiti Stream (Ruapehu Section 12, Fig. 16).

LITHOLOGY AND PETROGRAPHY

Deposits of the Te Herenga Formation exhibit great lithologic but little petrographic variation. All lithologic types, except mantle bedded breccias and tuffs (B and T) are represented in the measured sections and in other outcrops. Lava flows and associated monolithologic tuff breccias (TBM) comprise about half of the total measured stratigraphy. Lava flows, large angular clasts from the tuff breccias, and dykes exhibit uniform petrographic characteristics. In hand samples the most striking feature of the petrography is the conspicuous glomerophenocrysts of pyroxene which, in contrast to plagioclase, are prominent against the pale matrix. Olivine is absent. Intrusive microdiorite plugs are mineralogically similar to lavas and blocks of the host cone, but exhibit fine-grained intrusive textures with great variation in the degree of crystallinity.

AGE

A single whole rock K-Ar age of 0.230 ± 0.006 Ma is given by Stipp (1968), from a lava flow on Te Herenga Ridge. This dates the upper part of the formation, and the age is supported by the paleomagnetic data of Halama (1981), which show that the Te Herenga Fm lava flows of Te Herenga Ridge and Whakapapanui Gorge are all normally magnetized and therefore younger than the Brunhes/Matuyama boundary. The total

time span of Te Herenga Formation emplacement is unknown, but the absence of both paleosols and major intraformational unconformities suggests rapid cone construction.

VOLCANIC FACIES

(i) Central Facies

Outcroppings of small (tens of metres), irregular intrusive bodies comprise the uppermost portion of Pinnacle Ridge. These solidified within radially dipping tuff breccias and subordinate thin lava flows of the central cone. Brittle deformation of the tuff breccias and lavas is evident in local dip reversals and oversteepening of beds from 45 degrees to nearly vertical. The intrusives are highly jointed and shattered, are transected by a complex network of highly altered breccia dykes, are themselves pervasively altered to varying degrees, and are surrounded by a brownish aureole of hydrothermal alteration. Megascopic features of the central facies are shown in Figure 10, and outcrop features are given in Figure 11.

Plagioclase of the intrusives has commonly been totally replaced or veined with pale olive-green clays (montmorillonite, mixed layer illite/montmorillonite, and minor pyrophyllite), and pyroxenes are often replaced by clays and subhedral sulfides. The surrounding zone of hydrothermally altered tuff breccias and thin lava flows is about 80 metres wide, and is crudely zoned both laterally and vertically. An inner zone of orange-brown alteration (gossan) extends from the intrusions for a distance of about 30 metres. Here, the tuff breccias are intensely shattered, are cut by random veins of clay, and are pervaded by finely disseminated sulfides. Many of these breccias have the appearance of advanced spheroidal weathering. Outward from this, pervasive alteration, involving mostly clays and lesser sulfides, gives the breccias a deep green colour. Vertical and lateral zonation is further indicated by veins of colloform silica with associated kaolinite, at the outer periphery of the aureole.

FIG. 10. Aerial photograph of the northeastern slopes, showing megascopic features of the Te Herenga Formation exposed at upper Pinnacle Ridge. Note progressive oversteepening of strata toward the vent region, as a result of deformation by intrusive bodies.

The primary lithologies, deformation, and hydrothermal alteration are expected characteristics of volcanic vent regions. The montmorillonite and mixed layer illite/montmorillonite-dominated alteration assemblage implies relatively low temperatures (less than about 220°C., which is approximately the point at which illite plus chlorite become dominant), and/or a brief time for the activity of the system (Browne, 1978). Brief duration and low temperatures are consistent with the geology, since the intrusive bodies and the surrounding aureole cover only a small area of about 900 m². The hydrothermal system is inferred to have existed under near-surface conditions, as indicated by the hypabyssal textures of the intrusives, brittle behaviour of the deformed tuff breccias, and deposition of silica and kaolinite at the outer periphery of the aureole. The latter aspect is a common occurrence where hydrothermal waters cool and acidify under near-surface oxidizing conditions. The surface of the vent region was probably on the order of 50 to 100 vertical metres above the present-day exposures. Such processes of intrusion, with attendant deformation and hydrothermal alteration, can be imagined beneath the currently-active vent region of Ruapehu.

(ii) Proximal Facies

The proximal facies is well exposed along Pinnacle Ridge, on Te Herenga Ridge, and in the Whakapapanui Gorge which separates these ridges (Figs. 12 and 13). Further exposures occur along the unnamed ridge to the north of Whakapapaiti Stream, and in the headwaters of the Whakapapaiti Stream. Three measured sections are presented (Figs. 14, 15, 16), one from the Whakapapanui Gorge, one from Te Herenga Ridge, and one from the Whakapapaiti Valley. The two valley sections represent the lower portion of the proximal facies, and the Te Herenga Ridge section represents the upper portion.

Three major lithologic types are recorded in the sections. About half of the total measured stratigraphy consists of lava flows and associated monolithologic tuff breccias (TBM),

Legend

TE HERENGA FM.

- Lava flows
- TBh and SG, oversteepened at "1"
- Dykes and other intrusives
- Zone of hydrothermal alteration

WHAKAPAPA FM.

- Lava flows and autobreccias, I-w i k a u Mbr.
- Welded airfall tuff, Pinnacle Ridge Mbr.

FIG. 12. Proximal facies of Te Herenga Fm at Pinnacle Ridge. Photographs taken at Hut Flat.

FIG. 14. Ruapehu Section 1. 145 m of Te Herenga Fm exposed in Whakapapanui Gorge, northwest Ruapehu. Grid references for base of section are: T20/313154 (metric), N112/059708 (yard).

FIG. 15. Ruapehu Section 2. 80 m of TeHerenga Fm exposed at TeHerenga Ridge, northwest Ruapehu (see: Fig. 13). Grid references for base of section are: T20/307156 (metric), N112/054713 (yard).

FIG. 16. Ruapehu Section 12. 73 m of Te Herenga and Mangawhero Fms exposed in Whakapapaiti Valley, west Ruapehu. The contact of these formations occurs at 38 m, where tuff breccias of Mangawhero Fm rest unconformably on the glaciated surface of a Te Herenga Fm lava flow. Grid references for base of section are: S20/283151 (metric), N112/026700 (yard).

the remainder of the deposits being heterolithologic tuff breccias (TBh), and minor bedded sand and gravel deposits. Outcrop views of the major lithologies are given in Figure 17.

Lava Flows

Lava flows are present throughout the proximal facies but dominate the stratigraphy only in the upper portion of the cone complex (Ruapehu Section 2, Te Herenga Ridge, Fig. 15). The flows are lenticular in cross section and form an anastomosing outcrop pattern, where successive flows have infilled local topographic lows on the irregular surfaces of older flows. Fourteen measured flows range from 2 to 16 metres in thickness, and average 6.5 metres. Flow interiors are transected by blocky jointing, and platy jointing is nearly always developed near the bases. Flow banding is largely absent. Monolithologic tuff breccia (TBm) is almost invariably associated, and the transition from lava to breccia is abrupt but occurs along irregular contacts. Flows nearly always have spinose, irregular bases, but often exhibit non-blocky and distinctly planar top surfaces. However, weathering of the flow tops is weak or non-existent, suggesting that extrusion was punctuated by brief intervals of quiescence.

Monolithologic tuff breccias (TBm, TBmw)

These unsorted, oxidized tuff breccias are commonly associated with lava flows. Clasts usually do not exceed 0.4 metres, and are spinose and clinkery. The petrography of clasts is identical to that of lava flows, and complete size gradation exists down to lapilli and ash, where the latter consist of angular rock and crystal fragments. Most of these coarse deposits are clast-supported. Welding is not commonly developed.

The monolithologic tuff breccias were clearly produced by the autobrecciation of flowing lava. The flows and autobreccias closely resemble aa and block lava flows (Macdonald,

FIG. 17. Outcrop photograph of proximal facies lithologies of the Te Herenga Formation, upper Pinnacle Ridge.

1953), where the outer margins of the flows cool and become relatively brittle, leading to fragmentation in response to stresses imposed by the still-fluid, plastic interior of the flow. Blocky jointing is developed, but the flows have not brecciated en masse, and the fragmentation is restricted to the outer rinds of the flows and to the development of shear planes (platy jointing) near their bases. These features are characteristic of relatively viscous basaltic to low-silica andesitic lavas.

Heterolithologic tuff breccias (TBh)

Because of the great petrographic uniformity of essential magmatic material in the Te Herenga Formation, the TBh deposits are not strongly heterolithologic. The heterolithologic character is manifested by a clast population which exhibits only subtle variation in the abundance and relative proportions of phenocrysts; however, the clasts exhibit widely varying degrees of alteration, oxidation, and vesicularity in a given deposit. The most common TBh are massive or very weakly bedded, where poor stratification is produced by local horizons of angular, metre-sized blocks. These coarse, nearly monolithologic horizons are lenticular over lateral distances of tens of metres, and the angular clasts are unoxidized and petrographically identical to Te Herenga lava flows.

The host TBh for these local coarse horizons are more strongly heterolithologic. Angular to subrounded blocks of medium to light grey, dense, microvesicular, plag-cpx-opx phyric rock occur up to 0.5 metres but average 15 to 25 centimetres. Rounded, vesicular, palagonitized bombs are far subordinate to dense blocks. Clasts are supported by a massive tuffaceous matrix of angular to subrounded, dense, variably oxidized lapilli up to 2 centimetres, rounded yellow-grey pumice lapilli up to 2 centimetres, and coarse to medium crystal-vitric tuff. The tuffaceous matrix consists of rock and crystal fragments, and lacks glass shards. It is indurated but not welded.

Complete size gradation exists from 0.5 metre angular blocks to medium ash, and the deposits are generally matrix-supported. In the lower 23 metres of Ruapehu Section 12 (Fig. 15), stratification is well developed between depositional units, which average 2.5 metres in thickness, exhibit crude internal bedding, and have primary dips on the order of 25° . In Ruapehu Section 1 (Fig. 13), depositional units are tens of metres thick, and primary dips are generally 10 to 20° .

On lithologic criteria alone, these deposits cannot be interpreted unambiguously. The Te Herenga Formation TBh units have all the characteristics of relatively cold mass flows (lahars or debris flows), but collapse of eruption columns during explosive volcanism could also generate massive, unsorted heterolithologic deposits with abundant tuffaceous matrix. In the latter situation, the heterolithologic character results from simultaneous ejection of dense, already solidified fragments of the pre-existing cone, as well as violently effervescing fresh magmatic material. The most cogent argument in favour of a pyroclastic flow mechanism (collapse of eruption columns) is the fact that the TBh exhibit no lithologic change as they are traced into the vent region, aside from secondary hydrothermal alteration. Arguments in favour of laharic origins include (i) the abundance of subrounded clasts (2) a general absence of lithologic features to suggest high-temperature emplacement, such as charred vegetation, gas escape pipes, and pervasive oxidation, and (3) the association of TBh with moderately well sorted and bedded sand and gravel (see below).

The coarse, lenticular, nearly monolithologic breccias which are intercalated with massive TBh are not likely to have originated as coarse ballistic ejecta, since impact structures are absent. These breccias also differ from autoclastic breccias in that the blocks are larger, more angular, less oxidized, and not directly associated with lava flows. The large, equant blocks closely resemble those which are produced by the blocky jointing of lava flow interiors or volcanic

domes, suggesting that the coarse breccias originated by the gravitational collapse of solidified lavas on the upper slopes.

G.P.L. Walker (pers. comm., 1980) has suggested that if the TBh originated by major explosive eruptions, then the tuff matrix could be crystal-enriched, relative to lava flows, as a result of the glassy fragments having been blown away as fine dust. Such crystal enrichment is not evident either in the petrography, or in the chemistry: aside from secondary hydration and minor loss of silica and alkalis, the tuffaceous matrix is similar in bulk chemistry to the associated lava flows.

Since the TBh can be traced into the vent region without notable lithologic changes, question arises as to the mechanism of their generation. The answer relies more on structural than on lithologic criteria. At numerous localities along upper Pinnacle Ridge, within about 1 km of the vent region, thin lava flows and voluminous tuff breccias are observed to be oversteepened and often have dips between 60 degrees and vertical. In light of the numerous shallow intrusions that exist in the central facies, this oversteepening is strong evidence that the TBh were generated by gravitational collapse of the cone as a result of the deformation associated with the shallow intrusion of magma.

Most arguments therefore favour an origin for the Te Herenga TBh as secondary mass flows, generated largely by the gravitational collapse of unstable pyroclastic/autoclastic material on the steep upper slopes of the cone. The most probable mechanism was deformation associated with shallow intrusion of magma. The absence of primary airfall material in the stratigraphy probably also attests to the frequency of secondary processes, rather than to an original lack of primary airfall deposits during Te Herenga volcanism.

In an attempt to resolve this issue, paleomagnetic cores were taken from ca. the 73 metre and 94 metre intervals of Ruapehu Section 1 (Fig. 14), and natural remanent magnetization (NRM) data for these samples are given in Figure 18. The NRM vectors are neither random nor oriented with respect to the present-day axial dipole. No precise statements on emplacement temperatures can be made from the existing data, except to say that the deposits were not emplaced at magmatic temperatures. The samples require alternating field or thermal demagnetization to resolve the thermal remanent magnetization (TRM) component from post-depositional viscous overprint components of magnetization.

Moderately sorted, bedded sand and gravel deposits (SG)

These deposits comprise a minor component of the stratigraphy, and are always associated with TBh. Examples occur at the 99.5, 100.4 and 103.2 metre intervals of Ruapehu Section 1 (Fig. 14), as well as at numerous localities on Pinnacle Ridge. Figure 19 is an outcrop view of some Pinnacle Ridge deposits. The sand- and gravel-sized material is conspicuously planar bedded on a centimetre to decimetre scale, and the clasts and tuffaceous matrix are petrographically identical to those of the associated TBh.

No sag structures are present beneath the larger clasts, and they are therefore unlikely to be of airfall origin. They are interpreted as fluvial/colluvial deposits derived by the reworking of heterolithologic tuff breccias on the steep slopes of the cone.

Intrusive igneous bodies (I)

Numerous north-trending dykes have intruded tuff breccias and lava flows of the Te Herenga proximal facies (Fig. 20). A single dyke is recorded at the 102 metre interval of Ruapehu Section 1 (Fig. 14), and the geologic map of Pinnacle Ridge (Fig. 21) shows that numerous dykes traverse the ridge. The dykes range from about 0.5 to 3 metres in thickness, have similar petrographies to lava flows, and have not altered or

R-2 WHAKAPAPANUI

UPPER LOWER

○ ● CLASTS

◇ ◆ MATRIX

△ ▲ AXIAL DIPOLE

R-1 WHAKAPAPANUI

UPPER LOWER

○ ● CLASTS

◇ ◆ MATRIX

△ ▲ AXIAL DIPOLE

FIG. 20. North-trending dyke of Te Herenga Fm, Pinnacle Ridge. Note shear planes developed in the host tuff breccias.

FIG. 19. Colluvial deposits of Te Herenga Fm proximal facies, Pinnacle Ridge. This locality is denoted by "1" of Fig. 12.

FIG. 21. Geologic Map of Pinnacle Ridge, northwest Ruapehu.

deformed their host deposits except for the development of minor vertical shear planes in the surrounding tuff breccias. The dykes are prominent all along Pinnacle Ridge, but perhaps the most conspicuous example is Mead's Wall. Pinnacle Ridge was also the locus of fissure eruptions for the much younger Whakapapa Formation (see p.).

Dykes of the Te Herenga Formation are the most conspicuous on the mountain, and their extensive exposure is due to the advanced dissection of the Te Herenga cone relative to younger formations. Dyke intrusion represents the latest stage of Te Herenga volcanism, and the petrographic similarities between dykes and lava flows suggests that the dykes were feeders for the upper sequence of flows.

2.5 WAHIANOA FORMATION (New formation name)

DISTRIBUTION, THICKNESS AND VOLUME

The Wahianoa Formation is named for the Wahianoa valley, a prominent glacial valley of the southeastern slopes of Ruapehu. The Wahianoa Formation is exposed at the southeastern quadrant of Ruapehu; in the Wahianoa and Whangaehu valleys, and on the broad planeze surface which separates them (Fig. 22). Additional exposures occur at Girdlestone Peak, and limited local exposure of the upper part of the formation occurs on north Ruapehu in a 70 metre deep fluvial valley (Fig. 30). The formation consists of voluminous lava flows and tuff breccias with variable lithologies, and subordinate finer-grained tuffaceous deposits. These have been hydrothermally altered and intruded by several dykes and plugs in the near-vent region. The greatest thickness of Wahianoa Formation is exposed in the southern face of the upper Whangaehu valley, where 220 metres of near-vertical exposure have been described (Fig. 25). The initial volume of the formation cannot be established precisely. Assuming a simple cone-like geometry, and subtracting the post-erosional Te Herenga volume, the Wahianoa edifice was probably of the order 45 km³.

FIG. 22. Aerial photograph of southeastern slopes of Ruapehu. Wahianoa Fm is exposed in headwaters of Wahianoa and Whangaehu Rivers, and comprises the broad planeze surface between these valleys. Normal fault in the foreground is downthrown on the near side.

TYPE AREAS: Southern face of upper Whangaehu Gorge, and upper Wahianoa Valley

FORMATION BOUNDARIES

The Wahianoa Formation is nowhere seen to overlie the Te Herenga Formation or the subvolcanic basement. Distinction from the Te Herenga Formation is therefore not based on contact relations, but rather on the lesser degree of dissection for the Wahianoa Formation, and on major lithologic and petrographic differences.

The upper formation boundary is defined at two localities. At Girdlestone Peak, olivine-bearing lavas of the Mangawhero Formation unconformably overlie olivine-free lavas and tuff breccias of the Wahianoa Formation (Fig. 23). At north Ruapehu (Fig. 30), heterolithic tuff breccias of the Wahianoa Formation are unconformably overlain by olivine-bearing lavas of the Mangawhero Formation. These exposures demonstrate that degradation of the Wahianoa cone occurred prior to deposition of Mangawhero lavas.

LITHOLOGY AND PETROGRAPHY

Deposits of the Wahianoa Formation exhibit great lithologic and moderate petrographic variation. All lithologic types are represented in the measured sections and in other outcrops, but monolithic tuff breccias (TBM, TBMw) and associated lava flows are the most voluminous lithologies. Lava flows and clasts from the tuff breccias are generally porphyritic plag-cpx-opx andesites whose phenocryst contents vary from about 15 to 40 percent, and with light grey to black matrices. Some olivine-bearing lavas are present, but this mineral is not conspicuous.

AGE

No absolute chronology exists for the Wahianoa Formation, but it is believed to be younger than the Te Herenga Formation. This inference is substantiated by the lesser degree of dissection of the Wahianoa Formation, relative to Te Herenga

FIG. 23. Geology of the southwest face, Girdlestone Peak. The unconformable contact of Wahianoa and Mangawhero Formations is exposed here.

Formation. The Wahianoa Formation is certainly older than Mangawhero Formation which unconformably overlies it, but neither the age of the base of the Mangawhero Formation nor the time span of the hiatus are known.

VOLCANIC FACIES

(i) Central Facies

Deposits of the central facies are not as well exposed as those of the Te Herenga Formation because erosion has not carved as deeply into the Wahianoa cone complex. Furthermore, the central facies is inaccessibly exposed high in the headwaters of the Whangaehu River, a region of precipitous cliffs and unstable talus slopes. From the northern side of the Whangaehu valley and from the eastern summit region of Ruapehu, features are observed in the headwaters of the Whangaehu (Fig. 24) which appear analogous to those of the Te Herenga central facies. Pervasive hydrothermal alteration is evident in the yellow-brown discolouration of the deposits, and talus blocks of this material are abundant in modern fluvial deposits of the upper Whangaehu River. The deposits consist largely of altered tuff breccias with subordinate intercalated lava flows, and these are transected by several vertical, NW-trending dykes. The proportion of lava flows is decidedly less than for the proximal facies. Deep in the valley, podiform masses of lighter-coloured rock suggest the presence of intrusive bodies.

Although detailed lithologic descriptions of the tuff breccias were not obtained, the deposits are similar in overall lithology to the better-studied Te Herenga central facies. A central cone consisting largely of tuff breccias and lesser lava flows was invaded by several dykes. Attendant circulation of phreatic water produced an internal zone of hydrothermal alteration.

(ii) Proximal Facies

The proximal facies is well exposed on the southern wall

FIG. 24. Central facies of Wahianoa Fm exposed in headwaters of Whangapehu River, southeastern summit region of Ruapehu. Bulk of central facies consists of bedded tuffs and tuff breccias. Intrusive bodies are inferred only. Note the mantle of Crater Lake pyroclastics on Wahianoa Fm of Mitre Peak.

of the Whangaehu Gorge (Fig. 25), in the upper reaches of the Wahianoa valley (Fig. 26), and at Girdlestone Peak (Fig. 23). Six measured sections are presented (Figs. 27-32), three from the Whangaehu Gorge, one from north Ruapehu, one from Girdlestone Peak, and one from Wahianoa Valley.

A wide range of lithologic types is recorded in the sections, but lava flows and associated monolithologic tuff breccias (TBm, TBmw) of autoclastic origin predominate, comprising about 75 percent of the deposits.

Lava Flows:

These are the most conspicuous component of most sections, forming protruding, steep bluffs. The flows are lensoid in cross section, and range from clearly valley-filling to nearly planar (see Fig. 25). Twenty flows measured on RS3 range in thickness from 0.5 to 12 metres, with a mean of 4.5 metres. The flows are almost invariably associated with monolithologic tuff breccias. A rapid but gradational relationship is observed from massive, concordant lava, to irregular lava tongues intruding welded monolithologic tuff breccia, and then to unwelded tuff breccia.

Flow interiors are pervasively jointed to produce large, irregular, but generally equant angular blocks. Many flows exhibit intense, platy jointing which is often concentrated near the bases of flows. Conspicuous flow banding occurs in some flows, and near flow margins the banding is often tightly convolute. These features are displayed in Figures 33-35.

Most of the flows are broadly conformable and approximately flat lying, suggesting rapid effusion of successive flows with little opportunity for extensive intervening erosion. In a minority of cases time breaks were sufficient for erosion of major gullies, and the succeeding lava flows were confined to the valleys (Fig. 25).

Legend

WAHIAHOA FORMATION

- Lava flows
- Intrusive bodies
- Bomb-bearing TBh
- Bedded tufts and tuff breccias

FIG. 25. Wahiao Fm exposed in Whangaehu Gorge, southeast Ruapehu. Location of Ruapehu Section 3 is noted. Younger lava flows of Mangawhero Fm occupy the foreground.

FIG. 26. Wahianoa Formation exposed in Wahianoa Valley, southeast Ruapehu.

FIG. 27. Ruapehu Section 3. 223.5 m of Wahianoa Fm exposed in Whangaehu Gorge, southeast Ruapehu. Grid references for base of section are: T20/347094(metric), N122/098646 (yard).

FIG. 28. Ruapehu Section 4. 13.5 m of Wahianoa Fm exposed in the Whangaehu Gorge, southeast Ruapehu. Grid references for base of section are: T20/353092 (metric), N122/105643 (yard).

FIG. 29. Ruapehu Section 5. 64.4 m of Wahianoa Fm exposed in Whangaehu Gorge, eastern Ruapehu. Grid references for base of section are: T20/365093 (metric), N122/128640 (yard).

FIG. 30. Ruapehu Section 8. 37.5 m of Wahianoa Fm exposed in an unnamed stream valley of north Ruapehu. Grid references for base of section are: T20/342155(metric), N112/090712(yard).

FIG. 31. Ruapehu Section 7. 26 m of Wahianoa Fm exposed at Girdlestone Peak (see: Fig. 23). Grid references for base of section are: T20/311086(metric), N122/060636(yard).

FIG. 32. Ruapehu Section 6. 192 m of Wahianoa Fm exposed in Wahianoa Valley, southeast Ruapehu. Grid references for base of section are: T20/339073(metric), N122/090621(yard).

FIG. 33. Internal block jointing developed in Wahianoa Fm lava flow.

FIG. 34. Basal platy jointing and underlying auto-breccia of Wahianoa Fm lava flow.

FIG. 35. Flow banding near base of Wahianoa Fm lava flow.

Monolithologic tuff breccias (TBm, TBmw):

The TBm units are invariably associated with, and petrographically identical to, lava flows of the Wahianoa Formation. The breccias are chaotic, massive tuff breccias, containing generally blocky clasts of widely variable grain-size. Maximum clast size is generally less than 0.5 metres, with matrix material down to ash size. Clast roundness varies from angular to subrounded. A gradation from framework to matrix support is present. Large clasts and matrix almost invariably show strong oxidation to bright red colours.

Many units show a rapid gradational relationship to massive lava (Fig. 36). The lava flows possess irregular, rubbly, slaggy margins passing into welded, relatively coarse and angular breccia often intruded by thin discordant tongues of lava (RS 3, Fig. 27, 100-110metres). The welded breccia passes outwards into partially and then unwelded breccia which is more matrix-rich and with distinct rounding of the larger clasts. Thicker lava flows often contain lensoid internal pods of incipient brecciation (Fig. 37).

Excellent examples of these features occur in RS 7 (Fig. 31), where thin lenticular lava flows often pinch out into TBm and have internal zones of TBm, and in RS 5 (Fig. 29), where lava flows are intercalated with TBmw and with coarse bomb beds of airfall origin.

Well sorted tuffs, and lapilli and bomb beds (T; B, Bw).

Shower bedded, well sorted beds of probable airfall origin are rare in the Wahianoa Formation. A 20 cm unit of shower bedded pumiceous andesitic lapilli occurs at 12.1 metres in RS 4 (Fig. 28). An unwelded bomb bed occurs 30 metres above the base of RS 3 (Fig. 39), separated by several graded TBh units from a 1 metre thick sequence of airfall lapilli and ash (Fig. 40) at 20 metres above section base. Common characteristics of these units are: shower bedding defined by subtle variations in grain size, a mantling of underlying relief, better sorting than all other clastic units, and a predominance

FIG. 36. Transition from lava flow to autobreccia in Wahianoa Fm, approx. 100 m interval of RS 3. Height of scene is 6 m.

FIG. 37. Lenses of welded, incipient autobreccia in Wahianoa Fm lava flow, approx. 130 m interval of RS 3. Height of scene is 4 m.

FIG. 39. Unwelded bomb bed, 30 m interval of RS 3.

FIG. 40. Mantle-bedded airfall lapilli and ash, 20 m interval of RS 3.

of vesicular, scoriaceous or pumiceous essential clasts.

In RS 5 (Fig. 29), coarse agglutinate units (Bw) are interbedded with welded autobreccias (TBMw) and are distinguished from them only with difficulty. These Bw units are better sorted than the welded autobreccias and contain plastic, rounded, vesicular bombs as the major clast component. Thin, lenticular pods of dense, lava-like material are associated with Bw. These are generally less than 1 metre thick and often exhibit striking, flamelike flow banding.

The characteristics of the unwelded deposits suggest they are airfall magmatic deposits. They resemble historic and other young airfall deposits of the Tongariro Volcanic Centre; e.g., Ngauruhoe 1975 (Nairn and Self, 1978), Poutu Lapilli (Topping, 1973), and Ohakune Andesite Formation (this volume). The Bw units are interpreted as welded airfall tuffs which were produced during eruptions from a nearby but unexposed vent. The thin, dense, lava-like units associated with Bw are considered to be densely welded equivalents of Bw, where compactional welding has obscured the original bomb outlines. The contorted banding in many of these densely welded Bw units suggests secondary flowage, and they are interpreted as rheomorphic welded tuffs. During high rates of effusion, densely welded airfall can become mobilised by gravity and give rise to genuine lava flows; such a process has been observed during historic Hawaiian-type eruptions. Apparently, the welded airfall deposits were being generated concurrently with the effusion of lava flows and associated autobreccias. The flowing lava may have carried the airfall ejecta away from the vent region, in similar manner to that observed for the 1955 eruption of Kilauea (Macdonald, 1972, p.215).

Heterolithologic tuff breccias (TBh)

This diverse group contains several distinct types of units, ranging from nearly monolithologic to strongly heterolithologic, from matrix to framework supported, and from

massive to graded bedding. Three types of unit are described here.

Type A consists of a range of large (0.1 to 1 metre diameter) clasts, which are framework supported and with interstitial ash matrices. Clasts include (1) fresh grey and black andesite, (2) red oxidised andesite, and (3) weathered brown andesitic pumice. Most clasts are subrounded to sub-angular, but some well-preserved bombs occur. The units possess planar, non-erosive bases and planar tops. Frequently, the basal 10 - 20 cm of bed is reversely graded, passing upwards into massive tuff breccia. An excellent example of such a unit is found 1.6 - 2.6 metres below the top of RS 4 (Fig. 41).

Type B contains a similar clast population, but the clasts are floating in brown matrices of ash- to lapilli-sized material. The large clasts include black, breadcrusted blocks. Large clasts are sometimes restricted to the upper half of these deposits, yielding a reversely graded lithology. Weakly developed internal stratification is manifested by the alignment and relative concentrations of larger clasts. Two reversely graded units occur at the 22.6 - 26.6 metre interval of RS 3 (Fig. 42). Similar matrix-supported but not reversely graded deposits comprise much of RS 8 (Fig. 30), and are common in RS 6 (Fig. 32; 0 - 7 metres, 70 - 95 metres).

Type C is an unusual variety of tuff breccia found in RS 3 (Fig. 27; 59.2 - 63.2 metre, 176 - 189 metre and 207 - 211 metre intervals). These are matrix-supported, crudely stratified deposits (Fig. 43) which are continuous across most of the southern wall of the Whangaehu Gorge. Large clasts, comprising approximately 25 percent of the deposits, are dominated by striking black volcanic bombs. The bombs, up to 3 metres in diameter, possess delicate breadcrusted exteriors and dense, nonvesicular interiors often cut by arcuate cooling cracks (Fig. 44). The cracks frequently divide individual bombs into a number of discrete, isolated fragments (Fig. 45).

26.6 m

22.6 m

Matrix-supported, reversely
graded heterolithic tuff
breccia; 22.6-26.6 m interval
of RS 3 (see: Fig. 27).

The remainder of the large clasts consist of subangular to subrounded blocks of dense, microvesicular or nonvesicular grey or oxidised red andesite up to 25 cm in size, and subordinate weathered brown andesite lapilli. Measurements of natural remanent magnetization (NRM) on cores drilled from large clasts indicate that the black breadcrusted bombs have a consistently aligned NRM, whereas dense subrounded blocks exhibit nearly random NRM (Fig. 46).

Type A and B tuff breccias are considered to be the products of lahars generated on the upper slopes of the Wahianoa cone. The deposits are clearly the products of mass flows, and the massive nature of the deposits and the abundance of matrix material suggest the transportation mechanisms were debris flows (Johnson, 1970; Middleton and Hampton, 1976) or slurry flows (Carter, 1975). In these mechanisms, large clasts are dispersed in and suspended by matrices consisting of slurries of fine particles and water, with finite yield strengths. Deposition is by mass emplacement or freezing, explaining the massive nature of the heterolithologic tuff breccias. Frequently the flow interiors move as rigid plugs with little internal movement of clasts (Middleton and Hampton, 1976). Plug flow explains transportation without abrasion of volcanic bombs having delicate surface features.

The dominance of a single lithology in many heterolithologic tuff breccias suggests the origin of the mass flows was often the failure or collapse of a single rock unit, be it either pyroclastic material or fragmented lava. A variety of factors combine to make the upper portions of composite volcanoes likely sites for mass collapse. These include (1) steep initial slopes, (2) rapid accumulation rates of often unstable pyroclastic material, (3) extrusion of gravitationally unstable spines, domes and flows of lava, and (4) a variety of possible mechanisms to trigger the collapse of unstable material. The latter includes (1) volcanic seismic events, (2) loading resulting from deposition of new material on an

R-4 WHANGAEHU

UPPER LOWER

○	●	BOMB-CLASTS
□	■	ROUNDED CLASTS
△	▲	AXIAL DIPOLE

FIG. 46. NRM vectors for "Type C" heterolithic tuff breccia. Five breadcrusted bomb clasts and five rounded clasts were cored at the 77 m interval of Ruapehu Section 3 (Fig. 27). "Upper, lower" refers to vectors in upper or lower hemispheres of the equal-area plot. Present-day axial dipole is noted. Vectors for bomb clasts are clustered, suggesting cooling from temperatures above average blocking temperature. Displacement of these from present axial dipole is consistent with down-dip rotation to the SE, as a result of slumping after cooling. Other clasts display random vectors, consistent with emplacement below blocking temperatures.

already unstable deposit, (3) explosions resulting from extrusion of lava onto snow, onto water-saturated ground, or into water courses, and (4) deformation associated with subterranean movement of magma.

The reversely graded bases of many tuff breccia units can be explained by the hypothesis of Naylor (1980), who suggested that the strongly sheared bases of debris flows are relatively weak and can therefore only support smaller clasts. Neall (1976) has subdivided lahars into volcanic mudflows (50 percent or more sand- and mud-sized material) and debris flows (less than 50 percent fine material). By these definitions, type A and type B tuff breccias correspond to debris flows and mud flows, respectively. However, in sedimentological terms the distinction has little meaning, since the two types of deposit were probably transported by similar mechanisms and can be regarded as parts of a continuous spectrum. Debris flow mechanisms have been described for flows with as little as 20 percent clay-sized material (Curry, 1966). Dispersal pressure between large clasts may also have some role in sediment transport for the most matrix-poor units.

Type C deposits require a more complex explanation because of the presence of large black volcanic bombs. It is likely that the bombs were transported and deposited in a hot and plastic condition and that the arcuate cooling cracks post-date deposition, because the bombs would not likely have survived any mode of transportation in their present highly fractured state. However, there is an absence of signs to indicate that the matrix was ever at an elevated temperature, such as charred vegetation, oxidation, or gas escape pipes. The magnetic measurements suggest that the bombs were deposited in their present positions at a temperature near the Curie point, whereas the remaining clasts were closer to minimum blocking temperatures. In form, the bombs are strikingly similar to vulcanian deposits from the 1975 eruption of Ngauruhoe.

Possible mechanisms are: (1) hot, plastic airfall ejecta falling onto a pre-existing volcanoclastic deposit, mobilizing it as a lahar, and becoming incorporated into the cold material, and (2) the hot bombs are one clast component of a generally cold lahar which was generated directly by explosive eruption. It is clear from experimental studies related to eruption columns (Wilson, 1976) that the slow rate of heat conduction through clasts severely limits heat exchange between large clasts and surrounding fluid, permitting hot large clasts to be transported finite distances in a cold medium without rapid cooling. One other example of this type of deposit, with mixed hot and cool clasts, has been described from Mt St Helens by Hoblitt and Kellogg (1979).

Bedded sand and gravel (SG)

Cross- and planar-bedded, well sorted sands and gravels are commonly associated with heterolithologic tuff breccias in the Wahianoa Formation, but comprise a minor component of the overall stratigraphy. Contact relations with TBh range from abrupt to gradational, and from irregular to nearly planar. SG units are nearly always less than a metre in thickness. A second mode of occurrence is as discrete pockets of high angle cross bedded sand in large interstices of coarse autoclastic and airfall breccias (Figs. 47, 48).

The good sorting, sedimentary structures, and heterolithologic character of these units indicate that they are fluvial deposits. Discrete SG beds with abrupt, planar to irregular contacts with over- and underlying units were probably the products of sheet wash during periods of high rainfall. Other SG units overlies TBh and are gradational into the TBh without changes in matrix colour or clast petrographies (e.g., the 6 - 8 metre interval of RS 6; Fig. 32). These SG may have been produced by de-watering of the underlying laharic TBh.

Interstitial cross bedded sands in coarse breccias are clearly not the products of a single depositional event since (1) large clasts sometimes exhibit welding at points of contact,

FIG. 47. Cross-bedded sand filling interstices of coarse breccia; 19.2 -19.8m interval of RS 3 (see: Fig.27).

FIG.48. Cross-bedded sand in coarse breccia; Wahianoa Fm at T20/337093, N122/088644.

which is indicative of emplacement at temperatures above the vapourization temperature of water, and (2) no aqueous fluid can transport metre-sized blocks and fine sand simultaneously. The cross bedded, fine matrices are clearly secondary fluvial additions to coarse, primary, highly permeable pyroclastic or autoclastic deposits. Additional examples are found in Mangawhero Formation SG deposits. Modern analogues to these "mixed deposits" can be seen at a number of locations around Ruapehu where modern streams, in times of flood, have washed sand into open pore spaces in older coarse fluvial or pyroclastic/autoclastic deposits. The "mixed deposits" are considered to be analogous to sieve deposits described from alluvial fan environments (Hooke, 1967).

2.6 MANGAWHERO FORMATION (New formation name)

DISTRIBUTION, THICKNESS AND VOLUME

The Mangawhero Formation is named after the Mangawhero River, which drains part of the southwestern flank of Ruapehu. The formation is extensively exposed over most of Ruapehu, except for the southeastern slopes, and its deposits form the present-day high peaks (except Te Heuheu, the northernmost summit region) and main cone of Ruapehu. Compared to older formations, the deposits have been less deeply incised by glacial and fluvial erosion (Fig. 49), but numerous local intraformational fluvial unconformities are present. The vast majority of the deposits are lava flows and associated autoclastic breccias, with a total exposed thickness of up to 120 metres and an estimated volume of 35 km³.

TYPE AREA: Headwaters of the Mangaturuturu River, southwest Ruapehu

FORMATION BOUNDARIES

Localities for the lower boundary have been described under Wahianoa Formation. An additional exposure of the basal contact occurs in the headwaters of the Whakapapaiti Stream (RS 12, Fig. 15), where black, plagioclase-phyric and grey olivine-bearing lavas of the Mangawhero Formation unconformably rest on the glaciated surface of a Te Herenga Formation lava

FIG. 49. A: Aerial photograph of southwestern slopes of Ruapehu, showing tabular lava flows and autobreccias of Mangawhero Fm.
 B: Northeastern slopes, showing main cone of Mangawhero and Whakapapa Fms.

Pyramid Peak (P) comprises tephra of Whakapapa Fm. Remnants of older cones comprise Wahianoa Fm of Whangaehu Gorge (WG) and Te Herenga Fm of Pinnacle Ridge (PR). Localities for stratigraphic sections in Mangawhero Fm are also shown.

flow. The base of the formation is thus defined both by conspicuously unconformable relations with Wahianoa and Te Herenga Formation deposits, and by an abrupt change in the phenocryst mineralogy of the deposits across the contact. The petrographic distinction is an important one, as numerous intraformational glaciofluvial unconformities exist within the Mangawhero Formation. Were it not for the abrupt change to olivine-bearing eruptives, the lower formation boundary would be far less confidently defined.

Mangawhero Formation is locally overlain by post-glacial eruptives of the Whakapapa Formation. The relation is clearly unconformable on the flanks of Ruapehu, but not in the western summit region. Whakapapa Formation of the northern summit region (Te Heuheu Ridge) is separated from upper Mangawhero deposits of Paretetai-tonga, by the Whakapapa Glacier. No unconformity can be identified, and in the western summit region there is a suggestion that activity from summit vents was continuous across the Mangawhero/Whakapapa boundary.

AGE

On the basis of two K-Ar dates from the middle of the formation (Stipp, 1968; Fig. 5, this volume), the numerous intraformational unconformities, and the overall degree of dissection, the writer speculates that Mangawhero volcanism occurred over a time interval between about 50,000 and 15,000 years ago. This encompasses the brief time at which parasitic volcanism occurred (see below).

LITHOLOGY AND PETROGRAPHY

Mangawhero deposits are present in RS 9 through 13 (Figs 15, and 50-53). About 96 percent of these deposits consist of lava flows and monolithologic tuff breccias (TBm), and the remainder are heterolithologic tuff breccias (TBh), sand and gravel (SG), and mantle- or shower-bedded tuffs (T).

FIG. 50. Ruapehu Section 9. 76 m of Mangawhero Fm exposed at Girdlestone Peak, southeastern summit region of Ruapehu (see: Fig. 23). Grid references for base of section are: T20/313087 (metric), N122/062636 (yard).

FIG. 51. Ruapehu Section 10. 42.5 m of Mangawhero Fm exposed beneath Tahurangi (see: Fig. 59), southern summit region of Ruapehu. Grid references for base of section are: T20/309098 (metric), N122/057647 (yard).

FIG. 53. Ruapehu Section 13. 117 m of Mangawhero Fm exposed in an unnamed stream valley of northeast Ruapehu. Grid references for base of section are: T20/351135(metric), N122/101690(yard).

Lava Flows

Twenty-nine lava flows, measured from all Mangawhero sections, range from 1.5 to 35 metres, and average 8.4 metres in thickness. Flows are nearly always associated with TBm, and the transition from flow to breccia is abrupt. Most flows have rubbly margins, but nearly planar tops are present, suggesting brief erosion between flows. Blocky and platy jointing of the flow interiors is characteristic, but some glassy flows have well-developed columnar jointing.

The flows exhibit widely varying petrographies, from black, glassy dacites, to medium grey olivine basalt. Conspicuously olivine-bearing flows are particularly abundant at, but not restricted to, the base of the formation.

Monolithologic tuff breccias (TBm)

These incorporate all the characteristics of TBm deposits described perviously for other formations and are accordingly interpreted as autoclastic breccias formed by the fragmentation of flowing lava. A drawing of the often chaotic association among lava flows and TBm is presented as Figure 54.

Heterolithologic tuff breccias (TBh)

This lithology is not abundant in the Mangawhero Formation. In the measured sections, an example occurs at the 38 - 44 metre interval of RS 12 (Fig. 15). Rounded, strongly heterolithologic clasts are supported in indurated, yellow-brown tuffaceous matrices. Crude internal stratification is commonly developed as relatively coarse horizons in a generally finer-grained deposit, and the TBh are commonly associated with SG deposits. TBh and SG occur throughout the formation as local, valley-filling deposits intercalated with the more voluminous lava flows and autobreccias. TBh are interpreted as fluvial-laharic units, which are the depositional counterparts of the numerous intraformational fluvial unconformities.

Fig. 54. Chaotic association of lava flows and autoclastic breccias, lower 16 m of Ruapehu Section 11 (see: Fig. 52).

Bedded, sorted sand and gravel (SG)

Examples of these deposits occur at the 14.2 - 14.8 and 41.5 - 42.5 metre intervals of RS 10 (Fig. 51), and at the 16 - 20 metre interval of RS 11 (Fig. 52).

The deposits in RS 10, and expanded view of which is given in Figure 55, range from crudely bedded sandy gravels to planar- and cross-bedded fine sand and mud. They are interpreted as fluvially reworked airfall material. Deposits in RS 11 (Fig. 56) include bedded, framework-supported coarse gravels which alternate with cross-bedded pebbly sands, and are interpreted as fluvial deposits. A second lithology occurs as coarse, clast-supported TBM, where the interstices are filled with cohesive but uncemented, trough cross-bedded fine sand and silt. This is interpreted as being of identical origin to similar SG units of the Wahianoa Formation.

Well sorted, mantle- and shower bedded tuffs and lapilli tuffs (T)

These deposits are rare in the Mangawhero Formation. Two examples occur at the 14.8 - 16.5 and at the 41.5 metre interval of RS 10 (Fig. 51; expanded drawings in Fig. 57). Shower and mantle bedding are well developed, and the deposits are interpreted as primary magmatic and phreatomagmatic airfall units. At the 41.5 metre interval of RS 10, alternating coarse ash and fine ash laminae contain coarse lapilli with bomb sags.

Intrusive bodies (I)

Intrusive bodies are restricted to a few vertical dykes. None are recorded in the measured sections, but numerous conspicuous examples occur at Girdlestone Peak (Fig. 23). Many of these dykes are dark and olivine-bearing, and are petrographically similar to the associated lava flows. Several metres of the surrounding country rock are commonly altered to a deep brown colour. A few are breccia dykes having lithologies nearly identical to autoclastic tuff breccia, but differing from the latter in that they are not pervasively oxidized. These dykes

FIG. 55(left). SG deposits of Mangawhero Fm; 41.5-42.5 m interval of Ruapehu Section 10 (see: Fig. 51).

FIG. 56(right). SG deposits of Mangawhero Fm; 16-20 m interval of Ruapehu Section 11 (see: Fig. 52).

FIG. 57. Bedded tuffs and lapilli tuffs of Mangawhero Fm; 14.8-16.8 m and 41.5 m intervals of Ruapehu Section 10 (see: Fig. 51).

exhibit clear intrusive relationships to the host deposits (Fig. 58), and surrounding deposits of the Wahianoa Fm are locally oversteepened. Park (1886) noted that: *"On the north side of this peak (Girdlestone) there is a great boss or dome of dark smooth pitchstone in which the lines of fluxion are well marked"*. This intrusive body was not identified by the present writer but is almost certainly related to the dark, ol-bearing Mangawhero dykes described above.

Discussion

Because younger formations such as the Mangawhero are not deeply eroded and are exposed over large areas, they afford an opportunity to evaluate the areal distribution of vent regions and their eruptive products.

Most of the Mangawhero Formation was produced by subaerial effusion of lava as tabular flows, and a large quantity of autoclastic tuff breccia is associated with these flows. Local fluvial unconformities occur throughout the formation, as lava flows were emplaced onto previously dissected terrain. Perched terraces of heterolithologic tuff breccia (lahars) and fluvial deposits are observed in present-day stream courses, and similar deposits were intercalated between Mangawhero lava flows.

Eruptions issued from several centres in the summit region. In the southern part of this region, dips of Mangawhero deposits are radially disposed around a point between Crater Lake and Tahurangi. Several intraformational unconformities are evident in the deposits beneath Tahurangi (Fig. 59), sometimes having broad, U-shaped outcrop traces, suggestive of alpine glaciation during the period of deposition. Many deposits beneath Tahurangi and in the cliffs between Tahurangi and Paretetaitunga exhibit hydrothermal alteration, confirming that a vent existed in the southern part of what is now the Crater Lake Basin.

Cathedral Rocks (Fig. 60) consist of hydrothermally altered heterolithologic and monolithologic tuff breccias of

FIG. 58. Dykes of Mangawhero Fm at Girdlestone Peak.
A: Intrusive breccia with unbrecciated margins.
B: Subvertical dyke cutting lava flows and autobreccias of Mangawhero Fm.

FIG. 59. Glacial unconformities developed in Mangawhero Fm beneath Tahurangi (Ruapehu summit). Crater Lake in foreground. (NZGS photo by D.L. Homer).

FIG. 60. Cathedral Rocks, western summit region of Ruapehu. The exposure comprises altered tuff breccias of Mangawhero Fm, erupted from a vent which occupied the Summit Plateau (to the left of photograph). The dipping lavas and tuff breccias at the right of the photo form a small planeze surface.

FIG. 61. Feeder dyke for northern Flank eruptions of Mangawhero Fm at locality T20/329156(metric), N112/077713(yard).

the Mangawhero Formation. Hydrothermal alteration intensifies northwestward, and individual depositional units are separated by bedding planes which dip to the southeast. These observations imply a source vent which occupied the region of the present-day Summit Plateau.

Another apparent vent region is Girdlestone Peak. The Wahianoa-Mangawhero boundary is defined here, and some of the most complex geology on the mountain is exposed (Fig. 23). Both formations are intruded by irregular dykes of massive lava and breccia.

A single Mangawhero flank vent is documented on north Ruapehu, where a vertical dyke is observed to have fed a dacite flow (Fig. 61).

2.7 WHAKAPAPA FORMATION (New formation name)

DISTRIBUTION, THICKNESS AND VOLUME

The Whakapapa Formation is named after the Whakapapa skifield on the northwestern slopes of Ruapehu. The formation is defined as conspicuously young, post-glacial lava flows, autoclastic breccias, and pyroclastics which exhibit only minor fluvial erosion, although the deposits of the summit region have undergone minor erosion by Holocene alpine glaciers. Eruptions occurred from at least six discrete vents, and the deposits from each of these vents are given Member status. The Whakapapa lava field of northwest Ruapehu, the Taranaki Falls lava flow, and the lavas and pyroclastics of the Te Heuheu Ridge all erupted from a vent at the northern summit region of Ruapehu, and comprise the Iwikau Member. A second summit vent is the currently-active Crater Lake vent, which erupted minor pyroclastics and lava flows that comprise the Crater Lake Member. Flank eruptions occurred as well. Two lava fields and minor pyroclastics were produced during flank eruptions on the northern slopes of Ruapehu, comprising the Tama Member. Voluminous lava flows and lesser pyroclastics comprise the Rangataua Member, which erupted from a single flank

vent on the southern slopes of Ruapehu. Welded airfall tuff and vertical dykes of the Pinnacle Ridge Member issued from fissures along this ridge.

The formation is neither thick nor voluminous. A maximum thickness of about 50 metres is exposed in the upper Whakapapanui Gorge, northwest Ruapehu, where the Whakapapa lava field has been deeply incised by fluvial erosion (Fig. 74). Summation of the volumes for individual Members yields a total volume of 2.6 km^3 for Whakapapa Formation.

FORMATION BOUNDARIES

Lava flows and fragmental deposits of the Whakapapa Formation unconformably overlies those of all other formations, except in the region of Paretetaitonga, where Mangawhero and Whakapapa deposits do not exhibit unconformable relations. No upper formation boundary is defined, because modern eruptives from the Crater Lake vent are included in the formation definition.

TYPE AREAS: each defined member comprises its own type area.

LITHOLOGY, PETROGRAPHY AND GENESIS OF MEMBERS

RANGATAUA MEMBER

The lava flows and essential pyroclastic material are plag-cpx-opx andesites with dark grey to black matrices.

The vent region for these eruptives is a low, elongate mound of welded and unwelded pyroclastics (Fig. 62). A measured section of Rangataua lithologies, taken near the vent region, is shown in Figure 63. At the base of the section, angular blocks and lesser moderately vesicular bombs up to 15 cm are supported in a thoroughly welded, oxidized, micro-vesicular matrix. No sag structures are present beneath the large clasts, and the deposit is poorly sorted and lacks internal stratification. It is interpreted as a pyroclastic flow. Above this are shower-bedded lapilli tuffs. These are well sorted but contain some red scoriaceous bombs up to

FIG. 62. Aerial photograph of the southern slopes of Ruapehu. Vent region for the Rangataua Member is enclosed in box outline. Lava flows travelled southward from this source. Gray ridge below vent region is lateral moraine covered by pyroclastics at the right of the vent region. Locality for RS 14 is circled.

FIG. 63. Ruapehu Section 14. 12.5 m of Rangataua Member (Whakapapa Fm) exposed in a stream valley to the east of the vent region, south Ruapehu. Grid references for base of section are: T20/306065 (metric), N122/055612 (yard).

10 cm. The sorting and shower bedding indicate an airfall origin. The welded unit above this exhibits excellent internal stratification and good sorting of the individual welded clasts. The deposit is interpreted as welded airfall (agglutinate). At the top of the section, a lava flow and autoclastic breccia are exposed.

In this section, the violence of eruptions is seen to have decreased with time, from emission of a small pyroclastic flow, to deposition of airfall pyroclastics, to the relatively mild effusion of lava flows. Such a stratigraphy is consistent with interpretation that the vapour-rich top of a magma chamber was first erupted, then followed by mild effusion of voluminous but relatively de-gassed lava flows. The Rangataua lava flows are the most extensive and voluminous on Ruapehu; They extend nearly 14 km from source, have an average aggregate thickness of about 60 metres, cover an area of 24.3 km^3 , and have an aggregate volume of 1.5 km^3 . The flows, of which there are at least two and a maximum of six, are excellent examples of block lava. The flows are narrow (about $\frac{1}{2}$ km) to a distance of about 7 km from source, due to cooling of the margins and construction of high stopbanks of blocky debris. Subsequent drainage of the central channel has produced a trough-like cross section. Beyond 7 km from source, the flows have spread laterally on gentler topography of the ring plain, producing immense lobes with steep blocky flow fronts exceeding 30 metres in height.

TAMA MEMBER

This member consists of lava flows and minor pyroclastics which erupted from two flank vents on the northern slopes of Ruapehu (Fig. 64). No well exposed vertical sections through these deposits are known, but ground traverses have confirmed some of the same lithologies as are present for the Rangataua member. The northern lava field comprises two flows of block lava that issued from a single vent at the southern limit of the field. These cover an area of 6.5 km^2 and have a volume of about 0.2 km^3 . The vent is evident as a low mound of coarse, locally welded airfall ejecta consisting largely of blocks

(Fig. 65). The eruptives are dark grey andesites.

A second block lava flow of lesser volume and area is present on the northern slopes at about 1,900 metre elevation. This lava is black low-silica andesite. The vent region for this flow is an inconspicuous low mound of blocky debris at the southern limit of exposure.

Minor shower-bedded lapilli tuffs were produced during the early stages of activity from these vents (Fig. 66).

PINNACLE RIDGE MEMBER

Between about 1,550 and 1,900 metre elevation, the Te Herenga Formation of Pinnacle Ridge is unconformably mantled by welded breccias and tuffs (Figs. 21 and 67). The deposit is exposed over an area of about 0.8 km^2 and has a volume of about 0.01 km^3 . Stratigraphic sections are presented in Figure 68. In distal sections at lower elevations, the deposit consists of internally stratified and well sorted pyroclastics exhibiting widely varying degrees of welding (RS 15A and B; Figs. 68 and 69). The deposit has a steep primary dip, and in the densely to moderately welded portions, moderately vesicular to pumiceous essential clasts are flattened parallel to the stratification, giving the appearance of ignimbrite (Fig. 70). A second clast component is present as accessory subangular to subrounded lithic blocks of the Te Herenga Formation which were derived from the underlying lateral moraine and colluvium (Fig. 71).

Higher on the ridge, the deposit still exhibits internal stratification (Figs. 72 and 73), but it is thicker, is overall more densely welded, and generally contains larger accidental lithics (RS 15C).

The welded character of the deposit led Parsons (unpub. map in files of N.Z. Geological Survey, Rotorua) to term it an ignimbrite. Although dense welding and eutaxitic texture are

FIG. 67. Oblique aerial photograph of the northwestern slopes of Ruapehu. Welded airfall tuff of Pinnacle Ridge Mbr, Whakapapa Fm, is outlined. Locations of dykes for Pinnacle Ridge Mbr are shown with arrows.

FIG. 68.

Ruapehu Sections 15 A,B,C.
Welded airfall tuff of
Pinnacle Ridge Member,
Whakapapa Fm, exposed at
Pinnacle Ridge, NW Ruapehu.
Grid references for bases
of sections are:
A: T20/317163, N112/065722,
B: T20/321163, N112/068721,
C: T20/318152, N112/065707.

FIG. 72. Internal stratification in welded airfall tuff, Pinnacle Ridge Member.

FIG. 73. Thick, densely welded airfall tuff near the vent region for Pinnacle Ridge Member. Note the large lithic block from underlying Te Herenga Fm.

indeed well developed, the deposit as a whole does not exhibit regular zones of internal welding, such as are produced by compactional flattening of pumice clasts in welded pyroclastic flows. Rather, the degree of welding is irregularly developed in the vertical sense, and the deposit thins and grades laterally over short distances into poorly- and non-welded stratified equivalents.

These are precisely the characteristics of welded airfall tuffs (Sparks and Wright, 1979). If the Pinnacle Ridge welded airfall tuff did not undergo major secondary mass flowage (rheomorphism), as appears to have been the case, then thickness and maximum size of accidental lithics would be expected to increase toward the vent. Using these criteria, the vent region must have been in the vicinity of the upper-elevation limits of exposure. Indeed, a feeder dyke for these deposits parallels the ridge crest, and can be traced southward up the ridge for a distance of 1.2 km (Fig. 21). The dyke is irregular in trend, and varies from about 1.5 to 3 metres in thickness. At its southern limit of exposure, the dyke is overlain by its own welded airfall ejecta. The erosional remnant of a second dyke is present as a single outcrop in the headwalls of the Whakapapanui Gorge (see: O'Shea, 1957, p.59). Apparently, Pinnacle Ridge was the site of volcanism during both Te Herenga and Whakapapa times, although the character of the eruptions differed considerably.

The juvenile magmatic material of the Pinnacle Ridge Member is black andesite with conspicuous plagioclase phenocrysts.

IWIKAU MEMBER

Many eruptives of the Whakapapa Formation, including the voluminous andesite flows of the Whakapapa lava field, can be traced to the northern summit region of Ruapehu. The Iwikau

Member is defined as all eruptives that issued from this northern vent during Whakapapa time. The original morphology of the vent region is obscured by the broad ice field of the Summit Plateau, and Holocene alpine glaciers have modified the

vent rim. Te Heuheu Ridge and its southwestward extension consist of thin lava flows, autoclastic breccias, and pyroclastics which dip radially away from the Summit Plateau. These deposits are well exposed on the high northern slopes beneath Te Heuheu. The most voluminous lithologies are thin (generally less than 2 metres) lava flows and autoclastic tuff breccias with variable degrees of welding. Other deposits are sorted and stratified, and contain essential pumiceous to moderately vesicular clasts. Vesicular clasts occur up to about 20 cm, and the deposits are often weakly welded at clast contacts. These are interpreted as coarse airfall ejecta. In one coarse, oxidized airfall deposit on the northern slopes below Te Heuheu, the abundance of accidental metamorphic enclaves is remarkable, and approaches several volume percent of the deposit. The enclaves are largely granoblastic to foliated quartz-biotite-garnet rock fragments, which can exceed 10 cm. A large area of the northern and northeastern flanks of Ruapehu is blanketed by primary and reworked pale brown andesite pumice lapilli which were erupted from this northern vent, as deduced from the coarsening and thickening of the airfall pumice as Te Heuheu is approached.

A valley-filling deposit of pervasively oxidized and moderately welded heterolithologic tuff breccia travelled eastward from the northern summit region into the headwaters of the Mangateoteonui Stream, NE Ruapehu. This is interpreted as a pyroclastic flow on the basis of its poor sorting, lack of internal stratification, heterolithologic character, valley-filling disposition, and evidence for high temperature emplacement. It is one of only a few pyroclastic flows which have been identified on Ruapehu.

Voluminous lava flows issued from the northern summit region onto the northwestern slopes. Both the Taranaki Falls lava flow and the Whakapapa skifield lava flows travelled about 8.5 km from source. The Whakapapa lava field (Fig.8) consists

of at least six flows, covers an area of 10.5 km^2 , and has an estimated aggregate volume of 0.75 km^3 . The lavas and associated monolithologic tuff breccias are well exposed throughout the Whakapapa skifield (Fig. 74) and along the Bruce Road, to their termination at the Silica Springs track. These exposures provide excellent opportunity to study the process of autobreciation. Autoclastic breccias are commonly welded in the near-vent region, where flows are thin. As more distal regions are traversed, the character of the autobreccias changes from angular, clast-supported and welded, to angular, clast-supported and unwelded, to subrounded clasts floating in unwelded, mostly lapilli-sized matrices. The latter, especially, closely resemble lahars, except for their monolithologic character, and represent viable parent material for secondary mass flows (lahars and debris flows). Figure 75 illustrates these lithologies.

CRATER LAKE MEMBER

Crater Lake Basin (Fig. 76) is a topographic feature of complex origin. Today, much of the area is covered by small alpine glaciers that terminate at the margins of Crater Lake and occupy the headwaters of the Wahianoa. During Mangawhero eruptions, a vent certainly existed not far south of the modern Crater Lake. Since that time, the basin has been greatly modified by glacial erosion and probably also by explosive volcanism. A larger basin, of combined erosional and explosive origin, and represented by the high peaks around Crater Lake, existed prior to the onset of activity from the present Crater Lake vent. Pyramid Peak (Fig. 77), a tephra mound of about 0.002 km^3 volume was constructed within this larger depression, obstructing the valley which previously drained Crater Lake Basin into the headwaters of the Whangaehu. Pyramid Peak consists of several lithologic types: thin lava flows with associated monolithologic tuff breccias; layers of oxidized scoriaceous bombs up to 0.5 metres, usually stratified and including subordinate dense, angular blocks; welded breccias and tuffs, some of which are well sorted; and shower-bedded

FIG. 74. Block lava flows and autoclastic breccias of Iwikau Mbr. Exposed at Whakapapa Skifield, NW Ruapehu, by fluvial erosion. Locality T20/314140 (Metric), N122/061695 (yard).

FIG. 75. Autobrecciation of block lava flows of Iwikau Member, exposed at Whakapapa skifield and along Bruce Road, northwest Ruapehu.

- A: Incipient brecciation of lava, one km from the northern summit vent. The flow is internally sheared, but no fragmental matrix is present.
- B: Sheared lava flow resting on coarse autobreccia with angular clasts, 4 km from vent.
- C: Voluminous autobreccia with subrounded clasts and abundant matrix, 6 km from vent.

FIG. 76. Crater Lake basin, photographed from Ruapehu summit. Lake outlet at centre of photo. Pyramid Peak, a tephra mount, to the right.

FIG. 77. Mantle-bedded pyroclastics and subordinate lava flows of Pyramid Peak.

units which include block and ash with sag structures, and tuffs/lapilli tuffs. Local unconformities are common, and the deposits are mantle-bedded over the rim of the tephra cone.

Most of these deposits are coarse airfall and ballistic ejecta, with minor effusive activity represented by thin lava flows. Some of the airfall pyroclastics were ejected more than a kilometre from the vent; a mantle of welded pyroclastics covers the eastern slopes of Tahurangi and part of the arête between Girdlestone and Tahurangi. Mitre Peak, a hydrothermally altered erosional remnant of the Wahianoa cone, is mantled on its southwestern face by welded airfall pyroclastics from the Crater Lake vent.

Ejection of coarse airfall pyroclastics onto the outer flanks of Ruapehu has occurred during very recent times, as deduced from the above observations, and from observations on the outer slopes to the south of Tahurangi. Above 2,000 metres on the southern slopes (nearly 3 km from Crater Lake), highly vesicular, black, glassy cowdung bombs up to 75 cm are observed. They commonly contain inclusions of Crater Lake mud, are very fragile, and are sometimes draped plastically over the substrate. These bombs have certainly not been re-deposited, and they indicate that coarse, hot, airfall ejecta have issued from Crater Lake during magmatic eruptions, to a radius of nearly 3 km from source.

AGE

Dating of some Whakapapa Formation deposits has been accomplished by Topping (1974) on the basis of tephra stratigraphy. Topping (1974) estimated that the Whakapapa lava field was erupted between 5,000 and 10,000 years ago, and that the large lava field on the northern flank of Ruapehu was erupted between 5,000 and 9,700 years ago. The northern crater of Ruapehu, which in the present study is considered to have been active during both Mangawhero and Whakapapa deposition, was considered by Topping (1974), to have emitted numerous

tephra deposits between about 10,000 and 14,000 years ago, with sporadic activity continuing until about 5,000 years ago. Topping (1974) also considered that 2,500 years ago, little tephra were being emitted from Ruapehu, and that tephra erupted from Ruapehu since then probably came from the currently active Crater Lake vent. Most activity from this vent has occurred since 1,819 years ago (post Taupo eruption).

No quantitative age estimates exist for the Rangataua Member. These lavas have undergone only minor fluvial erosion and weathering, and morphologically appear to be of similar age as, or only slightly older than, the Whakapapa and Tama lava fields. A provisional age for the oldest Whakapapa Formation deposits is therefore suggested as approximately 15,000 years before present, with the most recent activity (since 2,500 years ago) occurring at the Crater Lake vent.

TAWHAI FALLS LAVA FLOWS

Two block lava flows form an isolated exposure in the Whakapapanui Stream, northwest Ruapehu ring plain (N112/014787). These flows are dark grey, nearly aphyric andesites which have no petrographic analogues on NW Ruapehu. The flows overlies older block lavas with petrographic characteristics similar to those of the Whakapapa Mbr. The Tawhai Falls flows are therefore part of Whakapapa Fm, but are not given Member status. Their precise age is unknown.

2.8 THE ORIGIN OF LAHAR MOUNDS DEPOSITS, NW RUAPEHU

The lahar mounds (Fig. 78) occur as part of Grindley's (1960) Murimotu Lahars Formation. Topping (1974) estimated the age of last emplacement of the deposits at 9,500 to 12,500 years ago, on the basis of their tephra cover. The exposures occur along SH 48 at a road cutting 4 km NW of the Chateau, and at another cutting 50 metres north of the junction of SH 47 and SH 48.

These deposits have created interest not only from a volcanological perspective, but also from an historical one, for they have been variously interpreted since the late 1800's. Hill (1891) considered that the mounds were blisters on the surface of a lava flow that had travelled over water-saturated ground. Cowan (1927) considered them to be bubbles within lava, and Bossard (1928) speculated that the bubbles originated by explosions of volatiles from a gas-rich lava. Park (1926) considered the mounds as drumlin-like features which were deposited by a retreating glacier. Grange and Hurst (1929) were the first to suggest that the mounds were lahar deposits. Healy (1965) suggested that one or more lahars and one or more glowing avalanches came down the Whakapapanui Valley from the northern summit region of Ruapehu. Current opinion appears to favour an origin by eruptions of Ruapehu Crater Lake. *Copied*

The bulk of the lahar mounds are probably debris flows, as deduced from the fact that little clay- or silt-sized material is present, and by the predominance of one clast type for individual depositional units. The mounds exhibit crude internal stratification which is manifested by changes in the relative proportions of clast types, indicating several episodes of deposition. These observations suggest "dry" failure of sectors of the cone at different times and from several source areas. The source areas have been deduced through study of the clast petrographies.

FIG. 78. Map of 'lahar mounds' deposits, their inferred source regions, and probable paths of the debris flows. Unit 1 probably came from the Tama Lakes area. Units 2 and 3 originated in the upper Whakapapanui Gorge, northwest Ruapehu.

Clasts from the interior portion of the SH 48 lahar mound (Fig. 79) are predominantly of altered hornblende dacite. The present writer is confident that no lavas with this petrography occur on NW Ruapehu, and the only documented locality for hornblende-bearing lava is at the lower Tama Lake, in the saddle between Ruapehu and Tongariro. This depositional unit was probably generated during the phreatic eruptions that produced the Tama Lakes craters (ca. 10,000 years ago; Topping, 1974), and travelled down the Wairere Stream to the site of deposition. The mound morphology was developed in this initial deposit from the Tama region.

Later depositional units have mantled the hummocky topography and are thickened on the stoss side of the SH 48 lahar mound. Directly overlying the initial hummocky deposit is a second unit with three types of clast, which closely resemble the Pinnacle Ridge, and Iwikau Members of Whakapapa Fm, and Te Herenga Fm. The third and uppermost tuff breccia is oxidized, suggesting hot emplacement, and the clasts are largely of one petrographic type, similar to that of Whakapapa Member lava flows.

Thus, the clast types suggest that the two younger depositional units originated in the upper Whakapapanui Gorge, near the Top-o-the-Bruce, and travelled down the Whakapapanui Stream where they may have been further mobilized by water or steam. Similarly to the first deposit from the Tama area, the momentum of the debris flows apparently carried them over the stream bank at a bend in the course, leading to loss of momentum and deposition on flat topography.

Topping (1974) has suggested that Ruapehu Crater Lake has been active only for about the past 2,500 years. The present writer has found no evidence of the vesiculated bombs and fragments of metamorphosed lake mud which are characteristic of historic ejecta from Crater Lake. Thus, neither the age of the mounds (greater than ca. 9,500 years b.p.) nor their clast petrographies indicate a Crater Lake source for these

FIG. 79. Photograph and drawing of lahar mound exposed along SH 48. See Fig. 78 for provenance of depositional units. Lithologic descriptions of units are given in the text.

deposits. Rather, the lahar mounds appear to have originated during phreatic eruptions of Lower Tama (ca. 10,000 years b.p.), and from slope failure in the Whakapapanui Gorge/Pinnacle Ridge area of NW Ruapehu. It is not known whether the upper debris flows from Whakapapanui were generated directly as a result of eruptions in this region, but it seems likely that the emplacement of welded airfall tuff and autoclastic breccias of the Whakapapa Fm contributed in some manner to slope instability.

2.9 GLACIAL FEATURES OF RUAPEHU MASSIF

Identification of glacial deposits in volcanic terrains is difficult since they so closely resemble lahars (Neall, 1976; Mathews, 1967). Both mechanisms produce diamictites, and no lithologic criteria can be considered reliable. In this study, the distinction has relied upon constructional morphology: lahar deposits fill valleys and are tabular in form whereas moraine deposition constructs parabolic ridges on the landscape.

The distribution of deposits considered to be of glacial origin is shown in Fig. 80. Aerial and ground photographs of glacial features are presented in Figures 81-83.

No precise statements can be made as to the chronology of glacial deposits on Ruapehu; only rarely can alpine glacial features be dated directly, as a result of near-absence of plant detritus and the uncertainty of its provenance in these regions. The most deeply incised glacial valleys of Ruapehu occur on the two oldest formations, and thus all glacial features must be younger than upper Te Herenga Fm (0.23 Ma). They can therefore only represent glaciations during the Waimean and Otiran Stages of the New Zealand Quaternary. Glacial features developed on Te Herenga Fm of NW Ruapehu are locally overlain by Mangawhero Fm, suggesting that these moraines and valleys were created during the Waimean Stage. Moraines developed on Mangawhero Fm of SW Ruapehu must be younger than about 30,000 years, which implies construction during the

FIG. 80. Glacial moraines of Ruapehu massif. Mapped directly from vertical aerial photographs, using criterion of constructional morphology.

Otiran Stage. There is good evidence for a minimum of three advances during Otiran time, as deduced from the nested triads of moraine ridges in two valleys of SW Ruapehu. The Wahianoa Valley glacial features (SE Ruapehu) are probably also of Otiran age, since the terminal and lateral moraines have undergone only minor dissection, and since the Mangawhero Fm deposits have been incised as well as those of Wahianoa Fm. Finally, relatively minor glaciation of the summit region has occurred during the Aranuiian Stage, as deduced from glacial features developed on Whakapapa Fm (post ca. 10,000 years) at high elevations. The present-day summit region is occupied by small alpine glaciers.

2.10 FAULTING

Faults on Ruapehu (Fig. 84) are those of the Taupo Fault Belt (Grindley, 1960), a system of high-angle NNE-trending normal faults which extends from the Tongariro Volcanic Centre to the Bay of Plenty. Vent locations at Ruapehu have clearly been controlled by regional faulting. The most conspicuous examples of these faults occur on the northern flanks of Ruapehu, where fault scarps exhibit vertical displacements of up to 4 metres. No horizontal component of displacement can be proved. None of the normal faults have displaced lava flows of the Whakapapa Formation.

Greater structural complexity is encountered on the southeastern and southern flanks of Ruapehu, where the faults progressively change trend from NNE to E-W. The E-W faulting is characteristic of Wanganui Basin structures of the south, where Quaternary volcanism is absent. Downthrow occurs mainly on the southern sides of these faults, and several parasitic vents at Ohakune are localized along an E-W fault scarp which displaces Pliocene marine sediments and deposits of the Ruapehu ring plain.

High on the massif, fault traces are generally not topographically expressed, as a result of cover by eruptives from summit vents. An exception occurs on the southern and

FIG. 84. Fault traces on Ruapehu massif. Mapped directly from vertical and oblique aerial photographs.

southwestern flanks of Ruapehu (labelled "A" in Fig. 84), where the trace of a north-dipping fault traverses Mangawhero and Wahianoa Formations. The sense of displacement is unknown. This fault differs from most others in its relatively low dip angle.

2.11 IMPLICATIONS FOR VOLCANIC HAZARD ASSESSMENT AT RUAPEHU

Knowledge of the prehistoric record provides an opportunity to examine processes occurring at time scales of 10^3 to 10^5 years, in contrast to historic observations.

The most voluminous lithologies at Ruapehu are lava flows, autoclastic breccias, and secondary mass flows. These preserve a record of major, largely magmatic episodes which probably occurred over periods of 10^2 to 10^4 years. Lava flows themselves involve comparatively little hazard since they are slow-moving and their courses can be predicted. However, the associated production of voluminous autobreccias during lava extrusion presents a great hazard during major magmatic eruptions. If mobilized by gravity, hot autobreccias can become pyroclastic avalanches, and remain as unstable deposits long after effusion has ceased. Frequent failure of sectors of the cone is an expected consequence when a large proportion of the mountain consists of unstable fragmental deposits which are supported only by jointed and shattered lava flows.

On Ruapehu, the paucity of primary airfall units is remarkable. On steep and unstable terrain, poorly consolidated airfall units have low preservation potentials, and a geographic separation of lithologies results. While unconsolidated airfall deposits are rare on the massif, at distal exposures 10 km east of the mountain, Holocene airfall deposits are the rule and lava flows are exceptional. The geographic separation of lava flows and coarse tuff breccias from coeval airfall deposits is considered to be a result of secondary processes; unconsolidated airfall deposits being rapidly eroded and re-deposited as a component of the tuffaceous matrices in lahars and debris flows. Hazlett (1977) has made

a similar deduction at San Cristobal Volcanic Complex, Nicaragua. In regions with relatively humid climates (New Zealand and Central America), this geographic separation may be a fundamental characteristic of steep-sided composite cones, and has two implications for hazards assessment. First, the geographic separation suggests a high frequency of lahar and debris flow generation on the massif. Second, if the frequency and volumes of tephra are to be evaluated for purposes of hazards assessment, the studies must be performed in distal regions where a relatively complete airfall stratigraphy is preserved.

Modern studies have justifiably emphasized present-day activity from the Crater Lake, and have recognized the propensity of lahar generation from this vent (Fig. 85). The pre-historic record suggests that other mechanisms for lahar generation were also operative. For the Te Herenga Formation, voluminous secondary mass flows were probably generated by slope instability associated with intrusive deformation. For Wahianoa Formation, "Type C" heterolithologic tuff breccias indicate that lahars with a "hot" clast component were generated directly as a result of magmatic eruptions. In Mangawhero Formation, numerous valley-filling lahars and intercalated fluvial sediments suggest frequent but local slope failures, perhaps during periods of heavy rainfall. The failure of unstable deposits in the upper Whakapapanui Gorge, NW Ruapehu, is suggested as a mechanism for lahar mounds deposition, which occurred during deposition of Whakapapa Formation.

These examples provide some justification for slope stability evaluation over a large portion of the upper slopes. In addition, studies of the Te Herenga and Waihia Formation suggest that deformation of the present-day summit region may herald not only magma intrusion and lahar generation from Crater Lake, but also an increased probability of "dry" slope failure on the upper flanks of Ruapehu.

FIG. 85. Aerial Photograph of Whangaehu lahar fan, eastern ring plain of Ruapehu. The fan has resulted from eruptions of Crater Lake during ca. the past 2500 years.

No evidence for eruption of voluminous pyroclastic flows is found in the prehistoric record, in contrast to the situation at some other andesitic composite cones (e.g., Asama, Aramaki, 1963). Composite andesite cones commonly produce voluminous pyroclastic flows, and post-eruptive collapse of the vent regions is often associated with their effusion. This contrasts with Ruapehu, where no evidence for large collapse depressions is found. Furthermore, the mechanism for summit collapse, which commonly involves withdrawal of magmatic support subsequent to the extrusion of voluminous pyroclastics (Williams, 1941) is absent at Ruapehu: pyroclastic flows are neither abundant nor do they have large individual volumes. Small-volume "pyroclastic avalanches" occurred at Ngauruhoe to the north of Ruapehu in 1975 (Nairn and Self, 1978), and the prehistoric record of Ruapehu indicates that similar small-volume pyroclastic flows also contributed to the Whakapapa Formation (Rangataua and Iwikau Members), but only as a minor component.

3. GEOLOGY OF RELATED VENTS

3.1 INTRODUCTION

Parasitic activity at the Tongariro Volcanic Centre is neither extensive nor voluminous, occurring at only two localities. These are the tephra cones and lava flows of Pukeonake, and numerous small craters in the vicinity of Ohakune. The total volume of parasitic eruptives is less than about 0.5 km^3 . The locations of these vents reflect structural trends in the subvolcanic basement. Parasitic activity contrasts with that of the main massif: Short-lived eruptions have produced small, monogenetic tephra cones and minor lava flows, as opposed to the voluminous and long-continued effusion of pyroclastics and lava flows on the massif. Parasitic volcanism probably commenced within the last 25,000 years, and were thus late-stage eruptions, relative to Ruapehu massif.

Hauhungatahi is an additional eruptive centre which lies to the west of Ruapehu. This vent is not considered to be a parasitic centre, since its construction probably began prior to, or during the earliest stages of activity on Ruapehu massif.

3.2 GEOLOGY OF THE PUKEONAKE VENTS

Topping (1974) has discussed the geology of Pukeonake vents in detail. Most of his conclusions have been confirmed by this writer, and portions of the geologic discussion which follows are paraphrased after Topping (1974).

PROPOSED RE-DEFINITION OF PUKEONAKE ANDESITE FORMATION

This writer agrees with Topping's (1974) suggestion that Grindley's (1960) Pukeonake Andesite Formation should be re-defined. The formal definition given below incorporates both the observations of Topping (1974) and observations made during the present study. This definition differs from that of Grindley (1960) in that Pukeonake Andesite here includes both pyroclastics and lava flows, and the areal distribution is re-defined. In particular, several lava flows mapped by Grindley (1960) as Pukekaikiore Andesite are included within Pukeonake Andesite.

DISTRIBUTION AND THICKNESS

The formation is named after Pukeonake, a conspicuous, 143 metre high tephra cone to the west of Tongariro massif. The formation is defined as lava flows, autoclastic breccias, and pyroclastics which occur in this region and which are identified by their conspicuous olivine phenocrysts. Lava flows were confined to valleys and are now exposed only in road cuttings and stream courses over about a 55 km² area to the west of Tongariro (Fig. 86). The deposits are covered by about 5 metres of rhyolitic and andesitic tephra. The formation thickness is highly variable, ranging from the 30 metres of pyroclastics exposed at Pukeonake tephra cone, to the 5 - 10 metre lava flows which travelled westward from their sources.

FORMATION BOUNDARIES

The base of the formation has not been observed, but Pukeonake Andesite almost certainly overlies dissected deposits of the Tongariro ring plain. Where a complete stratigraphy has been preserved (e.g., the exhumed crater of Pukeonake tephra cone), Pukeonake Andesite is overlain by the Oruanui Formation, a conspicuous rhyolitic tephra which erupted from the Taupo region about 19,800 years ago.

LITHOLOGY

Pukeonake Andesite Formation consists of both near-vent pyroclastics and associated tabular lava flows. The pyroclastics are well exposed by stream erosion and recent quarrying at Pukeonake tephra cone. The pyroclastics are mantle bedded over the rim of a central crater. Dark gray to black scoriaceous bomb and lapilli beds with bombs and blocks up to 1.5 metres are present. These alternate with beds in which the large clasts rest in matrices of more pumiceous yellow-grey lapilli and coarse ash. Although pyroclasts range from bomb to medium ash size, individual beds are moderately to well sorted. In the upper portion of the cone, coarse bomb and lapilli beds are locally welded, and an internal unconformity is present.

FIG. 86. Distribution of Pukeonake Andesite Formation.

Associated valley-confined lava flows traversed much of the quadrant to the west of Pukeonake. Non-vesicular lava flows have medium grey matrices (e.g., Mahia Rapids), and vesicular flows are usually black. All of the tephra and lavas contain conspicuous olivine phenocrysts. Exposed thicknesses are on the order of 4 - 10 metres, and often exhibit well-developed flow banding. Two smaller rounded hills to the north of Pukeonake consist of non-vesicular lava flows, and lava with abundant large irregular vesicles; no pyroclastics are found at these exposures.

AGE

Pukeonake Andesite is overlain by Oruanui Formation (Topping, 1974), a rhyolitic tephra unit which erupted about 19,800 years ago. This provides a minimum age for the eruptions, and the absence of a conspicuous paleosol or erosional break at the Pukeonake-Oruanui contact suggests that Pukeonake Andesite erupted not long before the Oruanui was emplaced.

ORIGIN OF PUKEONAKE ANDESITE FORMATION

Prior to 19,800 years ago, lava flows and coarse airfall ejecta issued from several parasitic vents to the west of Tongariro. Three mounds collectively define a N-S lineament which parallels the trend of vents on the main massifs, and is clearly related to regional faulting of the subvolcanic basement. Pukeonake tephra cone was the source of voluminous, coarse, locally welded and locally dispersed airfall deposits which were produced by relatively mild fire fountaining eruptions. Many of the finer ash- to lapilli-sized fall units exhibit palagonitization of the pumiceous fragments. The finer grain size and palagonitization indicate a minor component of phreatomagmatic activity, when water gained access to the vent. Two smaller mounds to the north of Pukeonake tephra cone consist of dense to vesicular lava flows; no airfall ejecta are associated with these, and no appreciable andesitic or rhyolitic tephra cover is present. These vents probably erupted mainly lava flows, and then underwent substantial erosion.

TYPE AREAS

Pyroclastics of the vent region are well exposed in the quarry at Pukeonake tephra cone. Several of the lava flows are exposed in road cuttings along State Highway 47 between Taurewa and Mahuia Rapids.

3.3 GEOLOGY OF HAUHUNGATAHI

Twelve kilometres to the northwest of Ruapehu, the crescentic plateau Hauhungatahi (Fig. 87) consists of lava flows which cap a sequence of ash and breccia units, in turn resting on Miocene (Kapitean Stage) marine siltstones. A geologic cross section of Hauhungatahi is given in Figure 88.

DISTRIBUTION AND THICKNESS OF HAUHUNGATAHI ANDESITE FORMATION

Hay (1967) mapped Hauhungatahi Andesite Formation as "*olivine-augite-hypersthene-labradorite andesite*" but made no mention of its lithology or probable age in the accompanying map text. The formation is named after Hauhungatahi, the 1,519 metre apex of this broad plateau, and is only exposed over an 11 km² area, on and around the margins of the plateau. It is defined as ol-bearing lava flows, autoclastic breccias, and pyroclastics which are exposed on the plateau of Hauhungatahi. Measured sections have not been obtained, but approximately 8 metres of lava flows overlie at least 50 metres of pyroclastics.

FORMATION BOUNDARIES

Hauhungatahi Andesite Formation rests on Kapitean Stage marine siltstones. The basal contact is poorly exposed, and probably occurs at between 1,100 and 1,200 metres elevation around the steep outer slopes of the plateau. A lower elevation limit for the basal contact is provided by documented fossil localities in the underlying marine sediments (Gregg, 1960, p.34), which do not exceed 1,100 metres elevation. Hauhungatahi Andesite is overlain by weathered unnamed andesitic tephra, by weathered rhyolitic Oruanui Formation, and by weathered andesitic tephra of the Tongariro Subgroup (Topping, 1974, section 242).

FIG. 87. Aerial photograph of Hauhungatahi, a deeply eroded volcano to the west of Ruapehu.

FIG. 88. Geologic cross-section of Hauhungatahi.

LITHOLOGY

Several pale purple divine-bearing lava flows comprise the upper portion of the formation, and are responsible for the mesa-like topography. Near the summit, the lavas are highly frost shattered into vertical plates, but elsewhere they are massive. The lowest flow rests on weathered, monolithologic tuff breccia. Large, weathered talus blocks from these lavas commonly occur around the plateau, and are mixed with the overlying andesitic tephra to form a surrounding apron of colluvial deposits. Deeply weathered pyroclastics are well exposed beneath the upper lava flows in the steep concavity of the eastern plateau (Fig. 89). Here, alternating units of weathered block and ash (black, angular clasts in a green, clay-rich matrix), and weathered greenish yellow fine ash occur (well developed planar and cross stratification, and sag structures beneath rounded bombs). Welded tuff breccia occurs near the base of the formation (weathered green ash and lapilli matrix with grey subangular blocks up to 4 cm). The entire pyroclastic sequence is transected by high-angle fractures which are filled with red and green clay. All clasts in the pyroclastic deposits have the same petrography as the overlying lava flows, except for some variation in the degree of vesicularity.

The lower welded tuff breccias probably represent pyroclastic flow deposits which issued from an unexposed but nearby vent region during the early stages of activity. The upper pyroclastics are largely airfall and re-worked airfall material, as deduced from the internal stratification and the presence of bomb sags. This early tephra cone was then armoured by several lava flows and minor associated autoclastic breccias. Assuming a 4 kilometre radius and a 400 metre height for the original cone, which are considered to be maximum probable dimensions, the original edifice did not exceed 10 km^3 in volume.

AGE

Topping (1974, p.111) identified Oruanui Formation within the sequence of andesitic tephra which overlies Hauhungatahi

FIG. 89. Pyroclastics beneath upper sequence of lava flows, Hauhungatahi. Base of lowest lava flow is shown at top of photograph, resting on autoclastic breccia. Exposed in the steep gully of the eastern concavity.

Andesite, providing a minimum age of 19,800 years for the formation. However, the Hauhungatahi Andesite is probably much older than this minimum age. The eroded morphology of the cone suggests that it is one of the oldest volcanic features of the Tongariro region. Furthermore, during the construction of Ruapehu massif, the surrounding area must have been a region of voluminous deposition, forming the Ruapehu ring plain. Yet Hauhungatahi Andesite rests on Tertiary marine sediments, about 200 metres above the encircling surface of the Ruapehu ring plain. This implies extensive erosion of Hauhungatahi Andesite and the underlying marine sediments, prior to advanced construction of Ruapehu massif and deposition of its ring plain. The Hauhungatahi deposits are also deeply weathered, suggesting antiquity relative to Ruapehu massif. Hauhungatahi was probably active prior to, or only during the earliest stages of construction of Ruapehu massif, and may have an age on the order of 0.5 Ma.

TYPE AREA

The best exposures of Hauhungatahi Andesite Formation exist in the precipitous gully of the eastern concavity.

3.4 GEOLOGY OF THE OHAKUNE VENTS

A copy of the following research paper is presented:

Houghton, B.F., and Hackett, W.R., 1984. Strombolian and phreatomagmatic deposits of Ohakune Craters, Ruapehu, New Zealand: A complex interaction between external water and rising basaltic magma. *Jour of Volcanology and Geothermal Res.*, 21, 207-231.

After initial reconnaissance by the present writer, detailed field work and laboratory studies were made jointly with Dr. B.F. Houghton of the New Zealand Geological Survey, Rotorua. The first draft was produced by Dr. Houghton, and subsequently modified by the present writer and by several other reviewers.

STROMBOLIAN AND PHREATOMAGMATIC DEPOSITS OF OHAKUNE CRATERS, RUAPEHU, NEW ZEALAND: A COMPLEX INTERACTION BETWEEN EXTERNAL WATER AND RISING BASALTIC MAGMA

B.F. HOUGHTON¹ and W.R. HACKETT²

¹ *New Zealand Geological Survey, P.O. Box 499, Rotorua (New Zealand)*

² *Department of Geology, Victoria University of Wellington, Wellington (New Zealand)*

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ABSTRACT

Houghton, B.F. and Hackett, W.R., 1984. Strombolian and phreatomagmatic deposits of Ohakune Craters, Ruapehu, New Zealand: a complex interaction between external water and rising basaltic magma. *J. Volcanol. Geotherm. Res.*, 21: 207–231.

The Ohakune Craters form one of several parasitic centres surrounding Ruapehu volcano, at the southern end of the Taupo Volcanic Zone. An inner scoria cone and an outer, probably older, tuff ring are the principal structures in a nested cluster of four vents.

The scoria cone consists of alternating lava flows and coarse, welded and unwelded, strombolian block and bomb beds. The strombolian beds consist of principally two discrete types of essential clast, vesicular bombs and dense angular blocks. Rare finer-grained beds are unusually block-rich. The tuff ring consists of alternating strombolian and phreatomagmatic units. Strombolian beds have similar grain size characteristics to scoria cone units, but contain more highly vesicular unoxidised bombs and few blocks. Phreatomagmatic deposits, which contain clasts with variable degrees of palagonitisation, consist of less well-sorted airfall deposits and very poorly sorted, crystal-rich pyroclastic surge deposits.

Disruption by expanding magmatic gas bubbles was a major but relatively constant influence on both strombolian and phreatomagmatic eruptions at Ohakune. Instead, the nature of deposits was principally controlled by two other variables, vent geometry and the relative influence of external water during volcanism. During tuff-ring construction, magma is considered to have risen rapidly to the surface, and to have been ejected without sufficient residence time in the vent for non-explosive degassing. Availability of external water principally governed the eruption mechanism and hence the nature of the deposits. Essential clasts of the scoria cone are, by comparison, dense, degassed and oxidised. It is suggested that a change in vent geometry, possibly the construction of the tuff ring itself, permitted lava ponding and degassing during scoria cone growth. During strombolian eruptions, magma remaining in the vent probably became depleted in gas, leading to the formation of an inert zone, or crust, above actively degassing magma. Subsequent explosions had therefore to disrupt both this passive crust and underlying, vesiculating magma "driving" the eruption. Cycles of strombolian eruption are thought to have stopped when the thickness of the inert crust precluded explosive eruption and only recommenced when some of this material was removed, either as a lava flow or during phreatomagmatic explosions when external water entered the vent. Such explosions probably formed the unusually fine-grained and block-rich beds in the strombolian sequence.

The Ohakune deposits are an excellent example of the products of explosive eruption of fluid, gas-rich basic magma vesiculating under very near-surface conditions. A complex interplay of rate of magma rise, rate and depth of formation of gas bubbles, vent geometry, abundance of shallow external water, wind velocity and accumulation rate of ejecta determines the nature of deposits of such eruptions.

INTRODUCTION

General processes of strombolian eruption and related phreatomagmatic activity are well-known, from detailed studies of short historical eruptions (Moore et al., 1966; Booth and Walker, 1973; Self et al., 1974; Guest et al., 1974; Kienle et al., 1980) and theoretical studies (Blackburn et al., 1976; Sparks, 1978; Wilson, 1980; Sheridan and Wohletz, 1981). Characteristics of grain size and clast morphology of such deposits are also well-established (Heiken, 1972; Walker and Croasdale, 1972). However, there are few published bed-by-bed investigations of entire scoria-cone or tuff-ring sequences documenting textural variations within single units and transitions between effusive, strombolian and phreatomagmatic deposits.

This paper attempts to document in detail one very well-exposed sequence with numerous transitions between effusive, strombolian, violent strombolian and phreatomagmatic activity and to draw general conclusions about transitions between these eruptive styles.

REGIONAL SETTING

The Ohakune Craters form one of several parasitic volcanic centres surrounding the andesitic composite volcano Ruapehu, at the southern extremity of the Taupo Volcanic Zone, in central New Zealand (Fig. 1). The monogenetic parasitic vents are typically strombolian or phreatomagmatic. Basement beneath Ruapehu is a sequence of Pliocene-Miocene marine sediments (Hay, 1967). South of Ruapehu these strata form fault-bounded blocks protruding through the laharic ring plain of the volcano (Fig. 2). The Ohakune Craters are located on the southern margin of one such fault block and magma probably reached the surface along the near-vertical east-west fault system associated with this block. The Ohakune deposits are immediately underlain by the laharic and alluvial fan which extends southwards from Ruapehu. The deposits are as yet undated but are overlain directly, without any indication of sustained erosion or weathering, by a 20,000-year-old rhyolitic ash from Taupo Volcano. The Ohakune tephra is a distinctive two-pyroxene, olivine low-silica andesite contrasting with the strongly plagioclase-phyric andesites of the main cone of Ruapehu.

OHAKUNE CRATERS

The Ohakune Craters form a nested cluster of four well-defined eruptive centres. The two principal structures, an inner scoria cone and outer tuff

Fig. 1. General geology of southern Taupo Volcanic Zone modified after Grindley (1967) and Hay (1967).

ring, are concentric, with two smaller pits set on the eastern rim of the tuff ring (Fig. 2). A number of small, less well-defined crater forms are visible on aerial photographs of the surrounding area. The craters lie on the flat, gently sloping swampy surface of the Ruapehu lahar fan, which is cut by numerous minor streams, fed by springs discharging from the fault scarp to the north. It is clear that the region is now, and was probably at the time of eruption, one of abundant groundwater. The inner scoria cone is 500 m wide and rises 28 m above the moat separating it from the tuff ring. The southeastern floor of the cone is a northwest-sloping planar surface, which drops abruptly into a steep-walled pit beneath the northwestern wall of the cone.

The outer tuff ring is asymmetrical and between 600 and 1000 m wide, and 20 m high. Surrounding the craters is a thin (<2 m) blanket of distal ejecta, extending eastward and southward for at least 2 km.

Fig. 2. Sketch map of the geology of Ohakune Craters. Localities 1, 2, 3 as in text. Localities 4 and 5 are railway cuttings through the western and southern margins of the scoria cone and localities 6 and 7 are cuttings through the northwestern and southeastern rim of the tuff ring.

Scoria cone

The scoria cone consists of an alternation of strombolian block and bomb beds and massive lava flows (Fig. 3). A quarry at location 1 in Fig. 2 provides an excellent near-radial section through the upper 16 m of the cone. The sequence can be subdivided into lava flows (L), and welded (W), and nonwelded (S) block and bomb beds (Fig. 4). Dips measured on the surfaces of L and W beds average 25° . A 1-m unconformable mantle of phreatomagmatic ejecta is present on the inner wall of the cone at this locality.

The sequence at locality 1 is dominated by coarse-grained, relatively well-sorted, framework-supported S beds (Fig. 3). The S beds are superficially monotonous but contain crude bedding and variations in the proportions of clast types. Red oxidised clasts of essential, low silica andesite form 95–99% of any sample of the deposits. The essential clasts have a unique, plagioclase-poor mineralogy not recognised in any other deposits in the Ohakune area. Essential clasts are of two distinct types: (1) well-formed fusiform to ovoid bombs, with moderately vesicular cores and “breadcrust” rinds; and (2) dense, angular non-vesicular to microvesicular essential blocks. Three types of accidental clast are present in minor amounts: quartzose xenoliths, baked sedimentary inclusions and well-rounded boulders of plagioclase-phyric Ruapehu andesite. The morphology of the latter suggests they are derived from laharic deposits and not primary volcanic material.

Fig. 3. Near-radial, 16 m section through the scoria cone at Locality 1, Fig. 2 (also Fig. 4). *L* are lava flows, *S* unwelded and *W* welded strombolian block and bomb beds. Locations of unusually fine-grained horizons in the *S2* interval are shown (samples 2 and 8). The position of the scoria cone rim is arrowed.

The thick sequence (*S2*) between *L2* and *W1* is typical of the *S* beds and was sampled in detail. A sharp colour change corresponding to increased oxidation of the clasts occurs 5.0 m above *L2* at the level of a prominent concentration of essential blocks. Two atypically finer-grained beds, containing a concentration of dense clasts, occur at 1.2 m and 6.5 m above the base of *S2* (Fig. 3).

Welded block and bomb beds alternate with the unwelded *S* beds in the sequence. Two welded beds (*W1*, *W2*) are well exposed at the top of the sequence at locality 1. The welded beds form resistant ridges, standing out from the more easily eroded *S* beds. Welding is dense, obscuring the primary pyroclastic texture of the beds. Scoriaceous partially welded lenses occur throughout the deposits, often around large dense essential or accidental clasts. Transitions upward and downward through partly welded material into *S* beds are gradational over distances of several centimetres.

Tuff ring

The best exposures of the deposits are on the southern margin of the tuff ring (locality 2) where several quarry faces are oriented both radially and tangentially to the ring (Fig. 5). The tuff ring consists entirely of pyro-

212

Fig. 4. Representative section through scoria cone at Locality 1. White clasts are bombs, black clasts dense essential blocks. Plots of variation with stratigraphic height of (A) range (—) and mean (○) densities of bombs and blocks, (B) ratio of bombs to essential blocks, and (C) % of sample finer than 1 mm.

clastic beds. One major face (A) shows individual beds thinning markedly up the inner wall of the tuff ring before sloping gently down the outer wall (Fig. 6). A composite stratigraphic sequence for the quarry is given in Fig. 7. The sequence is readily subdivided into black, relatively well-sorted, bomb layers (S beds), pale brown, less well-sorted block and bomb layers (Pb beds) and dark brown, poorly sorted ash beds (Pa beds).

S beds in the sequence contrast with the S beds of the scoria cone, in containing principally highly vesicular unoxidised bombs and only relatively minor proportions of dense, degassed essential clasts. The brown colouration of the P beds is due to variable palagonitisation of essential clasts. Pb beds contain internal bedding and often develop bedding sags at the contact to

Fig. 5. Sketch of geometry and stratigraphy of quarry at Locality 2 of Fig. 2, Ohakune tuff ring.

underlying Pa beds. The Pa beds are massive or planar-bedded, but contain internal low angular unconformities, irregular thickness variations and planed erosional contacts (Fig. 8).

Distal apron

The distal apron of ejecta from Ohakune extends southwards and eastwards to North Ohakune township. An excellent exposure 1 km from the craters (locality 3, Fig. 2) contains 2.4 m of bedded tephra (Fig. 9). The

Fig. 6. Face A, locality 2 (see Fig. 8) oriented radially to tuff ring, vent to the left. Note thickening of black strombolian unit (S3) on inner wall of ring and rapid thinning of black S units relative to intervening lighter coloured P units.

deposits are of 3 types, coarse Pb beds, fine-grained Pa layers and isolated ballistic bombs.

The Pb and Pa beds may be correlated with the equivalent units with the tuff ring. Low angle cross bedding and dune bedforms are common in Pa beds at distal localities, and absent in the tuff ring. However, a similar transition, from massive sheet-like material with undulations in bed thickness into more distal material containing dune bedforms, occurs in the deposits of some historical cold, wet pyroclastic surges e.g. Taal Volcano, 1965 (Moore, 1967), or White Island volcano, 25 August, 1977 (Houghton et al., 1979), which are presumed to be analogues to the Ohakune deposits. Isolated ballistic blocks up to 1.0×0.3 m are concentrated at two levels in the section (Fig. 9). These are probably correlative with S beds of the tuff ring, or possibly with Pb beds produced by the most violent explosive events.

GRANULOMETRIC STUDIES

Introduction

Samples of 10–20 kg weight were collected for grainsize analysis by dry-sieving. Sieves at $\frac{1}{2}\phi$ intervals were used for clasts bigger than 2 mm, because of the large sample size, whereas sieves at the normal 1ϕ interval were used for finer material. Size fractions for each sample were then split into the

Fig. 7. Representative stratigraphic column through the tuff ring at Locality 2. Fresh, glass bombs are cross-hatched, palagonitised bombs white and dense essential blocks are black. Variation of mean clast density (●) and the range of clast density (—) with stratigraphic depth shown on right.

following components: vesicular essential bombs, dense essential blocks, accidental lithic clasts and crystals. Density measurements were made for each sample by cutting cuboids from 8–10 large clasts and measuring their masses and dimensions. Samples were collected from localities 1 and 2 but not the distal apron where weathering of clasts precluded sieving. Granulometric data on the samples are summarised in Table I.

Scoria cone

Grain size. The majority of samples collected from S beds are coarse ($M_d > 32$ mm), relatively well-sorted ($\sigma_\phi = 1.5$ – 2.0) deposits containing less than

Fig. 8. Locality 2, Ohakune tuff ring. Pb bed in lower one third of frame and Pa bed at level of hammer, overlain by coarse-grained S2 bed. Note irregular thickness variations in Pa bed. Vent direction is away from the camera.

Fig. 9. Sketch of and stratigraphic column for section through distal apron at Locality 3 in Fig. 2. The Ohakune deposits are overlain by approximately 2 m of younger andesitic airfall ash erupted from the Tongariro volcanic centre.

5% fine material and a high proportion (65-90%) of scoriaceous bombs. The samples are comparable with, but rather coarser than, most of the strombolian samples (Fig. 10) of Walker and Croasdale (1972). The two samples from fine-grained beds in the S2 sequence are much less well-sorted, plotting in the surtseyian field.

The principal variation in proportion of clast types is between dense and vesicular essential clasts, as accessory lithics are never abundant and crystals

TABLE I

Characteristics of pyroclastic units of Ohakune Craters

Unit	Predominant grain size	Sorting	Bedding characteristics	Clast type	Oxidation state	Density
<i>Scoria cone</i>						
1. Normal	Fine bomb— coarse lapilli	Relatively good	Internally and mantle- bedded	Vesicular and subordinate dense essential clasts	Highly oxidised	High
2. Fine-grained units	Fine lapilli —coarse ash	Relatively poor	Internally and mantle- bedded	Subequal amounts of vesicular and dense material	Highly oxidised	High
<i>Tuff ring and apron</i>						
1. S	Fine bomb— coarse lapilli	Relatively good	Internally and mantle- bedded	Highly vesicular fresh glassy bombs	Fresh and unoxidised	Low
2. Pb	Coarse lapilli	Moderate	Internally and mantle- bedded	Fresh and palagonitised clasts	Fresh and unoxidised	Low
3. Pa	Fine ash	Very poor	Erosive base, irregular thickness variations, low angle cross bedding and dune forms in distal sections	Fresh and palagonitised clasts enriched in dense constituents (crystals and degassed blocks)	Fresh and unoxidised	Low

form only a small proportion of the sub-2 mm size fractions. Three samples contain a high proportion of dense essential blocks (Fig. 4), the two fine-grained samples mentioned previously and a sample collected at the level of the prominent parting and colour change in S2.

Fig. 10. Plot of grain-size distribution, by weight, for samples from the S2 interval of the Ohakune scoria cone. Closed symbols represent coarse-grained block and bomb beds, open symbols unusually fine-grained beds (see Fig. 3). Inset plot of median diameter versus Inman sorting coefficient.

Clast density. The calculated average densities and ranges of density for block and bomb populations in the S beds are shown in Fig. 4. Density averages for the two populations vary sympathetically through the sequence, and there is a clear separation between the block and bomb populations for all samples, except in one sample where one bomb with a dense core overlaps with the block population. Average densities of the block populations vary from 2.13 to 2.60, the latter tending towards the value for samples from degassed, nonvesicular Ohakune lava flows or basaltic liquids (Macdonald, 1963; Carmichael et al., 1974). Average densities of the bomb populations vary from 1.39 to 1.59. Density ranges are generally greater for bomb

Fig. 11. Density variation through W2 welded airfall unit at two sections 10 m apart, Locality 1, scoria cone.

populations than for block populations, suggesting greater variability in the actively vesiculating material than in the degassed material disrupted by explosions.

Density of welded units. Difficulty in recognising clast boundaries precluded measurement of flattening ratios or determination of densities of individual clasts in the W beds. Bulk densities were determined on large (100–200 mm) cuboids for two sections through the thicker welded unit (Fig. 11). This figure shows the typical pattern of variation in welding and density through the units. The bulk of the deposit is densely welded, with no visible trace of clast boundaries and bulk densities of $2.1\text{--}2.3\text{ g cm}^{-3}$. Lenzoid zones within the deposit, either localised around large lithics or parallel to bedding are partly welded, show clear clast boundaries, and have densities of 1.7 to 1.9 g cm^{-3} .

Tuff ring

Grain size. The S beds of the tuff ring are in general coarser and better sorted than the Pb beds (Fig. 12). The S beds approximate to a straight line trend

Fig. 12. Plot of grain-size distribution, by weight, for tuff ring samples.

with positive gradient (Fig. 13), extending across the upper edge of the strombolian field on the σ_ϕ/Md diagram of Walker and Croasdale (1972). Three of the four Pb samples plot in the surtseyan field, with the fourth close to the field boundary. While all tuff ring samples contain an appreciably larger fine tail than the scoria cone deposits, this is generally more marked in Pb than S beds. Difficulties in disaggregating the indurated Pa beds prevented extensive sampling for grain-size analysis, but the 3 samples analysed are extremely poorly sorted and bimodal.

Fig. 13. Plot of median diameter versus Inman sorting coefficient for samples of airfall origin collected from tuff ring. Symbols as for Fig. 10. Field of strombolian samples from the scoria cone is circled.

When grain-size analyses for all the probable airfall units (i.e. S and Pb beds) are plotted on a σ_ϕ/Md diagram a near-linear trend of poorer sorting with decreasing grain size emerges. Normal S beds from the scoria cone are grouped at the coarse-grained, relatively well-sorted extremity and are separated from the poorly sorted Pb and fine scoria cone samples by the tuff ring S beds. There are major contrasts in the proportion of clast types between tuff ring and scoria cone samples. Tuff ring samples are dominated by highly vesicular bombs and contain few essential blocks. S beds generally contain 90–100% bombs and Pb beds 60–90%.

Clast density. Densities of clasts in the tuff ring samples are appreciably lower than samples from the scoria cone. In any sample clast densities show a similar scatter about an average value, to the scoria cone but there is little or no variation in average density through the sequence (Fig. 7). Surprisingly, bombs in S and Pb samples show no significant contrast in density.

INTERPRETATION

Model for scoria cone growth

Activity during deposition of the Ohakune scoria cone alternated between effusive and explosive eruptions. The normal products of explosive vol-

canism at Ohakune are relatively monotonous and very coarse grained, relatively well-sorted and only locally dispersed and hence of typically strombolian character. There were however, three types of departure from this pattern of behaviour to produce: (1) similarly coarse grained units unusually rich in degassed blocks; (2) finer-grained, less well-sorted block-rich beds; and (3) welded airfall units.

All clasts in the scoria cone deposits are dense and oxidised relative to the black, highly vesicular bombs of the strombolian beds in the tuff ring. However, with the exception of the oxidation state of iron, the clasts are chemically identical. This suggests that while magma rose freely and was discharged rapidly during the history of the tuff ring, scoria cone magma experienced a period of degassing prior to explosive eruption. The close chemical similarities suggest that the magma at depth remained constant in composition throughout construction of both tuff ring and scoria cone and it seems likely degassing during cone construction took place under near-surface conditions in the immediate vicinity of the vent. This is best accomplished by ponding in a small lava lake prior to eruption.

The degassed relatively dense nature of clasts and the low abundance of phreatomagmatic deposits, in the scoria cone relative to the tuff ring, may be explained by a single factor. This is the construction of some structure or barrier at the vent which both excluded water and permitted lava ponding. The tuff ring itself was probably this structure. Once this barrier existed, lava rose rapidly and ponded and eruptive activity was dominated by explosive eruptions powered by magmatic degassing, at or close to the lava:air surface. Lava ponding also supplies a mechanism to explain the two discrete types of essential clasts, vesicular bombs and dense blocks, found in the deposits. Gas segregation, during scoria cone growth, probably commenced some distance below the explosive foci and large bubbles grew (Fig. 14), removing additional gas from the magma as they rose (McGetchin et al., 1974; Blackburn et al., 1976). Bubble growth therefore scavenged and depleted gas in the lava pond (Sparks, 1978). Each explosion ejected the portion of surrounding magma disrupted by explosive expansion of the bubble at or near the surface, but left behind a gas-depleted region which contributed gas to the bubble but was not disrupted. The result was development of a zone or crust of degassed but hot lava above actively degassing material in the lava pond. Once this crust formed, any subsequent explosions had to disrupt both the actively degassing magma 'driving' the explosion and the overlying crust which played an essentially inert role in the explosion (Fig. 14).

In this model the vesicular volcanic bombs represent the actively degassing component of the magma and the dense, angular essential blocks the lava crust. Presumably the rate of magma supply or vent geometry varied such that at times unwelded block and bomb beds (S beds) were deposited, whereas at other times the rate of accumulation was sufficiently high (Sparks and Wright, 1979) for welding to occur (W beds). The W beds represent the

Fig. 14. Model for explosive expansion of gas bubbles during strombolian phases of construction of the Ohakune scoria cone modified after Wilson (1980). In (a) expansion of gas disrupts actively vesiculating magma-ejecting scoriaceous bombs. Such explosions deplete the remaining magma in gas. With time a degassed crust forms on the lava and explosions disrupt both this crust and the underlying vesiculating magma (b). Finally a critical crust thickness is reached which precludes explosive disruption by magmatic gas and only non-explosive degassing can occur, through cracks and fractures in the crust.

products of periods of very rapid explosive fire fountaining, which presumably prevented formation of an extensive crust of degassed magma. Welding of these units was probably a combination of spattering and agglutination of individual bombs on landing, and deformation in response to loading by further ejecta, rather than purely spattering. This is shown by lenses of only partly welded bombs enclosing large dense blocks, in regions of decreased stress surrounding such blocks. Such zones would not be expected if spattering was the only welding mechanism. For any strombolian eruption to continue, the balance of rates of supply of fresh gas-rich magma and removal of magma must exceed the rate of depletion of gas in magma remaining in the vent. In some instances this is achieved by removal of degassed magma as lava flows, either immediately below the cone (e.g. Etna, 1974; Guest et al., 1974) or at considerably lower elevation (e.g. Etna, 1971; Booth and Walker, 1973). It is clear that at Ohakune the rate of depletion in gas exceeded the rate of magma removal from the lava pond. Thus a form of cyclic activity was established. With time, explosions depleted gas in the ponded magma, producing both an increase in clast density and an increase in the proportion of dense blocks to vesicular bombs. As the lava crust thickened, this deepened the foci of explosions and level of vesiculation and increased the minimum amount of work required to be done by gas expansion to disrupt a portion of the lava pond. A normal strombolian cycle of deposition therefore concluded when explosive gas release ceased or reached a level where ejecta no longer clears the crater rim.

An analogy to this exists in the 1976–1978 eruptions of White Island volcano (Houghton et al., 1979). Three cycles of strombolian eruptions alternating with phreatomagmatic eruptions were recorded. During strom-

224

bolian phases, early eruptions ejected highly vesicular bombs produced by disruption of actively vesiculating magma, but the end of each strombolian phase was marked by a change to a clast population dominated by angular incandescent blocks and by a decreased frequency of explosions to as low as 1 per 15 to 100 minutes.

At Ohakune there appear to have been 2 distinct types of event which followed a strombolian cycle. If magma supply to the lava pond continued, the inert crust was rafted upwards until magma overtopped the scoria cone rim and a lava flow formed. Removal of degassed material with the flow presumably retriggered explosive activity and a return to strombolian eruption. The layer of blocky slabs in the centre of the section at locality 1, probably formed when a lava flow overtopped another, lower, section of the cone.

The alternative sequence of events is where water appears to have gained temporary access to the vent. Although degassed, the crust was hot, molten and potentially capable of flashing water to steam. Such explosions would produce a clast population of fine grain size, rich in dense angular blocks, e.g. the fine-grained, poorly sorted units, within the S beds, which have the grain-size characteristics of phreatomagmatic deposits. A strong predominance of blocky, nonvesicular clasts also suggests that expansion of magmatic gas was not the only explosive mechanism in their generation. Such phreatomagmatic explosions presumably reduced the thickness of crust and hence promoted commencement of another strombolian cycle.

Model for tuff ring formation

Tuff rings are generally associated with phreatomagmatic eruptions and scoria cones with the strombolian style of eruption. The Ohakune tuff ring consists, however, of alternating strombolian and phreatomagmatic deposits. Such deposits are uncommon but not unknown e.g. Rothenberg volcano, East Eifel (Schmincke, 1977), Ukinrek Maars, Alaska (Kienle et al., 1980), Mt. Leura and Tower Hill, Victoria, Australia (J.V. Wright, pers. commun., 1982).

The S beds of Ohakune tuff ring are of magmatic airfall origin and are probably strombolian. The very vesicular nature of clasts, absence of angular degassed blocks and very consistent clast density through the sequence suggests that, during strombolian intervals, magma rose rapidly and continuously and was discharged quickly with little opportunity for near-surface degassing, cooling, oxidation, or reaction with wall material. Bombs in the S beds of the tuff ring are more expanded and less dense than scoria cone analogues. This probably means that fragmentation of the tuff ring magma took place at the peak of vesiculation, whereas fragmentation of scoria cone magma took place after the near-surface magma had already undergone substantial degassing. However the S beds of the tuff ring are less well-sorted and possess a distinct, finer than 1 mm, tail suggesting that there was some limited involvement of water in the explosions.

The Pb beds are clearly phreatomagmatic (abundance of palagonite, poor sorting and fine grain size relative to S beds) and also clearly airfall (presence of internal and mantle bedding, impact sags in underlying Pa beds). They contrast to many maar deposits (Lorenz, 1970, 1973; Schmincke, 1977; Kienle et al., 1980), and indeed to most basaltic deposits in the Taupo Volcanic Zone, in their very low abundance of accessory and accidental lithic clasts. This presumably indicates very shallow foci of explosion and vesiculation. The magma which rose along the fault line at Ohakune was gas rich and evidently reached near-surface levels before undergoing explosive vesiculation. It is therefore probable that explosive eruptions would have commenced without the presence of water, and clast morphology suggests vesiculation was generally already advanced when steam-generated explosions occurred. The role of water was therefore limited to modifying the form of the explosions rather than being their sole cause.

The P intervals at Ohakune lack a number of typical features of many phreatomagmatic eruptions such as accretionary lapilli and vesiculated tuff (Lorenz, 1974; Schmincke, 1977). This probably reflects directly the abundance of water in the eruption column and surrounding atmosphere, and hence indirectly reflects the relative abundance of water and magma at the point of explosion. The model of tuff ring growth is one of very rapid and continuous flow of fluid magma towards the surface, with vesiculation commencing at very shallow levels. Conditions at the vent would have governed whether explosions during this relatively continuous flow of magma were driven by explosive expansion of vesicle gas bubbles ("dry" vent) or by steam explosions ("wet" vent) or by both. Removal of magma by either explosive mechanism always followed quickly on from arrival at the surface without extended ponding or non-explosive degassing.

It remains to invoke a mechanism for alternately permitting and denying access of water to the vent. Scoria cone growth is generally very rapid (Bullard, 1947; Self et al., 1974; Guest et al., 1974). Comparison with historical equivalents (Foshag and Gonzalez, 1956; Wood, 1980; White Island 1976–1978) suggests construction of the Ohakune deposit was probably achieved over a period of several weeks to several months. Hence discrete eruption intervals (S, P, etc.) were probably of the order of several days to several weeks. This level of frequency would be consistent with two possible explanations: (1) a direct correlation with precipitation, with phreatomagmatic eruptions following short duration, high intensity rainstorms; or (2) a "self-sustaining" process whereby the net discharge of heat through the adjacent country from the magma column periodically dried the near-vent area, permitting strombolian eruption.

The latter has the disadvantage of not supplying a mechanism to stop strombolian eruptions. The top of strombolian beds do not show marked enrichment in degassed essential blocks (implying crust formation) or accessory material (suggesting blocking of the vent by wall-collapse) and it therefore seems more likely that influence of sudden pulses of water abruptly ended strombolian periods.

General character of the Ohakune deposits

In explosive basaltic volcanism a wide spectrum exists, from volcanic explosions caused by reaction of magma with external water, through events where water is an influence, to eruptions where external water is not involved. The Ohakune deposits represent the middle ground where the role of water ranges from a minor to a controlling influence but where shallow vesiculation was probably always a factor in promoting the critical rapid transfer of heat. The Ohakune deposits are an excellent example of the range of products produced by explosive volcanism involving fluid, gas-rich basic magma vesiculating under very near-surface conditions. The late onset of vesiculation was presumably due to a very rapid rate of magma ascent.

Very near-vent processes governed the nature of explosions, and hence particle size and morphology, in the case of both scoria cone and tuff rings. The controlling factor during scoria cone formation was the influence and extent of lava ponding, degassing and crust formation. By contrast the tuff ring was constructed during rapid and free discharge of vesiculating magma and the determinant variable was the magma:water ratio.

DISCUSSION

Criteria for recognising eruption type

In many recent studies clast morphology reflects, or is taken to reflect, eruptive mechanism (Heiken, 1972; Walker and Croasdale, 1972; Gutman, 1976; Schmincke, 1977; Self et al., 1980). Strombolian explosions are considered to produce clasts shaped by forces of surface tension, and phreatomagmatic explosions angular clasts bounded by fracture surfaces. The Ohakune study suggests particle morphology may, in some cases, be an equivocal and less reliable criterion than the earlier-established criteria of grain size, sorting and dispersal. Beds consisting entirely of expanded vesicular bombs are certainly the products of magmatic eruptions but dense blocky clasts may be phreatomagmatic or may reflect disruption of a degassed crust during magmatic explosions. Thus clast morphology reflects not necessarily the contrast between phreatomagmatic and magmatic explosions but whether the clast forms by expansion of an endogenous or an exogenous gas phase. The exogenous case includes not only generation of steam by heating of external water but also disruption of inert degassed magma by expanding magmatic gas generated by adjacent and generally underlying vesiculating magma.

Factors governing explosive basaltic volcanism

Explosive basaltic eruptions are small in terms of volume, discharge rate, dispersive power and violence. In addition most strombolian or phreato-

magmatic eruptions are modelled as a sequence of innumerable small closely spaced explosions whereas plinian eruptions of more viscous magma approximate to a continuous 'steady state' gas blast. It is therefore not surprising that slight changes in a number of variables or small variations in very localised, near-vent processes have a much stronger influence on basaltic eruptions. Factors governing the form of basaltic volcanism include:

- (1) rate of rise of magma,
- (2) rate of rise and depth of formation of gas bubbles,
- (3) depth of explosive expansion of bubbles,
- (4) vent geometry,
- (5) abundance of external water,
- (6) wind velocity,
- (7) rate of accumulation of ejecta.

Rate of magma rise has a major influence on eruption style. A very low rate may prevent phreatomagmatic eruption by excluding water from the vent by evaporation of groundwater by a thermal front preceding the magma (Schmincke, 1977), or by evaporation (Shepherd et al., 1979) or displacement of a crater lake (Gregg, 1960). Strombolian, or phreatomagmatic, eruption may occur if magma ascends more rapidly. The formation of welded or nonwelded layers during strombolian eruption is principally a function of rate of accumulation of ejecta. However, if other factors such as eruption column height, wind velocity, and violence remain effectively constant, accumulation rate probably varies directly with rate of magma rise. At velocities above a critical level strombolian activity is superseded by steady-state fire fountaining and production of lava flows (Wilson and Head, 1981).

Episodes of explosive basaltic volcanism are typically short-lived (Wood, 1980) and end abruptly with retreat of magma from the vent. It is hard to sustain strombolian eruption once the rate of magma ascent has declined and fresh actively vesiculating magma is no longer reaching the surface. However, if water can reach the retreating lava column, phreatomagmatic explosions may accompany column retreat, modifying and enlarging the subsurface conduit. Deposits of such waning events are often lithic-rich because the explosive foci are progressively deeper than earlier strombolian and phreatomagmatic events and because material from wall-rock collapse is re-ejected during the late stage events. It is not surprising therefore that late-stage aprons of lithic ejecta are associated with many events, e.g. Tarawera, 1886 (Cole, 1970), Ukinrek 1977 (Self et al., 1980), White Island March 1977 (Houghton et al., 1979). The deep portion of the crater within Ohakune scoria cone and the thin mantling of phreatomagmatic material at locality 1 presumably formed in this fashion. Fluctuations in magma column height is also common while eruption continues (Jagger and Finch, 1924; Kienle et al., 1980), with a major influence on eruptive style.

Rate of magma rise combines with the second and third factors to deter-

mine the depth of magmatic explosions and hence to some extent the proportions of essential and accessory ejecta. They probably also strongly influence the depth of phreatomagmatic explosions in cases where abundant external water is present, because vesiculation is commonly held to be one means of increasing contact area between magma and water and hence rate of heat transfer (Colgate and Sigurgeirsson, 1973; Schmincke, 1977; Self and Sparks, 1978). Where vesiculation and explosions occur at very shallow depths a tuff ring rich in essential ejecta results. Higher proportions of accessory material and maar-like collapse structures are thought to be the products of deeper-seated explosion (Schmincke, 1977).

Vent geometry influences eruptive style in a number of ways. The overall configuration of vent location seems important in determining style and duration of eruptions. For extended strombolian eruptions as recorded at Northeast Crater Etna (McGetchin et al., 1974) it seems essential that degassed magma is removed as lava flows from either adjacent or flank vents. Eruptions from a single simple vent as at Ohakune are invariably of short duration and magnitude.

Changes in vent geometry during an eruption may also alter the eruptive style. The association of maars/tuff rings with valleys and depressions and adjacent strombolian cones with higher ground is well known (Heiken, 1971; Lorenz, 1975; Schmincke, 1977), but even ephemeral accumulation of ejecta about a vent may act to exclude water from the vent and change the course of an eruption. The pattern of discrete phreatomagmatic explosions during the early growth of Surtsey was altered several times by temporary formation of a tephra barrier prior to the final exclusion of seawater (Thorarinsson et al., 1964) and the onset of continuous strombolian eruption. A similar pattern seems to have occurred during construction of the Ohakune tuff ring. Construction of a ring or cone during eruption may also promote ponding of magma, permitting extensive degassing and cooling of the lava during the prolonged residence time at the vent. Such a process must inevitably alter the pattern of explosive activity. While blocky ejecta derived from degassed lava crust are not commonly described from basaltic scoria cones, they are probably misinterpreted as accessory material in instances where the magma petrography is not distinctly different from earlier phases.

Another possible change to vent geometry involves failure or removal of part of a newly constructed tuff ring or cone, either inwards partly blocking the vent and increasing the proportion of lithic ejecta (Booth and Walker, 1973), or outwards either permitting or in response to rafting by lava flows.

The effects of wind speed and direction, in governing the distribution of the products of explosive volcanism, if not their nature, are well documented.

The effects of the relative abundance of external water during basaltic volcanism are best considered through the water:magma ratio which reflects both rate of magma rise and availability of water. Several authors have sug-

Sheridan and Wohletz, 1981). Deposits of water-rich systems show the typical features expected from phreatomagmatic explosions, pronounced bedding sags below ballistic clasts, adhesion of wet tephra on steeply inclined surfaces, extreme soft sediment deformation, accretionary lapilli and vesiculated tuffs. However, in the same way that magmatic gas may play a crucial role in such eruptions, by promoting rapid heat transfer, external water may play an important part in eruptions which show few signs of phreatomagmatic influence (Schmincke, 1977; Sheridan et al., 1981). External water probably played two important roles during essentially magmatic eruptions at Ohakune. Firstly, contact of the actively vesiculating magma with some external water during strombolian phases of tuff ring construction is the probable cause of more efficient magmatic disruption and hence fine grain size and poorer sorting relative to analogous deposits of the scoria cone. Secondly, steam explosions disrupting the degassed crust of the lava pond during scoria cone growth, to produce the fine grained block-rich beds, acted to promote strombolian eruption by reducing pressure on the underlying gas-rich magma.

The Ohakune deposits demonstrate only some of the complex controls on processes of explosive basaltic volcanism. Despite the widespread occurrence of cones and tuff rings and some excellent accounts of gross cone structure and analogous historical eruptions, there are few detailed bed-by-bed analyses of very proximal basaltic tephra. Coarse grain size and apparent monotony of such deposits are deterrents to detailed grain size analysis and study of clast morphology. However, it is these techniques which will offer further insights into explosive basaltic volcanism.

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4. SUMMARY OF GEOLOGIC HISTORY

Eruptions at Ruapehu probably commenced about 250,000 years ago from a vent near present-day upper Pinnacle Ridge (Fig. 90A). It is not known if Ruapehu was a multiple volcano at this time; present exposures indicate a central vent region with dykes radiating from it to the NNW. These early eruptions were petrographically uniform, and comprise the Te Herenga Formation. Early eruptions constructed a steep cone of tuff breccias and subordinate lava flows. The tuff breccias were probably originated by upper slope failure associated with shallow intrusion and deformation of the host cone. Hydrothermal alteration attended intrusion of microdiorite plugs in the central facies. Lava flows and autoclastic breccias were then emplaced onto the fragmental cone, and were probably fed by late-stage dykes.

A period of erosion then followed (Fig. 90B), involving glaciation(s) over unknown time interval(s). Degradation of the Te Herenga cone cannot confidently be attributed to any single glacial episode, and it was probably glaciated during several periods of ice advance.

The eroded morphology of Hauhungatahi suggests that this centre was active concurrently or prior to the earliest eruptions of Ruapehu. Hauhungatahi consists of basal pyroclastics with a capping of lava flows, and rests on Tertiary marine sediments.

Wahianoa Formation was apparently erupted from a central vent to the NW of Mitre Peak (Fig. 90C). The central facies is characterized by hydrothermal alteration, intrusion of several dykes, and the possible presence of intrusive plugs. A radially-dipping sequence of alternating lava flows, tuff breccias, and subordinate airfall and fluvial deposits comprise the proximal facies. The tuff breccias were emplaced as autoclastic breccias and secondary mass flows. Several tuff

breccias have a clast component which was deposited at relatively high temperatures, implying generation of these deposits attendant with magmatic eruptions. Clasts and lava flows exhibit moderate hand specimen petrographic variation.

Degradation of the Wahianoa edifice (Fig. 90D) is indicated by erosion of the upper slopes (unconformity at Girdlestone Peak) and attendant deposition of secondary mass flows at lower elevations (RS 8, Fig. 30).

Mangawhero Formation was unconformably emplaced onto the eroded Wahianoa cone (Fig. 90E). The vast majority of the deposits are lava flows and associated autobreccias, with subordinate fluvial laharic material occurring as local valley-filling deposits. Subordinate airfall material occurs in exposures of the summit region. Ruapehu was a multiple volcano during Mangawhero time. Eruptions were fed by dykes exposed at Girdlestone Peak and at one locality on north Ruapehu. Summit eruptions issued from several vents between Tahurangi and the northern Summit Plateau. In the southern summit region, sufficient time passed between eruptive episodes for the establishment of small alpine glaciers. Eruptions may have spanned a period from about 50,000 to 15,000 years ago, but only two dates from the middle of the formation constrain this estimate. The base of the formation is marked by the appearance of conspicuously olivine-bearing lavas, including one basalt flow. Petrographic variation is great, ranging from olivine basalt to dacites.

During emplacement of later Mangawhero deposits (20,000 to 25,000 years ago), parasitic eruptions occurred at several isolated, monogenetic vents. The Ohakune and Pukeonake vents produced minor volumes of ol-bearing lava flows and airfall pyroclastics.

Whakapapa Formation erupted from four flank and two summit vents during post-glacial time (ca. 15,000 years ago to the present (Fig. 90F). Volcanism in the northeastern summit

FIG. 90. Schematic drawings of Ruapehu history, viewed from the west.

A: Construction of Te Herenga cone.

B: Erosion of Te Herenga cone. Orange colours represent the hydrothermally altered interior.

C: Construction of Wahianoa cone, from summit vent(s) to the southeast.

D: Erosion of Te Herenga and Wahianoa cones.

E: Construction of Mangawhero cone, largely from summit vents.

F: Erosion of Mangawhero cone and eruption of Whakapapa Fm from flank and summit vents.

See Fig. 6 for absolute chronology and inferred glacial stages.

region may have been continuous across the Mangawhero/Whakapapa boundary. The bulk of the deposits are andesite lava flows and autoclastic breccias, with subordinate airfall pyroclastics present at the vent regions. Welded airfall tuff (Pinnacle Ridge Member) and small pyroclastic flows (Rangataua and Iwikau Members) are also represented. Activity from the Crater Lake vent continues to the present day.

The present study indicates that Ruapehu was a multiple-vent volcano during at least ca. the past 30,000 years. Alpine glaciers have modified the vent morphologies of Mangawhero and Whakapapa Formations in the summit region. No evidence for major explosive or collapse events has been found anywhere on the mountain. The present writer therefore concludes that the broad, irregular summit results from multiple-vent eruptions and glacial erosion. In this writer's opinion, the only summit areas which exhibit vestiges of original vent structure and morphology are the Crater Lake, the larger depression encircling Crater Lake, and the Summit Plateau. All other bowl-like depressions are considered to be cirques.

5. GEOLOGY OF WAIMARINO BASALT (new formation name)

The following manuscript has been submitted for publication, and is currently awaiting editorial review:

Hackett, W.R., in press. The Waimarino Basalt: A new basalt locality from the Taupo Volcanic Zone, New Zealand.
(submitted to New Zealand Journal of Geology and Geophysics for publication as a note)

THE WAIMARINO BASALT: A NEW BASALT LOCALITY FROM THE TAUPO
VOLCANIC ZONE, NEW ZEALAND

William R. Hackett
Department of Geology
Victoria University
Private Bag
Wellington

ABSTRACT

Waimarino Basalt (new formation name) is a previously unreported basalt occurrence in the Taupo Volcanic Zone (TVZ). Field relations, major element, and petrographic data show that the Waimarino Basalt is a primitive basalt magma type which erupted to the southeast of Lake Taupo about 15,000 years ago. In contrast to previously reported basalts from the TVZ, the petrography and chemistry are consistent with direct derivation from the mantle, involving little or no modification by differentiation processes. The age and composition of Waimarino Basalt suggest that it is a manifestation of Holocene volcanism in the Taupo Arc.

KEYWORDS

Waimarino Basalt; new formation name; primitive basalt; Holocene volcanism; modal mineralogy; major element data.

¹Present address: William R. Hackett, Department of Geology,
Idaho State University, Box 8072, Pocatello, Idaho,
U.S.A., 83209

INTRODUCTION

The Waimarino Basalt (new formation name), like most basalt exposures in the TVZ, comprises only a few outcrops. The type locality, at grid reference N112 414969, is one of several local exposures within a radius of 0.5 km (Fig. 1). The basalt and overlying andesitic tephra are best exposed along the eastern side of the Waimarino River. The western side largely consists of Taupo Pumice Alluvium, but additional exposures of Waimarino Basalt colluvium occur in cuttings along Motiti Road.

The river has cut a deep and narrow gorge through the underlying Rangitaiki Ignimbrite, exposing at least 6 m of this unit at the base of the section (Fig. 2). The ignimbrite is unwelded, of medium gray colour, and holds conspicuous phenocrysts of quartz, plagioclase, and weathered ferromagnesian minerals. The contact with the overlying basalt is not exposed, but can be inferred within a metre of section. At all nearby exposures where the basalt is absent, andesitic tephra unconformably overlie the Rangitaiki Ignimbrite, and at the type section the andesitic tephra appear to conformably overlie the basalt. A non-conformable relation between the basalt and the Rangitaiki Ignimbrite is therefore inferred.

Approximately 10 m of basalt breccia occur above the ignimbrite, 5 m of which are well exposed in a road cutting. The breccia is strictly monolithologic, but clast types are gradational from dense, largely unoxidized angular lava

fragments up to 2 m, to variably oxidized, microvesicular, subangular to subrounded scoriaceous fragments of decimetre to centimetre size. The centimetre-sized microvesicular clasts are usually rounded, suggesting attrition. Dense, tabular clasts are present, similar to those produced by viscous shear at the bases of lava flows. No clasts with bomb-like morphologies are present. The deposit is very poorly sorted, unwelded, and clast-supported or nearly so. It is interpreted as an autoclastic breccia, formed by the fragmentation of flowing lava.

At the Waimarino River road cutting, modern humic soil is developed directly on the basalt breccia, but farther north along the same cutting, 2.5 m of bedded, yellow-brown, weathered andesitic tephra are exposed. These have a 0.5 m chocolate-coloured paleosol developed at the top, and represent distal equivalents of the Tongariro Subgroup (Topping, 1973). Taupo Pumice Alluvium occurs above the andesitic tephra.

AGE OF THE WAIMARINO BASALT

The age of the basalt is certainly constrained between that of the underlying Rangitaiki Ignimbrite (ca. 300 Ka) and the overlying Taupo Pumice deposits (ca 1.8 Ka). Oruanui Breccia (19.8 Ka) is absent at the type locality, but overlies the Rangitaiki Ignimbrite at nearby exposures to the northwest (P. Froggatt, pers. comm., 1982). This rhyolite breccia was deposited throughout the region, but has subsequently been removed by erosion - probably the same period of erosion that

planed the top of the Rangitaiki Ignimbrite. It is unlikely that the basalt breccia would have remained on the landscape after this extensive period of erosion, and it is highly probable that the basalt is younger than 19.8 Ka.

The base of the overlying Tongariro Subgroup has been dated at 13.8 Ka (NZ 1559, Topping 1973). The thickness of these tephra near the type locality suggests a complete or nearly complete section of the Subgroup. The Waimarino Basalt therefore has a probable age between 19.8 Ka (Oruanui Breccia) and 13.8 Ka (base of the Tongariro Subgroup).

PETROGRAPHY

In hand specimen, the rock comprises conspicuous, light green, 2-3 mm phenocrysts of olivine and clinopyroxene, set in a dark gray aphyric matrix. Plagioclase is restricted to the groundmass.

The modal mineralogy and crystallization sequence are presented in Table 1. Euhedral to subhedral phenocrysts of forsteritic olivine and calcic clinopyroxene are set in a hyalopilitic matrix with calcic labradorite, orthopyroxene, titanomagnetite, rare subcalcic augite, and olivine (Fig. 3). Interstitial acid residuum is present, comprising dusty brown glass, plagioclase, and minor alkali feldspar. Magnesian olivine phenocrysts commonly contain microphenocrysts of translucent brown chrome spinel. Aggregates of olivine,

clinopyroxene, brown glass, and chrome spinel form clusters up to 3 mm in diameter.

MAJOR ELEMENT COMPOSITION

A bulk rock major element analysis and normative mineralogy are presented in Table 2, along with an analysis of average high-alumina basalt from the TVZ (Cole, 1973). Additional bulk rock trace element and mineral data will be reported in a later publication.

DISCUSSION

The Waimarino Basalt is a subalkaline basalt, as deduced from the petrography (orthopyroxene and interstitial acid residuum in the groundmass), chemistry (low in alkalis with respect to silica: Macdonald and Katsura, 1964; Irvine and Baragar, 1971), and normative mineralogy (quartz tholeiite). The rock is properly termed a magnesian quartz tholeiite.

Waimarino Basalt represents a magma type which differs both petrographically and compositionally from high-alumina basalts of the TVZ. In contrast to high-alumina types (Cole, 1973), Waimarino Basalt lacks plagioclase phenocrysts, is low in alumina, and has a high $Mg/Mg+Fe^{++}$ ratio. The latter aspect suggests derivation from the mantle wedge beneath the TVZ, with little or no subsequent modification by crystal fractionation.

Cole and Lewis (1981) have suggested that a Holocene volcanic arc occupies the eastern side of the TVZ, and has produced mainly olivine-bearing andesites. The age and location of Waimarino Basalt suggest that this magma type represents upper mantle anatexis, precursory to andesitic arc volcanism of the Taupo Arc.

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LIST OF FIGURES

Figure 1. Index map of North Island, and locality map for Waimarino Basalt Formation.

Figure 2. Measured stratigraphic section of Waimarino Basalt and associated units at the type locality, N112 414969.

Figure 3. Photomicrograph of Waimarino Basalt under plane polarized light, showing phenocrysts of olivine and clinopyroxene in a hyalopilitic matrix. Long dimension of photograph represents 4.2 mm.

LIST OF TABLES

Table 1. Modal mineralogy and crystallization sequence for Waimarino Basalt. Mode was determined by point counting two thin sections. Compositions of phenocryst and groundmass minerals were obtained using the electron microprobe.

Table 2. Bulk rock major element analysis and CIPW normative mineralogy of Waimarino Basalt. Average high-alumina basalt of the TVZ is given for comparison.

Fig. 1

Fig. 2

Fig. 3

<u>MODAL MINERALOGY</u>		
<u>Phenocrysts</u>		<u>Groundmass</u>
olivine	16.1	
clinopyroxene	7.4	
spinel	≤ 1	
<hr/>		<hr/>
23.5		76.5

<u>CRYSTALLIZATION SEQUENCE</u>		
	<u>Phenocrysts</u>	<u>Groundmass</u>
spinel	100 Cr/Cr + Al = 80	100Cr/Cr + Al = 30 to 40
olivine	Fo ₉₁	Fo ₇₄
clinopyroxene	100Mg/Mg + Fe = 85	100 Mg/Mg + Fe = 75
orthopyroxene		100Mg/Mg + Fe = 74
plagioclase		An ₈₀ to An ₅₅

Table 1. Modal mineralogy and crystallization sequence for Waimarino Basalt. Mode determined by point counting two thin sections. Phenocryst and groundmass mineral compositions obtained by EPMA.

1		2		3	
SiO ₂	52.18	qz	1.04	SiO ₂	51.07
TiO ₂	0.47	or	2.57	TiO ₂	1.05
Al ₂ O ₃	12.68	ab	14.03	Al ₂ O ₃	17.50
Fe ₂ O ₃	1.96	an	26.26	Fe ₂ O ₃	9.64 ^a
FeO	6.58	di	17.25	FeO	
MnO	0.16	hy	34.96	MnO	0.17
MgO	13.15			MgO	6.58
CaO	9.60	mt	2.87	CaO	10.57
Na ₂ O	1.64	il	0.90	Na ₂ O	2.73
K ₂ O	0.43	ap	0.12	K ₂ O	0.50
P ₂ O ₅	0.05			P ₂ O ₅	0.27
LOI	0.70		100.00		
Total	99.60				
Mg [*]	78.08				

$$\text{Mg}^* = 100 \text{ Mg} / \text{Mg} + \text{Fe}^{2+}$$
^a total iron expressed as FeO

1. Waimarino Basalt. Average of ten x-ray fluorescence determinations, using method of Norrish and Hutton, 1969.
2. CIPW normative mineralogy of Waimarino Basalt.
3. Average high-alumina basalt of TVZ (Cole, 1973).

Table 2. Bulk rock major element analysis and CIPW normative mineralogy of Waimarino Basalt. Average high-alumina basalt of TVZ is given for comparison.

PART II: PETROLOGY AND GEOCHEMISTRY

1. GENERAL INTRODUCTION

1.1 PREVIOUS WORK

Clark (1960) provided an excellent overview of the petrography of lavas from Tongariro Volcanic Centre, showing that the lavas are characteristically porphyritic, with ubiquitous labradorite- bytownite, bronzite- hypersthene, and augite phenocrysts set in intersertal, pilotaxitic or hyalopilitic groundmasses. Titanomagnetite is a common but minor constituent, occurring as microphenocrysts, inclusions in large phenocrysts, and as a groundmass phase. Olivine occurs in many rocks, usually as a minor constituent. Pigeonite rarely forms minute crystals and thin coronas surrounding hypersthene. Resorbed hornblende is rare. Apatite occurs as an accessory groundmass mineral and as inclusions in plagioclase. The details of mineral zonations in these rocks are complex, with both feldspar and ferromagnesian phenocrysts often showing resorbed cores, overgrowths, and oscillatory zonation.

Clark (1960) classified many specimens from Ruapehu as labradorite andesites (with plagioclase phenocrysts greater than twice the abundance of pyroxenes), but labradorite- pyroxene andesites were also noted (plagioclase less than twice the pyroxene abundance).

O'Shea (1957) described the detailed petrography for a few dykes and a sequence of lava flows on northwest Ruapehu. These correspond to Te Herenga Formation, and to the Iwikau and Pinnacle Ridge Members of Whakapapa Formation, in the present study. Lavas from Tawhai Falls (Whakapapa Fm, this study) and from Mahuia Rapids (Pukeonake Andesite Fm, this study) were also described.

Cole (1978) described the mineralogy and petrography of andesites from Tongariro Volcanic Centre. Representative modal data were given, as well as partial chemical analyses for pyroxenes.

Bulk rock chemical analyses from Ruapehu, Hauhungatahi, Pukeonake and Ohakune are given by Clark (1960), Topping (1974) and Cole (1978). Cole (1979) has compiled analyses of lavas of the Taupo Volcanic Zone to 1978, and descriptions and sample localities indicate that analyses from Ruapehu (n=11) are labradorite or labradorite- pyroxene basic (53-57 wt % SiO_2) and acid (57-63 wt % SiO_2) andesites from Whakapapa (n=8) and Mangawhero Formations (n=2) defined in the present study. Analyses of olivine basic andesites from Pukeonake (n=5; no trace elements), Hauhungatahi (n=3) and the Ohakune vents (n=3) are also given. No analyses from the older Ruapehu formations or of olivine- bearing Ruapehu lavas are given in Cole (1979). Thus, prior to the present study, about 25 bulk rock chemical analyses, ranging from 54-61 % SiO_2 , were documented from Ruapehu, Hauhungatahi, Pukeonake and Ohakune.

1.2 NATURE AND SCOPE OF THIS STUDY

Specimens for petrographic and chemical analysis were collected during the field studies reported in Part I. The rock suite comprises spatially and temporally related lavas and enclaves that erupted from Ruapehu and related vents during about the past 0.5 m.y. Samples were collected from the outermost 100- 200 metres of the composite cone and its satellite vents, as this is the total depth of exposure. While coverage therefore exists for only about the upper 20 % of the estimated 110 km^3 total volume, stratigraphic coverage of this portion is very thorough.

Because of their potential role as parental magmas to the voluminous andesites, olivine- bearing lavas were particularly thoroughly collected and analyzed, creating a sample bias. However, this exhaustive

collection has allowed the identification of two basalt magma types, one from Ruapehu, and the other from an isolated occurrence 43 km to the northeast. Both of these basalts have great relevance to the petrogenesis of intermediate magmas.

Most specimens are from the fresh, relatively unoxidized interiors of lava flows, and the sample population is therefore lithologically biased. There are several practical reasons for this: Flows exhibit steplike erosional topography which facilitates sequential sampling, airfall material is rare and commonly oxidized on Ruapehu, and most tuff breccias are altered or oxidized.

The present work expands earlier observations in four respects: (1) The larger sample population (184 bulk rock chemical analyses; 200 thin sections) is considered representative of the subaerially exposed portion of Ruapehu Volcano and its related vents; "related vents" include the parasitic centres at Ohakune, the older cone of Hauhungatahi, and Waimarino Basalt. The latter is an isolated occurrence 40 km northeast of Ruapehu and outside the Tongariro Volcanic Centre, but the Waimarino Basalt magma type is relevant to petrogenesis of Ruapehu andesites. (2) A stratigraphic context for interpretation is provided in Part I. (3) Quantitative mineral analyses and detailed petrography are used to discuss the origins of entrained crystalline material, and (4) the data provide a base from which to evaluate petrogenetic processes.

Major goals of this section are to show the types, compositions and associations of minerals within the sample population, as well as the compositional diversity of bulk rocks. Some petrogenetic implications of the phenocryst and xenolith associations are given, but detailed discussion and quantitative models are presented in Part III, Petrogenesis.

1.3 RESULTS

Modal mineralogy of selected whole rocks and igneous nodules is given in Tables 1-6. Photomicrographs of lavas, igneous nodules, and metamorphic xenoliths are presented in Figures 91-97. Mineral compositions were obtained by electron microprobe analysis and are listed in Appendices III, IV, and V for lavas, igneous nodules, and metamorphic xenoliths, respectively. Mineral analyses from selected lavas and igneous nodules are presented in graphical form as Figures 98-104.

Major element and trace element data for 144 fresh bulk rocks from Ruapehu and related vents are reported in Appendix II. In addition, 13 analyses are given for altered rocks, and 27 bulk rock analyses of igneous and metamorphic enclaves contained in the lavas. Strontium isotopic data (courtesy of Mr. Ian Graham) are given in Appendix II for 22 fresh bulk rocks, selected to span the entire compositional range from basalt to dacite, and also for seven xenoliths. Only major and trace element data from the 144 fresh bulk rocks are considered here; metamorphic xenolith compositions and isotopic data will be discussed under Part III, Petrogenesis. Results of the 144 unaltered bulk rock analyses are presented in Figures 105-109.

2. PETROGRAPHY

2.1 TE HERENGA FORMATION

Photomicrographs and modal data are given in Fig 9I and Table 1. The formation comprises petrographically and compositionally similar basic andesite lava flows, dykes and tuff breccia clasts. Specimens contain 30-55 % phenocrysts of labradorite-bytownite, augite and bronzite-hypersthene, with ubiquitous but minor titanomagnetite phenocrysts (Fig 9IA,B). A few specimens contain traces (2-4 grains per thin section) of resorbed olivine as groundmass microphenocrysts (Fo₆₇; Fig 9IC). These olivines lack chrome spinel inclusions, are in equilibrium with coexisting pyroxene phenocryst cores, and represent the final stages of olivine crystallization from basic andesites. Groundmasses generally have higher plagioclase: total pyroxenes and higher orthopyroxene: clinopyroxene ratios than coexisting phenocryst assemblages: Table 1, columns 2 and 7 are modes of groundmass only.

Microdiorite plugs (Fig 9ID,E; Table 1, col 9) have the same crystal assemblage and similar bulk compositions as dykes and lava flows. As a consequence of advanced crystallization, the plugs have higher plagioclase: pyroxene ratios, and most are nearly holocrystalline. Portions of these hypabyssal intrusions are hydrothermally altered, as are surrounding lava flows and tuff breccias (Fig 9IF,G,H).

FIG 91. PHOTOMICROGRAPHS FROM TE HERENGA FORMATION

A. Basic andesite, Mead's Wall dyke. Large phenocrysts of labradorite (An_{80-79}), augite (Mg_{72-70}), bronzite (Mg_{73-70}), and microphenocrysts of titanomagnetite are set in a fine intergranular matrix of the same mineralogy. Crossed nicols (XN). Field width, 2.8 mm. References: Appendix II, analysis 2; Appendix III; Table 1.

B. Basic andesite lava flow, Te Herenga Ridge. Same phenocryst assemblage as (A). This texture is representative of lava flows from Te Herenga Fm. XN. Width, 4.2 mm. References: Appendix II, analysis 10; Appendix III.

C. Same lava as (B), but enlarged to show embayed olivine microphenocryst (Fe_{67}) with orthopyroxene corona. Plane polarized light (PPL). Width, 1.7 mm. Reference: Appendix III.

D. Microdiorite intrusion, upper Pinnacle Ridge. Lineated subhedral phenocrysts of plagioclase, with subordinate clinopyroxene, orthopyroxene and opaque oxide are set in an intergranular matrix of the same minerals. PPL. Width, 2.8 mm. Reference: Appendix II, analysis 9.

E. Microdiorite intrusion, upper Pinnacle Ridge. Hypidiomorphic-granular rock comprising plagioclase (An_{78-40}), hypersthene (Mg_{67}), augite (Mg_{71}) and opaque oxide. Patches of clouded mesostasis contain quartz and minor alkali feldspar. XN. Width, 2.8 mm. References: Appendix II, analysis 12; Appendix III; Table 1.

F. Altered hypabyssal intrusion, upper Pinnacle Ridge. Large phenocrysts of plagioclase, clinopyroxene and orthopyroxene are set in a fine intergranular matrix with disseminated pyrite. Clinopyroxene at centre has been partially replaced by pyrite. PPL. Width, 2.8 mm. Reference: Appendix II, analysis 157.

G. Hydrothermally altered lava flow, upper Pinnacle Ridge. Original matrix and most pyroxenes have been replaced by pale green clay and by sulfides. PPL. Width, 2.8 mm. Reference: Appendix II, analysis 148.

H. Hydrothermally altered microdiorite, upper Pinnacle Ridge. Pyroxenes exhibit alteration to clay and sulfides. PPL. Width, 2.8 mm. References: Appendix II, analysis 153.

FIG. 91.

TABLE 1. Modal data from Te Herenga Formation. Data are given in volume percent, as determined by counting a minimum of 1000 points per thin section. Bulk rock numbers refer to analysis numbers of Appendix II. Columns 1-4 - lava flows; 5 - clast from heterolithic tuff breccia; 6, 7 - Mead's Wall dyke; 8 - Pinnacle Ridge dyke; 9 - Pinnacle Ridge microdiorite plug. 'PLAG' - plagioclase phenocrysts; 'CPX' - clinopyroxene phenocrysts; 'OPX' - orthopyroxene phenocrysts; 'OP' - opaque oxides; 'XENO' - metamorphic xenoliths; 'TOTAL' - phenocrysts as a total of the whole rock; '21a' and '2a' - point counts of groundmass only.

Bulk Rock	1	2	3	4	5	6	7	8	9
	21	21a	8	24	13	2	2a	6	12
PLAG	37.6	28.1	28.7	25.5	29.6	28.6	24.4	24.6	72.2
CPX	8.2	3.1	4.8	2.0	9.7	6.8	4.8	1.5	8.2
OPX	7.1	4.4	5.9	6.7	7.1	7.7	11.6	4.4	9.5
OP	2.1	6.4	1.1	0.5	1.6	0.5	8.2	0.4	2.6
XENO	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.0
TOTAL	55.0	-	40.6	34.7	48.0	43.6	-	31.4	92.5
100 plag/ pl+cpx+opx	68.4	78.9	72.6	74.5	63.8	66.3	59.8	80.6	80.3
cpx/ cpx+opx	0.5	0.4	0.5	0.2	0.6	0.5	0.3	0.3	0.5

2.2 WAHIANOA FORMATION

Photomicrographs are given in Fig 92 and modal data are found in Table 2. Specimens have 14-39 % phenocrysts, but most are about 30% phyrlic. Some specimens are texturally and mineralogically similar to Te Herenga Fm, but overall there is greater compositional (54-61% SiO_2) and petrographic diversity. A few specimens (e.g., Table 2, bulk rock 50) contain traces of oxidized amphibole.

Petrographic diversity is shown by widely varying plagioclase: pyroxene ratios, clinopyroxene: orthopyroxene ratios, presence of resorbed olivine xenocrysts with chrome spinel inclusions, and complex zonation patterns and overgrowths, especially for pyroxenes. A few lavas are relatively "clean", and disequilibrium textures are not present for any minerals (Fig 92A). In others, phenocrysts are dominated by plagioclase aggregates (Fig 92B) or by pyroxene aggregates and discrete pyroxenes with internal resorption zones and overgrowths (Fig 92C-G). Resorbed and mantled plagioclase (Fig 92F), and resorbed forsteritic olivine with chrome spinel inclusions and orthopyroxene coronas sometimes accompany the pyroxene textures (Fig 92H-J).

It is noteworthy that only 6 of 32 thin sections examined lack significant amounts of crystal aggregates, or resorbed and mantled crystals. The hypidiomorphic-granular aggregates range in size from 3-5 mm, to rare blocks approaching 8 cm. The aggregates have anorthositic-gabbroic- websteritic mineralogy, and they can comprise significant proportions of the total phenocryst assemblages in porphyritic rocks, producing substantial variations in plagioclase: pyroxene ratios and bulk compositions. Olivine is generally absent in these fragments and occurs instead as discrete, embayed, orthopyroxene-mantled, forsteritic crystals which seldom exceed a few volume percent. These are xenocrysts on the

basis of petrography (chrome spinel inclusions, strong resorption and reaction) and composition (too forsteritic to be in equilibrium with host rocks). Pervasive mantling of pyroxenes, by coronas with about 10 % greater Mg* than cores, is characteristic of rocks with olivine xenocrysts. Details of these zonation patterns will be presented in Part III, Petrogenesis, but it is appropriate to state here that the mantled phenocrysts are interpreted as products of magma mixing and crystal accumulation.

FIG 92. PHOTOMICROGRAPHS FROM WAHIANOA FORMATION

A. Acid andesite lava flow, south Ruapehu. Phenocrysts of labradorite (An_{58-56}), orthopyroxene (opx; Mg_{74-62}), augite (Mg_{63}) and titanomagnetite are set in a pilotaxitic matrix. Disequilibrium textures are absent. PPL. Field width, 4.2 mm. References: Appendix II, analysis 59; Appendix III; Table 2.

B. Acid andesite, Whangaehu Gorge. Phenocryst assemblage is dominated by bytownite (An_{76-73}), which occurs predominantly as 1-2 mm hypidiomorphic-granular anorthosite fragments. Groundmass plagioclase is labradorite (An_{55}). Interpreted as a plagioclase-accumulative lava. Crossed nicols (XN). Width, 4.2 mm. References: Appendix II, analysis 46; Appendix III; Table 2.

C. Basic andesite, Whangaehu Gorge. From left to right are: resorbed plagioclase (pl; An_{65-54}), two reversely zoned augites (cpx; Mg_{87-69}), and a composite grain of twinned clinopyroxene and spongy orthopyroxene. XN. Width, 4.2 mm. References: Appendix II, analysis 31; Appendix III; Table 2.

D, E. Same rock as (C), showing reversely zoned augite with Mg_{72-69} core and Mg_{87-76} rim. XN. Width, 1.3 mm.

F. Ditto, showing resorbed plagioclase with An_{64-59} core and thin, clear An_{65} rim.

G. Ditto, showing twinned clinopyroxene over fritted orthopyroxene.

H. Olivine basic andesite, Whangaehu Gorge. Phenocrysts of labradorite (An_{66}), augite (Mg_{78-68}), orthopyroxene (Mg_{77-68}) and olivine are set in an intersertal matrix. Resorbed olivines (ol; Fo_{90-87}) contain chrome spinel inclusions and have orthopyroxene coronas. XN. Width, 4.2 mm. References: Appendix II, analysis 27; Appendix III; Table 2.

I. Same rock as (H), showing embayed forsteritic olivine (Fo_{90}) with chrome spinel and orthopyroxene corona at upper left, clinopyroxene cluster at bottom centre, and mantled clinopyroxene (Mg_{68} core; Mg_{76} rim) at lower right. XN. Width, 1.6 mm.

J. Ditto, showing twinned cpx jacket enclosing spongy opx.

FIG. 92.

TABLE 2. Modal data from Wahianoa Formation. See Table 1 for notations. From left to right, the data are arranged according to type and abundance of exotic crystalline material. Columns 1,2 - plagioclase accumulative lavas; 3,4 - cpx (opx-ol) accumulative; 5 - cpx-opx-ol accumulative; 6 - olivine accumulative; 7 - pyroxene-olivine accumulative; 8 has trace of resorbed biotite or hornblende; 9,10 have traces of olivine; 11-16 are increasingly "clean" lavas with little or no disequilibrium textures or grain aggregates.

OTHER: a. oxidized hornblende or biotite anhedral
b. amphibole with opaque coronas.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Bulk Rock	46	44	30	31	27	35	58	61	48	26	42	39	53	50	32	59
PLAG	32.2	24.9	10.8	13.8	13.1	20.2	14.5	20.4	26.0	19.8	21.3	21.2	23.7	25.8	9.4	10.8
CPX	0.3	0.1	11.2	14.1	6.5	4.5	7.8	5.5	1.7	6.9	5.5	4.4	2.4	1.0	4.2	0.2
OPX	1.7	0.6	2.8	4.5	7.4	7.7	6.6	4.1	8.4	5.9	6.9	6.9	5.5	7.3	1.7	2.1
OP	0.0	0.0	0.0	0.0	0.0	0.1	0.1	1.4	0.2	0.0	0.7	1.5	0.1	1.3	0.0	0.6
OL	0.0	0.0	0.1	0.2	2.2	1.9	0.3	0.0	0.7	1.2	0.0	0.0	0.1	0.0	0.0	0.0
XENO	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	1.7	0.0	0.2	0.4	0.4	0.0	0.0	0.0
OTHER	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.6a	0.0	0.0	0.0	0.0	0.0	0.1b	0.0	0.0
TOTAL	34.2	25.6	24.9	32.6	29.2	34.6	29.3	32.0	38.7	33.8	34.6	34.4	32.2	35.5	15.3	13.7
100 plag/ pl+cpx+opx	94.2	97.3	43.5	43.1	48.5	62.7	50.2	68.0	72.0	60.7	63.2	65.2	75.0	75.6	61.4	82.4
cpx/ cpx+opx	0.2	0.1	0.8	0.8	0.5	0.4	0.5	0.6	0.2	0.6	0.6	0.4	0.3	0.1	0.3	0.1

2.3 MANGAWHERO FORMATION

Photomicrographs are given in Fig 93 and modal data are found in Table 3. Phenocrysts are the same plagioclase + two pyroxene + opaque oxide $\pm$ olivine $\pm$ apatite assemblage as reported for other formations, but Mangawhero Fm is characterized by great compositional (52-63 % SiO_2) and textural diversity.

Petrographic features previously described for Wahianoa Fm are even more pronounced here: Igneous rock fragments and high-temperature overgrowths on phenocrysts are common. Igneous fragments range in size from 2-5 mm, and are hypidiomorphic- granular pieces of pyroxenite (Fig 93I) to anorthosite (Fig 93J). These involve substantial proportions of the total phenocryst assemblages in some specimens, as shown in Table 3, cols 2 and 4, where small igneous fragments comprise 19 and 15 % of bulk rocks, and in both rocks they account for half of the total "phenocryst" abundances.

Olivine is present in significant amounts (up to 7 vol %) in many of these accumulative rocks, as well as in specimens that are relatively free of igneous inclusions. Olivine is an essential phenocryst in basic rocks, but with increasing silica content of bulk rocks, olivine gradually disappears until only 1-2 rounded microphenocrysts are observed in the groundmass of rocks with up to 58 % SiO_2 . The proportions of plagioclase and orthopyroxene, and the orthopyroxene: clinopyroxene ratio systematically increase as olivine disappears. These petrographic trends from basalt to dacite are shown in Table 2, cols 19-25, and Fig 93 A-F. Olivines from these specimens are in equilibrium with coexisting pyroxene cores and with bulk rocks, precluding xenocrystic origin. Olivine xenocrysts do occur in trace amounts for other lavas (e.g., Fig 93H).

Though often present in only trace amounts, forsteritic olivine is a

nearly ubiquitous component of specimens with strongly developed disequilibrium textures (Fig 93M-R; Table 2, cols 11-15). These specimens include basic and acid andesites with forsteritic olivine up to Fo_{90} , and with conspicuous mantled phenocrysts having high-temperature jackets over resorbed cores. Euhedral microphenocrysts of magnesian orthopyroxene (up to Mg_{90}) are invariably present.

In summary, olivine occurs in three petrographic associations: (1) as trace forsteritic xenocrysts in pyroxene-accumulative rocks whose main petrographic feature is the presence of pyroxenite and gabbro fragments, (2) as a primary phenocryst of basalt and basic andesites, but progressively disappearing with increasing bulk rock acidity as a consequence of olivine-liquid reaction, and (3) as forsteritic crystals in mixed magmas whose signature is the presence of internally resorbed phenocrysts with high temperature jackets. These petrogenetic hypotheses will be quantitatively evaluated in Part III, Petrogenesis.

FIG 93. PHOTOMICROGRAPHS FROM MANGAWHERO FORMATION

A. Olivine basalt, north Ruapehu. Phenocrysts of plagioclase (pl; An_{81-49}), clinopyroxene (cpx; Mg_{80-69}), olivine (ol; Fo_{90-79}) and minor orthopyroxene (Mg_{80-69}) are set in a felted, microvesicular matrix. Largest clinopyroxenes often have thin clear rims (Mg_{80}) on pale green cores (Mg_{69}). Some plagioclase has resorbed cores (An_{71}) and thin, clear rims (An_{80}). Olivine lacks orthopyroxene coronas and contains chrome spinel inclusions. PPL. Width, 4.2 mm. References: Appendix II, analysis 63; Appendix III; Table 3.

B. Olivine basic andesite, north Ruapehu. Similar petrography as (A), but with less olivine (Fo_{78-68}) and clinopyroxene (Mg_{84-69}), and more plagioclase (An_{65}) and orthopyroxene (Mg_{73}). PPL. Width, 4.2 mm. References: Appendix II, analysis 64; Appendix III; Table 3.

C. Groundmass olivine (ol; Fo_{70-68}) in lava (B), exhibiting rim oxidation but not orthopyroxene coronas; olivine has not yet reacted with liquid. PPL. Width, 1.7 mm.

D. Olivine-bearing acid andesite, north Ruapehu. Euhedral plagioclase (An_{77-50}), lesser pyroxenes (Mg_{69-67}), and opaque oxide microphenocrysts are set in a felted matrix with rare olivine microphenocrysts (Fo_{67}). XN. Width, 4.2 mm. References: Appendix II, analysis 88; Appendix III; Table 3.

E. Rare groundmass olivine (ol; Fo_{67}) in lava (D), surrounded by orthopyroxene (opx) and titanomagnetite corona. Olivine has now reacted with liquid to form orthopyroxene. XN. Width, 0.6 mm.

F. Dacite, Mangaturuturu Valley, SW Ruapehu. Phenocrysts of plagioclase (An_{53}), orthopyroxene (Mg_{67}), rare clinopyroxene, and opaque oxide microphenocrysts are set in a felted matrix. No olivine or igneous fragments are present. PPL. Width, 4.2 mm. References: Appendix II, analysis 107; Appendix III; Table 3.

G. Dacite lava flow, north Ruapehu. Apatite microphenocryst (ap; 0.2 mm) is associated with orthopyroxene (opx) and plagioclase. Note opaque, rod-like inclusions parallel to c-axis, and tabular habit. PPL. Reference: Appendix II, analysis 109.

H. Dacite, Whakapapaiti Valley, W Ruapehu. Phenocrysts of plagioclase, hypersthene (Mg_{61-59}) and augite are set in a felted matrix with abundant plagioclase and opaques. Olivine xenocryst (Fe_{85}) with chrome spinel inclusions and orthopyroxene corona is circled. Aggregate of two pyroxenes, plagioclase, oxides and glass occurs at left. PPL. Width, 4.2 mm. References: Appendix II, analysis 108; Appendix III.

I. Olivine-bearing basic andesite, Girdlestone Peak. Total pyroxenes exceed plagioclase, comprising abundant large clinopyroxene crystals and two- pyroxene aggregates. Interpreted as a pyroxene- accumulative lava. XN. Field width, 4.2 mm. References: Appendix II, analysis 72; Table 3.

J. Acid andesite, north Ruapehu. Plagioclase crystals (An_{83-73}) greatly exceed pyroxenes (Mg_{73-70}), and occur predominantly as hypidiomorphic- granular anorthosite fragments. Interpreted as a plagioclase-accumulative lava. XN. Field width, 4.2 mm. References: Appendix II, analysis 100; Appendix III; Table 3.

K. Olivine-bearing basic andesite, north Ruapehu. Clinopyroxene and plagioclase commonly occur as hypidiomorphic-granular aggregates and as embayed crystals. XN. Field width, 4.2 mm. Reference: Appendix II, analysis 73.

L. Olivine-bearing basic andesite, showing oscillatory-zoned clinopyroxene megacryst. PPL. Field width, 4.2 mm. Reference: Appendix II, analysis 68.

M. Olivine basic andesite, N Ruapehu. Phenocrysts of labradorite (An_{58-50}), augite (Mg_{86-61}), orthopyroxene (Mg_{85-64}) and olivine (ol; Fe_{85}) are set in a pilotaxitic matrix. Large olivine at upper left, mantled augite at lower right. XN. Field width, 4.2 mm. References: Appendix II, analysis 69; Appendix III; Table 3.

N. Same rock as (M), showing mantled augite with Mg_{61} core and Mg_{85} jacket. XN. Field width, 1 mm.

O. Same rock as (M). Mantled augite at centre, jacketed orthopyroxene (core = Mg_{64} , jacket = Mg_{85}) at extreme right. XN. Field width, 0.5 mm.

P. Olivine acid andesite, Girdlestone Peak. Phenocrysts of orthopyroxene, clinopyroxene, olivine, and subordinate plagioclase are set in an intersertal matrix. Pyroxenes are strongly jacketed or zoned. Compare to Fig 106E,F; these are also hybrid magmas. Clinopyroxene (cpx) at upper right has Mg_{72} core and Mg_{85} mantle. Olivine (ol; Fe_{92-91}) at bottom centre has chrome spinel inclusions and orthopyroxene corona. Resorbed hypersthene (hy; Mg_{70} core), jacketed by spongy bronzite (Mg_{88}), lower right. The abundant grey, medium-relief microphenocrysts are enstatite (Mg_{90}). XN. Field width, 4.2 mm. References: Appendix II, analysis 81; Appendix III; Table 3

Q. Olivine acid andesite, Girdlestone Peak, showing spongy orthopyroxene jacketed by clear, magnesian clinopyroxene. XN. Field width, 4.2 mm. References: Appendix II, analysis 87; Appendix III; Table 3.

R. Same rock as (P), showing resorbed hypersthene (hy), jacketed by spongy bronzite (br), in turn overgrown by clinopyroxene (cpx). XN. Field width, 0.8 mm.

FIG. 93.

FIG. 93.

TABLE 3. Modal data from Mangawhero Formation. See Table 1 for notations. The data are arranged according to petrographic characteristics. Columns 1-4 are pyroxene- and plagioclase-accumulative lavas, where "a" denotes point count of igneous rock fragments only, as a proportion of whole rock; 5,6 - pyroxene-plagioclase accumulative; 7 - weakly accumulative in plagioclase and pyroxenes, asterisk denotes opaque oxide derived from pyroxene oxidation; 8 - plagioclase accumulative; 9 - weakly plagioclase- and pyroxene-accumulative; 10 - probable mixed magma, plus pyroxene accumulation; 11-14 - mixed magmas with strongly jacketed pyroxenes; 15 - weak development of pyroxene jackets; 16-18 - nearly free of cumulate fragments; 19-25 - lavas that are relatively free of igneous rock fragments and disequilibrium textures, arranged sequentially from basalt to dacite.

Bulk Rock	1	2	3	4	5	6	7	8	9	10	11	12
	76	76a	72	72a	80	75	99	100	89	101	81	87
PLAG	13.7	8.4	14.5	4.3	11.1	16.3	24.3	12.2	10.7	10.0	0.6	5.9
CPX	11.9	6.7	13.2	6.1	11.0	10.2	9.7	1.2	10.6	8.9	5.9	9.0
OPX	7.8	3.8	5.4	4.6	7.8	7.0	6.9	3.3	10.0	6.9	8.2	10.5
OP	0.0	0.0	0.0	0.0	0.2	0.3	6.1*	0.1	0.0	0.0	0.0	0.0
OL	0.6	0.2	0.5	0.4	0.0	0.0	0.0	0.0	0.3	0.1	1.6	0.5
XENO	0.0	-	0.0	-	0.0	0.0	1.5	0.0	0.0	0.0	0.0	0.0
TOTAL	34.0	19.1	33.6	15.4	30.1	33.8	48.5	16.8	31.6	25.9	16.3	25.9
100 plag/ pl+cp+opx	41.0	44.4	39.9	28.7	37.1	48.7	57.3	73.1	34.2	38.8	4.1	23.2
cp+/ cp+opx	0.6	0.6	0.7	0.6	0.6	0.6	0.6	0.3	0.5	0.6	0.4	0.5

TABLE 3. continued.

Bulk Rock	13	14	15	16	17	18	19	20	21	22	23	24	25
	93	69	83	96	109	105	63	64	65	66	88	90	107
PLAG	9.2	10.1	3.6	11.4	21.2	29.5	10.3	16.6	8.3	14.3	24.3	11.9	12.1
CPX	10.1	5.5	3.5	2.9	3.1	6.7	7.3	4.0	5.4	5.4	6.1	1.3	0.4
OPX	9.3	4.2	1.7	2.1	5.9	9.7	2.1	2.7	2.0	1.8	7.6	1.9	1.5
OP	0.0	0.0	0.1	0.0	0.7	1.8	0.2	0.0	0.1	0.0	0.9	0.0	0.7
OL	0.6	2.1	0.3	0.0	0.0	0.0	7.0	3.8	4.7	4.4	0.1	0.0	0.0
XENO	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.1	0.0	0.0
TOTAL	29.2	21.9	9.5	16.4	30.9	47.7	26.9	27.4	20.5	25.9	39.1	15.1	14.7
100 plag/ pl+cp+opx	32.2	51.0	40.9	69.5	70.2	64.3	52.3	71.2	52.9	66.5	63.9	78.8	86.4
cp+/ cp+opx	0.5	0.6	0.7	0.6	0.3	0.4	0.8	0.6	0.7	0.7	0.4	0.4	0.2

2.4 WHAKAPAPA FORMATION

Photomicrographs are presented in Fig 94 and modal data are found in Table 4. Most specimens are plagioclase + orthopyroxene + clinopyroxene + opaque oxide acid andesites, with one basic andesite and three dacites also documented. The acid andesites exhibit some of the crystal-accumulation features described for other formations, as shown in Fig 94A-G. Hypidiomorphic- granular fragments of websterite, gabbro and anorthosite are common in these lavas, occurring as 3-8 mm clusters but occasionally exceeding 1 centimetre. Olivine is rare in nodules and as discrete crystals in lavas. Opaque oxides are a ubiquitous accessory, occurring as discrete subhedral microphenocrysts, as inclusions in pyroxenes, and as a component of the nodules. Hornblende occurs as a resorbed accessory mineral in one lava (Table 4, col 7).

Petrographic features of Pinnacle Ridge Member (Fig 94D-F) are consistent with its origin as welded airfall tuff (see: p 102-108). This deposit is mineralogically and texturally heterogeneous; e.g., some specimens lack olivine microphenocrysts.

FIG 94. PHOTOMICROGRAPHS FROM WHAKAPAPA FORMATION

A. Basic andesite, upper lava field of Tama Member, N Ruapehu. Phenocrysts of plagioclase, orthopyroxene, clinopyroxene and minor opaque oxide microphenocrysts are set in a hyalopilitic matrix. Nearly all plagioclase is internally fritted, with clear rims. Much spongy bronzite is present, some of it forming aggregates of large crystals. Noritic gabbro fragments (opx-cpx-plag) up to 6 mm are present. PPL. Field width, 4.2 mm. References: Appendix II, analysis 111; Table 4.

B. Acid andesite, Iwikau Member, exposed along Bruce Road. Phenocrysts of plagioclase, clinopyroxene, orthopyroxene and minor opaque oxide microphenocrysts are set in a pilotaxitic matrix. Most large plagioclase are internally fritted. Small gabbro fragments (centre) are commonly present in lavas of Iwikau Mbr. PPL. Field width, 4.2 mm. References: Appendix II, analysis 117; Table 4.

C. Acid andesite, Rangataua Member, S Ruapehu. Plagioclase, orthopyroxene, clinopyroxene, and minor opaque oxide occur in a hyalopilitic matrix. Two varieties of plagioclase are present; one clear and euhedral, the other rounded and internally sieved or clouded. Gabbro fragments (not shown) are also present. Rangataua Member is the only known occurrence of amphibole-bearing igneous nodules (see: Fig 96M,N,O). References: Appendix II, analysis 126; Table 4.

D. Acid andesite, densely welded airfall tuff of Pinnacle Ridge Member, NW Ruapehu. Plagioclase, clinopyroxene and orthopyroxene phenocrysts with minor opaque oxides and a trace of olivine are set in an opaque, non-vesicular matrix of oxidized glass and crystallites. Olivines (ol; centre) rarely contain chrome spinel inclusions, and have orthopyroxene coronas. Gabbro fragments are common. PPL. Field width, 4.2 mm. References: Appendix II, analysis 120; Table 4.

E. Moderately welded airfall tuff of Pinnacle Ridge Member. Irregular bands of non-vesicular, oxidized glass alternate with cryptocrystalline bands, producing a texture that appears eutaxitic in hand specimen (see: Fig 70, p 106). PPL. Field width, 4.2 mm.

F. Weakly welded airfall tuff, basal 0.5 m of Pinnacle Ridge Member. Irregular vesicles (V) are only partially collapsed.

G. Acid andesite dyke of Pinnacle Ridge Member, Whakapapanui Gorge. Large, hypidiomorphic- granular anorthosite fragments (An_{80}) are the only conspicuous crystals, and the rock is interpreted as being plagioclase-accumulative. The fragments are set in a pilotaxitic matrix with plagioclase (An_{80-53}), bronzite (Mg_{77}), augite (Mg_{77}) and opaque oxide microphenocrysts. XN. Field width, 4.2 mm. References: Appendix II, analysis 118; Appendix III; Table 4.

H. Acid andesite, Tawhai Falls, NW Ruapehu. The nearly aphyric texture is atypical of Ruapehu lavas. Rare phenocrysts comprise plagioclase, with subordinate orthopyroxene and clinopyroxene. XN. Field width, 4.2 mm. References: Appendix II, analysis 122; Table 4.

FIG. 94.

TABLE 4. Modal data from Whakapapa Formation. Data are arranged in order of increasing silica content. Most samples contain igneous rock fragments of 2-5 mm size. Columns 1-3 - basic and acid andesites with norite and websterite nodules; 4 - acid andesite with anorthosite nodules; 5 - acid andesite with minor anorthosite nodules; 6 - nearly aphyric acid andesite; 7 - acid andesite with norite nodules and minor amphibole; 8 - acid andesite with two generations of plagioclase; 9 - dacite with garnet-biotite gneiss xenoliths. 'AM' - amphibole; see Table 1 for other notations.

	1	2	3	4	5	6	7	8	9
Bulk Rock	111	116	117	118	120	122	124	126	130
PLAG	19.2	27.6	24.5	12.9	9.6	6.2	17.3	24.7	25.0
CPX	4.4	9.7	4.9	0.7	1.9	0.4	1.1	4.8	1.8
OPX	9.2	7.1	9.5	0.7	1.6	0.3	5.0	6.3	5.8
OP	0.2	1.5	0.8	0.0	0.0	0.0	0.8	0.5	0.5
OL	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
XENO	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.8
AM	0.0	0.0	0.0	0.0	0.0	0.0	0.8	0.0	0.0
TOTAL	33.0	45.9	39.7	14.3	13.1	6.9	25.1	36.3	33.9
100 plag/ pl+cpx+opi	58.2	60.1	61.7	90.2	73.3	89.9	68.9	68.0	73.7
cpx/ cpx+opx	0.3	0.6	0.3	0.5	0.5	0.6	0.2	0.4	0.2

2.5 LAVAS FROM SOURCES OTHER THAN RUAPEHU

2.5.1 Waimarino Basalt Formation

Though Waimarino Basalt is not geographically related to Ruapehu, this primitive magma type is an end member for hybrid magmas that are found at Ruapehu and its satellitic vents. Waimarino Basalt has already been described in Part I, but a photomicrograph and modal data are given here as Fig 95G and Table 5, column 1.

2.5.2 Hauhungatahi Andesite Formation

Specimens from Hauhungatahi are coarsely crystalline, as shown in Fig 95A. Clinopyroxene is present as glomerophenocrysts up to 6 mm, where it sometimes coexists with minor orthopyroxene and olivine. Orthopyroxene occurs only as small (< 0.6 mm) phenocrysts. Olivine comprises sub- to anhedral phenocrysts that seldom exceed 1 mm. The largest grains contain chrome spinel inclusions, and many olivine grains are rimmed by clino- or orthopyroxene. Accessory opaque oxides occur as microphenocrysts. Groundmasses range from felty to intergranular, and minor zeolite is present in some specimens.

These lavas are more coarsely crystalline than those of Ruapehu, and appear to be largely free of igneous rock fragments. Some clinopyroxene accumulation is possible, on the basis of the abundant glomerophenocrysts.

2.5.3 Pukeonake Andesite Formation

Basic andesite lava flows and pyroclastics from Pukeonake have uniform and distinctive composition and texture. Characteristic petrographic features are shown in Fig 95 E,F,G. Large (up to 1.5 mm) forsteritic olivine crystals and dunite nodules, with chrome spinel inclusions and orthopyroxene coronas, are a diagnostic petrographic

feature. Clinopyroxene occurs as phenocrysts up to 2 mm and as glomerophenocrysts; this mineral commonly has thin, clear outer mantles which are optically continuous with, but more Mg-rich than grain interiors. Two varieties of orthopyroxene are present: Large grains comprise embayed hypersthene core regions with spongy bronzite jackets, and the jackets are often optically discontinuous with cores. Small phenocrysts and microphenocrysts of spongy or clear bronzite form a second variety, and are normally zoned. Large plagioclase phenocrysts often contain inclusions of hypersthene and augite, and have clear bytownite jackets over clouded labradorite core regions. Titanomagnetite occurs as rare microphenocrysts and inclusions. Matrix textures vary from hyalopilitic in quenched tephra, to finely intergranular in thick lava flows.

2.5.4 Ohakune Andesite Formation

Basic andesite tephra from the Ohakune vents differs from Ruapehu lavas and tephra, in that plagioclase is absent as large phenocrysts and rarely exceeds 0.4 mm (Fig 95 B). Clinopyroxene-orthopyroxene-olivine nodules up to 8 mm are conspicuous, comprising several percent of hand specimens. Large forsteritic olivines in these nodules commonly contain chrome spinel inclusions and are partially mantled by orthopyroxene. The groundmass assemblage comprises plagioclase, clinopyroxene, orthopyroxene, opaque oxides and olivine (Fo₇₅) microlites in brown, microvesicular, silicic glass.

2.5.5 Core of Lahar Mound, State Highway 48, NW Ruapehu

Lithology and genesis of the Lahar Mounds have been discussed on pages 116-120. The core of one of these mounds comprises hornblende dacite, having no known petrographic or compositional equivalent from Ruapehu Massif. Textural features are shown in Fig 95 C,D, and modal data

are given in Table 5, column 5.

Phenocrysts are plagioclase, brown hornblende and minor titanomagnetite microphenocrysts. Some hornblendes reach several millimetres and can be distinguished in hand specimens. Ferrohypersthene crystals are present (Fig 95 D), and hypersthene jackets suggest these are xenocrysts.

FIG. 95. PHOTOMICROGRAPHS OF NON-RUAPEHU LAVAS

A. Olivine-bearing basic andesite lava flow, Hauhungatahi. The coarse texture is typical of lava flows from Hauhungatahi. Phenocrysts of plagioclase (An_{89-69}), clinopyroxene (Mg_{84}), orthopyroxene (Mg_{84-76}), olivine (Fo_{87-81}) and opaque oxide microphenocrysts are set in a sparse intergranular matrix with minor zeolite. PPL. Field width, 4.2 mm. References: Appendix II, analysis 135; Appendix III, bulk rock 133; Table 5.

B. Olivine-bearing basic andesite, Ohakune vents. Large (to 4 mm) aggregates of augite (cpx; Mg_{84-82}) + bronzite (opx; Mg_{83-80}) + olivine (ol; Fo_{88-85}) + chrome spinel are set in a hyalopilitic matrix. Groundmass contains plagioclase (An_{78-68}), orthopyroxene (Mg_{76}), clinopyroxene (Mg_{72}) and minor olivine (Fo_{78}). XN. Width, 4.2 mm. References: Appendix II, analysis 137; Appendix III; Table 5.

C. Hornblende dacite, core of Lahar Mound on Highway 48. Phenocrysts of plagioclase (An_{44-40}), orthopyroxene (Mg_{70}), clinopyroxene (Mg_{73}), brown hornblende (circled; Mg_{60}) and opaque oxide microphenocrysts are set in a felsitic matrix. PPL. Width, 4.2 mm. References: Appendix II, analysis 144; Appendix III; Table 5.

D. Same rock as (C), but enlarged to show rare ferrohypersthene (fhy; Mg_{43}) with hypersthene jacket (hy; Mg_{60}) and a few opaque oxide grains. PPL. Field width, 0.6 mm.

E. Olivine-bearing basic andesite, glassy tephra of Pukeonake Scoria Cone. Phenocrysts comprise clinopyroxene, orthopyroxene, plagioclase and olivine in a hyalopilitic matrix. Plucked dunite nodule (Fo_{94-87}) with chrome spinel inclusions and bronzite corona at right. Embayed plagioclase (An_{56-52}) at upper left. Hypersthene (Mg_{70}) with acid glass inclusions and spongy bronzite jacket (Mg_{83}), lower left. PPL. Field width, 4.2 mm. References: Appendix II, analysis 136; Appendix III, bulk rock 139; Table 5.

F. Same rock as (E), showing characteristic textures of phenocrysts, considered to have resulted from magma mixing. Embayed and euhedral plagioclases at left. Mantled clinopyroxene with Mg_{77-70} core and Mg_{84-79} rim zone, at lower centre. Jacketed orthopyroxene with embayed hypersthene core and spongy bronzite mantle, upper right. Numerous euhedral bronzite microphenocrysts (Mg_{87-70}) are also present. XN. Field width, 4.2 mm.

G. Lava of Waimarino Basalt Formation. Phenocrysts are forsteritic olivine (Fo_{92-74}) with chrome spinel inclusions, and clinopyroxene (Mg_{86-82}) in a hyalopilitic matrix. PPL. Field width, 4.2 mm. References: Appendix II, analysis 132; Appendix III; Table 5.

FIG. 95.

TABLE 5. Modal data from non-Ruapehu lavas. Data are arranged in order of increasing bulk rock silica content. Column 1 - Waimarino Basalt; 2 - Hauhungatahi basic andesite; 3 - Pukeonake basic andesite (a mixed magma); 4 - Ohakune basic andesite; 5 - hornblende dacite from core of Lahar Mound. 'AM' - amphibole; see Table 1 for other notations.

Bulk Rock	1	2	3	4	5
	132	135	139	141	144
PLAG	0.0	41.4	7.5	0.0	16.0
CPX	7.4	14.3	9.4	7.6	2.8
OPX	0.0	5.2	7.4	1.3	2.9
OP	0.2	0.1	0.0	0.0	0.4
OL	16.1	1.0	1.7	0.7	0.0
XENO	0.0	0.0	0.0	0.0	0.0
AM	0.0	0.0	0.0	0.0	1.1
TOTAL	23.7	62.0	26.1	9.6	23.2
100 plag/ pl+cpx+opx	0.0	68.0	29.1	0.0	73.7
cpx/ cpx+opx	1.0	0.7	0.6	0.8	0.5

2.6 IGNEOUS NODULES

Numerous examples of millimetre-sized "glomerophenocrysts" and "grain aggregates" of three or more crystals have been shown in Figs 91-95. These comprise a significant proportion of the phenocryst assemblage in many specimens, and they can exert major control on plagioclase: pyroxene and clinopyroxene: orthopyroxene ratios, as well as total phenocryst content. The 2-5 mm fragments almost certainly represent smaller equivalents of centimetre-sized igneous nodules derived from magma freezing or crystal accumulation in the subvolcanic or plutonic environment.

Nodules are defined by the present writer as *igneous-appearing* rock fragments. Diagnostic criteria for deducing igneous origin include hypidimorphic- granular rock texture, together with oscillatory zonation of constituent minerals. Many inclusions have an overall metamorphic appearance, with xenoblastic to poikiloblastic textures, but if relict igneous textures are locally preserved, the present writer considers them to be igneous nodules in spite of the fact that they have undergone slight metamorphism. Thus, there is some textural overlap between rock fragments that are called igneous nodules and those that are called metamorphic xenoliths (section II-2.7).

The photomicrographs of Fig 96 illustrate the textural and mineralogical diversity of nodules. The textural effects of thermal metamorphism and cataclasis are apparent in Figs 96E,G,H,I,J, the major consequences being local development of xenoblastic texture, destruction of oscillatory zonation, and formation of aluminous spinel and glass. Other nodules are largely unaffected by metamorphism (e.g., Figs 96A,C).

Nodules have diverse mineral assemblages comprising dunite (Fig 95E), harzburgite (Fig 96K,L), pyroxenites (Figs 92I, 93I, 95B), websteritic to anorthositic gabbros and diorite (Fig 96A-J), and anorthosite (Figs 92B,

93J, 94G). Nodules with amphibole (Fig 96N,O) occur at only one locality.

The plagioclase + orthopyroxene + clinopyroxene + opaque oxide diorite nodules with interstitial glass probably represent liquid compositions, since their mineralogy and mineral proportions are comparable to the basic andesite hypabyssal intrusions: Compare Figs 91E and 96A. Nodules dominated by one mineral (anorthosites, websteritic gabbros, hornblendites) are almost certainly crystal cumulates from basic to acid andesite parent magmas.

Igneous lamination, as would be shown by alignment of tabular plagioclase and orthopyroxene, is absent in these nodules (except for Fig 96K, harzburgite), suggesting that gravitative settling of crystals to form rhythmically layered cumulates was not a common process. More likely, draughts of basaltic to acid andesitic magma were injected along high-angle normal faults of the upper crust. Magma batches could nucleate crystals onto conduit walls, producing variolitic textures (Fig 96B), could become sheared after solidification (Fig 96H), and could be filter-pressed to yield gabbroic rocks with little interstitial residuum. Repeatedly occupied, vertical, planar conduits would also imply high surface area to volume ratios for magma batches in the upper crust, providing opportunity for thermal alteration and entrainment of country rocks.

Especially noteworthy is the occurrence of peridotite nodules (Figs 95B,E; 96K,L), which are rarely associated with calc-alkaline volcanics. These nodules are found in basic andesite tephra and lava flows from Pukeonake, where they comprise abundant millimetre-sized fragments, and rarely reach centimetre size. Primary minerals in these peridotites are refractory, suggesting that they are upper mantle fragments or cumulates from primitive basaltic magma.

FIG 96. PHOTOMICROGRAPHS OF IGNEOUS NODULES

A. Diorite in dacite host lava, Mangawhero Formation, N Ruapehu. Labradorite (An_{57}), hypersthene (Mg_{64}), minor augite (Mg_{68}), rare titanomagnetite and ilmenite, and interstitial brown glass are present. PPL. Field width, 4.2 mm. References: Host rock in Appendix II, analysis 105; nodule minerals in Appendix IV.

B. Gabbro in acid andesite lava of Iwikau Member, NW Ruapehu. Plagioclase, orthopyroxene, clinopyroxene and minor opaque oxides comprise this hypidiomorphic- granular nodule. Plagioclase and orthopyroxene locally form variolitic textures, with interstitial xenomorphic- granular plagioclase, pyroxenes and oxides. XN. Field width, 4.2 mm. Reference: Host rock is Appendix II, analysis 114.

C. Websteritic gabbro in acid andesite lava of Iwikau Member, NW Ruapehu. The mineral assemblage is clinopyroxene + orthopyroxene + plagioclase. PPL. Field width, 4.2 mm. Reference: Host rock is Appendix II, analysis 114.

D. Coarse clinopyroxene + plagioclase gabbro in acid andesite of Wahianoa Formation. PPL. Field width, 4.2 mm. Reference: Host rock is Appendix II, analysis 143.

E. Gabbro nodule in stream boulder derived from Iwikau Member, NW Ruapehu. Minerals are plagioclase, orthopyroxene, clinopyroxene and opaque oxide. Textures range from coarse hypidiomorphic- granular to fine xenomorphic- granular. In the latter situation, recrystallized pyroxenes poikilitically enclose opaque oxides. Interpreted as an incipiently metamorphosed gabbro, since igneous textures are preserved. Crossed nicols (XN). Field width, 4.2 mm. No cross-references.

F. Gabbro nodule in welded airfall tuff, Pinnacle Ridge Member, NW Ruapehu. Plagioclase, two pyroxenes and opaque oxides comprise this hypidiomorphic- granular fragment. PPL. Field width, 4.2 mm. References: Host rock is Appendix II, analysis 120.

G. Anorthositic gabbro from acid andesite lava flow, Iwikau Member, NW Ruapehu. Subhedral bytownite (An_{77}) is the dominant mineral, with lesser bronzite (Mg_{76}), augite (Mg_{78}) and opaque oxide (not analyzed). Oxides are poikilitically encased in plagioclase and pyroxenes. XN. Field width, 4.2 mm. References: Host rock is Appendix II, analysis 117; mineral analyses from nodule in Appendix IV.

H. Sheared gabbro from Te Herenga Formation lava flow, NW Ruapehu. Most of the rock exhibits mortar texture, and is a dense mass of finely comminuted pyroxenes and plagioclase (upper left half of photo). Large sheared plagioclase (not analyzed), clinopyroxene (Mg_{82}) and orthopyroxene (Mg_{76}) are locally present (lower right of photo). References: Bulk nodule in Appendix II, analysis 172; minerals from nodule in Appendix IV.

I. Gabbro nodule from tephra of Pukeonake Scoria Cone. Local xenomorphic- granular patches are present (circled) in this plagioclase- two pyroxene- opaque oxide rock. Interpreted as a weakly metamorphosed gabbro. XN. Field width, 4.2 mm. No cross-references.

J. Diorite from tephra of Pukeonake Scoria Cone. The rock comprises labradorite (An_{58}), hypersthene (Mg_{69}), augite (Mg_{69}) and Al-Fe-Mg spinel. Textures include coarse hypidiomorphic- granular, fine xenomorphic- granular, and plagioclase poikilitically enclosing pyroxenes and spinel. Anhedral spinel (circled) is hercynite. Interstitial pools of brown silicic glass (gl; 62 % SiO_2) are present. The rock is probably a metamorphosed diorite. PPL. Field width, 4.2 mm. Reference: Appendix IV, analyses 136-3,6,8,9,11.

K. Harzburgite nodule from tephra of Pukeonake Scoria Cone. Olivine (ol; Fo_{88}) comprises most of the rock. Irregular bands of orthopyroxene (opx; Mg_{87}), and rare clinopyroxene (Mg_{84}) are present. Chrome spinel is an accessory. Rare inclusions of plagioclase (An_{70}) are present in olivine. Veins of aluminous, intermediate (54 % SiO_2), pale brown vesicular glass are present. Origin is uncertain. Coexisting olivine and plagioclase require pressure < 9 kb; the rock is either depleted plagioclase peridotite of upper mantle origin, or a cumulate from basaltic magma that crystallized orthopyroxene as well as olivine. PPL. Field width, 4.2 mm. Reference: Appendix IV, analyses 136-1,6,9,10,16,17,38,50,59.

L. Same rock as (K), showing vein of vesicular glass (gl; 54 % SiO_2) with euhedral Cr-Fe-Mg-Al spinel (picotite). The chrome spinel in glass is overgrown by, and coexists with, rare discrete euhedra of Al-Mg-Fe spinel. The aluminous spinel is a crystallization product of the glass, whereas the chrome spinel has similar composition to inclusions in olivine and is probably a residual phase after partial melting of the host rock. PPL. Field width, 0.6 mm.

M. Norite from lava flow of Rangataua Member, South Ruapehu. The rock comprises bytownite (An_{87}), bronzite (Mg_{75}) and minor augite (Mg_{80}), with a trace of pargasitic hornblende (Mg_{71}), brown silicic glass (68 % SiO_2) and pyrrhotite (confirmed by EPMA but analysis not reported). Hornblende is present only as 0.1-0.3 mm anhedral inclusions in orthopyroxene. Rangataua Member contains the only known hornblende- and pyrrhotite-bearing igneous nodules. PPL. Field width, 2.3 mm. References: Bulk nodule in Appendix II, analysis 167; mineral analyses in Appendix IV.

N. Same rock as (M), enlarged to show hornblende inclusion (am; circled) in bronzite. PPL. Field width, 0.3 mm.

O. Igneous amphibolite nodule from Rangataua Member. Pargasitic hornblende (Mg_{67}) poikilitically encloses bytownite (An_{79}), bronzite (Mg_{70}) and ilmenite, and is surrounded by strongly oxidized, pseudo-opaque glass (68 % SiO_2). The glass contains plagioclase and pyroxene microphenocrysts. This nodule has the same mineralogy as rock (M), but hornblende is much more abundant, and the ferromagnesian crystals are slightly more iron-rich. Reference: Appendix IV, analyses 167-3,4,6,9,11,12,17.

FIG. 96.

FIG. 96.

TABLE 6. Modal data from igneous nodules. None of these nodules have been analyzed as bulk rocks, so 'Bulk Rock' designation refers to bulk rock analyses of host lavas in Appendix II. 'Field' refers to field names of nodules, listed in Appendix IV mineral analyses. See Table 1 for other notations.
 Column 1 - dunite from tephra of Pukeonake Scoria Cone; 2 - harzburgite from Pukeonake; 3 - "glomerophenocrysts" in Ohakune basic andesite; 5 - gabbro nodule in Tama Mbr, Whakapapa Fm (only 400 points counted); 6 - diorite nodule from Iwikau Mbr, Whakapapa Fm.

Bulk Rock Field	136 H7x-6	136 H7x-2	137 F4	117 B3x	116 D1	124 E6
PLAG	0.0	0.0	0.0	54.8	62	75.0
CPX	0.0	0.0	74.0	9.1	18	6.0
OPX	3.1	22.8	13.0	36.1	13	14.4
OP	2.5	1.6	0.0	0.0	0	3.9
OL	91.9	69.3	13.0	0.0	0	0.7
AM	0.0	0.0	0.0	0.0	0	0.0
GLASS	2.5	6.3	0.0	0.0	7	0.0
TOTAL	100.0	100.0	100.0	100.0	100	100.0

2.7 METAMORPHIC XENOLITHS

2.7.1 Introduction

Metamorphic xenoliths are rock fragments derived from the subvolcanic basement. Excluded in the present discussion are igneous nodules with recognizable hypabyssal or plutonic igneous textures, even though these are often partially overprinted by metamorphism. Metamorphic xenoliths are ubiquitous in lava flows and pyroclastics of Ruapehu and related vents. They are conspicuous in outcrop and generally range from 0.5 to 3 cm in size, although blocks of greywacke up to 70 cm have been found. Xenoliths are texturally and mineralogically diverse, reflecting a variety of metamorphic conditions and protoliths.

2.7.2 Petrography and Mineralogy

Photomicrographs are given in Fig 97. Xenoliths comprise both foliated and non-foliated metamorphic rocks with textures of regional and contact metamorphism. Many have been strongly overprinted by pyrometamorphism during transport in host magmas, as shown by breakdown of biotite and garnet, and the presence of silicic glass and accessory sanidine in some specimens. Discussion is given by listing specific rock types and referring to the photomicrographs.

Metaquartzites (Fig 97A) are nearly monomineralic rocks, but biotite is present in variable quantities. Biotite gneisses often have quartzose bands, suggesting a genetic link between quartzites and gneisses. When biotite is abundant in quartzites, it forms irregular decussate bands, and is often associated with Al-Fe spinel and hematite, or rarely with alkali feldspar.

Hornfelses are finely xenomorphic-granular rock fragments of basic to intermediate composition, with light to medium grey colour and ranging in size from 0.5 to 1.5 cm. Two varieties are present. The first is basic

to intermediate in bulk composition (see: section III-6.3 and Fig 121 for discussion of xenolith bulk compositions) and is dominated by anhydrous minerals comprising poikiloblastic to xenoblastic andesine-labradorite, hypersthene with up to 6 wt % Al_2O_3 , minor Al-Fe spinel, titanomagnetite, ilmenite, clinopyroxene and apatite, and rare alkali feldspar. Quartz is absent. Mineralogically, these rocks vary from norites and gabbros to anorthosites (Fig 97 B,C). Many have been affected by pyrometamorphism, with crystals floating in pale brown silicic glass.

The second hornfels type is more aluminous and silica- poor in bulk composition, and contains almandine- pyrope garnet, anhedral cordierite with traces of fibrolite inclusions, Al-Fe spinel, and oligoclase (Fig 97 F). Titaniferous biotite and traces of alkali feldspar are sometimes present.

Biotite- plagioclase- spinel schists and gneisses (Fig 97 G,H) comprise brick red to dark grey fragments up to 8 centimetres. Essential minerals are titaniferous biotite, andesine which is often reversely zoned up to 10 mol %, and Al-Fe spinel, where the latter mineral is locally a product of biotite breakdown. Other minerals that are commonly but not always present include: Quartz, garnet with opacite and hypersthene coronas, cordierite, sanidine, aluminous hypersthene, apatite, ilmenite, hematite, graphite, and silicic glass. Hypersthene is present in nearly all specimens, both as discrete grains and as partial coronas on almandine- pyrope garnet. In spite of the presence of biotite, most specimens are only weakly foliated, due to the decussate texture of this mineral. Contorted, macroscopic banding is developed by alternating biotite- spinel- (garnet- cordierite- hypersthene) and andesine- quartz- (sanidine- hypersthene) layers. Specimens with sanidine and glass do not contain cordierite.

Low- grade metagreywackes have outcrop equivalents in the surrounding main ranges of North Island. Some specimens are mylonitic (Fig 97 D) and unaffected by pyrometamorphism. The mineral assemblage is chlorite, quartz, albite, muscovite and epidote. Millimetre- wide veins

of finely granoblastic quartz are common.

Tertiary siltstones (Fig 97 E) are found only at the Ohakune vents, where they comprise yellow- orange porcellanite blocks in volcanic ejecta. Sintering of the clay matrix has occurred, and the blocks were almost certainly entrained from shallow levels since Tertiary sediments form outcrops near the Ohakune vents.

Hydrothermally altered andesites (not illustrated), though not derived from the subvolcanic basement, are described here. They form yellow- brown, centimetre- sized blocks in lava flows and pyroclastics. Many blocks are flinty, due to sintering of their clay- rich matrices. Pyroxene and plagioclase phenocrysts are replaced by clays, leaving a relict porphyritic texture. Microscopically, these rocks are structureless masses of greenish- brown or pale tan clay, with minor disseminated white mica and sulfides.

2.7.3 Relative Abundances and Stratigraphic Trends

Xenoliths are ubiquitous and are found in all eruptive units, regardless of stratigraphic position. They approach 1 % of some lava flows, as judged by visual inspection of planar outcrop faces, but most flows contain only 10-20 millimeter- to centimeter- sized fragments per 10 square metres of surface. White, saccharoidal quartzites are the most conspicuous and probably also the most abundant variety. Nearly equal to these, though generally smaller and less conspicuously grey- coloured, are the fine grained pyroxene hornfelses with intermediate plagioclase as the dominant mineral. All other types are rare. Of these, the most abundant are cordierite- garnet hornfelses and biotite- plagioclase- (quartz- garnet) gneisses.

Quartzites and feldspathic hornfelses exist at all stratigraphic levels, but gneiss fragments have not been found in Te Herenga Formation (earliest cone- building period) and they seem to be more common with

increasing stratigraphic height. Quartzose and gneissic fragments achieve maximum abundance in a coarse airfall deposit of Iwikau Member (youngest eruptive period; see p. 109). The Whakapapa Skifield is a prime area for collecting, where lava flows of Iwikau Member are freshly exposed in the Whakapapanui streambed and in road cuttings.

FIG 97. PHOTOMICROGRAPHS OF CRUSTAL XENOLITHS

A. Saccharoidal quartzite, Ohakune vents, consisting of clouded, strained quartz with seriate grain boundaries. Grains are elongate and of varied sizes. Some quartzites contain significant amounts of biotite, suggesting a genetic link to schists and gneisses. Many specimens have clear, interstitial glass. Quartzites are the most abundant xenolith type. Crossed nicols (XN). Field width, 1.7 mm. References: Appendix II, analysis 184.

B. Coarse pyroxene hornfels, from lava flow of Iwikau Member, NW Ruapehu. This xenoblastic rock contains andesine-labradorite, hypersthene, augite and opaque oxide, and is probably a metamorphosed igneous rock. Pyroxene hornfelses are the second most abundant xenolith type, ranging from norites to anorthosites. Plane polarized light (PPL). Field width, 4.2 mm. Reference: Appendix II, analysis 170.

C. Banded pyroxene hornfels, Iwikau Member, NW Ruapehu. This fine xenoblastic rock comprises labradorite, aluminous bronzite, titanomagnetite, Al-Fe spinel, and minor titaniferous biotite and alkali feldspar. PPL. Field width, 4.2 mm. Reference: Appendix V, under field name "B3x".

D. Metagreywacke, 70 cm block in Iwikau Member pyroclastics, high northern slopes of Ruapehu. The rock has the same mineral assemblage (chlorite- quartz- albite- muscovite- epidote) and cataclastic texture as greenschist facies metagreywackes from the Kaimanawa Range to the east of Ruapehu. PPL. Field width, 4.2 mm. References: Appendix II, analysis 181; Appendix V, under field name "N112C".

E. Tertiary siltstone, in ejecta from Ohakune vents. Clouded grains of clastic quartz are set in a matrix of partially fused clay. Blocks of Tertiary sediment are rare on Ruapehu but are common at the Ohakune vents, where they have been baked to yellow- orange porcellanites. XN. Field width, 1.7 mm. No cross- references.

F. Hornfels inclusion from accessory lithic block of Ruapehu andesite, contained in ejecta from Ohakune vents. The rock contains xenoblastic oligoclase, cordierite (cord), aluminous ferrohypersthene (opx), Al-Fe spinel, and almandine- pyrope garnet. The garnet has opacite and orthopyroxene coronas. PPL. Field width, 1.7 mm. Reference: Appendix V, under field name "Xc".

G. Gneiss fragment in microperlitic dacite block, N Ruapehu. The rock is irregularly banded, with decussate titaniferous biotite and Al-Fe spinel bands (left) alternating with andesine- rich xenoblastic layers (plag; right). Minor alkali feldspar and a trace of ilmenite are also present. Note garnet (gar) with corona of opacite and aluminous ferrohypersthene. PPL. Field width, 4.2 mm. References: Host dacite is Appendix II, analysis 130; mineral analyses from xenolith in Appendix V, under field name "N112A".

H. Gneiss, from coarse airfall tephra of Iwikau Member, upper northern slopes of Ruapehu. The rock contains quartz, titaniferous biotite, Al-Fe spinel, almandine- pyrope garnet, aluminous ferrohypersthene, sanidine, minor ilmenite, and hematite. Banding is developed by alternating quartzofeldspathic and biotite- spinel- garnet layers. PPL. Field width, 4.2 mm. References: Appendix V, under field name "B10xi".

FIG. 97.

3. SURVEY OF MINERAL CHEMISTRY IN LAVAS

3.1 OLIVINE

Olivine occurs in lavas spanning the entire compositional range from basalt to dacite (Fig 98), though it exceeds 1% only in basalts and basic andesites. Together with clinopyroxene, it is an essential phenocryst in basalts (Figs 93A, 95G), and occurs as conspicuous, 1-3 mm subhedral crystals. In basalts, the cores of olivine phenocrysts are Fo₈₅₋₉₂ and commonly contain chrome spinel inclusions. Olivine also occurs in the groundmass of basalts, and basic and acid andesites (Figs 91C; 93A,B,C,D,E; 95A,B,G), where it represents the final stages of crystallization during reaction with liquid:

Where olivine-liquid reaction has formed orthopyroxene in basic andesites, the forsterite content of olivine phenocryst rims equals the appropriate enstatite content of orthopyroxene cores, according to the olivine-orthopyroxene equilibrium study of Medaris (1969). Olivine crystallization is terminated at forsterite contents ranging from Fo₆₈ to Fo₈₂, in groundmass liquids of bulk rocks having 53 to 58% SiO₂. Thus, olivine-liquid reaction does not occur at an identical forsterite- or bulk rock silica content for all specimens. Several explanations can be given for this: (1) According to equation 1, olivine-liquid reaction is influenced by the activity of silica in liquids from which olivine is crystallizing. Silica activity in turn is controlled by temperature, pressure, and fugacity of

H₂O, all of which are expected to vary from rock to rock, according to the reservoir and eruptive histories of individual magma batches. (2) Bulk rock silica contents do not reflect *residual* liquid compositions because quenching occurs at different stages of crystallization for individual magma batches, and because bulk rock compositions reflect the influence of accumulated xenocrysts and igneous rock fragments.

Olivine crystals are common in acid andesites and in a few dacites (Figs 92H,I; 93H,I,K,L,M,N,O,P,Q,R; 94D; 95B,E,F). Most of these are certainly xenocrysts, on petrographic grounds (coexistence with orthopyroxene phenocrysts, corroded olivine margins with orthopyroxene coronas, presence of chrome spinel inclusions in forsteritic olivine), and on the basis of olivine-liquid equilibrium calculations, using either $K_d = 0.3$ (Roeder and Emslie, 1970) or $K_d = 0.4$ (Nicholls, 1974). These olivines probably originate from entrainment of the crystallization products of basaltic magma or from magma mixing, and are discussed further in Part III, Petrogenesis.

Within the entire rock suite, olivine composition ranges from Fo₉₄ to Fo₆₇. In single rocks and individual crystals, the variation is less than 15 mol percent forsterite.

CaO contents of olivine crystals in lavas and nodules lie between 0.07 and 0.20 wt %, average 0.13 wt %, and in single crystals are constant from cores to rims (i.e., within analytical uncertainty of the microprobe). The role of pressure as a control on Ca in olivine is arguable (Stormer, 1973) but absence of detectable Ca zonation in olivine and its coexistence with plagioclase suggest low pressure (< 9 kb) olivine crystallization. Indeed, the observed range of CaO values in olivine is consistent with 1 atmosphere crystallization of olivine from melts having the 6 - 10 wt % CaO appropriate for basalts and basic andesites (Watson, 1979).

3.2 PYROXENES

Pyroxenes (Fig 98) are second only to plagioclase in phenocryst abundance; hence, most lavas are two pyroxene acid or basic andesites. Augite and bronzite/hypersthene are the most commonly observed compositions. The modal ratio of clinopyroxene: orthopyroxene is usually near 1:1 for basic andesites, but varies substantially from basalts ($\text{cpx} > \text{opx}$) to dacites ($\text{cpx} < \text{opx}$). Orthopyroxene always exceeds clinopyroxene abundance in the groundmass of lavas. The proportion of total pyroxene to plagioclase phenocrysts also varies widely. General increase of plagioclase: pyroxene, and orthopyroxene: clinopyroxene ratios with increasing silica contents of bulk rocks is considered to be a result of fractional crystallization, while aberrant ratios (e.g., andesites with clinopyroxene $\gg$ plagioclase, or with plagioclase $\gg$ total pyroxenes) are considered to result from accidental entrainment of igneous rock fragments from the plutonic environment.

3.2.1 Clinopyroxene

Clinopyroxene is an essential phenocryst mineral in all lavas, though it decreases in proportion relative to orthopyroxene with increasing silica contents of bulk rocks. In basalts, it co-precipitated with olivine (+ chrome spinel) as early phenocrysts, and in more evolved rocks it crystallized with orthopyroxene, plagioclase and Fe-Ti oxides. Most clinopyroxene phenocrysts are smoothly and normally zoned, and lack zoning reversals or overgrowths. However, in some lavas augite phenocrysts have Mg-rich jackets up to several hundred microns wide (e.g., Figs 92C,D,E,I; 93M,N,O,P; 95E,F) and/or overgrowths of one pyroxene on another, where the overgrowths are often more magnesian than the cores (e.g., Figs 92C,D,E,J; 93Q,R). These compositional reversals and

overgrowth patterns are attributed to the effects of magma mixing and to entrainment of exotic crystals.

All analyses are augites, except for Waimarino Basalt which contains diopside and endiopside phenocrysts (Fig 98A). The limited Mg/Fe compositional range is a mineralogical reflection of the weak iron enrichment trend of bulk rocks (Fig 107). Clinopyroxene analyses (Appendix III) show that the non-quadrilateral components Ti, Al, Fe^{3+} and Na together comprise only 2 to 5 atom % of total cations. Aluminium is nearly always sufficient to fill tetrahedral sites with Si, and the remaining octahedrally coordinated Al is generally less than 1 % of total cations. No consistent trends of Al and Ti zonation are apparent, and weak sector zonation with respect to Al and Ti probably accounts for most individual-grain variations. Cation totals generally preclude significant amounts of Fe_2O_3 (0.X wt %), and for this reason pyroxene analyses have not been re-calculated for Fe^{3+} .

3.2.2 Subcalcic Augite and Pigeonite

Clark (1960) has reported rare pigeonite as rims on augite phenocrysts and in the groundmass of intermediate lavas from the Tongariro Volcanoes. The present writer has observed pigeonite in the groundmass of only one Ruapehu lava (Appendix III, 59-5). Subcalcic augite has been identified in only one rock (Fig 98A), where it occurs as 20 - 50 micron groundmass crystals. These are interpreted as metastable quench crystals.

3.2.3 Orthopyroxene

In basic andesites, orthopyroxene gradually replaces olivine as the

major calcium-poor ferromagnesian phenocryst (see section 3.1). Most analyses (Fig 98) are bronzite or hypersthene. Ferrohypersthene occurs in one dacite (Fig 95D) and enstatite microphenocrysts occur in some hybrid magmas having primitive basalt as an end-member (e.g., Fig 93P). Orthopyroxene is normally zoned, but in some lavas fritted cores are overgrown by Mg-rich jackets. These jacketed orthopyroxenes coexist with similarly zoned augites and with jacketed plagioclase (Fig 95E,F), and are interpreted as being the products of magma mixing.

Since orthopyroxene has no 8-fold site, Al and Na are lower than in coexisting clinopyroxene. Al_2O_3 generally ranges between 1 and 3 wt %, most of it tetrahedrally coordinated. No consistent core-to-rim Al zonation is apparent.

3.3 FELDSPARS

Plagioclase is ubiquitous and the most abundant mineral of the rock suite. It is the only phenocryst feldspar phase and is a major constituent of the groundmass in all rocks. Only two specimens, Waimarino Basalt (Figs 99A and 95G), and Ohakune basic andesite (Fig 95B) lack plagioclase phenocrysts.

Analyses are presented in terms of Ab-An-Or end members in Fig 99. The compositional range is An_{89-40} , but the majority of crystals are labradorite. Plagioclase is more calcic than the corresponding normative feldspar of bulk rocks, suggesting that potassium and to a lesser extent sodium are concentrated in the finely crystalline to glassy matrices.

Plagioclase is often complexly zoned. Phenocrysts are nearly always oscillatory zoned, especially in their outer portions, and a general trend of normal zonation is superposed. Thin, clear rims are present on most phenocrysts, and these are compositionally similar to groundmass

FIG. 99. Plagioclase compositions from lavas and igneous nodules of Ruapehu and related vents. Analyses are reported in mol % of anorthite- albite- orthoclase end members. Plagioclase analyses from lavas are given in Appendix III, and from nodules in Appendix IV. Analyses are from the same rocks as Fig 98. Normative plagioclase is calculated from bulk rock analyses of Appendix II.

- A: Waimarino Basalt (52.18 % SiO_2 ; bulk rock analysis in Appendix II-32).
 B: Basalt, Mangawhero Fm, Ruapehu (52.23 % SiO_2 ; Appendix II-63).
 C: Five basic andesites from Te Herenga Fm, Mangawhero Fm, Hauhungatahi and Ohakune (53.15-56.79 % SiO_2 ; Appendix II-10,64,71,133,137).
 D: Andesite, Mangawhero Fm, Ruapehu (58.54 % SiO_2 ; Appendix II-88).
 E: Three dacites from Mangawhero and Whakapapa Fms, Ruapehu (63.39-65.64 % SiO_2 ; Appendix II-110,129,131).
 F: Twelve igneous nodules (not all nodules contain plagioclase). Data points correspond to full analyses given in Appendix IV.

crystals. Inclusions of glass, cryptocrystalline material, pyroxenes and titanomagnetite are common. Apatite inclusions are occasionally present in plagioclase of acid andesites and dacites. Plagioclase can be internally fritted and clouded, or clear and euhedral, often in the same rock. Synnnetic phenocrysts and grain aggregates are common. In some specimens, plagioclase dominates the phenocryst assemblage and consists of hypidiomorphic- granular anorthosite fragments (Figs 92B, 94G). Abrupt, calcium-rich jackets sometimes occur over fritted core regions (Fig 95E,F), and these crystals are found in association with jacketed pyroxenes. Thus, the zonation and textural features of plagioclase record one or more of three petrographic phenomena: Closed- system crystallization, together with pyroxenes and oxides, from melt whose residue comprises the groundmass; entrainment of exotic crystalline material, or mixing of magmas. For individual lavas, plagioclase phenocrysts are often polygenetic (e.g., Fig 94C) and reflect two or more of the above processes.

Alkali feldspar is rare as microlites in hyalopilitic groundmasses, and occurs as quartz- orthoclase intergrowths in the mesostasis of intrusive rocks (Fig 91E).

3.4 OXIDES

Oxide minerals form ubiquitous microphenocryst inclusions in silicate phenocrysts and in groundmasses. Three oxides occur as primary minerals: Chrome spinel, titanomagnetite, and rare ilmenite.

Chrome spinel occurs as microscopic sub- to euhedral inclusions in forsteritic olivines, and rarely in magnesian clinopyroxenes associated with these olivines. It is restricted to olivine of Fo₈₅ or greater, and so is effectively limited to basaltic rocks or to olivine xenocrysts in evolved

rocks. The inclusion crystals are generally homogeneous (Figs 100, 101, 102), are poor in $\text{TiO}_2\text{-FeO-Fe}_2\text{O}_3$, rich in $\text{Cr}_2\text{O}_3\text{-MgO-Al}_2\text{O}_3$, and have compositions similar to refractory chrome spinels from boninites, peridotite nodules, alpine peridotites and layered basic intrusions (Fig 103). By contrast, discrete groundmass crystals are often strongly zoned, with outer mantles similar in composition to discrete groundmass titanomagnetite (Fig 100). This indicates reaction (and oxidation) between early- formed chrome spinel and liquid, involving enrichment of spinel rims in total Fe, Fe^{3+} and Ti, and depletion in Cr, Mg, Al. Chrome spinel precipitation terminates when olivine reaches about Fo_{85} , and is thereafter replaced by titanomagnetite as the oxide phase (Figs 101, 102). This is generally coincident with the onset of clinopyroxene crystallization, suggesting that the appearance of clinopyroxene as the Cr-sequestering phase may be a control on spinel- liquid reaction (Irvine, 1967), together with the effects of oxidation and silica enrichment of residual liquids (Haggerty, 1976).

In basic andesites to dacites, titanomagnetite (Fig 104) forms ubiquitous microphenocrysts included in all silicate minerals except olivine, and in groundmasses. Titanomagnetites range between 6 and 20 wt % TiO_2 (29 to 58 % ulvospinel), while stoichiometry permits up to 33 wt % TiO_2 . This, together with the rarity of coexisting ilmenite, reflects the Ti-poor bulk compositions of host rocks (Buddington and Lindsley, 1964), as well as the effects of increasing acidity and oxygen fugacity during groundmass crystallization (Haggerty, 1976).

Ilmenite occurs sporadically in acid andesites and dacites. Crystals vary between 49 and 31 wt % TiO_2 , and TiO_2 often exceeds FeO, suggesting subsolidus oxidation (Buddington and Lindsley, 1964).

Several factors preclude the use of coexisting titanomagnetite and

FIG 100. Oxide mineral compositions from Waimarino Basalt (bulk rock is Appendix II, analysis 132). Complete mineral analyses are given in Appendix III: 132. Inclusions in forsteritic olivine phenocrysts are homogeneous Cr-Al-Mg spinels (picotites) with 52-59 % Cr_2O_3 and 0.2 % TiO_2 . Groundmass crystals are strongly zoned chromian titanomagnetites with 2-8 % Cr_2O_3 and 4-6 % TiO_2 . Tie lines link cores (filled circles) and rims (open circles) of single grains. Compare with Figs 101 and 102.

FIG 101. Oxide mineral compositions from basalt of Mangawhero Fm, Ruapehu. Complete mineral analyses are given in Appendix III, under bulk rock 63. Inclusions in olivine phenocrysts are Cr-Al-Mg spinels (picotites) with 48-50 % Cr_2O_3 and 0.5 % TiO_2 . These are slightly less refractory than inclusion spinels from the more primitive Waimarino Basalt (Fig 100). Groundmass crystals and inclusions in pyroxene phenocrysts are titanomagnetites with 0.1-0.3 % Cr_2O_3 and 7-13 % TiO_2 .

FIG 102. Oxide mineral compositions from two basic andesites of Mangawhero Fm and Hauhungatahi. Complete mineral analyses are given in Appendix III: 71,133. Inclusions in olivine phenocrysts are Cr-Al-Mg spinels (picotites) with 45-47 % Cr_2O_3 and 0.5 % TiO_2 . These picotites are less refractory than basaltic chrome spinels, but similarity of composition suggests a genetic link to basaltic parent magmas. Inclusions in pyroxenes are titanomagnetites with 0.5 % Cr_2O_3 and 9-10 % TiO_2 .

FIG 103. Composite diagram of all oxide compositions from basalts and basic andesites of Figs 100–102. Labelled fields are from Crawford (1980). Refractory chrome spinels of the present study are similar to spinels from boninites, peridotite nodules in alkali olivine basalts, Alpine-type harzburgites and stratiform basic intrusions. However, chrome spinels in lavas of the present study are succeeded by titanomagnetite, and oxide compositions diverge from those of boninites, intrusions and nodules.

FIG 104. Composition diagram for iron-titanium oxides from lavas of Ruapehu and related vents. Equilibrium tielines at 900 °C are taken from Haggerty (1976). Single bold line is for coexisting oxides in bulk rock 105 (dacite), the only documented titanomagnetite-ilmenite pair. This crosses equilibrium tielines, probably as a consequence of subsolidus oxidation. Complete analytical data are given in Appendix III.

ilmenite as indicators of magmatic temperature and oxygen fugacity. First, ilmenite rarely coexists with titanomagnetite, due to Ti-poor melt compositions. Second, titanomagnetite compositions are well outside the limits of Buddington and Lindsley's (1964) calibrated temperature- oxygen fugacity curves.

3.5 AMPHIBOLE

Amphibole is very rare, and occurs as an accessory constituent in only three lavas; two acid andesites and a dacite. Analyses from two of these occurrences are reported in Appendix III, and a photomicrograph of hornblende dacite is given in Fig 95 C. Crystals are small (0.1-0.3 mm), acicular, and pleochroic brown or green. In lavas, they always exist as discrete microphenocrysts and never as inclusions in other silicates. Coronas of opaque material (opacite) are always present. All three analyses of Appendix III are silica- undersaturated, ferroan pargasitic hornblendes according to the classification of Leake (1978). These limited data indicate that amphiboles are slightly less magnesian than coexisting pyroxenes.

3.6 APATITE

Apatite is an accessory mineral (2 - 4 grains per thin section) in about half of all rocks > 60 % SiO_2 . It forms stubby microphenocrysts (0.1-0.3 mm) with weak grey or brown pleochroism and opaque, rod-like inclusions parallel to the c-axes (Fig 93G). It is present as inclusions in plagioclase and hypersthene as well as in groundmasses, indicating co-precipitation with silicates and oxides in evolved magmas. Mertzman (1977, p. 225) has described apatites with similar petrographic features

from orogenic andesites of the Medicine Lake Volcano. The inclusion crystals are characteristically oriented parallel to host mineral zonation, suggesting apatite crystallization in response to local concentration gradients adjacent to growing silicate minerals, particularly plagioclase, and low diffusivity of phosphorus in silicate melts, as suggested by Green and Watson (1982). These authors further suggest that calc alkaline magma series do not achieve apatite saturation until andesite- dacite compositions are reached, and this is confirmed by petrographic data reported here.

3.7 OTHER MINERALS

Microscopic tridymite prisms occur as linings to lenticular shear cavities in some lava flows. Occasional quartz anhedral or fine xenomorphic- granular quartz aggregates up to 4 mm are found in some lavas. Tridymite forms from vapour phase crystallization, but quartz is certainly xenocrystic and derived from quartzites of the subvolcanic basement (see: 2.7 Crustal Xenoliths). Strongly resorbed, oxidized biotite and garnet occur in some dacites (Fig 122 A,B), as well as hercynite microlites (Appendix III, analysis 91-4). These three minerals are certainly xenocrysts, since they occur in the assemblage of gneissic xenoliths found in the lavas. Pyrite and clay minerals occur as secondary minerals in some intrusive rocks and lava flows, as a consequence of hydrothermal alteration (Fig 91 F,G,H). Pyrrhotite has been identified in one igneous nodule (Fig 96M).

4. SUMMARY OF MINERALOGY AND PETROGRAPHY

The principal phenocryst minerals in lavas are the anhydrous silicates plagioclase, clinopyroxene, orthopyroxene and olivine, with

subordinate opaque oxides. Ilmenite, hornblende and apatite are rare accessory minerals. With increasing acidity from basalts to dacites, changes occur in the types, relative proportions and compositions of phenocryst minerals. In basalts, the dominant minerals are forsteritic olivine and magnesian clinopyroxene, with subordinate bytownite/labradorite, bronzite and chrome spinel. In basic andesites, olivine is replaced by orthopyroxene as a consequence of reaction with silicic liquid, chrome spinel ceases to crystallize and titanomagnetite appears, and the phenocryst ratios orthopyroxene: clinopyroxene and plagioclase: total pyroxenes increase. Phenocryst minerals of basic and acid andesites are labradorite, hypersthene and augite, with minor titanomagnetite microphenocrysts. In acid andesites and dacites, labradorite/andesine dominates the phenocryst assemblage, with lesser pyroxenes, minor opaque oxides, and a trace of apatite.

Textures and zonation of plagioclase and pyroxenes are complex, suggesting polygenetic origins for phenocrysts in many lavas. Mantled phenocrysts with high temperature overgrowths $\pm$ internal resorption indicate magma mixing, while other zonation patterns may reflect crystal accumulation.

Igneous nodules contain the same types and compositional ranges as minerals in host lavas, commonly exhibit hypidiomorphic- granular textures that are partially overprinted by xenoblastic metamorphic textures, and form 2-5 mm sized crystal aggregates in many lavas. Nodules and xenocrysts derived from them exert major influence on the "phenocryst" assemblages of many lavas. These observations suggest that the nodules are co-genetic igneous rock fragments from the hypabyssal-plutonic environment, entrained within batches of erupting magma as they rose along previously occupied conduits. No pervasive evidence is found in the nodules for polybaric crystallization involving hydrous phases (e.g., hornblende, biotite) in the plutonic environment.

Millimetre- to centimetre- sized metamorphic xenoliths from the subvolcanic basement are very common in lavas and pyroclastics. The most common varieties are saccharoidal quartzite and feldspathic hornfels, with subordinate garnet- biotite- plagioclase gneiss.

5. IMPLICATIONS OF MINERAL ASSEMBLAGES AND COMPOSITIONS FOR PETROGENESIS

Some qualitative evaluations of pressure, temperature, water content and oxygen fugacity during crystallization are possible, using the observed mineral compositions and assemblages. The results of olivine-spinel and two-pyroxene thermometry indicate crystallization temperatures ranging from 1150⁰ C for basalt, to 960⁰ C for dacite.

Low pressure crystallization (< 7kb) in crustal reservoirs is suggested by abundant metamorphic inclusions and by the following aspects of mineralogy: (1) The coexistence of olivine and plagioclase in andesite lavas and igneous inclusions (including ultramafic nodules; Fig 96K) requires crystallization pressures < 7 kb, since at higher pressures these phases will react to form aluminous pyroxenes + spinel (Green and Hibberson, 1969). (2) The calcium content of olivine is low and nearly constant from cores to rims, suggesting low pressure, nearly isobaric olivine crystallization. (3) The observed concentrations of Al, Na and Ti in pyroxenes, although dependent not only on pressure but also on temperature, cooling rate, silica activity, and coexisting minerals, are low enough to at least preclude pressures > 10 kb (cf.: high pressure pyroxenes crystallized from andesite by Green, 1972).

Comparison with the experimental results of other studies suggests that Ruapehu andesites were water-undersaturated, but not completely anhydrous, during phenocryst mineral growth. To achieve agreement between observed eruption temperatures and experimentally determined andesite liquidus temperatures, 2-5 wt % H₂O is required in the melt (Gill, 1981, Table 4.1, Fig 4.1). In addition, Eggler (1972) concluded that most andesite magmas must contain < 3 wt % H₂O because plagioclase

phenocrysts are common. These deductions are generally applicable to the present study, given the estimated crystallization temperatures reported here, and the ubiquity of plagioclase phenocrysts in lavas. That is, Ruapehu lavas probably contained only a few wt % water during phenocryst precipitation.

Quantitative estimates of oxygen fugacity during crystallization are precluded by the rarity of coexisting titanomagnetite-ilmenite pairs. Using coexisting Fe-Ti oxides from andesites, other authors have estimated fO_2 ranging from Ni-NiO buffer conditions to 1-2 log units above Ni-NiO, at temperatures of 900⁰ - 1100⁰ C (Gill, 1981, Fig 5.9).

6. BULK ROCK MAJOR AND TRACE ELEMENT COMPOSITION

6.1 INTRODUCTION

Major goals of this section are: (1) to illustrate compositional limits of the rock suite, (2) classify rocks to provide a basis for terminology, (3) show the relative abundances of rock types, and (4) use variation diagrams to suggest differentiation processes. Although fractional crystallization has not yet been rigorously demonstrated as a differentiation mechanism, petrography, mineralogy and bulk rock chemical variation strongly imply that fractional crystallization of basaltic magma has produced much of the chemical variation. However, petrography also indicates that most rocks are porphyritic and may not represent liquid compositions; other samples have features that suggest magma mixing. Considering these observations, deviation from expected liquid lines of descent, and scatter on interelement variation diagrams is anticipated.

Chemical analyses for 144 unaltered whole rocks from Ruapehu and related vents are presented as summary diagrams in Figs 105-109. The SiO_2 histogram of Fig 105 shows that specimens vary from basalt to dacite, but most are basic or acid andesites. The MgO histogram (Fig 105) illustrates the unlinking of MgO and SiO_2 ; these oxides usually behave antithetically during differentiation. As a consequence of crystal accumulation and magma mixing, rocks varying only between 8-9 % MgO are as diverse as basalt to acid andesite on the basis of their silica contents. Similarly, rocks varying only between 3-4 % MgO include basic andesite to dacite.

In view of these observations, the petrogenesis of andesites cannot be a simple process that involves closed-system fractional

FIG. 105. MgO and SiO₂ histograms for 144 bulk rocks from Ruapehu and related vents. Silica divisions for basalt, andesite and dacite are from Gill (1981). Arithmetic mean of 144 analyses is 57.81 wt % SiO₂.

crystallization. Quantitative assessment of differentiation processes will be undertaken in Part III: Petrogenesis, but first a synopsis of chemical traits for the sample population is given.

6.2 CLASSIFICATION

Gill (1981) has proposed a classification of intermediate volcanic rocks on the basis of silica and potash contents. The central trapezoid of Fig 106 defines the compositional limits for "orogenic andesites". Basic and acid andesites are distinguished at 57 % SiO_2 ; the terms 'basic-' and 'low silica andesite' are used interchangeably by the present author. 134 of the 144 bulk rocks are some variant of orogenic andesite. Most are medium- K andesites, and all rocks meet Gill's additional criteria that TiO_2 be less than 1.75 % and be hypersthene- normative. All rocks, including the two basalts, are quartz- normative.

Peacock (1931) proposed a classification based on the silica content at which CaO and $\text{Na}_2\text{O} + \text{K}_2\text{O}$ trends intersect on Harker diagrams. According to this criterion, the rock series is calcalkalic ("calcalkaline", in current useage), since $\text{CaO} = \text{Na}_2\text{O} + \text{K}_2\text{O} = 5.8 \%$, at 61 % SiO_2 .

Calcalkaline rock series characteristically exhibit weak iron enrichment, relative to tholeiitic series. The rock series of Ruapehu and related vents is calcalkaline according to the criteria of Fig 108.

In summary, the 144 rock analyses range from basalts (2) to dacites (8), but are dominated by medium- K acid and basic andesites (120). All rocks contain less than 1 % TiO_2 and are quartz- normative. The rock series is calcalkaline according to the original definition of Peacock (1931), and also according to later definitions based on trends of iron enrichment.

FIG. 106. Silica-potash diagram (after Gill, 1981, p.6) for 144 bulk rocks from Ruapehu and related vents. Field of "orogenic andesites" is the bold trapezoid at the centre of the figure.

6.3 MAJOR ELEMENTS

Silica (Fig 107) exhibits nearly continuous variation from basalts to dacites, but a compositional gap is apparent at 61.5- 63 % SiO_2 and is especially distinct on the potash diagrams (Figs 106, 107). The hiatus is not a result of selective sampling, and suggests that acid andesites and dacites may differ petrogenetically. Most data points cluster between 56-60 % SiO_2 , which reiterates the histogram of Fig 105 and reflects domination of the sample population by andesites. For andesites, considerable scatter is apparent on all diagrams, but particularly for Al_2O_3 , MgO , and Mg number. The major mineral phases in andesitic rocks are plagioclase and pyroxenes, with subordinate olivine and opaque oxides. These phenocryst minerals are lower in silica than host liquids, and fractionation will produce silica enrichment, as well as pronounced effects for Al_2O_3 , MgO , and Mg number. Considering the high phenocryst contents of lavas and the petrographic evidence for crystal accumulation and magma mixing, it is likely that accumulation and magma mixing have acted concurrently with fractional crystallization, producing considerable deviation from possible liquid lines of descent on variation diagrams.

Alumina provides an illustration of this open-system behaviour, and several impressions emerge from the Al_2O_3 - SiO_2 diagram: (1) Both basalts are low- alumina types but differ substantially in wt % Al_2O_3 . (2) The horizontal "string" of data points at 16-18 % Al_2O_3 and 53-60 % SiO_2 may represent a liquid line from Ruapehu basalt. If so, alumina reaches a maximum at 55 % SiO_2 and then decreases slightly; this would require increasing plagioclase: pyroxene ratios in fractionating mineral

FIG 107. Silica variation diagrams for 144 bulk rocks from Ruapehu and related vents. The two basalts are circled; 'WB' is Waimarino Basalt, 'RB' is Ruapehu basalt. Open squares in Mg-number diagram denote 13 relatively aphyric rocks ranging from basic andesite to dacite. Large filled circles denote average medium-K basic and acid andesites of Gill (1981, p.99). Vectors to phenocryst minerals are based on analytical data of Appendix III, and are generalized to allow for solid solution in minerals.

FIG 108. Trends of iron enrichment for bulk rocks from Ruapehu and related vents. The two basalts are circled.

A. AFM diagram. Curve separating tholeiitic (TH) from calcalkaline (CA) fields is that of Irvine and Baragar (1971). Weak iron enrichment in basalts and basic andesites is indicated by crossing of Fe/Mg ratio lines, but no absolute iron enrichment occurs (Fig 107). Acid andesites and dacites have nearly constant Fe/Mg. Considerable scatter is evident, reflecting the influence of crystal accumulation and magma mixing.

B. Tholeiitic (TH) and calcalkaline (CA) volcanic rocks, as defined by Miyashiro (1974). Only 15 analyses are plotted. Two basalts and 13 relatively aphyric specimens, ranging from basic andesite to dacite.

assemblages, which is consistent with petrographic trends from basalts to acid andesites. (3) On the basis of petrography, other data points of lower Al_2O_3 (13.5-15.5 %) that roughly trend toward Waimarino Basalt probably reflect magma mixing between Waimarino Basalt and acid andesites/dacites. (4) Specimens with $> 19 \%$ Al_2O_3 have anorthosite fragments and high plagioclase: pyroxene ratios, suggesting plagioclase accumulation.

Calcium correlates negatively with silica, a strong indication that clinopyroxene and plagioclase fractionation are mechanisms of differentiation. High CaO values above the main trend are produced by accumulation of plagioclase.

Magnesium falls rapidly in basic rocks and then decreases less rapidly in rocks $> 55 \%$ SiO_2 , producing a convex- downward curvature. This trend would be expected from fractional crystallization of basalt, with early olivine + pyroxene removal, followed by plagioclase + pyroxene removal from intermediate magmas. Data points above this possible liquid line have petrographic features suggesting pyroxene $\pm$ olivine accumulation, or magma mixing.

Manganese behaves similarly to magnesium, and relatively high MnO values of many andesites can be attributed to pyroxene (0.2-0.7 % MnO) accumulation.

Total iron correlates negatively with silica and does not go through a maximum. This, together with $\text{FeO}^t \approx \text{CaO}$, is typical of calc alkaline volcanic suites (Gill, 1981, p. 107). Petrography suggests that fractionation of pyroxenes (ca. 7-25 % FeO^t), olivine (8-28 % FeO^t), and minor opaque oxides (25-80 % FeO^t) is the mechanism for suppression of iron enrichment.

Mg number shows considerable scatter and negative correlation with silica. The negative correlation is explained by the same arguments

as given for MgO variation. Overall, Mg numbers are significantly higher than for the average medium-K andesites of Gill (1981), although relatively aphyric samples approximate Gill's averages and probably define a liquid line of descent.

The high Mg numbers of some intermediate rocks are a consequence of several factors: (1) Since Mg number is $100\text{Mg} / \text{Mg} + \text{Fe}^{2+}$, the oxidation state of iron will be influential. As an example, the two andesites with $\text{Mg}^* > 80$ are oxidized bombs from the Ohakune vents, with $\text{Fe}_2\text{O}_3/\text{FeO} > 2$. When three visibly oxidized samples (with $\text{Fe}_2\text{O}_3/\text{FeO} > 1$) are eliminated, the entire rock suite ranges 0.19–0.78 and averages 0.44 $\text{Fe}_2\text{O}_3/\text{FeO}$. This is higher than the 0.25–0.35 $\text{Fe}_2\text{O}_3/\text{FeO}$ range found by Fudali (1965) for medium-K andesites at 1 atmosphere, 1200 C, near Ni-NiO buffer conditions. Thus, Gill (1981, p. 109) used $\text{Fe}_2\text{O}_3/\text{FeO} = 0.3$ when calculating Mg^* for orogenic andesites, but stated there is no rigorous way to choose this ratio. $\text{Fe}_2\text{O}_3/\text{FeO}$ ratios have not been changed from *measured* values by the present writer when calculating Mg numbers. Therefore, Mg numbers are generally higher than those of Gill's average medium-K andesites, and the average measured $\text{Fe}_2\text{O}_3/\text{FeO} = 0.44$ reported here can probably be attributed to slight subaerial oxidation of lava flow interiors, from which the samples were largely taken. As an indication of the extent of oxidation, 44 % of samples have $\text{Fe}_2\text{O}_3/\text{FeO} < 0.4$, and these average 0.32 $\text{Fe}_2\text{O}_3/\text{FeO}$. (2) Since olivine and pyroxenes have higher Mg^* than coexisting liquids, accumulation of ferromagnesian minerals influences Mg^* of bulk rocks, producing scatter at higher Mg^* than for relatively aphyric samples. (3) Two basalts with high Mg^* are identified, and petrography indicates magma mixing between these basalts and evolved magmas. As a consequence of linear mixing trends, hybrid magmas

will have higher Mg^* than magmas on a convex- downward liquid line, at equivalent silica contents.

Only the two basalts have Mg^* high enough to be in equilibrium with mantle olivine: If mantle olivine is $\geq Fo_{87}$ (Sato, 1977) then primary melts must have $Mg^* \geq 67$ if $K_d = 0.3$ (Roeder and Emslie, 1970). However, if fusion occurs at lower temperatures (≈ 1100 C) and hydrous conditions, then $K_d \approx 0.4$ (Nicholls, 1974) and Mg^* of primary melts will be ≥ 73 . Other than the basalts, samples with high Mg^* result from magma mixing, ferromagnesian mineral accumulation, and/or secondary oxidation.

Low titanium ($< 1.3\%$ TiO_2) is characteristic of rocks at convergent plate boundaries, and TiO_2 and FeO^t contents usually correlate positively with each other and negatively with silica in orogenic andesites (Gill, 1981, p. 111). Ruapehu specimens are low in TiO_2 , but much scatter and a weak positive correlation with silica is evident, in contrast to iron variation. Petrography and trace element geochemistry (see vanadium discussion) suggest fractionation of titanomagnetite, and negative correlation of TiO_2 with silica could be anticipated. However, opaque oxides are minor phases, and the effects of titanomagnetite fractionation on TiO_2 of bulk rocks must be weighed against the effects of co-precipitating silicate minerals. Pyroxenes contain only about 0.2-0.7% TiO_2 , and olivine and plagioclase concentrations are below the EPMA detection limit for TiO_2 . Hence, silicates in general have lower TiO_2 than bulk rocks, and their fractionation will tend to negate the decrease of TiO_2 associated with titanomagnetite fractionation.

Phosphorous contents in orogenic andesites are characteristically low, between 0.05-0.30 wt % P_2O_5 (Gill, 1981, p. 112). Values reported

here vary from 0.05-0.20 wt % P_2O_5 , have a weak positive correlation with silica in the range 52-62 % SiO_2 , and then decrease in bulk rocks > 62 % SiO_2 . This is consistent with petrography, since apatite is found as a trace mineral in about half of all rocks > 60 % SiO_2 , and could be a fractionating phase only in acid andesites and dacites.

Alkalies correlate positively with silica. No significant K- bearing phenocrysts (hornblende, biotite, K-feldspar) have been identified in the lavas, and potassium is strongly incompatible through the entire compositional range. Sodium is contained in plagioclase (2-6 wt % Na_2O), is therefore more compatible than potassium, and has a weaker positive correlation with silica for rocks with 52-59 % SiO_2 . In bulk rocks > 59 % SiO_2 , sodium is rather constant; this probably reflects the increasing role of plagioclase fractionation relative to pyroxenes in evolved liquids, and the increasing albite component of plagioclase during fractionation. Some scatter is produced by crystal accumulation and magma mixing.

6.4 TRACE ELEMENTS

Selected trace elements are plotted against **rubidium** in Fig 109. Rubidium is strongly incompatible during differentiation and increases 6-fold over the range 53-63 % SiO_2 . The bulk distribution coefficient for Rb is probably close to zero through the entire compositional range, since no phenocryst minerals are Rb- sequestering phases. If $D_{bulk, Rb} = 0$ and perfect fractional crystallization is assumed, then application of the Rayleigh Law shows that about 80 % fractional crystallization of basaltic magma is required to produce acid andesites with 60 % SiO_2 . The

FIG 109. Rubidium variation diagrams for 144 bulk rocks from Ruapehu and related vents. Basalts, circles; basic andesites, triangles; acid andesites, crosses; dacites, rhombs. Note the minor abscissa scale change on the Ni-Rb diagram. Vectors indicate liquid lines generated by perfect fractional crystallization of individual phenocryst minerals, and the percentages crystallized are shown in parentheses. Vectors that continue off scale are not terminated by arrows. Calculation of vectors assumes Rayleigh Law behaviour, and mineral-melt distribution coefficients of Gill (1981, Table 6.3).

compositional gap at 100-120 ppm Rb corresponds to the SiO_2 hiatus between acid andesites and dacites, a further indication that dacites may not be genetically related to andesites by fractional crystallization alone.

Zirconium is an incompatible, high field strength cation and shows a positive linear correlation with rubidium. **Barium** also correlates positively with Rb, and high Ba values are characteristic of the rock suite: Even basalts have 100-200 ppm Ba, which is 2-10 times the abundances reported for oceanic tholeiites (Basaltic Volcanism Study Project, 1981).

Strontium varies largely between 200-300 ppm for most rocks. This near-constancy is typical of orogenic andesites (Gill, 1981), and suggests that $D^{\text{Sr}}_{\text{bulk}} \approx 1$ during differentiation. A cluster of values at 15-20 ppm Rb and 300-500 ppm Sr includes Waimarino Basalt, a primitive quartz tholeiite with relatively high Sr, together with its proposed differentiates (see: Part III, Petrogenesis). The high Sr of Waimarino Basalt (348 ppm) is a useful geochemical fingerprint and will be used later to identify hybrid magmas that mixed with it. In the range 30-90 ppm Rb, many lavas with Sr > 280 ppm are plagioclase-accumulative or hybrids produced by mingling of Waimarino Basalt and evolved magmas.

Vanadium decreases regularly with increasing Rb, and follows the trend of FeO^t . This suggests fractionation of vanadium-bearing phase(s) throughout the compositional range, and petrographic evidence indicates that opaque oxides (with V^{3+} substituting for Fe^{3+}) and pyroxenes are influential. If $D^{\text{Rb}}_{\text{bulk}} = 0$, $D^{\text{V}}_{\text{plagioclase}} = 0$, $D^{\text{V}}_{\text{pyroxenes}} = 1.1$, $D^{\text{V}}_{\text{titanomagnetite}} = 30$ and plagioclase:pyroxenes = 1, then calculations using the Rayleigh equation show that $D^{\text{V}}_{\text{bulk}} \approx 1.3$ to produce the observed V-Rb variation, and ≈ 0.02 weight fraction titanomagnetite is required in the fractionating mineral assemblage. This small but necessary amount of titanomagnetite agrees with petrography.

Nickel and Chromium are strongly compatible elements during fractionation of olivine, pyroxenes and opaque oxides. In basalts and basic andesites with 15-30 ppm Rb, fractionation of olivine, pyroxenes and chrome spinel is suggested by the rapid decrease of Ni and Cr concentrations. Acid andesites and dacites with Rb > 30 ppm achieve relatively constant values of around 20 ppm Ni and Cr, again suggesting efficient removal by early fractionation of ferromagnesian minerals from parental magmas. The net result is a convex-downward trend on compatible-incompatible element diagrams (e.g., Ni-Rb, Cr-Rb); this trend can be reproduced using the Rayleigh equation, assuming $D_{\text{bulk}}^{\text{Rb}} \approx 0$ and $D_{\text{bulk}}^{\text{Ni,Cr}} > 1$. Thus, the trend is highly suggestive of fractional crystallization of basaltic magma. However, considerable scatter at high Cr and Ni occurs, similarly to MgO and Mg* diagrams, and concurrently high compatible-incompatible element values cannot be explained by closed-system fractional crystallization alone. Possible reasons for this scatter include open-system accumulation of ferromagnesian crystals and mixing of basic and acid magmas. As an indication of the pervasive influence of magma mixing and ferromagnesian mineral accumulation, it is instructive to note that nearly all samples contain > 10 ppm Ni and Cr. Even some dacites contain > 50 ppm Ni and > 100 ppm Cr, and these rocks have small xenocrysts of forsteritic olivine with chrome spinel inclusions (Fig 93H).

PART III: PETROGENESIS

".... apparently as many roads lead
to andesite as to Rome."

Gill (1981, p. 314)

1. INTRODUCTION

1.1 GENERAL STATEMENT

The field, geochemical and petrographic data of Parts I and II will now be applied toward constructing petrogenetic hypotheses. It is shown in Part I that lavas from Ruapehu and related vents are spatially (except Waimarino Basalt, which lies 45 km NE of Ruapehu) and temporally related. This, together with the nearly continuous but scattered compositional variation of bulk rocks shown in Part II, strongly implies consanguinity of the rock series, at least in the range of basalts to acid andesites. It has been demonstrated that samples are characteristically porphyritic, suggesting that many lavas do not represent liquid compositions. The minerals of lavas and nodules are anhydrous, and their mineral chemistry indicates low pressure crystallization, presumably in crustal reservoirs. Many lavas appear to be accumulative in igneous xenocrysts or rock fragments. Others exhibit petrographic features, such as mantled and reversely zoned phenocrysts, that are best explained by magma mixing; still others contain high- grade metamorphic xenoliths in various stages of assimilation, providing circumstantial evidence for crustal contamination and reservoiring in crustal magma chambers.

The major goal of Part III is to examine petrogenetic hypotheses that explain within- suite chemical and petrographic diversity. While no single path leads to andesite, fractional crystallization of basaltic magma is the principal process that explains compositional and mineralogical diversity. This follows the POAM (plagioclase- orthopyroxene/olivine- augite- magnetite) model of Gill (1981). Two time-transgressive basalt magma types are identified as parental to Ruapehu andesites. These magma types are exemplified by two unique field occurrences of basaltic

lava: Waimarino Basalt and Ruapehu basalt (from Mangawhero Fm).

Operating concurrently with fractional crystallization are the second-order processes crystal accumulation, magma mixing and assimilation of crustal material. Thus, diversity of rock composition and texture can be explained only by 'integrated models', as suggested by Gill (1981) and T.H. Green (1980).

1.2 NATURE OF THE NORTH ISLAND PLATE BOUNDARY

Cole and Lewis (1981) and Cole (1984) discuss the major structural features of North Island. The features shown in Fig 110 are considered to result from right- lateral oblique convergence between the Pacific and Indian Plates. The Hikurangi Trough (or Trench) to the east of North Island is regarded as a structural trench that marks the Indian- Pacific plate boundary and is the topographic expression of the suture marking plate collision. West of the trench is a 150 km- wide accretionary prism characterized by imbricate thrust faults in thick Upper Cretaceous to Quaternary turbidites. The accretionary prism is bounded on the west by a frontal ridge of Upper Paleozoic- Mesozoic greywacke, which forms the main axial ranges of North Island. The North Island Shear Belt (Cole, 1984) is a zone of dextral transcurrent faults that cuts obliquely across the frontal ridge. Thus, oblique convergence is manifested by compressional features to the east (thrust faults of the accretionary prism) and dextral strike- slip features to the west (North Island Shear Belt). The Taupo Volcanic Zone (TVZ; also see Fig 1 and accompanying discussion) comprises a young andesite- dacite volcanic arc along its eastern side (Taupo Arc; Cole and Lewis, 1981), and a western volcano- tectonic depression (Taupo-Rotorua Depression; Grindley, 1960) involving normal faulting and rhyolitic graben fill. The depression is interpreted by Cole and Lewis (1981) and Cole (1984) as an ensialic marginal basin. Ruapehu

FIG. 11Q. Tectonic elements of the Taupo-Hikurangi arc-trench system (from: Cole, 1984, fig 9).

is at the southern limit of the TVZ and can be considered as part of the Taupo Arc, but neither the marginal basin nor its associated rhyolitic volcanism extend this far south (see Fig 1).

Geophysical studies have led to the recognition of tectonic features that are germane to discussion of andesite petrogenesis. Current geophysical interpretations are synthesized in Fig 111. Perhaps the most speculative aspect of Fig 111 is the inferred shallow depth to the asthenosphere (ca. 30 km) beneath Ruapehu. Although this interpretation is only inferred by published geophysical data, it is consistent with those data and has been supported during discussion with colleagues. Furthermore, as will be shown later, petrogenesis of quartz- normative basalts requires melting of the upper mantle at depths less than about 60 km, implying the presence of shallow asthenosphere beneath the TVZ. Although the depth to asthenosphere beneath the TVZ is not well constrained, the following features are implied by geophysical data: (1) The existence of a westward- dipping seismic zone that reaches 80 km depth beneath Ruapehu, (2) the presence of anomalous (low- Q) mantle above the seismic zone and occurring only beneath the TVZ region, and (3) thin crust and lithosphere beneath the TVZ, in contrast to surrounding regions with about 35 km crustal thickness.

1.3 PREVIOUS WORK ON PETROGENESIS OF TVZ ERUPTIVES

Steiner (1958) and Clark (1960) are the first to use petrography and bulk rock major element chemistry to discuss the origins of TVZ magmas. Three distinct groups of volcanic rocks are recognized by these authors: (1) A "Main Basic Series", showing continuous variation from basalt to dacite, is considered to result from combined fractional crystallization and crustal assimilation, involving a contaminated high- Al basalt parent

magma. (2) An "Accumulative Series" of basic andesites (53-57 % SiO_2 , with relatively low Al_2O_3 and high MgO) is aberrant from chemical trends of the Main Basic Series and is petrographically characterized by " ... a notable amount of olivine phenocrysts" (Steiner, 1958). The Accumulative Series is considered to have originated by gravitational accumulation of early- crystallized olivine $\pm$ clinopyroxene, in combination with limited fractional crystallization of olivine basalt magma. (3) A "Continuous Acid Series" of rhyolites and ignimbrites is excluded from being derived by fractional crystallization of the contaminated basaltic magma. Rather, the rhyolites and ignimbrites are viewed as having been " ... derived from an acid magma resulting from transfusion of acid gneiss in prolonged contact with basaltic magma at great depth" (Steiner, 1958). Thus, two parent magmas are postulated for TVZ eruptives- one basaltic and one rhyolitic- and these in turn produced three distinct magma series. Fractional crystallization of basaltic magma, accumulation of early-formed igneous crystals and selective crustal assimilation are considered by Steiner (1958) and Clark (1960) to be petrogenetic processes in basic to intermediate volcanics of the TVZ.

Ewart and Stipp (1968) use K, U, Th and $^{87}\text{Sr}/^{86}\text{Sr}$ to infer petrogenesis of TVZ lavas. They conclude that TVZ rhyolites are derived by widespread partial fusion of eugeosynclinal greywacke-argillite sediments. Data for andesites are interpreted as being inconsistent with their derivation by fractional crystallization of outcropping high- Al basalts, or by direct mantle derivation involving a single- stage process. Andesite data are interpreted as being most consistent with crustal assimilation by basalt or by a primary andesitic magma, with greywacke-argillite sediments acting as the contaminant.

Duncan (1970) rules out andesite origin by assimilation as being inconsistent with bulk rock major and trace element compositions, and

shows that neither mixtures of (high- Al basalt) + (rhyolite) nor (high- Al basalt) + (greywacke/argillite) can approximate the major and trace element composition of average andesite. Duncan (1970) therefore proposes an origin from a subducting lithospheric plate by a two-stage process similar to that proposed by Taylor (1969).

Cole (1973) compiles field data, petrography and bulk rock chemical analyses from high- Al basalts of the TVZ; all high-Al basalt localities are shown to be associated with rhyolitic eruptive centres. Cole and Teoh (1975) describe the petrography and bulk rock chemistry of Pureora andesite volcano (an older volcanic centre to the NW of the Tongariro volcanoes), and argue that the lavas are pyroxene- accumulative basic andesites.

Cole (1978) provides the first major research paper dealing only with andesites of the Tongariro Volcanic Centre. Bulk rock major and trace element analyses, modal data and partial mineral analyses are given. Tongariro, Ngauruhoe and Ruapehu lavas are shown to be "normal" calcalkaline andesites (57-63 wt % SiO_2 and corresponding to acid andesites of the present study) and low-Si andesites (53-57 % SiO_2 and corresponding to basic andesites of the present study). Some low-Si andesites are regarded as phenocryst- rich cumulates. A model is presented in which subducted oceanic crust tectonically assimilates sediments at the eastern side of North Island, and eventually produces amphibolite at depth. Breakdown of amphibolite leads to hydration of the overlying mantle and lower crust, and eventually phlogopite eclogite is produced at depths of about 90 km. Then, a multistage mechanism of magma genesis is envisaged (Green and Ringwood, 1968; Ringwood, 1975), involving partial melting of phlogopite eclogite and subsequent fractionation of this magma in the upper mantle or lower crust, producing "normal" and low-Si andesites. Crustal contamination of TVZ andesites is

suggested by Cole (1978), after comparing Tongariro andesites (with relatively high Na_2O , K_2O , Rb, Ba and Zr) with island arc andesites such as those of Tonga (Ewart and Bryan, 1973). Cole (1978) considers the contaminant to be sediments of the accretionary prism that became tectonically mixed with basalt at the top of the downgoing slab.

Cole (1979) reviews the structure, petrology and genesis of TVZ volcanics and presents a modified version of the multistage magma genesis model, with several changes from the earlier phlogopite eclogite melting model (cf.: Cole, 1978). New seismic interpretations by Adams and Ware (1977) led Cole (1979) to place the depth to the top of the subducting slab beneath the Tongariro volcanoes at about 80 km and not 170 km as suggested earlier by Hamilton and Gale (1968). Cole (1979) proposes that amphibolite (and not phlogopite eclogite) would break down at 80–100 km depth, generating intermediate magma that would subsequently fractionate to produce the Tongariro andesites. Rare earth element data given in Cole (1979) are shown to be non-supportive of eclogite melting. Pyroxene andesites are regarded as accumulative lavas, while olivine low-Si andesites are considered to be a separate, more basic magma. Cole (1982) reviewed andesites of the Tonga- Kermadec- New Zealand region and maintained the same multi-stage hypothesis as Cole (1979).

Cole, Cashman and Rankin (1983) present rare earth element data for andesites and basalts of the TVZ. Least squares mixing models indicate that neither high-Al nor low-Al basalts (specifically, the low-Al Red Crater Basalt, Tongariro; Cole 1978) are likely parents for labradorite or labradorite- pyroxene andesites. However, the Red Crater basalt is thought to be directly related to olivine low-silica andesites and olivine andesites of the Taupo Arc by fractionation. The source region of andesites is inferred to be garnet- free, due to flat heavy rare earth

element patterns on chondrite- normalized plots, but the authors concede that the source could be either the top of the subducting plate or a hydrated lower portion of the mantle wedge. All lavas are believed to have undergone crustal contamination, on the basis of light rare earth element enrichment, though the composition and source of the contaminant is not specified by Cole, *et al.* (1983).

Reid and Cole (1983) discuss the origin of TVZ dacites (63-68 % SiO_2) and use quantitative petrologic models to conclude that a number of processes have operated on a local scale to produce dacite. These processes include: Fractional crystallization of andesite, andesite fractionation plus crustal contamination, partial melting of greywacke, and partial melting plus magma mixing. Thus, TVZ dacites are shown by Reid and Cole (1983) to be a minor (5 km^3 total volume) but petrogenetically diverse group.

Reid (1983) discusses the origin of rhyolitic rocks of the TVZ. Major element, trace element and rare earth element analyses for the greywacke basement surrounding the TVZ are presented, as well as new rare earth element analyses for rhyolites. Least- squares mixing calculations and Rayleigh fractionation models are used to show that the rhyolites are not likely to have been derived through fractional crystallization of basaltic or andesitic parents. Rather, non- modal melting of granulite with a bulk composition equivalent to the Western Basement can reproduce most geochemical features of the rhyolites.

1.3.1 Comments on Previous Work

In the 25 years since the origins of TVZ lavas were first studied, major petrogenetic hypotheses for andesitic rocks have included fractional crystallization of basaltic magma (Steiner, 1958; Clark, 1960)

and slab melting (Cole 1978, 1979, 1982). Some basic intermediate lavas were considered to be accumulative in phenocryst minerals, and all andesitic lavas were considered by all authors to have undergone crustal contamination, though no consensus exists as to the nature of the contaminant. Most quantitative modelling of andesite genesis has been simplistic, involving mixtures of high-Al basalt + greywacke/argillite or rhyolite, and compositions used in modelling were averages of published analyses. The inability of high-Al basalt fractionation to produce andesites (Ewart and Stipp, 1968; Cole, *et al.*, 1983) is consistent with the complete geographic separation of high-Al basalts and andesites (Cole, 1973). The existence of a second, low-Al basalt magma type, in geographic association with andesitic lavas, was first recognized by Cole (1978; Red Crater basalt, Tongariro), but attempts to model "average labradorite and labradorite-pyroxene andesite" as a derivative of this low-Al basalt were unsuccessful (Cole, *et al.*, 1983), implying yet another parental magma type for these andesites. At present, no satisfactory quantitative petrogenetic model exists for andesites of the TVZ.

The present writer will argue that fractional crystallization of low-Al, quartz-normative basaltic magmas, together with phenocryst accumulation, magma mixing and crustal contamination, can explain diversity of composition and texture. With the exception of magma mixing, these are not new to discussion of TVZ andesite genesis; however, the present data base is more extensive and quantitative modelling is therefore better constrained.

2. THE ROLE OF THE MANTLE WEDGE

As shown in Fig 111, the "low-Q upper mantle zone" of Mooney (1970) implies the existence of an asthenosphere wedge beneath North Island. The wedge may be shallower beneath TVZ relative to surrounding regions in order to explain the very high heat flow, which requires efficient heat transfer to the surface and implies shallow asthenosphere convection beneath TVZ. The depth to the top of the slab is ca. 80 km beneath Ruapehu (Reyners, 1980) and this has several petrogenetic implications: (1) The mantle wedge can comprise only plagioclase- and spinel peridotite, since garnet peridotite is stable only at depths > 80-90 km (D.H. Green and Ringwood, 1970; and assuming oceanic geotherm of D.H. Green and Ringwood, 1967). (2) At 80 km depth, the hydrated upper portion of the slab will have achieved an amphibolite mineral assemblage, and amphibolite dehydration is probably near completion by the time the slab has reached 75-100 km depth (Anderson, *et al.*, 1976; Delaney and Helgeson, 1978). This would liberate water and possibly other volatile constituents ("IRS fluid" of Gill, 1981) into the overlying mantle wedge, significantly lowering its melting point. Only at depths > 80-100 km would the anhydrous slab achieve eclogite mineralogy (Ringwood, 1974); therefore, the slab is not assumed to be eclogitic beneath Ruapehu.

Whether the slab melts or not is a matter of speculation, and depends on the assumed degree of slab heating as it subducts (e.g., thermal models of Toksoz, *et al.*, 1971; Griggs, 1972). The present writer considers that subsolidus slab dehydration, and not slab melting, occurs beneath Ruapehu, fluxing the overlying mantle wedge and allowing hydrous partial melting of peridotite in the wedge. Reasons for this conviction include: (1) Presence of anomalous mantle beneath TVZ, which can be interpreted as partially molten or perhaps veined peridotite, (2) Basalts, axiomatically the products of peridotite anatexis, are parental magmas to

andesites at Ruapehu. The doctrine of simplicity is applied by the present writer: If basaltic magma, even in minor volume, is found in geographic association with calc-alkaline andesites and if basalt can quantitatively be demonstrated as the parent magma of andesites, then more complex petrogenetic hypotheses (e.g., the multi-stage model of Ringwood, 1974) become less viable.

Two new basalt magma types have been identified during the present study. Waimarino Basalt, though it is a unique, isolated occurrence that is geographically unrelated to Ruapehu, represents a magma type that is important in petrogenesis of Ruapehu lavas. Ruapehu basalt is also a unique occurrence, but is associated spatially and temporally with andesitic lavas of Mangawhero Fm, Ruapehu. These two basalts have many compositional traits in common (e.g., both are quartz-normative), but are sufficiently different to be considered as separate magma types. Bulk rock analyses of these basalts, together with other basalt magma types, are given in Table 7.

2.1 PRIMITIVE NATURE OF WAIMARINO BASALT

Quartz-normative basalts and basic andesites can originate by differentiation of parental basalts, and porphyritic lavas with high Mg^* can originate by accumulation of refractory ferromagnesian crystals. It is therefore necessary to argue that Waimarino Basalt (with 23.5 % phenocrysts) is: (1) a liquid composition; i.e., not accumulative in olivine and clinopyroxene, and (2) a primary magma of the upper mantle that has not undergone significant modification by fractionation processes.

Texture and mineral compositions suggest that the Waimarino Basalt (hereafter, WB) is not accumulative. If forsteritic olivine crystals were added to a basic andesite magma (whose composition is represented by the WB groundmass), we would expect an abrupt compositional change

TABLE 7. Basalt analyses from this study, with comparative analyses from other sources. All major element analyses are recalculated to 100%, anhydrous.

	1	2	3	4	5	6	7
SiO ₂	52.55	52.61	53.92	53.58	56.30	52.5	49.35
TiO ₂	0.47	0.66	0.20	0.30	0.22	0.54	0.84
Al ₂ O ₃	12.77	15.68	12.99	14.8	8.14	10.6	15.55
Fe ₂ O ₃	1.97	2.72	1.25	1.93	2.44	1.3	0.98
FeO	6.63	6.39	6.36	6.96	7.37	10.3	8.25
MnO	0.16	0.16	0.15	0.16	0.18	0.16	0.18
MgO	13.24	8.79	13.28	9.28	19.38	13.2	10.70
CaO	9.67	9.70	10.30	11.00	4.86	8.9	12.04
Na ₂ O	1.65	2.61	1.15	1.59	0.87	2.1	1.90
K ₂ O	0.43	0.58	0.41	0.22	0.20	0.24	0.11
P ₂ O ₅	0.05	0.09	0.01	0.03	0.03	0.03	0.09
Mg*	78	71	79	68	81	64	70
Q	0.6	1.5	3.3	-	7.7	-	0
Cr	1070	389	850	283	1930	2060	680
Ni	310	135	339	88	540	310	255
V	217	254	203	188	136	-	-
Rb	15	12	14	2.6	4	-	2.4
Sr	348	200	62	167	63	-	78
Ba	123	193	45	40	30	-	12*
Zr	47	50	16	15.7	30	-	47
Nb	15	2	1.0	1.4	1.5	-	6.3
Y	13	17	7	6.0	4	-	20
La	5.2	-	1.09	0.74	2.50	-	3.50
Ce	10.5	-	2.19	2.05	5.46	-	8.7
Pr	1.2	-	0.23	0.31	0.61	-	-
Nd	5.1	-	1.02	1.68	2.84	-	-
Sr87/86	0.70448	0.70478	0.70559	0.70323	0.70465	-	0.7025*
Ti/Zr	60	79	71	115	42	-	107

(1) Weimerino Basalt (bulk rock 132, this study)

(2) Rupehu basalt (bulk rock 63, this study)

(3) Upper Pillow Lava, Troodos Ophiolite, Cyprus (sample 9 of Cameron, *et al.*, 1983)

(4) Island arc basalt from high-Mg group, Island Arc Basalt Reference Suite, New Britain (sample 1A-1 of Basaltic Volcanism Study Project, 1981)

(5) Boninite from upper boninite unit, Cape Vogel, Papua New Guinea (sample 2, field number B6, Cameron, *et al.*, 1983)

(6) Basaltic komatiite, Belingwe Greenstone Belt, Rhodesia (sample NG137, Cameron, *et al.*, 1979)

(7) Primary N-type (type 1) mid ocean ridge basalt, Project FAMOUS area, Mid-Atlantic Ridge; Ocean Floor Basalt Reference Suite (sample OF-3R of Basaltic Volcanism Study Project, 1981)

- not reported in original source

* 'typical value' from Table 1.2.5.4, Basaltic Volcanism Study Project, 1981

Mg* molecular ratio of Mg/Mg + Fe²⁺
Q weight percent normative quartz

within the olivine crystals, since the groundmass liquid is in equilibrium with Fo₇₄. This is not observed; olivine phenocrysts are always smoothly zoned from cores to rims (Fo_{92.5}-Fo₇₄), as shown by microprobe traverses across several large grains. Furthermore, olivine microphenocryst cores reach Fo₈₉ and are also smoothly zoned. Clinopyroxene crystals exhibit similar zonation patterns. These features suggest heterogeneous nucleation and growth of olivine and clinopyroxene from an evolving liquid whose residue comprises the groundmass, not addition of exotic ferromagnesian crystals into a basic andesite liquid.

Sparse olivine-clinopyroxene glomerophenocrysts do not have hypidiomorphic- granular texture and contain abundant interstitial glass with similar composition to groundmass glass. Thus, they are not interpreted as accidental nodules, but rather as cognate phenocrysts that nucleated and grew in close proximity.

We now test whether the forsteritic olivine cores (Fo_{92.5-90.8}) are in equilibrium with the bulk rock, when the bulk rock composition is assumed to represent the primitive liquid from which these olivines grew. Application of the Roeder and Emslie (1970) distribution coefficient:

$$(Fe/Mg)^{ol} / (Fe/Mg)^{liq} = 0.3$$

indicates that the liquid that crystallized Fo_{92.5-90.8} had an Mg/Mg+Fe²⁺ (mol) ratio of 0.78-0.75. This is within the observed bulk rock limits of Mg/Mg+Fe²⁺ = 0.78 (calculated using the titrimetric FeO) and 0.74 (calculated using total iron as Fe²⁺). Hence, the bulk rock, if regarded as a liquid composition, is in equilibrium with its olivine phenocryst cores when $K_D = 0.3$.

Olivine phenocryst cores are nickeliferous (0.3-0.4 wt % NiO) and a

distribution coefficient $D_{\text{Ni}}^{\text{ol-liq}} = [\text{ppm Ni, olivine cores} / \text{ppm Ni, bulk rock}] = 7.0-7.8$ is calculated. This is comparable to published olivine-liquid distribution coefficients for Ni in basaltic magmas having the 13 wt % MgO of Waimarino Basalt [cf.: Fig. 2 of Irving's (1978) review of experimental trace element partitioning], and is a further suggestion of olivine-liquid equilibrium.

Having used petrography and mineral chemistry to show that WB was probably once entirely liquid, it remains to argue that WB is a primitive magma. Clarke and O'Hara (1979) have noted that if a lava is a primary magma, then the calculated or observed olivine composition should approximate to that of the residual mantle source region. Upper mantle olivines, particularly those from depleted peridotites, lie in the range Fo_{94-89} (Sato, 1977). Waimarino Basalt, with $\text{Fo}_{92.5-90.8}$, meets Clarke and O'Hara's (1979) criterion for primitive status. The observed abundances of MgO (13.15 wt %), Ni (310 ppm) and Cr (1070 ppm) are also appropriate for primitive magmas.

As a final argument for primitive status, Waimarino Basalt plots within the primary melt field of Hanson and Langmuir's (1978) MgO-FeO pyrolite melting grid at 1 atmosphere under anhydrous conditions. Conditions indicated by the grid are 30 % melting at 1300 C, with Fo_{92} and minor pyroxene left in the residue.

2.2 PRODUCTION OF QUARTZ NORMATIVE MAGMAS IN THE UPPER MANTLE

Since Waimarino Basalt is interpreted as a primitive magma type, comparison with some experimentally- derived liquids is worthwhile. Liquids with normative compositions near the plane of silica saturation (quartz tholeiites and olivine- poor tholeiites) have been generated experimentally by anatexis of pyrolite and natural lherzolite. Quartz

tholeiites have been generated from peridotite under both water-saturated (Green, 1973, and the complementary study of Nicholls and Ringwood, 1973) and anhydrous conditions (Jaques and Green, 1980). Anhydrous melting at low pressure is generally considered appropriate for the source regions of mid ocean ridge basalts (MORB), whereas hydrous melting of the mantle wedge is probably more likely for subduction-related basaltic magma (Nicholls and Ringwood, 1973), with hydrous fluid derived from subducted oceanic lithosphere. The pressure- percent melting grid of Fig 112 is based on water- saturated, water- undersaturated and anhydrous melting experiments. The grid indicates that anhydrous melting of peridotite (or pyrolite) can yield quartz normative liquids only to pressures < 7 kb, with degrees of melting on the order 15-35 % (Jaques and Green, 1980). Quartz normative liquids can be generated to pressures of about 18 kb under water- saturated conditions (Green, 1973). The extension of quartz normative melts to higher pressures under hydrous conditions is attributed to expansion of the stability field of olivine (Kushiro, 1972), permitting mantle olivine to be in equilibrium with silica- saturated melts. Other important features of the grid are: (1) The high pressure limit of the hydrous melt field implies a 60 km *maximum* depth of melting beneath Ruapehu. (2) Partial melting in the upper mantle is restricted to the plagioclase peridotite and Al-pyroxenes + spinel peridotite stability fields. [This is confirmed by REE studies on TVZ lavas (e.g., Cole, *et al.* 1983); that is, a garnet-free residuum is suggested by REE patterns of TVZ basalts and andesites.] (3) Quartz tholeiites are produced to greatest depths (ca. 60 km) under water-saturated conditions and when the percentage of melting is 25-30 %. It is appropriate to consider the slab as a source of hydrous fluid, since dehydration of amphibole is expected to occur at depths between 60 and 100 km (Delaney and Helgeson, 1978).

As a comparison to Waimarino Basalt, Green (1973) reports that

FIG. 112. Petrogenetic grid of pressure vs. percent melting for hydrous and anhydrous pyrolyte. High pressure limit of hydrous melt field represents water-saturated pyrolyte. Peridotite phase transitions in asthenosphere are from Green and Ringwood, 1970. Geophysical features are superposed on the grid, to show application to North Island plate boundary.

magnesian quartz tholeiite (5 % normative quartz) is produced by 32.5 % melting of pyrolite under water- saturated conditions, 10 kb, 1200⁰ C. This melt has $Mg^* = 75$, and the following mineral assemblages are observed at 10 kb: Olivine alone (Fo_{93}) is present as an equilibrium crystalline phase at 1200⁰ C, clinopyroxene and olivine are present at 1100⁰ C, and orthopyroxene first appears at 1050⁰ C. These experimentally determined features are remarkably similar to those calculated or observed for WB, and lend strong support to the hypothesis that WB was generated by 30-35 percent partial melting under hydrous conditions, in the spinel- or plagioclase peridotite stability field.

2.3 COMPOSITION OF RUAPEHU BASALT AND RELATIONSHIP TO WAIMARINO BASALT

Ruapehu basalt of Mangawhero Fm (hereafter, RB) has $Mg^* = 71$, suggesting that it, too is a primitive magma. Although RB bulk rock is in equilibrium with its Fo_{90} olivine phenocrysts, the bulk rock probably does not represent a primary liquid because petrography and mineral chemistry suggest accidental entrainment of igneous crystals from intermediate magma: Mantled pyroxene and feldspar crystals are present (Fig 93A). The cores of these grains have compositions appropriate for basic andesite liquids, but the outer mantles are in equilibrium with basaltic magma. These features are not likely to have resulted from magma mixing with an evolved end member (i.e., basic- or acid andesite) because bulk rock incompatible element concentrations are too low; for example, RB has only 12 ppm rubidium. In spite of the evidence for crystal accumulation, the present writer has nonetheless used RB as a parental magma in mixing calculations to derive andesites, since it is the only basaltic lava known from Ruapehu.

Relative to WB, RB has higher concentrations of Ti, Al, Fe, P and alkalies, and lower concentrations of compatible elements such as Mg, Cr and Ni (Table 7). This suggests RB may be a differentiate of the more primitive WB, but least-squares calculations (not reported) disprove olivine + clinopyroxene fractionation from WB to derive RB. Inspection of the bulk rock analyses provides confirmation: RB has much lower strontium and slightly lower rubidium than WB; this would require $D_{\text{Sr}}^{\text{bulk}} \gg 1$ and $D_{\text{Rb}}^{\text{bulk}} > 1$ during early fractional crystallization of WB, which is inconsistent with petrography. In addition, incompatible element ratios such as K/Rb and Ba/Zr are substantially different between the two basalts; these ratios would not be affected by fractional crystallization, implying different sources and/or melting processes. Consequently, they must be thought of as different magma types.

2.4 COMPARISON OF WAIMARINO BASALT WITH OTHER BASALT MAGMA TYPES

Waimarino Basalt (Table 7) is very similar to some of the Upper Pillow Lavas from the Troodos Ophiolite, the only notable differences being the higher Ti, Sr, Ba, Zr and LREE of WB. Sun and Nesbitt (1978) referred to these pillow lavas as "low-Ti ophiolitic basalts" and concluded that they were produced by hydrous melting of a depleted mantle source in an interarc basin or young island arc setting. Similarly, WB is believed to reflect young volcanism in the Taupo Arc (Hackett, in press). In terms of major elements, WB is also similar to basaltic komatiite, an Archaean magma type that has Phanerozoic analogues in the silica-oversaturated but highly compatible element-rich "boninite series" of primitive arc volcanism (Meijer, 1980). Cameron, *et al.* (1979) have shown that Phanerozoic boninite petrographically resembles Archaean basaltic

komatiite, and the range of boninite compositions overlaps that of basaltic komatiites. Waimarino Basalt does not meet the strict petrographic definition of boninite, since it is neither glassy nor does it have orthopyroxene phenocrysts; the former is due to subaerial extrusion of WB (as opposed to submarine boninite), and the latter reflects the more silica-poor bulk composition of WB relative to boninites. However, WB has many of the same major and trace element features that Meijer (1980) proposed as characteristic of "boninite series" volcanic rocks (Fig 113).

Moderate to high degrees of peridotite melting (ca. 30 %) characterize WB and tholeiites in general, so a comparison of WB with other tholeiites is undertaken. Relative to 'primary' ocean ridge (MORB) and island arc tholeiites (IAT), WB is enriched in the incompatible elements K, Rb, Sr, Ba and LREE, and has higher $^{87}\text{Sr}/^{86}\text{Sr}$, MgO , Mg^* , Cr and Ni (Table 7). It also differs from MORB and IAT in having a lower Ti/Zr ratio (Fig 113). The concurrently high compatible element abundances (Mg, Cr, Ni) and low Ti and P of Waimarino Basalt suggest melting of previously depleted mantle or retention of residual phases (ilmenite, rutile, sphene, apatite?) in the source. However, the degree of partial melting that is implied by the bulk composition and by comparison with experimental results seems to preclude residual phases other than olivine + orthopyroxene in the source of WB.

The present writer therefore favours melting of a depleted source, but this cannot explain the LIL element-enriched character of WB, relative to other tholeiites. Although data for Waimarino Basalt are incomplete, the MORB-normalized pattern of WB is similar to that of island arc tholeiites (Fig 114), where continental crust is absent in the overriding plate. Depletion of Ta to Yb in WB and IAT relative to MORB can be attributed to higher degrees of partial melting and/or lower degrees of fractionation than MORB (Pearce, 1984). Enrichment of Sr to Th in WB and IAT relative to MORB must result from enrichment processes affecting

FIG 113. Major and trace element characteristics of 'boninite series' volcanic rocks and island arc tholeiites (from: Meijer, 1980, figs 4 and 6).

A. Plot of normative components enstatite (in orthopyroxene), quartz and ilmenite x 10. Boundary curve separating boninite series from other series is drawn by Meijer (1980) on the basis of mineralogy, texture and other chemical components (e.g. high Mg, Cr, Ni in boninite). Bold arrows show differentiation trends of volcanic rock series; boninite series rocks are generally silica-oversaturated and have low concentrations of h.f.s. elements such as Ti, Zr, and Y, so they plot at the extreme right of the diagram. Differentiation trends of basalts of this study (WB, RB; see section III-3 for modelling of fractional crystallization) are similar to those of island arc tholeiites, but WB appears transitional between boninite series and arc tholeiites, using criteria of this plot.

B. Plot of TiO₂ versus Zr. Note boninite series rocks have Ti/Zr ratios substantially less than the average chondritic value of 110, in contrast to arc tholeiites. Basalts of the present study have Ti/Zr ratios similar to boninite series, but differentiation trend of RB does not parallel that of boninite series.

FIG. 114. MORB- normalized plot of Waimarino Basalt (filled circles connected by bold lines) and island arc tholeiites (shaded area). Normalizing values of 'typical N-type MORB' (from Pearce, 1984, fig 3a) are given at base of diagram. Island arc tholeiites are from the Lesser Antilles, Tonga, South Sandwich Islands and Oman (Pearce, 1984).

their source regions or from contamination during ascent through the crust (Pearce, 1984). Although the data of Fig 114 do not permit discrimination of the source of LIL element enrichment for WB, the present writer emphasizes the similarity with IAT and suggests that the enrichment of WB at least partially owes to metasomatism of the mantle source region. The origin of metasomatic fluids is suggested to be the subducting slab.

Other workers have attributed the enrichment of incompatible elements in TVZ lavas to contamination by continental crust; e.g., Ewart and others' (1977) comparison of Tonga- Kermadec with New Zealand volcanic rocks. Minor crustal contamination of WB is likely, since WB contains rare mm-sized quartzite xenoliths. However, mineralogy and bulk rock chemistry strongly suggest that WB is a primitive magma type that erupted after little or no fractionation (section II-2.1). It therefore seems likely to the present writer that incompatible element enrichment of WB at least partially owes to enrichment of its mantle source region, and not entirely to the effects of crustal contamination. Orogenic andesite derivatives must inherit these characteristics; i.e., some measure of the LIL- and LREE-enriched character of TVZ andesites is probably due to parental (and primary) magma characteristics, and not solely to the effects of crustal contamination of andesite during its rise and storage in the upper plate.

The present writer concludes that the role of the mantle wedge beneath Ruapehu is to produce basaltic magma, by anatexis of the asthenosphere and/or the subcontinental lithosphere. This process is probably catalyzed by hydrous, metasomatic fluids from the subducting slab. The resulting melts include quartz- normative but primitive basalt that is depleted in P and Ti, and enriched in Sr, LIL, LREE and radiogenic strontium, relative to MORB and IAT. The origin of the LIL- LREE- ^{87}Sr -enriched component in parental basalts is arguable, but probably reflects both mantle metasomatism (slab component) and contamination during rise

and storage of magma (crustal component).

2.5 ULTRAMAFIC NODULES AS POSSIBLE SAMPLES OF UPPER MANTLE

Most igneous nodules found in Ruapehu lavas are pyroxene-plagioclase rocks, but rare, cm-sized nodules of dunite and harzburgite (Fig 96 K,L) are found in tephra of Pukeonake Scoria Cone. It will be argued later that the lavas of Pukeonake are hybrid in origin, involving mixing of primitive basalt and dacite. The ultramafic rock fragments were undoubtedly brought up as a component of the primitive basalt, but their interpretation remains uncertain: They could represent either crystal cumulates from primitive basalt, or accidental upper mantle fragments. At present, they raise more questions than they answer.

Whatever their origin, the mineralogy is refractory: harzburgite (Fig 96 K,L) contains Fo₈₈, dunite nodules contain Fo₉₂₋₈₈ (no photomicrographs, but see analyses in Appendix IV-136-2,5), and one olivine crystal in a Pukeonake lava flow is Fo₉₄ (Appendix III-139-7). All dunites and harzburgites contain refractory chrome spinel with 52-53 wt % Cr₂O₃.

The dunite nodules are equigranular-polygonal in texture, but harzburgite (Fig 96 K,L) has bands of orthopyroxene that suggest penetrative deformation, perhaps as a result of upper mantle diapirism. Veins of silicic, aluminous, alkali- and volatile- rich glass are present in the ultramafic nodules (see Appendix IV-136-50,16 for glass analyses), the Mg-numbers of which are far too low for the glass to be in equilibrium with olivine of the host nodules. Nor is the glass likely to derive from the enclosing andesitic host magma, since the host magma can only react with, but not melt, such refractory nodules. The possibility exists that

these nodules represent depleted mantle with volatile-rich metasomatic veins, the latter having melted during decompression.

3. THE ROLE OF BASALT FRACTIONATION

Bowen (1928) argued persuasively that fractional crystallization is a common process in nature and can explain much of the compositional diversity of igneous rocks. Gill (1981) presents previously published quantitative fractionation models from diverse regions of orogenic andesite volcanism, and argues that fractional crystallization of basaltic magma is "...by far the most common and extensive process" that produces orogenic andesites. Gill (1981) refers to this as "POAM" (plagioclase + orthopyroxene/olivine + augite + magnetite) fractionation.

The bulk rock compositional variation shown in Figs 107 and 109 suggests that removal of the phenocryst minerals olivine, pyroxenes, plagioclase and opaque oxides may be an important differentiation mechanism for the Ruapehu rock suite. Accordingly, quantitative modelling of fractional crystallization has been undertaken: Summarized results of least squares mixing calculations are given in Tables 8 and 9, and calculated vs. observed mineral proportions are compared in Fig 115.

3.1 CRITERIA FOR CHOICE OF SAMPLES REPRESENTING LIQUID COMPOSITIONS

It has been shown in Part II that nearly all lavas are porphyritic, and petrographic evidence for crystal accumulation and magma mixing exists in many samples. Therefore, the present writer has been selective in choosing samples for quantitative modelling of fractional crystallization. The essential criterion for choosing rocks that approximate to liquid compositions is not total phenocryst content, but rather the textural relations of phenocrysts. As far as possible, the writer has' chosen samples that are free of crystal aggregates and mantled phenocrysts.

3.2 DISCUSSION OF LEAST SQUARES MODELLING

Fractional crystallization of Ruapehu and Waimarino basalt magma types, and their possible derivative liquids has been modelled in stepwise fashion; i.e., from basalt to basic andesites, then basic to acid andesite, then acid andesite to dacite. This is necessary because the types and proportions of phenocryst minerals change significantly from basalt to dacite. The reported calculations are the results of extensive trial and error on selected samples.

Calculated and observed phenocryst assemblages are compared in Fig 115. The reader is reminded that the calculated fields show the mineral proportions that are *removed* in order to achieve a match with the parent magma, therefore the calculated and observed proportions for a given rock should not be compared directly. For example, in Fig 115B, the small amount of plagioclase removal required by calculation is consistent with the observed large amount of plagioclase in rock 11-135 because the parent magma does not contain plagioclase phenocrysts at all. That is, the calculated mineral proportions in derivative magmas ideally should fall somewhere between the proportions observed in the parent and derivative magmas. The following features of Fig 115 are worthy of mention: (1) The observed assemblages from basalt to dacite in Fig 115A summarize the petrographic information of Part 11-2.1 to 2.5. That is, opaque oxides are minor but ubiquitous in lavas, the proportion of plagioclase phenocrysts and the orthopyroxene: clinopyroxene ratio increase with bulk rock acidity, and olivine disappears in basic andesites as a consequence of reaction with liquid. (2) The calculated mineral assemblages are generally in excellent agreement with the observed assemblages. Especially noteworthy is the requirement of minor opaque oxide fractionation, which was suggested earlier by major and trace element trends for the rock suite (Figs 107-109). (3) The calculated mineral proportions for dacite do

FIG 115. Comparison of calculated and observed mineral proportions during fractional crystallization. Calculated mineral proportions are from least squares mixing models of Tables 8 and 9. Observed mineral proportions are from modal data of Tables 1, 3 and 5; since modes have not been obtained for rocks II-1, II-106 and II-133, rocks of nearly identical petrography from the same formations have been used (II-2, II-107 and II-135). 'OL' = olivine, 'CPX' = clinopyroxene, 'OPX' = orthopyroxene, 'PLAG' = plagioclase, 'OP' = opaque oxides.

A. Fractional crystallization of Ruapehu basalt magma type to yield andesites and dacite
B. Fractional crystallization of Waimarino Basalt magma type to yield basic andesite of Hauhungatahi

not agree with petrography, since the calculated total pyroxenes and clinopyroxene: orthopyroxene ratio are excessively high.

In Table 8, the calculated and observed bulk rock compositions are in good agreement for the steps: (Ruapehu basalt) - (minerals) = (basic andesites), and: (Basic andesite) - (minerals) = acid andesite. Small discrepancies in compatible elements such as Cr can be explained by minor pyroxene $\pm$ opaque oxide accumulation, in spite of careful sample selection. Substantial discrepancies involving *incompatible* elements occur in several calculations of Table 8, where the observed incompatible element concentrations of derivative lavas are too high to be explained by fractional crystallization alone. Barium, Rb, Zr and K_2O are components that would be affected by contamination processes, and the calculations suggest that fractional crystallization has acted concurrently with crustal contamination (see: Part III-6 for further discussion of the role of the crust). Incompatible element discrepancies for the step: (Acid andesite) - (minerals) = (dacite) are so large that the simple fractional crystallization model (Table 8, VI-6) must be rejected, even though these rocks differ by only 5 wt % SiO_2 . The writer has modelled several acid andesite-dacite combinations, and this calculation has the lowest residuals; no amount of manipulation will improve the major discrepancies for the incompatible elements K_2O and Rb since no K- or Rb-bearing phenocrysts are present in these rocks. The failed dacite calculation implies that process(es) in addition to fractional crystallization operate during dacite petrogenesis, and a mechanism is required for increasing the K and Rb values above the concentrations allowed by simple fractional crystallization of acid andesite. The writer proposes two hypotheses: (1) Since major discrepancies exist only for the incompatible elements, fractional crystallization may indeed operate, but in combination with selective assimilation of crustal material. The

TABLE 8. Summary of least squares mixing calculations for fractional crystallization series from Ruapehu basalt. Complete results of calculations are found in Appendix VI; headings are calculation numbers tabulated in Appendix VI. 'II-63', etc. = bulk rock analysis numbers of Appendix II; 'VARIABLE' = components of mix utilized to achieve match with observed parent magma composition; 'OL' = olivine; 'CPX' = clinopyroxene; 'OPX' = orthopyroxene; 'PLAG' = plagioclase; 'TMT' = titanomagnetite; 'CRSP' = chrome spinel; '% XTL' = weight percent crystallized; 'CUM %' = cumulative weight percent crystallized from basalt parent; ' ΣR^2 ' = sum of squares of oxide residuals; 'DISAGREEMENTS' are noted if oxide residuals are > 0.1 or if calculated vs. observed trace element concentrations in derivative magma differ by $> 20\%$.

CALCULATION VI-1				CALCULATION VI-2			
PARENT MAGMA (II-63)				PARENT MAGMA (II-63)			
	OBS	CALC			OBS	CALC	
SiO ₂	52.23	52.23		SiO ₂	52.23	52.23	
TiO ₂	0.66	0.68		TiO ₂	0.66	0.66	
Al ₂ O ₃	15.57	15.58		Al ₂ O ₃	15.57	15.58	
FeO ^t	8.76	8.76		FeO ^t	8.76	8.76	
MnO	0.16	0.13		MnO	0.16	0.13	
MgO	8.73	8.73		MgO	8.73	8.73	
CaO	9.63	9.63		CaO	9.63	9.62	
Na ₂ O	2.59	2.54		Na ₂ O	2.59	2.47	
K ₂ O	0.58	0.54		K ₂ O	0.58	0.58	
P ₂ O ₅	0.09	0.10					
DERIVATIVE MAGMA (II-1)				DERIVATIVE MAGMA (II-64)			
	OBS	CALC			OBS	CALC	
Ba	218	275		Ba	232	230	
Rb	23	17		Rb	17	15	
Sr	216	222		Sr	222	224	
Zr	55	69		Zr	59	60	
V	251	241		V	265	236	
Cr	86	85		Cr	128	135	
Ni	36	37		Ni	53	56	
MODEL: Ruapehu Basalt to basic andesite of Te Herenga Fm				MODEL: Ruapehu basalt to basic andesite, both of Mangawhero Fm			
DISAGREEMENTS: Ba, Rb, Zr				DISAGREEMENTS: none			
PARENT MAGMA (II-63)				PARENT MAGMA (II-63)			
	OBS	CALC			OBS	CALC	
SiO ₂	52.23	52.23		SiO ₂	52.23	52.23	
TiO ₂	0.66	0.68		TiO ₂	0.66	0.66	
Al ₂ O ₃	15.57	15.58		Al ₂ O ₃	15.57	15.58	
FeO ^t	8.76	8.76		FeO ^t	8.76	8.76	
MnO	0.16	0.13		MnO	0.16	0.13	
MgO	8.73	8.73		MgO	8.73	8.73	
CaO	9.63	9.63		CaO	9.63	9.62	
Na ₂ O	2.59	2.54		Na ₂ O	2.59	2.47	
K ₂ O	0.58	0.54		K ₂ O	0.58	0.58	
P ₂ O ₅	0.09	0.10					
DERIVATIVE MAGMA (II-1)				DERIVATIVE MAGMA (II-64)			
	OBS	CALC			OBS	CALC	
Ba	218	275		Ba	232	230	
Rb	23	17		Rb	17	15	
Sr	216	222		Sr	222	224	
Zr	55	69		Zr	59	60	
V	251	241		V	265	236	
Cr	86	85		Cr	128	135	
Ni	36	37		Ni	53	56	
MODEL: Ruapehu Basalt to basic andesite of Te Herenga Fm				MODEL: Ruapehu basalt to basic andesite, both of Mangawhero Fm			
DISAGREEMENTS: Ba, Rb, Zr				DISAGREEMENTS: none			

TABLE 8. continued

CALCULATION VI-3				CALCULATION VI-6			
PARENT MAGMA (II-64)				PARENT MAGMA (II-88)			
OBS	CALC	VARIABLE	WT FRACTION	OBS	CALC	VARIABLE	WT FRACTION
SiO ₂	53.15	II-88	0.433	SiO ₂	58.54	II-106	0.609
TiO ₂	0.68	PLAG	0.311	TiO ₂	0.68	PLAG	0.238
Al ₂ O ₃	17.05	OPX	0.150	Al ₂ O ₃	17.41	CPX	0.077
FeO ^t	8.54	CPX	0.078	FeO ^t	6.85	DPX	0.061
MnO	0.13	TMT	0.028	MnO	0.11	TMT	0.014
MgO	6.66	% XTL	56.4	MgO	3.75	% XTL	39.4
CaO	8.79	CUM %	63.4	CaO	7.05	CUM %	77.8
Na ₂ O	2.77	ΣR ²	0.0123	Na ₂ O	3.16	ΣR ²	0.2790
K ₂ O	0.68			K ₂ O	1.20		
P ₂ O ₅	0.10			P ₂ O ₅	0.10		
DERIVATIVE MAGMA (II-88)				DERIVATIVE MAGMA (II-106)			
OBS	CALC			OBS	CALC		
Ba	311			Ba	514		
Rb	41			Rb	124		
Sr	234			Sr	255		
Zr	86			Zr	198		
V	181			V	117		
Cr	43			Cr	29		
Ni	28			Ni	19		
MODEL: Basic andesite to acid andesite, both of Mangawhero Fm				MODEL: Acid andesite to dacite, both of Mangawhero Fm			
DISAGREEMENTS: Ba, Cr				DISAGREEMENTS: K ₂ O, Rb, Zr, Cr			

contaminant would need to be rich in incompatible elements, and may originate by anatexis of metamorphic xenoliths. (2) While acid andesites can largely be explained by protracted fractionation of parental basaltic magma, the Ruapehu dacites may be more closely related to TVZ rhyolites, in the sense that they are the products of crustal melting (cf: Reid and Cole, 1983). This possibility is supported by the compositional gap that exists between acid andesites and dacites on interelement variation diagrams (Figs 107,109).

It is also noteworthy that the RB magma type has produced not only intraformational andesitic differentiates, but also differentiates in the much older Te Herenga Fm. This implies that the RB magma type, represented by a single basalt lava flow in Mangawhero Fm., is time-transgressive in the magma system of Ruapehu.

Calculations for fractionation of Waimarino Basalt magma type are presented in Table 9. In part, potential derivative magmas of the WB magma type were chosen on the basis of their high Sr concentrations relative to other basic andesites, since WB is characterized by high Sr. Waimarino Basalt lacks plagioclase phenocrysts, and Sr should therefore be incompatible during the early stages of fractionation, prior to major plagioclase crystallization. Calculated and observed results are in excellent agreement for Hauhungatahi basic andesite (Fig 115B, and Table 9, VI-4). The discrepancy for chromium can be explained by minor clinopyroxene accumulation, and this is consistent with the petrography of Hauhungatahi samples. Though not accounted for in the calculation, Sr isotopic ratios also differ between WB (0.70448) and Hauhungatahi (0.70423), suggesting significant isotopic differences between batches of WB magma type as a consequence of mantle source heterogeneity and/or varying degrees of crustal contamination. A further implication of this calculation concerns the stratigraphic context of the lavas: The WB magma type (age of WB at type locality is 14-20 Ka) has apparently

fractionated to produce Hauhungatahi basic andesites, which are among the oldest eruptives of the Tongariro Volcanic Centre. Clearly, single magma batches cannot have been involved and the calculations imply that magmas of the WB type may have been time transgressive.

A calculation to derive Ohakune basic andesite from Waimarino Basalt is given in Table 9, VI-5. The high bulk rock Sr of Ohakune lavas (ca. 340 ppm) relative to Ruapehu basic andesites (ca. 220 ppm) cannot be a result of accidental plagioclase entrainment, since Ohakune lavas contain only minor, euhedral plagioclase microphenocrysts. Rather, the high bulk rock Sr of Ohakune basic andesites suggests that these lavas may be differentiates of a high-Sr parental basalt that fractionated predominantly ferromagnesian minerals. The WB magma type is a probable parent for Ohakune basic andesite because WB at its type locality has high bulk rock Sr, lacks plagioclase phenocrysts, and erupted nearly synchronously with the Ohakune vents. However, large trace element disagreements are present in the calculation to derive Ohakune basic andesite from the WB parent. Discrepancies for Cr and Ni can be explained by accumulation, since the Ohakune lavas contain small peridotite nodules; these nodules could be construed as cumulate fragments from the WB parent since the major nodule minerals are olivine and clinopyroxene. The disagreements for Ba, Rb and Zr cannot be explained in this manner. The calculation suggests that the Ohakune basic andesite may be: (1) The fractionation product of a parental basaltic magma type that is similar to Waimarino Basalt, but richer in Ba, Rb and Zr, or (2) the combined result of WB fractionation, accumulation and crustal contamination. The latter hypothesis is supported by the presence of small peridotite nodules and crustal rock fragments in Ohakune lavas, as well as slight enrichment of Ohakune lavas in radiogenic strontium ($^{87}\text{Sr}/^{86}\text{Sr} = 0.70456$) relative to the proposed WB parent ($^{87}\text{Sr}/^{86}\text{Sr} = 0.70448$).

The preceding results and discussion show that simple fractional

crystallization cannot entirely explain the petrographic and bulk rock chemical variation of Ruapehu lavas, even after careful sample selection. In a general way, fractional crystallization of basaltic magma is consistent with the petrographic and bulk rock chemical variation of andesites, but few individual mixing calculations of parent-derivative lavas are entirely satisfactory. This is true for several reasons: (1) Parental basalts may not be well characterized. Two basalt magma types, represented by two unique field occurrences, have been identified and used in quantitative modelling. There may be other basalts that produce different liquid lines from those calculated here (e.g., Red Crater basalt, Tongariro; Cole, et al., 1983). (2) Models that assume simple fractional crystallization are seldom satisfactory because fractional crystallization is apparently contemporaneous with other differentiation processes such as accumulation of igneous crystals, magma mixing and crustal contamination. In the following sections, these processes are examined more closely.

4. THE ROLE OF CRYSTAL ACCUMULATION

4.1 INTRODUCTION

Accumulation of igneous crystals in TVZ eruptives was first proposed by Steiner (1958) and Clark (1960), who considered an "Accumulative Series" of basic andesites that originated by accumulation of olivine and pyroxene into host liquids that were derived by fractional crystallization of a basaltic parent. Cole and Teoh (1975) demonstrated that the basic andesites of Pureora Volcano, TVZ, are pyroxene-accumulative, and Cole (1979) suggested that some varieties of pyroxene-rich basic andesites from the TVZ are accumulative in pyroxenes.

Ewart (1982) shows that significant statistical correlations exist between phenocryst modes and bulk rock compositions of basic to intermediate lavas from the southwestern Pacific. Plagioclase correlates with Al_2O_3 ; olivine with MgO, Ni, and Cr; and augite with MgO. These correlations, together with the phenocryst-rich textures of most orogenic lavas, are considered by Ewart (1982) to reflect both phenocryst accumulation and extraction during low pressure fractional crystallization processes. Arculus, *et al.* (1983) describe andesites from the 1951 cumulodome of Mount Lamington; these were contaminated by olivine and orthopyroxene from harzburgites of the underlying Papuan Ultramafic Belt. Mertzman (1977) documents an accumulative basalt from the Medicine Lake Highland, California, which is a linear mixture of basic andesite and olivine + plagioclase. Thus, recent studies from other regions of orogenic volcanism imply that "open system" differentiation is a common process, and that crystal accumulation is a natural corollary to fractional crystallization. Accumulation can be anticipated at polygenetic volcanoes such as Ruapehu, where fresh influxes of intermediate magma continually

re-occupy old conduits and accumulate igneous crystals from earlier episodes of magma consolidation.

Bowen (1928) and McBirney (1979) have shown that exotic crystals will exhibit one of three relationships with liquid. (1) If the added crystals are mineral(s) that the host magma could have precipitated at an earlier stage of differentiation, then the host magma cannot melt the crystals but will react with them to form mineral(s) that are equilibrated with the host magma. An example is a forsteritic olivine xenocryst in dacite host magma (Fig 93H): The host magma is in equilibrium with orthopyroxene, and has reacted with the exotic olivine to form an orthopyroxene corona. (2) The added crystals are of similar types and compositions to those the host magma is actively precipitating (Fig 96A): In this situation no reaction occurs, the exotic crystals simply add to the existing phenocryst assemblage, and would be virtually indistinguishable from cognate phenocrysts. (3) The added crystals are minerals that the host magma could precipitate at later stages of differentiation (Fig 122 A,B): In this situation, the added minerals can be congruently or incongruently melted, with the heat of fusion being supplied by latent heat of crystallization of phenocrysts from the host magma.

In schemes 1 and 2, no new melt is produced when igneous crystals are added to host magmas; this process is defined as accumulation, and is the subject of the present section. Scheme 3 involves the production of melt and/or vapour, with possible addition of these mobile phases to host magmas. This is defined as an assimilation process, and is the subject of section III-6.

4.2 EFFECTS OF ACCUMULATION

Igneous nodules from Ruapehu lavas are generally gabbroic in mineralogy and the products of their disaggregation are pyroxenes,

plagioclase and olivine. Pyroxenite and anorthosite fragments are also found. Most nodules probably are not cognate in the strict sense; i.e., they are derived from previous magma batches and not from the host lavas in which they are entrained, as judged by compositional and zonation differences between nodule minerals and discrete, euhedral phenocrysts. Nonetheless, nodules and discrete crystals derived from them are broadly co-genetic with the suite of lavas, since the nodules are cumulates or frozen liquids from magmas of basaltic to dacitic composition.

Lavas with significant amounts of hypidiomorphic- granular igneous rock fragments and/or disequilibrium phenocryst mineral assemblages (e.g., forsteritic olivine in dacite; Fig 93H) are certainly accumulative and do not represent liquid compositions. The habit of crystals and crystal clusters is thus of greater importance than phenocryst abundances; for example, a clinopyroxene- rich lava would not necessarily be considered accumulative since basic andesites and basalts characteristically have substantial amounts of clinopyroxene phenocrysts. However, if most clinopyroxene occurs in mm-sized websterite or gabbro fragments, then textural evidence for accumulation exists. In addition to texture, bulk rock chemistry is also an important criterion, although entrainment of igneous rock fragments or crystals does not necessarily lead to deviation from liquid compositions and fractional crystallization curves on variation diagrams. For example, if the accumulated crystals comprise a mineral assemblage that is similar to a previous crystal extract assemblage from the host lava, then the solid- liquid mixture will fortuitously have a bulk composition near the liquid line of descent since fractionated minerals are being added back into the host magma. However, if the accumulated crystals are nearly monomineralic, then major deviations from "POAM-type" liquid lines can occur. In Fig 116, "phenocryst" mineral abundances in accumulative lavas are compared with phenocryst abundances in non- accumulative lavas, where the latter are

suggested in section III-3 to approximate liquid lines of descent from parental basalts. Thus, the ability to compare with fractional crystallization series is essential for identification of accumulative lavas: Figure 117 illustrates some of the effects of accumulated crystals on bulk rock compositions.

Mineral chemistry and zonation patterns are additional criteria for recognizing accumulative lavas, although the relationship between added crystals and host liquid is not necessarily that of disequilibrium: Reaction or zonation depends on the types and compositions of the added crystals, relative to the equilibrium phenocrysts of the host magma, as well as residence time of the added crystals in host magma. Continued growth of the added crystals is possible only in situation (2), where the added crystals are of the same mineralogy as cognate phenocrysts. Several zonation patterns may result. The first is normal zonation, as when magnesian augite is added to acid andesite in equilibrium with a more iron-rich augite; here, the added crystals would be difficult to distinguish from cognate phenocrysts. The second is development of a more refractory overgrowth or jacket (Fig 93A) around the added crystals, as when intermediate augite (Mg_{69}) is added to basaltic magma in equilibrium with magnesian augite (Mg_{80}).

An example of reaction with refractory crystals is provided by Ohakune basic andesite (Fig 95B): The groundmass liquid is in equilibrium with its ferromagnesian microphenocrysts, which have $Mg^* \approx 75$ (assuming $K_d = 0.3$). By contrast, the augite, bronzite and olivine of the crystal clusters have $Mg^* = 88-80$, and are most likely derived from basaltic magma. Bronzite in the crystal clusters is anhedral and surrounds forsteritic olivine; it is interpreted as a reaction product of olivine and liquid.

FIG 116. Phenocryst mineral proportions for accumulative and non-accumulative lavas. Rubidium is used as a differentiation index. Total phenocryst minerals for each lava have been normalized to a volume fraction of 1. Complete modal data are found in Tables 1-5. Numbers with arrows correspond to bulk rock analysis numbers of Appendix II.

A. Fractional crystallization series from Ruapehu Basalt to acid andesite; dacite (107) is not a simple fractional crystallization product of acid andesite but is nonetheless relatively aphyric and free of exotic crystals [see Fig 93A-F for photomicrographs]. Compare these regular mineralogical trends with B and C.

B. Lavas that are judged to be accumulative in ferromagnesian minerals; note the high ferromagnesian mineral abundances and the irregular variations in mineral abundances, as compared with A [see Figs 92C,H and 93I for photomicrographs].

C. Lavas that are judged to be accumulative in plagioclase; the major feature, when compared with A and B, is domination of the mineral assemblages by plagioclase [see Figs 92B, 93J, 94D,G for photomicrographs; calculations VI-14,15 of Appendix VI show bulk rocks 46 and 118 are linear mixtures of non-accumulative acid andesite and bytownite].

FIG. 117. Some effects of accumulation on bulk rock compositions. Numbers in parentheses correspond to bulk rock analysis numbers of Appendix II. The same accumulative rocks are plotted as in Fig. 116. Fractional crystallization series from Waimarino Basalt (WB; open circles) and Ruapehu Basalt (RB; filled circles) are shown for comparison; dashed line to dacite (107) signifies uncertainty of fractional crystallization relationship, but the dacite is relatively aphyric. In addition to high Sr, plagioclase-accumulative lavas have 18.5-20.5 wt % Al_2O_3 (see Fig. 107). Ferromagnesian-accumulative lavas are also displaced from liquid lines. Cr/V exhibits similar behaviour as Cr or Ni vs. Rb, and MgO or Mg^* vs. SiO_2 ; compare with Figures 107 and 109.

4.3 SUMMARY OF MAJOR POINTS CONCERNING THE ROLE OF ACCUMULATION

(1) Accumulation is a pervasive process, affecting lavas of all compositions. This contrasts with the narrower view of previous workers, who recognized only basic andesites as examples of accumulative lavas.

(2) Accumulation involves addition of plagioclase as well as ferromagnesian minerals, in contrast to the views of earlier workers who identified only olivine and pyroxenes as accumulative minerals.

(3) Accumulation of igneous crystals and rock fragments is commonplace, and most lavas do not represent liquid compositions. Beneath polygenetic composite volcanoes such as Ruapehu, the accumulation process is considered to be a natural corollary of fractional crystallization, involving entrainment of previously congealed magma, as repeated influxes of new magma re-occupied old conduits.

5. THE ROLE OF MAGMA MIXING

5.1 INTRODUCTION

The claimed significance of magma mixing in orogenic lavas ranges from major (i.e., as an alternative to crystal-liquid fractionation; Eichelberger, 1975) to minor (i.e., back-mixing of magmas that are related by fractional crystallization; Mc Birney, 1980; Green, 1980). Published references to magma mixing have proliferated in the past ten years, and most examples are from volcanic arc settings. Sakuyama (1981) describes R-type and N-type rocks from two Japanese volcanoes, according to the presence or absence of reversely zoned mafic phenocrysts. Sakuyama (1981) considers that the chemical trends and petrographic features of R-type rocks (reversely zoned) result from magma mixing, and that magma mixing is common in calc-alkaline (hypersthene series of Kuno, 1950) volcanic rocks of Japan. Grove, *et al.* (1982) and Gerlach and Grove (1982) have identified hybrid lavas from the Medicine Lake Highland, California, ranging in composition from basic andesite to rhyolite. These authors propose an integrated model of calc-alkaline magma genesis, involving fractionation, assimilation and mixing.

Petrographic and chemical evidence of magma mixing is uncommon at Ruapehu and its satellite vents; only about 6 specimens of the 144 total bulk rocks are considered to have originated by magma mixing. Hybrid magmas are largely restricted to the upper cone complex (Mangawhero Fm) and young satellite vents (Pukeonake). Field relations suggest that these massif and satellite vents erupted synchronously, probably 20-30 Ka.

The present writer considers that mixing is a second-order process, involving back-mixing of magmas whose individual compositions were largely predetermined by fractional crystallization. Like crystal

accumulation, this process is viewed as another manifestation of open-system magma evolution beneath polygenetic Ruapehu volcano, involving mingling of magmas in common conduits.

5.2 MINERALOGICAL EFFECTS OF MAGMA MIXING

The lavas of Ruapehu and related vents are characteristically porphyritic, and magma mixing is best recorded in zonation patterns of the phenocryst minerals. Examples of mineral zonation patterns in hybrid magmas from Pukeonake (a parasitic vent of Ruapehu and Tongariro) and from a lava flow of Mangawhero Fm are given in Fig 118. Crystals in these lavas have four origins: (1) Phenocrysts that were originally present in the basic end member include, most notably, forsteritic olivine and chrome spinel. These minerals are normally zoned, and crystallization was terminated by reaction with the hybrid liquid after mixing occurred. Forsteritic olivine has bronzite coronas, and discrete chrome spinel in the groundmass has rims of titanomagnetite. (2) Phenocrysts that were originally present in the evolved (andesitic to dacitic) end member include augite, hypersthene and intermediate plagioclase. As a consequence of heating during magma mixing, these minerals underwent resorption, producing anhedral and internally fritted grains. (3) New minerals, precipitated from the hybrid liquid after mixing, occur in two habits. First, they occur as high temperature mantles on resorbed cores of hypersthene, augite and plagioclase. The mantled phenocrysts are characteristic of the "R-type" (reversely zoned) lavas of Sakuyama (1981). Second, minerals were precipitated from the hybrid liquid as microphenocrysts and groundmass grains. These discrete crystals are highly significant because they demonstrate the presence of a hybrid liquid whose residue comprises the quenched groundmass. They have

FIG 118. Mineral zonation patterns in two hybrid magmas. Zonation patterns are based on electron microprobe spot analyses; complete EPMA data are found in Appendix III.

A. Bulk rock 139, high-Mg basic andesite of Pukeonake. All silicate phenocrysts show evidence of reaction with liquid (olivine with orthopyroxene coronas), or have high temperature mantles (pyroxenes and plagioclase). Note the presence of microphenocrysts and groundmass crystals with compositions similar to phenocryst mantles. Photomicrographs from this rock are given in Fig 95 E,F.

B. Bulk rock 81, high-Mg acid andesite of Mangawhero Fm, Ruapehu. Mineral zonation patterns similar to 'A' are present. For grains with few data points, dashed lines show zonation patterns inferred from optical examination. Photomicrographs from this rock are given in Fig 93 P,R.

refractory cores that are similar in composition to the most magnesian/calcic portions of phenocryst mantles, and are normally zoned due to fractional crystallization of the hybrid liquid. (4) Accidental crystals and fragments of igneous and metamorphic rock are present. At Pukeonake, these include dunite, harzburgite, gabbro, diorite, and a variety of hornfelsic to gneissic metamorphic rock fragments that were initially present in the end member magmas (e.g., ultramafic nodules were almost certainly a component of the basaltic end member) or were entrained after mixing and during eruption (e.g., metamorphic rock fragments that bear little overprinting by pyrometamorphism).

Phenocrysts that were initially present in the end member magmas (i.e., types 1 and 2) are petrogenetically significant because they enable the characterization of end members to form the hybrid. For example, the forsteritic olivines and chrome spinels in the hybrid lavas of Fig 118 suggest that one end member was primitive basalt. The augite, labradorite and hypersthene cores of resorbed and mantled phenocrysts have similar compositions to phenocrysts in Ruapehu acid andesites and dacites, implying that the second end member was andesitic to dacitic in bulk composition. The preservation of phenocrysts from both end members suggests that magma mixing occurred just prior to eruption and quenching; indeed, the mixing events may have triggered the eruptions (cf.: Sparks, *et al.*, 1977).

5.3 DISCUSSION OF LEAST SQUARES MODELLING, AND GEOCHEMICAL EFFECTS OF MAGMA MIXING

Six least squares mixing calculations, deriving hybrid lavas as linear mixtures of two end members, are given in Table 10. All of the potential hybrid lavas were chosen on the basis of clear petrographic evidence for

Table 10, continued

CALCULATION VI-10					CALCULATION VI-11				
MAJOR ELEMENTS OF HYBRID (11-87)					MAJOR ELEMENTS OF HYBRID (11-93)				
	OBS	CALC	END MEMBER	WT FRACTION		OBS	CALC	END MEMBER	WT FRACTION
SiO ₂	58.48	58.45	11-132	0.46	SiO ₂	58.83	58.88	11-132	0.42
TiO ₂	0.63	0.64	11-129	0.54	TiO ₂	0.66	0.65	11-129	0.58
Al ₂ O ₃	14.06	14.06			Al ₂ O ₃	14.39	14.15		
FeOt	6.22	6.50	ΣR ²	0.2904	FeOt	6.30	6.36	ΣR ²	0.2821
MnO	0.12	0.11			MnO	0.09	0.10		
MgO	7.85	7.66	MODEL: (acid andesite 11-87) = (Waimarino Basalt 11-132) + (Ruapehu dacite 11-129)		MgO	7.29	7.24	MODEL: (acid andesite 11-93) = (Waimarino Basalt 11-132) + (Ruapehu dacite 11-129)	
CaO	6.88	7.09			CaO	6.81	6.90		
Na ₂ O	2.74	2.51			Na ₂ O	2.92	2.57		
K ₂ O	1.55	1.82			K ₂ O	1.63	1.92		
P ₂ O ₅	0.12	0.11			P ₂ O ₅	0.13	0.11		
TRACE ELEMENTS OF HYBRID					TRACE ELEMENTS OF HYBRID				
	OBS	CALC	DISAGREEMENTS: FeO, MgO, Na ₂ O, K ₂ O, Rb, Cr, Ni			OBS	CALC	DISAGREEMENTS: Al ₂ O ₃ , Na ₂ O, K ₂ O, Rb, Cr, Ni	
Ba	316	354			Ba	353	371		
Rb	58	81			Rb	66	86		
Sr	278	279			Sr	266	274		
Zr	122	139			Zr	127	146		
V	166	172			V	151	169		
Cr	409	551			Cr	317	512		
Ni	116	162			Ni	89	150		

Table 10, continued

CALCULATION VI-12					CALCULATION VI-13				
MAJOR ELEMENTS OF HYBRID (II-82)					MAJOR ELEMENTS OF HYBRID (II-81)				
	OBS	CALC	END MEMBER	WT FRACTION		OBS	CALC	END MEMBER	WT FRACTION
SiO ₂	58.09	58.09	II-132	0.47	SiO ₂	58.07	57.94	II-132	0.51
TiO ₂	0.63	0.63	II-129	0.53	TiO ₂	0.58	0.63	II-129	0.49
Al ₂ O ₃	14.08	13.97			Al ₂ O ₃	13.49	13.94		
FeOt	6.41	6.50	ΣR ²	0.3258	FeOt	6.41	6.66	ΣR ²	0.6945
MnO	0.10	0.11			MnO	0.10	0.11		
MgO	7.90	7.70	MODEL: (acid andesite II-82) = (Waimarino Basalt II-132) + (Ruapehu dacite II-129)		MgO	8.37	8.13	MODEL: (acid andesite II-81) = (Waimarino Basalt II-132) + (Ruapehu dacite II-129)	
CaO	6.71	7.10			CaO	7.05	7.31		
Na ₂ O	2.68	2.48			Na ₂ O	2.90	2.43		
K ₂ O	1.51	1.79			K ₂ O	1.45	1.70		
P ₂ O ₅	0.12	0.11			P ₂ O ₅	0.11	0.10		
TRACE ELEMENTS OF HYBRID					TRACE ELEMENTS OF HYBRID				
	OBS	CALC	DISAGREEMENTS: Al ₂ O ₃ , MgO, CaO, Na ₂ O, K ₂ O, Rb, Cr, Ni			OBS	CALC	DISAGREEMENTS: SiO ₂ , Al ₂ O ₃ , FeO, MgO, CaO, Na ₂ O, K ₂ O, Rb, Cr, Ni	
Ba	328	350			Ba	279	334		
Rb	55	80			Rb	51	75		
Sr	283	281			Sr	297	286		
Zr	124	137			Zr	108	131		
V	163	173			V	170	176		
Cr	411	561			Cr	470	599		
Ni	118	164			Ni	121	175		

magma mixing. Disagreements are more numerous and squared residuals are higher than in fractional crystallization calculations, because the hybrids are calculated as linear mixtures of only two end members. The calculated trace element abundances are unconstrained and should therefore give a good indication of the viability of the mixing process. In this regard, there is good agreement for the first four calculations (VI-8 to VI-11). The calculations have several implications: (1) Basaltic magma is an end member of all hybrids. The present writer acknowledges that this is partly a matter of recognition; i.e., mixtures of basalt and acid andesite/dacite are easily recognized, whereas mixtures of compositionally similar lavas could be easily overlooked because the petrographic and geochemical effects are more subtle. (2) In all calculations, basalts and evolved magmas have mixed in approximately equal proportions. Again, this is partly a matter of recognition; e.g., if a small amount of dacite mixed with a large amount of basalt, the dacite phenocrysts would likely be destroyed. (3) Both RB and WB magma types apparently have mixed with more evolved magmas.

Representative bulk rock analyses of hybrid lavas are given in Table 11, with an acid andesite of the Ruapehu basalt fractional crystallization series given for comparison. In the variation diagrams of Fig 119, comparison is made between hybrid lavas and lavas of the fractional crystallization series from WB and RB. Deviation of hybrid lavas from mixing lines suggests that the end member lavas are not well characterized, or that other processes (such as crystal accumulation) have acted concurrently with magma mixing. The main geochemical effects of magma mixing are to produce lavas with concurrently high compatible and incompatible element abundances (see Ni-Rb plot of Fig 119). Magma mixing has produced several chemically (and petrographically) distinctive high-magnesium andesites; those that mixed with Waimarino Basalt have

inherited not only the high MgO, Ni and Cr of this magma type, but also its high Sr.

TABLE 11. Representative bulk rock analyses of hybrid lavas. Columns 1-3 are hybrid lavas; for comparison, column 4 is acid andesite of fractional crystallization series from Ruapehu basalt.

- (1) Basic andesite, Mangawhero Fm (bulk rock 69; see calculation 8 of Table 10)
 (2) Acid andesite, Mangawhero Fm (bulk rock 81; see calculation 13 of Table 10)
 (3) Basic andesite, Pukeonake (bulk rock 136; see calculation 9 of Table 10)
 (4) Acid andesite, Mangawhero Fm (bulk rock 88; not a hybrid lava)

	1	2	3	4
SiO ₂	55.42	58.07	56.53	58.54
TiO ₂	0.66	0.58	0.72	0.68
Al ₂ O ₃	16.66	13.49	14.52	17.41
Fe ₂ O ₃	1.75	2.91	1.12	2.25
FeO	5.71	3.79	5.88	4.82
MnO	0.13	0.10	0.11	0.11
MgO	6.32	8.37	8.97	3.75
CaO	8.45	7.05	7.38	7.05
Na ₂ O	2.81	2.90	2.88	3.16
K ₂ O	0.93	1.45	1.49	1.20
P ₂ O ₅	0.11	0.11	0.13	0.10
LOI	0.78	0.82	0.66	1.05
Sum	99.73	99.64	100.39	100.12
mg*	66.4	79.7	73.1	58.1
Ba	287	279	332	311
Rb	29	51	54	41
Sr	232	297	302	234
Zr	70	108	114	86
V	208	170	184	181
Cr	180	470	591	43
Ni	70	121	213	28

FIG. 119. Variation diagrams comparing hybrid lavas with those of fractional crystallization series. Numbers within diagram correspond to bulk rock analysis numbers of Appendix II. Lavas of fractional crystallization series from Waimarino Basalt (WB) and Ruapehu basalt (RB) are shown as open circles connected by thin curves. Hybrid lavas are shown as filled circles. End member magmas to form hybrids are shown as open squares, and bold lines denote linear mixtures of end members. See Table 10 for least squares mixing calculations to derive hybrid magmas.

6. THE ROLE AND NATURE OF THE CRUST

6.1 INTRODUCTION

Geophysical studies, field mapping and xenolith studies are three methods that can be used to infer crustal composition, and the thermal and deformational history of the crust (Kay and Kay, 1981). Geophysical studies of crustal structure and composition beneath the TVZ are lacking, and results of the unreversed Wellington Crustal Refraction Profile (Eiby, 1955) are controversial (Garrrick, 1968). Thus, geophysical interpretations of crustal structure, composition and thickness are equivocal, although TVZ heat flow and P_n velocities suggest thin crust and lithosphere, as summarized in Fig 111.

Mesozoic greywacke forms much of the surface outcrop of North Island, and the Axial Range of North Island is composed almost entirely of this rock type, although it is the least known area of greywacke in New Zealand (Korsch and Wellman, 1985). Hay (1967) and Grindley (1960) mapped respective areas to the west and east of Ruapehu, where the surrounding ranges comprise low grade metagreywackes and argillites. South of Ruapehu, the greywacke is veneered by unmetamorphosed Tertiary marine sediments (Fleming and Steiner, 1950). While Mesozoic greywacke and Tertiary mudstones do occur as xenoliths (see: section II-2.7), it is significant that most crustal fragments have no clear outcrop equivalents in the surrounding terrain. Thus, xenoliths are interpreted with difficulty because geophysical and outcrop constraints are lacking.

Magmas have sampled a great variety of fragments from the subvolcanic basement. These are important petrogenetically because they suggest mechanisms of crustal contamination, and are also valuable toward deducing the mineralogy and composition of the crust. However,

xenolith studies seldom allow construction of an accurate crustal cross section (Kay and Kay, 1981). At Ruapehu, this is true for several reasons: (1) There is no reliable way to depth-order crustal xenoliths since the mineral assemblages often preclude P-T calculations, and since there is pervasive evidence for mineralogical disequilibrium, particularly overprinting by pyrometamorphism. (2) It cannot be assumed that lavas have representatively sampled wall rocks along their paths. (3) Some xenoliths may be more easily destroyed than others. In spite of these limitations, a discussion of inferred metamorphic conditions, compositional variation of xenoliths, and petrogenetic implications is given below. General petrographic and mineralogical data for xenoliths have already been reported in section II-2.7.

6.2 METAMORPHIC CONDITIONS IN THE CRUST

A summary of metamorphic conditions inferred from xenolith mineralogy is given in Fig 120. Evidence for high temperature metamorphic conditions is varied and consistent: (1) plagioclase has intermediate compositions (andesine- labradorite), (2) biotite has high TiO_2 content in the presence of ilmenite and spinel, (3) muscovite is absent (except in a few albite- epidote metagreywacke xenoliths with outcrop analogues), which suggests high grade metamorphism, (4) garnets are almandine- pyrope solid solutions, where the pyrope component is indicative of high temperature, (5) sillimanite, though it occurs rarely as fibrolite inclusions in cordierite, is the only aluminosilicate polymorph observed, and (6) results of garnet- biotite geothermometry (Goldman and Albee, 1977) indicate equilibration temperatures of $650\text{--}750^\circ\text{C}$ for schists and gneisses.

Inappropriate mineral assemblages and textural disequilibrium

generally prohibit accurate pressure estimates, but qualitative estimates suggest low to moderate pressures appropriate to crustal depths: Metamorphosed basic igneous rocks are garnet-free, and plagioclase-orthopyroxene or plagioclase-olivine reactions to form garnet or spinel, respectively, are absent. The garnet-free, gabbroic mineralogy of metabasites suggests P-T conditions lower than those necessary to produce a garnet granulite mineralogy (Fig 120).

Some hypersthene-bearing pelitic schists and hornfelses contain coexisting cordierite and almandine. Winkler (1979, p. 234) states that "... the pair cordierite plus almandine is restricted to a specific P-T range in high grade regional metamorphism and in the regional hypersthene zone (granulite facies)". The experimental data of Currie (1971) suggest pressure limits of 4-7 kilobars for coexisting cordierite + almandine + sillimanite + quartz. This pressure range corresponds to crustal depths of 10-20 km.

The presence of crystalloblastic hypersthene in many xenoliths and the virtual absence of amphibole indicate metamorphic conditions in the regional hypersthene zone (granulite facies) (Winkler, 1979). No specific P-T range is implicit, the essential requirement for hypersthene being $P_{H_2O} \ll P_{total}$. In regional metamorphic terrains, this condition is usually met only in the deep crust, where rocks have undergone protracted metamorphism and loss of volatiles. However, "dry" conditions can also be attained beneath magmatic belts, where rocks have been subjected to high temperatures at moderate to low pressures (e.g., high T - low P facies series of Miyashiro, 1974). Depth of origin of xenoliths therefore remains an unsolved problem, but the hypersthene-bearing rocks certainly originated at high temperatures and under nearly anhydrous conditions.

The textures and mineralogy of primary regional metamorphism have been overprinted by secondary processes, operating on two different time

scales. First, high grade regional metamorphic rocks seem to have undergone progressive regional metamorphism during a rising geothermal gradient. This process was operative over a relatively long time span (perhaps on the order of 10^6 years), but rates were not slow enough to maintain equilibrium. The major effects of progressive regional metamorphism are smooth reverse zoning of plagioclase and garnet (increasing pyrope molecule outward), plus the development of aluminous orthopyroxene as coronas on garnet and as disseminated crystals. These features suggest increasing temperature, and progression from upper amphibolite facies conditions to regional hypersthene (granulite facies) conditions. The presence of hypersthene is the essential mineralogical criterion for granulite facies, but titaniferous biotite is still present.

Second, xenoliths underwent the brief but intense effects of pyrometamorphism during transport in host magmas. These effects include: (1) breakdown of biotite to Al-Fe spinel and other, as yet unidentified, reaction products, (2) thermal alteration of garnet, forming opacite coronas, (3) crystallization of sanidine (perhaps as a product of biotite breakdown) from rocks of appropriate composition, and (4) the production of interstitial silicic-alkaline glass, or even complete melting. These features indicate progression to sanidinite facies conditions, as metamorphic rock fragments were transported in host magmas having temperatures of ca. 900 to 1000⁰ C.

Overall, mineral assemblages suggest high temperature metamorphic conditions, in the low to moderate pressure region of the granulite, pyroxene hornfels and sanidinite facies.

6.3 XENOLITH BULK COMPOSITIONS

Important major element characteristics of xenoliths are summarized in Fig 121, and Table 12 gives representative major and trace element

TABLE 1.2. Representative bulk rock analyses of metamorphic xenoliths from the present study, with comparative analyses from other sources.

	1	2	3	4	5
SiO ₂	69.86	62.14	66.6	74.40	64.58
TiO ₂	0.53	0.77	0.63	0.19	0.78
Al ₂ O ₃	14.67	15.93	16.2	14.70	16.91
Fe ₂ O ₃	3.73	6.04	0.46	0.22	1.02
FeO	-	-	3.0	2.05	4.46
MnO	0.04	0.11	0.05	0.07	0.07
MgO	1.24	2.37	1.10	0.97	1.71
CaO	1.89	3.04	1.50	2.08	2.18
Na ₂ O	3.73	3.84	3.20	1.97	3.11
K ₂ O	2.47	2.12	4.50	2.20	2.69
P ₂ O ₅	0.11	0.16	0.14	0.08	0.16
LOI	2.50	3.36	2.34	1.43	3.14
Sum	100.77	99.88	99.72	100.36	100.81
Ba	633	549	-	-	651
Rb	91	65	139	-	109
Sr	266	459	227	-	215
V	73	122	-	-	130
Cr	46	42	-	-	67
Ni	-	-	-	-	19
Sr87/86	-	-	0.7107	-	-
K/Rb	225	270	251	-	205

Columns 1-4 are greywacke- argillite outcrops, and Ngauruhoe xenoliths.

- (1) Average Eastern Basement (Reid, 1983, Table 1)
- (2) Average Western Basement (Reid, 1983, Table 1)
- (3) Clay-rich argillite outcrop (Ewart & Stipp, 1968; sample P.26186)
- (4) Average of three analyses of "vitrified acid gneiss" xenoliths from the 1954 eruption of Ngauruhoe (Steiner, 1958; Table 1).

Columns 5-9 are metasedimentary xenoliths of the present study; other trace element data are found in Appendix II:

- (5) Bulk rock 181; low grade (epidote- muscovite- albite ...) metagreywacke- argillite with cataclastic texture
- (6) Bulk rock 182; low grade (ep- mu- ab ...) metagreywacke- argillite
- (7) Bulk rock 183; completely fused greywacke (see Fig 120E)
- (8) Bulk rock 184; metaquartzite
- (9) Bulk rock 166; hypersthene- glass- sanidine- spinel- biotite schist.

Columns 10-13 are metaigneous xenoliths of the present study; other trace element data are found in Appendix II:

- (10) Bulk rock 175; spinel- two pyroxene- plagioclase hornfels
- (11) Bulk rock 174; oxide- augite- plagioclase- hypersthene hornfels
- (12) Bulk rock 168; apatite- glass- oxide- hypersthene- plagioclase hornfels
- (13) Bulk rock 162; hematite- glass- biotite- augite- opaque oxide- hypersthene- plagioclase hornfels.

Column 14 is an altered xenolith:

- (14) Bulk rock 177; hydrothermally altered clay- plagioclase- two pyroxene andesite

Table 12, continued

	6	7	8	9	10	11	12	13	14
SiO ₂	67.22	72.09	96.68	49.23	54.62	54.25	50.07	48.17	56.98
TiO ₂	0.59	0.41	0.00	1.06	0.69	0.43	1.09	1.50	0.55
Al ₂ O ₃	16.82	12.81	0.77	25.18	17.05	10.66	24.88	16.66	16.86
Fe ₂ O ₃	0.79	0.47	-	2.95	2.06	1.28	-	1.74	0.57
FeO	3.26	2.45	0.40	4.26	6.02	6.80	6.87	10.96	7.04
MnO	0.06	0.02	0.02	0.12	0.17	0.18	0.07	0.29	0.15
MgO	1.29	0.95	0.16	2.96	5.04	12.77	2.41	8.55	5.33
CaO	0.95	1.07	0.31	4.19	9.16	10.15	8.46	9.17	9.94
Na ₂ O	4.35	3.09	0.19	4.50	3.58	2.10	4.21	1.46	1.21
K ₂ O	3.02	2.12	0.07	3.72	0.66	0.33	0.23	0.10	0.09
P ₂ O ₅	0.13	0.08	0.03	0.26	0.11	0.07	0.12	0.05	0.09
LOI	0.44	3.25	-	0.68	0.98	0.77	1.03	1.41	1.21
Sum	98.92	98.81	98.63	99.11	100.14	99.79	100.16	100.06	100.02
Ba	567	356	-	1650	103	125	326	92	53
Rb	133	84	-	144	18	8	0	2	2
Sr	182	191	-	713	411	179	481	207	191
V	81	50	-	164	238	189	197	363	191
Cr	52	27	-	66	96	823	80	234	96
Ni	20	10	-	25	18	268	22	101	33
Sr87/86	0.71255	0.70975	-	-	0.70652	0.70540	-	-	-
K/Rb	189	210	-	215	304	343	∞	415	374

data for xenoliths. Some xenoliths are texturally and compositionally similar to subaerially exposed greywacke-argillite, but most are basic to intermediate in bulk composition and have quartz-free, anhydrous mineral assemblages, suggesting derivation from unexposed metabasites within or beneath the greywacke. Using the criteria of Fig 121, three compositional groups (and numerous subgroups) are recognized.

GROUP 1: Metasedimentary xenoliths (analyses 159, 166, 181, 182, 183, 184) plot on the left side of Fig 121. The great variation in $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratios reflects the varying quartz/clay ratios in the original sediments. Several subgroups are distinguished.

1a: Metaquartzites are nearly pure silica and were probably quartz arenites prior to metamorphism, or quartz segregation veins produced during metamorphism. Although represented by only one analysis (184; Table 12), this is a very abundant xenolith type.

1b: Metagreywackes/argillites (analyses 181, 182, 183) have compositions similar to greywacke/argillite outcrops. Rock 183 is a completely fused greywacke (Fig 121, Table 12, Fig 120E) with a bulk composition nearly identical to Steiner's (1958) "vitrified acid gneiss". Although it appears similar to average TVZ rhyolite on Fig 121, rock 183 is compositionally similar to average Eastern Basement, as shown by its Rb, Sr and V abundances (Table 12). Rocks 181 and 182 are more argillaceous than average Eastern or Western Basement. This is reflected by their higher values of Rb (Table 12), which are similar to the Rb concentration of Ewart and Stipp's (1968) argillite outcrop.

Strongly argillaceous metasediments (analyses 159, 166) plot at the extreme lower left of Fig 121. The extremely K- and Al-rich bulk compositions (Table 12) of these fine grained, high grade schists are reflected by normative corundum, and the presence of modal sanidine,

cordierite ($\pm$ fibrolite inclusions), aluminous spinel (hercynite) and biotite. High LIL element abundances suggest that these rocks are metamorphosed claystones, and not residues after partial melting of greywacke/ argillite basement.

Strontium isotopic ratios for three metasedimentary xenoliths (159, 182, 183) are uniformly high, ranging from 0.70975 to 0.71255 (Mr. Ian Graham, analyst).

GROUP II: Metaigneous xenoliths have fine-grained crystalloblastic textures, vary from basic to intermediate in silica content, and plot on the right side of Fig 121. Representative analyses are given in Table 12. Most are basic to intermediate hornfelses with compositions displaced to the right of the TVZ igneous trend, toward pyroxene and plagioclase. This suggests that the metabasites may represent metamorphosed subvolcanic TVZ igneous rocks that are accumulative to varying degrees in plagioclase, pyroxenes ($\pm$ olivine in original rocks), and opaque oxides. Note that the crystalloblastic metaigneous xenoliths are compositionally similar to nodules with igneous textures, where the latter are shown in Fig 121 as open circles with diagonal slashes.

Metaigneous rock compositions (Fig 121, Table 12) are gradational from those that plot close to the TVZ igneous trend (rock 175), to those that probably represent metamorphosed pyroxene cumulates (rock 174, with high MgO, Cr, Ni), plagioclase cumulates (rock 168, with high Al_2O_3 and Sr), and opaque oxide $\pm$ pyroxene cumulates (rock 162, with high total FeO and V). Strontium isotopic ratios of three metaigneous xenoliths range from 0.70540 to 0.7063 (Mr Ian Graham, analyst).

Rock 172 (sheared gabbro; Fig 96H) is compositionally and texturally an unusual xenolith. High compatible element concentrations

suggest a cumulate rock, but it is also rich in Ba (373 ppm) and Rb (47 ppm). Given the cataclastic texture of the rock, the bulk composition suggests that it may be a tectonic mixture (fault gouge) of basic igneous rock and greywacke/argillite.

The wide range in chemical composition of the metaigneous rocks and the divergence of their compositions from those of TVZ magma types is strong evidence against many xenoliths being simply frozen basic to intermediate magmas, although they could be crystal cumulates from these magmas. The temporal relationship between metaigneous rock fragments and their host lavas is largely unknown: The metabasites could represent metamorphosed frozen magmas and crystal cumulates associated with Quaternary TVZ volcanism, or samples of the eugeosynclinal, subgreywacke basement prior to TVZ volcanism. Distinction between (1) older crust and (2) metamorphosed cogenetic igneous rock fragments cannot be made using the present data. However, such a distinction would be important because (1) implies that the metaigneous xenoliths may be of regional significance and therefore useful in geophysical studies of crustal structure and composition, and in studies of rhyolite genesis, whereas (2) implies that the metaigneous rocks may occur only beneath Ruapehu, and are therefore only of local geophysical and petrogenetic significance. Additional mineralogical and geochemical studies of Ruapehu xenoliths are currently being done by Mr Ian Graham, and may resolve this question.

GROUP III: Altered xenoliths contain clay as a common feature, suggesting subsurface hydrothermal alteration. Rock 177 (Table 12) is extremely low in LIL elements and is interpreted as a hydrothermally altered andesite. Rock 158 is an altered diorite with abundant plagioclase, hypersthene, opaque oxide and interstitial clay. Rock 160 is a fine grained, massive aggregate of cryptocrystalline clay.

6.4 ROLE OF THE CRUST IN PETROGENESIS OF RUAPEHU LAVAS

6.4.1 Physical Role of the Crust

Kuno (1968) first suggested that the crust beneath orogenic volcanic belts can be considered as a "density filter" that affects the buoyant rise of magmas, and Gill (1973) used this concept to explain the greater relative abundance of silicic volcanic rocks in continental anorogenic provinces, as compared with oceanic provinces. Ewart, *et al.* (1977) suggest that crustal thickness and composition may partially control along-strike abundance patterns of magmas in a single zone of orogenic volcanism: The Tonga-Kermadec island arc is situated on thin oceanic crust and has abundant basalts, while New Zealand has thicker continental crust, fewer basalts and abundant andesites. Ruapehu is a fine example of andesite dominance: In spite of the parental relationship that has been demonstrated between mantle-derived basalts and their andesitic derivatives, only one basalt flow has been found on the entire mountain. The present writer believes there are three reasons why basaltic magma rarely arrives on the surface at Ruapehu: (1) Parental quartz tholeiites are generated under hydrous conditions, and "wet" basalts are expected to fractionate at least olivine prior to eruption, due to the negative slopes of solidus and liquidus curves (Nicholls and Ringwood, 1973); (2) the buoyant rise of dense basalts from their mantle source regions is slowed or halted by the lighter continental crust, increasing the probability of fractionation (and assimilation) in crustal magma chambers; and (3) fresh influxes of basaltic magma are likely to encounter evolved magma (andesites, dacites) from previously emplaced batches, leading to basalt consolidation or magma mixing within the crust.

6.4.2 Geochemical Role of the Crust

In the central portion of the Taupo Volcanic Zone, voluminous rhyolite is considered to result from partial melting of greywacke granulite basement (Reid, 1983). Therefore, in adjacent regions it is to be expected that the crust might contribute to the compositions of basaltic magmas and their derivatives. The ubiquity and small size of metamorphic xenoliths in Ruapehu lavas suggest that the ratio of xenolith surface area to magma mass is high, increasing the possibility of contamination. The high grade mineral assemblages of xenoliths show that crustal rocks beneath Ruapehu were subjected to high temperatures even before entrainment in magma, so relatively little heat is needed to achieve anatexis under sanidinite facies conditions. The breakdown of xenoliths in host magmas (Fig 122) is strong physical evidence for contamination, since the production of melt or vapour in xenoliths will greatly increase chemical exchange between xenoliths and host magmas.

Some geochemical effects of assimilation are shown in Figs 123 and 124. In section III-3 it was suggested that andesites are the fractional crystallization products of basalts, but fractional crystallization alone cannot explain the Sr isotopic heterogeneity shown in Fig 123. The high $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of metasedimentary xenoliths imply that xenoliths have contributed radiogenic Sr to host lavas. The present writer considers that fractional crystallization and assimilation of crust are concurrent processes, since the heat needed to melt xenoliths is supplied by latent heat of crystallization of phenocrysts from host magmas (Bowen, 1928); this is supported by the positive correlation of $^{87}\text{Sr}/^{86}\text{Sr}$ with SiO_2 in lavas, where dacites may be the most contaminated because they are also the most fractionated. Considering the Sr isotopic data, the successful fractional crystallization calculations show that these calculations can accommodate the geochemical effects of concurrent fractionation and

FIG 122. PHYSICAL EVIDENCE FOR ASSIMILATION OF CRUSTAL MATERIAL

A,B. Gneiss fragment in microperlitic dacite block; same deposit and locality as Fig 97 G. Note clouding and partial melting of andesine. Garnet (left) and biotite (right) are both breaking down to opaque material. Xenoliths of the gneiss are found throughout the host rock, from individual crystals to cm- sized fragments. A: Crossed nicols. B: Plane polarized light, with gneiss fragment outlined. Field width, 4.2 mm. References: Host dacite is Appendix II, analysis 131; mineral analyses from a similar xenolith in Appendix V, under field name "N112A".

C. Quartz- biotite- spinel gneiss from Iwikau Member airfall, N Ruapehu. Much of the biotite has broken down to opaque material; mineral analyses from similar fragments show this to be Al-Fe spinel (hercynite). Glass vein with biotite relicts is present at lower left. PPL. Field width, 4.2 mm. (No analytical data; xenolith is field name "B10xf".)

D. Gneiss, from dacite lava flow of Mangawhero Formation, W Ruapehu. Minerals are andesine, titaniferous biotite, almandine- pyrope garnet, aluminous hypersthene and apatite. Clouding of feldspars, and breakdown of biotite and garnet are advanced. Disaggregation and invasion by magma is attended by oxidation of ferromagnesian phenocrysts in the host lava. PPL. Field width, 4.2 mm. References: Appendix V, under field name "J1x". Host lava is Appendix II, analysis 110.

E. Reticulite xenolith, from tephra of Pukeonake Scoria Cone. This is a buff- coloured, completely melted greywacke (as deduced from bulk chemistry), comprising clear vesicular glass (72 % SiO_2) with cordierite and spinel microlites. PPL. Field width, 4.2 mm. References: Bulk xenolith is Appendix II, analysis 183. Analyses of glass and cordierite in Appendix V, under field name "H7x-20".

F. Web texture in pyroxene hornfels from lava flow of Rangataua Member, S Ruapehu. Labradorite, hypersthene and titanomagnetite are floating in pale brown silicic (71 % SiO_2) glass. Note daughter crystal of acicular apatite with surrounding pleochroic halo. PPL. Field width, 0.6 mm. Reference: Appendix V, under field name "Gx".

FIG. 122.

A. METAMORPHIC XENOLITHS

B. LAVAS

FIG 121. Strontium isotopic data from metamorphic xenoliths and lavas, using SiO_2 as a differentiation index. All Sr isotopic determinations are courtesy of Mr. Ian Graham. Numbers within diagrams correspond to bulk rock analysis numbers of Appendix II.

A. Metamorphic xenoliths include highly radiogenic metasediments and less radiogenic metaigneous rocks. Refer to Fig 121 and accompanying discussion for criteria used to distinguish igneous from sedimentary.

B. Lavas of Ruapehu and related vents exhibit positive correlation of $^{87}\text{Sr}/^{86}\text{Sr}$ with SiO_2 , suggesting concurrent fractional crystallization and contamination by radiogenic Sr from crustal sources. Arrows from Ruapehu basalt (RB) and Waimarino Basalt (WB) indicate successful fractional crystallization calculations to form basic andesite derivatives; less radiogenic derivative (133; Hauhungatahi) of Waimarino Basalt can be explained only if WB magma type is isotopically heterogeneous through time. Dashed lines from hybrid magmas indicate end members used to form the hybrids (see Table 10 for mixing calculations).

crustal assimilation in basalts to acid andesites. However, attempts to model dacite by simple fractional crystallization of acid andesite have failed because the geochemical effects of assimilation are too great (Table 8, calculation VI-6). Major elements and compatible trace elements are in good agreement (except Cr, which can be explained by accumulation of a few grains of pyroxene or spinel), suggesting that fractional crystallization is indeed operative. The calculation fails because the observed incompatible element concentrations in dacite (K, Rb) are too high for the degree of fractionation allowed, suggesting selective assimilation of these elements from a crustal source. The failed calculation suggests that the contaminant would be high in K and Rb, and would have a low K/Rb ratio:

$$K_{\text{obs}} - K_{\text{calc}} = 0.51 \text{ wt } \% K_2O = 4233 \text{ ppm K}$$

$$Rb_{\text{obs}} - Rb_{\text{calc}} = 124 - 68 = 56 \text{ ppm Rb}$$

$$K/Rb_{\text{contaminant}} = 4233/56 = 76.$$

Variation of K/Rb for the rock suite is shown in Fig 124. The smooth and regular variation of K/Rb suggests consanguinity of samples, and the decrease of K/Rb with differentiation can be explained in part by fractionation of plagioclase, olivine and pyroxenes since Rb is more incompatible than K in these silicate phases. However, K/Rb decreases more rapidly than Shaw's (1968) Main Trend; petrographic evidence from lavas and nodules shows that this cannot be the result of amphibole fractionation. The present writer considers that the deviation from Shaw's Main Trend is a result of crustal assimilation: Metasedimentary xenoliths have bulk rock K/Rb of 189-215, the high grade metasediments contain biotite (low K/Rb $\approx$ 80; Shaw, 1968), and biotite in these xenoliths is observed to break down during pyrometamorphism (Figs 120, 122). Microprobe and optical results show that biotite breakdown is not simple

FIG. 124. Potassium-rubidium variation in lavas of Ruapehu and related vents. Fractional crystallization series (open circles) from Waimarino Basalt (WB) and Ruapehu basalt (RB) are indicated by curved vectors. Dashed line is a power law curve that fits the trend of the data. Shaw's (1968) Main Trend, indicated by bold curve, is defined on the basis of covariance analysis on 12 rock suites, which include a wide variety of continental and oceanic rock types. Ranges of K/Rb in silicate minerals given at left are from Shaw (1968), who suggests that negative deviation from the Main Trend can be explained by (a) amphibole (high K, low Rb, $K/Rb \approx 1100$) removal, or (b) biotite (high K, high Rb, low $K/Rb \approx 80$) addition.

dehydration, but involves incongruent melting of biotite to form hercynite. Mass balance suggests that the other, as yet unanalyzed, reaction products are probably liberated in the form of a mobile, hydrous fluid rich in SiO_2 , K_2O , and Rb. Nedelec and Paquet (1981) report a similar occurrence, involving incongruent melting of biotite in high grade gneisses, to produce uncharacterized "metallic oxides", glass, and a "mobile hydrous phase". The glass and hydrous fluid produced by biotite melting probably have $^{87}\text{Sr}/^{86}\text{Sr} \gg ^{87}\text{Sr}/^{86}\text{Sr}_{\text{bulk xenolith}}$. This is because biotite is a Rb-rich phase, and ^{87}Sr is produced by decay of ^{87}Rb . Pushkar and Stoesser (1975) report anatectic glass in a quartz monzonite xenolith, where the bulk xenolith has $^{87}\text{Sr}/^{86}\text{Sr} = 0.7058$, and the glass has $^{87}\text{Sr}/^{86}\text{Sr} = 0.7229$, leading these authors to state (p. 671): "... the high ratio in the glass supports the supposition that the glass has a large component of biotite-derived strontium".

The preceding arguments support the idea that crustal assimilation is a selective process, involving the addition of incompatible elements (particularly K and Rb) and radiogenic Sr to host magmas. One mechanism of this selective contamination is inferred to be incongruent melting of biotite, the only major hydrous, LIL-rich phase that is present in xenoliths. In regard to selective assimilation, Watson (1982) states:

"If basalt magma induces local melting of crustal rocks, the assimilation process becomes one of liquid-state interdiffusion. In this case, the varying diffusivities of ions and their differing preferences for silicic relative to basaltic melts can produce marked selective contamination effects. Selective contamination of ascending basaltic magmas is particularly likely in the case of K_2O , which may be introduced in substantial amounts even when other elements remain unaffected." (from the Abstract)

Thus, experimental evidence supports the idea of selective assimilation, as proposed by Steiner (1958) and by the present writer. Assimilation is a process that should be modelled concurrently with fractional crystallization, and the nature of the contaminant should be constrained by the observed melting relations in xenoliths, not by simply adding bulk xenoliths to bulk magmas.

7. MAGMA EVOLUTION IN TIME AND SPACE: A RETURN TO THE STRATIGRAPHIC CONTEXT

A synopsis of compositional diversity for Ruapehu formations and related vents is given in Fig 125. **Hauhungatahi** (0.5 m.y.?) is probably the oldest vent of the Tongariro Volcanic Centre, and the lavas are rather uniform in petrography and bulk composition. Least squares mixing calculations suggest that the basic andesite of Hauhungatahi may be a differentiate of the Waimarino Basalt magma type. If so, the WB magma type is remarkably time transgressive.

Lavas of the **Te Herenga Fm** represent the oldest known eruptives on Ruapehu. The lavas are petrographically uniform, olivine-free basic andesites and a few acid andesites (range: 53.8-58.8 % SiO_2). Least squares mixing calculations suggest that the most basic Te Herenga sample may be a differentiate of the Ruapehu basalt magma type, although the only known exposure of this basalt is in the younger Mangawhero Fm. Most basic andesites of Te Herenga Fm have similar compositions to lavas on the liquid line of descent from Ruapehu basalt, and the limited intraformational compositional variation can be explained by continued fractionation of pyroxenes and plagioclase to produce rare acid andesite. A few samples may be mildly accumulative in pyroxenes, as suggested by pyroxene clusters and bulk rock Cr up to 97 ppm.

Lavas of the **Wahianoa Fm** include basic and acid andesites in about equal abundance (range: 54.3-61.2 % SiO_2), and there is greater compositional diversity than in the older Te Herenga Fm. Many lavas are petrographically similar to Te Herenga Fm, and most have compositions near the liquid line of descent from Ruapehu basalt, suggesting they are differentiates of this magma type. Some lavas are unequivocally accumulative in pyroxenes $\pm$ olivine (bulk rocks 27, 30, 31, 57, 58, 60), on

FIG 125. Compositional diversity of lavas and pyroclastics from Ruapehu formations and satellite vents. "Freq" means number of analyses. Waimarino Basalt (not shown) erupted at about the same time as upper Mangawhero Fm.

the basis of petrography and bulk chemistry (all of these have 200-300 ppm Cr). Others are accumulative in plagioclase (bulk rocks 46, 47, 52, 54), as judged by petrography and their high Sr and Al_2O_3 .

Lavas of the **Mangawhero Fm** exhibit great petrographic and compositional variation, from basalt to dacites (range: 52.2-63.6 % SiO_2). The only known subaerial exposure of the Ruapehu basalt magma type occurs in Mangawhero Fm, and least squares mixing calculations show that this parental basalt has produced intraformational basic- and acid andesite differentiates, the liquid line being defined by bulk rocks 63, 64, and 88. Attempts to model dacite by perfect fractional crystallization of acid andesite have failed because these calculations do not account for the effects of selective assimilation (see: section III-6.4.2). Some lavas are accumulative in pyroxenes $\pm$ olivine (bulk rocks 72, 76, 92, 101), plagioclase and pyroxenes (bulk rocks 75, 80, 99) or plagioclase alone (bulk rock 100). Petrographic and geochemical studies have also led to the recognition of several basic- and acid andesite hybrid magmas (bulk rocks 69, 81, 82, 87, 93) in the upper part of the formation. One of these (69) involves Ruapehu basalt as an end member, but the others may be mixtures of dacite and Waimarino Basalt magma type (see: Table 10).

Pukeonake, a parasitic vent to the north of Ruapehu, erupted ca. 25 Ka, about the same time as upper Mangawhero Fm. The lavas and pyroclastics of Pukeonake show unequivocal petrographic and geochemical evidence for magma mixing between Waimarino Basalt magma type and dacite (Table 10; Figs 118, 119). The **Ohakune** vents also erupted about 25 Ka, and these plagioclase- free basic andesites are believed to be differentiates of a magma type that is similar, but not identical to Waimarino Basalt.

Waimarino Basalt erupted about 15 Ka, from an isolated vent to the southeast of Lake Taupo. In spite of its geographic separation from Ruapehu, the petrography, mineralogy, bulk rock chemistry and field

relations of Waimarino Basalt have received detailed attention because of its primary status and its potential parental role for andesitic lavas of the calc alkaline suite. Eruptions at Ohakune, Pukeonake and summit eruptions of upper Mangawhero Fm on Ruapehu all occurred about 25-15 Ka, and all involved magmas of the Waimarino Basalt type. These observations suggest that batches of Waimarino Basalt magma type were emplaced throughout the southern TVZ between 25-15 Ka. When Waimarino Basalt was emplaced beneath Ruapehu, it either mingled with evolved melts to produce mixed magmas (hybrids of Pukeonake and upper Mangawhero Fm), or underwent fractionation (Ohakune basic andesite); only at a locality far removed from the Tongariro Volcanoes was it able to arrive at the surface in primitive condition.

Lavas of the **Whakapapa Fm** include olivine-free acid andesites, one basic andesite and two dacites that erupted from summit and flank vents during Holocene time (range: 56.6-65.6 % SiO_2). Most lavas are acid andesites, and overall the lavas are more evolved than in the underlying Mangawhero Fm. No quantitative modelling has been done on any lavas from Whakapapa Fm, but most are petrographically and geochemically similar to acid andesites of Mangawhero Fm, suggesting derivation from Ruapehu basalt magma type. Several lavas appear to be mildly accumulative in pyroxenes and plagioclase (111-115), and two are plagioclase-accumulative (118, 120).

8. EPILOGUE

In the final chapter of Orogenic Andesites and Plate Tectonics, Gill (1981) discusses "some outstanding problems requiring clarification", and poses questions that provide directions for continued research in orogenic andesites. Ruapehu is a large, composite andesite volcano associated with a convergent plate boundary, and is in many ways typical of Quaternary, subduction-related, calc alkaline volcanism at continental margins worldwide. Thus, conclusions regarding petrogenesis of Ruapehu andesites provide answers to some general questions about the origin of andesites.

A major goal of the present field and laboratory studies has been to give evidence for the primary role of basalt fractionation in petrogenesis of Ruapehu andesites. The mineralogy and bulk rock chemistry of basic andesites converge on basalt, and the parental role of basalt is strongly suggested by successful calculations to derive calc alkaline andesites from it. But in all scientific inquiry, new answers typically raise new questions. Thus, the first question:

Why do orogenic andesites predominate at convergent plate boundaries if they are simply the products of basalt differentiation which occurs anywhere?

Several replies are relevant. First, the parental basalts identified in the present study are quartz-normative, and have ca. 52 wt % silica. One of them, Waimarino Basalt, has primitive characteristics which suggest that it originated by hydrous partial melting of the mantle wedge, with volatiles probably supplied by slab dehydration ("IRS fluid" of Gill, 1981). Thus, parental basalts at Ruapehu are more silicic than basalts in other tectonic settings (e.g., MORB), and comparatively small degrees of

fractional crystallization are necessary to produce andesites: Mixing calculations of the present study suggest that fractionation of 16-30 wt % crystals will yield basic andesite derivatives from silica- oversaturated basaltic parents. Second, when basaltic magmas rise through previously occupied and heated conduits beneath composite volcanoes, they are subjected to the modifying effects of magma mixing and crustal contamination. Third, the crust of the overriding plate probably acts as a filter which inhibits the passage of dense basalts, increases the tendency of basalts to crystallize in crustal reservoirs, and favours the rise and eventual eruption of less dense andesitic derivatives. In spite of concerted efforts by the present writer to collect and analyze mafic lavas, and thereby to "establish the basalt connection", only a single basalt lava flow has been found on Ruapehu massif, demonstrating the rarity of basaltic lavas. A second question is related to the first:

Where are the necessary crystal cumulates?

Mixing calculations based on phenocryst minerals in lavas indicate that most of the cumulates will be gabbroic in composition; i.e., of 'POAM' mineralogy, and this is consistent with the most common kind of igneous inclusion found in Ruapehu andesites. The cumulates are minor in volume, are part of a gabbroic lower crust, and their presence within the crust may or may not be geophysically detectable. Consider a cylindrical parcel of crust beneath Ruapehu, with the following dimensions: 10 km radius from Ruapehu summit, and 15 km deep, yielding a volume of $4,650 \text{ km}^3$. The total volume of Ruapehu lavas, allowing for erosion, is about 150 km^3 . Mixing calculations suggest that ca. 50-60 wt % fractionation of 'POAM' minerals from parental basalts is necessary to produce average Ruapehu andesite with 58 wt % silica. Thus, ca. $75-90 \text{ km}^3$ of gabbroic cumulates should be present beneath Ruapehu, comprising only 2% of the assumed

4,650 km³ of crust in which they reside.

Can basalt fractionation account for all of the petrographic and geochemical features of the rock suite?

No, it cannot. There is convincing petrographic and geochemical evidence for three second- order processes: accumulation of igneous crystals from earlier episodes of magma consolidation, magma mixing in common conduits, and crustal contamination. These are termed 'second-order' processes because they operate concurrently with fractional crystallization, and they affect lavas whose bulk compositions were largely pre-determined by basalt differentiation.

Lavas containing exotic igneous crystals of plagioclase, pyroxenes and olivine are common: about 10% of rocks in the sample population (n=144) are unequivocally accumulative in one or more of these phases. If lavas containing only a few hypidiomorphic-granular rock fragments or unequilibrated phenocrysts are considered, then the majority of lavas are accumulative to some degree and few lavas represent liquid compositions.

Magma mixing is less common than entrainment of igneous rock fragments: Only about 4 % of the lavas have petrographic and geochemical evidence for hybrid origin, and these are restricted to parasite cones and the upper cone complex of Ruapehu. Documented examples of hybrid lavas involve mixing of distinguishable end members such as basalt and dacite, but magma mixing may be more common than is recognized because back-mixing of similar end members will yield more subtle petrographic and geochemical effects.

All lavas may have undergone crustal contamination to varying degrees, since metamorphic rock fragments are ubiquitous and are often

affected by anatexis. Crustal assimilation is apparently a selective process that largely affects Sr isotopic ratios and incompatible element abundances of lavas. The positive correlation between differentiation indices (wt % SiO_2 , ppm Rb, etc.) and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of lavas, together with the inability of simple 'POAM' fractional crystallization to explain dacite petrogenesis, suggest that crustal contamination has operated concurrently with fractional crystallization. One mechanism of contamination may be the breakdown of biotite in metamorphic xenoliths, involving the liberation of LIL- and ^{87}Sr - rich fluid into host lavas. A final question concerns possible alternatives to crustal contamination:

Can processes other than 'selective crustal interaction' account for isotopic compositions within otherwise consanguineous-seeming suites of orogenic andesites which are more heterogeneous and radiogenic than those of intra-oceanic basalts? For example, is mantle heterogeneity a viable alternative?

The physical and geochemical evidence for crustal contamination of andesites and dacites is convincing, but basalts of the TVZ are also heterogeneous in LIL element concentrations and Sr isotopic ratios. The two parental basalts reported here are not related by fractional crystallization, are sufficiently different to be considered as separate magma types, and may have originated in geochemically or mineralogically distinctive source regions. Waimanalo Basalt has geochemical features

Thus, I end this discussion on a note of uncertainty: The relative roles of mantle heterogeneity and crustal contamination in basalt petrogenesis are currently unknown, and will require further collection and detailed geochemical analysis of TVZ basalts, as well as further inquiry into the geochemical budget of the crustal contamination process. Continued TVZ basalt studies may also lead to recognition of other andesite liquid lines, in addition to those reported here. However, these are matters for other dissertations by other people.

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APPENDICES I - VI

APPENDIX I: STRATIGRAPHIC DESCRIPTIONS OF MEASURED SECTIONS

1. INTRODUCTION

Written stratigraphic descriptions are given for 15 measured sections, constituting about 1.5 km of Ruapehu stratigraphy. Localities for measurement were selected on the basis of degree of exposure, and relevance to formation definition.

The most common method of measurement, given the remoteness and relief of the terrain, was the "eye height" method, in which the observer sights horizontally and counts the number of eye heights as he moves through the section. In addition, a metre stick was used for measurement of clast sizes and other stratigraphic parameters. Dr. B.F. Houghton accompanied the writer into the field many times, and on these occasions we measured with steel tapes. During field measurement, the deposits were sketched at appropriate scales onto graph paper. Thus, the text figures are accurate visual representations of lithology. The reported thicknesses have been corrected for dip angle, so they represent true stratigraphic thicknesses. The steep slopes and terrace-like topography of valley walls often required that the measured sections be moved laterally; this re-locating is noted in the descriptions.

Ruapehu Section 3 is given particularly thorough description because the deposits are lithologically and genetically diverse; other sections are described more briefly because they are lithologically simple or because the deposits have already been discussed adequately in the text.

2. DESCRIPTIONS

RUAPEHU SECTION 1. 145 m of Te Herenga Formation exposed in Whakapapanui Gorge, northwest Ruapehu. Grid references for base of section: T20/313154; N112/059708. Refer to Fig 14, p. 42, for drawing. This section represents the lower portion of the proximal facies of Te Herenga Formation.

Basal 3m covered; then 2.5m lava flow w rubbly base and top, platy and blocky interior; then 13m heterolithologic tuff breccia, buff-grey colour, poorly sorted from sandy matrix to 0.7m subrd porphyritic clasts w similar petrography to lava flows but having variable degrees of oxidation and hydroth alteration, local 1-3m thick lenses of coarser tuff breccia are nearly monolithologic and appear sim to autobreccia but are not juxtaposed against lava flows; then 1.7m lava flow; then 0.3m monolithologic tuff breccia w reddened, angular clasts to 0.3m and clearly derived by autobrecciation of lava flow above it. Remainder of section contains similar lithologies, but note sandy horizon (SG) at 99.5m, 100.2m, and 103.5m intervals, interpreted as fluvial deposits; and 0.5m porphyritic andesite dyke at 101m interval.

RUAPEHU SECTION 2. 80 m of Te Herenga Formation exposed at Te Herenga Ridge, northwest Ruapehu. Grid references for base of section: T20/307156; N112/054713. Refer to Fig 15, p. 43, for drawing. This section represents the upper portion of the proximal facies of Te Herenga Formation; i.e., is stratigraphically above RS-1. Stipp (1968) collected lava from Te Herenga Ridge, which gave a K-Ar age of 0.23 Ma.

The entire section comprises lava flows and monolithologic tuff breccias that originated by autobrecciation of the lava flows. The tuff breccias are red, poorly sorted coarse rubble, comprising angular oxidised clasts derived from the over- and underlying lava flows; ash-grade material is rare and most clasts are of cm-dm size.

RUAPEHU SECTION 3. 223.5 m of Wahianoa Formation exposed in Whangaehu Gorge, southeast Ruapehu. Grid references for base of section: T20/347094; N112/098646. Refer to Fig 27, p. 63, for drawing. This section is representative of the proximal facies of Wahianoa Formation.

3m oxidised, monolithologic tuff breccia; then 4m lava flow; then 2m oxidised monolithologic tuff breccia; then 8m dark grey finely porphyritic lava flow w rubbly base and top; then 2.5m tuff breccia w subang black andesite clasts supported by pale yellow-brown ash-lapilli matrix; then 0.2m dk grey & red lapilli in pale yell-brn mtx, draped over lava blocks of underlying tuff breccia, trough cross bedding in thicker portions; then 0.1m shower bdd ash & lapilli; then 0.25m dk grey pumice lapilli in weathered yell-brn crs to med ash mtx; then 2.5m block & ash unit, non-stratified, w large 5-90cm ang clasts of dense black andesite and lesser red oxidised andesite, in a poorly indurated sandy red-brn mtx, largest clasts at top of unit; then 1.9m reversely graded tuff breccia w sharp planar cntcts at base and top, upper 50cm is planar bdd, as def by laminations in mtx, aligned clasts in upper 1m define crude bedding; then 2m mtx-supp tuff brecc, rev graded, basal 1m weakly stratified as def by aligned clasts, lg clasts are black breadcrusted blocks, red oxidised subang blocks and weathered yellow pumice, some andesite blocks have yellow weath rinds, brown sandy mtx; then 1.5m bomb- and lapilli-bearing ash, deep brown, mtx-rich, ashy deposit, bombs to 40cm are mod vesic, breadcrusted and slaggy, contains thin chocolate brn secondary clay veins; then 2m agglomerate w rdd black mod vesic clasts to 1.2m in a black-dk grey ash/lapilli mtx, unwelded, discrete pods of banded white & yell-brn clay occupy some interstices of mtx, these clays are not baked nor is the dep oxidised, lower 1m is coarser than upper; then 6m lava flow w slaggy base; then 4m covered; then 1m unwdd monolithologic tuff breccia (autobreccia); then 8.3m lava flow; then 8m welded monolithologic tuff breccia w subvertical slabs of slaggy material, clasts have slaggy margins, top is grey, becoming incr red toward base, clasts are petrogr sim to underlying lava flow; then 7.2m heterolithologic tuff breccia, clasts up to 1.5m are internally shattered and breadcrusted, w mod vesic cores and 2cm dense glassy rinds, other clasts are dense subrdd/subang blocks, contains weathered andes pum lapilli to 2cm, mtx in upr 4m is pale yel-brn ash w subordinate lapilli, mtx in lwr 1.7m is dk red-brn w continuous laminated bands nr top; then 0.5m finely porphyritic, thin, highly vesic, discontin lava flow, grading laterally into blocks and mantling the underlying tuff breccia; then 3.5m unwelded monolithologic tuff brecc w 80% dense to mod vesic subang/subrdd clasts to 0.5m but avg 20cm, set in a brick-red mtx of med ash and lapilli; then 1.5m lava flow w irreg rubbly cntcts; then 1m weakly to nonwelded monolithol tuff brecc w oxidised ang clasts to 35cm but avg 10cm, set in red mtx of ash/lapilli; then section moves 100m laterally to west; then 4m microvesic, porphyritic dk grey lava flow; then 7m oxidised monolithologic tuff brecc, grading downward from mod wdd to unwdd at base; then 69m intercalated slaggy lava flows and wdd to unwdd monolithologic tuff breccs, local m-thick lenses of agglutinate w subrdd bombs to 30cm may be airfall material; then 14m covered interval, section moves 20m east; then 15.6m heterolithologic, mtx-supp tuff brecc (Type C TBh) w several internal cntcts separating depositional units, breadcrusted internally shattered bombs/blocks of black mod vesic lava range 3m to 20cm, second clast type is dense grey andesite as subrdd blocks to dm-size, less common weathered andes pum lapilli, mtx is pale yel-brn lithic-crystal tuff; then 2.6m med grey porphyritic lava flow; then 10.5m crs monolithologic tuff brecc comprising red slaggy semi-plastic lava blocks to several m, in fmwk support, w little mtx of red lithic lapilli tuff; then 3.8m mtx-supp heterolithologic tuff brecc, sim to other Type C TBh described above; then 13.6m of intercalated lava flows and densely to weakly wdd monolithologic tuff breccias (of autoclastic origin).

RUAPEHU SECTION 4. 13.5 m of Wahianoa Formation exposed in the Whangaehu Gorge, southeast Ruapehu. Grid references for base of section: T20/353092; N122/105643. See Fig 28, p. 63, for drawing. The main purpose of this section is to show lithology of heterolithologic tuff breccias that form the planeze surface between the Wahianoa and Whangaehu valleys.

Basal 0.5m is monolithologic tuff brecc assoc w overlying lava flow; then then 4.5m massive lava flow w arcuate vertical jnt planes & subhoriz anastomosing platey jnts, 30m to east scoriaceous material bends up around lava flow, isolating it as a discrete pod; then 0.5m agglutinated tuff brecc that grades downward into massive lava flow and has sharp upper cntct; then 2.5m poorly exposed tuff brecc w blocks to 2m; then 3m mtx-supp heterolithologic tuff brecc w subang dense to pum blocks to 60cm and few subrdd bombs, crude subhoriz stratification shown by blocky horizons, mtx is pale brn predom crs ash to lapilli w dk grey-brn pumiceous andesite lapilli; then sharp cntct to 90cm mtx-rich, rev-graded nearly monolithologic tuff brecc, basal 10cm is mtx-poor lapillistone, grading upward to fmwk-supp heterolith tuff brecc w clasts to 10cm; then 10cm dk brn-grey sand w 5mm thick mud band at top; then 20cm well sorted lapilli tuff w weath brn & grey andes pum up to 4mm, weak shower bedding; then 20cm band of heterolith tuff brecc; then 5mm laminated band of poorly sorted ash-lapilli; then 1.2m massive heterolith tuff brecc w subrdd/subang clasts of dk grey mod to weakly vesic andesite up to 75cm, some clasts w breadcrust texture, mtx is pale brn, poorly sorted crs ash/lapilli, v weak rev grading.

RUAPEHU SECTION 5. 64.4 m of Wahianoa Formation exposed in Whangaehu Gorge, eastern Ruapehu. Grid references for base of section: T20/365093; N122/128640. See Fig 29, p. 65, for drawing. This section illustrates the close association between lava flows and welded to unwelded autoclastic breccias.

The entire section comprises porphyritic andesite lava flows and associated monolithologic tuff breccias. The tuff breccias range from unwelded to densely welded, and intercalated lenses of tuff breccia within the flows demonstrate that the tuff breccias are of autoclastic origin. However, some of the tuff breccias have the appearance of coarse, stratified, agglutinated airfall and may represent plastic bomb beds that were rafted on top of flowing lava.

RUAPEHU SECTION 6. 192 m of Wahianoa Formation exposed in Wahianoa Valley, southeast Ruapehu. Grid references for base of section: T20/339073; N122/090621. See Fig 32, p. 68, for drawing of section. This section contains similar lithologies to RS-3, and is therefore not described in detail. Like RS-3, it represents deposits of the proximal facies of Wahianoa Fm, but RS-6 is about 1-2 km farther from the inferred Wahianoa Fm vent area. The main lithologic differences, relative to RS-3, are a slightly higher proportion of sand & gravel (SG) deposits, and absence of 'Type C' heterolithologic tuff breccias in RS-6.

RUAPEHU SECTION 7. 26 m of Wahianoa Formation exposed at Girdlestone Peak. Grid references for base of section: T20/311086; N122/060636. See Fig 31, p. 67, for drawing. The entire section comprises thin lava flows and associated monolithologic tuff breccias (autobreccias), and exemplifies near-vent proximal facies deposits of the Wahianoa Formation.

RUAPEHU SECTION 8. 37.5 m of Wahianoa Formation exposed in an unnamed stream valley of north Ruapehu. Grid references for base of section: T20/342155; N112/090712. This section is about 5-6 km from the inferred Wahianoa Fm vent region, and comprises largely 'laharic' deposits of the distant proximal facies.

Base of section begins at stream course; basal 2.7m comprises rev-graded heterolith

tuff brecc, 2-20cm andesite clasts are subrd/ subang and have var deg of oxid & vesicularity, clasts are supported in indurated, red-brn poorly sorted sandy mtx, grades upward into overlying clast-supp unit; then 0.6m clast-supp heterolith tuff brecc w mod to highly vesic ang blocks of dk grey andesite to 20cm size; then 0.3m of fining-upward ash & lapilli crystal-vitric tuff; then 13m heterolithologic tuff brecc w diverse clasts ranging 20cm to 1cm floating in a red-brn indurated mtx of crs to med ash, lenticular horizons of coarse (blocks to 80cm) clast-supp tuff brecc are present, partings suggest numerous 2-5m thick depositional units; then sharp undulating cntct to 0.4m thick sand & gravel deposit w low-angle cross bedding and pinches out over 30m lateral distance; then sharp cntct to 7m thick, unstrat, poorly sorted heterolithol tuff brecc w abrupt planar top and sim appear to lower tuff breccs; then 3.4m thick heterolithol tuff brecc w lg ang clasts to 1m, locally, largest clasts are nearly self-supporting and overall the deposit is nearly clast-supp, red-brn sand-gravel mtx has local horizons of low angle cross bedding that pinch out over lateral dist of 1-2m; then sharp cntct to 0.2m unit of planar bdd med sand that pinches out laterally; then 1.7m of heterolithol tuff brecc sim to basal unit; then undulating cntct to red poorly sorted (mm-3cm size clasts) lapilli tuff w "wavy" internal stratification; then 7.5m heterolithol nearly clast-supp tuff brecc, lg ang clasts (to 1.5m) are predom dense lava but some (to 60cm size) are internally shattered and breadcrusted.

RUAPEHU SECTION 9. 76 m of Mangawhero Formation exposed at Girdlestone Peak, southeastern summit region of Ruapehu. Grid references for base of section: T20/313087; N122/062636. See Fig 50, p. 85, for drawing. The entire section comprises lava flows and intercalated coarse, monolithologic, clast-supported tuff breccias (autoclastic breccias), and needs little additional description. In the 26-41 m interval, some tuff breccias are weakly heterolithologic, suggesting minor reworking and mixing during slope failure.

RUAPEHU SECTION 10. 42.5 m of Mangawhero Formation exposed beneath Tahurangi, southern summit region of Ruapehu. Grid references for base of section: T20/309098; N122/057647. See Fig 51, p. 86, for drawing.

Base of section determined by limit of deep snow and crevasses; basal 5m is porphyritic andesite lava flow w feldspathic hornfels xenos to 1cm; then 1.5m rubbly, fmwk-supp monolithol tuff brecc w ang clasts to 8cm and set in a sparse mtx of red crs ash & ang lapilli rock frags; then 8m podiform (valley-confined) porphyritic lava flow w irreg top sfc; then 0.5m sand & gravel w prominent cross bedding fills valleys in lava flow top; then 1.5m lapilli tuff w well sorted shower & mantle bedded ash/fine lapilli layers, reworked top w channel fillings of sand & gravel; then 9m crs, red, fmwk-supp monolithol tuff brecc, ang clasts to 1.7m comprise oxidised microvesicular porphyritic andesite; then 15m porphyritic andesite lava flow w platy jnting and tension gashes nr base and sharp upr cntct; then 1.5m welded, fmwk-supp monolithol tuff brecc; then 0.2m alternating planar bdd layers of crs grit & fine mud w bomb sags nr base (airfall from hydroth explosion?); then 40cm mod/well sorted lapilli tuffs/tuffs, interbedded w lensoid cross bedded fine tuffs and varve-like mud laminae; then 0.5m bedded lapilli tuff, clasts to 3cm define crude bedding, crs, ang clasts at bottom of unit.

RUAPEHU SECTION 11. 117 m of Mangawhero Formation exposed in Mangaturuturu River Valley of southwest Ruapehu. Grid references for base of section: S20/279103; N122/024652. See Fig 52, p. 87, for drawing. Nearly all of the section consists of lava flows and associated monolithologic tuff breccias (autobreccias), and this lithologic association is typical of the western slopes of Ruapehu, which are largely covered by lava flows of Mangawhero Fm. The chaotic association of thin andesite lava flows and autoclastic breccias is particularly well displayed in the basal 13m of the section. Local pods of heterolithologic tuff breccia and sand & gravel are probably valley-

confined mudflow and fluvial deposits.

RUAPEHU SECTION 12. 73 m of Te Herenga and Mangawhero Formations exposed in Whakapapaiti Valley, west Ruapehu. Grid references for base of section: S20/283151; N112/026700. See Fig 16, p. 44, for drawing.

The basal 23m comprises numerous deposits of heterolithologic tuff breccia, with each unit unsorted and unstratified, and separated by parting planes from lithologically similar surrounding units. The subrounded clasts are nearly monolithologic, comprising dense porphyritic andesite which is petrographically identical to Te Herenga Fm lava flows. Then at the 23 m interval, heterolithologic tuff breccia grades upward into oxidised, framework-supported monolithologic tuff breccia (autoclastic breccia) that is clearly associated with the overlying porphyritic lava flow. The top of the Te Herenga Fm lava flow (at 38m interval) has a glacially-eroded, planar top, and this marks the unconformity between Te Herenga Fm and the overlying deposits of Mangawhero Fm. The 38-43 m interval comprises matrix-supported heterolithologic tuff breccia whose clasts are petrographically different and more diverse than clasts of heterolithologic tuff breccias at the base of the section. The remaining 30 m of section comprise black and dark grey, internally shattered porphyritic andesite lava flows of Mangawhero Fm., with distinctive petrography from older lavas of the Te Herenga Fm.

RUAPEHU SECTION 13. 117 m of Mangawhero Formation exposed in an unnamed stream valley of northeast Ruapehu. Grid references for base of section: T20/351135; N122/101690. See Fig 53, p. 88, for drawing. The entire section comprises lava flows and associated monolithologic tuff breccias, and needs no additional description.

RUAPEHU SECTION 14. 12.5 m of Rangataua Member (Whakapapa Formation) exposed in a stream valley to the east of the vent region, south Ruapehu. Grid references for base of section: T20/306065; N122/055612. See Fig 63, p. 100, for photograph and drawing.

The basal 3m comprise welded, poorly sorted, unstratified, monolithologic tuff breccia w ang blocks and mod vesic bombs up to 15cm, supp in an oxidised microvesicular mtx; then 1.5m of shower-bedded lapilli tuffs w scoriaceous bombs up to 10cm; then densely to mod wdd agglutinate w bombs up to 20 cm and well devel internal strat and good sorting; then 1m red monolithologic tuff brecc w angular clasts identical to overlying lava flow; then 3.8m porphyritic andesite lava flow w basal platy jnts, fractured interior and rubbly but locally eroded top.

RUAPEHU SECTIONS 15a,b,c. Welded airfall tuff of Pinnacle Ridge Member (Whakapapa Formation) exposed at Pinnacle Ridge, northwest Ruapehu. See Figs 68-73, p. 105-107, and accompanying text discussion, for lithologic description.

APPENDIX II: BULK ROCK CHEMICAL ANALYSES

1. INTRODUCTION

Chemical analyses of major and trace elements for 184 bulk rocks are given. Strontium isotopic ratios are also given for selected samples. Three categories of rocks have been analyzed: (1) unaltered lava flows and fragmental deposits, (2) hydrothermally altered and/or weathered rocks, and (3) igneous and metamorphic rock inclusions. Unaltered lava flows and fragmental deposits are further subdivided according to formations, using stratigraphic terminology defined in Part I. Within each category or formation, analyses are listed in order of increasing silica content.

Bulk rock analyses are designated as follows:

ANALYSIS #	These numbers are referred to in the text, when presenting point counts, photomicrographs, chemical data, etc., for bulk rocks.
SAMPLE	Refers to field number written on the sample when it was collected.
LOI	Total volatiles expressed as loss on ignition, after firing at 1,000 ⁰ C for 1-2 hours.
TOTAL	Sum of major oxides and loss on ignition.
FeO(t)	Total FeO + Fe ₂ O ₃ expressed as FeO.
" - "	Not analyzed.
" n.d. "	Analyzed, but not detected.
VUW number	These numbers are reported with the grid references and descriptive notes of section 4, this Appendix. They are formal sample numbers of the Petrology Collection, housed in the Geology Department, Victoria University of Wellington.

2. SAMPLE COLLECTION AND PREPARATION

Specimens averaging 1 kilogram were collected in the field, and care was taken to obtain fresh, unoxidized material, except when hydrothermally altered rocks were specifically sought. Approximately one half of each specimen (400-500 g) was then broken into 1 cm cubes, using a hydraulic splitter. The cube surfaces were then examined for metamorphic or igneous rock inclusions in an effort to minimize the effect of foreign materials on bulk rock chemistry. Xenoliths (generally 0.5-3 cm size, but occasionally reaching decimetres) were separated from host rocks, using a cold chisel or diamond saw. Host rock adhering to xenoliths was removed by grinding on a cast iron lap, prior to analysis of the xenoliths. The rock cubes or xenoliths were then placed in a TEMA swing mill with tungsten carbide grinding discs, and ground to 200 mesh powder. Care was taken to avoid excessive heating (and oxidation) of the samples during grinding. Bulk rock powders (ca. 300 g) were then stored in polythene bags.

3. ANALYTICAL METHODS

3.1 X-ray Fluorescence Analysis of Bulk Rocks.

XRF analyses were made during 1979-1982, using a Siemens SRS-1 spectrometer housed in the Analytical Facility, Victoria University. Major element analysis was performed on glass fusion discs, by the method of Norrish and Hutton (1969). Addition of ammonium nitrate to the fusion mixture, rather than sodium nitrate, allowed Na_2O determination. Correction for background was made by analysis of a series of oxide + SiO_2 fusion discs. Trace element analyses were made on 4 cm diameter, boric

acid- backed, pressed powder pellets containing 3.5 g of sample. All samples were analyzed in duplicate. Seven unknowns were analyzed at one time, together with an appropriate international rock standard and an SiO_2 background disc. Details of analytical methods, and discussion of accuracy and precision are found in Roser (1983). Kennedy, *et al.* (1981) give results for eight U.S.G.S. rock standards that were analyzed at the same time and under the same instrumental conditions as this writer's samples.

3.2 Determination of Ferrous Iron and Loss on Ignition

FeO in bulk rocks was determined using the titrimetric dichromate method of Sarver (1927), as described in Shapiro and Brannock (1962). Loss on ignition (LOI) was determined by firing 1-2 g of sample for 1-2 hours at $1,000^\circ \text{C}$ and determining weight loss. Weight losses were corrected for FeO oxidation during firing.

3.3 Strontium Isotopic Ratios

Ratios of strontium 87 to strontium 86 for selected bulk rocks and xenoliths were obtained by Mr. Ian Graham at the Institute of Nuclear Sciences, Lower Hutt. Bulk rock powders were dissolved using a mixture of hydrofluoric, nitric, and perchloric acids, leaving chloride residues which were centrifuged to remove insoluble material and flushed through calibrated ion exchange resin columns with 2.5N HCl to separate elemental strontium from other cations, particularly rubidium. This yielded a pure fraction of SrCl_2 for isotopic analysis, using the single- filament method of ionization.

4. PETROGRAPHIC AND LOCALITY DESCRIPTIONS

Descriptive information for all analyzed bulk rocks is given below. Grid references are based on the New Zealand national thousand-yard grid of the 1:63,360 scale NZMS 1 topographic map series. Metric grids are also given from the 1:25,000 scale NZMS 270 topographic map series. Sheets T20 and S20 of NZMS 270 were used as a topographic base for the 1:25,000 geologic map that is inside the back cover of this dissertation.

5. REFERENCES

- Kennedy, P.C., Palmer, K. and Roser, B.P. 1981. Chemical analyses of the eight U.S.G.S. rock standards: BHVO-1, MAG-1, QLO-1, RGM-1, SCo-1, SDC-1, SGR-1, STM-1. Publication of the Geology Department, Victoria University of Wellington, 16 pp.
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TE HERENGA FORMATION (analyses 1-24)

ANALYSIS NUMBER	SAMPLE NUMBER	GRID REFERENCES		LOCALITY NOTES	PETROGRAPHIC NOTES
		yard	metric		
1	A39	14765	N112/063703	T20/317148	Pinnacle Ridge talus block intergranular, 2 pyroxene basic andesite; sparse olivine microphenocrysts replaced by chlorite.
2	A9	14738	N112/058710	T20/312155	Mead's Wall dyke, 6 m wide dyke porphyritic, 2 pyroxene basic andesite; abundant plagioclase and pyroxene aggregates to 3 mm.
3	A37	14763	N112/067689	T20/319135	Pinnacle Ridge, 40 m diameter, orthogonally jointed diorite stock intergranular plagioclase, 2 pyroxene diorite.
4	A20	14747	N112/059708	T20/312154	Whakapanui Gorge; lava flow at 40 m interval of RS 1 porphyritic, 2 pyroxene basic andesite.
5	A91	14776	N122/067688	T20/319134	Pinnacle Ridge diorite intrusion porphyritic, intergranular plagioclase, 2 pyroxene diorite, minor pyroxene alteration to clay.
6	Alpha2	14746	N122/067692	T20/319137	Pinnacle Ridge, NE-trending, 2 m wide dyke porphyritic, 2 pyroxene basic andesite with abundant plagioclase aggregates to 3 mm, and feldspathic hornfels fragments
7	A4	14733	N112/049717	T20/307160	Te Herenga Ridge; lava flow at 36 m interval of RS 2 porphyritic, 2 pyroxene basic andesite.
8	A8	14737	N112/050718	T20/307161	Te Herenga Ridge; lava flow at 78 m interval of RS 2 porphyritic, 2 pyroxene basic andesite; plagioclase aggregates to 2 mm are present
9	A93	14778	N122/066689	T20/318135	Pinnacle Ridge diorite intrusion porphyritic, intergranular plagioclase, 2 pyroxene diorite, minor pyroxene alteration to clay.
10	A5	14734	N112/049717	T20/307160	Te Herenga Ridge; lava flow at 48 m interval of RS 2 porphyritic, olivine-bearing basic andesite, olivine present only as microphenocrysts in groundmass.
11	A7	14736	N112/050718	T20/308161	Te Herenga Ridge; lava flow at 72 m interval of RS 2 porphyritic, 2 pyroxene basic andesite with abundant plagioclase aggregates to 2 mm.
12	A92	14777	N122/066689	T20/318134	Pinnacle Ridge diorite intrusion hypidiomorphic-granular plagioclase, 2 pyroxene diorite.
13	Alpha1	14745	N122/065695	T20/317140	Pinnacle Ridge; clast from tuff breccia strongly porphyritic 2 pyroxene basic andesite with abundant pyroxene and pyroxene-plagioclase aggregates.

ANALYSIS NUMBER	SAMPLE	VUV NUMBER	GRID REFERENCES		LOCALITY NOTES	PETROGRAPHIC NOTES
			yard	metric		
14	A36	14762	N122/066691	T20/318136	Pinnacle Ridge; greenish-black lava flow	finely porphyritic, 2 pyroxene basic andesite.
15	A32	14758	N122/063696	T20/317141	Pinnacle Ridge; 3 m wide, NW-trending dyke	finely porphyritic, 2 pyroxene basic andesite.
16	A1	14730	N112/049717	T20/307160	Te Herenga Ridge; lava flow at 4 m interval of RS 2	porphyritic, 2 pyroxene basic andesite.
17	A3	14732	N112/049717	T20/307160	Te Herenga Ridge; lava flow at 25 m interval of RS 2	porphyritic, 2 pyroxene basic andesite.
18	A6	14735	N112/050718	T20/308161	Te Herenga Ridge; lava flow at 56 m interval of RS 2	porphyritic, 2 pyroxene basic andesite.
19	A25	14751	N112/059708	T20/312154	Whakapapanui Gorge; clast in tuff breccia at 97 m interval of RS 1	porphyritic, 2 pyroxene basic andesite with pyroxene-plagioclase aggregates to 3 mm.
20	L24	14743	N112/029702	S20/285146	Whakapapanui Valley; glaciated lava flow at 37 m interval of RS 12	porphyritic, 2 pyroxene basic andesite.
21	A2	14731	N112/049717	T20/307160	Te Herenga Ridge; lava flow at 12 m interval of RS 2	porphyritic, 2 pyroxene basic andesite.
22	A13	14741	N112/038704	S20/294147	lava flow along arete to N of Whakapapanui Valley	porphyritic, 2 pyroxene basic andesite.
23	A27	14753	N112/059708	T20/312154	Whakapapanui Gorge; lava flow at 107 m interval of RS 1	porphyritic, 2 pyroxene basic andesite.
24	A42	14767	N112/030701	S20/286145	Whakapapanui Valley; dense clast from tuff breccia at 2 m interval of RS 12	porphyritic, 2 pyroxene acid andesite.

WAHIANOA FORMATION (analyses 25-62)

ANALYSIS NUMBER	SAMPLE	VUW NUMBER	GRID REFERENCES		LOCALITY NOTES	PETROGRAPHIC NOTES
			yard	metric		
25	X13	14922	N122/106644	T20/355094	thin lava flow at 63.5 m interval of RS 3	strongly porphyritic, olivine- bearing basic andesite
26	Q1DR	14897	N112/090712	T20/342155	dense clast from tuff breccia at 1 m interval of RS 8	black, finely porphyritic, 2 pyroxene basic andesite, internally fritted plagioclase, clinopyroxene phenocrysts to 2 mm
27	X56	16713	N122/089645	T20/339094	lava flow along ridge between Wahianoa and Whangaeahu Valleys	porphyritic, olivine basic andesite, olivine phenocrysts up to 3 mm
28	L12	14857	N112/090712	T20/342155	N Ruapehu; clast from tuff breccia at 2 m interval of RS 8	porphyritic, 2 pyroxene basic andesite
29	X14	14923	N122/106644	T20/356094	breadcrusted bomb from tuff breccia at 60 m interval of RS 3	porphyritic, olivine- bearing basic andesite with fritted plagioclase and sparse plagioclase aggregates
30	SB	14905	N122/097643	T20/346092	lava flow, SW rim of Whangaeahu Gorge	porphyritic, olivine- bearing basic andesite, pyroxene- phytic base of same flow as analysis 48
31	4	14903	N122/096644	T20/345093	block from tuff breccia, ridge between Whangaeahu and Wahianoa Valleys	black, porphyritic, olivine- bearing basic andesite
32	9	14909	N122/107643	T20/357093	lava flow at 212 m interval of RS 3, Whangaeahu Gorge	finely porphyritic, 2 pyroxene basic andesite
33	X15	14924	N122/107644	T20/357094	lava flow at 43 m interval of RS 3, Whangaeahu Gorge	strongly porphyritic basic andesite with abundant plagioclase and pyroxene-opaque oxide aggregates to 3mm
34	16	14916	N122/108645	T20/358095	lava flow, S rim of Whangaeahu Gorge	as per analysis 33; plagioclase aggregates to 3mm and clinopyroxene aggregates to 6 mm
35	X16-	14925	N122/107644	T20/357094	lava flow at 32 m interval of RS 3, Whangaeahu Gorge	porphyritic, olivine basic andesite with olivine to 2 mm and olivine gabbro fragments to 3 mm
36	X51	14929	N122/090645	T20/339094	clast from autobreccia, ridge between Wahianoa and Whangaeahu Valleys	porphyritic, olivine bearing basic andesite with abundant plagioclase and pyroxene aggregates to 2 mm

ANALYSIS NUMBER	SAMPLE	VUV NUMBER	GRID REFERENCES yard	metric	LOCALITY NOTES	PETROGRAPHIC NOTES
37	X52	14930	N122/085646	T20/334095	clast from tuff breccia; ridge between Wahianoa and Whangaeahu Valleys	porphyritic, 2 pyroxene basic andesite
38	8	14908	N122/107643	T20/357093	lava flow from 217 m interval of RS 3, Whangaeahu Gorge	porphyritic, 2 pyroxene basic andesite
39	X53	16710	N122/081648	T20/330098	lava flow; ridge between Wahianoa and Whangaeahu Valleys	porphyritic, 2 pyroxene basic andesite with pyroxene aggregates to 2 cm
40	X22	14926	N122/106644	T20/356094	clast from tuff breccia at 18 m interval of RS 3	porphyritic, olivine- bearing basic andesite
41	10	14910	N122/107643	T20/357093	slaggy bomb from tuff breccia, 210 m interval of RS 3	porphyritic, 2 pyroxene acid andesite
42	X23	14927	N122/106644	T20/356094	lava flow, 10 m interval of RS 3, Whangaeahu	porphyritic, 2 pyroxene acid andesite with abundant pyroxene and pyroxene- plagioclase aggregates to 2 mm
43	X12	14921	N122/106644	T20/356094	lava flow, 85 m interval of RS 3, Whangaeahu	strongly porphyritic acid andesite with plagioclase- pyroxene and plagioclase aggregates to 7 mm
44	3	14902	N122/096644	T20/345093	lava flow from ridge between Wahianoa and Whangaeahu Valleys	porphyritic, 2 pyroxene acid andesite; strongly plagioclase-phyric
45	14	14014	N122/108644	T20/358094	lava flow, 125 m interval of RS 3, Whangaeahu	strongly porphyritic acid andesite with abundant plagioclase and plagioclase- pyroxene aggregates to 2 mm
46	13	14913	N122/108644	T20/358094	lava flow, 121 m interval of RS 3, Whangaeahu	strongly plagioclase-phyric acid andesite with plagioclase aggregates to 3 mm
47	11	14911	N122/107644	T20/357094	lava flow, 162 m interval of RS 3, Whangaeahu	strongly plagioclase-phyric acid andesite with plagioclase aggregates to 3 mm
48	5A	14904	N122/097643	T20/346093	lava flow, SW rim of Whangaeahu Gorge	porphyritic, olivine- bearing acid andesite; top of same flow as analysis 30

ANALYSIS NUMBER	SAMPLE	VUW NUMBER	GRID REFERENCES		LOCALITY NOTES	PETROGRAPHIC NOTES
			yard	metric		
49	6	14906	N122/097643	T20/346093	lava flow, SW rim of Whangaehu Gorge; underlies analysis 48 flow	porphyritic, 2 pyroxene acid andesite
50	X54	16711	N122/081646	T20/330096	dyke in NE headwall of Wahianoa Valley	strongly porphyritic, 2 pyroxene acid andesite with trace of hornblende microphenocrysts
51	X50	14928	N122/094644	T20/343094	lava flow, ridge between Wahianoa and Whangaehu Valleys	porphyritic, 2 pyroxene acid andesite with abundant plagioclase aggregates to 4 mm
52	1	14900	N122/095644	T20/344094	lava flow, ridge between Wahianoa and Whangaehu Valleys	porphyritic, 2 pyroxene acid andesite with abundant plagioclase aggregates to 4 mm
53	7	14907	N122/106643	T20/356093	lava flow, ridge between Wahianoa and Whangaehu Valleys	porphyritic, 2 pyroxene acid andesite with abundant plagioclase aggregates to 4 mm; few pyr-plag aggregates to 2 mm
54	2	14901	N122/095644	T20/344094	lava flow, ridge between Wahianoa and Whangaehu Valleys	porphyritic, 2 pyroxene acid andesite; strongly plagioclase- phyric
55	M10	14873	N122/060636	T20/311086	lava flow, 24 m interval of RS 7, Girdlestone Peak	porphyritic, 2 pyroxene acid andesite with abundant feldspathic hornfels inclusions
56	W1	16719	N122/089622	T20/338066	lava flow, 27 m interval of RS 6, Wahianoa Valley	strongly porphyritic, 2 pyroxene acid andesite with gabbro and anorthositic fragments to 5 mm
57	M3	14865	N122/063615	T20/316066	lava flow, S Ruapehu, underlies flow of analysis 60	porphyritic, 2 pyroxene acid andesite
58	W3	16721	N122/086623	T20/335067	lava flow, 148 m interval of RS 6, Wahianoa Valley	strongly porphyritic, olivine-bearing acid andesite with abundant diorite & olivine gabbro fragments to 4 mm
59	M5	14867	N122/063611	T20/316062	lava flow, S Ruapehu	porphyritic, 2 pyroxene acid andesite
60	M4	14866	N122/063615	T20/316066	lava flow, S Ruapehu	porphyritic, 2 pyroxene acid andesite

ANALYSIS NUMBER	SAMPLE	VUW NUMBER	GRID REFERENCES		LOCALITY NOTES	PETROGRAPHIC NOTES
			yard	metric		
61	W4	16722	N122/078624	T20/327068	lava flow, 173 m interval of RS 6, Wahianoa Valley	porphyritic, 2 pyroxene acid andesite with abundant diorite nodules
62	Wh Stm.	16718	N122/137643	T20/387093	lava flow, near Whangaeahu swing bridge	porphyritic, olivine-bearing acid andesite with sparse pyroxene aggregates to 3 mm

MANGA WHERE FORMATION (analyses 63-110)

ANALYSIS NUMBER	SAMPLE	VUV NUMBER	GRID REFERENCES yard	metric	LOCALITY NOTES	PETROGRAPHIC NOTES
63	L10.15A	14854	N112/081715	T20/330166	steeply dipping lava flow along E side of unnamed stream, above falls	light grey olivine basalt with olivine and clinopyroxene phenocrysts to 1 mm, and a few orthopyroxene phenocrysts
64	L21	14859	N112/083715	T20/332166	lava flow, above flow of analysis 67	porphyritic, olivine basic andesite, few jacketed orthopyroxene phenocrysts, and internally sieved plagioclase phenos to 1 mm
65	E7	14822	N112/069721	T20/321164	lava flow; unconformably overlies Te Herenga Fm on Pinnacle Ridge; same flow as analysis 69	porphyritic, olivine basic andesite
66	L22	14860	N112/083715	T20/335158	lava flow, above flow of analysis 64	porphyritic, olivine basic andesite with clinopyroxene and plagioclase-pyroxene aggregates to 3 mm
67	L20	14858	N112/083715	T20/335158	lowest lava flow in bluff, S of Tama Mbr lava field	porphyritic, olivine-bearing basic andesite with clinopyroxene and plagioclase-pyroxene aggregates to 5 mm
68	L23	14861	N112/083715	T20/335158	lava flow, above flow of analysis 66	porphyritic basic andesite with oscillatory-zoned clinopyroxene to 8 mm and pyroxene-plagioclase aggregates to 4 mm
69	A41	14841	N112/069721	T20/321164	same lava flow as analysis 65, Pinnacle Ridge	porphyritic, olivine basic andesite with abundant jacketed pyroxenes
70	L9	14853	N122/101690	T20/351135	lava flow at 2 m interval of RS 13	porphyritic, 2 pyroxene basic andesite with abundant pyroxene and plagioclase aggregates to 3 mm
71	L6	14850	N122/099690	T20/348136	lava flow at 50 m interval of RS 13	porphyritic, 2 pyroxene basic andesite with a few pyroxene-plagioclase aggregates to 4 mm
72	M11	14874	N122/062636	T20/313087	clast from autobreccia at 6 m interval of RS 9	porphyritic, 2 pyroxene basic andesite with abundant pyroxene-plagioclase aggregates to 2 mm
73	L11	14856	N112/102715	T20/352158	lava flow, unnamed stream, N Ruapehu	strongly porphyritic, 2 pyroxene basic andesite with abundant plagioclase aggregates and clinopyroxene megacrysts to 3 mm
74	C2	14790	N122/125684	T20/375130	lava flow, Mangatoetoeui Gorge	porphyritic, 2 pyroxene acid andesite

ANALYSIS NUMBER	SAMPLE	VUW NUMBER	GRID REFERENCES		LOCALITY NOTES	PETROGRAPHIC NOTES
			yard	metric		
75	E3	14812	N122/078718	T20/327169	lava flow, underlies flow of analysis 109	porphyritic, 2 pyroxene acid andesite with abundant pyroxene-plagioclase aggregates to 3 mm
76	N3	14883	N122/017650	S20/274101	lava flow, 34 m interval of RS 11	porphyritic, olivine-bearing acid andesite
77	L1	14844	N122/097688	T20/346134	lava flow, 115 m interval of RS 13	porphyritic, 2 pyroxene acid andesite with abundant plagioclase and clinopyroxene aggregates to 2 mm; few hornfels inclusions
78	L3	14846	N122/097688	T20/346134	lava flow, 96 m interval of RS 13	porphyritic, olivine-bearing acid andesite; pyroxene aggregates to 3 mm; few jacketed orthopyroxenes; spinel-plag hornfels
79	J3	14831	N122/018690	S20/275141	lava flow, Whakapapa Valley, underlies that of analysis 108	porphyritic, 2 pyroxene acid andesite with abundant plagioclase-pyroxene aggregates
80	E2	14811	N122/079719	T20/328170	lava flow, underlies flow of analysis 75	porphyritic, 2 pyroxene acid andesite with abundant pyroxene-plagioclase aggregates
81	M17	14880	N122/063637	T20/314089	pluglike body, NW side of Girdlestone Peak	olivine acid andesite with jacketed pyroxenes, fritted plagioclase, and dunitic nodules to 3 mm with opt coronas
82	M9	14872	N122/058635	T20/309087	lava flow, unconformably overlies lithologies of RS 7	olivine-bearing acid andesite with jacketed pyroxenes and fritted plagioclase
83	P4	14893	N122/025643	S20/282095	lava flow in steep valley with waterfall	porphyritic, olivine-bearing acid andesite with sparse pyroxene aggregates
84	P3	14892	N122/025643	S20/282095	lava flow in steep valley with waterfall; overlies flow of analysis 83	finely porphyritic, olivine-bearing acid andesite
85	C1	14789	N122/126684	T20/376130	lava flow, Mangatoetoeuui Gorge	porphyritic, 2 pyroxene acid andesite
86	T3	16715	N122/058646	T20/309098	lava flow, 33 m interval of RS 10, near Ruapehu Summit	porphyritic, 2 pyroxene acid andesite

ANALYSIS NUMBER	SAMPLE	VUV NUMBER	GRID REFERENCES		LOCALITY NOTES	PETROGRAPHIC NOTES
			yard	metric		
87	M8'	14871	N122/062642	T20/313094	lava flow, saddle between Girdlestone Peak and Ruapehu Summit	olivine- bearing acid andesite with jacketed pyroxenes, olivine xenocrysts with opt coronas, and a few dunite nodules to 6 mm
88	L2	14845	N122/097688	T20/346134	lava flow, 105 m interval of RS 13	porphyritic, 2 pyroxene acid andesite
89	M16	14879	N122/063638	T20/314090	vertical breccia dyke, saddle between Girdlestone Peak and Ruapehu Summit	porphyritic, olivine- bearing acid andesite with jacketed pyroxenes, fritted plagioclase, and plag-pyroxene aggregates
90	J4	14832	N122/018690	S20/275141	lava flow, Whakapapa Valley; underlies flow of analysis 79	porphyritic, olivine- bearing acid andesite with abundant feldspathic hornfels inclusions
91	J5	14833	N122/018690	S20/275141	lava flow, Whakapapa Valley; underlies flow of analysis 90	porphyritic, 2 pyroxene acid andesite with pyroxene and plagioclase aggregates to 5 mm
92	N4	14884	N122/018650	S20/275102	lava flow, 51 m interval of RS 11	porphyritic, 2 pyroxene acid andesite
93	P6	14895	N122/026638	S20/283090	lava flow, above Mangaturuturu silica terraces	porphyritic, olivine- bearing acid andesite
94	C3	14791	N122/122680	T20/372126	lava flow, Mangatoetoe Gorge	porphyritic, 2 pyroxene acid andesite
95	J6	14834	N122/017692	S20/274143	lava flow, Whakapapa Valley; underlies flow of analysis 91	porphyritic, 2 pyroxene acid andesite
96	J7	14835	N122/016693	S20/273144	lava flow, Whakapapa Valley; underlies flow of analysis 95	finely porphyritic, 2 pyroxene acid andesite
97	N2	14882	N122/017649	S20/274101	lava flow, 24 m interval of RS 11, Mangaturuturu Valley	porphyritic, 2 pyroxene acid andesite
98	J11	14838	N112/031702	S20/287146	lava flow, Whakapapa Valley, 58 m interval of RS 12	black, 2 pyroxene acid andesite; plagioclase- pyroxene and olivine gabbro fragments present

ANALYSIS NUMBER	SAMPLE	VUV NUMBER	GRID REFERENCES		LOCALITY NOTES	PETROGRAPHIC NOTES
			yard	metric		
99	M15	14878	N122/063636	T20/314088	lava flow, 70 m interval of RS 9	strongly porphyritic, oxidized, 2 pyroxene acid andesite with abundant mm-sized cordierite hornfels inclusions
100	E1	14810	N112/080721	T20/329172	lava flow, in unnamed stream valley of N Ruapehu	porphyritic, 2 pyroxene acid andesite with abundant plagioclase and plagioclase-pyroxene aggregates to 3 mm
101	N1	14881	N122/024652	S20/279103	lava flow, 8 m interval of RS 11, Mangaturuturu Valley	porphyritic, 2 pyroxene acid andesite with pyroxene-plagioclase aggregates to 4 mm, and a few jacketed pyroxenes
102	J10	14837	N112/031702	S20/287146	lava flow, Whakapapaiti Valley; 70 m interval of RS 12	porphyritic, 2 pyroxene acid andesite with abundant pyroxene-plagioclase aggregates to 3 mm
103	N6	14886	N122/018651	S20/275103	lava flow, Mangaturuturu Valley, 73 m interval of RS 11	porphyritic, 2 pyroxene acid andesite with a few plagioclase-pyroxene-opaque oxide diorite fragments to 4 mm
104	N5	14885	N122/018650	S20/275102	lava flow, Mangaturuturu Valley, 69 m interval of RS 11	porphyritic, 2 pyroxene acid andesite with pyroxenite fragments to 4 mm
105	E5	14814	N122/076715	T20/325166	lava flow, N Ruapehu; overlies flow of analysis 109; forms top of cliff	strongly porphyritic, 2 pyroxene acid andesite with abundant plag-pyr nodules to 2 cm, and plag-hy-spinel hornfels to 1.5 cm
106	N8	14889	N122/016653	S20/273105	lava flow, Mangaturuturu Valley, 108 m interval of RS 11	porphyritic, 2 pyroxene acid andesite
107	N7	14888	N122/016653	S20/273105	lava flow, Mangaturuturu Valley, 92 m interval of RS 11	porphyritic, 2 pyroxene dacite with anorthosite and diorite fragments to 3 mm
108	J2	14830	N122/019689	S20/276140	lava flow, Whakapapaiti Valley; underlies flow of analysis 110	porphyritic, 2 pyroxene dacite with abundant pyroxene aggregates to 2 mm, few small forsteritic olivine xenocrysts
109	E4	14813	N122/076715	T20/325166	lava flow, N Ruapehu; overlies flow of analysis 75	porphyritic, 2 pyroxene dacite with abundant plagioclase-pyroxene aggregates up to 4 mm
110	J1	14829	N122/020688	S20/277139	lava flow, ridge crest S of Whakapapaiti Stream	porphyritic, 2 pyroxene dacite; garnet-biotite gneiss inclusions present up to 4 cm

WHAKAPAPA FORMATION (analyses 111-131)

ANALYSIS NUMBER	SAMPLE	VUV NUMBER	GRID REFERENCES		LOCALITY NOTES	PETROGRAPHIC NOTES
			yard	metric		
111	D2	14794	N122/082693	T20/331144	N Ruapehu, small block lava flow of Tama Member	strongly porphyritic, 2 pyroxene basic andesite with abundant gabbro and anorthosite inclusions up to 4 mm
112	B6	14785	N112/057708	T20/311154	road to Mead's Wall rope tow, lava flow above flow of analysis 114	porphyritic, 2 pyroxene acid andesite with clinopyroxene and pyroxene-plagioclase aggregates up to 3 mm
113	B4	14783	N112/054710	T20/308156	lava flow NW of Iwikau Shelter	porphyritic, 2 pyroxene acid andesite with clinopyroxene and pyroxene-plagioclase aggregates up to 3 mm
114	B5	14784	N112/055709	T20/309155	lava flow along dirt road to Mead's Wall rope tow	as per analyses 112 and 113, but with clinopyroxene aggregates up to 1 cm
115	Q1pp	14896	N122/063658	T20/317110	Pyramid Peak, Ruapehu summit region; scoriaceous bomb bed above white ash	porphyritic, vesicular, 2 pyroxene acid andesite with sieved plagioclase phenocrysts and plagioclase aggregates to 2 mm
116	D1	14793	N112/089722	T20/340164	dense block, near vent of Tama Member lava field	porphyritic, 2 pyroxene acid andesite
117	B3	14782	N112/038717	S20/295181	lava flow at Whakapapaiti trailhead	porphyritic, 2 pyroxene acid andesite with abundant pyroxene and plagioclase-pyroxene aggregates up to 3 mm
118	A30	14842	N112/059704	T20/313150	dyke below falls of upper Whakapapanui Gorge	black, 2 pyroxene acid andesite with abundant anorthosite and diorite fragments up to 3 mm
119	B2	14781	N112/039730	S20/294174	lowest lava flow in quarry near road to Whakapapa Skifield	porphyritic, 2 pyroxene acid andesite with abundant pyroxene and plagioclase-pyroxene aggregates up to 2 mm
120	E6pr	14819	N112/068722	T20/322164	Pinnacle Ridge; welded airfall tuff of Pinnacle Ridge Member	porphyritic, 2 pyroxene acid andesite with abundant plagioclase and plagioclase-pyroxene aggregates up to 6 mm
121	B10p	14786	N122/079688	T20/328139	high northern slopes of Ruapehu; airfall pumice lapilli and bombs of Iwikau Member	pumiceous, 2 pyroxene acid andesite; this is the host airfall deposit for "B10r" series of metamorphic xenoliths
122	H8	14828	N112/013787	-----	lava flow of Tawhai Falls	nearly aphyric, 2 pyroxene acid andesite

ANALYSIS NUMBER	SAMPLE	VUW NUMBER	GRID REFERENCES		LOCALITY NOTES	PETROGRAPHIC NOTES
			yard	metric		
123	G1	14801	N122/050610	T20/301064	S Ruapehu; lava flow near vent of Rangataua Member	porphyritic, 2 pyroxene acid andesite
124	E6	14818	N122/072685	T20/324131	lava flow, resting on Te Herenga Formation	porphyritic, 2 pyroxene, hornblende-bearing acid andesite, with sparse olivine gabbro nodules up to 1 cm
125	G4	14804	N122/034485	S20/299962	Karioti, lava flow above flow of analysis 126, Rangataua Member	strongly porphyritic, 2 pyroxene acid andesite with abundant pyroxene-plagioclase aggregates up to 3 mm
126	G3	14803	N122/040456	T20/305933	Karioti; steep terminus of block lava flow of Rangataua Member	porphyritic, 2 pyroxene acid andesite, abundant plag and pyx clusters to 3 mm; spinel-hy-plag hornfels inclusions to 1.5 cm
127	G5	14805	N122/055608	T20/306062	lava flow, 0.5 km E of Rangataua Member vent	porphyritic, 2 pyroxene acid andesite
128	H8a	14827	N112/013787	-----	Tawhai Falls, clast from autobreccia beneath lava flow of analysis 122	nearly aphyric acid andesite
129	K1g	14839	N112/002728	S20/261172	Whakapapa suspension bridge, black, glassy, autobrecciated lava flow along stream bank	finely porphyritic, 2 pyroxene dacite
130	N112a	---	N112/106719	T20/355161	N Ruapehu, from 1 m float block, no <u>in situ</u> outcrop recognized	microperlitic, 2 pyroxene dacite with abundant garnet-biotite-plagioclase gneiss inclusions up to 2 cm
131	N112b	---	N112/106719	T20/355161	N Ruapehu; from similar float block to that of analysis 130; no <u>in situ</u> outcrop found	microperlitic, 2 pyroxene dacite with abundant garnet-biotite-plagioclase gneiss inclusions up to 2 cm

RELATED VENTS (analyses 132-144)

ANALYSIS NUMBER	SAMPLE	VUV NUMBER	GRID REFERENCES		LOCALITY NOTES	PETROGRAPHIC NOTES
			yard	metric		
132	WB	---	N112/414969	-----	Waimarino River, SE of Lake Taupo; type locality of Waimarino Basalt Formation	olivine basalt with clinopyroxene and forsteritic olivine phenocrysts set in a hyalopilitic matrix of clinopyroxene, orthopyroxene, titanomagnetite, plagioclase and silicic glass
133	H5	14816	N111/947718	S20/212165	Hauhungatahi, near summit, beneath flow of analysis 143	intergranular, olivine basic andesite with clinopyroxene phenocrysts and aggregates up to 3 mm, and olivine microphenocrysts
134	H7-1	14825	N112/049895	-----	Pukeonake lava flow at cutting on State Highway 47	olivine basic andesite with large forsteritic olivine xenocrysts and rare dunite nodules up to 5 mm, and jacketed pyroxenes
135	H6	14817	N111/947719	S20/211166	Hauhungatahi Summit	intergranular, olivine basic andesite with clinopyroxene phenocrysts and aggregates up to 3 mm, and olivine microphenocrysts
136	H7a	14824	N112/062821	-----	Pukeonake scoria cone quarry; black, semivesicular block	olivine basic andesite with forsteritic olivine phenocrysts, and jacketed, internally sieved plagioclase and orthopyroxene
137	F4	14798	N121/887468	S20/149939	pyroclastics exposed at cutting on loop road of Ohakune Lakes Scenic Reserve	hyalopilitic, olivine- bearing basic andesite with olivine microphenocrysts and cpx-ol-opx aggregates of 3-4 mm size
138	H7-2	14826	N112/038870	-----	Pukeonake lava flow at cutting on State Highway 47	olivine basic andesite; as per analyses 134 and 136
139	H7	14848	N112/007819	-----	Pukeonake lava flow, Mahuia Rapids, near State Highway 47	olivine basic andesite; as per analyses 134, 136 and 138
140	F2	14796	N121/915512	S20/175977	Ohakune, quarry near railway; oxidized bomb from Strombolian airfall deposit	pylotaxitic, olivine- bearing basic andesite with conspicuous olivine- clinopyroxene aggregates up to 4 mm
141	F1	14795	N121/915511	S20/175976	Ohakune, quarry near railway; dense, unoxidized block	pylotaxitic, olivine- bearing basic andesite, as per analysis 137
142	F3	14797	N121/915512	S20/175977	Ohakune, quarry near railway; dense, unoxidized block	pylotaxitic, olivine- bearing basic andesite, as per analysis 140
143	H4	14809	N111/948718	S20/212165	lava from peak to SE of Hauhungatahi Summit	intergranular, olivine basic andesite, as per analysis 133
144	LM-1	14843	N112/005790	-----	road cutting on State Highway 48; clast from core of lahar mound	felsitic, hornblende- bearing, 2 pyroxene dacite with sparse ferrohypsthene microphenocrysts, and hornfels inclusions

ALTERED ROCKS (analyses 145-157)

ANALYSIS NUMBER	SAMPLE	VUW NUMBER	GRID REFERENCES		LOCALITY NOTES	PETROGRAPHIC NOTES
			yard	metric		
145	OP-1	14800	N121/914511	S20/174976	Ohakune, quarry S of railway	pale yellow- orange palagonite from rind on bomb, as per analysis 146 but with phenocrysts removed by sieving
146	OP-2	14800	N121/914511	S20/174976	Ohakune, quarry S of railway	pale yellow- orange, whole rock palagonite from rind on semiviscous bomb in phreatomagmatic airfall deposit
147	H10	14820	N111/950719	S20/214166	steep stream valley to E of Hauhungatahi Summit	green, weathered airfall ash and fine lapilli; crystal- vitric tuff
148	A35	14761	N122/065692	T20/317138	upper Pinnacle Ridge; central facies of Te Herenga Fm	intensely hydrothermally altered basic andesite, with pyroxenes and groundmass altered to green- brown clay
149	A26	14752	N112/058708	T20/311154	Whakapanui Gorge; altered clast from tuff breccia at 90 m interval of RS 1	altered, porphyritic, 2 pyroxene basic andesite
150	H4a	14815	N111/898706	S20/166155	near Erua, railway cutting 200 m NE of State Highway 4 overpass; large block from talus	intergranular olivine basic andesite with clinopyroxene aggregates to 4mm and minor zeolite in groundmass
151	A70	14772	N122/065691	T20/317136	upper Pinnacle Ridge; orthogonally- jointed diorite body; see Fig 11A of Part I	hydrothermally altered, porphyritic microdiorite with sulfides and minor pyroxene alteration to green clay
152	A45	14770	N122/067689	T20/319134	upper Pinnacle Ridge; diorite body of central facies, Te Herenga Fm	hydrothermally altered, hypidiomorphic- granular microdiorite with minor clay alteration
153	A38	14764	N122/067689	T20/319135	upper Pinnacle Ridge; diorite body of central facies, Te Herenga Fm	hydrothermally altered microdiorite with pyroxenes and groundmass altered to clay and sulfides
154	A32	14757	N122/063696	T20/317141	upper Pinnacle Ridge; lava flow of central facies, Te Herenga Fm	green, hydrothermally altered, 2 pyroxene basic andesite with pyroxenes altered to green clay
155	A33	14759	N122/063696	T20/315142	upper Pinnacle Ridge; lava flow of central facies, Te Herenga Fm	blue- green, hydrothermally altered, 2 pyroxene basic andesite
156	A34	14760	N122/063696	T20/315142	upper Pinnacle Ridge; lava flow of central facies, Te Herenga Fm	hydrothermally altered, 2 pyroxene basic andesite with disseminated sulfides
157	A31	14756	N122/062697	T20/314143	upper Pinnacle Ridge; intrusive body of central facies, Te Herenga Fm	dark green, hydrothermally altered basic andesite with minor plagioclase alteration to clay

XENOLITHS (analyses 158-184)

ANALYSIS NUMBER	SAMPLE	VUV NUMBER	GRID REFERENCES		LOCALITY NOTES	PETROGRAPHIC NOTES
			yard	metric		
158	WX-4		N122/085622	T20/335072	Wahianoa Valley; xenolith from lava flow at 134 m interval of RS 6	labradorite- hypersthene- augite- opaque oxide diorite with alteration of plagioclase to clay
159	B10xb		N122/079688	T20/328139	N Ruapehu; host deposit is Iwikau Member airfall tuff of analysis 121	apatite-cordierite-spinel-biotite-andesine gneiss; very fine-grained, with alternating bio-spinel and cord-plag layers
160	Bxa		N112/059733	T20/313194	Whakapanui Stream; boulder in stream bed, derived from lava flow of Iwikau Member	hydrothermally altered andesitic lava or tephra, with fibrous clay, cryptocrystalline clay, and quartz microphenocrysts
161	Bx10		N122/058699	T20/310150	Whakapapa Skifield; xenolith from lava flow of Iwikau Member	hornfels (no petrographic data)
162	B10xe		N122/079688	T20/328139	N Ruapehu; host deposit is Iwikau Member airfall tuff of analysis 121	hematite- glass- biotite- augite- opaque oxide- hypersthene- labradorite/andesine hornfels; xenoblastic and hypidioblastic
163	B61a		N112/057708	T20/311159	road to Mead's Wall rope tow; host Iwikau Member lava flow is analysis 112	hypersthene- spinel- titanomagnetite- andesine hornfels; very fine xenoblastic texture; plagioclase internally clouded
164	B31a		N112/038717	S20/295181	Whakapapa trailhead; host Iwikau Member lava flow is analysis 117	hypersthene- spinel- titanomagnetite- andesine hornfels with fine- grained xenoblastic texture
165	XX		N122/109646	T20/359096	SW rim of Whangaeu Gorge; this diorite is an 8 cm float block of unknown source	coarse, hypidiomorphic- granular, plag- opx- cpx- opaque oxide diorite with strongly clouded plag and minor clay alteration
166	B10rh		N122/079688	T20/328139	N Ruapehu; host deposit is Iwikau Member airfall tuff of analysis 121	hypersthene- glass- sanidine- spinel- biotite schist with very fine banding
167	G1x		N122/050610	T20/301064	S Ruapehu; host Rangataua Member lava flow is analysis 123	bytownite- bronzite- augite- hornblende- glass- pyrrhotite norite with hypidiomorphic- granular texture
168	A11x		N112/038704	S20/294147	ridge N of Whakapapa Valley; xenolith from unanalyzed Te Herenga Fm lava flow	apatite- glass- opaque oxide- hypersthene- labradorite hornfels with fine xenoblastic texture
169	WX5		N122/085622	T20/334066	Wahianoa Valley; xenolith from lava flow at 134 m interval of RS 6	altered, xenomorphic- granular, bronzite- augite- labradorite- opaque oxide gabbro
170	B61d		N112/057708	T20/311154	road to Mead's Wall tow; host Iwikau Member lava flow is analysis 112	augite- hypersthene- opaque oxide- andesine/labradorite hornfels with relatively coarse- grained xenoblastic texture

NO INDIVIDUAL VUV NUMBERS GIVEN; XENOLITHS ARE IN BOXES MARKED "RUAPEHU XENOLITHS".

ANALYSIS NUMBER	SAMPLE	VUV NUMBER	GRID REFERENCES		LOCALITY NOTES	PETROGRAPHIC NOTES
			yard	metric		
171	Bx22		N122/058699	T20/312145	Whakapapa Skifield, xenolith from unanalyzed lava flow of Iwikau Member	hornfels (no petrographic data)
172	Axa		N112/043743	T20/300184	Whakapapanui Stream, xenolith in stream boulder derived from Te Herenga Fm lava flow	labradorite- bronzite- augite gabbro, strongly sheared, with mortar texture
173	B5xa		N112/055709	T20/309155	road to Mead's Wall tow; host Iwikau Member lava flow is analysis 114	labradorite- bronzite- augite gabbro with hypidiomorphic-granular texture
174	B6xc		N112/057708	T20/311154	road to Mead's Wall tow; host Iwikau Member lava flow is analysis 112	opaque oxide- augite- andesine/labradorite- hypersthene hornfels with fine xenoblastic and poikiloblastic textures
175	Bxws		N112/043743	T20/300184	Whakapapanui Stream, xenolith in stream boulder derived from Iwikau Member lava flow	spinel- augite- hypersthene- andesine/labradorite hornfels with fine xenoblastic texture
176	W4x		N122/078624	T20/327068	Wahianoa Valley, host Wahianoa Fm lava flow is analysis 61	plagioclase- orthopyroxene- clinopyroxene- opaque oxide diorite nodule
177	M7x-1		N122/055640	T20/306092	S Ruapehu, xenolith from unanalyzed welded tuff of Mangawhero Formation	hydrothermally altered clay- plagioclase- 2 pyroxene andesite
178	Bx24		N122/058699	T20/312145	Whakapapa Skifield, xenolith from unanalyzed lava flow of Iwikau Member	hornfels (no petrographic data)
179	A14x		N112/036705	S20/292148	ridge N of Whakapapanui Valley, 20 cm xenolith in unanalyzed Te Herenga Fm lava flow	graphite- hematite- opaque oxide- quartz schist, very fine-grained emery rock, with quartz- hematite veinlets
180	T5x		N122/055648	T20/306100	SW rim of Crater Lake Basin, xenolith from unanalyzed Mangawhero Fm lava flow	altered andesite inclusion (no petrographic data)
181	N112c		N112/106719	T20/355161	N Ruapehu, 25 cm float block, believed derived from airfall deposit of analysis 121	epidote- muscovite- albite- quartz- chlorite metagreywacke, with cataclastic texture
182	Arg Xeno		N112/1115705	T20/364147	N Ruapehu, 70 cm tabular float block, possibly derived from airfall deposit of analysis 121	epidote- muscovite- albite- quartz- chlorite metagreywacke
183	H7x-21		N112/062821	-----	Pukeonake scoria cone quarry, 8 cm reticulite block from scoriaceous bomb/lapilli bed	highly vesicular, buff- coloured reticulite, comprising clear glass with cordierite and spinel microlites
184	FX-Q		N121/911516	S20/171981	Ohakune, quarry N of railway, 2 cm xenolith from lava flow exposed in quarry	saccharoidal quartzite with seriate grain boundaries and a trace of clear glass

NO INDIVIDUAL VUV NUMBERS GIVEN; XENOLITHS ARE IN BOXES MARKED "RUAPEHU XENOLITHS".

BULK ROCK CHEMICAL DATA FROM TE HERENGA FORMATION

ANALYSIS #	1	2	3	4	5	6	7	8	9	10
SAMPLE	A39	A9	A37	A20	A91	Alpha 2	A4	A8	A93	A5
OXIDE WT%										
SiO ₂	53.81	54.35	55.02	55.25	55.45	55.74	55.80	55.88	56.14	56.21
TiO ₂	.70	.65	.69	.66	.62	.74	.65	.65	.64	.65
Al ₂ O ₃	17.49	17.75	17.72	17.72	16.80	18.72	17.31	17.95	17.44	17.63
Fe ₂ O ₃	3.45	2.60	3.70	2.62	1.90	2.68	3.20	2.53	2.17	2.87
FeO	5.12	6.04	5.01	5.60	6.20	4.78	5.18	5.68	5.75	5.32
MnO	.14	.11	.11	.12	.14	.12	.18	.12	.11	.16
MgO	5.38	5.03	4.32	4.57	5.69	3.52	4.78	4.64	4.76	4.78
CaO	8.51	7.96	8.18	8.01	8.39	8.07	8.08	7.56	7.90	8.34
Na ₂ O	2.94	2.99	3.14	2.82	2.95	3.05	3.06	3.16	3.16	3.20
K ₂ O	.74	.61	.80	.74	.62	1.01	.65	.75	.78	.63
P ₂ O ₅	.10	.08	.10	.09	.08	.11	.06	.09	.09	.07
LOI	1.51	1.45	1.62	1.34	1.21	1.97	.97	1.33	1.04	.63
TOTAL	99.89	99.62	100.41	99.54	100.05	100.51	99.92	100.34	99.98	100.49
FeO(t)	8.22	8.38	8.34	7.95	7.91	7.19	8.06	7.95	7.70	7.90
Mg No.*	65.19	59.74	60.58	59.25	62.06	56.75	62.18	59.28	59.60	61.55
TRACE ELEMENTS (ppm)										
Ba	218	202	246	219	221	205	191	272	216	184
Rb	23	14	25	23	17	25	18	23	24	19
Sr	216	203	219	214	220	216	212	237	210	216
Pb	13	4	12	13	6	13	6	9	5	6
Zr	55	63	51	59	57	69	65	61	67	63
Nb	-	-	-	n.d.	2	1	-	-	1	-
Y	22	21	22	20	19	25	19	21	20	20
V	251	229	203	195	225	246	218	204	211	229
Cr	86	62	38	54	97	42	60	46	35	61
Ni	36	24	21	22	43	20	24	29	25	27
Cu	79	67	86	57	52	61	38	83	48	52
Zn	88	82	67	73	86	96	75	91	78	78
Ga	-	-	-	-	18	-	-	-	18	-
K/Rb	267.00	362.00	266.00	267.00	303.00	335.00	300.00	285.00	270.00	291.00
Rb/Sr	0.11	0.07	0.11	0.11	0.08	0.12	0.08	0.10	0.11	0.08
Sr ⁸⁷ / ₈₆	-	-	-	.70508	-	-	-	.70513	-	-

* 100Mg/Mg+Fe₂ (mol)

BULK ROCK CHEMICAL DATA FROM TE HERENGA FORMATION

ANALYSIS #	11	12	13	14	15	16	17	18	19	20
SAMPLE	A7	A92	Alpha 1	A36	A32'	A1	A3	A6	A25	L24
OXIDE WT%										
SiO ₂	56.21	56.30	56.32	56.38	56.44	56.55	56.55	56.55	56.55	56.67
TiO ₂	.67	.64	.70	.65	.66	.68	.65	.67	.69	.61
Al ₂ O ₃	17.50	17.05	17.37	17.37	17.77	17.26	17.42	17.48	17.59	17.50
Fe ₂ O ₃	2.58	3.01	2.81	4.14	2.29	2.86	2.56	2.87	2.84	1.92
FeO	5.82	4.70	5.40	4.00	5.72	5.48	5.76	5.43	5.49	5.40
MnO	.17	.11	.12	.11	.11	.19	.17	.18	.13	.11
MgO	4.68	4.56	4.48	4.64	4.56	4.21	4.63	4.63	4.54	4.74
CaO	8.06	7.63	7.92	7.55	8.35	7.80	7.94	8.08	7.89	7.82
Na ₂ O	3.24	3.15	3.15	3.02	3.11	3.33	3.21	3.12	3.12	3.13
K ₂ O	.79	.76	.74	.85	.70	.66	.68	.78	.74	.84
P ₂ O ₅	.08	.08	.09	.11	.10	.08	.07	.10	.08	.09
LOI	.49	1.39	1.43	1.51	.87	.85	1.01	.60	1.19	.56
TOTAL	100.29	99.38	100.53	100.33	100.68	99.95	100.65	100.49	100.85	99.39
FeO(t)	8.00	7.40	7.93	7.73	7.78	8.05	8.06	8.01	8.04	7.13
Mg No.*	58.90	63.36	59.65	67.40	58.69	57.79	58.89	60.31	-	61.00
TRACE ELEMENTS (ppm)										
Ba	251	223	232	259	222	164	202	238	298	253
Rb	21	24	24	25	22	15	18	21	20	30
Sr	238	197	250	264	197	215	218	239	256	224
Pb	6	6	15	17	15	6	8	7	13	7
Zr	63	62	61	65	56	59	61	62	55	72
Nb	-	3	n.d.	-	-	2	-	-	-	4
Y	20	20	21	23	23	22	18	20	22	23
V	228	187	251	180	240	241	216	215	228	188
Cr	48	42	56	52	67	38	42	45	55	70
Ni	35	21	30	33	30	22	21	28	23	35
Cu	54	54	54	65	53	38	67	48	53	52
Zn	78	67	80	64	82	82	77	75	76	73
Ga	-	17	-	-	-	17	-	-	-	19
K/Rb	312.00	263.00	256.00	282.00	264.00	322.00	314.00	308.00	307.00	232.00
Rb/Sr	0.09	0.12	0.10	0.09	0.11	0.80	0.08	0.09	0.08	0.13
Sr87/86	-	-	-	-	-	-	-	-	-	-

* 100Mg/Mg+Fe2 (mol)

BULK ROCK CHEMICAL DATA FROM TE HERENGA FORMATION

ANALYSIS #	21	22	23	24
SAMPLE	A2	A13	A27	A42
OXIDE WT%				
SiO ₂	56.77	56.91	57.01	58.78
TiO ₂	.65	.65	.71	.64
Al ₂ O ₃	17.37	17.25	16.90	18.98
Fe ₂ O ₃	3.11	2.90	3.53	2.45
FeO	5.10	5.26	5.20	3.70
MnO	.17	.13	.14	.09
MgO	4.56	4.34	4.40	2.42
CaO	8.08	7.37	7.12	6.94
Na ₂ O	3.14	3.16	3.20	3.67
K ₂ O	.74	.66	.77	1.04
P ₂ O ₅	.07	.09	.09	.11
LOI	.66	.83	1.25	1.17
TOTAL	100.42	99.55	100.32	99.99
FeO(t)	7.90	7.85	8.38	5.90
Mg No.*	61.44	59.52	60.13	53.82
TRACE ELEMENTS (ppm)				
Ba	205	205	220	279
Rb	20	17	23	34
Sr	217	220	218	258
Pb	8	6	17	28
Zr	61	60	58	76
Nb	-	3	-	-
Y	21	20	21	23
V	212	215	203	130
Cr	40	41	40	25
Ni	21	27	27	9
Cu	39	41	52	50
Zn	73	77	74	70
Ga	-	18	-	-
K/Rb	307.00	322.00	278.00	254.00
Rb/Sr	0.09	0.08	0.11	0.13
Sr ⁸⁷ / ⁸⁶	-	-	-	-

* 100Mg/Mg+Fe₂ (mol)

BULK ROCK CHEMICAL DATA FROM WAHIANOA FORMATION

ANALYSIS #	25	26	27	28	29	30	31	32	33	34
SAMPLE	X13	Q1DR	X56	L12	X14	5B	4	9	X15	16
OXIDE WT%										
SiO ₂	54.30	54.48	54.87	55.20	55.23	55.73	55.95	56.03	56.08	56.29
TiO ₂	.76	.67	.65	.72	.75	.69	.68	.66	.73	.67
Al ₂ O ₃	17.45	16.26	16.18	17.56	17.20	15.62	14.98	17.30	17.47	17.23
Fe ₂ O ₃	3.48	2.19	1.99	2.52	1.98	2.36	2.03	2.36	2.20	2.52
FeO	4.64	6.34	5.86	6.12	6.37	5.46	5.66	4.92	5.64	5.52
MnO	.13	.13	.13	.12	.14	.11	.12	.11	.12	.12
MgO	5.02	6.07	6.62	4.55	4.93	6.49	6.85	4.97	4.46	4.56
CaO	8.46	8.69	8.00	8.43	8.64	8.93	8.49	8.07	7.96	8.04
Na ₂ O	2.60	2.91	2.84	2.88	2.59	2.65	2.48	3.03	2.85	2.85
K ₂ O	.88	.73	.83	.74	.93	.90	.96	.79	1.08	1.00
P ₂ O ₅	.10	.09	.10	.09	.10	.08	.09	.09	.10	.10
LOI	1.51	.75	.93	.70	.89	.99	1.45	1.14	.63	.68
TOTAL	99.33	99.31	99.00	99.63	99.75	100.01	99.74	99.47	99.32	99.68
FeO(t)	7.77	8.31	7.65	8.39	8.15	7.58	7.49	7.05	7.62	7.79
Mg No.*	65.85	63.05	66.87	56.99	57.97	67.93	68.32	64.29	58.49	-
TRACE ELEMENTS (ppm)										
Ba	245	198	229	210	238	261	256	280	293	287
Rb	28	20	27	23	30	29	42	22	35	34
Sr	221	226	214	207	228	213	204	284	228	229
Pb	12	4	4	11	13	11	16	14	11	13
Zr	69	67	75	61	69	75	77	68	75	72
Nb	1	3	3	3	n.d.	2	-	n.d.	n.d.	1
Y	21	21	19	21	23	20	22	18	25	21
V	240	234	221	248	234	223	220	216	224	205
Cr	72	125	246	63	73	267	275	103	59	68
Ni	28	35	76	26	27	63	61	53	22	25
Cu	67	56	58	57	64	98	82	65	62	49
Zn	84	88	76	84	81	69	72	77	73	76
Ga	-	19	18	-	-	-	-	-	-	-
K/Rb	261	303	255	267	257	258	190	298	256	244
Rb/Sr	0.13	0.09	0.13	0.11	0.13	0.14	0.21	0.08	0.15	0.15
Sr87/86	.70521	-	-	-	.70518	-	-	-	-	-

* 100Mg/Mg+Fe2 (mol)

BULK ROCK CHEMICAL DATA FROM WAHIANOA FORMATION

ANALYSIS #	35	36	37	38	39	40	41	42	43	44
SAMPLE	X16	X51	X52	8	X53	X22	10	X23	X12	3
OXIDE WT%										
SiO ₂	56.38	56.38	56.45	56.73	56.88	56.91	57.11	57.24	57.45	57.67
TiO ₂	.68	.66	.68	.66	.66	.67	.65	.67	.67	.70
Al ₂ O ₃	16.83	19.35	17.32	16.81	17.17	17.00	17.21	17.18	17.94	19.70
Fe ₂ O ₃	2.14	2.68	2.55	2.52	2.33	2.03	1.74	2.32	1.63	2.05
FeO	5.70	3.42	5.04	4.96	5.30	5.44	5.50	5.24	4.59	3.68
MnO	.11	.09	.11	.13	.11	.12	.10	.11	.10	.09
MgO	5.19	3.58	4.46	5.25	4.56	4.43	4.95	4.44	4.35	2.08
CaO	8.06	7.71	7.24	8.19	7.43	7.71	8.10	7.55	7.90	7.26
Na ₂ O	2.84	3.52	3.27	3.06	3.21	2.94	3.25	3.02	3.13	3.63
K ₂ O	1.02	1.10	1.09	.92	1.09	1.11	.90	1.11	1.13	1.19
P ₂ O ₅	.10	.11	.10	.09	.10	.09	.09	.10	.12	.11
LOI	.64	1.88	1.32	.70	.81	.78	.73	.92	.51	1.10
TOTAL	99.69	100.48	99.63	100.02	99.65	99.23	100.33	99.90	99.52	99.26
FeO(t)	7.63	5.83	7.33	7.22	7.40	7.27	7.06	7.32	6.06	5.52
Mg No.*	61.87	65.10	61.19	65.35	60.52	59.20	61.59	60.16	62.81	50.18
TRACE ELEMENTS (ppm)										
Ba	269	273	251	257	255	212	233	267	312	307
Rb	31	37	39	29	39	38	30	37	36	35
Sr	224	309	228	269	231	232	278	230	305	312
Pb	10	8	9	12	7	14	13	8	14	12
Zr	75	88	85	68	85	81	69	82	81	90
Nb	n.d.	4	3	1	4	n.d.	1	n.d.	1	3
Y	20	19	21	20	21	21	17	22	20	18
V	223	169	197	209	194	203	215	207	185	178
Cr	141	77	60	124	59	81	114	75	109	23
Ni	60	32	30	45	36	33	54	34	50	19
Cu	73	53	48	77	50	60	77	65	48	52
Zn	72	64	75	71	78	73	78	73	63	66
Ga	-	18	18	-	17	-	-	20	-	-
K/Rb	273	247	232	263	232	243	249	249	261	282
Rb/Sr	0.14	0.12	0.17	0.11	0.17	0.16	0.11	0.16	0.12	0.11
Sr87/86	-	-	-	-	-	-	-	-	-	-

* 100Mg/Mg+Fe2 (mol)

BULK ROCK CHEMICAL DATA FROM WAHIANOA FORMATION

ANALYSIS #	45	46	47	48	49	50	51	52	53	54
SAMPLE	14	13	11	5A	6	X54	X50	1	7	2
OXIDE WT%										
SiO ₂	57.70	57.72	57.74	57.98	58.10	58.18	58.20	58.23	58.29	58.33
TiO ₂	.66	.68	.68	.75	.74	.64	.68	.71	.75	.70
Al ₂ O ₃	17.83	20.37	20.34	17.02	17.12	18.38	19.57	19.81	16.96	19.81
Fe ₂ O ₃	2.50	1.68	2.31	1.70	1.85	2.39	2.06	3.54	1.87	1.82
FeO	4.04	3.54	3.38	5.38	5.41	4.14	3.80	2.36	5.38	3.87
MnO	.09	.06	.08	.10	.11	.10	.08	.08	.10	.07
MgO	4.33	2.18	2.09	3.90	3.99	3.11	2.24	2.09	3.88	2.12
CaO	7.86	8.08	7.96	6.94	7.07	6.48	7.24	7.44	6.95	7.55
Na ₂ O	3.30	3.57	3.60	2.94	2.96	3.27	3.74	3.98	3.01	3.81
K ₂ O	1.11	1.24	1.24	1.43	1.40	1.22	1.18	1.21	1.43	1.22
P ₂ O ₅	.12	.13	.11	.12	.12	.10	.12	.13	.11	.12
LOI	.64	.40	.55	1.04	1.16	1.04	.92	.96	.90	.71
TOTAL	100.18	99.65	100.08	99.30	100.03	99.05	99.83	100.54	99.63	100.13
FeO(t)	6.29	5.06	5.46	6.91	7.07	6.29	5.65	5.54	7.06	5.51
Mg No.*	65.63	52.32	52.42	56.37	56.79	57.24	51.23	61.21	56.24	49.40
TRACE ELEMENTS (ppm)										
Ba	322	318	319	330	344	311	297	320	354	322
Rb	37	40	40	50	49	45	37	35	51	38
Sr	310	352	351	273	272	238	305	313	279	318
Pb	19	13	13	15	15	8	8	11	15	12
Zr	86	94	95	108	106	95	93	88	113	91
Nb	3	1	n.d.	2	n.d.	4	4	2	1	n.d.
Y	20	19	20	21	22	19	19	19	21	21
V	189	167	166	195	203	153	178	169	205	196
Cr	124	36	36	51	41	11	16	21	38	19
Ni	55	24	25	19	17	10	15	19	23	19
Cu	85	70	69	43	37	31	42	70	36	50
Zn	66	60	62	71	76	65	64	65	74	63
Ga	-	-	-	-	-	18	20	-	-	-
K/Rb	249	258	257	237	237	225	265	287	233	267
Rb/Sr	0.12	0.11	0.11	0.18	0.18	0.19	0.12	0.11	0.18	0.12
Sr87/86	-	-	-	-	-	-	-	-	-	-

* 100Mg/Mg+Fe₂ (mol)

BULK ROCK CHEMICAL DATA FROM WAHIANOA FORMATION

ANALYSIS #	55	56	57	58	59	60	61	62
SAMPLE	M10	W1	M3	W3	M5	M4	W4	WH.ST.
OXIDE WT%								
SiO ₂	58.52	58.90	59.74	59.97	60.40	60.95	61.03	61.20
TiO ₂	.70	.64	.78	.77	.72	.70	.57	.70
Al ₂ O ₃	16.74	17.69	15.02	15.08	17.59	15.10	15.63	15.75
Fe ₂ O ₃	1.46	2.13	1.25	1.14	1.90	1.15	1.90	1.42
FeO	4.74	4.50	4.80	4.82	4.40	4.44	3.78	4.48
MnO	.09	.09	.08	.07	.08	.08	.06	.10
MgO	4.35	2.96	5.48	5.28	2.54	5.36	4.69	3.79
CaO	6.76	6.60	6.17	6.09	5.93	5.87	6.44	6.02
Na ₂ O	3.01	3.59	2.97	3.19	3.56	3.23	3.35	3.10
K ₂ O	1.68	1.21	2.03	1.98	1.58	2.12	1.64	2.17
P ₂ O ₅	.12	.10	.15	.16	.13	.15	.13	.14
LOI	1.43	.39	.66	.59	.35	.41	.54	.57
TOTAL	99.60	98.80	99.13	99.14	99.18	99.56	99.76	99.44
FeO(T)	6.06	6.41	5.93	5.85	6.11	5.48	5.49	5.76
Mg No.*	62.05	53.96	67.05	66.13	50.71	68.27	68.86	60.12
TRACE ELEMENTS (ppm)								
Ba	334	329	420	464	391	434	-	427
Rb	69	42	88	86	57	93	59	99
Sr	262	228	229	240	243	219	356	256
Pb	10	6	13	13	10	10	10	12
Zr	128	96	160	163	119	159	117	160
Nb	5	5	7	7	5	6	3	5
Y	23	22	24	21	24	25	17	24
V	172	149	167	163	172	139	-	146
Cr	83	18	260	209	10	204	-	110
Ni	32	16	78	64	16	74	50	33
Cu	30	37	55	43	44	69	83	31
Zn	69	65	63	62	70	56	53	61
Ga	18	20	16	15	19	18	17	17
K/Rb	202	239	192	191	230	189	231	182
Rb/Sr	0.26	0.18	0.38	0.36	0.23	0.42	0.17	0.39
Sr ⁸⁷ / ⁸⁶	-	-	-	-	-	-	-	-

* 100Mg/Mg+Fe₂ (mol)

BULK ROCK CHEMICAL DATA FROM MANGAWHERO FORMATION

ANALYSIS #	63	64	65	66	67	68	69	70	71	72
SAMPLE	L1015A	L21	E7	L22	L20	L23	A41	L9	L6	M11
OXIDE WT%										
SiO ₂	52.23	53.15	53.37	53.45	53.83	54.11	55.42	55.46	55.56	56.06
TiO ₂	.66	.68	.69	.68	.69	.69	.66	.76	.77	.65
Al ₂ O ₃	15.57	17.05	16.97	16.93	17.08	17.46	16.66	17.39	17.40	14.76
Fe ₂ O ₃	2.70	3.27	2.97	2.55	2.84	2.33	1.75	2.27	2.31	1.69
FeO	6.34	5.60	5.34	6.00	5.88	6.12	5.71	5.58	5.52	5.14
MnO	.16	.13	.13	.14	.12	.13	.13	.12	.12	.09
MgO	8.73	6.66	7.05	6.92	6.70	5.95	6.32	4.71	5.00	7.49
CaO	9.63	8.79	8.84	9.05	8.91	8.69	8.45	8.32	8.11	7.86
Na ₂ O	2.59	2.77	2.69	2.88	2.85	3.01	2.81	2.90	2.93	2.69
K ₂ O	.58	.68	.66	.67	.68	.73	.93	1.04	1.11	1.15
P ₂ O ₅	.09	.10	.10	.09	.10	.11	.11	.12	.12	.11
LOI	.75	.88	1.72	.44	.79	.57	.78	1.13	1.09	1.48
TOTAL	100.03	99.76	100.53	99.80	100.47	99.90	99.73	99.80	100.04	99.17
FeO(t)	8.76	8.54	8.02	8.30	8.44	8.22	7.29	7.62	7.60	6.66
Mg No.*	71.05	67.94	70.17	67.27	67.00	63.40	66.36	60.07	61.75	72.20
TRACE ELEMENTS (ppm)										
Ba	193	232	386	221	246	255	287	273	314	283
Rb	12	17	16	17	18	19	29	33	35	46
Sr	200	222	226	215	213	223	232	234	253	233
Pb	8	4	16	6	2	3	14	14	11	7
Zr	50	59	68	58	57	64	70	76	83	102
Nb	2	3	3	3	2	3	-	1	n.d.	4
Y	17	21	21	23	19	21	22	21	20	21
V	254	265	235	261	262	242	208	233	218	192
Cr	389	128	225	144	130	83	180	74	133	367
Ni	135	53	83	50	48	37	70	59	45	121
Cu	81	58	52	59	57	57	46	58	60	66
Zn	83	84	81	85	81	82	70	77	72	78
Ga	15	17	-	17	17	20	-	-	-	16
K/Rb	385	332	342	327	314	319	266	262	263	208
Rb/Sr	0.07	0.08	0.07	0.08	0.08	0.09	0.12	0.14	0.14	0.18
Sr87/86	.70478	.70504	.70525	-	-	.70518	-	-	-	-

* 100Mg/Mg+Fe2 (mol)

BULK ROCK CHEMICAL DATA FROM MANGAWHERO FORMATION

ANALYSIS #	73	74	75	76	77	78	79	80	81	82
SAMPLE	L11	C2	E3	N3	L1	L3	J3	E2	M17	M9
OXIDE WT%										
SiO ₂	56.95	57.16	57.22	57.27	57.40	57.87	57.88	57.91	58.07	58.09
TiO ₂	.70	.67	.66	.68	.69	.68	.64	.66	.58	.63
Al ₂ O ₃	16.53	16.96	15.54	15.43	17.12	17.42	16.31	15.49	13.49	14.08
Fe ₂ O ₃	2.14	2.32	2.70	1.63	1.81	1.84	2.01	2.23	2.91	2.19
FeO	5.00	5.13	4.85	5.32	5.20	5.12	4.97	5.05	3.79	4.44
MnO	.10	.16	.16	.11	.10	.09	.09	.17	.10	.10
MgO	5.06	4.89	5.92	6.95	4.65	4.14	5.17	6.12	8.37	7.90
CaO	7.58	7.83	8.08	7.50	7.49	6.95	7.51	8.22	7.05	6.71
Na ₂ O	3.03	3.33	2.83	2.71	3.06	3.17	2.90	2.90	2.90	2.68
K ₂ O	1.23	1.02	1.20	1.39	1.20	1.19	1.14	1.21	1.45	1.51
P ₂ O ₅	.11	.10	.10	.11	.10	.09	.08	.10	.11	.12
LOI	.91	1.16	.65	.96	1.56	1.20	1.04	.56	.82	1.56
TOTAL	99.34	100.73	99.91	100.06	100.38	99.76	99.74	100.62	99.64	100.01
FeO(t)	6.93	7.22	7.28	6.78	6.83	6.78	6.78	7.05	6.41	6.41
Mg No.*	64.33	62.94	68.51	69.95	61.44	59.03	64.96	68.35	79.74	76.02
TRACE ELEMENTS (ppm)										
Ba	355	252	299	335	294	461	282	301	279	328
Rb	40	35	43	55	38	39	40	43	51	55
Sr	268	237	330	245	256	241	236	332	297	283
Pb	17	9	12	5	15	13	14	8	9	10
Zr	90	85	88	112	95	91	88	89	108	124
Nb	n.d.	-	-	4	1	2	n.d.	-	4	4
Y	22	22	22	21	20	21	20	23	18	17
V	198	201	201	191	194	193	195	205	170	163
Cr	185	90	215	280	88	61	172	229	470	411
Ni	66	32	65	103	32	36	68	65	121	118
Cu	41	59	70	40	60	81	56	69	82	75
Zn	68	74	73	66	71	86	69	69	71	67
Ga	-	-	-	16	-	-	-	-	15	16
K/Rb	255	242	232	210	262	253	237	234	236	228
Rb/Sr	0.15	0.15	0.13	0.22	0.15	0.16	0.17	0.13	0.17	0.19
Sr ⁸⁷ / ₈₆	-	-	-	-	-	-	-	-	.70472	-

* 100Mg/Mg+Fe₂ (mol)

BULK ROCK CHEMICAL DATA FROM MANGAWHERO FORMATION

ANALYSIS #	83	84	85	86	87	88	89	90	91	92
SAMPLE	P4	P3	C1	T3	M8'	L2	M16	J4	J5	N4
OXIDE WT%										
SiO ₂	58.22	58.27	58.27	58.35	58.48	58.54	58.67	58.68	58.83	58.83
TiO ₂	.73	.73	.67	.72	.63	.68	.63	.76	.79	.69
Al ₂ O ₃	16.33	16.29	17.03	17.44	14.06	17.41	14.18	17.36	16.89	15.14
Fe ₂ O ₃	1.85	1.83	2.00	1.76	1.82	2.25	1.55	2.10	2.09	1.90
FeO	4.36	4.40	5.32	4.80	4.58	4.82	4.89	3.90	4.31	4.76
MnO	.08	.09	.15	.10	.12	.11	.10	.08	.07	.09
MgO	5.06	5.56	4.41	3.60	7.85	3.75	7.37	3.39	3.77	6.70
CaO	7.04	7.09	7.37	6.81	6.88	7.05	6.78	6.74	7.00	7.05
Na ₂ O	3.27	3.18	3.38	3.15	2.74	3.16	2.79	3.15	3.05	2.96
K ₂ O	1.60	1.53	1.17	1.54	1.55	1.20	1.56	1.79	1.80	1.60
P ₂ O ₅	.14	.14	.09	.12	.12	.10	.13	.13	.15	.13
LOI	.36	.69	.75	1.44	.72	1.05	1.05	1.06	.68	.71
TOTAL	99.04	99.80	100.61	99.83	99.55	100.12	99.70	99.14	99.43	100.56
FeO(t)	6.03	6.05	7.12	6.39	6.22	6.85	6.30	5.79	6.19	6.47
Mg No.*	67.41	69.25	59.63	57.20	75.33	58.10	72.87	60.77	60.92	71.50
TRACE ELEMENTS (ppm)										
Ba	350	366	280	323	316	311	328	409	396	339
Rb	67	63	40	64	58	41	61	65	66	67
Sr	254	252	227	230	278	234	277	275	279	229
Pb	9	9	8	11	11	18	12	14	15	8
Zr	130	126	91	120	122	86	125	134	137	127
Nb	5	5	-	5	5	n.d.	6	3	2	6
Y	21	22	23	25	20	23	20	18	21	21
V	177	176	228	190	166	181	168	169	186	177
Cr	170	194	73	47	409	43	380	57	94	291
Ni	65	75	27	18	116	28	104	32	52	94
Cu	58	43	62	30	71	79	38	49	38	41
Zn	67	61	77	78	66	72	69	64	63	61
Ga	18	17	-	17	15	-	17	-	-	16
K/Rb	198	202	243	200	222	243	212	229	226	198
Rb/Sr	0.26	0.25	0.18	0.28	0.21	0.18	0.22	0.24	0.24	0.29
Sr ⁸⁷ / ₈₆	-	-	-	-	-	-	-	-	-	-

* 100Mg/Mg+Fe₂ (mol)

BULK ROCK CHEMICAL DATA FROM MANGAWHERO FORMATION

ANALYSIS #	93	94	95	96	97	98	99	100	101	102
SAMPLE	P6	C3	J6	J7	N2	J11	M15	E1	N1	J10
OXIDE WT%										
SiO ₂	58.83	58.99	59.06	59.06	59.10	59.18	59.39	59.81	59.95	60.17
TiO ₂	.66	.72	.79	.77	.75	.84	.62	.76	.77	.75
Al ₂ O ₃	14.39	15.83	16.91	17.19	15.33	16.12	16.41	17.92	15.24	16.74
Fe ₂ O ₃	1.49	1.57	2.21	1.52	1.40	1.87	2.25	2.65	2.01	1.38
FeO	4.96	5.45	4.00	4.06	4.88	4.43	3.62	4.07	4.36	4.49
MnO	.09	.15	.08	.08	.07	.13	.09	.14	.08	.13
MgO	7.29	4.62	3.74	4.14	5.74	3.35	4.96	2.60	5.43	3.27
CaO	6.81	7.05	6.63	7.01	6.54	6.15	6.32	6.58	6.38	6.31
Na ₂ O	2.92	3.15	2.91	3.02	2.85	4.61	3.10	3.66	3.27	3.53
K ₂ O	1.63	1.76	1.85	1.69	1.72	2.11	1.50	1.61	1.85	1.88
P ₂ O ₅	.13	.10	.13	.13	.14	.17	.14	.11	.14	.14
LOI	.68	.77	1.07	.83	.86	.59	1.19	.57	.60	.54
TOTAL	99.88	100.16	99.38	99.50	99.38	99.55	99.59	100.48	100.08	99.33
FeO(t)	6.30	6.87	5.99	5.43	6.14	6.11	5.64	6.45	6.17	5.73
Mg No.*	72.37	60.17	62.49	64.50	67.70	57.40	70.94	53.24	68.94	56.48
TRACE ELEMENTS (ppm)										
Ba	353	348	405	372	394	442	345	365	418	406
Rb	66	73	72	63	75	84	57	60	78	77
Sr	266	230	280	273	217	288	348	289	234	283
Pb	10	12	12	13	10	14	7	12	13	13
Zr	127	130	137	130	140	146	115	118	153	140
Nb	5	-	4	3	5	4	5	-	6	-
Y	21	24	21	20	19	24	23	25	25	24
V	151	180	181	194	180	194	168	198	173	173
Cr	317	122	81	119	237	83	126	15	234	57
Ni	89	35	48	76	76	32	53	11	77	31
Cu	49	52	40	39	34	50	37	43	51	51
Zn	58	71	58	64	62	69	63	75	68	64
Ga	17	-	-	-	18	18	20	-	18	19
K/Rb	205	200	213	223	190	209	218	223	197	203
Rb/Sr	0.25	0.32	0.26	0.23	0.34	0.29	0.16	0.21	0.33	0.27
Sr87/86	-	-	-	-	-	-	-	-	-	-

* 100Mg/Mg+Fe2 (mol)

BULK ROCK CHEMICAL DATA FROM MANGAWHERO FORMATION

ANALYSIS #	103	104	105	106	107	108	109	110
SAMPLE	N6	N5	E5	N8	N7	J2	E4	J1
OXIDE WT%								
SiO ₂	61.33	61.48	62.67	62.94	63.30	63.33	63.60	63.62
TiO ₂	.78	.79	.83	.80	.78	.79	.81	.84
Al ₂ O ₃	16.75	16.30	15.48	16.57	16.38	15.31	15.93	15.38
Fe ₂ O ₃	1.55	1.02	1.26	1.48	1.34	.98	1.43	2.06
FeO	4.32	4.76	4.13	3.70	3.76	3.86	3.68	3.20
MnO	.07	.07	.13	.06	.08	.05	.12	.04
MgO	3.21	3.12	3.30	2.22	1.84	2.99	2.51	3.12
CaO	5.87	5.77	5.29	4.80	4.47	5.00	4.65	4.76
Na ₂ O	3.49	3.23	3.13	3.34	3.58	3.20	3.32	3.03
K ₂ O	1.96	2.03	2.83	2.72	2.89	3.03	2.84	3.02
P ₂ O ₅	.17	.17	.15	.20	.21	.15	.14	.15
LOI	.66	.49	.61	.61	.52	1.02	.94	.97
TOTAL	100.26	99.23	99.81	99.44	99.15	99.71	99.97	100.19
FeO(t)	5.80	5.68	5.26	5.03	4.97	4.74	4.97	5.05
Mg No.*	56.97	53.88	58.74	51.67	46.58	57.99	54.86	63.47
TRACE ELEMENTS (ppm)								
Ba	420	419	522	514	495	529	525	537
Rb	83	85	112	124	130	135	121	131
Sr	250	249	234	255	267	218	228	220
Pb	13	11	13	14	17	19	16	19
Zr	156	159	196	198	209	216	205	223
Nb	7	6	-	8	8	7	7	7
Y	26	24	27	28	30	25	23	22
V	161	158	148	117	93	135	140	147
Cr	52	55	105	29	20	107	73	116
Ni	24	23	35	19	11	43	30	45
Cu	43	40	70	32	27	40	54	51
Zn	67	67	59	55	67	56	58	53
Ga	18	18	-	18	19	-	19	-
K/Rb	196	198	210	182	185	186	190	191
Rb/Sr	0.33	0.34	0.48	0.49	0.49	0.62	0.54	0.59
Sr87/86	.70581	-	.70575	.70596	-	-	.70623	.70545

* 100Mg/Mg+Fe₂ (mol)

BULK ROCK CHEMICAL DATA FROM WHAKAPAPA FORMATION

ANALYSIS #	111	112	113	114	115	116	117	118	119	120
SAMPLE	D2	B6	B4	B5	Q1PP	D1	B3	A30	B2	E6PR
OXIDE WT%										
SiO ₂	56.62	57.18	57.31	57.24	57.45	58.19	58.42	58.89	58.91	59.28
TiO ₂	.70	.67	.68	.68	.65	.71	.67	.77	.67	.78
Al ₂ O ₃	16.66	16.93	16.83	16.78	16.65	16.79	16.91	18.93	16.86	18.10
Fe ₂ O ₃	1.71	1.69	2.04	2.12	1.66	1.76	1.77	1.62	1.70	1.51
FeO	5.82	5.55	5.24	5.06	5.04	5.40	4.96	4.56	4.97	4.98
MnO	.15	.12	.12	.11	.08	.10	.11	.08	.10	.09
MgO	4.98	4.99	4.96	4.90	4.91	4.51	4.39	2.37	4.43	2.63
CaO	7.71	7.75	7.59	7.68	7.62	7.24	6.95	7.15	6.95	6.62
Na ₂ O	3.35	3.33	3.12	3.15	3.15	3.18	3.55	3.62	3.41	3.61
K ₂ O	1.33	1.38	1.36	1.35	1.32	1.52	1.60	1.58	1.57	1.62
P ₂ O ₅	.12	.12	.14	.13	.12	.13	.13	.13	.14	.14
LOI	.96	.77	.64	.62	.65	.61	.58	1.28	.55	1.00
TOTAL	100.11	100.48	100.03	99.82	99.30	100.14	100.04	100.98	100.26	100.36
FeO(t)	7.36	7.07	7.07	6.96	6.53	6.98	6.55	6.02	6.50	6.34
Mg No.*	60.39	61.57	62.78	63.31	63.45	59.81	61.20	48.08	61.37	48.48
TRACE ELEMENTS (ppm)										
Ba	303	344	344	345	307	325	365	263	379	364
Rb	52	53	51	52	50	63	62	53	62	56
Sr	258	299	290	293	306	241	280	328	283	304
Pb	9	10	12	12	9	13	13	16	17	17
Zr	94	111	108	100	102	115	123	113	130	114
Nb	-	-	-	3	4	-	-	-	-	4
Y	21	21	20	21	20	24	21	21	22	25
V	197	201	204	198	190	177	164	184	171	236
Cr	95	76	75	78	99	76	73	18	74	20
Ni	37	38	40	42	46	28	35	16	34	29
Cu	58	59	44	63	55	44	57	55	67	51
Zn	76	70	73	71	70	69	72	71	66	76
Ga	18	-	-	-	16	-	-	-	-	-
K/Rb	212	222	221	227	219	232	224	247	222	240
Rb/Sr	0.20	0.17	0.18	0.18	0.16	0.26	0.22	0.16	0.22	0.18
Sr87/86	-	-	-	-	-	-	.70537	-	-	-

* 100Mg/Mg+Fe₂ (mol)

BULK ROCK CHEMICAL DATA FROM WHAKAPAPA FORMATION

ANALYSIS #	121	122	123	124	125	126	127	128	129	130
SAMPLE	B10P	H8	G1	<u>E6</u>	G4	G3	G5	H8A	K1G	N112A
OXIDE WT%										
SiO ₂	59.45	59.67	59.73	59.92	59.99	60.00	60.01	60.19	63.39	65.42
TiO ₂	.70	.87	.73	.70	.73	.74	.73	.84	.78	.62
Al ₂ O ₃	16.61	17.20	17.15	17.55	16.67	15.94	16.49	16.98	15.13	15.34
Fe ₂ O ₃	2.02	2.24	2.05	1.94	1.38	1.40	1.16	2.41	1.41	.21
FeO	3.99	4.42	7.79	4.79	4.95	5.19	5.00	4.12	3.62	3.62
MnO	.12	.13	.16	.09	.09	.16	.10	.07	.06	.06
MgO	3.29	3.07	3.31	3.21	3.80	4.12	3.84	2.89	2.91	2.19
CaO	5.68	6.19	6.59	6.40	6.49	6.71	6.54	6.17	4.90	4.05
Na ₂ O	3.40	3.44	3.25	3.39	3.27	3.04	3.13	3.79	3.23	3.25
K ₂ O	2.05	1.85	1.74	1.78	1.82	1.86	1.80	1.89	2.99	2.90
P ₂ O ₅	.14	.13	.11	.14	.17	.12	.13	.16	.16	.12
LOI	3.11	1.32	.89	.70	.83	1.01	.92	.40	.99	1.23
TOTAL	100.56	100.53	100.50	100.38	100.19	100.29	99.85	99.91	99.57	99.01
FeO(t)	5.81	6.43	6.63	6.31	6.19	6.45	6.16	6.29	4.89	3.81
Mg No.*	59.50	55.31	55.19	55.64	57.77	58.59	57.78	55.56	58.89	51.88
TRACE ELEMENTS (ppm)										
Ba	429	439	372	375	424	416	406	386	551	508
Rb	88	70	74	72	79	78	76	78	137	124
Sr	221	262	244	250	290	288	287	257	221	211
Pb	13	16	13	19	16	15	11	13	17	27
Zr	155	151	127	127	141	135	140	148	218	180
Nb	5	-	-	-	-	-	7	6	7	5
Y	23	25	25	24	24	24	24	25	26	28
V	144	198	168	151	158	167	154	191	134	93
Cr	65	21	32	47	63	60	49	19	109	57
Ni	22	13	12	21	20	17	17	17	35	22
Cu	39	58	28	30	33	33	30	42	34	49
Zn	60	76	73	68	67	69	67	74	54	51
Ga	17	-	-	-	-	-	18	-	17	-
K/Rb	193	219	195	205	203	198	197	201	181	194
Rb/Sr	0.40	0.27	0.30	0.29	0.27	0.27	0.26	0.30	0.62	0.59
Sr87/86	-	-	-	-	.70589	-	-	-	.70540	.70617

* 100Mg/Mg+Fe₂ (mol)

BULK ROCK CHEMICAL DATA FROM WHAKAPAPA FORMATION

ANALYSIS # 131

SAMPLE N112B

OXIDE WT%

SiO ₂	65.64
TiO ₂	.62
Al ₂ O ₃	15.54
Fe ₂ O ₃	.86
FeO	3.70
MnO	.06
MgO	2.33
CaO	4.16
Na ₂ O	3.59
K ₂ O	2.92
P ₂ O ₅	.13
LOI	.92

TOTAL 100.47

FeO(t) 4.47

Mg No.* 52.88

TRACE
ELEMENTS
(ppm)

Ba	527
Rb	120
Sr	212
Pb	25
Zr	184
Nb	-
Y	26
V	101
Cr	63
Ni	22
Cu	32
Zn	55
Ga	-
K/Rb	202
Rb/Sr	0.57
Sr ^{87/86}	-

* 100Mg/Mg+Fe₂ (mol)

BULK ROCK CHEMICAL DATA FROM RELATED VENTS

ANALYSIS #	132	133	134	135	136	137	138	139	140	141
SAMPLE	WB	H5	H7-1	H6	H7A	F4	H7-2	H7	F2	F1
OXIDE WT%										
SiO ₂	52.18	55.34	56.31	56.45	56.53	56.79	56.82	57.01	57.05	57.07
TiO ₂	.47	.56	.71	.60	.72	.53	.68	.69	.55	.54
Al ₂ O ₃	12.68	15.00	14.71	15.42	14.52	14.50	14.36	14.29	15.09	14.94
Fe ₂ O ₃	1.96	2.77	1.21	3.02	1.12	2.11	1.23	1.68	5.69	2.76
FeO	6.58	5.06	5.70	4.95	5.88	6.07	5.71	5.54	2.80	5.24
MnO	.16	.11	.09	.19	.11	.19	.12	.15	.18	.19
MgO	13.15	7.13	8.01	6.24	8.97	7.07	8.77	8.64	6.77	6.53
CaO	9.60	9.45	7.23	8.65	7.38	9.05	7.19	7.26	8.85	9.04
Na ₂ O	1.64	2.21	2.92	2.25	2.88	2.32	2.63	2.75	2.52	2.49
K ₂ O	.43	.61	1.36	.69	1.49	.66	1.38	1.45	.62	.69
P ₂ O ₅	.05	.08	.13	.07	.13	.07	.12	.11	.08	.06
LOI	.70	1.14	1.32	2.12	.66	.73	.45	.83	.85	.81
TOTAL	99.60	99.46	99.70	100.65	100.39	100.09	99.46	100.40	101.05	100.36
FeO(t)	8.34	7.55	6.79	7.67	6.89	7.97	6.82	7.05	7.92	7.72
Mg No.*	78.08	71.52	71.46	69.20	73.11	67.49	73.24	73.54	81.16	68.95
TRACE ELEMENTS (ppm)										
Ba	123	180	350	193	332	141	324	361	148	147
Rb	15	17	58	19	54	15	57	53	15	17
Sr	348	450	276	454	302	342	275	274	391	389
Pb	2	6	9	6	8	6	10	10	2	6
Zr	47	53	123	58	114	57	114	116	56	57
Nb	1.5 ± 1	-	5	-	3	n.d.	4	3	-	-
Y	13	18	20	22	21	17	21	2	17	18
V	217	220	186	211	184	214	182	182	138	222
Cr	1070	234	415	200	591	271	510	529	228	200
Ni	310	35	158	35	213	50	185	208	46	36
Cu	83	73	78	70	95	104	70	92	82	96
Zn	77	71	69	70	67	74	67	68	67	74
Ga	12	-	15	-	16	17	16	-	15	-
K/Rb	254	317	195	301	229	288	201	223	343	301
Rb/Sr	0.05	0.04	0.21	0.04	0.18	0.06	0.21	0.20	0.04	0.05
Sr87/86	.70448	.70423	-	-	-	.70456	-	.70476	-	-

* 100Mg/Mg+Fe₂ (mol)

BULK ROCK CHEMICAL DATA FROM RELATED VENTS

ANALYSIS #	142	143	144
SAMPLE	F3	H4	LM-1
OXIDE WT%			
SiO ₂	57.16	57.52	64.61
TiO ₂	.55	.61	.51
Al ₂ O ₃	15.05	15.90	15.49
Fe ₂ O ₃	6.35	1.42	-
FeO	2.14	5.80	-
MnO	.17	.16	.07
MgO	6.69	5.78	2.50
CaO	9.00	9.16	4.09
Na ₂ O	2.54	2.74	3.15
K ₂ O	.67	.79	2.95
P ₂ O ₅	.07	.12	.13
LOI	.60	.70	2.07
TOTAL	100.99	100.70	100.04
FeO(t)	7.86	7.08	4.06
Mg No.*	84.78	63.97	56.43
TRACE ELEMENTS (ppm)			
Ba	148	232	463
Rb	17	24	123
Sr	376	482	218
Pb	3	6	16
Zr	60	61	174
Nb	3	-	6
Y	17	19	26
V	175	178	68
Cr	210	152	82
Ni	41	26	29
Cu	105	75	25
Zn	73	60	52
Ga	13	-	18
K/Rb	309	273	199
Rb/Sr	0.05	0.05	0.56
Sr ⁸⁷ / ⁸⁶	-	-	-

* 100Mg/Mg+Fe₂ (mol)

BULK ROCK CHEMICAL DATA FOR ALTERED ROCKS

ANALYSIS #	145	146	147	148	149	150	151	152	153	154
SAMPLE	OP-1	OP-2	H10	A35	A26	H4A	A70	A45	A38	A32
OXIDE WT%										
SiO ₂	39.83	40.46	44.64	52.45	52.82	54.14	54.16	55.50	55.68	57.42
TiO ₂	.76	.69	.67	.60	.72	.54	.52	.65	.65	.58
Al ₂ O ₃	21.54	18.87	18.88	16.33	18.31	14.69	16.58	17.57	17.10	18.70
Fe ₂ O ₃	-	-	6.65	5.60	3.67	1.98	4.24	3.44	4.59	2.71
FeO	-	-	2.74	1.74	5.04	5.56	3.16	4.14	3.72	1.98
MnO	.14	.16	.17	.06	.12	.11	.22	.07	.09	.04
MgO	4.19	6.23	5.38	5.36	4.79	8.78	4.35	4.33	4.37	2.35
CaO	2.31	3.34	4.23	5.94	6.76	8.70	7.07	7.19	7.52	5.25
Na ₂ O	.70	.79	.59	2.00	2.64	1.99	2.76	2.95	2.77	3.04
K ₂ O	.12	.12	.25	.73	.60	.38	.74	.76	.90	1.02
P ₂ O ₅	.08	.08	.02	.09	.07	.07	.08	.09	.10	.05
LOI	20.65	19.68	15.36	8.79	4.94	2.42	5.60	2.26	2.67	6.03
TOTAL	100.75	100.63	99.58	99.69	100.48	99.36	99.48	98.95	100.16	99.17
FeO(t)	9.38	9.19	8.73	6.78	8.34	7.34	6.97	7.23	7.85	4.42
Mg No.*	-	58.75	77.77	-	-	73.78	-	65.08	-	-
TRACE ELEMENTS (ppm)										
Ba	-	190	-	209	203	129	209	251	255	247
Rb	-	10	-	23	20	7	26	22	27	35
Sr	-	198	-	210	255	557	194	213	213	190
Pb	-	0	-	13	14	2	4	4	14	11
Zr	-	87	-	60	61	50	62	62	62	67
Nb	-	4	-	-	-	2	2	3	-	-
Y	-	0	-	25	27	14	17	22	22	26
V	-	154	-	255	225	185	168	247	206	272
Cr	-	153	-	89	54	353	58	63	68	79
Ni	-	51	-	76	29	79	35	26	32	24
Cu	-	135	-	63	56	71	29	60	69	73
Zn	-	74	-	88	81	59	80	60	79	68
Ga	-	-	-	-	-	16	16	18	-	-
K/Rb	-	100	-	263	249	451	236	287	277	242
Rb/Sr	-	0.05	-	0.11	0.08	0.01	0.13	0.10	0.13	0.18
Sr ⁸⁷ / ₈₆	-	-	-	-	-	-	-	-	-	-

* 100Mg/Mg+Fe₂ (mol)

BULK ROCK CHEMICAL DATA FOR ALTERED ROCKS

ANALYSIS #	155	156	157
SAMPLE	A33	A34	A31
OXIDE WT%			
SiO ₂	57.54	58.48	58.96
TiO ₂	.59	.59	.52
Al ₂ O ₃	17.87	18.76	18.55
Fe ₂ O ₃	3.81	4.30	2.76
FeO	2.38	1.30	3.64
MnO	.05	.01	.10
MgO	2.54	1.37	3.07
CaO	2.93	4.55	7.28
Na ₂ O	1.47	2.66	3.51
K ₂ O	.73	.78	.99
P ₂ O ₅	.05	.04	.09
LOI	10.80	7.82	1.11
TOTAL	100.76	100.66	100.58
FeO(t)	5.81	5.16	6.13
Mg No.*	-	-	-
TRACE ELEMENTS (ppm)			
Ba	265	227	250
Rb	34	22	33
Sr	136	192	236
Pb	11	13	16
Zr	71	66	63
Nb	-	-	-
Y	17	15	19
V	217	221	158
Cr	68	76	31
Ni	33	35	18
Cu	106	50	23
Zn	88	32	73
Ga	-	-	-
K/Rb	178	294	249
Rb/Sr	0.25	0.11	0.14
Sr ⁸⁷ / ⁸⁶	-	-	-

* 100Mg/Mg+Fe₂ (mol)

BULK ROCK CHEMICAL DATA FOR XENOLITHS

ANALYSIS #	158	159	160	161	162	163	164	165	166	167
SAMPLE	WX-4	B10XB	BXA	BX10	B10XE	B6XA	B3XA	XX	B10XH	GLX
OXIDE WT%										
SiO ₂	36.30	42.23	44.28	47.95	48.17	48.88	49.11	49.20	49.23	49.38
TiO ₂	4.34	1.40	.45	1.37	1.50	1.45	1.19	.34	1.06	.20
Al ₂ O ₃	20.28	26.11	21.09	18.03	16.66	25.42	24.66	19.19	25.18	20.01
Fe ₂ O ₃	6.42	8.17	0.00	3.15	1.74	4.97	4.72	1.04	2.95	1.43
FeO	13.78	3.55	0.00	6.12	10.96	2.91	2.91	6.54	4.26	5.74
MnO	.54	.26	0.00	.13	.29	.07	.06	.11	.12	.14
MgO	8.98	3.91	.09	6.64	8.55	2.50	2.56	7.32	2.96	8.10
CaO	5.71	5.54	.12	13.24	9.17	8.77	9.74	8.64	4.19	11.69
Na ₂ O	1.30	2.67	4.57	2.01	1.46	3.58	2.88	2.29	4.50	1.49
K ₂ O	.62	4.10	1.67	.23	.10	.57	.51	.15	3.72	.29
P ₂ O ₅	.30	.09	.09	.18	.05	.20	.21	.01	.26	.03
LOI	1.43	1.97	26.19	1.40	1.41	.81	1.44	4.99	.68	0.00
TOTAL	100.00	100.00	100.24 ^a	100.45	100.06	100.12	99.99	99.82	99.11	98.50
FeO(t)	19.56	10.91	.20	8.95	12.52	7.38	7.16	7.48	6.92	7.03
Mg No.*	53.73	66.25	100.00	65.91	58.16	60.49	61.05	66.61	55.32	71.55
TRACE ELEMENTS (ppm)										
Ba	340	924	135	127	92	766	241	83	1650	80
Rb	45	171	9	9	2	18	19	5	144	10
Sr	356	272	146	374	207	899	552	236	713	287
Pb	29	31	4	3	5	18	11	3	22	6
Zr	259	71	46	69	19	463	187	17	285	16
Nb	23	n.d.	-	6	n.d.	11	6	1	13	-
Y	66	20	1	23	11	29	18	10	31	9
V	517	397	107	264	363	220	227	220	164	119
Cr	154	523	162	266	234	76	109	133	66	214
Ni	76	102	3	72	101	24	37	47	25	58
Cu	217	140	13	66	10	49	37	37	36	95
Zn	287	192	4	71	96	90	118	65	114	80
Ga	30	27	4	22	19	-	-	19	38	15
K/Rb	114	199	1374	212	415	263	223	249	215	241
Rb/Sr	0.13	0.63	0.06	0.02	0.01	0.02	0.03	0.02	0.20	0.03
Sr87/86	-	.71004	-	-	-	-	-	-	-	.70593

* 100Mg/Mg+Fe₂ (mol)

a S=2.93 O=S=1.47 original total=101.71

BULK ROCK CHEMICAL DATA FOR XENOLITHS

ANALYSIS #	168	169	170	171	172	173	174	175	176	177
SAMPLE	Al1X	WX5	B6XD	BX22	AXA	B5XA	B6XC	BXWS	W4X	M7X-1
OXIDE WT%										
SiO ₂	50.07	51.62	53.63	53.84	54.03	54.03	54.25	54.62	56.47	56.98
TiO ₂	1.09	.57	.53	.59	.50	.54	.43	.69	.42	.55
Al ₂ O ₃	24.88	12.92	15.15	19.03	13.48	13.07	10.66	17.05	15.67	16.86
Fe ₂ O ₃	-	1.41	.94	1.73	.89	2.17	1.28	2.06	1.43	.57
FeO	-	7.70	7.34	6.86	6.99	7.78	6.80	6.02	6.56	7.04
MnO	.07	.15	.19	.12	.12	.21	.18	.17	.13	.15
MgO	2.41	13.90	10.32	5.48	12.88	10.01	12.77	5.04	8.93	5.33
CaO	8.46	7.93	8.85	7.20	6.69	7.79	10.15	9.16	5.82	9.94
Na ₂ O	4.21	1.64	2.56	3.32	1.80	2.09	2.10	3.58	2.55	1.21
K ₂ O	.23	.13	.26	.54	.76	.72	.33	.66	.94	.09
P ₂ O ₅	.12	.08	.08	.13	.04	.05	.07	.11	.08	.09
LOI	1.03	1.78	.92	.73	1.94	1.25	.77	.98	.90	1.21
TOTAL	100.16	99.83	100.77	99.57	100.12	99.71	99.79	100.14	99.90	100.02
FeO(t)	6.87	8.97	8.19	8.41	7.79	9.73	7.95	7.87	7.85	7.55
Mg No.*	-	76.29	71.47	58.74	76.65	69.63	76.99	59.87	70.81	57.43
TRACE ELEMENTS (ppm)										
Ba	326	141	134	168	373	179	125	103	237	53
Rb	0	3	4	15	47	26	8	18	34	2
Sr	481	184	234	366	335	231	179	411	281	191
Pb	2	5	6	4	17	10	6	10	9	7
Zr	151	58	35	40	37	46	39	49	67	52
Nb	8	3	n.d.	2	n.d.	n.d.	n.d.	n.d.	2	1
Y	17	17	15	12	17	15	14	19	10	17
V	197	199	199	177	190	216	189	238	137	191
Cr	80	1024	652	36	671	482	823	96	319	96
Ni	22	342	182	14	339	117	268	18	88	33
Cu	102	35	27	70	48	80	38	60	54	41
Zn	119	88	74	79	73	97	79	79	72	70
Ga	34	11	17	18	-	-	11	18	17	19
K/Rb	-	360	540	299	134	230	343	304	230	374
Rb/Sr	-	0.02	0.02	0.04	0.14	0.11	0.04	0.04	0.12	0.01
Sr87/86	-	-	.70630	-	-	-	.70540	.70652	-	-

* 100Mg/Mg+Fe₂ (mol)

BULK ROCK CHEMICAL DATA FOR XENOLITHS

ANALYSIS #	178	179	180	181	182	183	184
SAMPLE	BX24	A14X	T5X	N112C	ARGX	H7X-21	FX-Q
OXIDE WT%							
SiO ₂	57.95	59.34	62.19	64.58	67.22	72.09	96.68
TiO ₂	.61	1.09	.45	.78	.59	.41	0.00
Al ₂ O ₃	18.74	18.36	18.64	16.91	16.82	12.81	.77
Fe ₂ O ₃	1.32	2.56	.94	1.02	.79	.47	—
FeO	5.70	3.76	4.40	4.46	3.26	2.45	—
MnO	.10	.14	.08	.07	.06	.02	.02
MgO	3.88	2.10	2.06	1.71	1.29	.95	.16
CaO	7.33	8.19	6.15	2.18	.95	1.07	.31
Na ₂ O	2.21	.47	3.73	3.11	4.35	3.09	.19
K ₂ O	.50	.09	.50	2.69	3.02	2.12	.07
P ₂ O ₅	.10	.26	.10	.16	.13	.08	.03
LOI	1.83	4.36	.65	3.14	.44	3.25	0.00
TOTAL	100.27	100.72	99.89	100.81	98.92	98.81	98.63
FeO(t)	6.89	6.05	5.24	5.38	3.97	2.87	.40
Mg No.*	54.81	49.88	45.48	40.59	41.35	40.86	—
TRACE ELEMENTS (ppm)							
Ba	328	334	240	651	567	356	-
Rb	54	4	3	109	133	84	-
Sr	782	350	346	215	182	191	-
Pb	10	18	11	23	23	16	-
Zr	69	302	84	191	260	198	-
Nb	3	8	3	10	10	7	-
Y	16	36	15	28	27	20	-
V	196	177	101	130	81	50	-
Cr	29	34	1	67	52	27	-
Ni	8	18	8	19	20	10	-
Cu	35	254	30	26	20	15	-
Zn	72	86	60	75	59	49	-
Ga	21	-	18	-	21	12	-
K/Rb	77	187	1384	205	189	210	-
Rb/Sr	0.07	0.01	0.01	0.51	0.73	0.44	-
Sr ⁸⁷ / ⁸⁶	-	-	-	-	.71255	.70975	-

* 100Mg/Mg+Fe₂ (mol)

**APPENDIX III: MINERAL ANALYSES FROM LAVAS AND
PYROCLASTICS OF RUAPEHU VOLCANO AND RELATED VENTS.**

1. INTRODUCTION.

Electron microprobe analyses of phenocryst and groundmass minerals are given. Analyses of mineral groups (olivine, clinopyroxene, etc.) are tabulated in the same order as bulk rock analyses of Appendix II, to allow easy retrieval of mineral data. Thus, "bulk rock 2701" refers to analysis 27 of Appendix II, and the "01" is for computer tabulation purposes only. Locations and petrographic descriptions of bulk rocks are also found in Appendix II.

Mineral analyses are designated under 'SPEC' as follows:

- CORE phenocryst core
- RIM phenocryst rim
- RR reaction rim on phenocryst
- I intermediate between core and rim of phenocryst
- M microphenocryst; grains generally between 300 and 100 microns
- X xenocryst; embayed grain or grain in aggregate
- G;GMS groundmass; grains generally 70 to 20 microns
- a line connecting analyses indicates analyses on the same grain
- OL if a mineral name is given under SPEC, the analyzed grain was an inclusion in this mineral.

2. ANALYTICAL METHODS.

All analyses were made by the author during 1979-1982, using a JEOL 733 Superprobe housed in the Analytical Facility, Victoria University of Wellington.

Instrumental settings were:

Accelerating potential: 15 kilovolts

Specimen current : 1.2×10^{-08} amp, for minerals

: 1.5×10^{-09} amp, for glass analyses

Beam diameter : 3 and 10 microns for minerals

: 10 to 50 microns for glass.

Analyses were corrected for absorption, fluorescence, and atomic number using the method of Bence and Albee (1968), with alpha correction factors after Kushiro and Nakamura (1970), and with additional corrections for dead time, background and probe current drift. Data were reduced using a computer program supplied with the JEOL 733, and modified by Teruo Watanabe and Matsayuki Otsuki.

Natural and synthetic minerals and alloys were used as standards. Kakanui Augite was the internal standard most often used by the author to check analysis quality. Paul Morris compiled the following list of Kakanui Augite analyses made by JEOL 733 users between 1979 and 1981; the author contributed 16 % of these analyses.

III-1b

Kakanui Augite analyses (compiled by P. Morris, Victoria University):

	n	$\bar{x}$	s.d.	max.	min.	range	tabular
SiO ₂	87	50.56	0.441	51.91	49.85	2.06	50.73
TiO ₂	87	0.81	0.064	0.99	0.55	0.44	0.74
Al ₂ O ₃	87	8.29	0.203	8.83	7.69	1.14	7.86
FeO	87	6.26	0.180	6.61	5.64	0.97	6.77
MnO	87	0.13	0.038	0.25	0.02	0.23	0.13
MgO	87	16.08	0.257	16.74	15.30	1.44	16.65
CaO	87	16.04	0.256	16.49	15.29	1.20	15.82
Na ₂ O	87	1.31	0.082	1.52	1.04	0.47	1.27
K ₂ O	87	0.01	0.010	0.05	0.00	0.05	-
Cr ₂ O ₃	80	0.15	0.031	0.22	0.08	0.14	-
NiO	80	0.04	0.034	0.13	0.00	0.13	-
TOTAL		99.68					99.97

Theoretical detection limits are given for oxides of interest. These are generalized values since detection limits are calculated on the basis of peak/background ratios and peak intensity differences between unknowns and standards. Hence, detection limits will vary slightly from one analysis to another.

Theoretical detection limits (weight percent):

SiO ₂	0.10	MnO	0.12	K ₂ O	0.05
TiO ₂	0.09	MgO	0.10	NiO	0.12
Al ₂ O ₃	0.10	CaO	0.06	Cr ₂ O ₃	0.14
FeO(t)	0.12	Na ₂ O	0.09		

Analyses have been reported to 2 decimal places, but are significant only in the first decimal place.

3. REFERENCES.

Bence, A.E., and Albee, A.L., 1968. Empirical correction factors for the electron microanalysis of silicates and oxides. *Journal of Geology*, 76, 382-403.

Kushiro, I., and Nakamura, Y., 1970. Petrology of some lunar crystalline rocks. Proceedings Apollo 11 Lunar Science Conference, 1, 607-626.

MINERAL ANALYSES FROM LAVAS AND PYROCLASTICS
OF RUAPEHU AND RELATED VENTS

APPENDIX III
OLIVINE ANALYSES

BULK ROCK ANAL NO.	2701	2702	6301	6302	6303	6401	6402	6403	6404	6405	6406	6901	7101	7102	8101	8102	8701
SPEC	2.00	3.00	5.00	7.00	10.00	17.00	18.00	2.00	20.00	13.00	14.00	17.00	1.00	2.00	3.00	5.00	2.00
SiO ₂	40.36	39.91	40.57	39.53	41.23	39.34	39.08	38.15	38.07	38.09	36.36	39.72	40.78	40.63	41.56	40.80	39.11
TiO ₂	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
Al ₂ O ₃	.00	.00	.11	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
FeO	9.77	12.46	12.54	19.33	9.27	20.19	20.70	21.72	25.51	27.38	28.05	14.58	12.47	12.97	7.67	9.23	19.59
MnO	.14	.15	.12	.28	.14	41.45	40.82	39.72	38.77	35.74	33.04	45.81	46.67	45.52	50.40	49.97	40.86
MgO	48.94	47.17	46.00	40.84	47.93	.00	.00	.00	.00	.00	.00	.00	.00	.00	.07	.13	.09
CaO	.10	.15	.15	.17	.14	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
Na ₂ O	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
K ₂ O	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
Cr ₂ O ₃	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
NiO	.42	.34	.32	.00	.36	.00	.00	.00	.00	.00	.00	.22	.35	.25	.24	.19	.28
TOTAL	99.73	100.18	99.81	100.15	99.07	100.98	100.60	100.10	100.35	101.21	97.45	100.70	100.53	99.67	99.94	100.52	100.14
NUMBER OF CATIONS ON BASIS OF 4(O)																	
Si	.993	.990	1.008	1.009	1.015	1.000	1.000	.989	1.000	1.000	1.000	.989	1.005	1.012	1.007	.992	1.002
Ti	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
Al	.000	.000	.003	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
Fe	.201	.259	.261	.413	.191	.429	.443	.471	.560	.601	.645	.304	.257	.270	.155	.187	.420
Mn	.003	.003	.003	.006	.003	.000	.000	.008	.000	.000	.000	.005	.003	.003	.000	.004	.005
Mg	1.796	1.745	1.703	1.554	1.759	1.571	1.557	1.535	1.440	1.399	1.355	1.701	1.715	1.690	1.819	1.811	1.561
Ca	.003	.004	.004	.005	.004	.000	.000	.000	.000	.000	.000	.004	.003	.005	.002	.003	.002
Na	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
K	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
Cr	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
Ni	.008	.007	.006	.000	.007	.000	.000	.000	.000	.000	.000	.004	.007	.005	.005	.004	.006
TOTAL	3.004	3.008	2.988	2.987	2.979	3.000	3.000	3.007	3.000	3.000	3.000	3.007	2.990	2.985	2.988	3.001	2.996
Fe	89.90	87.10	86.70	79.00	90.20	78.50	77.80	76.50	72.00	70.00	67.70	84.80	87.00	86.20	92.10	90.60	78.80

BLANK SPACE REPRESENTS 'NOT ANALYZED'

0.00 REPRESENTS ANALYZED
BUT BELOW THEORETICAL LIMIT OF DETECTION.

APPENDIX III

OLIVINE ANALYSES

BULK ROCK ANAL NO.	8801	11001	11002	13201	13202	13203	13204	13205	13301	13302	13303	13701	13702	13703	13704	13901	13902
SPEC	16.00	11.00	12.00	51.00	4.00	5.00	15.00	57.00	1.00	5.00	6.00	5.00	30.00	32.00	25.00	7.00	44.00
SiO ₂	36.91	39.92	39.62	41.47	41.74	39.04	39.76	39.70	40.17	40.85	40.47	40.76	40.75	40.63	39.05	41.22	42.03
TiO ₂	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
Al ₂ O ₃	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
FeO	29.39	13.96	19.23	7.31	8.82	23.81	19.01	16.00	16.58	12.62	18.15	11.88	12.48	13.85	20.76	6.05	7.74
MnO	33.84	45.83	41.39	50.53	49.05	37.84	41.67	43.31	43.10	46.86	42.62	47.38	47.29	45.58	40.94	51.38	50.45
CaO	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
MgO	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
NiO	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
K ₂ O	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
Cr ₂ O ₃	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
TOTAL	100.74	100.40	100.80	99.85	100.15	101.35	101.24	99.64	100.21	100.74	101.65	100.48	100.80	100.47	101.29	99.35	100.85
NUMBER OF CATIONS ON BASIS OF 4(O)																	
Si	.987	.995	1.005	1.005	1.014	1.006	1.005	1.005	1.009	1.005	1.010	1.003	1.001	1.007	.995	1.000	1.009
Ti	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
Al	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
Fe	.857	.291	.408	.148	.179	.513	.402	.339	.348	.260	.379	.245	.256	.287	.442	.123	.156
Mn	.009	.003	.005	.000	.002	.008	.006	.006	.005	.004	.006	.004	.004	.004	.006	.000	.003
Mg	1.349	1.702	1.566	1.825	1.777	1.453	1.569	1.635	1.613	1.718	1.585	1.738	1.732	1.684	1.554	1.858	1.806
Ca	.002	.000	.000	.003	.004	.005	.005	.005	.004	.003	.004	.003	.003	.004	.004	.002	.000
Na	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
K	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
Cr	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
Ni	.003	.011	.007	.008	.006	.002	.005	.003	.000	.002	.000	.004	.000	.000	.002	.012	.010
TOTAL	3.007	3.002	2.991	2.989	2.982	2.987	2.994	2.993	2.979	2.992	2.984	2.997	2.996	2.988	3.004	2.995	2.984
Fe	67.20	85.40	79.30	92.50	90.80	73.90	79.60	82.80	82.30	86.90	80.70	87.60	86.90	85.40	77.60	93.80	92.00

BLANK SPACE REPRESENTS 'NOT ANALYZED'

0.00 REPRESENTS ANALYZED, BUT BELOW THEORETICAL LIMIT OF DETECTION.

APPENDIX III

OLIVINE ANALYSES

BULK ROCK	13903
ANAL NO.	8.00
SPEC.	— RIM
SiO ₂	40.40
TiO ₂	.00
Al ₂ O ₃	.00
FeO	12.32
MnO	1.14
MgO	46.71
CaO	.14
Na ₂ O	.00
K ₂ O	.00
Cr ₂ O ₃	.00
NiO	.43
TOTAL	100.14

NUMBER OF CATIONS ON BASIS OF 4(O)	
Si	1.001
Ti	.000
Al	.000
Fe	.255
Mn	.003
Mg	1.725
Ca	.004
Na	.000
K	.000
Cr	.000
Ni	.009
TOTAL	2.997

Fe	87.10
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BLANK SPACE REPRESENTS 'NOT ANALYZED'

0.00 REPRESENTS ANALYZED
BUT BELOW THEORETICAL LIMIT OF DETECTION.

APPENDIX III
CLINOPYROXENE ANALYSES

BULK ROCK ANAL. NO.	201	202	203	1001	1201	2701	2702	2703	2704	3101	3102	3103	3104	5901	5902	6301	6302
SPEC.	2.00	3.00	23.00	7.00	2.00	12.00	11.00	9.00	8.00	13.00	14.00	15.00	18.00	11.00	5.00	12.00	19.00
SiO ₂	51.56	50.70	51.12	51.58	51.36	49.87	51.41	51.10	51.74	51.31	50.75	52.43	50.95	51.67	51.25	50.96	51.55
TiO ₂	3.37	3.70	1.45	1.28	2.12	2.98	2.49	2.48	1.99	2.15	3.24	2.41	3.11	1.05	55	4.20	3.22
Al ₂ O ₃	9.23	10.53	14.43	12.97	10.68	11.28	8.03	10.95	8.86	11.89	10.79	4.79	9.03	14.80	25.48	7.16	8.10
FeO	2.33	2.27	14.41	15.15	14.83	13.63	15.91	14.41	15.92	14.87	15.66	18.54	16.31	14.22	17.40	15.64	14.98
MnO	19.95	20.19	18.90	17.47	20.54	18.39	19.37	18.51	19.24	18.03	17.22	19.86	18.69	17.00	4.01	20.57	20.40
CaO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NiO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
K ₂ O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cr ₂ O ₃	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TOTAL	88.80	100.53	99.28	99.45	100.64	97.40	98.07	98.03	98.73	99.63	98.95	99.77	99.19	99.92	99.75	99.59	99.75
NUMBER OF CATIONS ON BASIS OF 8(O)																	
Si	1.943	1.889	1.948	1.950	1.915	1.913	1.934	1.946	1.940	1.931	1.906	1.917	1.901	1.958	1.989	1.887	1.916
Ti	0.10	0.12	0.065	0.057	0.093	0.17	0.10	0.14	0.13	0.21	0.18	0.06	0.17	0.12	0.09	0.11	0.10
Al	1.05	1.63	0.85	0.87	0.93	1.35	1.10	0.94	0.88	0.95	1.43	1.04	1.37	0.47	0.25	0.183	0.11
Fe	3.03	3.28	4.60	4.10	3.33	3.63	2.53	3.39	2.78	3.74	3.39	1.47	2.82	4.69	8.19	1.222	2.88
Mn	0.07	0.09	0.13	0.13	0.07	0.10	0.06	0.12	0.07	0.08	0.00	0.06	0.09	0.16	0.25	0.005	0.03
Mg	0.07	0.09	0.13	0.13	0.07	0.10	0.06	0.12	0.07	0.08	0.00	0.06	0.09	0.16	0.25	0.005	0.03
Ca	0.06	0.06	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Na	0.06	0.06	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
K	0.028	0.029	0.023	0.014	0.021	0.040	0.022	0.030	0.022	0.034	0.039	0.024	0.16	0.19	0.00	0.021	0.025
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ni	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TOTAL	4.008	4.030	4.019	4.017	4.034	4.020	4.007	4.008	4.011	4.022	4.019	4.021	4.016	4.014	4.008	4.014	4.010
Mg*	72.20	70.20	63.60	67.60	71.20	68.30	77.90	70.70	76.20	69.00	72.10	87.30	76.30	63.10	54.90	79.60	75.60
Ca	41.90	41.60	35.10	35.70	41.30	39.60	40.40	39.30	39.70	37.40	36.20	40.10	38.40	34.90	8.20	42.80	42.50
Mg	41.90	41.00	40.90	43.00	41.50	40.90	46.20	42.50	45.70	42.90	45.90	52.00	46.60	40.60	48.70	45.30	43.40
Fe+Mn	16.10	17.40	24.00	21.30	17.20	19.50	13.40	18.20	14.60	19.70	17.90	7.90	15.00	.00	4.10	22.90	14.10

BLANK SPACES REPRESENT 'NOT ANALYZED'
0.00 REPRESENT ANALYZED
BUT BELOW THEORETICAL LIMIT OF DETECTION.

APPENDIX III
CLINOPYROXENE ANALYSES

BULK ROCK ANAL. NO.	6303	6304	6305	6401	6402	6403	6901	6902	6903	6904	6905	7101	7102	7103	7104	8101	8102
SPEC.	17.00	3.00	4.00	4.00	8.00	10.00	4.00	5.00	6.00	7.00	8.00	18.00	17.00	16.00	15.00	16.00	14.00
SiO ₂	51.50	50.91	53.59	51.82	53.57	50.44	49.88	51.73	49.81	51.38	51.50	52.10	51.33	51.63	51.41	51.00	52.91
TiO ₂	2.64	3.60	1.86	11.65	6.39	9.87	2.81	3.35	5.47	3.87	3.51	2.87	3.04	2.48	2.95	2.27	1.82
Al ₂ O ₃	9.70	10.91	7.32	14.37	18.37	15.36	13.90	6.68	6.40	5.38	5.10	9.04	9.40	9.94	10.06	10.54	5.72
FeO	14.93	13.70	16.70	19.28	19.46	18.16	12.26	17.04	15.75	17.16	16.96	14.58	14.30	14.38	14.04	14.88	18.06
MnO	19.89	18.83	19.76	19.28	19.46	18.16	18.63	20.33	20.31	20.39	20.31	20.24	19.99	19.20	19.72	18.52	19.79
CaO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MgO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
N ₂ O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
K ₂ O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cr ₂ O ₃	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TOTAL	99.63	99.46	100.35	97.12	97.79	93.63	98.90	100.44	98.79	99.46	98.60	99.94	99.18	98.72	99.28	98.85	99.20
NUMBER OF CATIONS ON BASIS OF 6(O)																	
Si	1.924	1.912	1.960	2.000	2.000	2.000	1.916	1.894	1.854	1.891	1.907	1.934	1.924	1.944	1.929	1.924	1.947
Ti	0.08	0.17	0.10	0.13	0.12	0.10	0.13	0.10	0.12	0.09	0.09	0.16	0.14	0.11	0.16	0.14	0.07
Al	1.16	1.59	0.80	1.27	1.58	1.40	1.27	1.18	1.40	1.68	1.53	1.26	1.34	1.10	1.31	1.01	0.79
Fe	3.03	3.43	2.24	4.46	2.04	3.20	4.46	2.04	1.99	1.66	1.58	2.81	2.95	3.13	3.16	3.33	1.78
Mn	0.06	0.08	0.05	0.11	0.05	0.03	0.11	0.05	0.03	0.05	0.04	0.05	0.07	0.09	0.08	0.08	0.05
Mg	0.82	0.767	0.910	0.702	0.797	0.908	0.702	0.930	0.874	0.941	0.936	0.807	0.799	0.807	0.785	0.837	0.991
Ca	0.02	0.02	0.013	0.048	0.021	0.022	0.048	0.021	0.022	0.021	0.018	0.027	0.028	0.021	0.020	0.031	0.13
Na	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
K	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ni	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TOTAL	4.013	3.997	3.989	4.029	4.025	3.999	4.029	4.025	4.019	4.020	4.006	4.001	4.004	3.993	3.998	4.011	4.007
Mg*	73.30	69.10	80.30	68.70	83.70	74.90	61.10	82.00	81.40	85.00	85.60	74.20	73.10	72.10	71.30	71.60	84.90
Ca*	41.00	40.40	40.40	39.80	38.90	38.60	39.80	41.20	42.90	42.00	42.30	42.40	42.10	40.70	41.70	38.90	40.00
Mg	43.00	40.90	47.60	41.30	51.10	45.40	36.50	48.00	46.30	49.10	49.20	42.50	42.00	42.40	41.30	43.40	50.80
Fe+Mn	16.00	18.70	12.00	39.90	10.00	16.00	23.70	10.80	10.70	8.90	8.50	15.10	15.90	16.90	17.00	17.70	9.20

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APPENDIX III
CLINOPYROXENE ANALYSES

BULK ROCK ANAL. NO.	13102	13103	13201	13202	13203	13204	13205	13206	13207	13208	13209	13210	13211	13212	13213	13301	13701
XC	14.00	18.00	28.00	6.00	7.00	12.00	13.00	18.00	79.00	84.00	86.00	88.00	89.00	82.00	83.00	8.00	20.00
SiO ₂	51.20	51.20	54.90	53.31	53.98	52.25	51.85	54.24	53.68	54.60	51.57	52.06	51.64	52.68	50.70	52.60	53.88
TiO ₂	1.98	1.26	5.40	2.39	1.69	3.72	4.46	1.43	1.69	1.9	2.18	3.15	3.35	1.85	1.95	2.15	1.51
FeO	13.46	13.98	13.07	4.79	5.83	6.33	5.00	5.38	6.30	5.07	11.33	7.87	8.96	11.45	12.19	6.21	6.43
MgO	14.31	11.38	22.09	16.31	17.44	15.96	16.42	17.56	18.84	16.07	15.83	16.80	17.74	18.48	16.25	19.97	17.13
MnO	17.13	19.91	8.25	21.47	20.50	21.22	21.28	20.43	18.45	24.01	17.19	18.88	16.73	13.49	16.01	19.53	20.11
N ₂ O	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
Cr ₂ O ₃	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
NiO	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
TOTAL	99.49	99.37	99.72	99.69	100.13	100.25	100.70	99.89	99.67	100.26	99.48	99.84	99.44	98.73	98.09	99.24	99.83

NUMBER OF CATIONS ON BASIS OF 6(O)																	
Si	1.937	1.960	1.998	1.952	1.967	1.913	1.886	1.978	1.962	1.999	1.933	1.918	1.907	1.960	1.929	1.938	1.974
Ti	.019	.012	.004	.004	.005	.008	.006	.003	.006	.000	.015	.010	.013	.008	.014	.005	.004
Al	.087	.057	.038	.103	.073	.161	.191	.062	.073	.008	.07	.07	.146	.081	.088	.093	.065
Fe	.426	.47	.39	.147	.178	.194	.177	.164	.193	.008	.035	.242	.277	.356	.388	.188	.067
Mn	.012	.010	.008	.004	.004	.004	.003	.006	.006	.006	.008	.004	.006	.010	.009	.007	.008
Mg	.807	.816	.833	.890	.847	.871	.891	.955	.738	.877	.715	.923	.977	1.025	.922	.987	.936
Ca	.030	.020	.015	.015	.010	.016	.014	.009	.007	.009	.014	.011	.007	.012	.018	.013	.014
Na	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
K	.000	.000	.000	.025	.007	.006	.012	.013	.006	.000	.000	.013	.008	.000	.000	.009	.005
Cr	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
Ni	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
TOTAL	4.012	4.005	3.999	3.982	3.991	4.004	4.009	3.988	3.996	3.996	4.010	4.003	4.003	3.990	4.021	4.011	3.993

Mg*	65.50	60.40	75.10	85.80	84.20	81.80	83.40	85.30	83.90	84.90	71.10	79.20	77.90	74.20	70.40	84.00	82.00
Ca	25.20	41.70	16.70	44.70	41.50	43.70	43.60	41.50	38.00	47.00	37.00	39.00	34.00	28.00	33.00	39.50	40.90
Mg	41.80	34.90	62.70	47.20	40.10	45.90	46.90	46.70	52.00	8.00	45.00	48.00	51.00	53.00	47.00	50.50	48.50
Fe+Mn	22.80	23.40	21.10	8.20	9.40	10.40	9.50	8.80	10.00	44.00	18.00	13.00	15.00	19.00	20.00	10.00	10.60

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APPENDIX III
CLINOPYROXENE ANALYSES

BULK ROCK	13702	13703	13901	13902	13903	13904	13905	13906	13907	13908	13909	14401
ANAL NO.	21.00	1.00	25.00	24.00	23.00	22.00	21.00	20.00	19.00	18.00	17.00	3.00
SPEC	-XR	G	CORE	CORE	CORE	CORE	CORE	CORE	CORE	CORE	CORE	CORE
SiO2	53.98	50.66	53.25	52.76	52.34	52.60	52.08	53.63	53.25	52.22	53.03	51.13
TiO2	1.12	3.16	2.14	2.34	2.16	2.45	2.06	2.15	1.55	1.76	2.43	2.63
Al2O3	6.03	11.19	8.59	9.13	11.22	6.62	7.56	6.04	7.70	9.34	6.66	2.13
FeO	17.87	15.73	16.33	15.75	15.03	16.48	16.11	17.50	17.08	15.95	17.15	9.91
MgO	20.28	16.38	18.98	18.34	17.64	20.23	20.88	18.96	18.74	19.09	19.98	14.81
CaO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	19.51
Na2O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.39
K2O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cr2O3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NiO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TOTAL	100.05	98.24	100.44	100.52	100.38	99.90	100.11	99.50	99.91	99.72	101.02	98.75

NUMBER OF CATIONS ON BASIS OF 6(O)												
Si	1.972	1.916	1.953	1.943	1.941	1.931	1.911	1.862	1.955	1.940	1.924	1.929
Ti	0.03	0.13	0.12	0.11	0.19	0.12	0.18	0.10	0.15	0.21	0.12	0.18
Al	0.48	1.41	0.93	1.02	0.94	1.15	1.43	0.93	0.80	0.82	1.06	0.95
Fe	1.84	1.54	2.64	2.78	3.60	2.03	2.32	1.85	2.37	2.90	2.02	3.13
Mn	0.05	0.08	0.06	0.04	0.07	0.00	0.07	0.06	0.06	0.07	0.04	0.08
Mg	0.973	0.87	0.893	0.865	0.831	0.902	0.829	0.954	0.935	0.883	0.952	0.833
Ca	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Na	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
K	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ni	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TOTAL	4.002	4.003	3.997	3.999	3.993	3.998	4.006	3.982	3.993	4.001	4.009	4.014

Mg*	83.70	71.50	77.20	75.70	69.80	81.60	79.20	83.80	79.80	75.30	82.50	72.70
Ca	40.60	43.70	39.10	38.90	38.90	42.30	41.30	39.40	38.50	39.20	40.10	40.60
Mg	49.70	46.40	46.80	45.30	43.80	47.00	46.20	50.50	48.80	45.50	49.20	42.90
Fe+Mn	8.70	18.90	14.10	14.80	18.30	10.70	12.50	10.10	12.70	15.30	10.70	16.50

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APPENDIX III
ORTHOPIYROXENE ANALYSES

BULK ROCK ANAL. NO.	201	202	1001	1201	2701	3101	3102	3103	3104	3105	5901	5902	5903	5904	6301	6302
SPEC.	9.00	10.00	8.00	1.00	6.00	1.00	3.00	4.00	12.00	18.00	1.00	2.00	6.00	10.00	15.00	18.00
SiO ₂	52.75	53.76	51.81	52.50	52.50	52.01	55.21	53.85	54.34	52.62	53.39	52.00	51.57	52.67	55.07	52.43
TiO ₂	17.56	16.80	17.33	20.67	15.40	19.73	7.55	13.27	13.99	18.23	16.30	22.47	24.08	21.21	2.00	1.58
Al ₂ O ₃	1.67	1.15	2.52	1.18	1.22	2.14	2.04	1.71	1.76	1.80	1.31	1.02	1.00	1.93	2.00	1.35
FeO	24.21	25.66	25.27	23.46	23.52	23.56	32.72	28.35	28.02	25.46	25.59	20.65	20.40	23.04	12.20	18.35
MnO	1.68	1.51	1.58	1.53	1.97	1.78	1.90	1.82	2.07	1.90	1.31	1.59	1.77	1.74	28.61	24.86
CaO	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
MgO	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
K ₂ O	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
Na ₂ O	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
Cl ₂ O ₃	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
TOTAL	98.39	99.54	99.16	100.11	99.38	99.87	100.89	99.77	99.70	100.80	98.37	98.66	99.66	100.32	100.72	99.56
NUMBER OF CATIONS ON BASIS OF 6(O)																
Si	1.958	1.963	1.910	1.946	1.950	1.924	1.916	1.934	1.950	1.916	1.967	1.973	1.953	1.953	1.949	1.931
Ti	.005	.008	.007	.008	.008	.008	.002	.006	.005	.011	.004	.010	.007	.007	.005	.007
Al	.073	.050	.109	.052	.054	.094	.084	.072	.033	.077	.057	.046	.040	.040	.083	.069
Fe	.545	.513	.534	.641	.603	.610	.255	.399	.422	.377	.502	.713	.763	.658	.374	.555
Mn	.010	.011	.012	.015	.015	.012	.004	.008	.010	.012	.010	.019	.018	.015	.006	.010
Mg	1.339	1.397	1.380	1.296	1.302	1.299	1.693	1.518	1.508	1.382	1.406	1.168	1.153	1.273	1.510	1.365
Ca	.067	.059	.062	.061	.078	.071	.071	.070	.080	.074	.052	.065	.072	.069	.067	.072
Na	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
K	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
Cr	.000	.000	.000	.000	.000	.000	.028	.009	.000	.000	.000	.000	.000	.000	.003	.000
Ni	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.004	.000
TOTAL	3.997	4.001	4.014	4.019	4.010	4.018	4.023	4.016	4.006	4.027	3.998	3.994	4.006	4.015	4.001	4.019
Mg*	70.70	72.70	72.20	66.80	68.40	68.00	88.30	70.20	78.10	71.30	73.70	62.10	60.20	65.90	80.10	70.70
Ca	2.40	3.10	3.10	3.00	3.90	3.60	3.80	3.50	4.00	3.70	2.60	3.30	3.60	3.40	3.40	3.60
Mn	68.30	70.50	69.50	64.40	65.20	65.20	84.90	78.10	74.60	68.30	71.40	59.40	57.50	63.20	77.20	67.80
Fe+Mn	28.30	26.50	27.30	32.60	30.60	31.20	11.50	20.40	21.40	28.00	26.00	37.30	38.90	33.40	19.40	28.60

BLANK SPACES REPRESENT 'NOT ANALYZED'

0.00 REPRESENTS ANALYZED,
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APPENDIX III
ORTHOPYROXENE ANALYSES

BULK ROCK	6303	6304	6305	6401	6901	6902	7101	7102	7103	7104	8101	8102	8103	8104	8105	8106	8107
ANAL NO.	23.00	21.00	22.00	21.00	12.00	13.00	12.00	11.00	7.00	15.00	12.00	10.00	9.00	8.00	7.00	21.00	5.00
SPEC	CORE	CORE	CORE	CORE	CORE	CORE	CORE	CORE	CORE	CORE	CORE	CORE	CORE	CORE	CORE	CORE	CORE
SiO2	53.57	51.75	55.24	53.26	51.48	54.36	53.12	53.58	54.11	53.20	53.43	53.31	57.13	56.46	56.43	56.94	53.15
TiO2	1.68	2.01	1.03	99	2.24	2.74	2.22	1.69	1.56	1.29	1.46	1.41	1.05	1.50	1.32	1.23	1.24
Al2O3	18.46	16.54	13.89	16.91	22.36	9.55	18.88	17.48	16.93	19.60	17.99	17.69	7.85	9.01	9.14	6.36	19.07
FeO	23.95	23.93	27.56	25.75	22.22	30.32	24.18	24.88	25.33	22.99	24.52	24.38	32.63	30.90	31.16	33.49	24.44
MgO	1.60	1.70	2.24	1.53	1.00	1.44	1.46	1.50	1.59	1.70	1.77	1.77	1.58	2.10	1.70	1.62	1.65
MnO	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
K2O	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
Cr2O3	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
NiO	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
TOTAL	99.76	99.56	100.59	99.08	100.33	98.97	100.50	99.67	100.16	99.97	99.80	99.23	101.05	100.76	100.29	100.69	99.76
NUMBER OF CATIONS ON BASIS OF 6(O)																	
Si	1.965	1.919	1.970	1.958	1.919	1.930	1.939	1.958	1.962	1.960	1.957	1.960	1.969	1.964	1.971	1.969	1.960
Ti	.004	.007	.006	.006	.007	.003	.007	.005	.008	.008	.006	.010	.003	.004	.003	.003	.007
Al	.072	.088	.044	.043	.098	.115	.096	.073	.067	.073	.063	.061	.043	.062	.054	.050	.035
Fe	.566	.606	.414	.520	.697	.244	.576	.534	.514	.604	.551	.544	.226	.262	.267	.183	.088
Mn	.011	.013	.009	.013	.015	.007	.013	.011	.011	.016	.010	.010	.003	.006	.005	.004	.013
Mg	1.310	1.323	1.466	1.411	1.235	1.635	1.057	1.355	1.370	1.263	1.338	1.337	1.677	1.603	1.622	1.718	1.344
Ca	.063	.067	.086	.061	.052	.055	.057	.059	.062	.067	.069	.070	.059	.078	.064	.060	.065
Na	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
K	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
Cr	.000	.000	.000	.000	.000	.006	.000	.000	.000	.000	.006	.000	.016	.009	.007	.022	.000
Ni	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
TOTAL	3.991	4.023	3.995	4.012	4.023	4.005	4.004	3.995	3.994	3.991	4.000	3.992	3.996	3.991	3.993	4.000	4.012
Mg*	69.80	68.60	78.00	73.10	63.90	85.00	69.50	71.70	72.70	67.60	70.80	71.10	88.10	85.90	85.90	90.40	69.30
Ca	3.20	3.30	4.40	3.00	2.80	2.80	2.90	3.00	3.20	3.40	3.50	3.60	3.30	4.00	3.30	3.10	3.20
Mg	67.20	65.90	74.20	70.40	61.80	82.30	67.10	69.20	70.00	64.80	68.00	68.20	85.30	82.20	82.80	87.40	66.90
Fe+Mn	29.60	30.80	21.40	28.60	35.60	14.80	30.00	27.80	26.80	31.80	28.50	28.20	11.70	13.80	13.90	9.50	29.90

BLANK SPACES REPRESENT 'NOT ANALYZED'

0.00 REPRESENTS ANALYZED
BUT BELOW THEORETICAL LIMIT OF DETECTION.

APPENDIX III
ORTHOPYROXENE ANALYSES

BULK ROCK ANAL. NO.	8802	8803	9101	9102	9103	10001	10002	10501	10502	10701	10801	10802	11001	11501	11801	12401	12402
SPEC.	3.00	3.00	10.00	11.00	3.00	15.00	16.00	4.00	5.00	3.00	5.00	6.00	25.00	1.00	1.00	12.00	12.00
SiO ₂	52.38	52.27	53.08	55.29	54.69	54.83	53.92	53.72	54.73	51.87	48.76	50.92	52.64	52.00	53.23	52.42	52.44
TiO ₂	1.70	1.20	1.40	1.25	1.43	1.08	1.68	1.87	2.1	1.41	5.54	1.13	3.30	1.87	2.69	1.34	1.57
FeO	20.06	19.50	19.45	13.74	13.58	17.08	18.17	20.60	20.48	20.60	23.09	24.64	17.24	18.18	14.17	20.76	21.71
Al ₂ O ₃	23.60	24.15	23.32	28.11	27.71	25.30	24.83	23.47	23.45	23.37	20.55	19.80	24.05	24.17	27.25	22.19	21.68
MnO	1.63	1.70	1.83	1.85	2.05	1.55	1.41	1.33	1.43	1.00	1.00	1.00	1.28	1.91	1.54	1.62	1.57
MgO	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
K ₂ O	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
Na ₂ O	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
CaO	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
Ni ₂ O ₃	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
TOTAL	100.10	99.97	100.13	100.71	100.27	100.28	100.81	100.74	101.75	99.94	98.36	98.28	99.28	98.81	99.60	99.05	98.81
NUMBER OF CATIONS ON BASIS OF 6(O)																	
Si	1.934	1.945	1.955	1.963	1.954	1.984	1.954	1.970	1.983	1.929	1.852	1.960	1.935	1.931	1.921	1.964	1.979
Ti	.008	.008	.008	.005	.007	.005	.008	.008	.005	.012	.008	.004	.010	.010	.005	.010	.006
Al	.074	.074	.081	.053	.060	.046	.072	.038	.041	.062	.248	.01	.130	.082	.115	.054	.025
Fe	.619	.602	.598	.408	.406	.517	.551	.632	.621	.641	.733	.783	.530	.565	.428	.650	.685
Mn	.014	.014	.012	.008	.010	.008	.010	.015	.015	.014	.163	.01	.013	.010	.010	.016	.020
Mg	1.305	1.329	1.291	1.488	1.476	1.365	1.342	1.284	1.267	1.295	1.008	1.136	1.051	1.338	1.466	1.239	1.220
Na	.062	.067	.076	.071	.079	.060	.055	.052	.055	.072	.000	.042	.000	.076	.059	.065	.063
Ca	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
K	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
Cr	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
Ni	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
TOTAL	4.019	4.039	4.005	3.996	4.003	3.985	3.997	3.999	3.989	4.025	4.010	4.007	3.987	4.012	4.009	3.998	3.998
Mg*	67.80	68.80	67.90	78.20	78.00	72.20	70.50	66.50	66.60	66.90	61.30	58.90	70.80	70.30	77.40	65.60	64.00
Ca	3.20	3.20	3.80	3.60	4.00	3.10	2.80	2.70	2.90	3.60	3.30	2.10	2.60	3.80	3.00	3.30	3.20
Mg	65.20	66.20	65.30	75.30	74.90	70.00	68.50	64.70	64.70	64.00	61.10	57.00	69.00	67.30	74.70	62.90	61.40
Fe+Mn	31.60	30.60	30.90	21.10	21.10	26.90	28.60	32.60	32.40	32.40	38.60	40.90	28.40	28.90	22.30	33.80	35.50

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APPENDIX III
ORTHOPYROXENE ANALYSES

BULK ROCK ANAL. NO.	12901	12902	12903	13101	13102	13103	13104	13105	13106	13107	13201	13202	13203	13301	13302	13701	13702
SPEC.	CORE	RIM	RIM	XC	CORE	CORE	RIM	MR	RIM	RIM	G	G	G	CORE	MC	I	XC
SiO ₂	52.15	53.23	52.15	52.77	51.51	51.25	52.23	51.33	50.22	51.24	55.59	54.08	54.31	55.95	55.20	55.09	55.75
TiO ₂	1.17	3.68	1.19	1.62	1.33	1.02	1.65	1.33	1.59	1.29	1.3	1.3	1.4	2.02	1.7	2.0	1.38
Al ₂ O ₃	19.37	16.31	18.80	18.20	23.50	25.61	21.21	27.22	28.15	30.98	13.04	15.76	16.11	10.17	14.82	11.22	12.00
FeO	23.50	23.32	23.52	24.44	20.54	19.63	22.99	17.81	16.50	15.28	27.76	25.63	25.22	29.56	26.15	29.36	29.13
MnO	1.76	3.03	1.95	1.38	1.76	1.30	1.20	1.34	1.39	1.36	2.24	2.14	2.31	1.65	1.15	1.00	1.51
CaO	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
MgO	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
K ₂ O	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
Na ₂ O	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
Sum	88.61	100.46	98.31	99.09	99.58	99.56	99.94	99.94	98.72	99.94	100.04	98.92	99.41	99.94	99.31	100.01	100.39
NUMBER OF CATIONS ON BASIS OF 6(O)																	
Si	1.979	1.925	1.953	1.951	1.948	1.955	1.941	1.971	1.959	1.997	1.983	1.979	1.985	1.968	1.997	1.923	1.970
Ti	.006	.010	.009	.006	.011	.007	.007	.004	.009	.005	.003	.005	.004	.004	.004	.003	.004
Al	.225	.157	.052	.070	.060	.046	.072	.042	.073	.013	.039	.036	.036	.084	.037	.036	.08
Fe	.606	.493	.585	.563	.745	.817	.659	.890	.918	1.010	.389	.482	.492	.299	.442	.307	.355
Mg	.013	.010	.011	.015	.016	.016	.013	.021	.019	.020	.011	.009	.011	.008	.008	.007	.006
Mn	1.311	1.267	1.313	1.347	1.158	1.116	1.274	1.019	.959	.888	1.477	1.398	1.374	1.551	1.410	1.572	1.555
Ca	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
Na	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
K	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
Sum	4.010	3.979	4.005	4.007	4.009	4.010	4.014	4.002	3.995	3.990	3.988	3.993	3.998	3.981	3.981	3.975	3.992
TOTAL	68.40	71.00	69.00	70.50	60.80	57.70	65.90	53.40	51.10	46.80	79.10	74.40	73.60	83.80	76.10	82.70	81.20
Mg*	3.40	6.20	3.90	2.80	3.60	2.70	2.40	2.80	3.00	2.90	4.40	4.30	4.60	3.20	3.80	2.20	2.80
Ca	65.60	67.10	66.00	68.00	58.20	55.70	63.90	51.30	49.00	45.00	75.20	70.90	69.80	80.80	72.90	80.60	78.80
Fe-Mn	31.00	26.70	30.10	29.20	38.20	41.60	33.70	45.90	48.00	52.10	20.40	24.80	25.60	16.00	23.30	17.20	18.50

BLANK SPACES REPRESENT 'NOT ANALYZED'

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APPENDIX III
ORTHOPIROXENE ANALYSES

BULK ROCK NO.	13703	13704	13901	13902	13903	13904	13905	13906	13907	13908	13909	13910	14001	14002	14003
—XR	13.00	8.00	6.00	5.00	4.00	3.00	2.00	20.00	2.00	1.00	26.00	13.00	15.00	16.00	8.00
—G	55.66	52.51	53.94	53.80	53.75	54.10	55.33	55.23	55.34	54.82	57.77	53.45	48.60	51.11	52.78
—SiO ₂	14.74	17.11	16.62	18.26	18.21	18.51	22.34	1.80	2.34	8.88	1.08	31.41	39.60	31.18	35.79
—Al ₂ O ₃	12.74	15.13	18.00	18.03	18.61	18.47	12.35	1.11	2.35	18.79	1.81	1.46	23.89	1.66	1.04
—FeO	22.22	26.30	23.94	23.97	23.56	23.98	28.25	30.00	28.25	24.47	31.88	17.71	14.26	23.91	18.74
—MnO	29.31	2.15	2.00	1.90	1.84	1.91	1.70	1.79	1.70	2.22	1.11	24.28	17.17	20.37	24.13
—CaO	1.60	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.09	1.28	1.73	1.73
—Na ₂ O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
—K ₂ O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
—Cl ₂ O ₃	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
—NiO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TOTAL	100.41	98.66	100.22	99.86	99.89	100.64	100.53	100.64	100.54	99.88	100.52	99.97	100.00	99.26	99.22

NUMBER OF CATIONS ON BASIS OF 6 (O)

Si	1.973	1.930	1.967	1.964	1.971	1.968	1.955	1.943	1.955	1.992	1.980	1.957	1.920	1.942	1.956
Al	0.031	0.066	0.070	0.067	0.066	0.067	0.066	0.075	0.066	0.038	0.045	0.043	0.006	0.074	0.046
Fe	0.031	0.074	0.070	0.065	0.065	0.065	0.068	0.075	0.098	0.030	0.042	0.083	0.102	0.077	0.081
Mg	0.378	0.465	0.549	0.552	0.571	0.562	0.365	0.327	0.365	0.510	0.242	0.258	1.120	0.760	0.581
Mn	0.007	0.009	0.006	0.010	0.009	0.006	0.008	0.007	0.008	0.011	0.005	0.005	0.024	0.022	0.010
Ca	1.549	1.459	1.301	1.309	1.287	1.305	1.487	1.573	1.487	1.326	1.642	1.335	0.840	1.154	1.335
Na	0.061	0.084	0.074	0.072	0.070	0.073	0.064	0.068	0.064	0.087	0.057	0.082	0.007	0.052	0.069
K	0.000	0.000	0.009	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.007	0.000	0.000	0.000	0.000
Cl	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Ni	0.000	0.000	0.000	0.003	0.003	0.004	0.003	0.008	0.003	0.000	0.011	0.000	0.000	0.000	0.000
TOTAL	4.003	4.027	3.991	3.986	3.984	3.990	3.986	4.006	3.986	3.974	3.991	3.989	4.019	4.011	4.009
Mg*	80.40	75.80	70.30	70.30	69.30	69.80	80.30	82.80	80.30	72.20	87.10	70.40	42.90	60.30	69.70
Ca	3.10	4.20	4.00	3.80	3.70	3.90	3.30	3.30	3.30	4.50	2.90	4.20	3.00	2.60	3.50
Mg*	77.30	72.30	67.30	67.30	66.40	66.90	77.30	79.60	77.30	68.60	84.40	67.30	52.50	58.00	66.90
Mg*	19.60	23.50	28.70	28.90	29.30	29.20	19.40	18.90	19.40	26.90	12.70	28.50	47.50	39.30	39.30

BLANK SPACES REPRESENT 'NOT ANALYZED'

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APPENDIX III

PLAGIOCLASE ANALYSES

BULK ROCK ANAL. NO.	201	202	203	1001	1201	1202	1203	1204	2701	3101	3102	3103	3104	3105	4601	4602	4603
SPEC.	7.00	8.00	15.00	6.00	5.00	6.00	60.00	7.00	15.00	6.00	7.00	8.00	10.00	11.00	3.00	4.00	5.00
SiO ₂	48.86	48.23	55.59	52.97	51.09	47.90	52.88	57.94	50.84	51.71	51.82	53.23	51.53	55.57	48.96	48.45	53.31
Al ₂ O ₃	31.78	31.78	27.52	28.84	30.67	32.47	28.59	25.80	29.75	29.96	29.61	28.72	29.59	28.41	31.56	32.12	28.13
FeO	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
MgO	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
MnO	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
CaO	16.09	16.17	10.98	11.44	14.17	16.17	11.66	8.45	13.61	13.52	12.88	12.14	13.14	10.91	14.81	15.66	11.71
Na ₂ O	2.32	2.13	5.29	4.61	3.75	2.47	4.82	6.87	3.72	4.07	4.35	4.49	3.77	4.90	3.02	2.72	4.98
K ₂ O	.05	.07	.15	.15	.17	.08	.30	.41	.18	.26	.27	.19	.13	.53	.07	.05	.26
Cr ₂ O ₃																	
NiO																	
TOTAL	99.91	99.12	100.87	98.98	100.33	99.79	98.72	99.98	98.87	100.04	99.46	99.67	99.21	99.70	98.94	99.49	99.22
NUMBER OF CATIONS ON BASIS OF 8 (O)																	
Si	2.243	2.232	2.497	2.426	2.324	2.206	2.446	2.604	2.339	2.356	2.371	2.423	2.365	2.526	2.262	2.232	2.439
Ti	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
Al	1.719	1.732	1.457	1.556	1.644	1.763	1.530	1.367	1.620	1.609	1.597	1.541	1.600	1.415	1.719	1.744	1.517
Fe	.031	.029	.046	.033	.018	.027	.018	.019	.038	.020	.020	.027	.034	.048	.020	.019	.032
Mn	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
Mg	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
Ca	.794	.802	.529	.561	.691	.798	.567	.407	.674	.660	.631	.592	.646	.531	.733	.773	.574
Na	.206	.191	.460	.409	.331	.221	.424	.599	.334	.359	.386	.396	.335	.432	.271	.243	.442
K	.003	.004	.017	.009	.010	.005	.017	.023	.010	.015	.016	.011	.007	.030	.004	.003	.015
Cr																	
Ni																	
TOTAL	4.996	4.990	5.006	5.001	5.018	5.020	5.002	5.019	5.015	5.019	5.021	5.004	4.997	4.989	5.009	5.014	5.019
Ar																	
Ab	79.10	80.40	52.80	57.30	67.00	77.90	56.20	39.60	86.20	63.80	61.10	59.30	65.40	53.50	72.70	75.90	55.70
Or	20.60	19.20	45.70	41.90	32.10	21.60	42.10	58.20	32.80	34.70	37.40	39.60	33.90	43.50	26.90	23.80	42.90
	.30	.40	1.70	.90	.90	.50	1.70	2.20	1.00	1.50	1.50	1.10	.70	3.00	.40	.30	1.40

BLANK SPACES REPRESENT 'NOT ANALYZED'

0.00 REPRESENTS ANALYZED
BUT BELOW THEORETICAL LIMIT OF DETECTION.

APPENDIX III

PLAGIOCLASE ANALYSES

BULK ROCK	8702	8703	8801	8802	8803	8804	9101	9102	9103	9104	10001	10002	10003	10004	10005	10006	10501
ANAL. NO.	11.00	12.00	9.00	8.00	6.00	7.00	8.00	7.00	8.00	5.00	1.00	3.00	27.00	28.00	29.00	30.00	14.00
SP. SPEC.	55.33	50.77	48.12	54.23	50.73	55.26	53.64	55.79	53.00	55.56	50.28	49.87	48.56	48.57	49.00	49.36	55.47
SI-02	27.01	29.08	31.09	28.22	31.06	27.40	28.54	27.71	29.45	26.09	31.10	32.08	33.33	32.45	31.94	32.70	28.52
AI-203	27.01	29.08	31.09	28.22	31.06	27.40	28.54	27.71	29.45	26.09	31.10	32.08	33.33	32.45	31.94	32.70	28.52
FeO	70.71	71.71	67.61	61.55	58.94	64.94	55.54	54.68	68.94	64.94	55.54	58.94	61.55	60.55	58.94	62.94	54.54
MnO	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00
MgO	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00
CaO	11.34	12.85	18.14	11.06	14.17	10.66	12.18	11.12	12.84	10.73	15.07	15.44	17.00	16.18	15.90	16.49	11.50
Na2O	3.80	3.60	2.59	5.23	3.52	5.59	4.50	5.17	3.93	4.74	3.00	2.43	1.84	2.30	2.30	2.39	2.53
K2O	2.60	2.26	2.08	2.20	1.11	2.35	2.27	2.28	2.21	1.85	1.12	1.12	0.06	0.06	0.06	0.06	2.23
SiO2	99.53	97.07	98.69	99.55	100.17	100.20	99.48	100.61	100.09	99.41	100.12	100.55	101.39	100.11	99.86	101.42	99.31
NUMBER OF CATIONS ON BASIS OF 8(O)																	
Si	2.509	2.375	2.221	2.463	2.309	2.497	2.441	2.501	2.403	2.539	2.295	2.266	2.198	2.223	2.247	2.231	2.473
Ti	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Al	1.443	1.603	1.741	1.511	1.666	1.459	1.531	1.454	1.575	1.406	1.673	1.717	1.772	1.751	1.727	1.742	1.459
Fe	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Mg	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Ca	0.051	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Na	0.034	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
K	0.034	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
CL	0.035	0.015	0.005	0.012	0.006	0.020	0.016	0.016	0.012	0.008	0.007	0.007	0.004	0.003	0.003	0.004	0.014
TOTAL	4.950	4.981	5.023	5.009	5.005	5.018	4.983	4.974	4.984	5.010	4.999	4.981	4.984	4.996	4.988	4.992	4.981
AN	59.90	65.00	77.10	53.30	68.50	50.30	60.00	53.40	63.60	48.70	73.00	77.20	83.20	79.30	79.00	80.30	57.00
AB	36.30	33.40	22.40	45.50	30.90	47.80	38.40	45.00	35.20	10.50	26.30	22.10	16.30	20.40	20.70	19.30	41.60
AB	3.80	1.60	1.50	1.20	1.90	1.90	1.60	1.60	1.20	1.50	0.70	0.70	0.40	0.30	0.30	0.40	1.40

BLANK SPACES REPRESENT 'NOT ANALYZED'

0.00 REPRESENTS ANALYZED, BUT BELOW THEORETICAL LIMIT OF DETECTION.

APPENDIX III
PLAGIOCLASE ANALYSES

BULK ROCK ANAL. NO.	10502	10503	10504	10505	10701	11001	11002	11003	11004	11501	11502	11503	11504	11505	11506	11801	11802
SiO ₂	52.12	54.81	54.95	51.62	56.22	55.06	57.16	53.71	55.22	48.08	52.72	46.65	47.42	52.52	53.98	47.71	47.71
Al ₂ O ₃	30.37	29.30	29.09	30.00	25.97	27.53	26.65	28.99	28.18	32.33	28.25	32.39	31.74	28.25	28.32	32.58	32.58
FeO	52.00	56.00	56.00	56.00	56.00	56.00	56.00	56.00	56.00	56.00	56.00	56.00	56.00	56.00	56.00	56.00	56.00
MnO	13.00	11.76	10.59	13.11	10.53	10.70	9.54	11.91	11.25	16.03	12.14	16.69	15.77	12.04	11.92	16.35	16.23
CaO	3.58	4.40	4.30	3.51	4.61	5.00	5.64	4.32	4.66	2.18	4.58	1.78	2.41	4.28	4.82	2.23	2.20
Na ₂ O	15.21	15.21	15.21	15.21	15.21	15.21	15.21	15.21	15.21	15.21	15.21	15.21	15.21	15.21	15.21	15.21	15.21
K ₂ O	15.21	15.21	15.21	15.21	15.21	15.21	15.21	15.21	15.21	15.21	15.21	15.21	15.21	15.21	15.21	15.21	15.21
TiO ₂	99.81	101.04	99.97	99.42	99.06	99.33	100.10	100.03	100.67	99.27	98.91	98.14	97.95	98.14	100.19	99.46	99.38
TOTAL	99.81	101.04	99.97	99.42	99.06	99.33	100.10	100.03	100.67	99.27	98.91	98.14	97.95	98.14	100.19	99.46	99.38
NUMBER OF CATIONS ON BASIS OF 8(O)																	
Si	2.367	2.450	2.473	2.348	2.561	2.517	2.567	2.431	2.480	2.219	2.421	2.184	2.221	2.428	2.443	2.203	2.191
Ti	1.658	1.544	1.543	1.608	1.395	1.459	1.411	1.548	1.491	1.758	1.529	1.787	1.752	1.539	1.510	1.773	1.789
Al	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Fe	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Mn	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Mg	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Ca	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Na	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
K	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Cr	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
TOTAL	4.973	4.931	4.851	5.004	4.963	4.979	4.984	4.993	4.993	4.992	5.014	4.995	5.009	4.996	5.008	5.008	5.011
Si	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ti	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Al	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mn	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ca	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Na	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
K	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TOTAL	86.20	58.80	56.00	67.90	52.60	52.90	48.80	58.10	54.30	79.90	58.70	83.50	78.00	60.10	57.00	80.00	80.10
Blank	32.80	39.90	42.10	30.60	41.80	44.40	48.80	39.80	43.30	19.90	40.00	16.10	21.50	38.60	4.60	19.70	19.60
Or	1.00	1.30	1.90	1.50	5.60	2.70	3.40	2.00	2.40	5.50	1.30	4.00	5.50	1.30	1.40	3.00	3.00

BLANK SPACES REPRESENT 'NOT ANALYZED'
0.00 REPRESENTS ANALYZED
BUT BELOW THEORETICAL LIMIT OF DETECTION.

APPENDIX III
PLAGIOCLASE ANALYSES

BULK ROCK ANAL NO.	13102	13201	13202	13203	13301	13302	13303	13701	13702	13703	13901	13902	13903	13904	13905	13906	13907
—RIM	4.00	22.00	23.00	21.00	12.00	13.00	11.00	27.00	11.00	4.00	4.00	5.00	6.00	7.00	8.00	24.00	25.00
SPEC.	58.59	49.73	50.90	51.99	46.83	49.15	51.60	49.55	50.78	51.71	56.56	56.90	58.06	50.49	51.58	49.61	50.41
SiO ₂	25.49	31.91	30.68	30.73	33.46	32.17	30.22	31.72	30.12	29.49	27.78	28.02	26.46	29.87	30.63	29.81	32.14
Al ₂ O ₃	.34	.00	.00	.00	.67	.00	.00	.82	.92	.98	.41	.46	.61	.38	.48	.49	.57
FeO	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
MgO	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
CaO	8.23	15.44	14.73	14.40	17.71	15.84	14.01	15.27	14.58	13.00	11.21	11.34	10.30	13.39	13.70	14.96	14.53
Na ₂ O	6.36	2.13	2.72	3.54	1.21	2.34	3.41	2.37	3.14	3.24	4.83	4.55	4.84	3.83	3.40	3.28	3.27
K ₂ O	.64	.00	.07	.10	.00	.05	.12	.07	.09	.10	.43	.44	.57	.09	.20	.20	.17
Cr ₂ O ₃																	
NiO																	
TOTAL	99.65	100.17	100.18	102.19	100.01	100.29	100.54	99.93	99.75	98.66	101.22	101.71	101.01	98.15	100.14	98.46	101.23
NUMBER OF CATIONS ON BASIS OF 8(O)																	
Si	2.632	2.267	2.319	2.329	2.156	2.242	2.343	2.268	2.327	2.381	2.517	2.517	2.581	2.339	2.341	2.308	2.275
Ti	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
Al	1.350	1.714	1.647	1.622	1.816	1.729	1.617	1.711	1.637	1.600	1.457	1.461	1.387	1.631	1.638	1.635	1.709
Fe	.013	.029	.034	.049	.028	.028	.038	.031	.035	.038	.015	.017	.023	.015	.018	.019	.022
Mn	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
Mg	.000	.014	.012	.008	.009	.000	.011	.009	.008	.010	.000	.000	.011	.007	.010	.008	.010
Ca	.396	.754	.719	.691	.874	.774	.683	.749	.716	.641	.535	.538	.491	.655	.666	.745	.702
Na	.554	.189	.240	.308	.108	.207	.299	.210	.279	.289	.417	.380	.417	.344	.300	.295	.286
K	.037	.000	.004	.006	.000	.003	.007	.004	.005	.006	.024	.025	.033	.013	.012	.012	.010
Cr																	
Ni																	
TOTAL	4.982	4.967	4.975	5.013	4.989	4.983	4.998	4.982	4.997	4.985	4.965	4.948	4.943	5.004	4.985	5.022	5.014
Blank spaces represent 'NOT ANALYZED'																	
0.00 REPRESENTS ANALYZED																	
BUT BELOW THEORETICAL LIMIT OF DETECTION.																	
Ab	40.10	79.90	74.70	68.80	89.00	78.70	69.10	77.80	71.60	68.50	54.80	56.50	52.20	65.10	68.10	70.80	70.30
Or	56.10	20.10	24.90	30.60	11.00	21.00	30.20	21.80	27.90	30.90	42.70	40.90	44.30	33.70	31.70	28.00	28.70
Gr	3.80	.00	.40	.60	.00	.30	.70	.40	.50	.60	2.50	2.60	3.50	1.20	1.20	1.20	1.00

APPENDIX III

PLAGIOCLASE ANALYSES

BULK ROCK ANAL. NO.	13908	14401	14402
SPEC. G	23.00	9.00	12.00
SiO ₂	53.47	56.72	57.82
TiO ₂	.00	.00	.00
Al ₂ O ₃	28.39	26.37	25.68
FeO	.69	.39	.23
MnO	.00	.00	.00
MgO	.19	.00	.00
CaO	12.28	9.19	8.51
Na ₂ O	4.12	6.14	6.71
K ₂ O	.27	.50	.49
Cr ₂ O ₃			
NiO			
TOTAL	99.41	99.31	99.44

NUMBER OF CATIONS ON BASIS OF 8(0)

Si	2.439	2.570	2.609
Ti	.000	.000	.000
Al	1.525	1.408	1.386
Fe	.027	.015	.009
Mn	.000	.000	.000
Mg	.013	.000	.000
Ca	.600	.448	.411
Na	.364	.541	.587
K	.016	.029	.028
Cr			
Ni			
TOTAL	4.984	5.009	5.010

Ap	61.20	43.90	40.10
Ab	37.10	53.20	57.20
Or	1.70	2.90	2.70

BLANK SPACES REPRESENT 'NOT ANALYZED'
0.00 REPRESENTS ANALYZED,
BUT BELOW THEORETICAL LIMIT OF DETECTION.

APPENDIX III
OXIDE ANALYSES

BULK ROCK	201	202	2701	2702	5901	6301	6302	6303	6304	6305	7101	7102	7103	7104	8101	8801	8802
FIELD NO.	A9	A9	X56	X56	M5	L1015A	L1015A	L1015A	L1015A	L1015A	L8	L6	L6	L6	M17	L2	L2
ANAL. NO.	11.00	21.00	1.00	13.00	8.00	8.00	9.00	27.00	1.00	2.00	4.00	13.00	14.00	20.00	4.00	1.00	13.00
MINERAL	TMT	TMT	CRSP	TMT	TMT	CRSP	CRSP	TMT	TMT	TMT	CRSP	TMT	OPX	TMT	CRSP	TMT	TMT
SPEC.	HY	GMS	OPX	CPX	GMS	OL	OL	GMS	CPX	CPX	OL	OPX	OPX	CPX	OL	OPX	CPX
SiO2	26	12.09	1.35	10.05	15.74	.61	.49	12.83	8.70	6.59	.55	.00	.13	.00	.00	.12	.17
TiO2	10.56	4.18	1.39	4.18	1.65	9.19	12.23	8.86	3.78	4.08	16.91	9.66	9.70	10.49	.15	11.13	13.52
Al2O3	1.04	2.37	12.39	4.14	35.35	11.46	8.54	40.04	48.11	49.53	6.92	4.84	4.78	4.10	4.57	2.65	1.50
Fe2O3	44.20	41.08	11.90	42.14	43.72	20.37	15.64	40.25	35.80	34.06	19.53	44.79	44.13	42.53	10.40	43.77	39.11
FeO	38.92	39.67	21.89	36.09	43.72	20.37	15.64	40.25	35.80	34.06	19.53	44.79	44.13	42.53	10.40	43.77	39.11
MnO	18	21	15	21	44	.00	.00	.38	.30	.24	10.08	2.78	3.28	3.28	.00	.30	.24
MgO	89	1.37	7.95	2.34	.91	8.65	11.96	.60	1.78	1.50	10.08	2.78	3.28	3.28	.00	1.11	.43
CaO	.96	.90	.00	.61	.36	48.77	49.95	.22	.33	.27	45.71	.54	.46	.41	.00	.00	.00
Cr2O3	.00	.00	41.82	.61	.00	48.77	49.95	.22	.33	.27	45.71	.54	.46	.41	.00	.00	.00
NiO	.00	.00	41.17	.00	.00	99.15	98.97	.10	.10	.10	99.40	.12	.12	.14	.11	.00	.00
TOTAL	97.01	97.69	97.52	95.95	98.27	99.15	98.97	95.48	97.12	96.40	99.40	98.62	97.85	96.43	97.70	98.90	97.79
OXYGENS	32.000	32.000	32.000	32.000	32.000	32.000	32.000	32.000	32.000	32.000	32.000	32.000	32.000	32.000	32.000	32.000	32.000
Si	.081	.000	.000	.052	.030	.125	.097	.032	.039	.000	.000	.000	.038	.000	.000	.036	.052
Ti	2.460	2.766	2.78	2.300	3.593	2.942	3.778	3.043	1.984	1.509	5.107	2.147	2.159	2.384	.031	2.519	3.121
Al	10.380	8.850	3.960	1.500	5.590	2.341	1.684	9.505	10.522	11.423	5.155	1.617	1.668	1.461	1.500	9.940	5.431
Fe2	10.083	10.090	5.004	9.184	11.099	4.624	3.427	10.617	9.080	8.729	4.223	8.838	8.694	8.972	3.948	9.912	9.035
Fe3	.047	.054	.035	.054	.113	3.500	4.670	.102	.077	.062	3.884	1.095	1.070	1.095	.000	.076	.062
Mn	.411	.621	3.238	1.061	.412	3.500	4.670	.282	.804	.685	3.884	1.225	1.434	1.302	4.084	.498	.197
Ca	.000	.000	.000	.052	.000	10.468	10.346	.074	.062	.043	9.344	.000	.000	.000	.000	.000	.000
Cr	.235	.216	9.036	.147	.086	10.468	10.346	.025	.079	.065	9.344	.128	.108	.098	12.258	.038	.075
Ni	.000	.000	.000	.000	.000	24.001	24.002	.000	.000	.000	24.001	.000	.000	.000	.000	.000	.000
TOTAL	24.001	24.000	24.000	24.000	23.999	24.000	24.002	24.000	23.998	23.990	24.001	24.000	24.000	24.000	24.000	24.000	23.999
Usp %	34.77	39.90	79.01	37.55	48.80	79.70	85.09	40.16	32.22	28.24	88.47	35.39	36.21	37.52	80.91	36.76	42.81
R2O3 %	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00

BLANK SPACES REPRESENT 'NOT ANALYZED'

0.00 REPRESENTS ANALYZED,
BUT BELOW THEORETICAL LIMIT OF DETECTION.

Fe2O3 calculated after Carmichael (1967)

APPENDIX III
OXIDE ANALYSES

BULK ROCK	9101	10001	10501	10502	10503	10504	10801	12401	13101	13201	13202	13203	13204	13205	13206	13207	13208
FIELD NO.	J5	J5	ES	ES	ES	ES	J2	E6	N1128	WB	WB	WB	WB	WB	WB	WB	WB
ANAL NO.	4.00	5.00	3.00	6.00	7.00	8.00	22.00	17.00	5.00	75.00	70.00	71.00	8.00	9.00	65.00	68.00	44.00
MINERAL	ALSP	ILM	ILM	TMT	TMT	TMT	ILM	ILM	ILM	CRSP	CRSP	CRSP	CRSP	CRSP	CRSP	CRSP	CRSP
SPEC	GMS	CPX	CPX	OPX	CPX	GMS	GMS	GMS	PLAG	OL	CORE	RIM	CORE	RIM	CORE	RIM	GMSC
SiO2	00.00	00.00	00.00	12.00	16.88	19.42	31.25	48.60	48.83	21.00	18.00	19.00	15.00	20.00	18.00	20.00	13.00
TiO2	72.72	36.96	38.34	12.57	16.88	19.42	31.25	48.60	48.83	7.71	9.49	9.75	10.38	12.86	9.64	8.20	5.14
Al2O3	52.52	1.94	18.28	40.96	33.71	28.35	29.50	5.91	5.13	6.38	5.08	5.24	4.23	4.23	5.34	9.19	15.18
Fe2O3	6.68	18.13	37.72	40.73	41.31	45.90	38.02	43.57	41.88	19.07	17.43	17.26	12.34	11.61	18.11	18.44	27.00
FeO	24.75	35.93	37.72	40.73	41.31	45.90	38.02	43.57	41.88	19.07	17.43	17.26	12.34	11.61	18.11	18.44	27.00
MnO	10.01	2.49	2.61	1.33	2.58	1.46	1.70	1.18	2.05	9.17	10.14	10.17	13.55	14.81	10.00	9.59	4.22
MgO	00.00	2.86	2.61	1.33	2.58	1.46	1.70	1.18	2.05	9.17	10.14	10.17	13.55	14.81	10.00	9.59	4.22
CaO	00.00	2.25	2.11	1.00	2.00	1.10	1.74	0.00	1.66	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00
Cr2O3	46.00	18.00	11.00	38.00	00.00	00.00	00.00	00.00	00.00	55.52	55.44	54.62	59.17	56.44	55.88	52.23	47.59
NiO	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.13	00.00	12.00	00.00
TOTAL	98.43	97.74	97.88	99.02	95.43	97.21	102.51	99.94	98.66	98.26	97.76	97.23	96.54	100.28	99.15	98.22	99.96
OXYGENS	32.000	6.000	6.000	32.000	32.000	32.000	6.000	6.000	6.000	32.000	32.000	32.000	32.000	32.000	32.000	32.000	32.000
Si	00.00	00.00	00.00	036.00	000.00	043.00	1.000	1.000	1.865	0.057	0.037	0.039	0.040	0.038	0.038	0.055	0.037
Ti	123.00	1.441	1.504	2.834	3.930	4.449	1.200	1.850	1.865	0.41	0.37	0.39	0.42	0.38	0.38	0.51	0.149
Al	14.023	1.118	0.32	9.36	2.85	5.17	1.059	1.000	1.008	2.486	3.028	3.122	3.344	3.834	3.038	2.837	1.718
Fe2	1.650	7.46	7.17	9.234	7.856	6.593	1.134	1.225	1.196	1.314	1.035	1.070	0.89	0.86	1.074	1.887	3.241
Fe3	4.688	1.557	1.645	10.205	10.695	11.103	1.623	1.844	1.779	4.361	3.946	3.922	2.719	2.456	4.051	4.207	6.403
Mn	0.058	0.22	0.08	0.71	0.45	0.63	0.14	0.029	0.020	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Mg	3.379	2.21	2.03	594	1.190	663	1.29	0.089	0.155	3.737	4.091	4.117	5.363	5.582	3.986	3.899	1.784
Ca	00.00	0.00	0.06	0.00	0.00	0.33	0.00	0.000	0.009	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Cr	0.082	0.007	0.005	0.90	0.00	0.00	0.030	0.000	0.000	12.003	11.863	11.730	12.423	11.284	11.814	11.264	10.869
Ni	00.00	0.00	0.00	0.00	0.00	0.00	0.000	0.000	0.000	23.999	24.000	24.000	24.000	24.000	24.000	24.000	24.000
TOTAL	24.001	4.112	4.120	24.000	24.001	24.001	4.189	4.037	4.032	88.24	90.62	90.31	99.36	92.65	90.28	83.39	72.71
UsP %	85.40	00.00	00.00	41.03	50.61	58.94	42.10	8.36	7.40	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00
8203 %	00.00	29.09	26.68	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00	00.00

BLANK SPACES REPRESENT 'NOT ANALYZED'

0.00 REPRESENTS ANALYZED
BUT BELOW THEORETICAL LIMIT OF DETECTION.

Fe2O3 calculated after Carmichael (1967)

APPENDIX III
OXIDE ANALYSES

BULK ROCK	13209	13210	13211	13212	13301	13302	13901	13902	13903	14401
FIELD NO.	45.00	42.00	48.00	43.00	15.00	41.00	17.00	17.00	13.00	13.00
MINERAL	WB	WB	WB	WB	CRSP	CRSP	CRSP	CRSP	CRSP	CRSP
SPEC.	—RIM	SP	SP	SP	OL	OL	OL	OL	OL	OL
SiO2	45.00	42.00	48.00	43.00	15.00	41.00	17.00	17.00	13.00	13.00
TiO2	4.68	5.64	5.88	6.35	1.62	9.95	1.44	13.48	14.98	14.98
Al2O3	3.42	3.00	2.92	2.70	6.52	7.01	38.93	34.53	2.19	2.19
FeO	48.93	50.36	50.81	51.00	8.85	19.81	41.51	43.07	43.07	43.07
Fe2	31.93	33.97	34.18	34.30	29.59	0.00	0.00	0.00	0.00	0.00
MnO	2.27	2.6	2.9	3.0	3.37	8.78	55	97	55	97
CaO	2.34	1.82	1.59	1.40	0.00	0.00	0.00	0.00	0.00	0.00
Cr2O3	7.82	5.71	2.91	1.84	49.78	51.84	0.00	0.00	0.00	0.00
NiO	7.82	5.71	2.91	1.84	49.78	51.84	0.00	0.00	0.00	0.00
TOTAL	99.52	100.87	99.04	98.68	99.97	97.96	96.02	96.02	96.02	96.22
OXYGENS	32.000	32.000	32.000	32.000	32.000	32.000	32.000	32.000	32.000	32.000
Si	1.041	1.247	1.325	1.441	3.559	2.172	3.44	3.175	3.478	3.478
Ti	1.193	1.040	1.032	1.061	2.001	1.883	1.439	1.439	1.439	1.439
Al	10.895	11.140	11.460	11.585	4.295	6.993	4.521	10.874	11.121	11.121
Fe3	7.901	8.350	8.568	8.801	3.810	1.419	3.570	257	446	446
Fe2	1.068	0.85	0.74	0.77	3.810	1.419	3.570	257	446	446
Mn	1.032	0.797	0.58	0.50	10.230	11.121	11.180	0.00	0.00	0.00
Ca	0.041	0.35	0.27	0.20	0.00	0.00	0.00	0.00	0.00	0.00
Cr	1.829	1.327	0.689	0.439	0.00	0.00	0.00	0.00	0.00	0.00
Ni	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
TOTAL	24.000	24.001	24.000	24.000	24.000	24.000	24.000	24.000	24.000	24.000
Usp %	27.33	26.77	25.71	25.42	82.46	83.73	87.16	42.30	48.97	48.97
R203 %	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

BLANK SPACES REPRESENT 'NOT ANALYZED'
0.00 REPRESENTS ANALYZED,
BUT BELOW THEORETICAL LIMIT OF DETECTION.
Fe2O3 calculated after Carmichael (1967)

APPENDIX III

AMPHIBOLE ANALYSES

BULK ROCK	12401	12402	12401	12402
FIELD	E6	E6	E6	E6
ANAL.	11	11	11	11
SPEC.	CORE	CORE	CORE	CORE
SiO2	42.61	40.23	42.01	42.01
TiO2	2.03	2.14	2.71	2.71
Al2O3	11.85	13.83	11.52	11.52
FeO	12.75	14.92	14.79	14.79
MnO	15	15	15	15
MgO	13.55	11.77	12.52	12.52
CaO	10.85	10.88	10.67	10.67
Na2O	2.21	2.37	2.43	2.43
K2O	4.1	3.9	.53	.53
H2O	2.01	1.98	2.00	2.00
P2O5				
F				
TOTAL	98.42	98.77	99.33	99.33
OXYGENS	23.000	23.000	23.000	23.000
Si	6.354	6.071	6.284	6.284
Ti	.228	.243	.305	.305
Al	2.083	2.459	1.030	1.030
Fe	1.589	1.883	1.850	1.850
Mn	.018	.031	.019	.019
Mg	3.012	2.647	2.791	2.791
Ca	1.734	1.758	1.710	1.710
Na	.638	.694	.703	.703
K	.078	.076	.100	.100
OH	2.001	2.000	2.000	2.000
P				
TOTAL	17.735	17.862	16.792	16.792
Mg*	65.50	58.40	60.10	60.10

BLANK SPACES REPRESENT 'NOT ANALYZED'

0.00 REPRESENTS ANALYZED, BUT BELOW THEORETICAL LIMIT OF DETECTION.

APATITE ANALYSES

BULK ROCK	10801	12601
FIELD	J2	G3
ANAL.	20	4
SPEC.	MC	MC
SiO2	19	.12
TiO2	.00	.00
Al2O3	.00	.00
FeO	.84	1.15
MnO	.00	.00
MgO	.16	.30
CaO	53.45	54.47
Na2O	.12	.10
K2O	.00	.00
H2O	.00	.00
P2O5	43.45	38.98
F		3.92
TOTAL	98.21	99.04
OXYGENS	24.000	.000
Si	.030	.000
Ti	.000	.000
Al	.000	.000
Fe	.111	.000
Mn	.000	.000
Mg	.038	.000
Ca	9.111	.000
Na	.036	.000
K	.000	.000
OH	.000	.000
P	5.853	.000
TOTAL	15.179	.000

APPENDIX IV: MINERAL ANALYSES FROM IGNEOUS NODULES.

Specifications, analytical methods and detection limits are the same as given in the introduction to Appendix III. Analyses of minerals in nodules are tabulated according to individual nodules, rather than by mineral species.

Bulk rock numbers refer to analysis numbers of Appendix II. If a nodule itself has been analyzed as a bulk rock, then this bulk rock analysis number is given. If not, then the bulk rock analysis number for the host lava is given.

MINERAL ANALYSES FROM IGNEOUS NODULES

APPENDIX IV

BULK ROCK	17201	17202	17203	10001	10002	10003	10501	10502	10503	10504	10505	11701	11702	11703	11801	11802	12401
FIELD	AXa	AXa	AXa	EI	EI	EI	ES	ES	ES	ES	ES	8BX	8BX	8BX	ASO	ASO	56
ANAL NO.	5.00	9.00	6.00	7.00	10.00	9.00	30.00	29.00	25.00	20.00	22.00	3.00	1.00	2.00	4.00	7.00	1.00
MINERAL	Cpx	OPX	OPX	PLAG	Cpx	TMT	PLAG	Cpx	OPX	ILM	TMT	PLAG	Cpx	OPX	PLAG	OPX	OPX
SPEC.	52.37	53.83	50.00	48.82	51.43	16.00	54.91	52.38	53.70	49.69	13.89	49.78	53.98	52.63	47.71	52.93	37.00
SiO2	1.14	1.11	1.11	1.08	1.07	1.05	28.57	2.31	1.33	1.17	32.59	32.77	2.27	1.85	32.58	1.85	1.00
TiO2	6.40	15.46	43.38	60.00	8.89	38.00	54.95	11.38	22.06	47.05	39.37	47.00	8.25	16.71	54.00	16.71	27.89
Al2O3	6.25	33.33	4.17	0.00	14.12	19.00	11.00	13.66	22.09	2.35	2.56	0.00	16.32	25.09	0.00	25.09	33.97
FeO	16.30	27.84	4.17	0.00	20.41	13.00	11.48	19.20	1.40	0.00	0.26	15.43	19.14	1.40	16.35	1.41	0.08
MnO	22.40	1.03	0.00	16.04	20.41	0.00	4.84	37.00	1.00	0.00	0.00	2.44	2.46	0.00	2.23	0.00	0.00
CaO	22.41	0.00	0.00	2.24	0.38	0.00	0.28	0.00	0.00	0.00	0.00	0.08	0.00	0.00	0.05	0.00	0.00
Na2O	0.00	0.00	0.00	0.06	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
K2O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cr2O3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TOTAL	99.34	99.80	100.16	100.11	98.79	98.24	100.42	100.24	101.40	100.13	97.68	100.97	100.75	98.33	99.46	98.34	99.39
OXYGENS	6.000	6.000	6.000	8.000	6.000	8.000	8.000	6.000	6.000	6.000	8.000	8.000	6.000	6.000	8.000	6.000	4.000
Si	1.963	1.946	1.946	2.234	1.935	0.13	2.488	1.953	1.868	1.883	0.16	2.249	1.968	1.980	2.203	1.947	0.987
Ti	0.047	0.051	0.000	0.000	0.016	0.093	1.513	0.102	0.058	0.010	0.229	1.745	0.010	0.006	0.000	0.007	0.000
Al	0.197	0.467	1.796	0.023	0.280	2.501	0.020	0.355	0.676	1.983	2.473	0.018	0.251	0.450	0.021	0.517	0.628
Fe3	0.008	0.010	0.012	0.000	0.009	0.013	0.000	0.008	0.013	0.015	0.020	0.000	0.006	0.009	0.000	0.012	0.010
Mn	0.892	1.500	0.308	0.000	0.792	0.045	0.000	0.760	1.308	0.202	0.286	0.000	0.886	1.423	0.000	1.384	1.384
Ca	0.881	0.040	0.000	0.787	0.928	0.011	0.553	0.767	0.055	0.000	0.021	0.747	0.747	0.054	0.809	0.056	0.002
Na	0.015	0.000	0.000	0.199	0.028	0.000	0.000	0.027	0.007	0.000	0.000	0.215	0.017	0.000	0.199	0.000	0.000
K	0.000	0.000	0.000	0.004	0.000	0.000	0.016	0.004	0.000	0.000	0.000	0.005	0.000	0.000	0.003	0.000	0.000
Cr	0.005	0.000	0.054	0.000	0.000	0.043	0.000	0.000	0.000	0.008	0.076	0.000	0.000	0.000	0.000	0.000	0.000
Ni	0.000	0.000	0.007	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
TOTAL	4.012	4.017	4.067	4.992	4.102	6.001	4.974	3.992	3.993	4.099	6.001	4.979	3.981	3.980	5.008	4.004	3.001
Ca	44.50	2.00	0.00	0.00	43.20	0.00	0.00	40.60	2.80	0.00	0.00	0.00	39.50	2.80	0.00	2.80	0.00
Mg	45.10	74.40	0.00	0.00	41.60	0.00	0.00	40.20	61.90	0.00	0.00	0.00	46.90	73.50	0.00	70.30	0.00
Fe+Mn	10.40	23.60	0.00	0.00	15.20	0.00	0.00	19.20	35.30	0.00	0.00	0.00	13.60	23.70	0.00	26.90	0.00
Mg*	82.00	76.30	0.00	0.00	73.80	0.00	0.00	68.20	64.10	0.00	0.00	0.00	77.90	76.00	0.00	72.80	68.50
Al*	0.00	0.00	0.00	79.50	0.00	0.00	56.80	0.00	0.00	0.00	0.00	77.20	0.00	0.00	80.00	0.00	0.00
Ab	0.00	0.00	0.00	20.10	0.00	0.00	41.50	0.00	0.00	0.00	0.00	22.20	0.00	0.00	19.70	0.00	0.00
Or	0.00	0.00	0.00	0.40	0.00	0.00	1.70	0.00	0.00	0.00	0.00	0.60	0.00	0.00	0.30	0.00	0.00

BLANK SPACES REPRESENT 'NOT ANALYZED'
 0.00 REPRESENTS ANALYZED,
 BUT BELOW THEORETICAL LIMIT OF DETECTION.

Fe2O3 calculated after Carmichael (1967)

APPENDIX IV

BULK ROCK	12402	12403	12404	16701	16702	16703	16704	16705	16706	16707	16708	16709	16710	16711	16712	16713	12901
FIELD NO.	E6	E6	E6	GIX	GIX	GIX	GIX	GIX	GIX	GIX	GIX	GIX	GIX	GIX	GIX	GIX	KIG
ANAL NO.	5.00	4.00	3.00	23.00	1.00	36.00	18.00	15.00	25.00	6.00	17.00	12.00	3.00	11.00	4.00	10.00	2.00
MINERAL	CPX	OPX	PLAG	CPX	OPX	AM	PLAG	PLAG	GLAS	OPX	AM	AM	PLAG	TMT	ILM	GLAS	CPX
SPEC	CORE	CORE	CORE	CORE	CORE	CORE	CORE	CORE	GLAS	CORE	CORE	CORE	CORE	CORE	CORE	CORE	CORE
SiO2	51.94	52.44	49.28	52.52	54.23	44.42	46.86	46.41	68.80	51.65	40.89	42.16	47.04	17.83	45.81	68.31	51.85
TiO2	1.30	1.18	1.76	2.38	1.19	2.31	3.00	3.18	1.03	2.84	12.56	11.17	33.63	3.32	10.86	1.11	1.39
Al2O3	1.53	1.18	31.18	2.63	1.82	11.88	33.95	34.18	14.65	2.84	12.56	11.17	33.63	27.10	10.86	13.01	2.78
FeO	9.12	20.56	57.00	6.79	15.56	10.18	28.00	31.00	4.00	17.93	11.70	14.29	47.00	43.15	30.12	3.70	6.64
MnO	30.30	54.00	0.00	20.00	32.00	13.00	0.00	0.00	0.00	23.33	13.16	12.22	0.00	1.30	8.29	0.00	1.18
MgO	14.31	22.89	0.00	15.39	26.37	14.29	0.00	0.00	5.51	23.54	13.47	12.13	0.00	1.85	8.92	2.27	16.29
CaO	21.17	1.25	14.93	21.73	1.23	11.43	18.20	17.90	2.90	2.11	11.39	10.95	17.31	1.08	1.34	1.96	20.38
Na2O	36.00	0.00	2.91	0.00	0.00	2.14	1.49	1.40	4.02	0.00	2.12	2.10	1.59	0.00	0.00	4.02	3.10
K2O	0.00	0.00	0.00	0.00	0.00	2.76	0.00	0.00	2.79	0.00	4.44	0.00	0.00	0.00	0.00	3.73	0.00
Cr2O3	0.00	0.00	0.00	0.00	0.00	0.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.00	0.00	1.14
NiO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TOTAL	99.03	98.62	99.00	99.79	99.62	97.74	100.78	100.20	98.70	98.90	95.26	96.56	100.04	93.84	97.26	96.11	98.96
OXYGENS	6.000	6.000	8.000	6.000	6.000	23.000	8.000	8.000	0.000	6.000	23.000	23.000	8.000	24.000	6.000	0.000	6.000
Si	1.956	1.971	2.275	1.939	1.962	6.453	2.141	2.131	0.000	1.916	6.167	6.347	2.162	4.028	0.028	0.000	1.926
Ti	0.008	0.005	0.000	0.011	0.005	0.252	0.000	0.000	0.000	0.014	0.287	0.319	0.000	4.175	1.694	0.000	0.011
Al	0.068	0.034	1.697	0.115	0.077	2.034	1.828	1.828	0.000	0.124	2.233	1.982	1.821	6.350	1.021	0.000	0.122
Fe3	0.287	0.646	0.222	0.209	0.471	1.237	0.111	0.111	0.000	0.556	1.476	1.799	0.118	11.238	1.239	0.000	0.206
Fe2	0.009	0.017	0.000	0.008	0.010	0.016	0.000	0.000	0.000	0.010	0.021	0.028	0.000	0.079	0.012	0.000	0.006
Mg	0.803	1.282	0.000	0.847	1.417	3.095	0.000	0.000	0.000	1.302	3.030	2.722	0.000	8.59	0.64	0.000	0.902
Ca	0.854	0.550	0.739	0.859	0.047	1.778	0.891	0.801	0.000	0.084	1.841	1.765	0.853	0.300	0.18	0.000	0.811
Na	0.268	0.000	0.260	0.111	0.000	0.602	0.132	0.132	0.000	0.000	0.648	0.613	0.142	0.000	0.000	0.000	0.022
K	0.000	0.000	0.000	0.000	0.000	0.141	0.000	0.000	0.000	0.000	0.085	0.138	0.000	0.000	0.000	0.000	0.000
Cr	0.000	0.000	0.000	0.000	0.000	0.023	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.025	0.000	0.000	0.000
Ni	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.004
TOTAL	4.011	4.005	5.000	3.997	3.989	15.631	5.003	4.903	0.000	4.006	15.788	15.713	4.996	24.501	4.068	0.000	4.010
Ca	43.70	2.50	0.00	44.70	2.40	0.00	0.00	0.00	0.00	4.30	0.00	0.00	0.00	0.00	0.00	0.00	42.10
Mg	41.10	64.30	0.00	44.10	72.90	0.00	0.00	0.00	0.00	66.70	0.00	0.00	0.00	0.00	0.00	0.00	46.90
Fe+Mn	15.20	33.20	0.00	11.20	24.70	0.00	0.00	0.00	0.00	29.00	0.00	0.00	0.00	0.00	0.00	0.00	11.00
Al	73.10	65.90	0.00	80.20	75.00	71.40	87.10	87.10	18.50	70.10	67.20	60.20	0.00	0.00	0.00	11.10	81.40
Si	0.00	0.00	73.50	0.00	0.00	0.00	87.10	87.10	0.00	0.00	0.00	0.00	85.80	0.00	0.00	0.00	0.00
Al	0.00	0.00	25.80	0.00	0.00	0.00	12.90	12.90	0.00	0.00	0.00	0.00	14.20	0.00	0.00	0.00	0.00
Cr	0.00	0.00	0.70	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

BLANK SPACES REPRESENT 'NOT ANALYZED'

0.00 REPRESENTS ANALYZED
BUT BELOW THEORETICAL LIMIT OF DETECTION.

Fe2O3 calculated after Carmichael (1967)

APPENDIX IV

BULK ROCK	12902	13701	13702	13703	13704	13705	13801	13602	13603	13604	13605	13606	13607	13608	13609	13610	13611
FIELD NO.	K1G	F4	F4	F4	F4	CPX	H7X-2	H7X-2	H7X-2	H7X-2	H7X-2	H7X-2	H7X-2	H7X-2	H7X-2	H7X-2	H7X-2
ANAL NO.	4.00	5.00	4.00	10.00	9.00	20.00	8.00	58.00	10.00	10.00	1.00	4.00	38.00	46.00	17.00	16.00	50.00
MINERAL	PLAG	OL	SP	OPX	PLAG	CPX	RTM	OPX	OPX	OPX	PLAG	SP	OPX	OPX	SP	SP	GLAS
SPEC.	CORE	CORE	OL	OL	OL	OL	RTM	CORE	CORE	RTM	OL	OL	INT	INT	INT	INT	INT
SiO2	47.74	40.76	00	55.09	59.79	53.88	40.77	40.22	54.13	54.60	50.32	42	52.01	50.92	00	00	54.40
TiO2	00	00	38	11	12	15	00	00	00	00	12	11	7.81	00	00	21	00
Al2O3	32.14	00	8.95	2.30	23.86	1.51	00	00	3.59	3.71	31.00	11.43	7.81	5.93	12.63	56.60	19.65
Fe2O3	00	00	8.68	00	00	00	11.30	12.63	8.86	8.57	51	17.07	9.16	5.19	22.32	10.24	5.63
FeO	46	11.88	20.03	11.12	1.00	6.43	48.16	46.27	30.25	31.14	00	17	29.12	15.43	11.65	19.23	4.13
MnO	00	00	00	24	00	26	18	16	16	17	10.98	10.98	29.12	19.71	00	00	9.46
MgO	00	47.38	8.70	29.86	7.28	20.11	18	13	1.41	1.31	3.24	00	1.36	40	00	00	3.06
CaO	15.48	00	00	1.10	00	19	00	00	00	00	00	00	00	00	00	00	1.36
Na2O	2.42	00	00	00	6.87	00	00	00	00	00	16	00	00	00	00	00	00
K2O	00	00	00	00	00	00	00	00	00	00	00	52.48	00	00	53.34	4.40	00
Cr2O3	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00
NiO	00	00	52.20	17	00	17	38	23	18	17	99.75	99.09	100.05	98.87	100.35	96.13	98.98
TOTAL	98.33	100.48	98.92	99.99	99.48	99.83	100.93	99.88	100.06	100.03	99.75	99.09	100.05	98.87	100.35	96.13	98.98
OXYGENS	8.000	4.000	8.000	6.000	8.000	6.000	4.000	4.000	6.000	6.000	8.000	8.000	6.000	6.000	8.000	8.000	000
Si	2.222	1.003	000	1.923	2.694	1.974	.998	1.000	1.898	1.910	2.303	000	1.824	1.876	000	000	000
Ti	0.000	0.000	019	003	1.004	004	000	000	004	003	000	021	005	012	014	085	000
Al	1.763	000	000	096	1.257	085	000	000	000	1.153	1.672	004	323	027	974	3.609	000
Fe3	.018	.245	1.138	328	038	197	231	263	260	251	019	318	269	160	1.222	1.395	000
Fe2	.004	.004	000	007	000	008	103	104	107	104	000	041	005	005	1.000	1.462	000
Mn	.000	.000	000	009	009	008	1.757	1.722	1.620	1.620	011	1.079	1.522	005	1.136	1.946	000
Mg	.772	1.738	.881	1.572	009	936	004	003	053	049	703	000	052	008	000	000	000
Ca	.219	.003	000	.042	352	014	000	000	000	000	000	000	000	000	000	000	000
Na	.005	.000	000	000	036	000	000	000	000	000	009	000	000	000	000	000	000
K	.000	.000	000	000	000	005	000	000	000	000	000	2.736	000	000	2.768	1.188	000
Cr	.000	.000	000	000	000	000	000	000	000	000	000	000	000	000	000	000	000
Ni	.000	.000	000	000	000	000	000	000	000	000	000	000	000	000	000	000	000
TOTAL	4.999	2.997	6.002	3.977	4.991	3.983	3.000	2.997	4.014	4.004	5.004	5.999	4.005	3.984	6.112	6.076	000
Ca	00	00	00	2.20	00	40.90	00	00	2.70	2.50	00	00	2.80	43.40	00	00	00
Mg	00	00	00	80.60	00	48.50	00	00	83.50	84.20	00	00	82.30	47.30	00	00	00
Fe+Mn	00	00	00	17.20	00	10.60	00	00	13.80	13.30	00	00	14.90	9.10	00	00	00
Fe*	00	87.60	00	8.70	00	82.00	88.40	86.00	86.20	86.60	00	00	85.00	84.10	48.20	00	56.60
Al	00	00	00	00	00	00	00	00	00	00	70.40	00	00	00	00	00	00
Ab	77.50	00	00	00	35.60	00	00	00	00	00	28.70	00	00	00	00	00	00
Or	22.00	00	00	00	60.80	00	00	00	00	00	00	00	00	00	00	00	00
Or	50	00	00	00	3.60	00	00	00	00	00	90	00	00	00	00	00	00

BLANK SPACES REPRESENT 'NOT ANALYZED'

0.00 REPRESENTS ANALYZED, BUT BELOW THEORETICAL LIMIT OF DETECTION.

Fe2O3 calculated after Carmichael (1967)

APPENDIX IV

BULK ROCK	13612	13613	13614	13615	13616	13617	13618	13619	13620	13621	13622	13623	13624	13625	13626	13627	13628
FIELD	H7X-6	H7X-6	H7X-6	H7X-10	H7X-14	H7X-14	H7X-14	H7X-14	H7X-14	H7X-16	H7X-16	H7X-16	H7X-16	H7X-16	H7X-17	H7X-17	H7X-17
ANAL. NO.	2.00	3.00	16.00	5.00	8.00	8.00	8.00	3.00	1.00	9.00	7.00	9.00	3.00	24.00	1.00	7.00	4.00
MINERAL	OL	SP	GLAS	OL	SP	SP	SP	PLAG	GLAS	CPX	SP	SP	PLAG	GLAS	OL	OPX	PLAG
SPEC.	CORE	GLAS	INT	CORE	CORE	CORE	CORE	CORE	INT	CORE	CPX	CPX	INT	INT	CORE	CORE	CORE
SiO2	41.15	53.56	53.56	41.83	52.72	51.45	1.02	54.23	62.03	53.20	.00	.61	50.44	60.27	37.29	53.01	48.44
TiO2	.00	.51	.00	.00	1.69	2.50	11.73	27.99	13.99	3.24	53.01	36.65	30.77	14.83	.00	3.09	32.80
Al2O3	.00	11.03	18.14	.00	.00	.00	11.73	.00	.00	.00	19.90	20.07	.00	.00	.00	.00	.00
FeO	10.26	16.47	6.12	7.83	18.97	11.91	22.92	.46	4.95	6.66	11.64	15.77	.36	7.45	26.92	16.22	.48
MnO	.00	.00	.12	.00	.00	.00	.00	.00	.00	.00	.35	.15	.00	.00	.39	.26	.00
MgO	47.58	11.44	4.40	50.69	23.32	15.12	11.32	11.40	2.27	16.42	17.71	13.07	.00	3.07	35.80	25.53	.00
CaO	.12	.00	8.32	.14	2.07	16.89	.00	.00	2.66	19.56	.22	.30	14.44	5.62	.15	1.46	16.23
Na2O	.00	.00	4.46	.00	.00	.00	.00	4.38	2.09	.00	.00	.00	.00	.00	.00	.00	.00
K2O	.00	.00	2.04	.00	.00	.00	.00	.00	2.30	.00	.00	.00	.00	1.98	.00	.00	.17
Cr2O3	.00	.00	.00	.00	.00	.00	.00	.00	.00	.14	4.28	6.93	.00	.00	.00	.00	.00
NiO	.31	.00	.00	.00	.11	.00	.23	.00	.00	.29	.67	.54	.00	.00	.25	.00	.00
TOTAL	99.42	99.27	98.63	101.13	99.53	99.28	98.52	98.90	94.68	100.27	97.78	94.24	99.13	98.32	100.70	99.97	100.12
OXYGENS	4.000	8.000	.000	4.000	6.000	6.000	8.000	3.000	.000	6.000	8.000	8.000	8.000	.000	8.000	6.000	8.000
Si	1.015	.000	.000	1.004	1.948	1.933	.000	2.478	.000	1.841	.000	.009	2.316	.000	.886	1.920	2.215
Ti	.000	.025	.000	.000	.011	.018	.043	.000	.000	.009	.000	.028	.000	.000	.000	.011	.000
Al	.000	.854	.000	.000	.073	.111	3.435	1.506	.000	.140	3.409	2.859	1.665	.000	.000	.132	1.788
Fe3	.212	.905	.000	.157	.583	.374	1.083	.017	.000	.204	.531	.811	.014	.000	.595	.491	.018
Fe2	.000	.000	.000	.000	.011	.009	.007	.000	.000	.000	.016	.008	.000	.000	.006	.008	.000
Mn	1.749	1.120	.000	1.813	1.284	.847	.932	.007	.000	.984	1.440	1.098	.000	.000	1.411	1.329	.000
Ca	.003	.000	.000	.004	.082	.880	.000	.537	.000	.767	.013	.020	.710	.000	.004	.037	.795
Na	.000	.000	.000	.000	.000	.034	.000	.386	.000	.020	.000	.000	.263	.000	.000	.000	.118
K	.000	.000	.000	.000	.000	.000	.000	.021	.000	.000	.000	.000	.000	.000	.000	.000	.000
Cr	.000	.000	.000	.000	.003	.000	.005	.000	.000	.005	.185	.337	.000	.000	.005	.000	.000
Ni	.008	.000	.000	.012	.000	.000	.000	.000	.000	.009	.000	.000	.000	.000	.009	.000	.000
TOTAL	2.985	5.999	.000	2.990	3.995	4.006	5.998	4.970	.000	3.989	6.000	5.999	4.978	.000	3.007	3.998	4.984
Ca	.00	.00	.00	.00	4.20	35.60	.00	.00	.00	41.10	.00	.00	.00	.00	.00	2.90	.00
Mg	.00	.00	.00	.00	65.50	44.30	.00	.00	.00	47.90	.00	.00	.00	.00	.00	71.30	.00
Fe+Mn	.00	.00	.00	.00	30.30	20.10	.00	.00	.00	10.90	.00	.00	.00	.00	.00	25.80	.00
Mg*	89.20	.00	41.80	92.00	68.80	69.40	.00	.00	44.60	81.40	.00	.00	.00	42.50	70.30	73.70	.00
An	.00	.00	.00	.00	.00	.00	.00	57.80	.00	.00	.00	.00	.00	.00	.00	.00	80.90
Ab	.00	.00	.00	.00	.00	.00	.00	40.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
Or	.00	.00	.00	.00	.00	.00	.00	2.20	.00	.00	.00	.00	1.00	.00	.00	.00	1.00

IV-4

BLANK SPACES REPRESENT 'NOT ANALYZED'

0.00 REPRESENTS ANALYZED,
BUT BELOW THEORETICAL LIMIT OF DETECTION.

Fe2O3 calculated after Carmichael (1967)

APPENDIX IV

BULK ROCK	13829
FIELD	H7X-17
ANAL. NO.	6.00
MINERAL	TMT
SPEC.	PLAG
SiO ₂	.00
TiO ₂	15.68
Al ₂ O ₃	6.26
Fe ₂ O ₃	29.50
FeO	36.03
MnO	.19
MgO	5.64
CaO	.27
Na ₂ O	.00
K ₂ O	.00
Cr ₂ O ₃	1.56
NiO	.19
TOTAL	95.32

OXYGENS

Si	8.000
Ti	.000
Al	.887
Fe ₂	1.543
Fe ₃	1.632
Mn	2.216
Cr	.012
Na	.618
K	.021
Ca	.000
Cr	.000
Ni	.091
TOTAL	6.000

Ca

.00

Mg

.00

Fe+Mn

.00

Mg*

.00

An

.00

Ab

.00

Or

.00

BLANK SPACES REPRESENT 'NOT ANALYZED'

0.00 REPRESENTS ANALYZED,
BUT BELOW THEORETICAL LIMIT OF DETECTION.Fe₂O₃ calculated after Carmichael (1967)

APPENDIX V: MINERAL ANALYSES FROM METAMORPHIC XENOLITHS.

1. INTRODUCTION

Mineral analyses from metaigneous and metasedimentary xenoliths are given. Specifications, analytical methods and detection limits are the same as given in the introduction to Appendix III. Mineral analyses from xenoliths are tabulated according to individual xenoliths, rather than by mineral species.

Bulk rock numbers refer to analysis numbers of Appendix II. If a xenolith itself has been analyzed as a bulk rock, then this bulk rock analysis number is given. If not, then the analysis number for the host lava is given. If neither the xenolith nor the host lava have been analyzed as bulk rocks, then no 'bulk rock' entry is made.

Xenolith minerals from specimens B10Xi, Xc and N112C were analyzed by M. Otsuki. All other analyses are by the author.

2. PETROGRAPHIC AND LOCALITY NOTES.

Several of these xenoliths have been analyzed as bulk rocks in Appendix II; locality and petrographic descriptions for these are given in Appendix II. Petrographic and locality descriptions for xenoliths not analyzed as bulk rocks in Appendix II are given below.

FIELD NUMBER	GRID REFERENCES		metric	LOCALITY NOTES	PETROGRAPHIC NOTES (most abundant mineral is given next to rock name)
	yard				
I1	N122/025590	S20/282044		Xenolith from lava flow on E bank of Mangaehuehu River, south Ruapehu. Host lava is VUV 14855 (not analyzed).	opaque oxide- hypersthene- andesine/labradorite hornfels; very fine xenoblastic texture; mineralogically and texturally similar to A11x hornfels.
Gx	N122/040456	T20/305933		Xenolith from lava flow of Rangataua Member, south Ruapehu. Host lava is analysis 126 of Appendix II.	apatite-opaque oxide-hypersthene-glass-labradorite hornfels. Texturally and mineralogically similar to A11x and I1 hornfels, but partial fusion is more advanced and the rock has web texture. See Fig 122F.
B3x	N112/038717	S20/295181		Xenolith from lava flow of Iwikau Member, Whakapapaiti trailhead. Host lava is analysis 117 of Appendix II.	alkali feldspar- biotite- titanomagnetite- spinel- hypersthene- labradorite hornfels. Finely banded xenoblastic texture: See Fig 97C.
B6xc/A	N112/057708	T20/311154		Xenolith from Iwikau Member lava flow, along road to Mead's Wall rope tow. Host lava is analysis 112 of Appendix II.	glass- augite- bronzite- andesine hornfels, with poikiloblastic texture and incipient fusion to pale brown glass.
J1x	N122/020688	S20/277139		Xenolith from Mangawhero Formation lava flow, along ridge crest S of Whakapapaiti Stream. Host lava is analysis 110.	apatite- hypersthene- almandine- biotite- hercynite- andesine gneiss. See Figure 122D.
B10xi	N122/079688	T20/328139		Xenolith from airfall tuff of Iwikau Member, north Ruapehu. Host deposit is analysis 121 of Appendix II.	ilmenite- hematite- ferrohypersthene- almandine- hercynite- biotite- sanidine- andesine- quartz gneiss. Contorted banding is developed by alternating quartzofeldspathic and biotite-rich layers. See Fig. 97H.
N112A	N112/106719	T20/355161		Xenolith within float block of microperlitic dacite, N Ruapehu. Host material is analysis 130 of Appendix II.	ilmenite- glass- ferrohypersthene- almandine- hercynite- biotite- orthoclase- andesine gneiss. See Fig. 122A,B.
Xc	N121/914512	S20/174976		Xenolith within accessory lithic block of Ruapehu andesite, ejecta of Ohakune vents. Host block has not been analyzed.	ilmenite- almandine- cordierite- hercynite- ferrohypersthene- oligoclase hornfels, with xenoblastic texture. See Fig. 97F.
Xd	N121/914512	S20/174976		Xenolith within accessory lithic block of Ruapehu andesite, ejecta of Ohakune vents. Host block has not been analyzed.	garnet- sillimanite- ilmenite- ferrohypersthene- cordierite- orthoclase- oligoclase hornfels. Texturally and mineralogically similar to "Xc", but sillimanite is present as fibrolite inclusions in cordierite poikiloblasts. See Figure 97F.

MINERAL ANALYSES FROM METAMORPHIC XENOLITHS

APPENDIX V

BULK ROCK	16801	16802	16803	16804	12601	12602	12603	12604	12605	11701	11702	11703	11704	11705
FIELD NO.	16801	16802	16803	16804	12601	12602	12603	12604	12605	11701	11702	11703	11704	11705
ANAL NO.	16801	16802	16803	16804	12601	12602	12603	12604	12605	11701	11702	11703	11704	11705
MINERAL	AlX	AlX	AlX	AlX	GX	GX	GX	GX	GX	B3X	B3X	B3X	B3X	B3X
SPEC	OPX	OPX	OPX	OPX	OPX	OPX	OPX	OPX	OPX	OPX	OPX	OPX	OPX	OPX
SiO2	50.84	50.84	50.84	50.84	52.50	52.50	52.50	52.50	52.50	52.48	52.48	52.48	52.48	52.48
Al2O3	6.25	6.25	6.25	6.25	1.66	1.66	1.66	1.66	1.66	4.65	4.65	4.65	4.65	4.65
FeO	19.34	19.34	19.34	19.34	21.83	21.83	21.83	21.83	21.83	16.05	16.05	16.05	16.05	16.05
MnO	23.61	23.61	23.61	23.61	22.86	22.86	22.86	22.86	22.86	25.73	25.73	25.73	25.73	25.73
CaO	30.00	30.00	30.00	30.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MgO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Na2O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
K2O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cr2O3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NiO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
P2O5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TOTAL	101.23	99.72	100.84	100.23	100.18	97.02	100.46	97.34	96.29	100.07	98.79	98.57	96.53	99.80
H2O	6.000	6.000	6.000	6.000	6.000	6.000	6.000	6.000	6.000	6.000	6.000	6.000	6.000	6.000
OXYGENS	1.842	1.842	1.842	1.842	1.947	1.947	1.947	1.947	1.947	1.893	1.893	1.893	1.893	1.893
Si	0.15	0.15	0.15	0.15	0.07	0.07	0.07	0.07	0.07	0.08	0.08	0.08	0.08	0.08
Al	0.267	0.267	0.267	0.267	0.073	0.073	0.073	0.073	0.073	0.198	0.198	0.198	0.198	0.198
Fe	0.586	0.586	0.586	0.586	0.677	0.677	0.677	0.677	0.677	0.484	0.484	0.484	0.484	0.484
Mn	0.111	0.111	0.111	0.111	0.105	0.105	0.105	0.105	0.105	0.18	0.18	0.18	0.18	0.18
Mg	1.275	1.275	1.275	1.275	1.263	1.263	1.263	1.263	1.263	1.384	1.384	1.384	1.384	1.384
Ca	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.012	0.012	0.012	0.012	0.012
Na	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
K	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Cr	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
P	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
TOTAL	4.008	6.000	4.994	3.983	4.008	6.163	4.963	7.711	0.000	3.997	6.000	6.001	15.195	4.982
Ca	60	60	60	30	1.20	1.20	1.20	1.20	0.00	60	60	60	60	60
Mg	67.70	67.70	67.70	33.60	63.80	63.80	63.80	63.80	0.00	72.90	72.90	72.90	72.90	72.90
Fe+Mn	31.70	31.70	31.70	33.60	35.10	35.10	35.10	35.10	0.00	26.40	26.40	26.40	26.40	26.40
Mg*	68.50	68.50	68.50	65.90	65.10	65.10	65.10	65.10	9.50	74.00	74.00	74.00	74.00	74.00
Al	0.00	0.00	0.00	55.90	50.30	50.30	50.30	50.30	0.00	0.00	0.00	0.00	0.00	0.00
Ab	0.00	0.00	0.00	43.00	47.70	47.70	47.70	47.70	0.00	0.00	0.00	0.00	0.00	0.00
Or	0.00	0.00	0.00	1.10	2.00	2.00	2.30	2.30	0.00	0.00	0.00	0.00	0.00	0.00

BLANK SPACES REPRESENT 'NOT ANALYZED'

0.00 REPRESENTS ANALYZED,
BUT BELOW THEORETICAL LIMIT OF DETECTION.

Fe2O3 calculated after Carmichael (1967)

APPENDIX V

BULK ROCK	11706	11707	11201	11202	11203	11001	11002	11003	11004	11005	11008	12/01	12/02	12/03	12/04	12/05	12/06
FIELD NO.	B3X	B3X	B6XC/A	B6XC/A	B6XC/A	JIX	JIX	JIX	JIX	JIX	JIX	B10X1	B10X1	B10X1	B10X1	B10X1	B10X1
ANAL NO.	19.00	16.00	1.00	2.00	4.00	10.00	1.00	90.00	70.00	4.00	5.00	6.00	22.00	3.00	4.00	28.00	19.00
MINERAL	PLAG	KSPR	CPX	OPX	PLAG	OPX	BIO	GAR	SP	PLAG	PLAG	OPX	GAR	GAR	BIO	ILM	PLAG
SPEC.	CORE	CORE	CORE	CORE	CORE	CORE	CORE	CORE	CORE	CORE	CORE	CORE	CORE	CORE	CORE	CORE	CORE
SiO2	54.78	63.64	52.61	53.88	56.79	48.46	36.60	39.21	.00	59.79	57.00	43.79	37.60	37.87	34.54	55.25	55.51
TiO2	.00	.25	.00	.00	.00	48.46	3.85	.00	.00	.00	.00	.37	.14	.00	.00	.00	.00
Al2O3	29.02	21.07	1.81	.37	27.04	7.01	17.30	22.22	55.98	25.78	28.57	11.03	21.15	21.27	17.80	55.35	27.70
Fe2O3	.43	.28	7.84	18.55	.41	25.74	16.14	27.41	3.77	.15	.16	29.14	25.82	29.33	15.78	34.78	.17
MnO	.00	.00	.18	.55	.00	.37	.00	.97	.14	.00	.00	.68	6.40	3.89	.00	1.42	.00
MgO	.00	.00	15.75	25.27	.00	17.57	13.11	9.28	6.49	.00	.00	14.60	5.48	5.78	11.38	2.56	.00
CaO	.00	.00	20.71	.80	9.88	.29	.00	1.34	.00	7.45	8.65	.15	2.79	1.47	.00	.00	.00
Na2O	4.59	4.38	.42	.00	5.84	.00	.72	.00	.00	.00	.00	.00	.00	.00	.45	.00	9.94
K2O	0.42	8.48	.00	.00	.00	.00	.00	.00	.00	0.91	.58	.18	.00	.00	8.82	.00	5.84
Cr2O3	.00	.00	.18	.11	.00	.00	.00	.00	.18	.00	.00	.00	.00	.00	.00	.00	.55
NiO	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
P2O5	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
TOTAL	100.50	99.42	100.08	99.53	100.35	99.85	86.42	100.43	96.73	100.85	100.21	99.94	99.38	99.61	93.10	94.55	99.71
H2O	8.000	8.000	6.000	6.000	8.000	6.000	23.000	12.000	8.000	8.000	8.000	6.000	12.000	12.000	3.910	6.000	8.000
OXYGENS	2.458	2.900	1.944	1.983	2.547	1.836	5.651	2.998	.000	2.647	2.541	1.699	2.988	3.000	5.298	.012	2.509
Si	.000	.009	.017	.000	.000	.012	.447	.000	.010	.000	.000	.011	.008	.000	.498	.110	.000
Ti	1.535	1.131	.079	.016	1.429	.313	3.148	2.004	3.808	1.346	1.501	.504	1.980	1.986	3.218	.012	1.476
Al	.016	.011	.243	.571	.015	.818	2.084	1.754	1.445	.005	.006	.945	1.715	1.943	2.025	.000	.006
Fe3	.000	.000	.006	.017	.000	.012	.000	.062	.007	.000	.000	.022	.430	.261	.012	.060	.000
Fe2	.000	.000	.888	1.385	.000	.093	3.016	1.058	.558	.000	.000	.844	.648	.683	2.602	.194	.000
Mn	.000	.000	.820	.031	.000	.012	.000	.110	.000	.000	.000	.006	.238	.125	.000	.000	.000
Mg	.539	.064	.030	.000	.508	.000	.215	.000	.000	.580	.454	.000	.000	.000	.133	.000	.482
Ca	.399	.388	.030	.000	.022	.000	1.713	.000	.000	.052	.033	.009	.000	.000	.000	.000	.517
Na	.027	.494	.000	.000	.000	.000	.000	.000	.007	.000	.000	.000	.000	.000	1.725	.000	.031
K	.000	.000	.005	.003	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
Cr	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
P	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
TOTAL	4.974	4.997	4.012	4.006	9.271	3.394	16.274	7.986	5.999	8.170	8.665	4.040	8.005	7.998	15.512	3.862	5.021
Ca	.00	.00	42.30	42.30	.00	.60	.00	.00	.00	.00	.00	.30	.00	.00	.00	.00	.00
Mg	.00	.00	44.80	44.80	.00	54.20	.00	.00	.00	.00	.00	46.50	.00	.00	.00	.00	.00
Fe+Mn	.00	.00	12.90	12.90	.00	45.20	.00	.00	.00	.00	.00	53.20	.00	.00	.00	.00	.00
Mg*	.00	.00	78.10	78.10	.00	54.90	59.10	37.60	.00	.00	.00	47.20	27.40	26.00	.00	.00	.00
Al	55.90	6.70	.00	.00	47.30	.00	.00	.00	.00	35.90	45.90	.00	.00	.00	.00	.00	47.00
Ab	41.30	41.00	.00	.00	50.50	.00	.00	.00	.00	58.80	50.40	.00	.00	.00	.00	.00	50.00
Or	2.80	52.20	.00	.00	2.20	.00	.00	.00	.00	5.30	3.70	.00	.00	.00	.00	.00	3.00

BLANK SPACES REPRESENT 'NOT ANALYZED'

0.00 REPRESENTS ANALYZED,
BUT BELOW THEORETICAL LIMIT OF DETECTION.

APPENDIX V

[illegible]

BLANK SPACES REPRESENT 'NOT ANALYZED'

0.00 REPRESENTS ANALYZED, BUT BELOW THEORETICAL LIMIT OF DETECTION.

APPENDIX VI: LEAST SQUARES MIXING CALCULATIONS

1. INTRODUCTION.

Quantitative modelling of fractional crystallization, magma mixing and crystal accumulation is undertaken, using the least- squares mixing programme of Wright and Doherty (1970), with format modifications by K. Palmer of the Analytical Facility, Victoria University of Wellington. The user must input major element compositions for parent liquid, derivative liquid and fractionating minerals. The programme then uses the input data matrix to calculate a "match" to the observed parent magma composition, by mixing fractionated minerals back into the derivative magma; this is algebraically equivalent to: (parent liquid) - (fractionated crystals) - (derivative magma). The programme follows an iterative procedure, whereby the best "match" is achieved when the sum of the squares of the residuals is minimized (R^2 ; 'residuals' are differences between calculated and observed individual oxide concentrations).

As Wright (1974) has indicated, setting up a mixing model is usually simple, but evaluation of the result can be complex. Ideally, residuals in the solution must be below reasonable analytical error, and then the solution must be evaluated for consistency with other petrologic, geologic and geophysical information. Although Wright (1974) suggests 0.1 % as an acceptable upper limit of individual oxide residuals, acceptance or rejection of a calculation on the basis of R^2 is entirely subjective. In addition to the input compositions, R^2 depends on the size of the matrix; e.g., if the number of fractionating minerals plus the derivative magma composition equals the number of bulk rock oxide components, then R^2 is algebraically required to equal zero, regardless of the validity of the input data.

2. PROCEDURE.

The following procedure has been used to derive and refine mixing calculations:

- (1) Use only observed bulk rock and mineral compositions, not averaged rock analyses or idealized mineral end members.
- (2) Choose parent and derivative magmas, and representative mineral analyses from the parent magma.
- (3) Evaluate results of calculation and attempt to decrease R^2 by modifying mineral compositions, within limits imposed by petrography and mineral analyses. This usually involves input of pyroxenes with different Mg/Fe, plagioclase with different An content, etc.

(4) When R^2 is considered to be minimized and mineral proportions are consistent with observed modal mineralogy, trace element calculations are undertaken, using the Rayleigh fractionation equation:

$$C_i^{\text{liquid}} / C_i^0 = F^{(D-1)}$$

where:

- C^0 - concentration of trace element 'i' in the parental liquid
- C_i^{liquid} - concentration of trace element 'i' in the residual liquid
- F - fraction of liquid remaining
- D - bulk distribution coefficient for trace element 'i', calculated using mineral-melt distribution coefficients of Gill (1981).

For magma mixing calculations, trace elements were calculated using a linear mixture of the two end members, with proportions of end members given by results of major element mixing calculations.

(5) Evaluate results of major and trace element calculations, and comment on validity of the model.

Calculations given here are the results of extensive trial and error, and modelling has been undertaken in stepwise fashion, to closely monitor fractionation.

3. RESULTS

Fractional crystallization calculations:

VI-1: [Ruapehu basalt (bulk rock analysis II-63)] - [cpx + plag + ol + oxide] - [basic andesite of Te Herenga Fm (II-1)]

VI-2: [Ruapehu basalt, Mangawhero Fm (II-63)] - [cpx + ol + plag + oxide] - [basic andesite of Mangawhero Fm (II-64)]

VI-3: [basic andesite of Mangawhero Fm (II-64)] - [plag + opx + cpx + oxide] - [acid andesite of Mangawhero Fm (II-88)]

VI-4: [Waimarino Basalt (II-132)] - [ol + cpx + plag + oxide] - [Hauhungatahi basic andesite (II-133)]

VI-5: [Waimarino Basalt (II-132)] - [ol + cpx + plag + oxide] - Ohakune basic andesite (II-137)]

VI-6: [acid andesite of Mangawhero Fm (II-88)] - [plag + cpx + opx + oxide] - [dacite of Mangawhero Fm (II-106)]

Magma mixing calculations are given in Table 10, p. 268, and are only listed here:

VI-8: [Ruapehu basalt, Mangawhero Fm (II-63)] + [acid andesite, Mangawhero Fm (II-78)] - [hybrid basic andesite, Mangawhero Fm (II-69)]

VI-9: [Waimarino Basalt (II-132)] + [dacite, Mangawhero Fm (II-106)] - [hybrid basic andesite, Pukeonake (II-136)]

VI-10: [Waimarino Basalt (II-132)] + [dacite, Whakapapa Fm (II-129)] - [hybrid acid andesite, Mangawhero Fm (II-87)]

VI-11: [Waimarino Basalt (II-132)] + [dacite, Whakapapa Fm (II-129)] - [hybrid acid andesite, Mangawhero Fm (II-93)]

VI-12: [Waimarino Basalt (II-132)] + [dacite, Whakapapa Fm (II-129)] - [hybrid acid andesite, Mangawhero Fm (II-82)]

VI-13: [Waimarino Basalt (II-132)] + [dacite, Whakapapa Fm (II-129)] - [hybrid acid andesite, Mangawhero Fm (II-81)]

Crystal accumulation calculations:

VI-14: [acid andesite, Whakapapa Fm (II-128)] + [plagioclase, An₈₀] - [plag-accumulative acid andesite, Whakapapa Fm (II-118)]

VI-15: [acid andesite, Wahianoa Fm (II-59)] + [plagioclase, An₇₆] - [plag-accumulative acid andesite, Wahianoa Fm (II-46)]

4. REFERENCES.

- Gill, J.B., 1981. Orogenic Andesites and Plate Tectonics, Springer-Verlag, New York, 390 pp.
- Wright, T.L., 1974. Presentation and interpretation of chemical data for igneous rocks. Contrib. Mineral. Petrol., **48**, 233-248.
- Wright, T.L. and Doherty, P.C., 1970. A linear programming and least squares computer method for solving petrologic mixing problems. Geol. Soc. Am. Bull., **81**, 1997-2008.

VI-1: Ruapehu basalt (II-63) - [CPX + PLAG + OL + TMT] = basic andesite (II-1) of Te Herenga Fm.

	DAU. II-1	OL	CPX	PLAG	TMT	PARENT II-63				
SiO ₂	53.81	40.56	51.88	53.51	0.12	52.23				
TiO ₂	0.70	0.00	0.40	0.00	8.69	0.66				
Al ₂ O ₃	17.49	0.00	2.95	28.30	3.77	15.57				
FeO ^c	8.22	12.54	7.37	0.45	77.27	8.76				
MnO	0.14	0.12	0.17	0.00	0.30	0.16				
MgO	5.38	46.00	16.29	0.00	1.77	8.73				
CaO	8.51	0.15	19.37	12.03	0.19	9.63				
Na ₂ O	2.94	0.00	0.00	4.73	0.00	2.59				
K ₂ O	0.74	0.00	0.00	0.18	0.00	0.58				
P ₂ O ₅	0.10	0.00	0.00	0.00	0.00	0.09				
							OBS	D bulk	CALC	
							Ba 193→218	0.00	275	
							Rb 12→23	0.00	17	
							Sr 200→216	0.70	222	
							Zr 50→55	0.10	69	
							V 254→251	1.15	241	
							Cr 389→86	5.30	85	
							Ni 135→36	4.65	37	
SiO ₂	CALC	OBS	RESID		VAR.	WT. FRAC				
TiO ₂	52.23	52.23	0.002		II-1	0.702				
Al ₂ O ₃	0.68	0.66	0.020		CPX	0.122				
FeO ^c	15.58	15.57	0.006		PLAG	0.098				
MnO	8.76	8.76	0.002		OL	0.063				
MgO	0.13	0.16	0.028		TMT	0.015				
CaO	8.73	8.73	0.001							
Na ₂ O	9.63	9.63	0.005		%XTL	29.8				
K ₂ O	2.54	2.59	0.045							
P ₂ O ₅	0.54	0.58	0.039							
	0.10	0.09	0.007							
		ΣR ²	0.0049							

VI-2: Ruapehu basalt (II-63) - [CPX + OL + PLAG + TMT] = basic andesite (II-64), both of Mangawhero Fm.

	DAU. II-64	OL	CPX	PLAG	TMT	PARENT II-63				
SiO ₂	53.15	40.56	50.95	51.86	0.12	52.23				
TiO ₂	0.68	0.00	0.40	0.09	8.69	0.66				
Al ₂ O ₃	17.05	0.11	4.19	29.99	3.77	15.57				
FeO ^c	8.54	12.54	7.16	0.96	77.27	8.76				
MnO	0.13	0.12	0.17	0.00	0.30	0.16				
MgO	6.66	46.00	15.63	0.15	1.77	8.73				
CaO	8.79	0.15	20.57	13.52	0.19	9.63				
Na ₂ O	2.77	0.00	0.29	3.98	0.00	2.59				
K ₂ O	0.68	0.00	0.00	0.11	0.00	0.58				
P ₂ O ₅	0.10	0.00	0.00	0.00	0.00	0.09				
							OBS	D bulk	CALC	
							Ba 193→232	0.00	230	
							Rb 12→17	0.00	15.5	
							Sr 200→222	0.36	224	
							Zr 50→59	0.00	59	
							V 254→265	1.42	236	
							Cr 389→128	7.05	135	
							Ni 135→53	6.02	56	
SiO ₂	CALC	OBS	RESID		VAR.	WT. FRAC				
TiO ₂	52.23	52.23	0.004		II-64	0.840				
Al ₂ O ₃	0.66	0.66	0.000		CPX	0.089				
FeO ^c	15.58	15.57	0.012		OL	0.037				
MnO	8.76	8.76	0.000		PLAG	0.028				
MgO	0.13	0.16	0.029		TMT	0.006				
CaO	8.73	8.73	0.004							
Na ₂ O	9.62	9.63	0.009		%XTL	16.0				
K ₂ O	2.47	2.59	0.122							
P ₂ O ₅	0.58	0.58	0.005							
	0.08	0.09	0.006							
		ΣR ²	0.0162							

VI-5: Waimanalo Basalt (II-132) - [OL + CPX + PLAG + CRSP] = Ohakune basic andesite (II-137)

[illegible]

VI-6: Acid andesite (II-88) - [PLAG + CPX + OPX + TMT] = dacite (II-106)
(Mangawhero Fm.) (Mangawhero Fm.)

	DAU. II-106	OPX	CPX	PLAG	TMT	PARENT II-88			
SiO ₂	62.94	51.48	51.67	52.87	0.22	58.54			
TiO ₂	0.80	0.25	0.43	0.00	11.45	0.68			
Al ₂ O ₃	16.57	2.23	1.05	29.34	2.35	17.41			
FeO ^t	5.03	22.35	14.79	0.48	76.94	6.85			
MnO	0.06	0.48	0.48	0.00	0.24	0.11			
MgO	2.22	22.22	14.22	0.00	1.06	3.75			
CaO	4.80	1.30	17.00	11.50	0.00	7.05			
Na ₂ O	3.34	0.00	0.25	4.51	0.00	3.16			
K ₂ O	2.72	0.00	0.00	0.17	0.00	1.20			
P ₂ O ₅	0.20	0.00	0.00	0.00	0.00	0.10			
							OBS	Dbulk	CALC
							Ba 311→514	0.00	510
							Rb 41→124	0.00	67
							Str 234→255	0.94	241
							Zr 86→198	0.00	141
							V 181→117	1.96	113
							Cr 43→29	3.91	10
							Ni 28→19	2.16	16
SiO ₂	CALC	OBS	RESID		VAR	WT FRAC			
TiO ₂	58.50	58.54	0.044		II-106	0.609			
Al ₂ O ₃	0.71	0.68	0.026		PLAG	0.238			
FeO ^t	17.47	17.41	0.057		CPX	0.077			
MnO	6.84	6.85	0.007		OPX	0.061			
MgO	0.11	0.11	0.003		TMT	0.014			
CaO	3.85	3.75	0.100						
Na ₂ O	7.10	7.05	0.052		% XTL	39.4			
K ₂ O	3.15	3.16	0.008		CUM %	77.8			
P ₂ O ₅	1.71	1.20	0.510						
	0.12	0.10	0.023						
		ΣR ²	0.2790						

VI-14 : acid andesite (II-128) + [PLAG, An₈₀] = plag-accum. acid andesite (II-118)
(both of Whakapapa Fm.)

	II-128	PLAG (An ₈₀)	II-118						
SiO ₂	60.17	47.71	58.89						
TiO ₂	0.84	0.00	0.77						
Al ₂ O ₃	16.98	32.58	18.93						
FeO ^t	6.29	0.54	6.02						
MnO	0.07	0.00	0.08						
MgO	2.89	0.06	2.37						
CaO	6.17	16.35	7.15						
Na ₂ O	3.79	2.23	3.62						
K ₂ O	1.89	0.05	1.58						
P ₂ O ₅	0.16	0.00	0.13						
									(No trace elements calculated)
	Calc	OBS	RESID	VAR	WT FRAC				
SiO ₂	58.94	58.89	0.050	II-128	0.890				
TiO ₂	0.75	0.77	0.022	PLAG	0.110				
Al ₂ O ₃	18.77	18.93	0.158						
FeO ^t	5.66	6.02	0.359						
MnO	0.06	0.08	0.018						
MgO	2.58	2.37	0.210						
CaO	7.33	7.15	0.177						
Na ₂ O	3.62	3.62	0.005						
K ₂ O	1.69	1.58	0.108						
P ₂ O ₅	0.14	0.13	0.013						
		ΣR ²	0.2447						

VI-15 : acid andesite (II-59) + [PLAG, An₇₆] = plag-accum. acid andesite
(both of Wahianoa Fm.) (II-46)

	II-59	PLAG (An ₇₆)	II-46						
SiO ₂	60.40	48.45	57.72						
TiO ₂	0.72	0.00	0.68						
Al ₂ O ₃	17.59	32.12	20.37						
FeO ^t	6.11	0.49	5.06						
MnO	0.08	0.00	0.06						
MgO	2.54	0.00	2.18						
CaO	5.93	15.66	8.08						
Na ₂ O	3.56	2.72	3.57						
K ₂ O	1.58	0.05	1.24						
P ₂ O ₅	0.13	0.00	0.13						
									(Trace elements not calculated)
	Calc	OBS	RESID	VAR	WT FRAC				
SiO ₂	57.75	57.72	0.027	II-59	0.80				
TiO ₂	0.57	0.68	0.108	PLAG	0.20				
Al ₂ O ₃	20.45	20.37	0.080						
FeO ^t	4.95	5.06	0.108						
MnO	0.06	0.06	0.004						
MgO	2.02	2.18	0.163						
CaO	7.87	8.08	0.211						
Na ₂ O	3.38	3.57	0.193						
K ₂ O	1.27	1.24	0.025						
P ₂ O ₅	0.10	0.13	0.027						
		ΣR ²	0.1405

Geologic Map of Ruapehu Volcano and Related Vents

Legend:

- Whakapapa Formation:** (Red) - Quaternary, mostly lava flows, some tephra, and some pyroclastic material.
- Waihi Formation:** (Orange) - Quaternary, mostly lava flows, some tephra, and some pyroclastic material.
- Te Herenga Formation:** (Pink) - Quaternary, mostly lava flows, some tephra, and some pyroclastic material.
- Mangawhero Formation:** (Purple) - Quaternary, mostly lava flows, some tephra, and some pyroclastic material.
- Glacial Moraines:** (Grey) - Quaternary, mostly sand and gravel, some silt and clay.
- Ring Plain Deposits:** (Light Grey) - Quaternary, mostly sand and gravel, some silt and clay.
- Marine Sediments:** (Dark Grey) - Quaternary, mostly sand and gravel, some silt and clay.
- Hydrothermal Alteration:** (Hatched) - Quaternary, mostly sand and gravel, some silt and clay.
- High Angle Faults:** (Solid Line) - Quaternary, mostly sand and gravel, some silt and clay.
- Normal Faults:** (Dashed Line) - Quaternary, mostly sand and gravel, some silt and clay.
- Strike Slip Faults:** (Dotted Line) - Quaternary, mostly sand and gravel, some silt and clay.
- Contacts:** (Thin Line) - Quaternary, mostly sand and gravel, some silt and clay.
- Pyroclastics:** (Stippled) - Quaternary, mostly sand and gravel, some silt and clay.
- Intrusive Bodies:** (Thick Line) - Quaternary, mostly sand and gravel, some silt and clay.

Map Symbols:

- Strike and Dip of Bedding:** (Symbol)
- High Angle Faults:** (Symbol)
- Normal Faults:** (Symbol)
- Strike Slip Faults:** (Symbol)
- Contacts:** (Symbol)
- Pyroclastics:** (Symbol)
- Intrusive Bodies:** (Symbol)

Correlation of Map Units:

Quaternary: Q1, Q2, Q3, Q4, Q5, Q6, Q7, Q8, Q9, Q10, Q11, Q12, Q13, Q14, Q15, Q16, Q17, Q18, Q19, Q20, Q21, Q22, Q23, Q24, Q25, Q26, Q27, Q28, Q29, Q30, Q31, Q32, Q33, Q34, Q35, Q36, Q37, Q38, Q39, Q40, Q41, Q42, Q43, Q44, Q45, Q46, Q47, Q48, Q49, Q50, Q51, Q52, Q53, Q54, Q55, Q56, Q57, Q58, Q59, Q60, Q61, Q62, Q63, Q64, Q65, Q66, Q67, Q68, Q69, Q70, Q71, Q72, Q73, Q74, Q75, Q76, Q77, Q78, Q79, Q80, Q81, Q82, Q83, Q84, Q85, Q86, Q87, Q88, Q89, Q90, Q91, Q92, Q93, Q94, Q95, Q96, Q97, Q98, Q99, Q100, Q101, Q102, Q103, Q104, Q105, Q106, Q107, Q108, Q109, Q110, Q111, Q112, Q113, Q114, Q115, Q116, Q117, Q118, Q119, Q120, Q121, Q122, Q123, Q124, Q125, Q126, Q127, Q128, Q129, Q130, Q131, Q132, Q133, Q134, Q135, Q136, Q137, Q138, Q139, Q140, Q141, Q142, Q143, Q144, Q145, Q146, Q147, Q148, Q149, Q150, Q151, Q152, Q153, Q154, Q155, Q156, Q157, Q158, Q159, Q160, Q161, Q162, Q163, Q164, Q165, Q166, Q167, Q168, Q169, Q170, Q171, Q172, Q173, Q174, Q175, Q176, Q177, Q178, Q179, Q180, Q181, Q182, Q183, Q184, Q185, Q186, Q187, Q188, Q189, Q190, Q191, Q192, Q193, Q194, Q195, Q196, Q197, Q198, Q199, Q200, Q201, Q202, Q203, Q204, Q205, Q206, Q207, Q208, Q209, Q210, Q211, Q212, Q213, Q214, Q215, Q216, Q217, Q218, Q219, Q220, Q221, Q222, Q223, Q224, Q225, Q226, Q227, Q228, Q229, Q230, Q231, Q232, Q233, Q234, Q235, Q236, Q237, Q238, Q239, Q240, Q241, Q242, Q243, Q244, Q245, Q246, Q247, Q248, Q249, Q250, Q251, Q252, Q253, Q254, Q255, Q256, Q257, Q258, Q259, Q260, Q261, Q262, Q263, Q264, Q265, Q266, Q267, Q268, Q269, Q270, Q271, Q272, Q273, Q274, Q275, Q276, Q277, Q278, Q279, Q280, Q281, Q282, Q283, Q284, Q285, Q286, Q287, Q288, Q289, Q290, Q291, Q292, Q293, Q294, Q295, Q296, Q297, Q298, Q299, Q300, Q301, Q302, Q303, Q304, Q305, Q306, Q307, Q308, Q309, Q310, Q311, Q312, Q313, Q314, Q315, Q316, Q317, Q318, Q319, Q320, Q321, Q322, Q323, Q324, Q325, Q326, Q327, Q328, Q329, Q330, Q331, Q332, Q333, Q334, Q335, Q336, Q337, Q338, Q339, Q340, Q341, Q342, Q343, Q344, Q345, Q346, Q347, Q348, 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Q515, Q516, Q517, Q518, Q519, Q520, Q521, Q522, Q523, Q524, Q525, Q526, Q527, Q528, Q529, Q530, Q531, Q532, Q533, Q534, Q535, Q536, Q537, Q538, Q539, Q540, Q541, Q542, Q543, Q544, Q545, Q546, Q547, Q548, Q549, Q550, Q551, Q552, Q553, Q554, Q555, Q556, Q557, Q558, Q559, Q560, Q561, Q562, Q563, Q564, Q565, Q566, Q567, Q568, Q569, Q570, Q571, Q572, Q573, Q574, Q575, Q576, Q577, Q578, Q579, Q580, Q581, Q582, Q583, Q584, Q585, Q586, Q587, Q588, Q589, Q590, Q591, Q592, Q593, Q594, Q595, Q596, Q597, Q598, Q599, Q600, Q601, Q602, Q603, Q604, Q605, Q606, Q607, Q608, Q609, Q610, Q611, Q612, Q613, Q614, Q615, Q616, Q617, Q618, Q619, Q620, Q621, Q622, Q623, Q624, Q625, Q626, Q627, Q628, Q629, Q630, Q631, Q632, Q633, Q634, Q635, Q636, Q637, Q638, Q639, Q640, Q641, Q642, Q643, Q644, Q645, Q646, Q647, Q648, Q649, Q650, Q651, Q652, Q653, Q654, Q655, Q656, Q657, Q658, Q659, Q660, Q661, Q662, Q663, Q664, Q665, Q666, Q667, Q668, Q669, Q670, Q671, Q672, Q673, Q674, Q675, Q676, Q677, Q678, Q679, Q680, 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