

Geological and petrological study of Rangitoto
Island, Auckland Volcanic Field(MEMORIAL
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Geological and petrological study of Rangitoto Island, Auckland Volcanic Field

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Abstract Rangitoto Island is the largest and youngest volcano in the Auckland Volcanic Field, New Zealand. It is the only volcano that produced tholeiitic basalt. All the others are alkali basalt or basanite.

Sixteen young lava flows overlying the older lava flows were mapped on the basis of aerophotographs and field observations. Thirteen samples from 12 lavas from among 17 lava flows (16 young + one old) were analyzed in order to investigate the variation of chemical compositions of the source magma. The compositional variations within Rangitoto basalt is caused by the accumulation of olivine and clinopyroxene phenocrysts.

Key words : Rangitoto, Auckland Volcanic Field, primary magma, tholeiite, shield volcano

INTRODUCTION

The Auckland Volcanic Field is one of the Pliocene-Quaternary alkali basalt provinces which are located behind the volcanic front of Taupo Volcanic Zone (Cole 1986; Smith 1989) (Fig. 1). This volcanism is caused by the upwelling of asthenospheric materials from deeper parts of the mantle (Heming 1980; Tatsumi & Tsunakawa 1992). The Auckland Volcanic Field is the youngest and the smallest of these volcanic provinces (Heming & Barnet 1986).

The Auckland volcanoes erupted from at least 48 centres, and most of them produced alkali basalt or basanite (Searle 1960; Heming & Barnet 1986; Smith 1989). They have been mapped by Searle (1964) and Kermode (1992) (Fig. 1). The volume of erupted material from each centre is generally small (mostly less than 0.1 km³). The total volume of lava flows and pyroclastic deposits for the whole Auckland Volcanic Field is estimated to be approximately 7 km³, and it was spread over about 100 km³ (Kermode 1989; Smith & Gamble 1993). The volcanic activity of the Auckland volcanoes probably began 140 ka and the youngest volcano, Rangitoto Island, was active within the last 600 years (Nicol 1992). Not only Rangitoto Island is the largest volcano in the Auckland Volcanic Field, but it is also tholeiitic in composition.

There are detailed studies of Rangitoto Island for geology (Searle 1964; Ballance & Smith 1982; Kermode 1989; Smith & Gamble 1993) and geophys-

ics (Robertson 1986). However there are few published petrological data (Searle 1960, 1962; Heming & Barnet 1986; Smith & Gamble 1993).

The aims of this paper are as follows: (1) to show the distribution of the recently mapped lava flows on the island that were distinguished on the basis of aerophotographs and field observations; and (2) to present data on the petrography and geochemistry of the Rangitoto basalt in order to discuss compositional variations within the lava.

GEOLOGY OF RANGITOTO ISLAND

Rangitoto Island is a 260 m high, 6 km diameter, symmetrical volcanic cone. There is a central summit scoria cone with a crater 60 m deep and 200 m in diameter. Many lava flows emerged through the flanks of the lower lava cone, and the total volume of basalt is estimated to be about 2 km³ (Ballance & Smith 1982; Kermode 1989; Smith & Gamble 1993). Rangitoto volcano could possibly have been active through an extended period. The ¹⁴C ages measured on wood and shell buried by Rangitoto ash on Motutapu Island (immediately to the east of Rangitoto) were 770-750 years (Fergusson & Rafter 1959; Brothers & Golson 1959). A sample of uncharred wood recovered from beneath a young Rangitoto lava flow gave a ¹⁴C age of 225 ± 110 years B.P. (McDougall *et al.* 1969). The interpretation of this result is discussed by Law (1975) and Nicol (1992). However, such a

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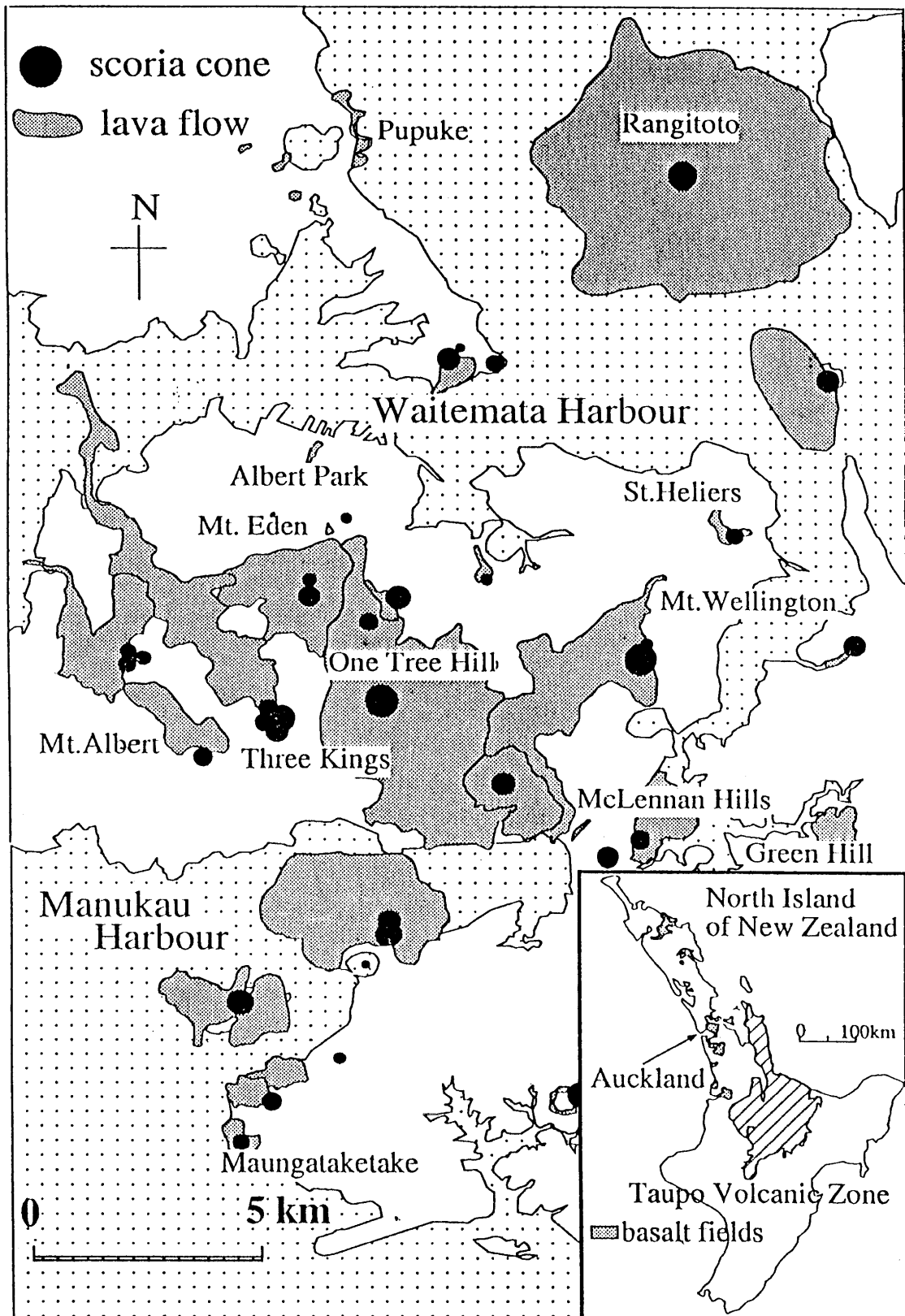


Fig. 1 Distribution of pyroclastic cones and lava flows in the Auckland volcanoes after Kermode (1989). The Auckland Volcanic Field is one of the Pliocene-Quaternary alkalic basalt provinces which are situated behind the volcanic front of the Taupo volcanic zone in North Island, New Zealand.

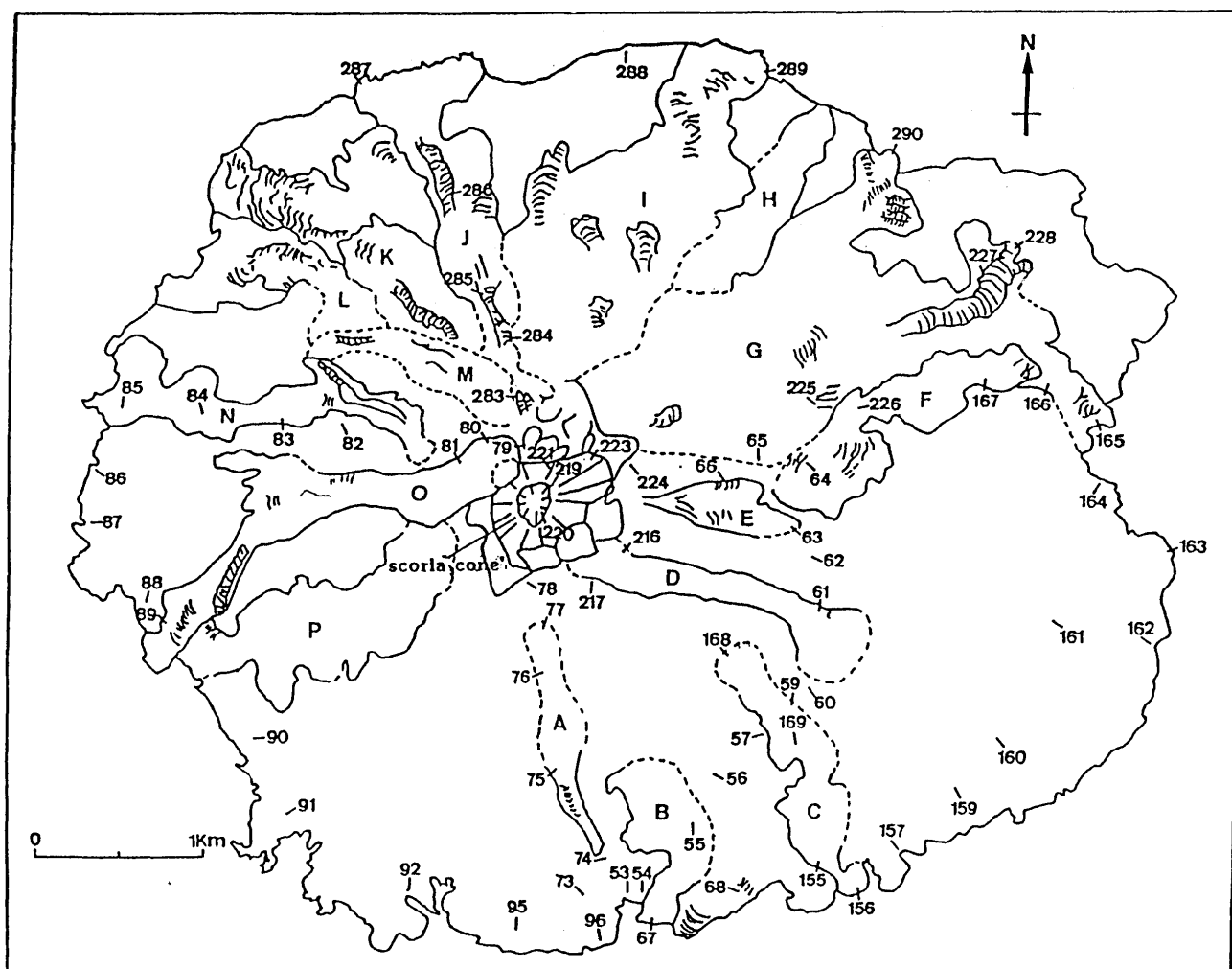


Fig. 2a Map of Rangitoto Island showing lava flows and sample locations. Sixteen young lava flows have been recently mapped by aerophotographs and field observations. Solid lines show the exact boundary between the two flows, and dashed line show the probable ones.

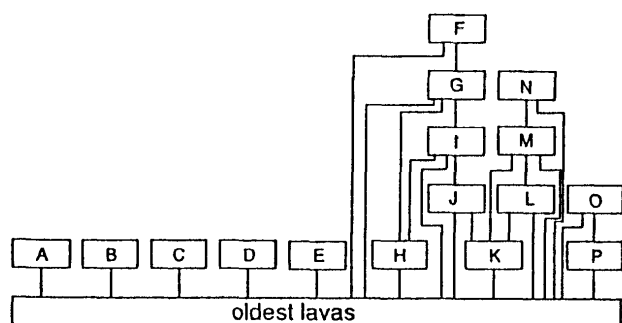


Fig. 2b Block diagram showing the stratigraphic relationships of lava flows on Rangitoto Island. Solid lines indicate confirmed stratigraphic relations based on field observations.

wide range of ages does not conflict with the new observations that demonstrate that the island has been formed by many intermittent lava effusions. Kermode (1989) suggested that initially 200 m deep explosion crater was formed at the base of the island, and that later, the scoria capped lava cone formed of broken and vesicular aa lava flows throughout. Ballance & Smith (1982) suggested a slightly different eruptive history for Rangitoto as follows: the eruption began as a series of phreatomagmatic explosions when magma broke through the sea floor at the entrance to Waitemata Harbour. A series of ash eruptions built up a low cone which separated the sea water from the magma. Next, intermittent explosive activity built up overlapping scoria cones. Finally, many lava flows broke out from fractures around the flanks of these cones to create the island. Previous geological maps of Rangitoto have lumped all the lava flows together, although there are many easily distinguished lava flows on the island.

Sato (1950) and Moriya (1978) showed that

the use of aerial photographs of lava fields is an important technique to discriminate lava flows and to clarify the stratigraphic relations of adjoining units. The basis of this method is to identify the inherent features of lava flows such as wrinkles, levees, lobes and frontal scarps. This technique was applied to Rangitoto Island, and sixteen young flows (labelled A to P) superimposed on the older ones were distinguished (Fig. 2a). The morphological information and stratigraphic relationships were confirmed by field observations. The lava effused from various vents on the flanks of the lava cone. The stratigraphic relationships of the flows are shown in Fig. 2b. All are aa textured with some well developed marginal levees.

PETROGRAPHY AND MINERAL COMPOSITIONS

All the Auckland volcanoes belong to the alkalic rock series except Rangitoto. The phenocrysts in alkali basalt are euhedral to subhedral olivine, with minor titaniferous clinopyroxene, and they generally include tiny spinel.

Rangitoto Island is the only volcano of tholeiitic basalt which forms vesicular, holocrystalline and porphyritic lavas. Modal analyses of samples from Rangitoto lavas are given in Table 1. The phenocrysts are olivine, with subordinate amounts of augite and rare plagioclase (Table 1). Olivine phenocrysts (about 1.0 mm) with spinel inclusions are generally euhedral to subhedral and slightly altered into brown-coloured iddingsite along cracks and rims. The great majority of titaniferous augite phenocrysts (0.5 mm) in the tholeiitic basalt are anhedral and form crystal clots with the olivine phenocrysts. Plagioclase phenocrysts (0.2 mm) occur as euhedral discrete grains. Some rocks from Rangitoto Island contain quartz xenocrysts surrounded by envelopes of glass rimmed with clinopyroxene. The coarse grained, holocrystalline groundmass has an intersertal texture composed of plagioclase, olivine,

Table 1 Modal analyses of Rangitoto basalt samples.

Sample No.	AK76	AK55	AK168	AK216	AK66-2	AK226	AK166
Lava name	A	B	C	D	E	F	G
olivine	8.6	7.4	9.1	5.7	7.1	5.6	6
clinopyroxene	2.3	1.6	3.7	1.8	1.4	2.3	3.2
plagioclase	0.6	0.2	0	0.4	0.1	0.1	0.2
xenocryst	0.1	1.2	0.3	0.4	1.1	0.5	0.6
groundmass	88.4	89.6	86.9	91.7	90.3	91.5	90

Sample No.	AK289	AK286	AK287	AK83	AK81	AK78
Lava name	I	J	J	N	O	oldest
olivine	10.1	4.5	4.6	6.8	7.1	4.6
clinopyroxene	3	2.8	1.8	1.9	1.9	4.3
plagioclase	0.4	0.5	0.3	0.3	0.1	1
xenocryst	1.4	1.1	0.3	0.8	0.8	0.6
groundmass	85.1	91.1	93	90.2	90.1	89.5

Table 2 Microprobe analyses of representative phenocrysts from Rangitoto basalt of refers to olivine; cpx to clinopyroxene; and pl to plagioclase.

	AK76 (wt.%)				
	ol-core	ol-rim	cpx-core	cpx-rim	pl-core
SiO ₂	38.50	37.55	49.73	50.78	52.79
TiO ₂	0.03	0.02	1.26	1.26	0.12
Al ₂ O ₃	0.01	0.05	4.37	2.95	28.00
FeO*	19.66	23.41	6.68	7.76	0.61
MnO	0.28	0.34	0.15	0.19	0.00
MgO	40.99	37.41	14.80	14.94	0.15
CaO	0.18	0.24	21.01	20.89	12.85
Na ₂ O	0.02	0.06	0.36	0.35	4.62
K ₂ O	0.00	0.00	0.00	0.00	0.25
Cr ₂ O ₃	0.02	0.00	0.78	0.68	0.21
NiO	0.13	0.13	0.00	0.00	0.00
Total	99.82	99.21	99.14	99.80	99.60

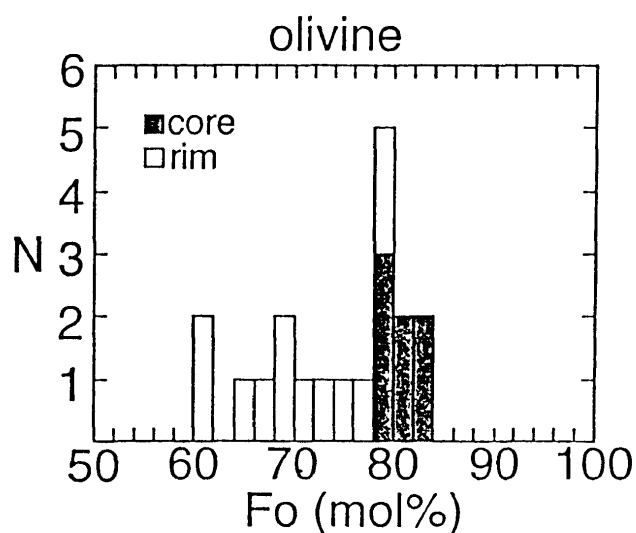


Fig. 3 Histogram of Fo for the olivine phenocrysts in the lavas from Rangitoto.

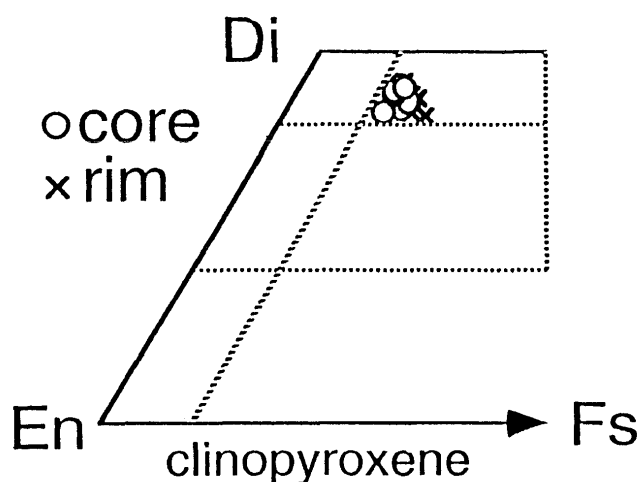


Fig. 4 Chemical compositions of the clinopyroxene phenocrysts.

Table 3 Whole rock compositions, and C.I.P.W. norms of the Rangitoto basalt samples.

Sample No.	AK76	AK55	AK168	AK216	AK66-2	AK226	AK166	AK289	AK286	AK287	AK83	AK81	AK78
Lava Name	A	B	C	D	E	F	G	I	J	J	N	O	oldest
SiO ₂ (wt%)	49.0	49.2	49.3	49.3	48.9	49.2	49.0	48.8	49.3	49.0	49.0	48.9	48.8
TiO ₂	2.06	2.10	2.01	2.12	2.11	2.12	2.09	1.89	2.11	2.09	2.09	2.09	2.14
Al ₂ O ₃	14.63	14.61	14.47	14.95	14.56	14.69	14.61	14.02	14.88	14.67	14.66	14.60	14.50
FeO*	11.25	11.39	11.32	11.10	11.21	11.20	11.20	11.47	11.21	11.20	11.29	11.22	11.24
MnO	0.15	0.16	0.15	0.15	0.15	0.15	0.15	0.16	0.15	0.15	0.16	0.15	0.15
MgO	8.48	8.54	8.79	7.73	8.38	8.37	8.40	9.54	7.93	8.25	8.50	8.50	8.25
CaO	9.51	9.52	9.35	9.63	9.53	9.57	9.57	9.22	9.59	9.44	9.50	9.55	9.54
Na ₂ O	3.18	3.25	3.13	3.26	3.21	3.22	3.13	3.00	3.34	3.14	3.20	3.19	3.18
K ₂ O	0.71	0.73	0.69	0.75	0.75	0.77	0.75	0.65	0.75	0.73	0.75	0.75	0.78
P ₂ O ₅	0.28	0.30	0.28	0.30	0.30	0.30	0.29	0.25	0.30	0.29	0.30	0.29	0.30
Total	99.23	99.79	99.49	99.30	99.06	99.54	99.16	99.03	99.57	98.92	99.43	99.27	98.88
FeO*/MgO	1.33	1.33	1.29	1.44	1.34	1.34	1.33	1.20	1.41	1.36	1.33	1.32	1.36
Qz(vol.%)	0	0	0	0	0	0	0	0	0	0	0	0	0
Or	4.2	4.3	4.1	4.4	4.5	4.6	4.4	3.8	4.4	4.3	4.4	4.5	4.7
Ab	27.0	27.5	26.5	27.6	27.3	27.3	26.7	25.6	28.3	26.8	27.2	27.1	27.2
An	23.7	23.1	23.5	24.1	23.3	23.4	23.8	23.0	23.5	23.9	23.4	23.4	23.2
Ne	0	0	0	0	0	0	0	0	0	0	0	0	0
Di	18.0	18.2	17.4	18.0	18.4	18.2	18.1	17.5	18.3	17.6	18.1	18.3	18.6
Hy	4.6	3.6	7.2	5.3	3.6	3.9	5.1	7.2	3.3	6.3	3.8	3.4	3.9
Ol	15.2	15.9	14.1	12.9	15.5	15.2	14.5	15.9	14.9	13.7	15.7	15.9	15.0
Mt	2.7	2.8	2.7	2.7	2.7	2.7	2.7	2.8	2.7	2.7	2.7	2.7	2.7
Il	3.9	4.0	3.8	4.2	4.0	4.0	4.0	3.6	4.0	4.0	4.0	4.0	4.1
Ap	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.6	0.7	0.7	0.7	0.7	0.7
Rb(ppm)	10	8	9	11	11	11	12	10	10	10	9	11	10
Sr	360	359	348	369	370	371	370	319	365	363	363	372	366
Ba	91	93	94	101	104	101	98	82	96	96	87	97	85
Y	22	24	22	24	23	23	22	22	23	23	23	23	22
Zr	146	151	143	152	153	153	151	133	152	149	153	151	154
V	261	253	256	263	254	260	259	231	262	246	264	250	266
Cr	278	272	289	251	291	294	296	312	249	273	293	278	288
Ni	150	151	167	127	147	153	142	204	133	141	154	151	143
Cu	61	63	62	63	63	64	62	72	63	59	61	65	64
Zn	105	110	104	103	106	107	106	104	108	98	109	101	107
Th	3	2	2	2	3	3	2	1	2	1	3	4	2
Nb	16	17	16	17	17	17	17	16	17	16	18	17	17
La	13	19	8	13	12	19	16	20	18	12	13	9	24
Ce	29	40	39	40	23	39	18	37	33	52	22	37	42

titaniferous clinopyroxene and magnetite.

Representative mineral compositions are listed in Table 2. Mineral compositions were determined by the JEOL JXA-733 electron-probe micro-analyser at the Institute of Geosciences, Shizuoka University. Corrections were made by the method of Bence and Albee (1968). Olivine phenocrysts are normally zoned, with a core composition of Fo₈₅-Fo₇₉ and a rim composition of Fo₇₉-Fo₆₀ (Fig. 3). Clinopyroxene phenocrysts are normally zoned, but less strongly than the olivine phenocrysts. In the pyroxene quadrilateral, they are projected into the salite fields (Fig. 4). Clinopyroxene phenocrysts are titanite with TiO₂ contents ranging from 1.26 to 3.53 wt.%. Plagioclase phenocrysts are normally zoned, ranging from An₇₈ to An₅₇.

WHOLE ROCK COMPOSITIONS

Thirteen lava samples from among 17 lava flows on Rangitoto Island were selected for chemical analysis based on microscopic observations of

thin sections. Major and trace element analyses were carried out with the Rigaku System 3080ES XRF at the Earthquake Research Institute, University of Tokyo. Representative whole-rock compositions and C.I.P.W. norms are presented in Table 3. C.I.P.W. norms were calculated assuming $Fe^{3+}/(Fe^{2+} + Fe^{3+}) = 0.15$. Rangitoto basalt is hypersthene normative (8 to 12 vol.%).

Variations in oxides against MgO are shown in Fig. 5. MgO is used as an abscissa because it shows wide variation which reflects modally variable olivine phenocrysts. The MgO ranges from 7.7 to 9.5 wt.% and most oxides show linear, tight variations against MgO. With decreasing MgO contents, SiO₂, Al₂O₃, CaO, TiO₂, Na₂O, K₂O and P₂O₅ slightly increase and FeO and MnO decrease. This chemical variation can be explained by the addition or subtraction of phenocrystic phases such as olivine and augite.

Selected trace elements are plotted against MgO in Fig. 6. Incompatible elements such as Rb, Sr, Zr, Y, Nb and Ba show a slight increase, and compatible elements, Ni and Cr, decrease with

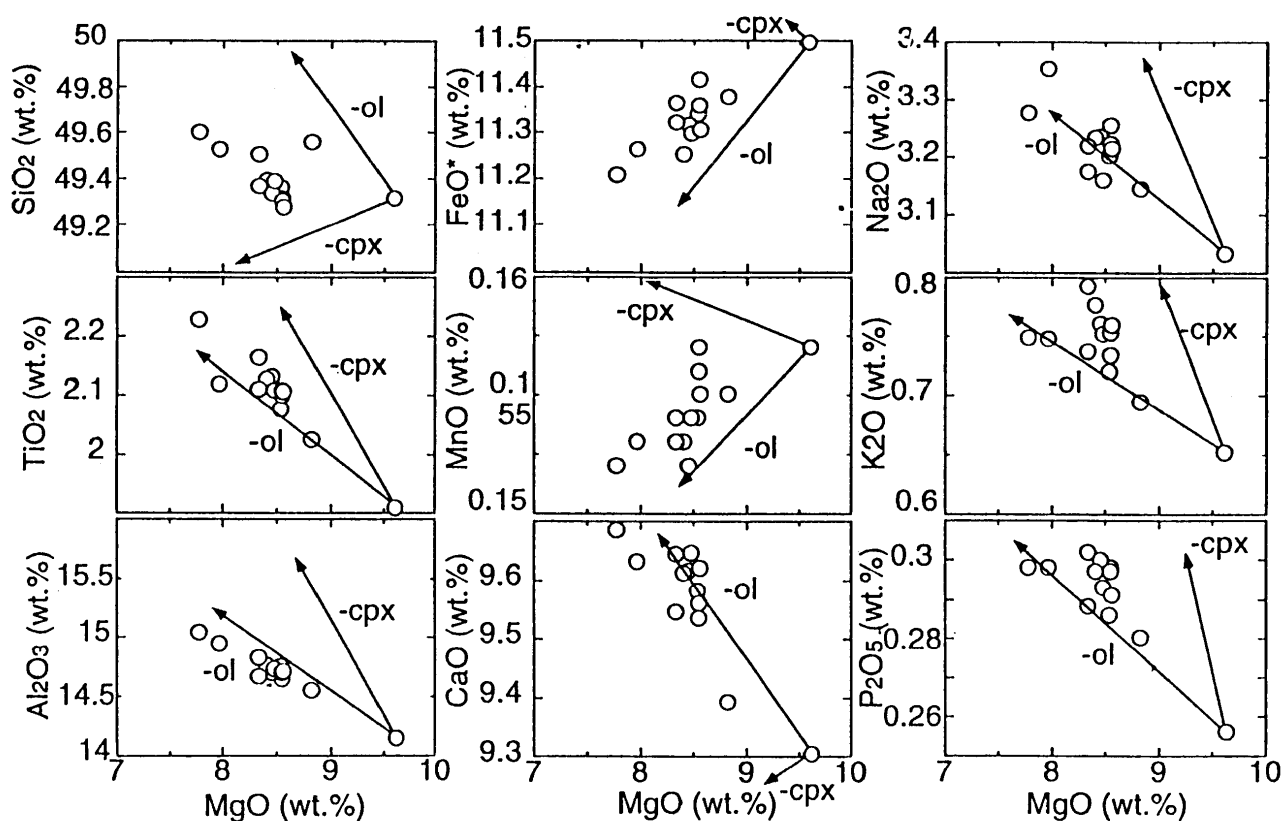


Fig. 5 Plots of major elements versus MgO for Rangitoto basalt samples. The arrows show the directions of fractionation of olivine and clinopyroxene phenocrysts.

decreasing MgO. However, V shows wide variation. The variations of incompatible elements are also consistent with the addition or subtraction of phenocrystic phases.

No systematic variation in chemical compositions related to the stratigraphic order (e.g., the sequence of F-G-I-J-oldest lavas in Fig. 2b) of each lava became apparent.

PARTITIONING OF Fe AND Mg BETWEEN OLIVINE PHENOCRYSTS AND THEIR HOST LAVAS

The equilibrium partitioning coefficient (K_D) of Fe and Mg between olivine and basaltic liquids is nearly constant (about 0.30) irrespective of temperature, pressure and chemical composition (Roeder & Emslie 1970; Takahashi & Kushiro 1983). The partition coefficient of Fe and Mg between core compositions of olivine phenocrysts in a Rangitoto basalt (sample AK76) and their host whole rock composition (Total Fe as ferrous) were calculated in order to see whether olivine phenocrysts are in equilibrium with the magma or not. The apparent K_D value of 0.353 is higher than the experimental value. This suggests that the olivine phenocrysts have more differentiated compositions than magma.

ORIGIN OF COMPOSITIONAL VARIATIONS WITHIN RANGITOTO BASALT

Chemical variations of whole rock compositions suggest the addition or subtraction of phenocrystic phases such as olivine and clinopyroxene. In order to assess this possibility quantitatively, least-squares mixing calculations were carried out for major elements and Rayleigh fractionation calculations were made for trace elements (Table 4). The composition of the most primitive sample was chosen as the initial, and the composition of the most differentiated sample as the final. The calculated compositional variations of major and trace elements are in good agreement with those of the actual compositions. The results of calculations show that the addition or subtraction of olivine phenocrysts, more than that of augite phenocrysts, is required for the major and trace element variations.

The K_D value for the Rangitoto basalt shows the olivine phenocrysts are not equilibrium with the host magma. Therefore, we have to consider the possibility of either phenocrystic accumulation or crustal contamination. Assuming that the phenocrystic phases are olivine only, approximately 6-8 wt.% of accumulation would account for the higher K_D . The modal amount of olivine plus clinopyroxene phenocrysts in the Rangitoto

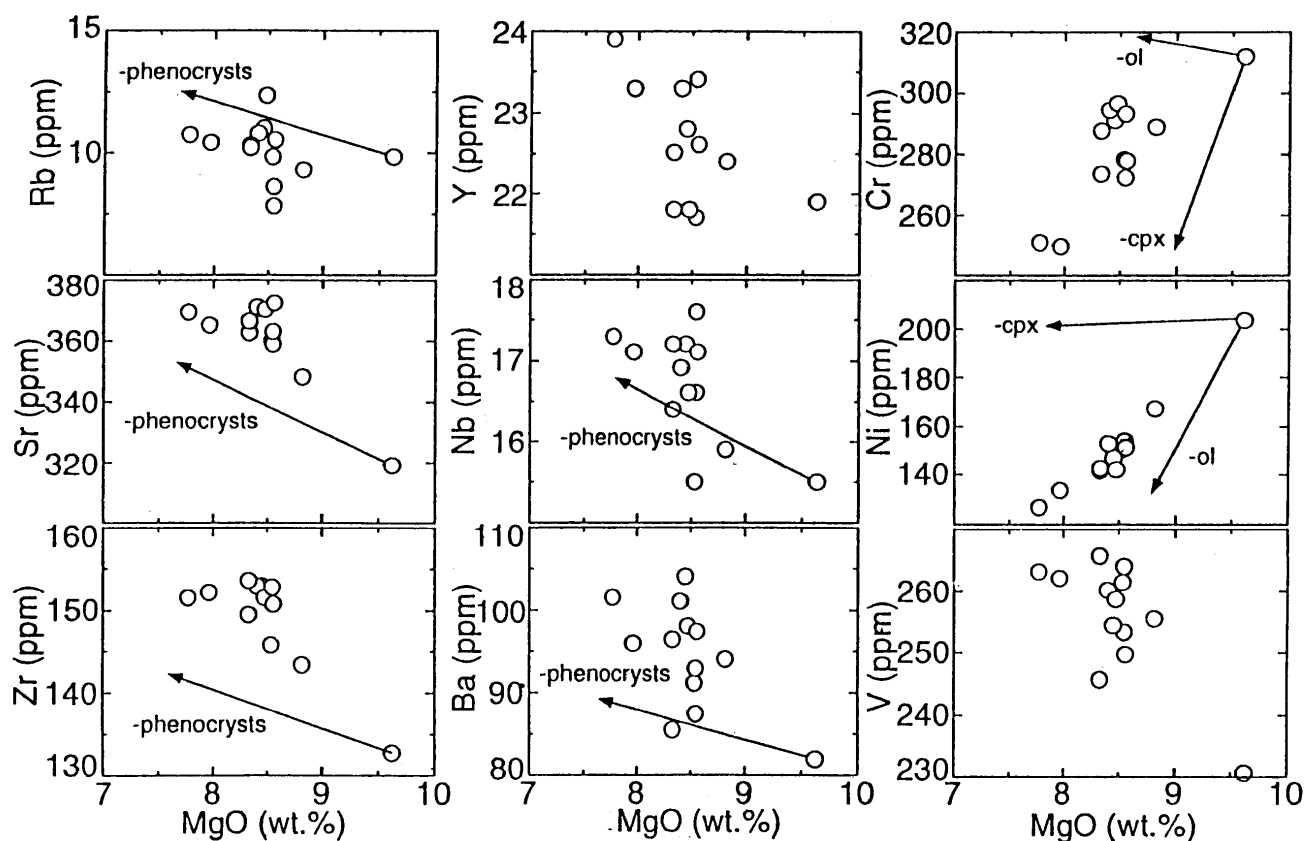


Fig. 6 Plots of selected trace elements versus MgO for Rangitoto basalt samples. The arrows show the direction of fractionation of phenocrysts.

Table 4 Results of least-square mixing calculations to reproduce compositional variations within lavas from Rangitoto based on the fractional crystallization model, and the trace element calculations by the Rayleigh fractionation model. The most primitive sample was chosen as the initial, and most differentiated one as the final.

	Initial	ol	cpx	Cal-Final	Final
SiO ₂ (wt%)	49.32	38.21	49.97	49.70	49.66
TiO ₂	1.91	0.01	1.13	2.02	2.14
Al ₂ O ₃	14.15	0.04	4.09	14.99	15.05
FeO*	11.58	19.14	7.03	11.15	11.18
MnO	0.16	0.25	0.15	0.15	0.15
MgO	9.63	40.81	15.20	7.77	7.79
CaO	9.31	0.23	20.17	9.64	9.70
Na ₂ O	3.03	0.02	0.42	3.33	3.28
K ₂ O	0.65	0.01	0.01	0.73	0.75
P ₂ O ₅	0.26	0.00	0.00	0.30	0.30
Cr ₂ O ₃	0.09	0.02	0.24	0.09	0.07
NiO	0.03	0.18	0.03	0.02	0.02
Subtracted %		5.62	1.31		
Total difference(%)				0.03	
Rb (ppm)	9.8			10.5	10.7
Sr	318.9			340.7	369.1
Ba	82.0			87.7	101.4
Zr	132.7			141.6	151.5
Nb	15.5			16.6	17.3

lavas is positively correlated with the whole rock compositions such as MgO and Ni (Fig. 7). This also suggests that the chemical variations of the Rangitoto basalt are caused by the phenocrystic accumulation (6 wt.% in mode). Some lavas from

Rangitoto contain quartz xenocrysts surrounded by envelopes of glass rimmed with clinopyroxene. These xenocrysts suggest some degree of basement rock contamination (Searle 1962). However, it can be concluded that the degree of basement rock contamination is very small when considering the compositional variations of major and trace elements and the result of least-square mixing calculation.

CONCLUSIONS

Sixteen young lava flows superimposed on the older lava flows can have been distinguished on the basis of aerial photograph interpretations and field observations.

Compositional variations within Rangitoto basalt are caused mostly by accumulation of olivine (and a subordinate amount of clinopyroxene) phenocrysts. The effects of crustal assimilation appear to be insignificant. There is no systematic variation in chemical compositions related to the stratigraphic position of each lava.

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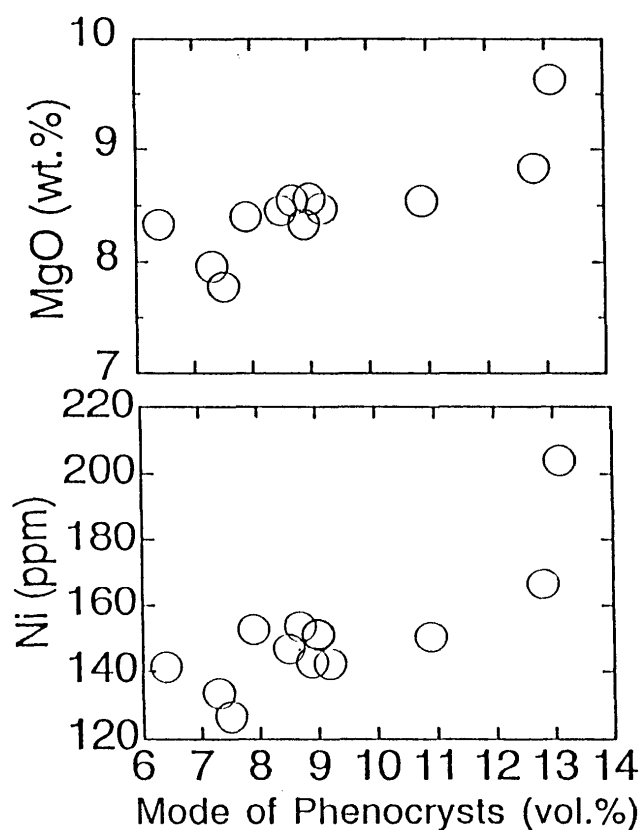


Fig. 7 MgO and Ni contents in Rangitoto basalt samples plotted against modal amount of olivine plus clinopyroxene phenocrysts.

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REFERENCES

- BALLANCE P. F. & SMITH I. E. M. (1982), Walks through Auckland's geological past. *Geological Society of New Zealand Guide Book* 5, 24p.
- BENCE A. E. & ALBEE A. L. (1968), Empirical correction factors for the electron microanalysis of silicates and oxides. *Journal of Geology*, **76**, 382-403.
- BROTHERS R. N. & GOLSON J. (1959), Geological and archeological interpretation of a section in Rangitoto ash on Motutapu Island, Auckland. *New Zealand Journal of Geology and Geophysics*, **2**, 569-577.
- COLE J. W. (1986), Distribution and tectonic setting of Late Cenozoic Volcanism in New Zealand. In: Smith I.E.M. ed., *Late Cenozoic Volcanism in New Zealand. Royal Society of New Zealand Bulletin*, **23**, 7-20.
- FERGUSON G. L. & RAFTER T. A. (1959), New Zealand ¹⁴C Age measurements-4. *New Zealand Journal of Geology and Geophysics*, **2**, 208-241.
- HEMING R. F. (1980), Patterns of Quaternary basaltic volcanism in the northern North Island, New Zealand. *New Zealand Journal of Geology and Geophysics*, **23**, 335-334.
- HEMING R. F. & BARNET P. R. (1986), The petrology and petrochemistry of the Auckland Volcanic Field. In: Smith I.E.M. ed., *Late Cenozoic Volcanism in New Zealand. Royal Society of New Zealand Bulletin*, **23**, 64-75.
- KERMODE L. O. (1989), *Pre-Conference Tour Auckland Geology*. Geological Society of New Zealand Annual Conference 1989, 32p.
- KERMODE L. O. (1992), *Geology of the Auckland urban area. Scale 1 : 50,000*. Institute of Geological and Nuclear Sciences geological map 2. 1 sheet and 63 p. Institute of Geological and Nuclear Sciences, Lower Hutt, New Zealand.
- LAW R. G. (1975), Radiocarbon dates for Rangitoto and Motutapu, a consideration of the dating accuracy. *New Zealand Journal of Science*, **18**, 441-451.
- MCDUGALL I., POLACH H. A. & STIPP J. J. (1969), Excess radiogenic argon in young subaerial basalts from the Auckland volcanic field, New Zealand. *Geochimica et Cosmochimica Acta*, **33**, 1485-1520.
- MORIYA I. (1978), Discrimination of fundamental volcanic landforms with aerial photographs (in Japanese). *Bulletin of the Volcanological Society of Japan*, **23**, 199-214.
- NICOL R. (1992), The eruption history of Rangitoto: reappraisal of a small New Zealand myth. *Journal of the Royal Society of New Zealand*, **22**, 159-180.
- ROBERTSON D. J. (1986), A paleomagnetic study of Rangitoto Island, Auckland, New Zealand. *New Zealand Journal of Geology and Geophysics*, **29**, 405-411.
- ROEDER P. L. & EMSLIE R. F. (1970), Olivine-liquid equilibrium. *Contributions to Mineralogy and Petrology*, **29**, 275-289.
- SATO H. (1950), Geomorphological classification of lava flows (in Japanese). *Scientific Papers, College, of Geography, University of Tokyo*, **1**, 114-132.
- SEARLE E. J. (1960), Petrochemistry of the Auckland basalts. *New Zealand Journal of Geology and Geophysics*, **3**, 23-40.
- SEARLE E. J. (1962), Quartzose xenoliths and pyroxene aggregates in the Auckland basalts. *New Zealand Journal of Geology and Geophysics*, **5**, 130-140.
- SEARLE E. J. (1964), *City of Volcanoes: A geology of Auckland*. Paul's Book Arcade, Auckland and Hamilton, 112p.
- SMITH I. E. M. (1989), New Zealand Intraplate volcanism: North Island. In: Johnson R. W., Knutson J., Taylor S. R. eds. *Intraplate volcanism in eastern Australia and New Zealand*, 157-162. Cambridge University Press, Cambridge, UK.
- SMITH I. E. M. & GAMBLE J. A. (1993), Northland and Taupo Zone Volcanism, North Island, New Zealand. *Excursion Guide for Field Trip of IAVCEI, 1993*. Australian Geological Survey Organization, 35p.
- TAKAHASHI E. & KUSHIRO I. (1983), Melting of a dry peridotite at high pressures and basalt magma genesis. *American Mineralogist*, **68**, 859-879.
- TATSUMI Y. & TSUNAKAWA H. (1992), Cenozoic volcanism, stress gradient and back-arc opening in the North Island, New Zealand: Origin of Taupo-Rotorua Depression. *The Island Arc*, **1**, 40-50.