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Ages of the Pliocene–Pleistocene Alexandra and Ngatutura Volcanics, western North Island, New Zealand, and some geological implications

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Abstract The Alexandra and Ngatutura Volcanics are the two southernmost of the Pliocene–Quaternary volcanic fields of western and northern North Island, New Zealand, northwest of Taupo Volcanic Zone (TVZ). The Ngatutura Basalts are an alkalic basaltic field comprising monogenetic volcanoes. The Alexandra Volcanics consist of three basaltic magma series: an alkalic (Okete Volcanics), calcalkalic (Karioi, Pirongia, Kakepuku, and Te Kawa Volcanics), and a minor potassic series. Twenty new K-Ar ages are presented for the Alexandra Volcanics and 9 new ages for the Ngatutura Basalts. Ages of the Alexandra Volcanics range from 2.74 to 1.60 Ma, and the ages of all three magma series overlap. Ages of the Ngatutura Basalts range from 1.83 to 1.54 Ma. Each basaltic field has a restricted time range and there is a progressive younging in age of the basaltic fields of western North Island from the Alexandra Volcanics in the south, to Ngatutura, to South Auckland, and then to the Auckland field in the north. Neither of the Alexandra nor Ngatutura Volcanics shows any younging direction of their volcanic centres or any age pattern within their fields, and there is no systematic variation in age with rock composition. Any correlation of age with degree of erosion of volcanic cones is invalid for these basaltic fields; instead, the degree of erosion may be controlled by the lithology of the cones and possibly by the extent of preservation offered by the thick cover deposits of the Kauroa, Hamilton, and younger tephra beds. Stratigraphic relations have enabled the earliest member of the Kauroa Ash Formation to be dated at 2.3 Ma. This formation represents a series of widespread rhyolitic plinian and ignimbrite eruptions probably derived from TVZ and initiated during the Late Pliocene.

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Keywords Alexandra Volcanics; Ngatutura Basalts; Pliocene; Pleistocene; volcanic rocks; numerical age; K-Ar; Kauroa Ash Formation

INTRODUCTION

The Alexandra and Ngatutura Volcanics are the two southernmost of the Pliocene–Quaternary basalt fields of western and northern North Island, northwest of Taupo Volcanic Zone (TVZ) (Fig. 1). In order from north to south these basalt fields are: Northland (Kaikohe–Bay of Islands field and Whangarei field — Heming 1980a, b; Ashcroft 1986), Auckland (Searle 1964; Heming & Barnet 1986), South Auckland (Rafferty & Heming 1979), Ngatutura Volcanics (Spratt & Rodgers 1975; Utting 1986), and the Alexandra Volcanics (Briggs 1983, 1986a; Keane 1985). Except for the Alexandra Volcanics, the basalt fields are predominantly alkalic in composition, and consist of spatially distinct fields, each containing numerous small volume monogenetic volcanoes composed of basaltic lava flows, scoria cones, and maars. These alkalic basalt fields are generally regarded as having a back-arc continental intraplate setting (e.g., Cole 1986). The Alexandra Volcanics consist of three magma series (R. M. Briggs & W. F. McDonough in prep., "Petrology of the Alexandra Volcanics, western North Island, New Zealand, and the petrogenesis of a coexisting convergent margin, alkalic intraplate, and potassic basalt magma series"): an alkalic (named the Okete Volcanics, Briggs 1983), a calcalkalic, and a K-rich mafic series, and they collectively occupy tectonic locations where the back-arc alkalic basalt fields are juxtaposed with and meet subduction-related magmas.

Some K-Ar radiometric ages of the Alexandra Volcanics were determined by Stipp et al. (1967), Stipp (1968), and Robertson (1976), and three of the volcanic centres of the Ngatutura Basalts have been dated by Stipp (1968).

The purpose of this paper is to present K-Ar whole-rock radiometric ages of 20 previously undated volcanic centres within the Alexandra Volcanics and 9 ages within the Ngatutura Basalt field. Also in this paper we discuss several implications of these ages. We argue that: (1) geomorphic expression and preservation of volcanic features may be unreliable guides to the age of a volcanic centre; (2) there is no apparent younging direction of volcanism within each of the fields; and (3) the ages of the basalts can be used to determine stratigraphically the age of the earliest member of the Kauroa Ash Formation.

ALEXANDRA VOLCANICS

The Alexandra Volcanics are the most voluminous (55 km^3) of the basalt fields and consist of three magma series (Briggs & McDonough in prep.): (1) an alkalic suite named the Okete Volcanics (Briggs 1983), which is broadly similar in form and lithology to the other basalt fields of northern and western

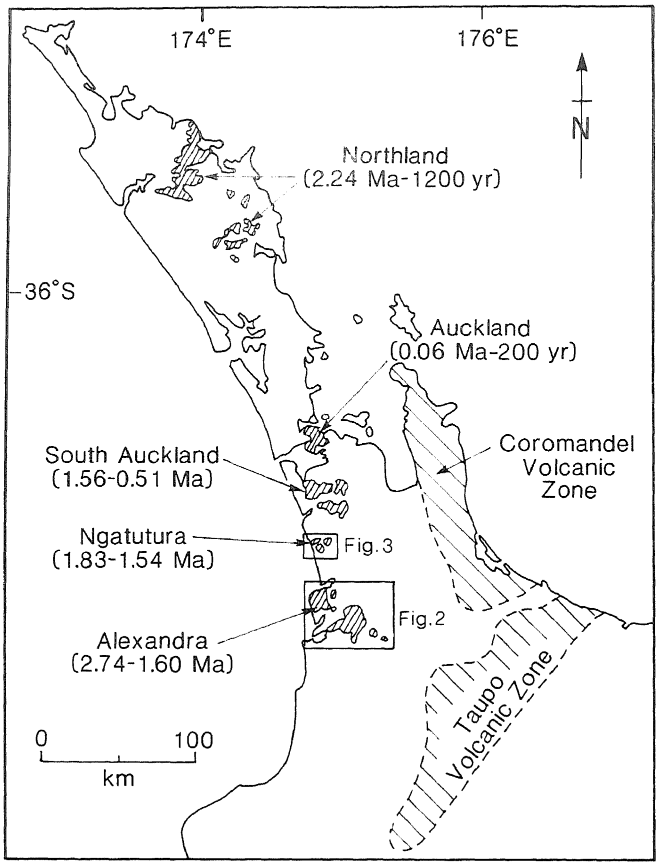

Fig. 1 Northern North Island showing the distribution and age range of Pliocene and Quaternary basalt fields in relation to Coromandel Volcanic Zone and Taupo Volcanic Zone. Ma, millions of years ago.

North Island; (2) a calcalkalic suite comprising large stratovolcanoes (Karioi and Pirongia) which form a volcanic chain with a pronounced northwesterly alignment — these stratovolcanoes are predominantly basaltic in composition but some high-K andesite lavas and dikes occur on Karioi and Pirongia; and (3) a K-rich mafic suite of basanites and absarokites which mainly occur as capping lavas on Pirongia volcano.

The calcalkalic volcanic chain extends from Karioi in the northwest, through Pirongia, to Kakepuku, Te Kawa, Tokanui, and Waikeria to the southeast (Fig. 2). All six volcanoes lie on a remarkably straight lineament striking 300° although there is no known surface fault with this orientation in the Waikato region (Briggs 1983, 1986a). They form low-angle composite cones or shields constructed of lava flows, volcanic breccias, dikes, lapilli-tuffs, and tuffs. Compositions are diverse and include ankaramites, transitional olivine basalts, tholeiitic basalts, high-Al basalts, and andesites. Ultramafic xenoliths are absent. A small deeply eroded mound at Puketotara, situated between Kakepuku and Pirongia, consists of weathered scoriaceous andesite and, like the small 30 m high mound at Tokanui, is unsuitable for K-Ar dating. Waikeria is unusual in that it is dacitic and not exposed at the surface, and it was found only in a drillhole sited on a magnetic anomaly identified by Mayhew (1985). The small eroded basalt cone at Kairangi, 7 km northwest of Maungatautari, is an isolated eruptive centre and its relationship to the Alexandra Volcanics or to Maungatautari is uncertain (Briggs 1986a, b). Both the Kairangi basalt and Waikeria dacite have compositions distinct from Maungatautari and the Alexandra Volcanics; both are thus included in Table 1 as undefined volcanics.

The Okete Volcanics have erupted from at least 27 volcanic centres and form either eroded scoria mounds, surrounded by an apron of several lava flows, or tuff rings (Keane 1985). Some Okete centres (e.g., Maungatawhiri) comprise a basal unit of finely comminuted volcanic tuffs probably resulting from initial phreatomagmatic eruptions caused by the interaction of ground water or seawater with magma below ground level. These eruptions were then followed by relatively quiet strombolian activity and the eruption of lava flows after the available water was exhausted or excluded from the vent. Other Okete centres (e.g., Papanuiti Point, 1 km north of Papanui Point) produced violent phreatomagmatic eruptions forming tuff rings comprised of airfall and pyroclastic surge deposits (Keane 1985). Each centre is thought to have been active over a very brief time range. Most of the Okete centres are isolated and spatially separated from the larger calcalkalic volcanoes of Karioi and Pirongia, although some Okete lavas are stratigraphically overlain by early Karioi lavas (Matheson 1981). Other Okete centres have been constructed on the flanks of the calcalkalic volcanoes (e.g., at Papanui and Waimaori on Karioi, and at Turitea on Pirongia). Most of the Okete Volcanics have erupted in the region east of Karioi and south of Raglan, although other centres occur to the southeast at Ngahape (Fig. 2). Volcanic vents can be located generally by the position of the scoria cone at each centre, but there is no structural alignment of the volcanic centres as in the calcalkalic series. Instead, the distribution of Okete volcanic centres is scattered, and there are no apparent spatial patterns, although some centres are aligned along north and northeast-striking Cenozoic faults (e.g., Whataipu, Karamu, Papanuiti Point — Kear 1960; Briggs 1983; Keane 1985). The Okete Volcanics have compositions which include basanites, alkali-olivine basalts, and hawaiites, and most lavas contain ultramafic xenoliths (Briggs & Goles 1984).

The K-rich mafic series on Pirongia occurs mainly as capping lava flows and parasitic vents on the flanks of the cone. However, some minor K-rich mafic lavas are intercalated within stratigraphically older sections of the lava sequence. Their locations do not appear to be structurally controlled within the edifice of Pirongia volcano. K-rich mafic lava compositions range from basanites with titanaugite phenocrysts to phlogopite-bearing absarokites.

NGATUTURA BASALTS

The Ngatutura Basalts consist of 16 small volume monogenetic volcanic centres situated south of Port Waikato on the west coast of the North Island (Fig. 1, 3). They are comprised of alkali basaltic lavas, dikes, volcanic breccias, and scoria cones, produced by strombolian eruptions (Utting 1986), and a diatreme at Ngatutura Point (Heming 1980c). Basaltic centres in the Waikaretu area (e.g., Pukekawa) form plateaux constructed of relatively extensive lava sheets. Some volcanic centres have weathered scoria cones still partially preserved, but no crater features have been observed. Other centres have isolated lava flows; associated scoria mounds, if originally present, have been entirely eroded. Both the Ngatutura Basalts and the Alexandra Volcanics are overlain by a cover of various beds of the Kauroa Ash Formation and the Hamilton Ash Formation (Ward 1967).

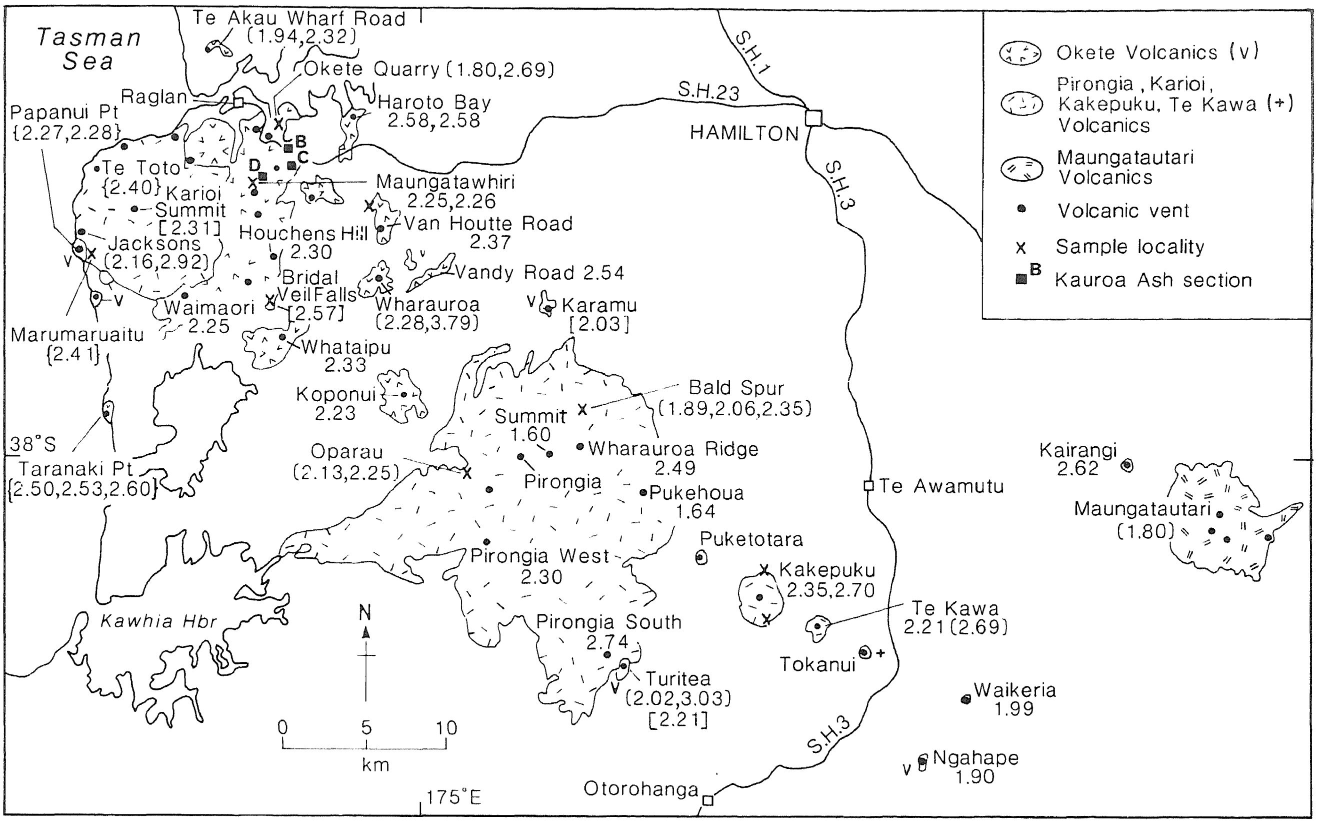

Fig. 2 Distribution of the Alexandra Volcanics showing the location of volcanic centres and their ages. Ages determined by previous authors are in brackets: Stipp et al. (1967) = { }; Stipp (1968) = [ ]; Robertson (1976) = ( ). The locations of stratigraphic sections at sites B, C, and D (Fig. 5) are indicated. S.H., state highway.

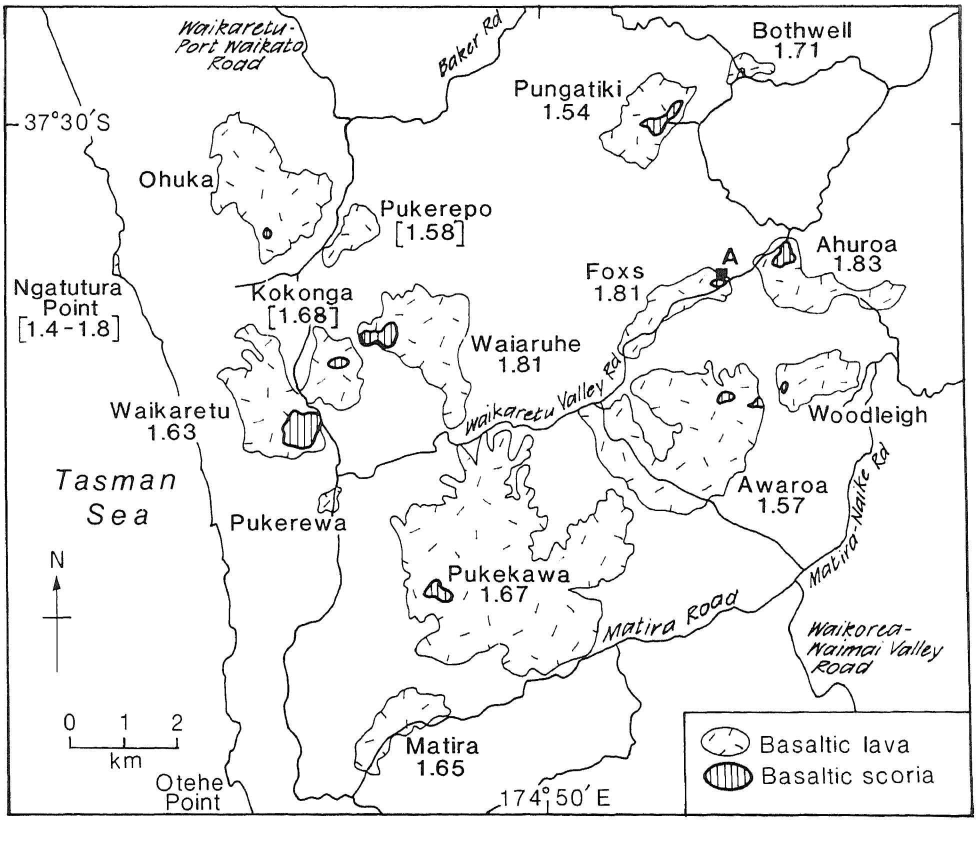

Fig. 3 Distribution of the Ngatutura Basalts showing the location of volcanic centres and their ages. Ages determined by Stipp (1968) are in brackets [ ]. The distribution of scoria cones is from Utting (1986), and the location of site A at Foxs centre (Fig. 5) is indicated.

Table 1 K-Ar age data, Ngatutura and Alexandra Volcanics, western North Island.

Field No.	*HRI Lab. no./Author	Rock type	Volcanic centre/ Location	Grid ref.†	K (wt %)	^{40}Ar (rad.) (10^{-8} cc STP/g)	Non-rad. ^{40}Ar %	K-Ar age (Ma)
Ngatutura Basalts								
Ng 74	S10-49	Hawaiite	Ahuroa, tributary of Naike Stm.	R13/771070	1.10 ± 0.02	7.82 ± 0.11	52.0	1.83 ± 0.04
Ng 69	S10-41	Hawaiite	Foxs	R13/743070	1.14 ± 0.02	7.99 ± 0.25	74.9	1.81 ± 0.07
Ng 129	S10-44	Nepheline hawaiite	Bothwell	R13/767118	1.36 ± 0.03	9.03 ± 0.12	51.8	1.71 ± 0.04
Ng 23	S10-45	Nepheline hawaiite	Pukekawa	R13/703021	1.53 ± 0.03	9.91 ± 0.13	49.4	1.67 ± 0.04
Ng 42	S10-42	Hawaiite	Matira, Matira Stm.	R14/700998	1.15 ± 0.02	7.35 ± 0.11	55.4	1.65 ± 0.04
Ng 106	S10-3	Nepheline hawaiite	Waikaretu	R13/670048	1.56 ± 0.03	9.85 ± 0.24	51.6	1.63 ± 0.05
Ng 65	S10-46	Nepheline hawaiite	Awaroa	R13/740050	1.52 ± 0.03	9.26 ± 0.15	58.5	1.57 ± 0.04
Ng 113	S10-4	Hawaiite	Pungatiki	R13/743108	1.29 ± 0.03	7.69 ± 0.18	47.7	1.54 ± 0.05
Ng 97	S10-43	Nepheline hawaiite	Waiaruhe, W. tributary of Waiaruhe Stm.	R13/707073	1.53 ± 0.03	10.76 ± 0.27	71.7	1.81 ± 0.06
a	JJS	Hawaiite	Pukerepo, Ohuka Quarry	R13/687085	1.700		60.0	1.58 ± 0.01
b	JJS	Hawaiite	Kokonga, Waikaretu Stm.	R14/688042	1.264		42.0	1.68 ± 0.04
c	JJS	Hawaiite	Ngatutura Point	R13/273798				1.4 - 1.8‡
Alexandra Volcanics								
(a) Okete Volcanics								
M181	S10-5	Basanite	Maungatawhiri, Cleaves cone	R14/764712	0.67 ± 0.02	5.85 ± 0.18	55.9	2.25 ± 0.10
M79B	S10-65	Basanite	Maungatawhiri, Ohiapopoko cone	R14/771720	0.98 ± 0.03	8.58 ± 0.12	52.1	2.26 ± 0.08
105C	S10-64	Hawaiite	Whataipu	R15/775621	0.55 ± 0.02	4.97 ± 0.11	66.5	2.33 ± 0.09
121	S10-6	Hawaiite	Koponui	R15/854578	0.77 ± 0.02	6.68 ± 0.20	56.7	2.23 ± 0.09
K60	S10-60	Alkali olivine basalt	Waimaori	R15/711635	0.92 ± 0.03	8.03 ± 0.10	48.8	2.25 ± 0.07
111	S10-56	Basanite	Haroto Bay	R14/822757	1.07 ± 0.02	10.71 ± 0.13	45.2	2.58 ± 0.06
111	S10-54					10.71 ± 0.23	66.0	2.58 ± 0.08
125	S10-58	Hawaiite	Ngahape	S16/168357	0.83 ± 0.03	6.11 ± 0.15	70.7	1.90 ± 0.07
108	S10-52	Basanite	Vandy Road	R15/871657	1.04 ± 0.02	10.25 ± 0.16	56.9	2.54 ± 0.07
116B	S10-57	Olivine tholeiite	Van Houtte Road	R15/816698	0.95 ± 0.03	8.72 ± 0.12	49.6	2.37 ± 0.08
109	S10-53	Hawaiite	Houchens Hill	R15/769668	0.73 ± 0.02	6.52 ± 0.11	60.4	2.30 ± 0.08
226a	DR	Basanite	Okete Quarry	R14/788749	0.908		37.0	2.69 ± 0.11
226b	DR	Basanite	Okete Quarry	R14/789743	0.816		28.8	1.80 ± 0.09
336	DR	Basanite	Te Akau Wharf Rd	R14/734797	0.870		21.1	1.94 ± 0.10
337	DR	Basanite	Te Akau Wharf Rd	R14/734797	0.916		25.3	2.32 ± 0.11
311a	DR	Alkali olivine basalt	Wharauroa	R15/827651	0.732		27.3	2.28 ± 0.12
311b	DR	Alkali olivine basalt	Wharauroa	R15/827651	0.635		30.5	3.79 ± 0.14
d	JJS	Basanite	Bridal Veil Falls	R15/771647	1.194		45.8	2.57 ± 0.03
2042	SCM	Olivine tholeiite	Taranaki Point	R15/673565	0.890		62.7	2.60 av.
2044	SCM	Olivine tholeiite	Taranaki Point	R15/671566	1.021		34.0	2.50 av.
2045	SCM	Olivine tholeiite	Taranaki Point	R15/670570	0.853		61.7	2.53 av.
e	JJS	Basanite	Karamu Quarry	S15/941645	1.138		26.1	2.03 ± 0.03
f	JJS	Basanite	Turitea Quarry	S15/989419	0.995		56.4	2.21 ± 0.03
269a	DR	Basanite	Turitea Quarry	S15/990417	1.068		30.9	2.02 ± 0.09
269b	DR	Basanite	Turitea Quarry	S15/990419	1.002		29.1	3.03 ± 0.10
2046	SCM	Olivine tholeiite	Papanui Point, Marumaruaitu Stm.	R15/649672	0.752		69.1	2.28 av.
2047	SCM	Olivine tholeiite	Papanui Point, Marumaruaitu Stm.	R15/649672	0.751		78.1	2.27 av.
(b) Pirongia Volcanics								
P31	S10-50	High-K andesite	Pirongia summit	S15/944552	2.49 ± 0.05	15.49 ± 0.15	35.6	1.60 ± 0.04
T8	S10-59	Hypersthene andesite	Pirongia South, Turitea	S15/991417	0.90 ± 0.03	9.56 ± 0.11	46.6	2.74 ± 0.09
P47	S10-63	Transitional olivine basalt	Pirongia East, Pukehoua	S15/001523	0.54 ± 0.02	3.44 ± 0.26	88.7	1.64 ± 0.13
P59	S10-48	Absarokite	Pirongia West No 1. Rd	S15/907494	2.02 ± 0.04	18.04 ± 0.18	36.8	2.30 ± 0.05
P38	S10-47	Absarokite	Pirongia, Wharauroa Ridge	S15/971556	1.47 ± 0.03	14.22 ± 0.41	74.0	2.49 ± 0.09
394	DR	Basalt	Pirongia, Bald Spur	S15/961563	1.372	0.113 nl/g	19.3	2.06 ± 0.10
396a	DR	Basalt	Pirongia, Bald Spur	S15/961563	1.234	0.093 nl/g	43.3	1.89 ± 0.06
396b	DR	Plagioclase separate	Pirongia, Bald Spur	S15/961563	0.372	0.035 nl/g	20.8	2.35 ± 0.20
277	DR	Basalt	Pirongia, Oparau	R15/894534	1.611	0.137 nl/g	17.3	2.13 ± 0.10
278	DR	Basalt	Pirongia, Oparau	R15/894534	1.700	0.153 nl/g	17.0	2.25 ± 0.10

(Continued on next page)

Table 1 *(Continued)*

Field No.	*HRI Lab. no./Author	Rock type	Volcanic centre/ Location	Grid ref.†	K (wt %)	^{40}Ar (rad.) (10^{-8} cc STP/g)	Non-rad. ^{40}Ar %	K-Ar age (Ma)
(c) Karioi Volcanics								
286a	DR	Plagioclase separate	Karioi, Jacksons Cut	R15/657690	0.594	0.069 nl/g	30.1	2.92 ± 0.12
286b	DR	Plagioclase separate	Karioi, Jacksons Cut	R15/657690	0.825	0.071 nl/g	23.5	2.16 ± 0.12
2048	SCM	Basalt	Karioi, Marumaruaitu Stm.	R15/657670	1.186		61.1	2.41 av.
g	JJS	Hornblende andesite	Karioi Summit	R15/687694	1.670		61.4	2.31 ± 0.02
h	JJS	Basalt	Karioi, Te Toto Gorge	R14/665720	0.878		33.3	2.40 ± 0.07
(d) Kakepuku, Te Kawa Volcanics								
T5A	S10-51	High-Al basalt	Kakepuku	S15/079445	0.91 ± 0.03	9.53 ± 0.37	80.7	2.70 ± 0.13
T16	S10-1	High-Al basalt	Kakepuku	S15/080478	1.00 ± 0.02	9.11 ± 0.25	47.1	2.35 ± 0.08
T3	S10-61	High-Al basalt	Te Kawa	S15/115445	0.78 ± 0.02	6.68 ± 0.13	63.4	2.21 ± 0.08
392	DR	Plagioclase separate	Te Kawa Quarry	S15/110442	0.526	0.056 nl/g	16.0	2.69 ± 0.20
Undefined volcanics								
Wk1	S10-7	Dacite	Waikeria drillhole	S15/172413	2.29 ± 0.05	17.71 ± 0.42	69.6	1.99 ± 0.06
M53A	S10-62	Olivine basalt	Kairangi	T15/307533	1.10 ± 0.02	11.17 ± 0.69	87.1	2.62 ± 0.17

* HRI Lab. no. = Laboratory number at Hiruzen Research Institute, with S10 prefix (new data, this paper).
Author: JJS, Stipp (1968); DR, Robertson (1976); SCM, Stipp et al. (1967).
† Based on the national 1000 m grid of the 1 : 50 000 topographical map series (NZMS 260).
‡ Rocks reported by Stipp (1968) as unreliable for dating, who preferred the range of values reported here.
SCM ages given here are their reported average ages of 2 or 3 determinations on the same whole-rock material.

Ngatutura Basalt eruption centres appear to overlie faults in the underlying Mesozoic–Cenozoic sedimentary strata, which follow the regional northeast-striking fault pattern mapped by Kear (1960, 1966) and Waterhouse (1978). Evidence for structural control of the Ngatutura Basalts is observed at Ngatutura Point (Fig. 3) where basalt dikes intrude along fault planes which have both a northeasterly (rarely exposed in the shore platform) and a northerly strike (exposed in coastal cliffs in the Kaawa section).

The Ngatutura Basalt lavas are fine-grained porphyritic olivine basalts of hawaiite and nepheline hawaiite compositions and commonly contain ultramafic xenoliths. Details of the mineralogy, geochemistry, and petrology of the Ngatutura Basalts are given in Utting (1986).

PREVIOUS GEOCHRONOLOGICAL STUDIES

Previous K-Ar age data have been recorded by Stipp (1968) for the Ngatutura Basalts, and by Stipp et al. (1967), Stipp (1968), and Robertson (1976) for the Alexandra Volcanics. Their data are included in Table 1 (for the sake of completeness) which presents all previous K-Ar age determinations together with our new data. Stipp (1968) reported three K-Ar ages for the Ngatutura Basalts from localities in the northwestern sector of the field, but he noted that the samples from Ngatutura Point were unreliable for dating because of alteration and the presence of numerous ultramafic xenoliths in these alkalic basalts. Stipp (1968) did many age determinations of Ngatutura Point samples and preferred an age range of 1.4–1.8 Ma, which is an interval that spans the duration of eruption of the entire Ngatutura field.

The Okete alkalic suite within the Alexandra Volcanics has only been formally recognised since Briggs (1983), so that the previous age data of Stipp et al. (1967), Stipp (1968), and Robertson (1976) were all recorded as collectively belonging to the Alexandra Volcanics. However, mapping by Matheson (1981), Briggs (1983), and Keane (1985) has subsequently enabled the volcanic formations for all previous K-Ar sample localities to be identified. The previous K-Ar age data of the above authors is consistent with the known stratigraphic relations, as described by Briggs (1983).

ANALYTICAL METHODS AND AGE CALCULATIONS

Rock samples were cut with a diamond saw into thin (5 mm) slices, to check for freshness and to eliminate coarse-grained phenocrysts and any ultramafic xenoliths in alkalic basalts, and then manually ground with an agate pestle and mortar. Approximately 10 g of the c. 60–80 mesh (250–200 µm) size fraction was separated using fresh nylon-sieve cloth, washed with distilled water, and oven dried. A portion of each separate was ground in an agate mortar and used for K analysis.

K analysis

Powder samples were treated with HF and HNO_3 in teflon beakers and analysed for potassium by flame photometry using a 2000 ppm Cs buffer. Multiple runs of two chemical standards (JG-1 and JB-1) indicated the accuracy and reproducibility of this method to be within 2%. An average value of duplicate runs was used in the age calculations.

Ar analysis

Samples were wrapped in aluminium foil, preheated for about 24 h at 180–200° C in a vacuum, and the argon extracted at 1500° C in an ultra-high vacuum line (atmospheric ^{40}Ar blank was less than 2×10^{-9} ccSTP). Reactive gases were purified by a Ti-Zr scrubber. Argon was analysed using an isotopic dilution method and ^{38}Ar spike in a 15 cm radius sector-type mass spectrometer with a single collector system designed and constructed by Nagao & Itaya (1986) at Okayama University of Science. Calibration of the ^{38}Ar spike is accurate to within about 1% (Nagao et al. 1984; Itaya & Nagao 1989).

It is essential that mass discrimination of the mass spectrometer is carefully checked when K-Ar dating young volcanic rocks. In the Hiruzen laboratory, such checking is routinely carried out several times with atmospheric argon of c. 2×10^{-7} ccSTP before the samples are run in the spectrometer. In some cases, the mass discrimination factor depends on the amount of argon introduced (T. Itaya & Okada unpubl. data). Therefore, in this study, the mass discrimination factor was determined using calibration curves (relating the mass fractionation factor and the quantity of introduced argon) given by analyses of variable amounts of atmospheric argon. The calibration curve was newly prepared each day of operation.

Age calculations

Calculations of the ages and their errors follow the methods described by Nagao et al. (1984) and Nagao & Itaya (1988) and use the decay constants of Steiger & Jäger (1977). Reproducibility for samples of late Pleistocene age is within the error (one standard deviation) (Itaya et al. 1984; Itaya & Nagao 1986, 1988). Table 1 shows duplicate analyses on sample 111 (lab nos. S10-56, S10-54) from the Okete Volcanics.

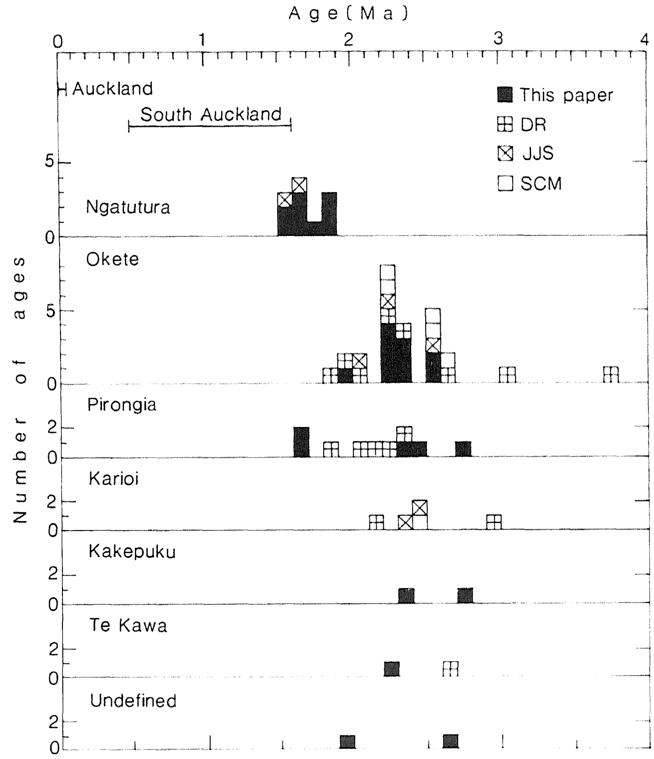

Fig. 4 Histogram summarising the frequency distribution of ages for each of the volcanic fields and formations. The range in ages for Auckland and South Auckland are shown for comparison. DR, data from Robertson (1976); JJS, Stipp (1968); SCM, Stipp et al. (1967).

AGE OF NGATUTURA AND ALEXANDRA VOLCANISM

Our new ages are generally in close agreement with those of previous age data and emphasise the limited span in age of each of the volcanic fields (Fig. 4).

Ngatutura Basalts

The Ngatutura Basalts range in age from 1.54 to 1.83 Ma. This range excludes the Ngatutura Point data of Stipp (1968), and his other two ages fall within this range.

Alexandra Volcanics

The Alexandra Volcanics have a total range in age from 1.60 to 3.79 Ma. However, we prefer a more restricted range in age for the Alexandra Volcanics from 1.60 to 2.74 Ma for the following reasons. Some of the older age determinations of Robertson (1976) appear anomalous, in particular the 3.79 Ma age from sample 311b from Wharauroa and the 3.03 Ma age from sample 269b from Turitea. Both of these age determinations are significantly older (by at least 1 Ma) than duplicate samples taken from the same locality. Robertson (1976) ground whole-rock samples and determined the ages of different grain-size fractions. He found that the smaller grain-size samples at Wharauroa and Turitea gave the older ages, but the relationship is not consistent because the smaller grain-size sample at Okete Quarry (226b) gave a significantly younger age. Robertson (1976) argued that these variations in age of the same sample may be determined by the relative abundance of glass in the groundmass which may dominate different grain-size fractions. However, he noted that this also was not consistent because the Te Akau Wharf Rd samples (336, 337) were from different sections of the same quarry but contained different modal abundances of glass which was not reflected in the ages determined on samples of equal grain size. We have examined these rocks petrographically in detail but have found that the groundmass is mainly crystalline and glass rarely forms more than about two modal percent of the groundmass (Keane 1985). We consider that the apparent older ages of Okete Volcanics may be caused by the presence of ultramafic xenoliths which are common and generally 5–20 mm in size. We eliminated this problem by initially cutting the rock sample into 5 mm slices so that any xenoliths could be identified and removed. Coarse-grained phenocrysts were also removed, but some of the calcalkalic rocks are extremely porphyritic, and the smaller phenocrysts were generally difficult to eliminate. This may be an important problem with samples carrying plagioclase phenocrysts which may contain excess Ar. This was demonstrated by Robertson (1976) for Pirongia where plagioclase separates (396b) gave older ages than the same whole-rock sample (396a).

Hence, we consider that the whole-rock ages reported here for the calcalkalic rocks (Pirongia, Karioi, Kakepuku, and Te Kawa) may actually be slightly younger because we have not determined the groundmass age (Itaya & Nagao 1988). Itaya & Nagao (1988) studied young (0.3–0.5 Ma) dacite lavas and demonstrated that porphyritic rocks with extremely coarse grained phenocrysts contained excess Ar and gave older ages than the fine-grained groundmass. However, this effect is considerably diminished in rocks with ages of about 2 Ma and may result in only slightly older ages. Also, for this reason, we have preferred not to include the 2.92 Ma age determined by Robertson (1976) on a plagioclase separate from Karioi (286a) as a reliable oldest age for the range in age of the Alexandra Volcanics.

Pirongia volcano has a complex and long volcanic history with the youngest age of 1.60 Ma (P31) at the summit and the oldest age of 2.74 Ma (T8) from a southern centre near Turitea. The K-rich absarokite capping lavas have intermediate ages of 2.30 (P59) and 2.49 Ma (P38) but are notably older than the calcalkalic lavas at the summit and at the parasitic cone of Pukehoua (1.64 Ma, P47) on the southeastern flank.

Karioi volcano also has a long (2.16–2.92 Ma) and complex history, and has a similar age to Kakepuku (2.35–2.70 Ma) and Te Kawa (2.21–2.69 Ma). Sample T16 was derived from a low, eroded cone on the northern flank of Kakepuku, which appears to be a younger separate vent; sample T5A is assumed to date the main cone of Kakepuku. Similarly, T3 is a sample from younger basalt lava (2.21 Ma) on Te Kawa, containing augite megacrysts, that stratigraphically overlies older olivine-augite-plagioclase ankaramitic lavas. These lavas were dated by Robertson (1976) on a plagioclase separate at 2.69 Ma (392).

Undefined volcanics

The samples from Waikeria and Kairangi are listed here as undefined volcanics because both have compositions distinct from the rest of the Alexandra Volcanics although their ages are similar. The basalt cone at Kairangi (2.62 Ma, M53A) is older than Maungatautari, which is an andesite-dacite volcano, dated at 1.8 Ma by Robertson (1983). However, it is likely that Maungatautari was erupted over a wide age span similar to that of the larger stratovolcanoes of the Alexandra Volcanics (i.e., >0.5 Ma). Thus, although the petrogenetic association of Kairangi to Maungatautari is uncertain (Briggs 1986b), the Kairangi age may record the inception of Maungatautari volcanism.

GEOLOGICAL IMPLICATIONS

Erosion of cones

Briggs (1983) pointed out that some geomorphological evidence suggested that the stratovolcanoes of the Alexandra Volcanics (i.e., Karioi, Pirongia, Kakepuku, and Te Kawa) become progressively younger to the southeast. The evidence was that Karioi in the northwest was the only volcano where dikes are exposed on the upper parts of the cone, therefore indicating that erosion might be most advanced on Karioi. Kakepuku appears relatively less dissected by deep radial gullies and valleys than either Pirongia or Karioi. Furthermore, Te Kawa is the only cone where a crater feature is still preserved, and the outer flank of the cone has a much straighter profile compared with the slightly concave surfaces of Kakepuku, Pirongia, and Karioi.

Kear (1957, 1959), in part following Cotton (1952), recognised four stages in the erosion of volcanic cones which were thought to have a useful age significance: (1) volcano stage, Holocene; (2) planeze stage (showing some remnant of original cone form), Holocene to Late Pliocene; (3) residual mountain stage (planezes absent, no recognisable original cone surface), Pliocene possibly to Late Miocene; and (4) skeleton stage (volcanic necks and radial dikes), Pliocene and Miocene. On this basis, Kear (1957, 1959) considered that Karioi–Pirongia volcanism was just entering the residual mountain stage. Kear did not discuss Kakepuku or Te Kawa and did not suggest any younging direction for the Alexandra volcanoes. Nevertheless, according to Kear's stages in the development of erosion of cones, Kakepuku would be classified as belonging to the planeze stage, and Te Kawa would be close to the volcano stage.

The radiometric age data now indicate that all the stratovolcanoes of Karioi, Pirongia, Kakepuku, and Te Kawa have broadly similar ages and do not young in any direction, and that any relationship of the development of erosion of volcanic cones to age must be examined with caution. Kear (1957, 1959) stated that allowances must be made in any erosional stage versus age relationship for rock type, size and complexity of the cone, geological history, location, and climate. In the Alexandra Volcanics, there is no significant difference in rock type, but Karioi and Pirongia are much larger and higher volcanoes with approximately twice as much present-day rainfall as Kakepuku and Te Kawa. Coastal marine erosion would obviously be greatest for Karioi. Kakepuku and Te Kawa, being closer to the Hauraki Volcanic Region and TVZ, would possibly have been better preserved by successive cover deposits of Pliocene–Quaternary tephra including the Kauroa and Hamilton Ash Formations. Nevertheless, there is no significant tephra cover on the slopes of Kakepuku and Te Kawa today, and the reason, especially for the minimal degree of erosion of Te Kawa, remains uncertain. It might be that the slopes of Te Kawa and Kakepuku are covered by a carapace of resistant lava that has inhibited erosion, but the poor exposures on these volcanoes makes this suggestion speculative.

Briggs (1983) and Keane (1985) also considered that the Okete volcanic centres with preserved scoria cones were likely to have a younger age than those centres where scoria cones were presumably totally eroded, or where there were only deeply dissected and highly weathered subaerial basalt-flow remnants. Scoria cones (but with no crater features) are still preserved at Houchens Hill (2.30 Ma), Maungatawhiri (2.26, 2.25 Ma), Waimaori (2.25 Ma), Haroto Bay (2.58 Ma), and Whataipu (2.33 Ma), but they are absent from Koponui (2.23 Ma), Vandy Rd (2.54 Ma), Te Akau Wharf Rd (2.11 Ma), and Wharauroa (2.92 Ma). These volcanoes have similar sizes and occur adjacent to each other and at similar altitudes. By analogy with those in the Auckland field, it is unlikely that they would erupt only lavas without an associated scoria cone in a subaerial environment. Hence, the presence or absence of basaltic scoria cones does not appear to be related directly to age, size, or climatic conditions but to the lithology. Some scoria cones contain partially welded agglomerate, formed from rapidly deposited bombs derived from magma with a high discharge rate, which would provide a more coherent and resistant rock mass. Other scoria cones are comprised of essentially unwelded, loose scoria, which would be easily erodible.

Age patterns within fields

The lack of any younging direction within the calcalkalic stratovolcanoes of the Alexandra Volcanics is also shown by the monogenetic volcanoes of the Okete Volcanics. No systematic age trends in the spatial distribution of the alkalic or calcalkalic suites of the Alexandra Volcanics can be detected, and this inference is supported by stratigraphic evidence around Karioi volcano where Okete and Karioi lavas are intercalated. Pirongia has the youngest ages of any of the calcalkalic volcanoes but has a wide eruptive age span of 1.14 Ma. The youngest ages of Okete Volcanics are at Ngahape, in the far southeastern edge of the field, and at Okete Quarry, near the northwestern edge.

Furthermore, there is no apparent systematic variation in age with rock composition. Differentiated late-stage andesitic dikes occur on the summit of Karioi, but on Pirongia andesitic lavas cap the area near the summit, while primitive transitional olivine basalt lavas occur at Pukehoua, and both have similar young ages. On the basis of preservation of scoria cones, Briggs (1986a) suggested that Okete volcanism changed from older, smaller volume basanite and alkali-olivine basalt volcanoes to younger, more voluminous and more differentiated hawaiites. However, the radiometric data preclude this suggestion. Moreover, Keane (1985) demonstrated petrographically at Maungatawhiri centre that the whole range of lava compositions from basanites to alkali-olivine basalts to hawaiites can occur in the same centre.

In general, the three geochemically and petrologically distinct calcalkalic, alkalic, and potassic magma series within the Alexandra Volcanics have no systematic variation or progression in age with composition among them.

Similarly, no younging trend can be detected within the Ngatutura Basalt field, or any trend in age with variation in composition between hawaiites and nepheline hawaiites. Most Ngatutura centres have eroded basaltic scoria cones and, as with the Okete Volcanics, there is no apparent relationship between size of the remnant scoria cone and the age of the centre. Also, by analogy with most of the Auckland volcanoes (except Rangitoto), we assumed that each monogenetic volcano within the field had a short eruptive cycle, possibly lasting only several months or tens of years at most. Rangitoto has the longest history of any volcano in the Auckland field and has recorded eruptions extending for nearly 1000 years from c. A.D. 850 to A.D. 1800 (Robertson 1986). However, it is the largest of the Auckland volcanoes and has a size and volume several times larger than any volcano in the Ngatutura or Okete fields.

Age patterns between fields

There is a progressive northwards younging in age of alkalic basaltic volcanism in western North Island from the Okete Volcanics (2.69–1.80 Ma) in the south, to the Ngatutura Basalts (1.83–1.54 Ma), South Auckland (1.56–0.51 Ma, Stipp 1968; Robertson 1976), and the Auckland field (0.06 Ma–200 years ago, Heming 1980a; Robertson 1986) to the north. The Auckland volcanic field is the youngest of the Quaternary basaltic fields of the North Island, probably including those in Northland, although the ages of the Northland lavas are poorly known.

The younging in alkalic volcanism from Okete to Ngatutura to South Auckland to Auckland in progressive steps cannot represent a southwards translation of the western North Island lithosphere over a stationary mantle hotspot because this is contrary to the direction of relative plate motion. It is also unlikely that the alkalic magmatism results from partial melting of rising diapirs originating from discrete upper mantle sources which by coincidence have formed the required pattern. A more favoured model could be the progressive northwards migration of an upper mantle source, possibly as a result of mantle wedge convection above the subducting slab. Whatever the origin, the upper mantle "plumes" responsible for alkalic magmatism must be generated above the subducting slab which extends beneath this region of western North Island (Adams & Ware 1977). This limits the depth of origin of these upper mantle "plumes" to less than about 250 km for Okete volcanism and less than about 300 km for Ngatutura volcanism, which are the respective depths to the underlying slab.

Age constraints on the Kauroa Ash Formation

The Kauroa Ash Formation is a sequence of strongly weathered rhyolitic tephra deposits (both airfall and pyroclastic flow deposits) in western North Island of uncertain age and source (Ward 1967; Salter 1979; Kirkman 1980). At the type site at Woodstock near Raglan (site B, Fig. 2), they consist of 15 informal ash members (labelled from stratigraphic bottom to top, K1–K15 inclusive) with 10 associated paleosols (Salter 1979). Keane (1985) observed that basaltic tephras erupted from the Maungatawhiri centre were intercalated with the earliest Kauroa Ash beds at two sites. One site is on the flank of Ohiapopoko cone and the other is near the summit of Cleaves cone; both cones form part of the Maungatawhiri centre. The stratigraphic relations are shown in Fig. 5 (sites C and D) and are consistent at both sites. Although we have dated only the lavas from these cones, it is reasonable, on the basis of the postulated short eruptive cycles of each monogenetic volcano, to assume that the lavas have essentially the same age as the associated basaltic tuffs. Hence, we have assigned the basaltic tuffs in the stratigraphic columns of Fig. 5 with the same age as the dated lavas of the cones. This enables an age of 2.25–2.26 Ma to be given to K1, the earliest of the Kauroa Ash beds. K1 is considered on this stratigraphic evidence to have been deposited rapidly and between intermittent volcanism on Maungatawhiri.

An incomplete sequence of Kauroa Ash beds overlies the Ngatutura Basalts, with only the upper and younger Kauroa Ash beds, K12–K15, overlying the basaltic tuffs at Foxs centre dated at 1.81 Ma (Fig. 5, site A). These Kauroa Ash beds were identified from their stratigraphic position and field characteristics and by direct comparison with those at Woodstock (see Appendix 1). However, some of the stratigraphic relations here are ambiguous and incompletely constrained because members older than K12 could have been deposited but subsequently totally eroded. Nevertheless, they indicate that K12 cannot be older than 1.81 Ma, and we consider that an age of about 1.81 Ma for K12 is realistic on the basis of time for the development of the buried paleosols on the earlier Kauroa Ash beds.

Ward (1967, 1972) observed that K15, defined as the Waiterimu Ash Member and youngest bed of the Kauroa Ash Formation, was interbedded with basaltic ash derived from Ahuroa, which we have dated at 1.83 Ma (Ng74). (Ward also considered that Ahuroa cone belonged to the Franklin Basalts, which are part of the South Auckland field, but detailed mapping and petrology clearly indicate that Ahuroa is part of the Ngatutura Basalts (Utting 1986)). Ward concluded that the Ahuroa cone must have been active when the eruptions that produced the Waiterimu Ash occurred. Thus, this would provide an age of 1.83 Ma for the Waiterimu Ash Member. However, we consider that the stratigraphic relations exposed on Ahuroa cone at Ward's site 10 are unreliable due to slumping, and contradict the stratigraphic relations at Foxs centre (site A). We prefer site A to that of Ahuroa cone because the stratigraphic relations are evidently more reliable. These relations imply that K15 must be younger than 1.81 Ma, and a suggested age of about 1.5 Ma, based on the time for development of paleosols (assuming c. 50 000–100 000 years for each paleosol — cf. Gibbs 1980; Green 1987), seems more likely. A minimum age for the Kauroa Ash Formation is given by the Ohinewai Ash Member (H1, H2), the oldest bed of the Hamilton Ash Formation, which unconformably overlies K15. The age of H1 is uncertain

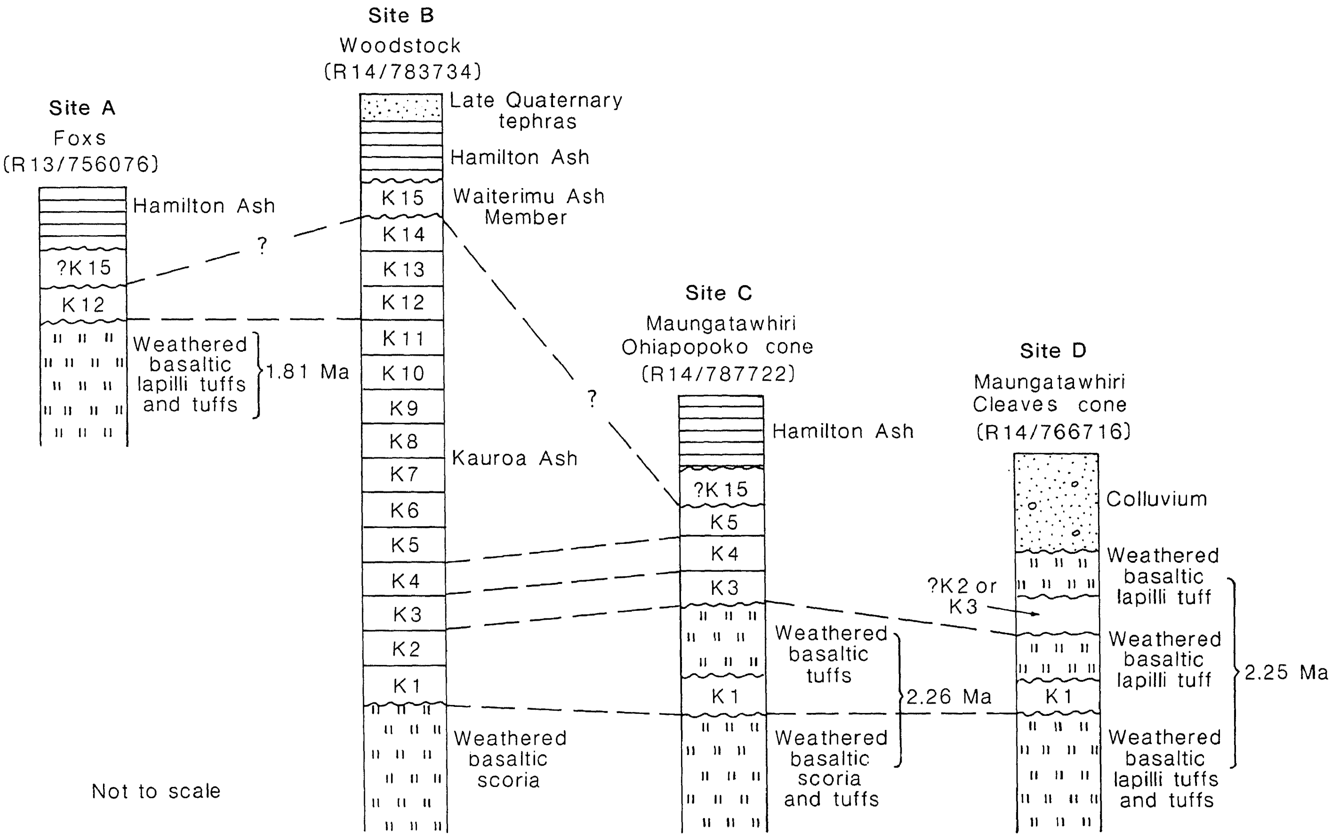

Fig. 5 Generalised sections of the stratigraphic relations between beds of the Kauroa Ash Formation and dated basaltic tephras at Foxs centre (site A, Ngatutura Basalts), the type site of the Kauroa Ash Formation at Woodstock, near Raglan (site B), and Maungatawhiri centre (sites C and D) (see also Appendix 1). The weathered basaltic scoria at the base of the Woodstock section is derived from the undated Maungataparu scoria cone (Keane 1985).

(Keane 1985) but an age between 300 000 and 400 000 years is preferred (McCraw 1975; Nelson 1988).

The Oparau Tephra, described as an ignimbrite by Pain (1975) in the Kawhia region, was provisionally correlated with K12 by Salter (1979). Pain (1975) also tentatively correlated the Oparau Tephra with the Ongatiti Ignimbrite, which was fission-track dated by Kohn (1973) at 0.75 Ma. The suggested age range for the Kauroa Ash Formation (2.3–1.5 Ma) given in this paper is considerably older than previously thought and eliminates any correlation between the Kauroa Ash beds and the Ongatiti Ignimbrite or any of the other Mangakino-derived eruptives (cf. Wilson 1986).

The maximum age of volcanism in the TVZ is discussed by Wilson et al. (1984), who suggested 2 Ma, but this age is poorly constrained because possibly older eruptives may be buried 2–3 km by younger volcanic products (Cole 1986). The age of volcanism in southern Coromandel Volcanic Zone (Fig. 1) is also poorly known, but some ages reported by Skinner (1986) overlap those given here for the Kauroa Ash Formation. The sequence of Kauroa Ash beds is thickest and best exposed in the Raglan–Kawhia districts (Fig. 2), and the Oparau Tephra, which may correlate with K12 (Salter 1979), has a maximum thickness of 8 m in the Kawhia Harbour region (Fergusson 1986). However, the Kauroa Ash beds form only isolated exposures in the Coromandel area, and the total Kauroa sequence is 1–3 m thick (Selby et al. 1971). We cannot discount a southern Coromandel Volcanic Zone source for the Kauroa Ash beds but on the available evidence we prefer a TVZ source. Thus, we consider that the Kauroa Ash Formation represents a series of early widespread rhyolitic plinian and ignimbrite eruptions from the TVZ which were initiated 2.3 Ma ago during the Late Pliocene.

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REFERENCES

Adams, R. D.; Ware, D. E. 1977: Subcrustal earthquakes beneath New Zealand; locations determined with a laterally inhomogeneous velocity model. *New Zealand journal of geology and geophysics 20*: 59–83.

Ashcroft, J. 1986: The Kerikeri Volcanics: a basalt-pantellerite association in Northland. *In*: Smith, I. E. M. *ed.* Late Cenozoic volcanism in New Zealand. *Royal Society of New Zealand bulletin 23*: 48–63.

Briggs, R. M. 1983: Distribution, form, and structural control of the Alexandra Volcanic Group, North Island, New Zealand. *New Zealand journal of geology and geophysics 26*: 47–55.

——— 1986a: Volcanic rocks of the Waikato region, western North Island, and some possible petrologic and tectonic constraints on their origin. *In*: Smith, I. E. M. *ed.* Late Cenozoic volcanism in New Zealand. *Royal Society of New Zealand bulletin 23*: 76–91.

——— 1986b: Petrology and geochemistry of Maungatautari, a medium-K andesite-dacite volcano. *New Zealand journal of geology and geophysics 29*: 273–289.

Briggs, R. M.; Goles, G. G. 1984: Petrological and trace element geochemical features of the Okete Volcanics, western North Island, New Zealand. *Contributions to mineralogy and petrology 86*: 77–88.

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.

Cotton, C. A. 1952: Volcanoes as landscape forms. 2nd ed. Christchurch, Whitcombe and Tombs.

Fergusson, D. A. 1986: Geology of inland Kawhia: emphasis on Te Kuiti Group stratigraphy and sedimentation. Unpublished M.Sc. thesis, lodged in the Library, University of Waikato, Hamilton.

Gibbs, H. S. 1980: Paleosols. Pp. 83–90 *in*: New Zealand soils. Wellington, Oxford University Press.

Green, B. E. 1987: Weathering of buried paleosols on late Quaternary rhyolitic tephras, Rotorua region, New Zealand. Unpublished M.Sc. thesis, lodged in the Library, University of Waikato, Hamilton.

Heming, R. F. 1980a: Patterns of Quaternary basaltic volcanism in the northern North Island, New Zealand. *New Zealand journal of geology and geophysics 23*: 335–344.

——— 1980b: Petrology and geochemistry of Quaternary basalts from Northland, New Zealand. *Journal of volcanology and geothermal research 8*: 23–44.

——— 1980c: The Ngatutura diatreme. *New Zealand journal of geology and geophysics 23*: 569–573.

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.

Itaya, T.; Nagao, K. 1986: A new calibration technique for young K-Ar ages. *Terra cognita 6*: 170.

——— 1988: K-Ar age determination of volcanic rocks younger than 1 Ma. *Memoir of the Geological Society of Japan 29*: 143–161.

——— 1989: Argon analysis and K-Ar dating with a newly constructed mass spectrometer. *Journal of mineralogy petrology and economic geology 84*: 132–133.

Itaya, T.; Nagao, K.; Nishido, H.; Ogata, K. 1984: K-Ar age determination of Late Pleistocene volcanic rocks. *Journal of the Geological Society of Japan 90*: 899–909.

Keane, A. J. 1985: The age, form and volcanic mechanisms of the Okete Volcanics near Raglan. Unpublished M.Sc. thesis, lodged in the Library, University of Waikato, Hamilton.

Kear, D. 1957: Erosional stages of volcanic cones as indicators of age. *New Zealand journal of science and technology 38*: 671–682.

——— 1959: Stratigraphy of New Zealand's Cenozoic volcanism north-west of the volcanic belt. *New Zealand journal of geology and geophysics 2*: 578–589.

——— 1960: Sheet 4—Hamilton. Geological map of New Zealand 1 : 250 000. Wellington, Department of Scientific and Industrial Research.

——— 1966: Sheet N55 — Te Akau. Geological map of New Zealand 1 : 63 360. Wellington, Department of Scientific and Industrial Research.

Kirkman, J. H. 1980: Mineralogy of the Kauroa Ash Formation of southwest and west Waikato, North Island, New Zealand. *New Zealand journal of geology and geophysics 23*: 113–120.

Kohn, B. P. 1973: Some studies of New Zealand Quaternary pyroclastic rocks. Unpublished Ph.D. thesis, lodged in the Library, Victoria University of Wellington, Wellington.

McCraw, J. D. 1975: Quaternary airfall deposits of New Zealand. *In*: Suggate, R. P.; Cresswell, M. M. *ed.* Quaternary studies. *Royal Society of New Zealand bulletin 13*: 35–44.

Matheson, S. G. 1981: The volcanic geology of the Mt Karioi region. Unpublished M.Sc. thesis, lodged in the Library, University of Waikato, Hamilton.

Mayhew, I. D. 1985: Geophysical investigations for the Te Kawa irrigation scheme. Unpublished M.Sc. thesis, lodged in the Library, University of Auckland, Auckland.

Nagao, K.; Itaya, T. 1986: Construction of mass spectrometer of oblique incident and exit type with triple collector for argon analysis. *Association of Mass Spectrometry annual meeting*.

——— 1988: K-Ar age determination. *Memoir of the Geological Society of Japan 29*: 5–21.

Nagao, K.; Nishido, H.; Itaya, T.; Ogata, K. 1984: K-Ar age determination method. *Bulletin of Hiruzen Research Institute 9*: 19–38.

Nelson, C. S. 1988: Revised age of a Late Quaternary tephra at DSDP Site 594, off eastern South Island and some implications for correlation. *Geological Society of New Zealand newsletter 82*: 35–40.

Pain, C. F. 1975: Some tephra deposits in the southwest Waikato area, North Island, New Zealand. *New Zealand journal of geology and geophysics 18*: 541–550.

Rafferty, W. J.; Heming, R. F. 1979: Quaternary alkalic and subalkalic volcanism in South Auckland, New Zealand. *Contributions to mineralogy and petrology 71*: 139–150.

Robertson, D. J. 1976: A paleomagnetic study of volcanic rocks in the South Auckland area. Unpublished M.Sc. thesis, lodged in the Library, University of Auckland, Auckland.

——— 1983: Paleomagnetism and geochronology of volcanics in the northern North Island. Unpublished Ph.D. thesis, lodged in the Library, University of Auckland, Auckland.

——— 1986: A paleomagnetic study of Rangitoto Island, Auckland, New Zealand. *New Zealand journal of geology and geophysics 29*: 405–411.

Salter, R. T. 1979: A pedological study of the Kauroa Ash Formation at Woodstock. Unpublished M.Sc. thesis, lodged in the Library, University of Waikato, Hamilton.

Searle, E. J. 1964: City of volcanoes. Auckland, Paul's Book Arcade.

Selby, M. J.; Pullar, W. A.; McCraw, J. D. 1971: The age of Quaternary surfaces at Waihi Beach. *Earth science journal 5*: 106–113.

Skinner, D. N. B. 1986: Neogene volcanism of the Hauraki Volcanic Region. *In*: Smith, I. E. M. *ed.* Late Cenozoic volcanism in New Zealand. *Royal Society of New Zealand bulletin 23*: 21–47.

Spratt, P. R.; Rodgers, K. A. 1975: The Ngatutura Volcanics, southwest Auckland. *Journal of the Royal Society of New Zealand 5*: 163–178.

Steiger, R. H.; Jäger, E. 1977: Subcommission on geochronology: convention on the uses of decay constants in geochronology and cosmochronology. *Earth and planetary science letters 36*: 359–362.

Stipp, J. J. 1968: The geochronology and petrogenesis of the Cenozoic volcanics of North Island, New Zealand. Unpublished Ph.D. thesis, lodged in the Library, Australian National University, Canberra.

Stipp, J. J.; Chappell, J. M. A.; McDougall, I. 1967: K/Ar age estimate of the Plio-Pleistocene boundary in New Zealand. *American journal of science 265*: 462–474.

Utting, A. J. 1986: The petrology and geochemistry of the Ngatutura Basalts. Unpublished M.Sc. thesis, lodged in the Library, University of Waikato, Hamilton.

Ward, W. T. 1967: Volcanic ash beds of the lower Waikato Basin, North Island, New Zealand. *New Zealand journal of geology and geophysics 10*: 1109–1135.

———— 1972: Pleistocene ash in the Waikato Basin: ages implied by changes in sea level. *New Zealand journal of geology and geophysics 15*: 678–685.

Waterhouse, B. C. 1978: Sheet N51—Onewhero. Geological map of New Zealand 1 : 63 360. Wellington, Department of Scientific and Industrial Research.

Wilson, C. J. N. 1986: Reconnaissance stratigraphy and volcanology of ignimbrites from Mangakino volcano. *In*: Smith, I. E. M. *ed*. Late Cenozoic volcanism in New Zealand. *Royal Society of New Zealand bulletin 23*: 179–193.

Wilson, C. J. N.; Rogan, A. M.; Smith, I. E. M.; Northey, D. J.; Nairn, I. A.; Houghton, B. F. 1984: Caldera volcanoes of the Taupo Volcanic Zone, New Zealand. *Journal of geophysical research 89 (B10)*: 8463–8484.

APPENDIX 1

Section descriptions for sites A, C, and D

Site A

Foxs centre, Ngatutura Basalts, road cutting on south side of Waikaretu Road (R13/756076)

3 m of Hamilton Ash Formation

K15 20 cm reddish brown (5YR 4/3) gritty clay; blocky and prismatic; occasional quartz crystals; paleosol developed in upper half,

K12 45 cm near strong brown (7.5YR 5/6) clay; fine blocky structure; sparse quartz crystals; mica books not observed,

20 cm near brownish yellow (10YR 6/6) and pale yellowish brown (10YR 6/4) sandy clay; coarse blocky structure; very firm; many quartz crystals and micabooks,

40 cm reddish yellow (5YR 6/6) clay; many mottles and mica books; grades downwards to

30 cm very pale brown (10YR 7/4) gritty clay; protruding orange mottles; Mn concretions,

Weathered basaltic tuffs; dark reddish brown (2.5YR 3/4) clay; occasional weathered basalt fragments; paleosol developed in upper part.

Site C

Maungatawhiri centre, Okete Volcanics, Ohiapopoko cone, road cutting on east side of Kauroa–Te Mata Road (R14/787722)

Up to 4 m of Hamilton Ash Formation over Kauroa Ash beds ?K15 and K5

K4 ~40 cm reddish yellow (5YR 6/6 to 6/8) gritty clay grading downwards to pale red (2.5YR 6/8) clay; crystal-rich with coarse sand crystals (with bipyramidal quartz) and white micaceous sand-sized books; black Mn streaks; occasional halloysite concretions up to 4 cm in diameter in upper part of bed,

K3 ~30 cm red (2.5YR 5/6) clay; sand-sized micaceous minerals present,

Basaltic paleosol; dark red (2.5YR 3/6) slightly gritty clay grading downwards to blotchy and greyish gritty clay; on >4m of weathered basaltic lapilli tuffs and tuffs,

K1 68 cm very pale brown (10YR 8/3) greasy clay, strong brown (7.5 YR 5/6) mottles and thin bands in upper half; massive; many quartz crystals; occasional halloysite concretions,

Weathered greyish brown (2.5Y 5/2) basaltic tuffs and lava.

Site D

Maungatawhiri centre, Okete Volcanics, Cleaves cone, 40 m east of Maungatawhiri Road (R14/766716).

Colluvium

80 cm graded basaltic lapilli tuff containing angular accessory Tertiary mudstone lithics; many grey and reddish juvenile basalt fragments; sharp boundary,

?K2 or K3 15 cm reddish yellow (7.5YR 6/8) clay; firm; halloysite nodules up to 8 cm diameter; sand-sized quartz crystals present; yellowish red (5YR 4/8) clay-skins; distinct boundary,

15 cm graded basaltic lapilli tuff containing angular blocks and lapilli up to 8 cm in diameter; set in a red oxidised ash matrix; diffuse boundary,

K1 >30 cm brown (7.5YR 5/2) to strong brown (7.5YR 5/6) blotchy clay; firm; massive,

Weathered basaltic lapilli tuffs, tuffs and lava.