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Magma mingling in an andesite pyroclastic flow of the Pourahu Member, Ruapehu volcano, New Zealand

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Abstract

We describe a magma mingling episode from Ruapehu volcano between two andesite magmas, one very much minor in volume relative to the other. The event acted to trigger eruption of the andesitic Pourahu pyroclastic flow which is preserved in a thick sequence of tephras and laharic deposits in the southeastern ring plain of the volcano. The predominant andesite is pale brown coloured and porphyritic containing phenocrysts of plagioclase–clinopyroxene–orthopyroxene–Fe-Ti oxides. Rare clasts of a darker andesite are different texturally, less vesicular, and contain distinctive microphenocrysts of plagioclase and quench olivine. Equally rare clasts, of streaky pumice consisting of interbanded 'dark' and 'light' andesite attest to mingling between these two andesite components.

Chemical analyses of discrete clasts demonstrate that the Pourahu pyroclastic flow andesites span much of the compositional spectrum of Ruapehu andesites. This observation demonstrates heterogeneity in the products of a relatively small eruption. The darker clast analyses and those from associated distal fall deposits lie within the fields defined by the dominant light coloured clasts. Phenocryst and microphenocryst geothermometry suggest slightly higher temperatures in the dark component. However, glasses from groundmass and phenocryst inclusions in the same specimen may differ considerably, leading us to conclude that many phenocrysts are in fact xenocrystic and were incorporated in the melts as they migrated towards the surface.

We prefer a model in which a small volume of hot andesite magma injects a vent-feeding magma chamber, triggering vesiculation and eruption. We infer that the process of magma withdrawal extended downward into the magma body causing the dark component to intermingle with the lighter (dominant) component, 'sucking' more dark magma into the chamber. Our observations are entirely consistent with the existence of a plexus of small, possibly interlinked magma chambers beneath Ruapehu.

'There are two extreme conditions with all intermediate possibilities; the one extreme gives a strongly curved course and the variation diagram shows strong bending.....'

'At the other extreme is the condition in which there is very little curvature in the course of crystallisation'

N.L. Bowen, 1928: *The evolution of the igneous rocks..'*

1. Introduction

Igneous activity at constructive and destructive plate boundaries involves processes of melt formation, extraction and eruption attended by modification processes such as crystal fractionation, and mixing or intermingling between crystals and melts (Rhodes et al., 1979; McBirney, 1980; Grove et al., 1982). Similarly, in plume-related settings such as Hawaii (Garcia et al.,

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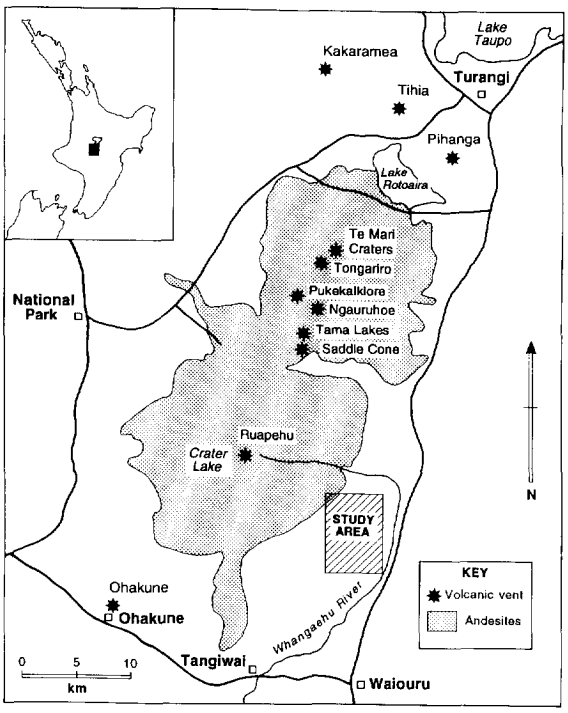

Fig. 1. Location map for the Pourahu pyroclastic flow study area on the southeastern ring plain of Ruapehu volcano. Location of major andesite vents in the Tongariro volcanic centre are shown.

1992) and Iceland (Blake, 1984; McGarvie et al., 1990; Furman et al., 1992) mixing and/or intermingling of melts has been documented on varying scales. Furthermore, where erosion and uplift have exposed the contents of crystallised magma chambers (for example, in the Eocene British Tertiary Volcanic Province or in Cordilleran Batholiths such as Chile) the effects of mixing may be particularly spectacular with the formation of net-vein complexes and associated hybrid rocks (Walker and Skelhorn, 1966; Gamble, 1979; Marshall and Sparks, 1984; Pitcher, 1993). From the above, mixing processes are clearly important in producing igneous rock diversity in the earth's crust. Given the significant thermal gradients in the outer thermal boundary layer, mixing processes between chemically contrasting magma batches will influence degassing, viscosity, eruption style and will have a significant impact on human activity through volcanic hazard. Nowhere is this more apparent than in the magmas of convergent plate margins, leading to much debate and not inconsiderable controversy in the literature (for example, Bowen versus Fenner, see Bowen, 1928 and more recently Grove et al., 1982; Brophy, 1987).

In the Taupo Volcanic Zone (TVZ) of New Zealand, 'mixing' processes have been identified throughout the entire spectrum of eruptives between basalt and rhyolite (Nairn, 1980; Graham and Hackett, 1987; Graham and Worthington, 1988; Gamble et al., 1990; Blake et al., 1992). Ruapehu volcano is the largest active, predominantly andesitic volcano in the TVZ, with an estimated volume of ~ 100 km^3 (Hackett and Houghton, 1988) and an eruptive history extending back at least 250 ka. Proximal andesite lavas from Ruapehu are relatively well described, Graham and Hackett (1987) recognising 6 'magma types' on the basis of petrography and geochemistry. At least one of these types (Type 6) was attributed directly to magma mixing processes but most show some textural evidence for manifest crystal–liquid disequilibrium.

Pyroclastic flows from the andesite volcanoes of the Tongariro National Park are rare features in the preserved volcano stratigraphy because they are usually small in volume, unconsolidated, and are rapidly eroded in the proximal vent facies and also because they have not been studied in detail. In this paper we report an example of magma intermingling from a young (~ 10 ka) pyroclastic flow deposit, part of the Pourahu Member of the Bullot Formation (Donoghue, 1991). This deposit is preserved best in several stream sections on the southeastern ring plain of Ruapehu volcano, (Fig. 1) and associated fall deposits are distributed on the ring-plain east of Ruapehu. Based upon isopachs on the fall deposits and mapping of the preserved extent of the pyroclastic flow, the unit erupted from a vent near the present summit plateau area of Ruapehu. The example is unusual because two andesitic melts intermingled, but did not mix completely, erupting to yield a pyroclastic flow deposit in which rare clasts of pumice are variably banded with light and dark layers. We first give details of the Pourahu Member pyroclastic flow unit in terms of the Tongariro Volcanic Centre (TgVC) tephrostratigraphic record, and then describe and characterise the compositions, concluding with evaluation of a model for the eruptive history.

2. Tephrostratigraphical and tephrochronological framework

The eruptive history of the TgVC in late Quaternary times (post 22,500 years) is recorded in eight andesitic tephra formations, representing eruptions from three TgVC volcanoes —Mt. Ruapehu, Mt. Tongariro, and Mt. Ngauruhoe, (Table 1) (Topping, 1973; Donoghue, 1991). The Formations have been dated using interbedded distal rhyolitic tephras which are correlated with eruptives from the Taupo and Okataina rhyolitic volcanic centres on the basis of their ferromagnesian mineral assemblages and glass shard chemistry. Radiocarbon ages obtained on peats interbedded with local andesitic tephras (Topping, 1973) provide additional chronostratigraphic control.

Late Quaternary tephras erupted from Mt. Ruapehu comprise two formations —the Bullot Formation and the Tufa Trig Formation, (Donoghue, 1991, and Table 1). Bullot Formation tephras represent the most active eruptive period at Mt. Ruapehu during the last 22,500 years. Most of the tephras are pumiceous and are interpreted to be the products of subplinian magmatic eruptions. The fall units are poorly sorted and dominated by vesicular andesitic pumice lapilli, occurring together with accessory lithic lapilli, and pumiceous bombs in some layers. With the exception of one member (Pourahu Member), these tephra eruptions preserve no record of having been accompanied by pyroclastic flows. Indeed, pyroclastic flows are uncommon in the record of Ruapehu eruptions and the Pourahu Member [pyroclastic flow unit] is the only recognised pyroclastic flow on the southeastern ring plain of Ruapehu. Hackett (1985) reported other small volume flows associated with the Rangitau and Iwikau members of the Whakapapa Formation of Ruapehu.

The upper contact of the Bullot Formation is marked by the base of the Pahoka Tephra, and the base of the formation is defined by the contact with the rhyolitic Kawakawa Tephra Formation (Wilson et al., 1988; Table 1). The type section for the Bullot Formation is on the southeastern Mt Ruapehu ring plain close to Bullot Track (reference T20/412108, map references refer to Department of Survey and Land Information,

Table 1
Tephrostratigraphy of the Poruhau Member (modified after Donoghue, 1991) in the context of Tongariro Volcanic Centre and relevant Taupo Volcanic Zone tephrostratigraphy. Note the stratigraphic positions of the key (radiocarbon dated) rhyolitic tephra horizons.

	Member	Source[d]	Age[a] (yr B.P)	^{14}C No.	Reference to age
Bullot Formation (upper)		Mt. Ruapehu	c. 10 000		
	Ngamatea lapilli-2	Mt. Ruapehu			
	Ngamatea lapilli-1	Mt. Ruapehu			Donoghue (1991)
	Pourahu Member	Mt. Ruapehu			
	L18-L17	Mt. Ruapehu			
	Shawcroft Tephra	Mt. Ruapehu			
	L16	Mt. Ruapehu			
Waiohau Tephra		OVC	11 250 ± 200	[NZ568]	Cole (1970)
Bullot Formation (upper)	L15-L8	Mt. Ruapehu			
?Rotorua Tephra[e]		OVC	13 450 ± 250		Nairn (1980)
Bullot Formation (upper)		Mt. Ruapehu			
Rotoaira Lapilli[e]		Mt. Tongariro	13 800 ± 200	[NZ1559]	Topping (1973)
Bullot Formation (upper)	L15-L8	Mt. Ruapehu			
Rerewhakaaitu Tephra		OVC	14 700 ± 200	[NZ716]	Pullar et al. (1973)
Bullot Formation (middle)	L7b-L4	Mt. Ruapehu			
Okareka Tephra		OVC	c. 17 000[c]		Nairn (1981)
Bullot Formation (lower)	L3-L1	Mt. Ruapehu			
Kawakawa Tephra Fm.		TVC	22 590 ± 230[b]		Wilson et al. (1988)

[a]All ^{14}C ages discussed are conventional ages in radiocarbon years B.P. based on the old (Libby) half life of 5568 years. Reference numbers e.g. [NZ568] refer to national radiocarbon database. [b]Average or combined radiocarbon age. [c]Estimated age, calendar years, e.g. c. 17 000[c]. [d]TVC = Taupo Volcanic Centre; OVC = Okataina Volcanic Centre; TgVC = Tongariro Volcanic Centre. [e]Exact stratigraphic position of these tephras relative to Bullot Formation Members is unknown.

1:50,000 series). Here the Bullot Formation is ~11 metres thick and comprises numerous horizontally bedded tephra units. Twenty-three members are defined from the type and reference sections. Two rhyolitic tephras (Table 1) are found interbedded with the formation and are correlated with the Okareka Tephra (~17,000 yr BP) and Rerewhakaaitu Tephra (radiocarbon dated at 14,700±200 yr B.P. [NZ716], see Table 1). The presence of these two distinctive interbedded rhyolitic tephras allows a useful, informal, subdivision of the Bullot Formation into upper, middle and lower units. Tephras younger than Rerewhakaaitu Tephra are referred to informally as 'upper' Bullot Formation tephras. Fifteen members are defined, including the Pourahu Member (Table 1).

2.1. *Pourahu Member (Bullot Formation)*

The Pourahu Member comprises two units—a pumiceous pyroclastic flow, and a coeval fall tephra, they do not occur together at any locality. The type locality for the pyroclastic flow is at the southern end of 'The Chute' in the Rangipo Desert [T20/437045] (Fig. 1 and Fig. 2a). The pyroclastic flow is exposed only at the type locality (Fig. 2a,b) and at a section further to the north in a quarry near Mangatoetoenui Stream [T20/459153]. The absence of sections exposing this member elsewhere within the Rangipo Desert precludes detailed mapping of this deposit and an accurate estimate of volume.

At the type locality, the Pourahu Member [pyroclastic flow unit] underlies another Bullot Formation member, Ngamatea Lapilli-1. The stratigraphy at sections further to the south of Mt. Ruapehu (Donoghue, 1991) shows that Ngamatea Lapilli-1 is younger than the rhyolitic Waiohau Tephra (dated [NZ568] at 11,250 yrs B.P., see Table 1) which is found interbedded with older Bullot Formation tephras (Table 1). The Pourahu Member [pyroclastic flow unit] is therefore older than Ngamatea Lapilli-1 and younger than Waiohau Tephra, and is relative-age dated at between ~11,250 and 10,000 years B.P.

3. Analytical methods

All chemical analyses reported in this work were undertaken in the Analytical Facility of Victoria University of Wellington. Whole-pumice analyses for major elements and trace elements were determined by X-ray fluorescence using a Philips PW 1404 spectrometer with methods outlined in Palmer (1990). Banded pumice samples were first sectioned by slicing with a rock saw. The discrete 'dark' and 'light' components were then separated using a hydraulic jaw splitter. Electron microprobe analyses were determined using a JEOL-733 Superprobe and full ZAF correction procedures. All analyses were made at 15-kV accelerating voltage. Minerals were analysed with a 1.8-nA electron beam current with a 3-micron diameter beam. Glasses were analysed with the electron beam defocussed to 10–20 microns and beam current <0.8 nA. Glass standard KN-18 was used as a monitor during glass analysis.

4. Petrology and geochemistry

The majority of pumice clasts from the Pourahu pyroclastic flow are a pale yellow-brown, sparsely porphyritic, moderately vesicular andesite (Fig. 2a). Most clasts are coated or partly coated with a veneer of fine, lighter coloured ash. Rare ($<1\%$) clasts are dark coloured and glassy and in some ($\ll 1\%$) of the light coloured clasts, streaks of this darker glassy component have resulted in banded clasts (Fig. 2b). These clasts were recorded in the central and upper parts of the pyroclastic flow deposit. It is these streaky pumice clasts which suggest that two contrasting melts have intermingled and herein we describe and characterise the petrology and geochemistry of both components. For convenience the contrasting components will be identified as the 'light' component and the 'dark' component.

The petrography of the coeval fall deposits have not been studied in detail, owing to the small clast size and their weathered nature. Donoghue (1991) has studied the mineralogy of sieved tephra samples, recording a crystal assemblage of plagioclase, clinopyroxene, orthopyroxene, Fe-Ti oxides, olivine, together with rare hornblende. Hornblende has not been recorded in any clasts from the pyroclastic flow studied to date so its occurrence in the sieved tephras may be accidental. In the following text, we concentrate on clasts from the pyroclastic flow.

4.1. Dark component

This component is rare, occurring as discrete clasts in the pyroclastic flow and as dark streaks interbanded with the dominant light component in other clasts (Fig. 2b). It is a pumiceous porphyritic andesite containing phenocrysts and microphenocrysts of plagioclase (microphenocrysts define fluidal texture), orthopyroxene, clinopyroxene and Fe-Ti oxides and rare, but distinctive, quench olivine microphenocrysts. These are set in a red-brown glass. Tiny mm-sized xenoliths with granular meta-igneous textures and comprising varying proportions of plagioclase, clinopyroxene, orthopyroxene and Fe-Ti oxides occur in most samples. In banded samples (Fig. 2c) the contact between the contrasting 'dark' and 'light' components is sharp, indicating that the two components did not mix efficiently. Point counting determined an average vesicularity of 36% for the 'dark' component. Modal analysis data are summarised in Table 2. Compositions of the plagioclase and pyroxenes are plotted in Figs. 3 and 4, respectively. Plagioclase phenocrysts are zoned complexly with strongly zoned outer rims changing from an inner rim zone around An_{74} to an extreme outer

Fig. 2. Field and photomicrographs of the Pourahu Formation Pyroclastic Flow Member. (a) Type section of the Pourahu Pyroclastic Flow Member in 'the Chute', southeastern ring plain of Ruapehu. (b) Clast of banded of pumice (left of hammer head) in the central part of the Pourahu Pyroclastic Flow Member. Note the poorly sorted nature of the clasts and the occasional lithic (andesite) clast, (right of hammer handle). (c) Contact between the 'light' (top) and 'dark' (bottom) components in banded sample. Note the microphenocryst laths of plagioclase in the dark component and the vesicular nature of the light component. A white line highlights the sharp contact. Field width is 3 mm.

Table 2
Average and ranges of modal analysis point count data (800 points per sample) for 'light' and 'dark' andesites of the Poruhau pyroclastic flow member. Recorded values are vesicle free. (mp) = microphenocrysts, np = not present, trace = present in trace amounts.

	Light component	*Range* ($n=6$)	*Dark component*	*Range* ($n=5$)
Plag	15.2	(12.2–19.5)	11.7	(8.0–16.6)
$Plag_{(mp)}$	9.5	(3.0–18.7)	17.7	(15.3–20.4)
Cpx	4.2	(1.9–7.4)	3.9	(2.1–5.5)
Opx	3.3	(1.0–5.4)	2.5	(1.0–3.8)
$Px_{(mp)}$	1.8	(0.8–3.1)	1.7	(0–4.2)
$Ol_{(mp)}$	np		trace	
Oxides	1.9	(0.8–2.7)	1.3	(0–2.7)
Xenoliths	0.6	(0–2.0)	0.2	(0–0.6)
Groundmass	63.6	(56.0–69.6)	60.9	(58.1–63.5)

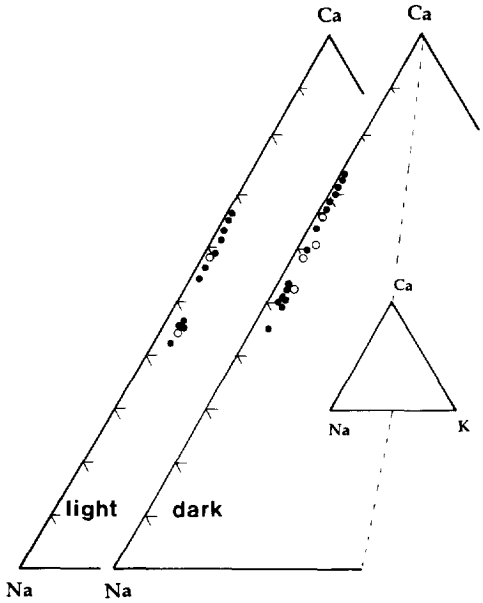

Fig. 3. Plagioclase analyses (Atom % Ca-Na-K) from the 'light' and 'dark' components for the Pourahu pyroclastic flow. Solid circles are phenocrysts, open circles microphenocrysts.

rim of An_{67}, mantling cores An_{49}–An_{53}. Microphenocryst compositions range between An_{52} and An_{67}, comparable to the outer rims of the phenocrysts. Clinopyroxene compositions are augite with phenocryst and microphenocryst compositions overlapping. Orthopyroxene phenocrysts are in some cases mantled by narrow rims of clinopyroxene; microphenocrysts of orthopyroxene are within the compositional range of the phenocrysts. Olivine microphenocrysts (100.Mg/(Mg+Fe) = 74 to 82) show a variety of shapes and forms (c.f. Donoghue et al., 1991) attributable to a quench origin.

Groundmass glass compositions were determined by electron microprobe for a number of discrete clasts and are listed in Table 3. These glasses, plotted in Fig. 5, range between 60% and 68% SiO_2. Glass inclusions in phenocrysts are mostly similar to the coexisting groundmass glass but in some crystals, more silicic glasses, similar to those of the 'light' component, have been measured. This observation hints at mixing processes which are far from simple, with melts picking up crystals from a number of sources.

4.2. Light component

Relative to the 'dark' component, this component is a pale yellow-brown colour, is slightly more vesicular (averaging ~46% vesicles), and contains larger phenocrysts and fewer microphenocrysts of plagioclase.

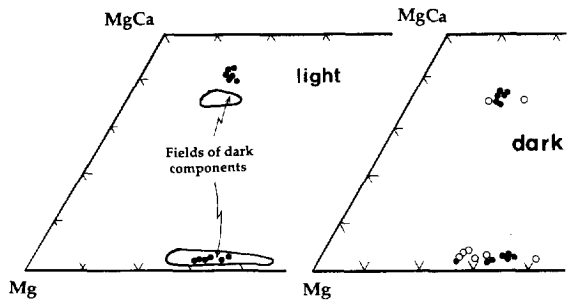

Fig. 4. Quadrilateral pyroxene analyses from the 'light' and 'dark' components of the Pourahu pyroclastic flow. Solid circles are phenocrysts, open circles are microphenocrysts.

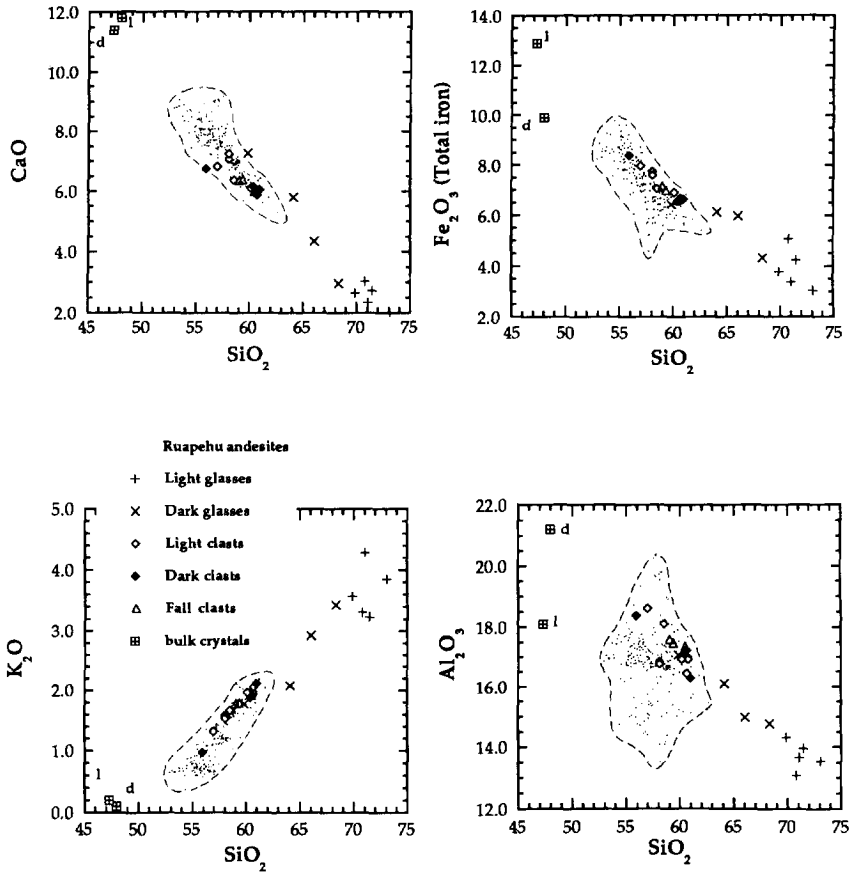

Fig. 5. Major-oxide SiO_2 versus Al_2O_3, Fe_2O_3, CaO and K_2O plots of whole single clasts (solid diamonds = dark component; open diamonds = light component), correlative fall deposits (open triangles) and groundmass glass (diagonal crosses = dark glass; vertical crosses = light glass) from the Pourahu Pyroclastic Flow Member. Note how the data plot with regard to the field of some 250 andesite analyses from Ruapehu volcano delineated by the area within the dashed line. Ruapehu data from Graham (1985); Hackett (1985); Wysoczanski (1989); Brooker (1992); JAG (unpubl. data). All data normalised to a loss-free basis prior to plotting. Fe_2O_3 = total iron. Two bulk crystal extract compositions are shown (squares with crosses), *d* = calculated by mass balance from averaged phenocryst content of 'dark' component and *l* = calculated from 'light' component.

Quench crystals of olivine are entirely absent although rare corroded and embayed xenocrysts (100 Mg/(Mg + Fe) = ~80) are mantled by overgrowths of orthopyroxene. It comprises the dominant clast component of the pyroclastic flow deposit. Modal data are summarised in Table 2. Phenocrysts comprise plagioclase, orthopyroxene, clinopyroxene and Fe-Ti oxides. Xenoliths are similar in texture and abundance to those recorded in the dark component. Plagioclase compositions are shown in Fig. 3 and range between An_{67} and An_{43}. Crystals are zoned normally but show none of the strong marginal zonation typical of plagioclase rims in the dark component. Clinopyroxene and orthopyroxene compositions are shown in Fig. 4. Clinopyroxene phenocryst compositions are slightly more Ca-rich than those of the dark component whereas the compositions of the orthopyroxenes overlap. Groundmass glass compositions, determined for a number of discrete clasts, are rhyolitic (71–73% SiO_2, Table 3) and consistently more felsic than those of the 'dark' component.

Table 3
Representative electron microprobe analyses of glasses from 'dark' and 'light' components of the Poruhau pyroclastic flow. All analyses undertaken with a beam defocussed to 10–20 microns. n = number of analyses, standard deviation (in parentheses) shown for the first column is typical of other sets of data.

	Pf/2 Dark ($n=9$)	Pf/1 Dark ($n=8$)	Pf/R Dark ($n=7$)	Pf/R Light ($n=7$)	Pf/2/1 Light ($n=9$)	Pf/1px incl ($n=3$)
SiO_2	68.38 (0.84)	66.06	64.07	71.08	69.89	70.8
TiO_2	0.85 (0.09)	0.96	0.71	0.67	0.72	0.61
Al_2O_3	14.77 (0.22)	14.98	16.65	13.66	14.32	13.08
FeO	3.78 (0.13)	5.36	4.66	3.04	3.38	4.55
MnO	0.23 (0.05)	0.19	0.21	0.24	0.20	0.15
MgO	0.94 (0.07)	1.33	1.14	0.60	0.73	1.02
CaO	2.97 (0.23)	4.35	5.33	2.34	2.65	3.04
Na_2O	4.87 (0.26)	4.49	4.56	4.13	4.50	3.91
K_2O	3.43 (0.03)	2.93	2.56	4.29	3.57	3.31
Cl	0.16 (0.04)	0.20	0.16	0.15	0.21	0.18
Total	100.38	100.85	100.05	100.2	100.17	100.65

4.3. Whole-rock compositions

Major oxide and trace-element analyses of representative whole pumice clasts are contained in Table 4. In Figs. 5 and 6, we compare this new data to a data base of more than 250 andesites from Ruapehu volcano (sources of data are given in fig. caption). Analyses of pumices from coeval Pourahu fall deposits elsewhere on the eastern Ruapehu Ring Plain are also included.

Taken as a whole, the compositions of the Pourahu clasts are similar geochemically to the more evolved andesites erupted from Ruapehu volcano. This is consistent with a trend towards more silica rich eruptives in the younger (post last glacial) lavas of Ruapehu (Graham and Hackett, 1987). In Fig. 5, the Ruapehu lavas define rather broad fields, due partly to the effects of crystal accumulation, principally of pyroxene and plagioclase (Graham and Hackett, 1987) and clearly reflected in the manner in which the Al_2O_3 and CaO plots fan out. Clasts of both 'dark' and 'light' components from the flow deposit define a reasonably coherent but overlapping array on these variation diagrams and the fall deposits plot securely within this array. This overlapping array renders end-member identification difficult, if not impossible, but may be an important clue to the manner in which andesitic melts evolve.

In this regard we have already noted distinctive petrographic and compositional differences in ground-

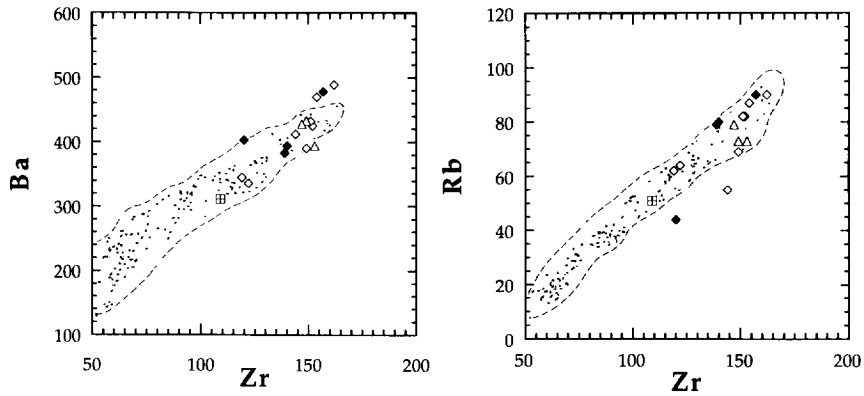

Fig. 6. Rb and Ba versus Zr (in parts per million) for whole-rock clasts and fall deposits of the Pourahu Pyroclastic Flow. Ruapehu andesite data are from data base described in caption to Fig. 6. Symbols as for Fig. 6 apart from square with cross which is a bulk matrix sample (<2 phi grain size) from the central part of the pyroclastic flow. Dashed line encloses field of Ruapehu andesites, as in Fig. 5.

Table 4
Representative chemical analyses of major and trace elements for individual clast from the Poruhau pyroclastic flow and coeval fall deposits (last two columns). Fe_2O_3 is total iron, LOI is lost on ignition to 1000°C, trace elements are in parts per million.

Sample No.	Pf-001 Dark	Pf-002 Dark	Pf-1/1994 Dark	Sch-001 Light	Pf-2/1/1994 Light	Pf-2/2/1994 Light	94011A Light	94011B Light	94010A Fall	94010B Fall
SiO_2	59.77	60.01	59.49	59.70	59.31	58.63	57.57	57.50	57.73	58.97
TiO_2	0.67	0.68	0.72	0.70	0.72	0.74	0.73	0.71	0.73	0.68
Al_2O_3	17.01	17.07	15.89	16.18	16.52	16.50	16.69	16.59	16.99	16.92
Fe_2O_3	6.54	6.51	6.46	6.46	6.51	6.73	7.68	7.52	6.77	6.43
MnO	0.11	0.11	0.10	0.10	0.10	0.10	0.12	0.12	0.11	0.10
MgO	3.51	3.41	3.70	3.54	3.52	3.76	4.60	4.71	3.77	3.30
CaO	5.90	6.12	5.91	5.90	5.74	5.95	7.01	7.18	6.22	5.85
Na_2O	3.37	3.43	3.29	3.16	3.11	3.10	3.01	2.99	3.00	3.17
K_2O	1.88	1.87	2.07	1.95	2.01	1.92	1.56	1.53	1.74	1.87
P_2O_5	0.14	0.14	0.14	0.13	0.14	0.13	0.12	0.12	0.14	0.15
LOI	1.40	0.76	2.51	1.64	2.41	2.57	1.02	0.99	2.50	2.23
Total	100.30	100.10	100.29	99.50	100.10	100.30	100.12	99.96	99.69	99.67
Sc	18	18	16	15	13	14	24	25	20	17
V	154	145	123	125	123	115	185	181	154	140
Cr	46	41	50	47	42	39	94	84	57	46
Ni	14	14	16	23	18	13	27	26	21	17
Cu	28	31	23	23	25	18	42	52	39	27
Zn	70	68	55	58	54	51	69	69	69	65
Ga	20	20	17	20	18	18	18	18	18	18
Rb	79	80	90	87	90	82	64	62	73	79
Sr	230	240	228	232	230	227	232	234	239	246
Y	24	25	25	25	27	25	24	25	25	24
Zr	139	140	157	154	162	151	122	119	149	147
Nb	4.5	5.8	6.0	5.5	6.0	5.0	4.0	5.0	4.0	4.0
Ba	383	394	478	470	489	432	336	345	433	428
La	15	15	19	19	18	17	13	14	16	16
Ce	35	37	40	43	42	37	28	31	33	34
Pb	14	13	11	14	14	12	9	11	12	13
Th	8.5	7	9	9	9	9.5	5	6	9	9
U	3	3	3	2	1	1	1	2	2	2

mass glasses which extend the range of compositions to rhyolite ($>70\%$ SiO_2). Glasses from the 'light' component are consistently richer in SiO_2, more potassic, less calcic, alumina and iron rich than those of the 'dark' component. The trends between glasses, clasts and bulk extracts (calculated from average modal abundance data, converted to wt%) are approximately linear and consistent with mixing.

Trace-element data shown in Fig. 6, are consistent with the range in compositions defined by the major oxides and extend over about 50% of the compositional range of previously analysed andesites from Ruapehu. Given the small volume of the Pourahu flow, this is perhaps surprising. However, it once again emphasises the complementary role of crystals and liquid, particularly the incompatible elements (Zr, Rb and Ba) which will strongly reflect the proportions of groundmass glass to suspended crystals.

5. Discussion

Melt physical properties such as temperature, density, viscosity, vesicularity and crystallinity are interrelated functions of chemical composition, cooling and emplacement history and will interact to influence magmatic processes such as differentiation, eruption style, vesiculation, explosivity, and fluid flow. Whenever contrasting melts intermingle, several scenarios may unfold:

(1) The melts may mix physically, thereby forming a hybrid.

(2) One melt may freeze (quench) against the juxtaposed melt, forming an acid–basic pillow or net-vein complex, and abruptly arresting the mixing process.

(3) The melts may mix partially but incompletely, particularly where the two end-member components are porphyritic, leaving phenocrysts from both magmas with strong disequilibrium textures.

(4) The melts may intermingle but not mix, forming a 'streaky' or 'banded' rock.

Where mixing has been efficient, the only evidence for the process may be disequilibrium textures in phenocryst phases and/or linear trends in Harker-type variation diagrams. Where mixing is limited or incomplete, streaky or banded rocks may result, which retain the identity of either or both end-members. In the latter instance there is frequently evidence for small-scale (mm) mixing via diffusion between the juxtaposed melts. The extent to which this process can take place will be both time, temperature and composition dependent.

Magma mixing has been argued to have a significant influence on the triggering of volcanic eruptions (Sparks et al., 1977). Hence recognition of this process in the volcanological record of young deposits from Ruapehu may have important consequences for hazard mitigation. In the simplest scenario, a new magma batch ascends into a magma chamber displacing magma and initiating eruption at the surface. In the recent literature a number of modifications of this theme have been offered and the varying roles of physical properties (i.e., density, temperature, etc.) have been emphasised (Huppert et al., 1984; Sparks and Marshall, 1986; Robin et al., 1990; Furman et al., 1992).

In the case of the Pourahu Member, our evidence suggests that two andesitic magmas have intermingled and in the following paragraphs we endeavour to isolate end-member compositions, to develop a model for the intermingling process and to address the question of hazard potential.

5.1. Physical conditions of mixing

For the dark component, equilibration temperatures, based upon Mg-Fe exchange in coexisting pyroxene phenocryst assemblages (Wood and Banno, 1973; Wells, 1977; Kretz, 1982) gave temperatures in the range 1050–1170°C, whereas microphenocrysts yielded temperatures in the range 1040–1120°C. Independent estimates based on texturally equilibrated coexisting magnetite-ilmenite gave slightly lower temperatures (980–1050°C). Similar calculations for juxtaposed phenocrysts in the light component yielded equilibration temperatures in the range 950–1020°C. The slightly higher temperatures recorded in the dark component are consistent with its more mafic character and the crystallisation of olivine microphenocrysts.

Table 5
Calculated (after Bottinga and Weill, 1970) anhydrous density data (kg/m^3) for 'light' and 'dark' glass components of the Poruhau pyroclastic flow. Model 1 refers to the least iron rich and model 2 to the most iron-rich compositions of the 'light' and 'dark' components.

T (°C)	Light model 1	Light model 2	Dark model 1	Dark model 2
900	2.44	2.47	2.54	2.60
1000	2.43	2.46	2.53	2.58
1100	2.42	2.45	2.51	2.57

Calculated density and viscosity (Bottinga and Weill, 1970; Shaw, 1972), based on glass compositions from the dark and light components, are summarised

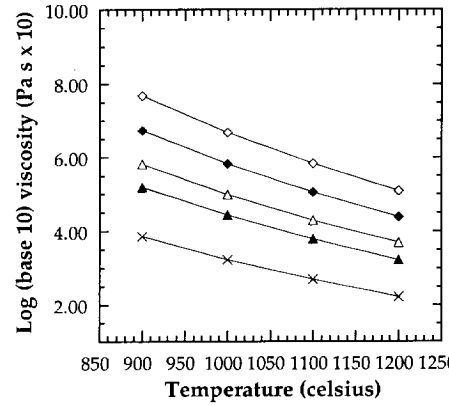

Fig. 7. Calculated temperature (°C) – viscosity (Pa s) (calculated after Shaw, 1972) relations for 'light' (diamonds, open symbols = anhydrous; closed symbols = 1% H_2O) and 'dark' (triangles, open symbols = anhydrous, closed symbols = 1% H_2O) glass components of the Pourahu Pyroclastic Flow. A primitive TVZ high-alumina basalt (TVZ-15, Kakuki basalt of Gamble et al., 1990, 1993 is shown for comparison. Note at a given temperature the viscosity of the 'light' component is around two Log_{10} units greater than the 'dark' unit.

in Table 5 and Fig. 7. In the temperature range constrained by the mineral thermometry, the light (more felsic) melts are less dense and more viscous, (by about 10–50 times) than the dark (mafic) melts. Using a conduit diameter of 100 m (reasonable in terms of the present-day magma bodies predicted by geophysical models, Latter, 1981), calculated Reynolds numbers are < 1 and therefore orders of magnitude lower than critical values for turbulent flow and more appropriate for laminar flow. Arguably, these physical parameters may reduce the potential for efficient stirring and mixing of the juxtaposed melts. Given the likely small temperature differences between the adjoining melts, and our petrographic observations which show the contact interfaces to be sharp and distinct on the scale of hand specimen and thin section (Fig. 2c), contrasting viscosity emerges as the major barrier to efficient mixing between the two components. Over the timespan (hours, days, months??) for which the melts may have been juxtaposed, this viscosity contrast may emerge as the critical physical barrier to diffusion and efficient mixing.

5.2. *Eruptive model*

Based upon our petrographic and geochemical observations, two subtly contrasting andesitic magma compositions are inferred to have intermingled. The 'dark' component contains microphenocrysts of olivine and abundant plagioclase. Furthermore, phenocryst phases in the 'dark' component show stronger evidence for disequilibrium with abrupt zoning in the outer rims of plagioclase phenocrysts and narrow clinopyroxene overgrowths mantling some orthopyroxene phenocrysts. We infer that this abrupt zonation marked the injection of the 'dark' magma into the chamber occupied by the predominant 'light' component.

From our field observations, the 'dark' component is distinctly minor but occurs both as discrete and as banded clasts. Using the major-oxide plots (Fig. 5), the clast data define an array between about 56–61% SiO_2 and the microprobe glass data extend from 60% to 73% SiO_2. Thus, the two fields overlap slightly and define a continuum which projects back towards the bulk crystal extract points (Fig. 5 and Table 6). In each case the bulk extract compositions are broadly basaltic but both are high in alumina, reflecting the significant effect of plagioclase in the phenocryst

Table 6
Calculated bulk extract compositions based upon average (wt.%) phenocryst assemblages in the 'light' and 'dark' components.

	Dark	Light
SiO_2	48.0	47.3
TiO_2	0.8	1.2
Al_2O_3	21.2	18.1
Fe_2O_3*	9.9	12.9
MnO	0.2	0.2
MgO	4.6	5.6
CaO	11.8	11.4
Na_2O	3.3	3.1
K_2O	0.1	0.2

assemblage. This effect is not entirely unexpected because of the likely near-neutral buoyancy of plagioclase in the melts. A first-order interpretation of the near-linear chemical trends would be simple mixing between a mafic and felsic andesite component, alternatively, mixing between melts and varying proportions of crystals. However, these interpretations are necessarily tempered by the chemical variations in the clasts and by glass inclusions in phenocrysts from both dark and light clasts. These inclusion glasses do not necessarily reveal a simple relationship to the host groundmass and suggest a more complex process which involves passage of melts through a plexus of magma chambers together with an associated scavanging of phenocrysts.

In formulating an eruption-emplacement model for the Pourahu pyroclastic flow we need to integrate factors such as the volume relationships of the 'dark' and 'light' components (Donoghue, 1991; this work), the documented record of Ruapehu volcanism over the past 10 ka (Hackett, 1985; Graham and Hackett, 1987; Houghton et al., 1987; Donoghue, 1991), and the information available from seismic monitoring of the volcano (Latter, 1981). These observations lead us to infer that the Pourahu event occurred during a time of intense volcanic activity in the Tongariro Volcanic Centre. Ultimately, this activity may have enhanced the preservation potential of the deposit on the ring plain. Furthermore, the work of Latter (1981) and Houghton et al. (1987) identified zones of S-wave attenuation at a number of levels and locations within the upper crust beneath Ruapehu and interpreted these as being due to small magma chambers. If such a plexus of chambers existed in the past, and were interconnected, an ideal

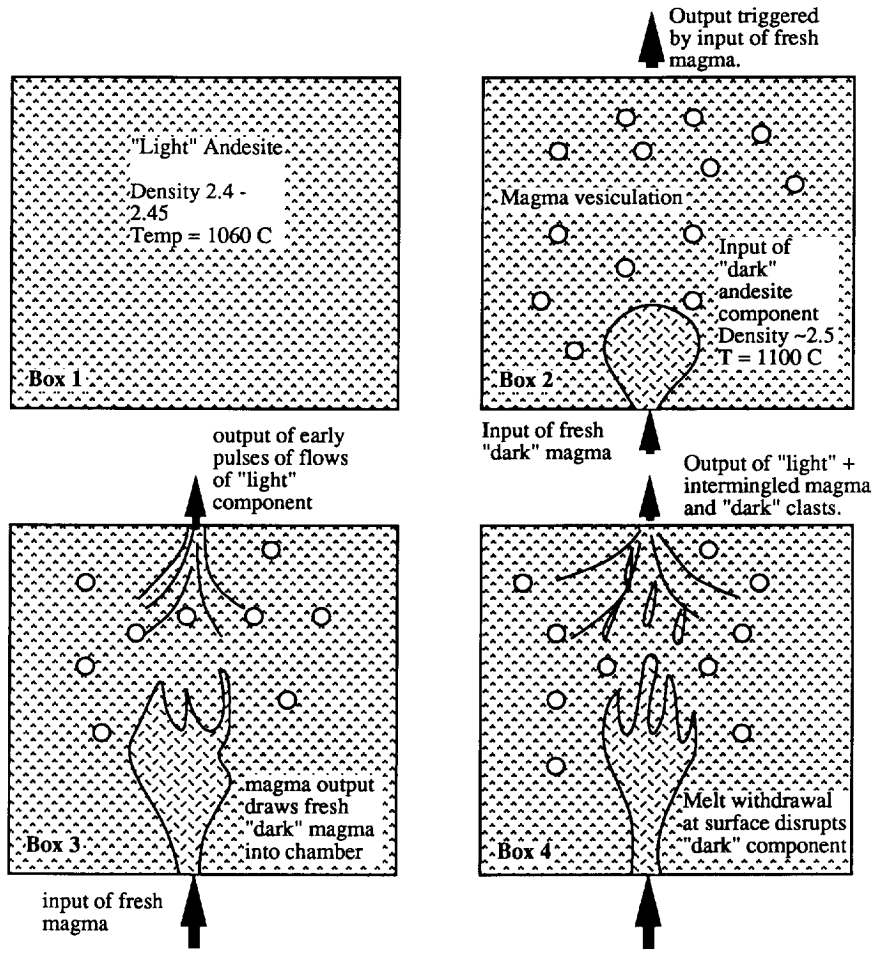

Fig. 8. Simple box model for eruptive history of the Pourahu pyroclastic flow. Box 1: 'Light' andesite resides in magma chamber beneath summit vent. Box 2: Injection of hot mafic 'dark' component into magma chamber of cooler 'light' magma initiates vesiculation and the eruptive episode through mass displacement and heat exchange. Box 3: Expulsion of magma from the chamber draws more melt into the chamber. Box 4: Continued melt withdrawal 'sucks' more 'dark' magma into chamber, leading to incomplete intermingling and development of streaky pumice.

environment for mixing would exist. We derive encouraging support for this assertion from the diverse suite of meta-igneous xenoliths and xenocrysts (often with relic exsolution in pyroxene) which are common in the lavas of Ruapehu and the TgVC (Graham and Hackett, 1987; Graham et al., 1988; Graham et al., 1990) and which attest to the existence of crystallising magma chambers beneath the volcanoes.

We propose the following model for the eruption (Fig. 8):

(1) 'Light' coloured andesite magma was contained in a high-level chamber beneath the active summit vent area (box 1).

(2) Fresh 'dark' magma injects into the bottom of the chamber. This melt is slightly hotter and denser (2.5–2.6 kg/m^3 as distinct from 2.4–2.45 kg/m^3) than the light component and ponds below it (box 2).

(3) Injection of this fresh melt initiates vesiculation in the light magma and the eruption commences (box 2).

(4) The eruption process 'sucks' more dark magma into the chamber and it is drawn into the eruption vortex (box 3) where:

(5) It becomes fragmented and erupted as discrete clasts or entrained as streaks or schlieren within the dominant light melt component (box 4).

We conclude that the Pourahu event was triggered by the ascent of a fresh batch of hot andesitic magma into a shallow magma chamber beneath the vent area. As it moved to the surface, this magma had already passed through other small magma reservoirs and had assembled a diverse cargo of xenocrysts and phenocrysts (glass inclusions in phenocrysts). These observations confirm the complex polybaric mixing and fractionation history which may be experienced by many andesitic magmas. Inevitably, this may be reflected in the rather unpredictable long and short term eruptive cycles of andesite-dacite volcanoes. For example, the recent eruptions of Pinatubo volcano (1991) in the Phillipines and Mt. St. Helens (1980) in the United States. Both of these events gave ample seismic warning of impending eruption, but the magnitude of the eruptions did not become apparent until it was too late (Mt. St. Helens) or inevitable (Pinatubo). Finally, concerning the future hazard potential on Mount Ruapehu, the Whangaehu River valley has a notorious history as a pathway for life threatening lahars from the crater lake of Ruapehu (Houghton et al., 1987). Our evidence suggests that pyroclastic flows erupting from the present summit area may also follow this route, with significant hazard implications for power transmission, road communications and the settlement of Waiouru.

6. Conclusions

(1) Pourahu pyroclastic flow is a rare preserved example of a pyroclastic flow deposit erupted from Ruapehu volcano during a period of peak activity about 10,000 years ago.

(2) Evidence of magma mingling derives from rare clasts of banded or streaky pumice and clasts of dark pumice which are minor constituents of the clasts making up the flow deposit.

(3) Electron microprobe analyses of adjoining glasses comprising the groundmass of the 'dark' and 'light' clasts are distinctive and confirm the mingling of contrasting melts.

(4) Differences between phenocryst entrained glass inclusions and host groundmass glasses imply that melts assemble a diversity of crystals enroute to the surface.

(5) Whole-rock chemical analyses of 'dark' and 'light' clasts overlap in bivariate plots of major and trace elements. This suggests that end-member identification will be imprecise, being complicated by variable elutriation and sequestering of crystals in the ascending melts. The net result of this process is that chemical trends will be smeared out and a small-volume eruption, such as the Pourahu, can produce a spectrum of compositions on a scale of individual clasts. The fact that these compositions cover a substantive portion of the field generated by some 250 separate analyses of Ruapehu lavas is significant and has important implications for the way in which andesites evolve. The means to investigate this are now to hand and careful micro-mineral methods such as isotopic disequilibrium studies of selected andesite deposits may unravel hidden complexities in andesite magma petrogenesis.

(6) Magma mixing processes have played a significant role in the evolution of the Pourahu eruption and are clearly significant in triggering eruptions throughout the TVZ.

(7) The upper reaches of the Whangaehu River valley will likely form a channelway for future pyroclastic flows from Ruapehu volcano.

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References

Blake, S., 1984. Magma mixing and hybridisation processes at the alkalic, silicic Torfajokull central volcano triggered by tholeiitic Veidivotn fissuring, S. Iceland. J. Volcanol. Geotherm. Res., 22: 1–31.

Blake, S., Wilson, C.J.N., Smith, I.E.M. and Walker, G.P.L., 1992. Petrology and dynamics of the Waimihia mixed magma eruption, Taupo Volcano, New Zealand. J. Geol. Soc. London, 149: 193–207.

Bottinga, Y. and Weill, D.F., 1970. Densities of liquid silicate systems calculated from partial molar volumes of oxide components. Am. J. Sci., 269: 169–182.

Bowen, N.L., 1928. The Evolution of the Igneous Rocks. Princeton University Press.

Brooker, J., 1992. The geology of north western Pinnacle Ridge, Te Heranga Formation, Ruapehu Volcano, New Zealand. Unpublished BSc (Hons) thesis, Victoria University of Wellington, 133 pp. (unpubl.)

Brophy, J.G., 1987. The Cold Bay Volcanic Centre, Aleutian Volcanic Arc: II. Implications for fractionation and mixing mechanism in calc-alkaline andesite genesis. Contrib. Mineral. Petrol., 97: 378–388.

Cole, J.W., 1970. Description and correlation of Holocene volcanic formations in the Tarawera –Rerewhakaaitu Region. Trans. R. Soc. N.Z., Earth Sci., 8(7): 93–108.

Donoghue, S.L., 1991. Late Quaternary volcanic stratigraphy of the southeastern sector of the Mount Ruapehu ring plain, New Zealand. PhD thesis, Massey University, New Zealand (unpubl.).

Donoghue, S.L., Stewart, R.B. and Palmer, A.S., 1991. Morphology and chemistry of olivine phenocrysts of Mangamate Tephra, Tongariro Volcanic Centre, New Zealand. J.R. Soc. New Zealand, 21: 225–236.

Furman, T., Meyer, P.S. and Frey, F., 1992. Evolution of Icelandic central volcanoes: evidence from the Austurhorn intrusion, southeastern Iceland. Bull. Volcanol., 55: 45–62.

Gamble, J.A., 1979. Some relationships between coexisting granitic and basaltic magmas and the genesis of hybrid rocks in the central complex of Slieve Gullion, north east Ireland. J. Volcanol. Geotherm. Res., 5: 297–316.

Gamble, J.A., Smith, I.E.M., Graham, I.J., Cole, J.W., Kokelaar, B.P., Houghton, B.F. and Wilson, C.J.N., 1990. The petrology, phase relations and tectonic setting of basalts from the Taupo Volcanic Zone, New Zealand and the Kermadec Island Arc – Havre Trough, S.W. Pacific. J. Volcanol. Geotherm. Res., 43: 235–270.

Gamble, J.A., Smith, I.E.M., McCulloch, M.T., Graham, I.J. and Kokelaar, B.P., 1993. The geochemistry and petrogenesis of basalts from the Taupo Volcanic Zone and the Kermadec Island Arc, S.W. Pacific. J. Volcanol. Geotherm. Res., 54: 265–290.

Garcia, M.O., Rhodes, J.M., Wolfe, G.E. and Ho, R.A., 1992. Petrology of lavas from episodes 2-47 of the Puu Oo eruption of Kilauea volcano, Hawaii: evolution of magmatic processes. Bull. Volcanol., 55: 1–16.

Graham, I.J., 1985. Petrochemical and strontium isotopic studies of lavas and xenoliths from Tongariro volcanic centre. PhD thesis, Victoria University of Wellington, 345 pp. (unpubl.).

Graham, I.J. and Hackett, W.R., 1987. Petrology of calc-alkaline lavas from Ruapehu volcano and related vents, Taupo Volcanic Zone, New Zealand. J. Petrol., 28: 531–567.

Graham, I.J. and Worthington, T., 1988. Petrogenesis of Tauhara Dacite (Taupo Volcanic Zone, New Zealand) Evidence for magma mixing between high-alumina andesite and rhyolite. J. Volcanol. Geotherm. Res., 35: 279–294.

Graham, I.J., Grapes, R.H. and Kifle, K., 1988. The origin and petrogenesis of vitrified metagreywacke xenoliths, Tongariro Volcanic Centre, New Zealand. J. Volcanol. Geotherm. Res., 35: 205–215.

Graham, I.J., Blattner, P. and McCulloch, M.T., 1990. Meta-igneous granulite xenoliths from Mount Ruapehu, New Zealand: Fragments of altered oceanic crust? Contrib. Mineral. Petrol., 105: 650–661.

Grove, T.L., Gerlach, D.C. and Sando, T.W. 1982. Origin of calc-alkaline series lavas at Medicine Lake volcano by fractionation, assimilation and mixing. Contrib. Mineral. Petrol., 80: 160–182.

Hackett, W.R., 1985. Geology and Petrology of Ruapehu volcano and Related vents. PhD thesis, Victoria University of Wellington, New Zealand (unpubl.).

Hackett, W.R. and Houghton, B.F., 1988. A facies model for a Quaternary andesitic composite volcano: Ruapehu, New Zealand. Bull. Volcanol., 51: 51–68,

Houghton, B.F., Latter, J.H. and Hackett, W.R., 1987. Volcanic hazard assessment for Ruapehu composite volcano, Taupo Volcanic Zone, New Zealand. Bull. Volcanol., 49: 737–751.

Huppert, H.E., Sparks, R.S.J. and Turner, J.S., 1984. Some effectes of viscosity on the dynamics of replenished magma chambers. J. Geophys. Res., 89: 6857–6877.

Kretz, R., 1982. Transfer and exchange equilibria in a [ortion of the pyroxene quadrilateral as deduced from natural and experimental data. Geochim. Cosmochim. Acta, 46: 411–421.

Latter, J.H., 1981. Location of zones of anomalously high S-wave attenuation in the upper crust near Ruapehu and Ngauruhoe volcanoes. J. Volcanol. Geotherm. Res., 10: 125–156.

McBirney, A.R., 1980. Mixing and unmixing of magmas. J. Volcanol. Geotherm. Res., 7: 357–371.

McGarvie, D., Macdonald, R., Pinkerton, H. and Smith, R.L., 1990. Petrogenetic evolution of the Torfajokull volcanic complex, Iceland. II The role of magma mixing. J. Petrol., 31: 461–482.

Marshall, L.A. and Sparks, R.S.J., 1984. Origin of mixed magmas and net-veined ring intrusions. J. Geol. Soc. London, 141: 171–182.

Nairn, I.A., 1980. Source, age and eruptive mechanisms of the Rotorua Ash. N.Z. J. Geol. Geophys., 23: 193–207.

Nairn, I.A., 1981. Some studies of the geology, volcanic history, and geothermal resources of the Okataina Volcanic Centre, Taupo Volcanic Zone, New Zealand. PhD thesis, Victoria University of Wellington, New Zealand (unpubl.).

Palmer, K., 1990. XRF analyses of granitoids and associated rocks, St John's Range, South Victoria Land, Antarctica. Anal. Contrib. 13. Victoria University of Wellington, 23 pp.

Pitcher, W.S., 1993. The Nature and Origin of Granite. Chapman and Hall, 321 pp.

Pullar, W.A., Birrell, K.S. and Heine, J.C., 1973. Named tephras and tephra formations occurring in the central North Island, with

some notes on derived soils and buried paleosols. N.Z. J. Geol. Geophys., 16(3): 497–518.

Rhodes, J.M., Dungan, M.A., Blanchard, D.P. and Long, P.E. 1979. Magma mixing at mid-ocean ridges: Evidence from basalts drilled near 22°N on the Mid-Atlantic Ridge. Tectonophysics, 55: 35–61.

Robin, C., Komorowski, J-C., Boudal, C. and Mossand, P., 1990. Mixed magma pyroclastic surge deposits associated with debris avalanche deposits at Colima volcano, Mexico. Bull. Volcanol., 52: 391–403.

Shaw, H.R., 1972. Viscosities of magnetic silicate liquids: an empirical method of prediction. Am. J. Sci., 272: 870–893.

Sparks, R.S.J. and Marshall, L.A., 1986. Thermal and mechanical constraints on mixing between mafic and silicic magmas. J. Volcanol. Geotherm. Res., 29: 99–124.

Sparks, R.S.J., Sigurdsson, H. and Wilson, L., 1977. Magma mixing: a mechanism for triggering acid explosive eruptions. Nature, 267: 315–318.

Topping, W.W., 1973. Tephrostratigraphy and chronology of late Quaternary eruptives from the Tongariro Volcanic centre. N.Z. J. Geol. Geophys., 16(3): 397–423.

Walker, G.P.L. and Skelhorn, R.R., 1966. Some associations of acid and basic igneous rocks. Earth-Sci. Rev., 2; 93–109.

Wells, P.R.A., 1977. Pyroxene thermometry in simple and complex systems. Contrib. Mineral Petrol., 62: 129–139.

Wilson, C.J.N., Switsur, V.R. and Ward, A.P., 1988. A new ^{14}C age for the Oruanui (Wairakei) eruption, New Zealand. Geol. Mag., 125: 297–300.

Wood, B.J. and Banno, S., 1973. Garnet-orthopyroxene and orthopyroxene-clinopyroxene relationships in simple and complex systems. Contrib. Mineral. Petrol., 42: 109–124.

Wysoczanski, R.J., 1989. Volcanology and petrology of the Iwikau Member, Whakapapa Formation, Mt. Ruapehu, Tongariro Volcanic Centre, New Zealand. BSc (Hons) thesis, Victoria University of Wellington, 103 pp. (unpubl.).