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K-Ar ages, paleomagnetism, and geochemistry of the South Auckland volcanic field, North Island, New Zealand

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Abstract The South Auckland volcanic field is one of the Pliocene–Quaternary intraplate basaltic fields in northern North Island. It consists of at least 97 monogenetic volcanic centres covering an area of c. 300 km^2, 38 km south of Auckland. Fifty-nine of the volcanic centres are characterised by mainly magmatic or effusive activity that constructed scoria cones and lava flows, while 38 are mainly phreatomagmatic or explosive that produced tuff rings and maars. Rock types consist of basanites, hawaiites, nepheline hawaiites, transitional basalts, and *ol*-tholeiitic basalts, with relatively minor amounts of nephelinites, alkali basalts, *Q*-tholeiitic basalts, and nepheline mugearites. Forty-three new K-Ar ages are presented, which range from 0.51 to 1.59 Ma, and show two peaks of activity at 0.6 and 1.3 Ma. Paleomagnetic determinations at 26 selected sites agree well with the paleomagnetic reversal time scale and support the K-Ar age data. Age data from each of the volcanic fields of Okete, Ngatutura, South Auckland, and Auckland, which constitute the Auckland intraplate basaltic province, show that they have developed within a time span of 0.3–1.1 Ma. After activity ceased in any particular field, a new field then developed 35–38 km to the north. These consistent time/space patterns indicate the possibility of a mantle source migrating northwards at c. 5 cm/yr. There is no correlation of rock composition with time, which is consistent with observations in the Northland intraplate province, but is not consistent with the formerly invoked rising diapir model.

Keywords South Auckland volcanic field; Pleistocene; volcanic rocks; K-Ar; paleomagnetism; geochemistry

INTRODUCTION

The South Auckland volcanic field is one of several Pliocene–Quaternary basalt fields in the northern North Island and consists of at least 97 monogenetic volcanic centres located within an area of c. 300 km^2. The South Auckland field covers extensive areas in the Pukekohe–Bombay–Tuakau–Pukekawa–Onewhero region south of Auckland City. The field is considered to represent an intraplate volcanic association that has developed on the Australian plate well behind the active convergent plate margin (Smith 1989). Taupo Volcanic Zone, which results

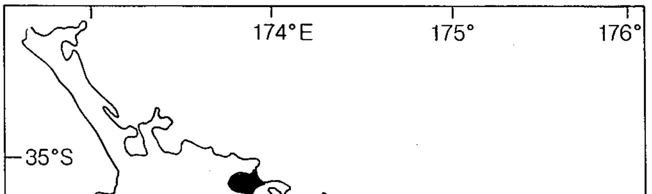

Fig. 1 Map of northern North Island showing the distribution of the intraplate volcanic fields, and the progressive northwards younging in age of the Okete, Ngatutura, South Auckland, and Auckland basalts.

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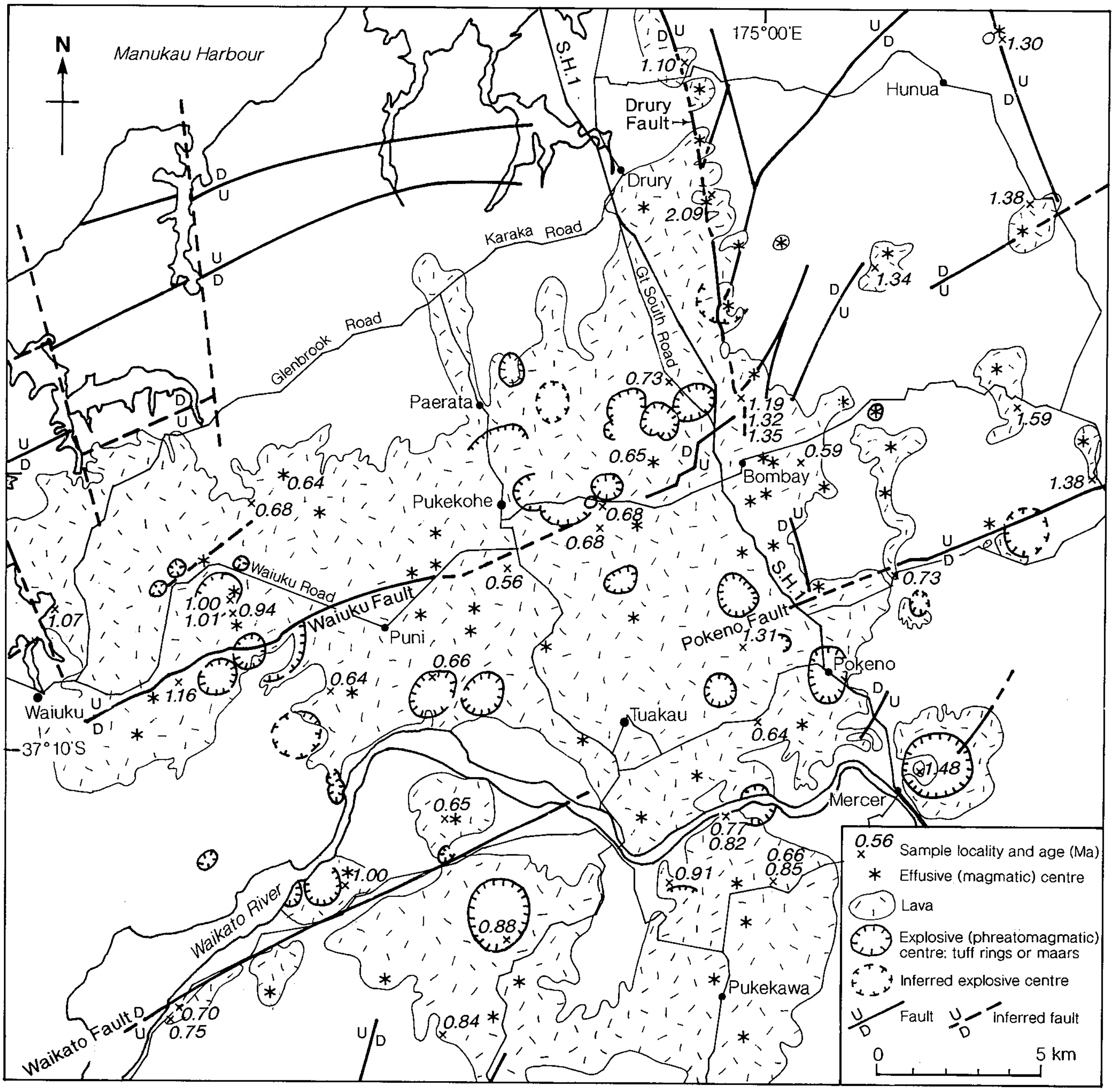

Fig. 2 Map of the South Auckland volcanic field showing the distribution of effusive and explosive volcanic centres, K-Ar ages, and structural patterns. Some data after Rafferty (1977) and Rosenberg (1991).

from interaction between the Pacific and Australian plates, lies 175 km to the southeast.

There is a progressive northwards younging in age of intraplate basaltic volcanism in northern North Island from the Okete Volcanics (2.69–1.80 Ma) in the south, to the Ngatutura Basalts (1.83–1.54 Ma), the South Auckland field (1.56–0.51 Ma; Stipp 1968; Robertson 1976), and to the Auckland field (0.14 Ma–500 yr ago; Wood 1991) to the north (Briggs et al. 1989) (Fig. 1). These volcanic fields contrast with those of Northland where volcanic activity occurred over a long duration from 9.7 Ma ago (Smith et al. 1993) and extended up to 1800–1300 yr ago (Kear & Hay 1961).

Twelve radiometric ages have been determined for the South Auckland volcanic field by Stipp (1968) and Robertson (1976), and the purpose of this paper is to present 43 new K-Ar ages, 26 paleomagnetic determinations, and to discuss some implications of these ages in terms of age patterns within the field. We also examine some preliminary geochemical data, in particular whether there are any relationships between age and composition of the volcanic rocks, and briefly describe their petrography.

SOUTH AUCKLAND VOLCANIC FIELD

The South Auckland volcanic field covers volcanic centres located west of Papakura and Drury in the north, Hunua Falls in the northeast, Pukekawa in the south, and extending to Waiuku in the west (Fig. 2). There are two contrasting types of volcanic centres: (1) mainly magmatic or effusive centres that have produced scoria cones and associated basalt lava flows, and (2) mainly phreatomagmatic or explosive centres that have constructed tuff rings and maars with or without a nested scoria cone. Fifty-nine of the centres are effusive and 38 are explosive. Tuff rings and maars vary in size from 0.5 to 2.5 km in diameter at Onewhero and Kellyville. Rosenberg (1991) determined that the type and style of volcanic activity (i.e. magmatic or phreatomagmatic) was controlled by the lithology and hydrology of the rocks underlying the volcanic centre. The South Auckland region is characterised by block faulting, and consists of uplifted blocks of Mesozoic greywacke, argillite, and conglomerate basement regionally unconformably overlain by late Eocene coal measures and Oligocene to early Miocene siltstones, sandstones, and limestones (Te Kuiti Group and Waitemata Group). Downfaulted blocks are infilled by marine and estuarine sandstones and siltstones of the Pliocene Kaawa Formation and Quaternary fluvial and estuarine sediments. The Pliocene and Pleistocene sediments, occurring in the Manukau lowlands and the Waikato River valley and floodplain, have high permeability, porosity, and transmissivity, and provide the main groundwater aquifer systems. Interaction of basaltic magma rising into these shallow (100–200 m) aquifers (Rosenberg 1991) produced phreatomagmatic eruptions that constructed tuff rings and maars, whereas the basement rocks generally did not contain sufficient groundwater or have suitable hydrological properties for explosive magma-water interactions to occur, resulting in quiet effusive activity characterised by strombolian to hawaiian eruptions.

Many of the South Auckland volcanic centres are located directly over fault lines, which appear to have provided the easiest upper crustal pathways for ascending magma. This is particularly shown by the alignment of volcanic vents along the ENE-striking Waiuku and Pokeno Faults and in the uplifted Hunua block, where the faults (e.g., the NNW-striking Drury Fault) have been important in structurally controlling the localisation of volcanic centres. However, other regions in the middle of the field (e.g., at Pukekohe) are underlain by thick sequences of basaltic lava, and any structural control that might occur in the underlying strata has been obscured and covered by volcanics and Tertiary strata.

The South Auckland region is situated in an oblique extensional tectonic environment characterised by a rhombic pattern of NNW- and ENE-striking block faulting (Spörli 1980). The throws on some of the faults are substantial, and gravity measurements across the Waikato Fault by Hochstein & Nunns (1976) indicate a throw of 2.7 km for the western section of the Waikato Fault, downthrown to the north, and decreasing eastwards to about 0.7 km near Tuakau.

Previous studies of the South Auckland volcanic field include geological mapping by Schofield (1967, 1976) and Waterhouse (1978), petrology and geochemistry by Rafferty (1977) and Rafferty & Heming (1979), and detailed physical volcanological studies of some of the tuff rings by Rosenberg (1991).

PETROGRAPHY

Under the classification of Johnson & Duggan (1989), the rocks in the South Auckland volcanic field are basanite (>5% *ne*; c. 25% of abundance of rock types), hawaiite (30–50% *an/an + ab*; c. 24% abundance), nepheline hawaiite (30–50% *an/an + ab*, >5% *ne*; c. 11% abundance), transitional basalt (0–10% *hy*; c. 12% abundance) and *ol*-tholeiitic basalt (>10% *hy*; c. 18% abundance), with minor nephelinite (>5% *ne*, <5% *ab*; c. 4% abundance), alkali basalt (0–5% *ne*; c. 1% abundance), *Q*-tholeiitic basalt (>10% *hy* with *Q*; c. 3% abundance), and nepheline mugearite (10–30% *an/an + ab*, >5% *ne*; <2% abundance). The lavas are fine to medium grained, vesicular, and porphyritic.

Nephelinites and basanites contain olivine as the sole or dominant phenocryst, with microphenocrysts of brown titanaugite, occasionally rimmed with green aegerine-augite. Olivine varies from euhedral to anhedral and embayed, and is often altered to iddingsite or bowlingite. Titanaugite in some basanites is glomeroporphyritic. The groundmass in nephelinites and basanites is generally intergranular and fine grained, and contains nepheline, titaniferous clinopyroxene, olivine, Fe-Ti oxides, apatite, carbonate, and devitrified glass sometimes altered to smectite-chlorite. Feldspar is absent from nephelinites and only occurs in the groundmass in basanites.

Transitional basalts, hawaiites, and *ol*-tholeiitic and *Q*-tholeiitic basalts contain olivine, colourless clinopyroxene, and plagioclase as phenocrysts, and have a coarse-grained, intergranular to intersertal groundmass comprised of colourless clinopyroxene, feldspar, olivine, titanomagnetite, ilmenite, and calcite. Biotite is rare in some nepheline hawaiites and hawaiites. Pilotaxitic textures are common. Nepheline mugearite has formed as segregation veins in hawaiite lavas and has a medium grained, doleritic texture consisting of olivine, titanaugite with aegerine-augite rims, aegerine, brown amphibole, nepheline, alkali feldspar, apatite, and Fe-Ti oxides.

Ultramafic xenoliths occur in some lavas and are best represented in nepheline hawaiite lavas at Stevenson's Quarry, Bombay, and in basanite lavas at Ridge Road Quarry (for locations, see Table 2). Their petrography and mineralogy has been discussed by Rodgers et al. (1975). Quartz xenoliths are also common and have reaction rims of clinopyroxene; clinopyroxene clots found in some lavas may be such reaction products where the original quartz has been completely resorbed. Some lavas have amygdules infilled with carbonate or zeolites.

GEOCHEMISTRY

Details of the geochemistry and isotopic compositions of these rocks will be discussed in later papers, but representative compositions of the different rock types are presented here in Table 1. SiO_2 contents vary from 41 to 52 wt% (Fig. 3), and total alkalis have a wide range from 3.2 to 7.7 wt%. Overall the rocks have a characteristic intraplate geochemical character and have low LILE/LREE and LILE/HFSE ratios.

The contrasting differences in petrography between the nephelinites and basanites with those of the transitional basalts, hawaiites, and *ol*- and *Q*-tholeiitic basalts are also reflected in their geochemistry. Nephelinites, basanites, and nepheline hawaiites are characterised by large incompatible element abundances (e.g., Zr = 194–491 ppm; Nb = 35–89 ppm), whereas transitional basalts, hawaiites, and *ol*- and

Q-tholeiitic basalts contain relatively smaller incompatible element abundances (e.g., Zr = 97–192 ppm; Nb = 9–29 ppm). However, there is a continuity of compositions shown by a plot of Differentiation Index (D.I.) versus normative 100 An/(An + Ab) (Fig. 4).

AGE OF SOUTH AUCKLAND VOLCANISM

Method

Analyses of K and Ar in South Auckland basalts, and calculations of ages and errors, were carried out at the Hiruzen Research Institute (Okayama, Japan) using the methods described by Nagao et al. (1984) and Itaya et al. (1991). Samples for K-Ar analysis were prepared using the procedure described by Briggs et al. (1989). K was analysed by flame photometry using a 2000 ppm Cs buffer and has an analytical error within 2% at the 2σ confidence level. Ar was analysed on a 15 cm radius sector-type mass spectrometer with a single collector system, using an isotopic dilution method and an Ar38 spike (Itaya et al. 1991). The decay constants for ^{40}K and ^{40}Ca, and the ^{40}K content in potassium used in the age calculations are from Steiger & Jäger (1977), and are 0.581 × 10^{-10}/yr, 4.962 × 10^{-10}/yr, and 0.0001167, respectively.

Results

K-Ar age data are presented in Table 2 and shown in Fig. 2. At some volcanic centres, two or three different lava flows were sampled (e.g., Stevenson's Quarry, Port Waikato Road, Te Kohanga tuff ring, Pukekawa II cone, Otau cone,

Table 1 Selected major (wt %) and trace element (ppm) XRF analyses of South Auckland Basalts.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
SiO_2	47.69	47.15	49.96	48.76	48.94	47.51	51.34	46.24	40.32	41.11	45.15	43.21	46.76	45.77
TiO_2	1.75	1.98	1.65	1.77	2.17	1.92	2.09	2.25	3.32	3.09	2.59	2.74	2.56	2.55
Al_2O_3	14.18	14.53	14.13	17.02	15.01	13.01	13.70	13.73	12.12	12.34	13.88	12.51	15.33	14.53
Fe_2O_3	2.16	2.11	1.94	1.80	2.01	2.12	1.79	2.24	2.42	2.30	2.00	2.06	1.96	2.20
FeO	10.81	10.54	9.70	9.02	10.03	10.59	8.94	11.22	12.10	11.50	10.00	10.32	9.79	10.98
MnO	0.20	0.18	0.17	0.16	0.16	0.16	0.21	0.18	0.21	0.22	0.19	0.18	0.19	0.23
MgO	9.07	8.68	8.33	8.25	6.81	10.31	7.96	10.05	10.00	9.71	9.56	11.50	7.16	5.65
CaO	9.48	8.85	9.02	8.66	9.26	8.56	8.99	9.47	9.74	10.39	9.10	10.45	8.43	7.46
Na_2O	2.83	2.93	2.75	2.87	3.23	2.80	2.81	3.14	4.30	4.95	3.32	3.35	4.58	5.47
K_2O	0.37	0.50	0.52	0.74	0.76	0.58	0.72	0.73	1.69	1.72	1.51	1.14	1.86	2.19
P_2O_5	0.18	0.29	0.19	0.27	0.29	0.27	0.27	0.35	0.95	1.15	0.62	0.61	0.58	1.05
LOI	1.48	2.21	1.40	0.81	1.50	1.99	1.10	0.56	2.44	1.54	1.84	1.70	0.90	1.41
Total	100.20	99.95	99.76	100.13	100.17	99.82	99.92	100.16	99.60	100.02	99.76	99.77	100.10	99.49
Mg	59.5	59.1	60.1	61.6	54.3	63.0	60.9	61.1	59.2	59.7	62.6	66.1	56.2	47.4
D.I.	26.4	28.3	26.7	28.8	32.2	27.7	29.0	28.3	30.4	32.6	32.3	26.1	40.7	47.3
Sc	26	26	24	22	23	19	25	24	18	19	19	23	15	12
V	216	209	193	204	224	185	210	227	263	255	232	277	218	159
Cr	362	329	278	275	244	303	316	278	191	209	263	342	195	75
Ni	213	189	193	147	103	244	161	181	171	163	189	268	118	69
Cu	68	49	72	52	62	77	49	65	55	56	64	71	55	57
Zn	99	97	101	99	96	107	108	100	135	135	98	112	103	132
Ga	23	22	22	24	22	22	22	23	25	24	24	23	26	28
As	1	2	1	2	2	1	1	1	4	5	3	2	4	4
Rb	5.2	6.2	11	17	14	9	15	12	33	29	24	19	30	38
Sr	258	311	256	349	367	315	321	387	1059	1201	746	717	816	1203
Y	47	25	22	24	26	21	25	21	27	32	26	27	27	38
Zr	97	136	108	138	138	135	141	130	376	358	311	275	353	451
Nb	10	15	10	15	17	15	13	18	70	74	55	57	58	84
Ba	65	90	77	153	131	89	115	120	270	358	260	247	290	412
La	18	13	9	18	19	14	13	15	64	84	44	49	49	100
Ce	30	40	31	49	45	46	45	46	146	174	101	105	106	186
Pb	2	3	4	5	5	4	6	3	5	5	6	4	7	7
Th	2	3	3	4	3	2	2	1	6	10	7	7	9	10
U	0.3	0.2	0.1	0.1	1.3	0.3	0.4	0.1	2.2	2.5	0.1	0.3	1.7	2.4
K/Rb	591	669	392	361	451	541	398	505	425	492	522	498	515	478
Rb/Sr	0.02	0.02	0.04	0.05	0.04	0.03	0.05	0.03	0.03	0.02	0.03	0.03	0.04	0.03
Zr/Y	2	5	5	6	5	6	6	6	14	11	12	10	13	12
Ba/Nb	7	6	8	10	8	6	9	7	4	5	5	4	5	5
Ba/La	4	7	9	9	7	6	9	8	4	4	6	5	6	4

1 Transitional basalt, Bucklands cone (SA84; 41685; R12/816383)
2 Transitional basalt, Puni Domain cone (SA39; 41640; R12/768378)
3 *ol*-tholeiitic basalt, Waitangi Falls (SA34; 41635; R12/646403)
4 *ol*-tholeiitic basalt, Bombay cone (SA81; 41682; R12/866454)
5 Hawaiite, Pukekawa II cone (SA20; 41621; R12/878308)
6 Hawaiite, Patumahoe Quarry (SA32; 41633; R12/712435)
7 *Q*-tholeiitic basalt, Drury Fault (SA31; 41632; R12/864528)
8 Alkali basalt, Onewhero tuff ring (SA17; 41618; R13/792290)
9 Nephelinite, Pukekawa III cone, W flow (SA50; 41651; R13/841279)
10 Nephelinite, Pukeotahinga cone (SA46; 41647; R13/739292)
11 Basanite, Ridge Road Quarry (SA3; 41604; R12/869383)
12 Basanite, Barriball Road tuff ring (SA37; 41638; R12/702398)
13 *ne*-hawaiite, Stevenson's Quarry (SA1; 41602; R12/872463)
14 *ne*-hawaiite, Peach Hill Road cone (SA62; 41663; R12/868498)

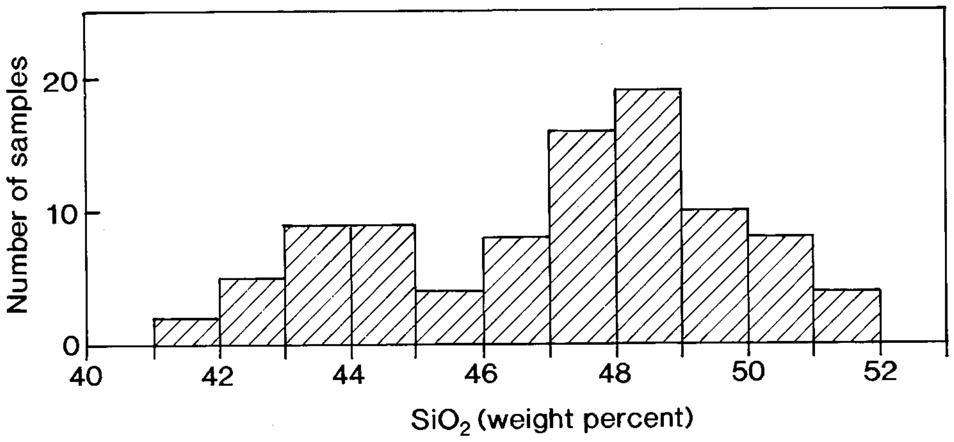

Fig. 3 Histogram of SiO_2 contents (wt%) for analysed rocks of the South Auckland volcanic field.

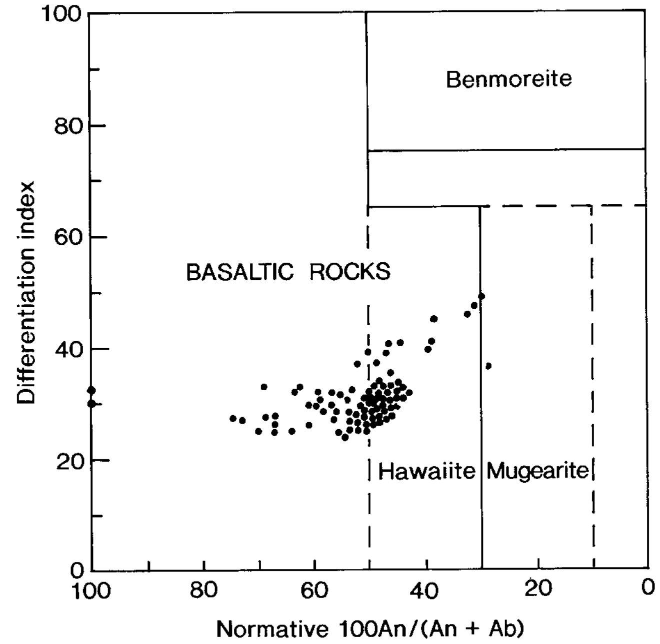

Fig. 4 Differentiation index versus normative plagioclase composition for the South Auckland volcanic field.

Patumahoe Quarry, and Barriball Road tuff ring), and the differences in ages are therefore considered to represent the age span of volcanic activity at that centre. In most cases the ages of different lava flows from the same volcanic centre fall within the calculated errors of the age determinations, which suggests that most volcanic centres are monogenetic volcanoes (i.e. built up by the products of one eruption or one eruptive phase, lasting several months to several years, and generally involving one magma type) (Cas & Wright 1987). However, at Stevenson's Quarry (range from 1.19 ± 0.04 to 1.35 ± 0.05 Ma) and Pukekawa II cone (0.66 ± 0.03 to 0.85 ± 0.05 Ma) there is a prolonged span of activity, which suggests that these volcanic centres are polygenetic volcanoes (Cas & Wright 1987) that have resulted from many eruptions, separated by relatively long periods. The two lavas sampled at Pukekawa II cone have distinct compositions (i.e. hawaiite and nephelinite), and if they are derived from the same centre, as inferred from field evidence, this suggests a span of activity of 190 ± 50 ka.

Four samples (41628, 41632, 41638, and 41644) were analysed for Ar in duplicate, and show quite high reliability for the K-Ar dates.

The ages obtained here for the South Auckland volcanic field range from 0.56 ± 0.05 to 2.24 ± 0.37 Ma. However, a slightly younger K-Ar age of 0.51 Ma has been recorded for Pukekohe Hill by Stipp (1968). Our oldest age is for the Drury Hills cone, where ages have been determined at 2.09 ± 0.37 Ma and 2.24 ± 0.37 Ma, but both these age determinations have large errors. In fact, the age of the Drury Hills cone appears to be anomalous because the oldest age of the rest of the volcanic centres is 1.59 ± 0.51 Ma (for Te Kohanga tuff ring, that also has a large error). The sample from the Drury Hills cone has quartz xenocrysts and olivine phenocrysts, which is a disequilibrium assemblage, and suggests the possibility of interaction with crustal material or older silicic volcanic rocks. These interactions produce anomalously older ages because the contaminant rocks have excess Ar. Hence, because of the question over the Drury Hills cone age, we consider the true age of the South Auckland volcanic field to lie in the range 0.51–1.59 Ma.

A histogram of the frequency distribution of the age data is shown in Fig. 5. Where more than one lava flow was dated from the same volcanic centre, the mean age of the volcanic centre was used in the histogram. Hence, the histogram shows the frequency distribution of 33 of the volcanic centres, rather than 43 (i.e. the total number of dates, but not including the duplicates for Ar analysis).

However, while only 33 of the 97 volcanic centres of the field have been sampled, they are considered to be mainly representative of the temporal variations in the field, although there may be an oversampling of the younger centres because older ones may have been partially or completely buried. The histogram shows that there are two peaks of volcanism at 0.6 and 1.3 Ma, although there has been more-or-less intermittent volcanism in the field in at least 97 volcanic centres, over a duration of c. 1 Ma.

Schofield (1958) subdivided the rocks of the South Auckland volcanic field into two formations—the Bombay Basalts and the Franklin Basalts—based on the morphology of the cones and volcanic landforms. The Franklin Basalts were designated as having volcanic forms that are better preserved than those of the older Bombay basalts, and these distinctions were subsequently extended by Kear (1961) in the Pokeno district and on the regional geological maps of Schofield (1967, 1976). However, our radiometric age data

Table 2 K-Ar age data, South Auckland volcanic field.

Sample no.*	HRI lab. no.†	Rock type	Volcanic centre/location	Grid ref. §	K (wt %)	^{40}Ar (rad.) (*10–8 cc STP/g)	Non-rad. 40Ar (%)	K-Ar age (Ma)	Formation (F / B)
41602	S16–145	*ne*-hawaiite	Stevenson's Quarry (Bombay)	R12/872463	1.487 ± 0.030	6.87 ± 0.19	56.0	1.19 ± 0.04	B
41603A	S16–146	*ne*-hawaiite	Stevenson's Quarry	R12/872463	1.605 ± 0.032	8.21 ± 0.23	57.0	1.32 ± 0.05	B
41603B	S16–147	*ne*-hawaiite	Stevenson's Quarry	R12/872463	1.603 ± 0.032	8.43 ± 0.23	56.2	1.35 ± 0.05	B
41604	S16–213	Basanite	Ridge Road Quarry	R12/869383	1.043 ± 0.021	5.32 ± 0.48	84.5	1.31 ± 0.12	B
41606	S16–148	Basanite	Smeed's Quarry	R12/862329	0.851 ± 0.026	2.56 ± 0.13	73.6	0.77 ± 0.05	F
41607	S16–212	Basanite	Smeed's Quarry	R12/862329	1.428 ± 0.029	4.57 ± 0.28	77.8	0.82 ± 0.05	F
41608	S16–149	Transitional basalt	Onepoto cone	R12/772333	0.528 ± 0.016	1.33 ± 0.19	90.0	0.65 + 0.10	F
41612	S16–150	Hawaiite	Pukekohe Cone	R12/796411	0.651 ± 0.020	1.42 ± 0.12	83.1	0.56 ± 0.05	F
41613	S16–151	Basanite	Pokeno–Tuakau Road	R12/872361	1.481 ± 0.030	3.66 ± 0.20	75.5	0.64 ± 0.04	F
41614	S16–211	Transitional basalt	Port Waikato Road	R13/693282	0.385 ± 0.019	1.04 ± 0.35	95.5	0.70 ± 0.24	F
41615	S16–210	Hawaiite	Port Waikato Road	R13/682274	0.389 ± 0.019	1.13 ± 0.43	95.9	0.75 ± 0.28	F
41616	S16–209	*ol*-tholeiitic basalt	Te Kohanga tuff ring	R12/736313	0.455 ± 0.014	2.80 ± 0.90	95.2	1.59 ± 0.51	F
41617A	S16–208	*ol*-tholeiitic basalt	Te Kohanga tuff ring	R12/736313	0.400 ± 0.012	1.55 ± 0.12	82.4	1.00 ± 0.09	F
41617B	S16–191	*ol*-tholeiitic basalt	Te Kohanga tuff ring	R12/736313	0.418 ± 0.021	1.59 ± 0.16	86.2	0.98 ± 0.11	F
41618	S16–190	Alkali basalt	Onewhero tuff ring	R13/792290	0.606 ± 0.018	2.06 ± 0.13	78.1	0.88 ± 0.06	F
41619	S16–189	Hawaiite	Kauri Road cone	R13/787245	0.982 ± 0.029	3.21 ± 0.23	80.8	0.84 ± 0.07	F
41620	S16–200	Hawaiite	Murray Road cone	R12/843309	0.727 ± 0.022	2.57 ± 0.14	75.5	0.91 ± 0.06	F
41621	S16–199	Hawaiite	Pukekawa II cone	R12/878308	1.186 ± 0.024	3.02 ± 0.12	67.2	0.66 ± 0.03	F
41622	S16–198	Nephelinite	Pukekawa II cone	R12/878308	0.782 ± 0.023	2.57 ± 0.12	71.5	0.85 ± 0.05	F
41623	S16–197	*ne*-hawaiite	Kellyville tuff ring	S12/926342	1.203 ± 0.024	6.92 ± 0.45	79.2	1.48 ± 0.10	F
41624	S16–152	Basanite	Pinnacle Hill cone	S12/919405	1.376 ± 0.028	3.91 ± 0.18	71.3	0.73 ± 0.04	B
41625	S16–195	*ne*-hawaiite	Mangatawhiri cone	S12/986432	1.575 ± 0.032	8.46 ± 0.16	40.3	1.38 ± 0.04	B
41626	S16–194	*ne*-hawaiite	Paparata cone	S12/963457	1.560 ± 0.031	9.65 ± 0.79	83.0	1.59 ± 0.13	B
41627	S16–192	Basanite	Red Hill cone	R12/863569	1.142 ± 0.023	4.86 ± 0.13	57.1	1.10 ± 0.04	B
41628	S16–174	Basanite	Hunua Falls	S12/962571	1.849 ± 0.037	9.32 ± 0.28	58.6	1.30 ± 0.05	B
–	S16–193	–	–	–	–	9.34 ± 0.27	58.2	1.30 ± 0.05	B
41629A	S16–173	Basanite	Otau cone	S12/971519	1.858 ± 0.037	9.94 ± 0.19	43.2	1.38 ± 0.04	B
41629B	S16–172	Basanite	Otau cone	S12/971519	1.890 ± 0.038	10.11 ± 0.18	40.3	1.38 ± 0.04	B
41630	S16–171	*ne*-hawaiite	Ararimu cone	S12/919500	1.917 ± 0.038	9.93 ± 0.17	36.6	1.34 ± 0.04	B
41631	S16–170	Hawaiite	Bombay cones	R12/894442	0.830 ± 0.025	1.90 ± 0.9	72.7	0.59 ± 0.03	F
41632	S16–153	*Q*-tholeiitic basalt	Drury Hills cone	R12/864528	0.697 ± 0.021	5.66 ± 0.99	91.6	2.09 ± 0.37	B
–	S16–96	–	–	–	–	6.05 ± 0.98	91.2	2.24 ± 0.37	B
41633	S16–169	Hawaiite	Patumahoe Quarry	R12/712435	0.526 ± 0.016	1.39 ± 0.13	84.9	0.68 ± 0.07	F
41634	S16–196	Hawaiite	Patumahoe Quarry	R12/712435	0.746 ± 0.022	1.85 ± 0.11	77.3	0.64 ± 0.04	F
41635	S16–167	*ol*-tholeiitic basalt	Waitangi Falls	R12/646403	0.582 ± 0.017	2.42 ± 0.48	92.6	1.07 ± 0.22	F
41636	S16–168	*ol*-tholeiitic basalt	Waiuku cone	R12/684377	0.447 ± 0.022	2.01 ± 0.46	93.5	1.16 ± 0.27	F
41637	S16–166	*ol*-tholeiitic basalt	Bald Hill cone	R12/702397	0.549 ± 0.016	2.00 ± 0.15	80.7	0.94 ± 0.07	B
41638A	S16–165	Basanite	Barriball Road tuff ring	R12/702398	1.091 ± 0.022	4.22 ± 0.26	77.5	1.00 ± 0.06	F
41638B	S16–163	Basanite	Barriball Road tuff ring	R12/702398	1.514 ± 0.030	5.94 ± 0.20	62.8	1.01 ± 0.04	F
–	S16–95	–	–	–	–	6.25 ± 0.23	66.8	1.06 ± 0.05	F
41639	S16–154	Basanite	Riverview Road cone	R12/736375	1.023 ± 0.020	2.52 ± 0.21	83.2	0.64 ± 0.05	B
41640	S16–162	Transitional basalt	Puni Domain cone	R12/768378	0.476 ± 0.024	1.21 ± 0.19	90.9	0.66 ± 0.11	F
41641	S16–161	Basanite	Pukekohe East tuff ring	R12/825432	1.406 ± 0.028	3.71 ± 0.12	63.0	0.68 ± 0.03	F
41642	S16–160	Basanite	Jericho Road cone	R12/828424	1.507 ± 0.030	3.98 ± 0.17	69.5	0.68 ± 0.03	F
41643	S16–188	Basanite	Rutherford Road cone	R12/836444	1.402 ± 0.028	3.55 ± 0.11	62.0	0.65 ± 0.03	F
41644	S16–164	*ol*-tholeiitic basalt	Raventhorpe tuff ring	R12/848470	0.780 ± 0.023	2.21 ± 0.38	91.5	0.73 ± 0.13	F
–	S16–207	–	–	–	–	2.08 ± 0.36	91.4	0.69 ± 0.12	F

*Samples lodged in the Geology Department, University of Auckland.
†Laboratory number at Hiruzen Research Institute.
§Based on the national 1000 m grid of the 1:50 000 topographical map series (NZMS 260).
Formation: B = Bombay Basalts ; F = Franklin Basalts.

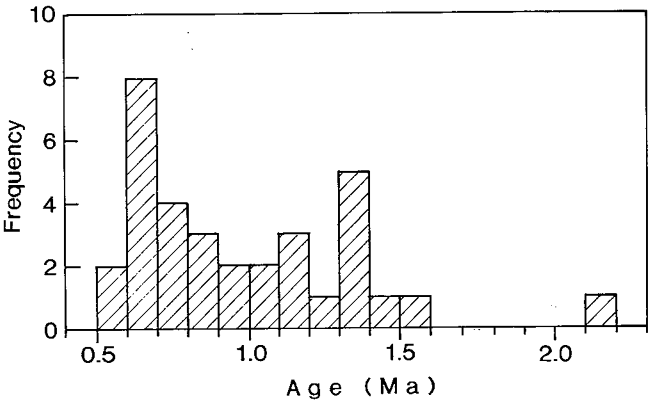

Fig. 5 Histogram of K-Ar ages of 33 volcanic centres in the South Auckland volcanic field.

show that any distinction in age based on geomorphology of the cones is invalid (see Table 2). A similar conclusion was made by Briggs et al. (1989), from the data for the Pliocene–Pleistocene Alexandra and Ngatutura Volcanics, who suggested that the morphological preservation of cones could not be related directly to age, size, climatic conditions, or a thick cover of younger tephra, but rather to the lithology. Scoria cones vary in their degree of welding, grain size, and rock mass strength, and these could be the important factors that control the preservation of such volcanic landforms.

AGE AND SPATIAL PATTERNS

There is no systematic younging in age in any direction within the field, apart from the apparently older ages in the northeast. Since there seems to be a regional younging of intraplate volcanic fields to the north (from Okete to Ngatutura to South Auckland to Auckland), it might have been expected that the youngest volcanic centres in South Auckland would have occurred in the northern part of the field, but no such trend is indicated by our data.

However, there does appear to be a pattern of younger volcanoes in the centre of the field in the region of Pukekohe, Pukekohe East, and Puni (Fig. 2), where there are clusters of volcanoes that have ages between 0.56 and 0.73 Ma. The older volcanoes appear to have a more peripheral and isolated distribution, although this may reflect burial and covering of older volcanoes by younger ones in the centre. Hence, it could be that earlier phases of volcanism were more widespread, but that the volcanism became more centrally focused with time.

There is no relationship between age of the volcanic centre and the style and type of volcanism (i.e. explosive or effusive). This supports the results of Rosenberg (1991) who demonstrated that the style and type of volcanism was controlled by other factors (i.e. the hydrology and lithology of the shallow underlying strata) and implies that these controlling factors have been present throughout the duration of the volcanic field.

There is also no systematic spatial pattern in geochemical composition within the field. This is indicated by a scatter plot (Fig. 6A) of north co-ordinate versus Differentiation Index (D.I.), which shows no systematic trends. It appears that nephelinites are confined to the south and *Q*-tholeiites to the north, although we consider more data are required to confirm this. There is also no strong correlation between the age and chemical composition of the lavas (Fig. 6B) (e.g., no trend of increasing differentiation with younging in age), although the older volcanic centres in the northeast of the field in the uplifted Hunua block tend to have higher D.I.s, and hawaiites are consistently younger than nepheline hawaiites. The general lack of systematic spatial or temporal trends in geochemistry suggests that each magma batch has evolved independently.

PALEOMAGNETISM

Methods

Paleomagnetic investigations of the South Auckland basalts were made to support the reliability of the K-Ar age determinations. Samples for paleomagnetic study were collected from as many dated volcanic centres as possible, where in-situ outcrops were available. One to 10 oriented block samples were taken from each site. Each sample was cut into cylindrical specimens 25 mm in diameter and height. At Te Kohanga and Barriball Road tuff rings, no in-situ lava could be obtained, so that a block tuff sample was collected, which was cut and set into a plastic cube of 21 mm on each side. One pilot specimen for each site was tested in progressive alternating field (a.f.) demagnetisation experiments. Most specimens were suitable so that one pilot specimen was sufficient for determining the peak alternating field intensity for demagnetisation of the remaining specimens. Measurements were carried out in the Department of Earth Sciences, University of Osaka Prefecture, using a Natsuhara-Giken AMM–85 spinner magnetometer and a DEM–8601M a.f. demagnetiser capable of generating up to 70 mT of peak alternating field.

Results

The site mean magnetic directions are shown in Fig. 7 and Table 3. Other paleomagnetic statistics are also tabulated. The mean directions are generally well clustered around the directions expected for the axial dipole field at normal and reversed polarities, although two sites have intermediate directions. The origin of these intermediate directions could be from a geomagnetic excursion or on the course of a geomagnetic reversal; however, this will not be discussed further here, since our interest in this paper is on magnetostratigraphy.

Figure 8 indicates the virtual geomagnetic pole (VGP) latitude versus K-Ar age. The ages of the geomagnetic polarity reversals are 0.73, 0.92, 0.97, 1.10, 1.11, and 1.67 Ma for Brunhes/Matuyama, top and bottom of Jaramillo and Cobb Mountain events, and top of the Olduvai event, respectively (Hsu et al. 1991, for Cobb Mountain event; Harland et al. 1982, for others). The sites of clear polarity agree well with the paleomagnetic reversal time scale, and confirms the reliability of the ages and paleomagnetic results.

Several sites around 1 Ma in age with normal polarity have large age errors, which could be constrained by the magnetostratigraphic data. For example, Raventhorpe tuff ring has an age of 0.73 ± 0.13 Ma, but considering that the polarity is normal, it could be read as $0.73^{+0.00}_{-0.13}$ Ma. Waitangi Falls and Waiuku Cone, which have relatively large errors of 1.07 ± 0.22 and 1.16 ± 0.27 Ma, respectively, could be

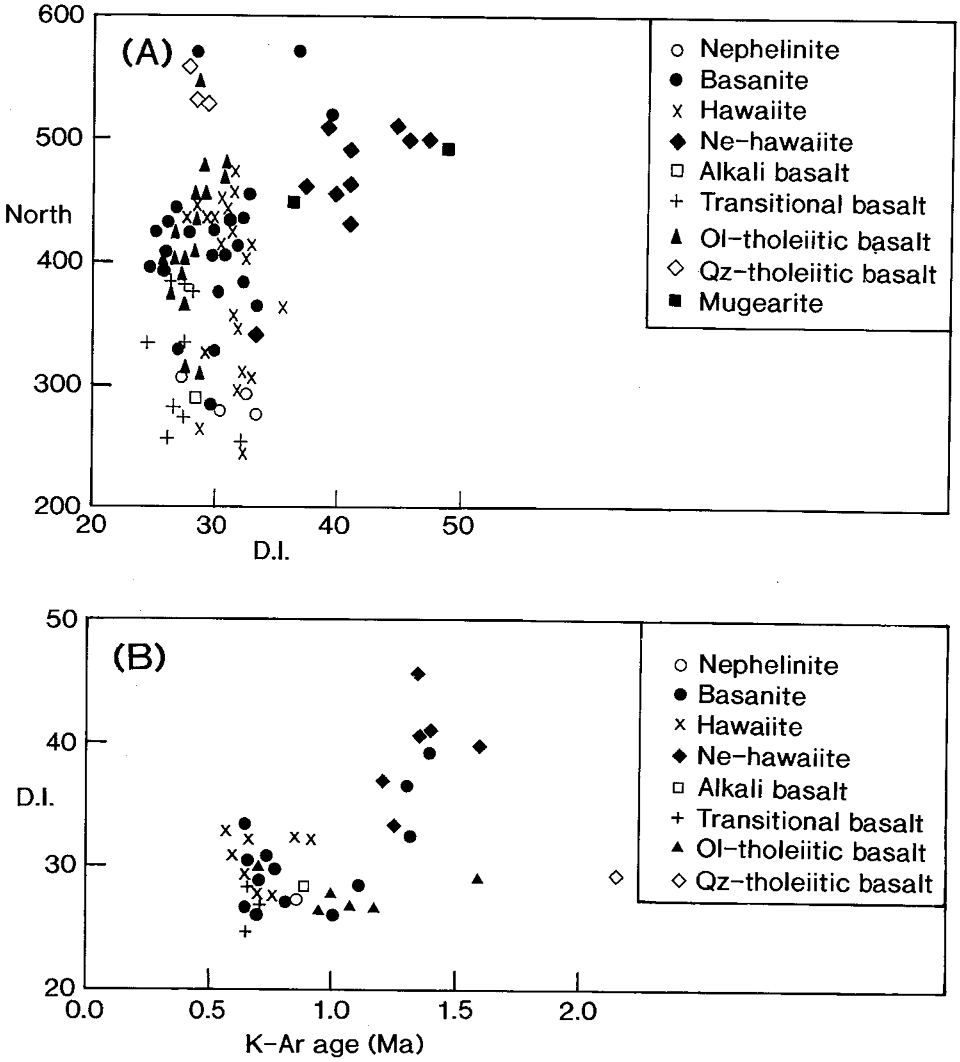

Fig. 6 **A**, Scatter plot of north co-ordinate versus Differentiation Index (D.I.) for the South Auckland volcanic field. **B**, Plot of D.I. versus age.

restricted to 1.10–1.11 Ma, although there is also a possibility that they lie in the Jaramillo event between 0.92 and 0.97 Ma. Similar constraints are also possible for Port Waikato Road, Te Kohanga tuff ring, Patumahoe Quarry, Barriball Road tuff ring, and Puni Domain cone.

REGIONAL IMPLICATIONS

The South Auckland volcanic field is an example of a mainly monogenetic (and occasionally polygenetic) volcanic association in which discrete eruption sequences have built at least 97 volcanic centres within a relatively small area of 300 km^2. The ages presented in this paper indicate that activity in the field began c. 1.6 Ma ago and ceased abruptly c. 0.5 Ma ago. There were two peaks of volcanism at 0.6 and 1.3 Ma, but the field was active for c. 1 Ma. Although we can recognise two discrete volcanic suites on the basis of petrography and geochemistry, these cannot be separated in terms of either time or spatial distribution.

The South Auckland field is one of three volcanic fields comprising the Auckland intraplate basaltic province (Smith 1989). Although the Okete Volcanics are closely associated spatially and temporally with volcanoes that have convergent margin characteristics, they have form and petrologic characteristics comparable to the rest of the Auckland intraplate basalts (Briggs & Goles 1984; Briggs & McDonough 1990) and should be included as a fourth field in the province. The available age data (Briggs et al. 1989; Wood 1991) indicate that each of the fields has developed within a time span of 0.3–1.1 Ma, and that after activity has ceased in any particular field, a new field has developed to the north. Thus, the Okete, Ngatutura, South Auckland, and Auckland fields, with median ages of 2.1, 1.7, 1.1, and 0.06 Ma, show geographic spacings of 38, 35, and 38 km, respectively. The significance of these time/space patterns is discussed in the following sections.

The Northland intraplate basaltic province lies 150–250 km to the north of the Auckland province and consists of similar clusters of monogenetic volcanoes grouped into fields. Recent work in the province (Smith et al. 1993) has shown that volcanic activity began c. 10 Ma ago and has continued into Recent times. Further, geochemical and temporal patterns that were established 8–10 Ma ago have persisted through to the present. These observations contrast with the time/space patterns of intraplate basaltic volcanism shown by the Auckland intraplate province and the Okete Volcanics, and place major constraints on a model to explain the origin of the magmas that have given rise to the volcanic fields.

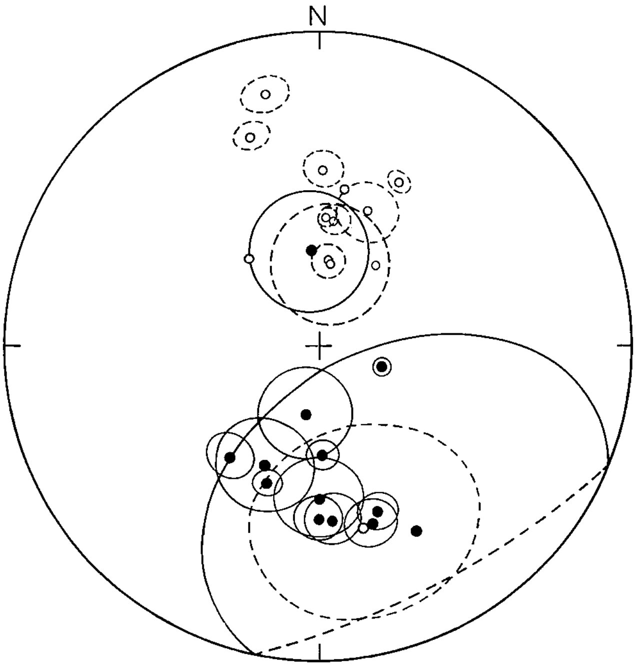

Fig. 7 Equal area projection of site mean direction. Solid and open points indicate projection onto the lower and upper hemisphere, respectively. Ovals are 95% confidence circles.

In Northland, magma sources have remained stationary with respect to underlying mantle sources. This observation is consistent with paleomagnetic work which shows that Northland has not rotated during the late Cenozoic (Shibuya pers. comm.). In contrast, the eastern part of the North Island has undergone pronounced rotation in Pliocene–Recent times (Walcott 1989). The Auckland intraplate province lies between the relatively stable Northland Peninsula and the mobile eastern segment of the North Island. Since volcanic activity in the Auckland intraplate province temporally overlaps the inception of arc-type volcanism in the central North Island and the development of large volume silicic caldera volcanoes in the Taupo Volcanic Zone, it is logical to seek a tectonic link between these contrasting volcanic associations. Magmas in the Auckland intraplate province are clearly mantle related, with no evidence for a subduction zone geochemical signature, and the observed time/space relationships are consistent with the notion of a mantle source migrating northwards at an apparent rate of c. 5 cm/yr.

Rafferty & Heming (1979) have suggested that the South Auckland field is a consequence of partial melting of a rising mantle diapir. Heming (1980) proposed a similar model for volcanism in the Northland province. Evidence for this model is a perceived temporal change from early eruption of alkaline magmas to later eruption of transitional and tholeiitic magmas representing deep and shallow melts, respectively, of the rising diapir. However, the data presented in this paper show no correlation of erupted rock compositions with time, and are similar to the data from the Northland province reported by Smith et al. (1993). These observations are not consistent with a rising diapir model. In Northland the magma source has apparently been essentially stable and capable of producing small volume melts over a period of nearly 10 Ma. In the Auckland province the magma source has produced a comparable

Table 3 Paleomagnetic data for South Auckland volcanic field.

Site no.	Volcanic centre/ location	Grid ref.	*N*	Demag (mT)	Dec (°)	Inc (°)	α95 (°)	Intensity (A/m)	VGP Lat. (°)	Long. (°)
NZ 1	Stevenson's Quarry	R12 872463	8	20	108.2	72.2	2.2	5.5E–1	–40.0	–142.9
NZ 2	Ridge Road Quarry	R12 869383	4	20	180.0	44.1	6	7.8E–1	–78.6	–5.0
NZ 3	Smeed's Quarry	R12 862329	10	20	160.3	42.9	5.1	1.0E+0	–69.2	–64.3
NZ 4	Pukekohe cone	R12 796441	6	20	165.4	–40.0	27.7	1.1E+0	–28.5	–20.4
NZ 5	Pokeno–Tuakau Road	R12 872361	8	20	1.2	–43.2	5	5.0E–1	77.8	–179.8
NZ 6	Port Waikato Road	R13 693282	6	20	–12.5	–19.1	5.5	3.0E+0	60.3	149.3
NZ 7	Port Waikato Road	R13 682274	7	20	–18.4	–30.5	4	1.9E+0	63.5	132.0
NZ 8	Te Kohanga tuff ring	R12 736313	1	20	–38.5	–60.6	–	7.7E–3	60.2	64.4
NZ 9	Onewhero tuff ring	R13 792290	8	20	–159.0	51.1	3.8	2.5E+0	–71.9	73.3
NZ 10	Kauri Road cone	R13 787245	8	20	–141.1	52.5	6.2	2.6E+0	–58.2	89.0
NZ 11	Murray Road cone	R12 843309	3	20	–155.4	55.4	12.3	2.0E+0	–70.3	88.4
NZ 12	Pukekawa II cone	R12 878308	2	20	151.9	33.4	50.4	1.0E–1	–58.9	–64.9
NZ 13	Kellyville tuff ring	S12 926342	7	20	175.5	43.5	6.9	4.1E+0	–77.5	–24.1
NZ 15	Mangatawhiri	S12 986432	5	20	–179.9	49.6	10.8	4.5E–1	–83.2	–4.2
NZ 16	Paparata cone	S12 963457	3	20	–168.2	72.0	12.3	2.0E–1	–68.7	157.2
NZ 18	Hunua Falls cone	S12 962571	9	30	162.7	40.3	6.5	1.0E+0	–69.5	–56.3
NZ 19	Otau cone	S12 971519	7	30	–5.3	65.0	15.6	1.3E–1	5.8	171.5
NZ 20	Ararimu cone	S12 919500	8	20	178.0	61.3	4.1	7.2E–1	–84.5	–169.3
NZ 21	Bombay cones	R12 894442	1	20	9.9	–48.3	–	2.0E+0	78.6	–135.8
NZ 23	Patumahoe Quarry	R12 712435	5	20	7.4	–67.5	4.5	1.5E+0	75.8	–24.8
NZ 24	Waitangi Falls	R12 646403	8	20	26.4	–41.4	2.8	1.3E+0	63.7	–118.5
NZ 25	Waiuku cone	R12 684377	4	20	20.2	–52.3	7.9	3.2E–1	72.9	–104.0
NZ 27	Barriball Road tuff ring	R12 702398	1	25	35.6	–63.8	–	2.5E–2	62.3	–66.6
NZ 29	Puni Domain cone	R12 768378	8	20	6.8	–56.6	3.9	5.2E+0	84.6	–93.9
NZ 30	Jericho Road cone	R12 828424	3	20	8.3	–68.3	15.7	2.3E+0	74.6	–24.8
NZ 32	Raventhorpe tuff ring	R12 848470	9	20	3.0	–56.2	2.2	2.1E+0	87.6	–103.9

N: number of samples; Demag: demagnetisation level; Dec: declination; Inc: inclination; α95: radius of 95% confidence circle; Intensity: geometric mean of magnetisation of samples after demagnetisation; VGP Lat. Long.: latitude and longitude of virtual geomagnetic pole position.

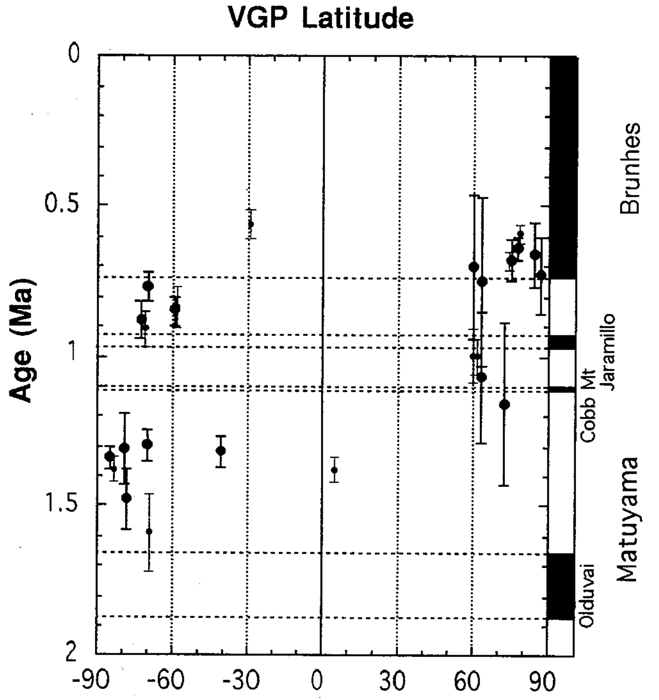

Fig. 8 Plots of virtual geomagnetic pole latitude versus K-Ar age. Large and small circles indicate sites with small (<10°) and large (>10°) 95% confidence circles, respectively, expressing the reliability of the VGP latitude.

range of basaltic magma compositions over a period of c. 2 Ma but the site of magma eruption has migrated northwards.

If the sense of movement of volcanic centres in the Auckland province is to be explained by a stationary magma source, then the Auckland region has moved southward at c. 5 cm/yr for the past 2 Ma relative to a stationary Northland; there is no evidence to support a movement of this magnitude. The alternative is that the source supplying magma to the volcanic fields in the province has migrated northwards. During the last 5 Ma, arc-type magmatism in the northern North Island has changed from the northwest orientation of the Miocene–Pliocene Northland–Coromandel calc-alkaline volcanoes to the present northeast orientation of the Quaternary Kermadec – Taupo Volcanic Zone volcanic system. Arguably, the Kermadec arc system has "captured" the Taupo Volcanic Zone by southward propagation during the last 2 Ma (Smith 1990). We suggest, therefore, that the apparent northward migration of magma sources in the Auckland intraplate province might be in response to inception of subduction at the southern end of a propagating convergent plate boundary in the region to the southeast of the province.

There is also the question of whether the magma source that is supplying small volume melts to each of the fields is the same. Preliminary geochemical and isotopic data suggest that the magma sources are distinct, but further work on this problem is in progress.

Another intriguing feature which remains to be explained is the regular spacing of volcanic fields in the Auckland province, and also the fact that in each field volcanic activity has begun and ended abruptly. If temporal patterns observed in the South Auckland and Okete fields hold, then the current volcanic episode centred on Auckland City could continue for another 900 000 years.

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