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Ages on weathered Plio-Pleistocene tephra sequences, western North Island, New Zealand

Âges de séquences de tephras Plio-Pleistocènes altérés, Île du Nord-Ouest, Nouvelle Zélande

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Abstract: *using the zircon fission-track method, we have obtained five ages on members of two strongly-weathered, silicic, Pliocene-Pleistocene tephra sequences, the Kauroa and Hamilton Ash formations, in western North Island, New Zealand. These are the first numerical ages to be obtained directly on these deposits. Of the Kauroa Ash sequence, member K1 (basal unit) was dated at 2.24 ± 0.29 Ma, confirming a previous age of* c. *2.25 Ma obtained (via tephrochronology) from K/Ar ages on associated basalt lava. Members K2 and K3 gave indistinguishable ages between 1.68 ± 0.12 and 1.43 ± 0.17 Ma. Member K12, a correlative of Oparau Tephra and probably also Ongatiti Ignimbrite, was dated at 1.28 ± 0.11 Ma, consistent with an age of 1.23 ± 0.02 Ma obtained by various methods on Ongatiti Ignimbrite. Palaeomagnetic measurements indicated that members K13 to K15 (top unit, Waiterimu Ash) are aged between* c. *1.2 Ma and 0.78 Ma. Possible sources of the Kauroa Ash Formation include younger volcanic centres in the southern Coromandel Volcanic Zone or older volcanic centres in the Taupo Volcanic Zone, or both. Of the Hamilton Ash sequence, the basal member Ohinewai Ash (H1) was dated at 0.38 ± 0.04 Ma. This age matches those obtained by various methods on Rangitawa Tephra of 0.34–0.35 Ma, supporting correlation with this Whakamaru-caldera derived deposit. The origin of the other Hamilton Ash beds is unknown but various younger volcanic centres in the Taupo Volcanic Zone are possible sources. The topmost member, Tikotiko Ash (H6–H7), is estimated to be aged between* c. *0.18 and 0.08 Ma. Various silicic pyroclastic deposits documented in North Island and in marine cores may be co-eval with members of the Kauroa Ash and Hamilton Ash sequences on the basis of their age.*

Keywords: *tephra, fission-track ages, zircon, geochronology, brown ashes, Kauroa Ash, Hamilton Ash, Oparau Tephra, Ongatiti Ignimbrite, Ohinewai Ash, Rangitawa Tephra, Plio-Pleistocene, Waikato region, New Zealand.*

Résumé : *en utilisant la méthode des traces de fission sur zircon, nous avons obtenu cinq âges sur des membres de deux séquences de téphras siliciques fortement altérés du Pliocène final et du Pléistocène : les formations de Kauroa Ash et de Hamilton Ash du North Island occidental, Nouvelle-Zélande. Ce sont les premiers âges numériques obtenus sur de tels dépôts. De la séquence de Kauroa Ash, le membre K1 (unité inférieure) a été daté de 2,24 ± 0,29 Ma, confirmant un âge de 2,25 Ma obtenu antérieurement (par téphrochronologie) à partir d'âges K/Ar de coulées de basalte associées. Les membres K2 et K3 ont donné des âges compris entre 1,68 ± 0,12 and 1,43 ± 0,17 Ma. Le membre K12, corrélatif du Oparau Tephra et probablement aussi de l'Ongatiti Ignimbrite, a été daté de 1,28 ± 0,11 Ma, ce qui est consistant avec un âge de 1,23 ± 0,02 Ma, obtenu par différentes méthodes sur l'Ongatiti Ignimbrite. Des mesures paléomagnétiques indiquaient que les membres K13 to K15 (unité supérieure, Waiterimu Ash) ont un âge compris entre environ 1,2 Ma and 0,78 Ma. Les sources possibles de la formation Kauroa Ash comprennent des centres volcaniques récents dans la partie méridionale de la Zone Volcanique Coromandel, ou des centres plus anciens de la Zone Volcanique Taupo, ou les deux. Le membre basal de la séquence de Hamilton Ash (H1) a été daté de 0,38 ± 0,04 Ma, ce qui correspond à l'âge de 0,34–0,35 Ma obtenu par différentes méthodes sur le Rangitawa Tephra, supportant ainsi la corrélation avec les dépôts dérivés de la caldera Whakamaru. L'origine des autres lits de la Hamilton Ash est inconnue, mais divers centres volcaniques récents de la Zone Volcanique Taupo sont possibles. L'âge du membre sommital de la Tikotiko Ash (H6–H7), est estimé entre 0,18 and 0,08 Ma. Divers dépôts pyroclastiques siliciques signalés dans la North Island et dans des carottes océaniques devraient être en corrélation avec des membres des séquences de la Kauroa Ash et de la Hamilton Ash, sur la base de leur âge.*

Mots-clés : *téphra, datations, trace de fission, zircon, géochronologie, cendre brun, Kauroa Ash, Hamilton Ash, Oparau Tephra, Ongatiti Ignimbrite, Ohinewai Ash, Rangitawa Tephra, Plio-Pléistocène, région Waikato, Nouvelle Zélande.*

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1. Introduction

Tephra deposits resulting from large-scale volcanic eruptions provide important stratigraphic markers that assist in correlating sequences in both terrestrial and marine environments, and in linking such sequences (e.g. Pillans *et al.*, 1993; Carter *et al.*, 1995; Naish *et al.*, 1996; Shane *et al.*, 1996a). They also provide juvenile mineralogical components for numerical dating and hence a means for independently testing the veracity of dates based on biostratigraphy, magnetostratigraphy or other methods (Naish *et al.*, 1996; Newnham *et al.*, 1999a; Shane, 2000). In addition, tephras are useful as recorders of volcanism, particularly in distal environments (e.g. Kyle & Seward, 1984; Lowe, 1988a; Shane *et al.*, 1996a, 1998; Shane, 2000), because proximal, near-vent deposits are complex and typically 'incomplete' with successive eruptive events tending to destroy or bury antecedent deposits (e.g. Krippner *et al.*, 1998).

In North Island, New Zealand, there is a record of explosive, rhyolite-dominated volcanism dating from *c.* 10 Ma in the Coromandel Volcanic Zone (CVZ) (Adams *et al.*, 1994; Shane *et al.*, 1998) and from at least *c.* 1.6 Ma in the Taupo Volcanic Zone (TVZ) (Houghton *et al.*, 1995; Wilson *et al.*, 1995a; Krippner *et al.*, 1998) (Fig. 1). Despite considerable research in recent years on the stratigraphy, age, and composition of eruptives from CVZ and especially TVZ, there remain extensive, thick sequences of Quaternary or older pyroclastic deposits (including both fallout tephras and ignimbrites) in the North Island with no known source and little or no age control. Many of these deposits, commonly weathered (sometimes very strongly), have been broadly mapped as portmanteau units termed 'undifferentiated brown tuffs' or 'brown ashes' (Fig.1; Pullar *et al.*, 1973). Detailed regional studies have commenced on such deposits in an attempt to document their stratigraphic inter-relationships and to correlate them with defined units, to determine their ages, and to identify their modes of emplacement and sources (e.g. Briggs *et al.*, 1996; Manning, 1996; Newnham *et al.*, 1999b). We have begun similar work on two extended, Pliocene-Pleistocene sequences of strongly-weathered, silicic, tephra deposits in western North Island in the Waikato region, namely the Kauroa Ash and Hamilton Ash beds (Fig. 1). In this paper we review the stratigraphy of these two long sequences. We then present new zircon fission-track (ZFT) age determinations for four members of the Kauroa Ash sequence and for one member of the Hamilton Ash sequence, the first radiometric ages to be obtained directly on these deposits. Our results show that the members K1 (basal unit) to K12 (Oparau Tephra) of the Kauroa Ash sequence were erupted between *c.* 2.25 and *c.* 1.2 Ma, and that member H1 (Ohinewai Ash) of the Hamilton Ash sequence was erupted *c.* 0.38 Ma. Some implications regarding possible eruptive sources and correlations arising from these new ZFT age determinations are discussed.

Our results are part of an ongoing programme of research on the Kauroa and Hamilton deposits including a revision of their stratigraphy, measurements of palaeomagnetic polarity and magnetic susceptibility, and analyses of various physical, mineralogical and geochemical properties together with further ZFT dating. Findings from these studies will be reported later.

2. Stratigraphy of Kauroa and Hamilton Ash sequences

2.1. Kauroa Ash Formation

The Kauroa Ash Formation comprises a sequence, up to *c.* 12 m thick, of extremely weathered, clay-rich (*c.* 70–90% <2-μm clay), multiple tephra deposits and associated paleosols, together possibly with interbedded loessic materials in places (Kirkman, 1980; Kamp & Lowe, 1981; Selby & Lowe, 1992; Briggs *et al.*, 1994; Horrocks, 2000). The formation was initially recognised and defined in the Waikato region by Ward (1967), with the type locality recorded at 'Woodstock', near Raglan (Fig. 1; Waterhouse & White, 1994). (The name 'Woodstock' derives from the original name of the adjacent farm.) The sequence is underlain by basaltic deposits of the Okete Volcanic Formation including lava dated at *c.* 2.25 Ma by Briggs *et al.* (1989), and overlain by the Hamilton Ash Formation, of which the lowermost member (H1) is dated indirectly at *c.* 0.35 Ma by tephrochronology (see below).

Two members of the Kauroa Ash sequence have been individually defined. The uppermost is Waiterimu Ash, named from the type locality at grid reference S13/095096 near Waiterimu (Fig. 1; Ward, 1967). (Grid references here and elsewhere in the text are based on the metric 1: 50,000 topographical map series NZMS 260.) The other is Oparau Tephra, an ignimbrite named from the type locality at R15/797477 at Papakura Creek (Fig. 1A; Pain, 1975; Fergusson, 1986). Salter (1979) subsequently divided the Kauroa Ash Formation at Woodstock into fifteen major members, K1 (base) to K15 (top), and this sequence, slightly modified following further work (Briggs *et al.*, 1994), is shown in Fig. 2. Distinctive sand-sized 'micaceous' or platy minerals in beds K3 and K12 have been identified as kaolinite books and stacks (Salter, 1979).

No direct radiometric ages have been obtained on any members of the Kauroa Ash Formation. However, Briggs *et al.* (1989) used tephrochronology to show that member K1 is likely to be aged *c.* 2.25 Ma because it occurs intercalated with co-eruptives of K/Ar-dated alkali basalts (basanite) of the Okete Volcanics at nearby Ohiapopoko cone (2.26 ± 0.08 Ma) and Cleaves cone (2.25 ± 0.10 Ma) of the Maungatawhiri centre (Fig. 1A). The stratigraphic inter-relationships used to obtain this age for K1 at Ohiapopoko are shown in Fig. 3. An age of <1.81 Ma was assigned to members K12 (Oparau Tephra) and K15 (Waiterimu Ash) because these members unconformably overlie co-eruptives of K/Ar-dated alkali basalts (hawaiite) of the Ngatutura Volcanics at Foxs centre (1.81 ± 0.07 Ma) in the northern Waikato region (Briggs *et al.*, 1989; Fig. 1).

2.2. Hamilton Ash Formation

The Hamilton Ash Formation comprises a sequence, up to *c.* 6 m thick, of strongly weathered, clay-textured (*c.* 60–85% <2-μm clay) multiple rhyolitic tephra beds and associated paleosols (Tonkin, 1970; Kamp & Lowe, 1981; Selby & Lowe 1992; Lowe & Percival, 1993; Briggs *et al.*, 1994). The sequence may also contain intercalated loessic beds at some sites (e.g., Birrell *et al.*, 1981). The formation, widespread throughout the Waikato and Coro-

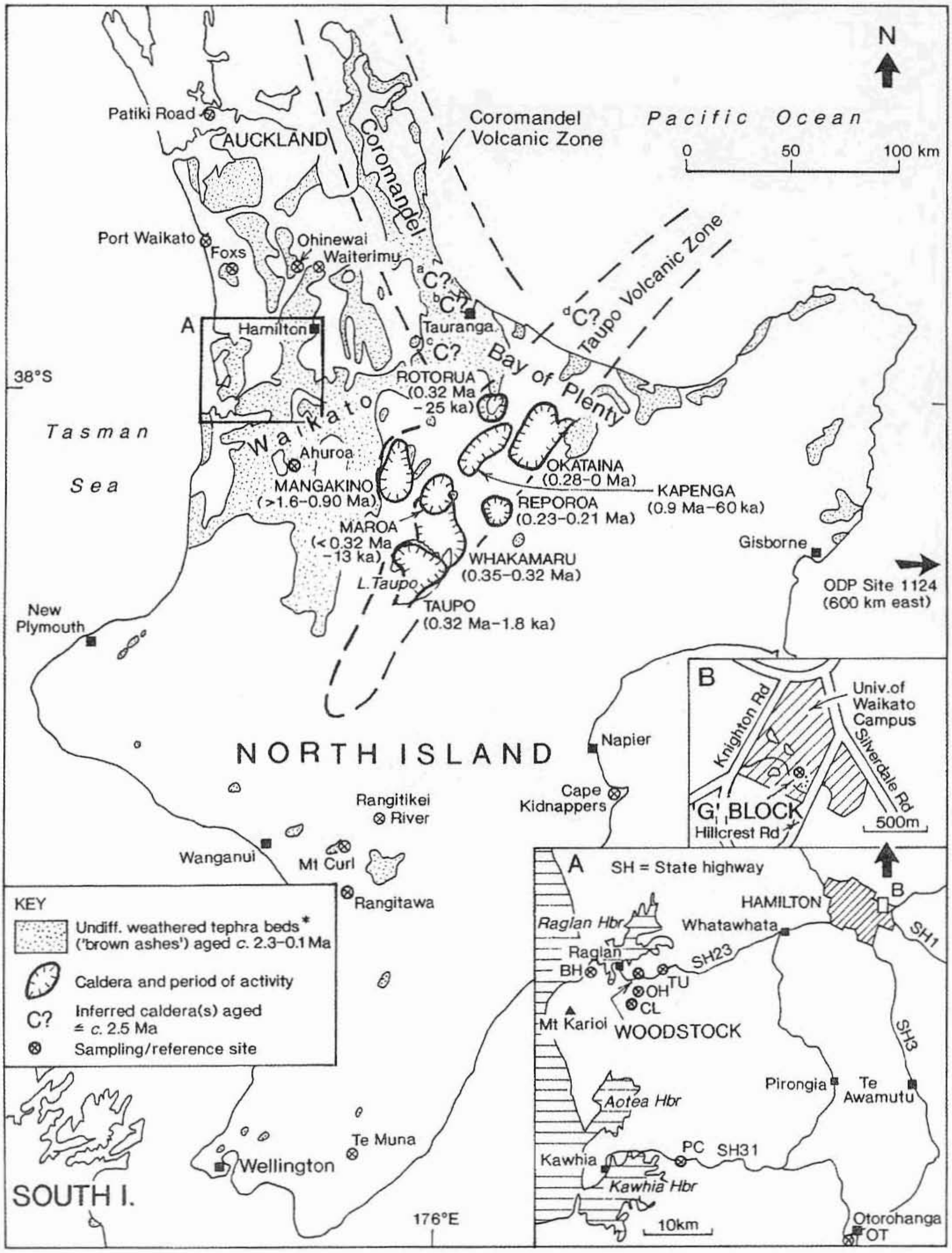

Figure 1. *Generalised distribution of weathered Plio-Pleistocene tephra deposits in North Island, New Zealand, and locations of possible source caldera volcanoes in Taupo and Coromandel volcanic zones. Caldera age ranges after Houghton et al. (1995) and Wilson et al. (1995a); inferred calderas: a, 'Katikati'; b, 'Te Puna'; c, 'Kaimai'; d, 'offshore BOP' (see text). Insets A and B show locations of ZFT sampling sites at Woodstock and 'G Block', and reference sections at Bryant Home (BH), Te Uku (TU), Ohiapopoko cone (OH), Cleaves cone (CL), Papakura Creek (PC), and Otorohanga (OT). Locations of other sections referred to in the text are shown on the main map.*

**After Pullar et al. (1973) and Kohn et al. (1992); named deposits (general occurrence, approximate age ranges) include Hamilton Ash beds (Waikato–Coromandel–Bay of Plenty, c. 0.1–0.35 Ma), Rangitawa Tephra (southern North Island, c. 0.35 Ma), Kauroa Ash beds (Waikato–W. Bay of Plenty, c. 2.3–0.35 Ma), Pahoia Tephra beds (W. Bay of Plenty, c. 2.2–0.35 Ma), and Tablelands Tephra beds (E. Bay of Plenty, <c. 0.5 Ma).*

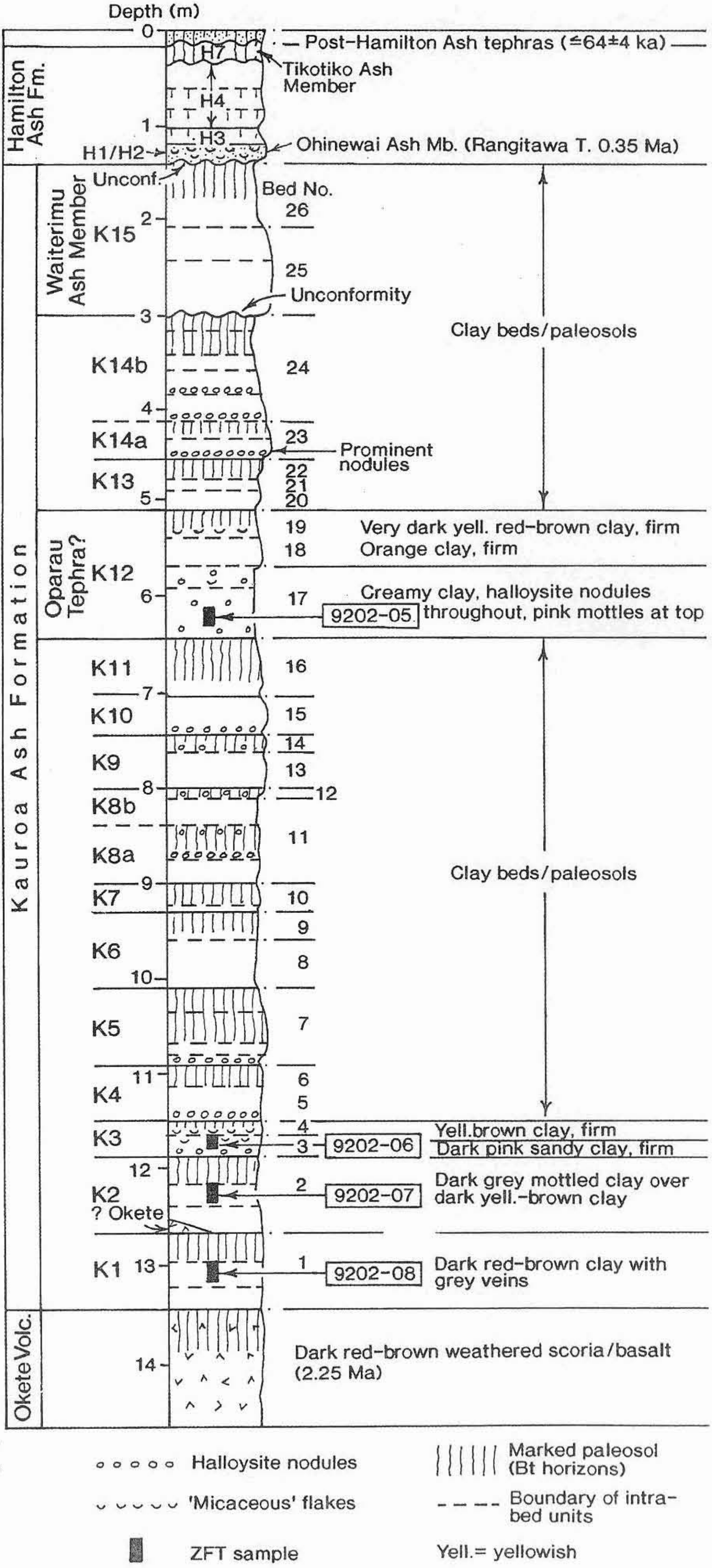

Figure 2. *Stratigraphy of the Kauroa Ash and other formations at Woodstock site (Fig.1A) at R14/783734, and sampling positions for ZFT dating of Kauroa beds K1–K3 and K12 (ages obtained are listed in Table 3). After Briggs et al. (1994, p. 32).*

mandel regions, was initially defined by Ward (1967), following Taylor (1933), with the type locality at R14/813729 near Te Uku (Fig. 1A; Waterhouse & White, 1994). The sequence is underlain, usually with a marked erosional unconformity, by the Kauroa Ash Formation, of which the uppermost member has an age of <1.81 Ma as described above. It is overlain by a composite group of younger, multi-sourced tephra formations, the basal one being the Rotoehu Ash Member of the Rotoiti Tephra Formation (Pain, 1975; Lowe, 1986, 1988b; Froggatt & Lowe, 1990). Rotoehu Ash has an age of 64 ± 4 ka based on K/Ar-dating of encapsulating lavas (Wilson *et al.*, 1992; Lowe & Hogg, 1995), but could be younger (c. 45 ka) according to Lian & Shane (2000).

Ward (1967) divided the Hamilton Ash Formation into members numbered from H1 (basal unit) to H9. However, members H8 and H9 (formerly defined as the 'Mairoa Ash Member', but now known to comprise the Rotoehu Ash and younger tephras) are redundant, and so the uppermost beds of the Hamilton sequence are H6 and H7 (top unit). These two beds together define the Tikotiko Ash Member, with the type locality recorded at S16/030313 near Otorohanga (Fig. 1A ; Ward, 1967). Commonly, the Tikotiko Ash and overlying composite tephra beds provide multisequal soil parent materials throughout the Waikato–southern Auckland region (Selby & Lowe, 1992; Bakker *et al.*, 1996; Lowe, 2000).

The oldest member in the Hamilton Ash Formation, numbered H1 or H2 depending on locality, was defined as the Ohinewai Ash Member by Ward (1967) with the type section at S13/018104 near Ohinewai (Fig. 1). This member was renamed Ohinewai Tephra Formation by Vucetich *et al.* (1978) at the same locality. A possible correlative, Aratora Tephra Formation, was defined by Vucetich *et al.* (1981) at Ahuroa Road (S16/061138) near Te Kuiti (Fig. 1; see also Birrell *et al.*, 1981). The Ohinewai Ash is characteristically pinkish- to brownish-grey in colour, silty, halloysitic, and contains distinctive sand-sized golden 'platy' minerals identified as 2:1:1 interstratified micaceous-kaolinite intergrades (Shepherd, 1984; Lowe & Percival, 1993). A thin (*c.* 5 cm) yellowish layer containing coarse sand-sized quartz crystals marks the base of the tephra (Fig. 4).

No direct radiometric ages have been obtained on any members of the Hamilton Ash Formation. However, based on tephrostratigraphic correlations with tephra deposits in central and southern North Island (e.g., Pillans & Kohn, 1981), and in deep-sea cores, Ohinewai Ash has been identified as the Rangitawa Tephra (also known formerly as Mt Curl Tephra) (Nelson *et al.*, 1985; Froggatt *et al.*, 1986; Black *et al.*, 1988; Nelson, 1988; Kohn *et al.*, 1992; Hesse, 1994; Pillans *et al.*, 1992, 1996). Rangitawa Tephra is considered to be a distal correlative of Whakamaru-group ignimbrites of similar age and derived from the Whakamaru caldera volcano (Fig. 1; Froggatt *et al.*, 1986; Kohn *et al.*, 1992; see also Brown *et al.*, 1998). This correlation was based on similarities of stratigraphic position and mineralogy, and on major element compositions of glass obtained by electron microprobe analysis (summarised in Table 1). Rangitawa Tephra has generally accepted ages (Table 2) of 0.345 ± 0.012 Ma on the basis of FT dating, and 0.340 ± 0.007 Ma from marine oxygen isotope (MOI) stratigraphy (it occurs within glacial MOI Stage 10 in two marine cores, DSDP 594 and SO-36-61; Pillans *et al.*, 1996). The validity of these ages was disputed by Vella & Vucetich (1995, 1996) and Vella (1997) (see also Vucetich *et al.*, 1996), but these criticisms were refuted by Kohn et al. (1996) and Pillans & Kohn (1998).

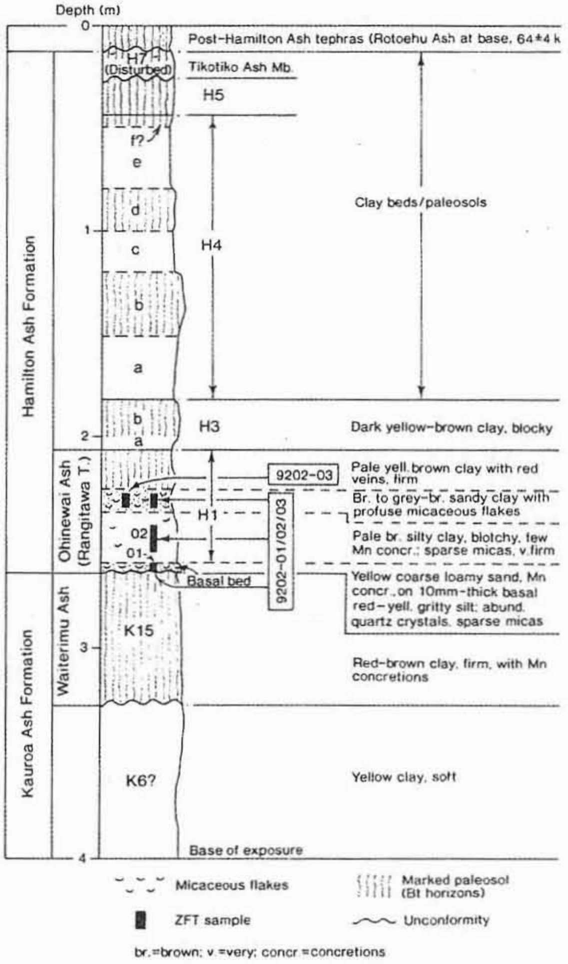

Figure 4. *Stratigraphy of the Hamilton Ash and other formations at G-Block site at S14/143767, and sampling positions for ZFT dating of Hamilton Ash bed H1 (ages obtained are listed in Table 3). Sample 9202-01/02/03 is a composite. Abund. = abundant.*

The stratigraphic and age relationships for a sequence of Hamilton Ash beds, including Ohinewai Ash, are shown in Fig. 4. This section was exposed in 1988 on the south side of an excavation for the construction of 'G' Block in the School of Science and Technology, University of Waikato, Hamilton (Fig. 1B).

3. Zircon fission-track dating

3.1. Experimental procedures

Tephra samples, each approximately 5 kg, were taken from the sections at Woodstock and 'G' Block (Figs. 2 & 4). Analytical procedures followed those reported by Green (1985) and Kamp *et al.* (1989). Zircon concentrates were separated from the samples using standard magnetic and heavy-liquid techniques. Zircon separates were embedded in FEP Teflon™ at *c.* 300° C, ground to reveal internal

	Rangitawa Tephra				Ohinewai Ash (H1)[3]	Mt Curl Tephra
Anal. No.[2]	*1*	*2*	*3*	*4*	*5*	*6*
SiO_2	78.20 (0.32)	77.34 (0.28)	77.95 (0.15)	78.15 (0.32)	77.91 (0.22)	78.09 (0.30)
Al_2O_3	12.42 (0.13)	12.21 (0.09)	12.24 (0.12)	12.41 (0.19)	12.31 (0.10)	12.33 (0.21)
TiO_2	0.13 (0.05)	0.14 (0.04)	0.14 (0.02)	0.14 (0.04)	0.15 (0.03)	0.14 (0.03)
FeO[4]	1.02 (0.10)	1.04 (0.05)	1.06 (0.06)	0.97 (0.10)	1.06 (0.07)	1.01 (0.08)
MgO	0.12 (0.03)	0.12 (0.02)	0.12 (0.02)	0.12 (0.03)	0.12 (0.02)	0.12 (0.02)
CaO	0.77 (0.09)	0.82 (0.03)	0.82 (0.04)	0.80 (0.06)	0.80 (0.04)	0.79 (0.04)
Na_2O	3.23 (0.24)	3.59 (0.17)	3.19 (0.07)	3.21 (0.15)	3.35 (0.26)	3.30 (0.16)
K_2O	4.11 (0.18)	4.52 (0.16)	4.23 (0.12)	4.22 (0.14)	4.30 (0.19)	4.33 (0.15)
Cl	na	0.22 (0.02)	0.25 (0.03)	na	na	na
Water[5]	5.20 (0.90)	5.92 (0.61)	3.01 (0.68)	4.83 (2.73)	4.71 (0.65)	4.55 (0.13)
n	16	10	13	10-20	20	132

[1] Means and standard deviations (in parentheses) of n analyses (individual glass shards) normalized to 100% loss-free (wt.%). Analyses by Jeol JXA-733 electron microprobe at Analytical Facility, Victoria University of Wellington, using a 10–20-µm beam, 80-nA beam current, and accelerating voltage of 15 kV, with standards and other conditions as in Froggatt (1983). na, not analysed.

[2] All material from type locations (Fig. 1): *1-3*, Rangitawa Stream (S23/196165); *5*, Ohinewai (S13/018104); *6*, Mt Curl section (S22/194322). Analyses *1*, *5*, *6* from Froggatt *et al.* (1986); *2* from Kohn *et al.* (1992); *3* from Manning (1996); *4* from Shane (2000).

[3] The mineralogy of H1, distinguished by coarse quartz and plagioclase grains and micaceous-kaolinite intergrade crystals (which probably originated from the dissolution of biotite and recrystallisation at linear boundaries: Lowe & Percival, 1993), matches that of Rangitawa and Mt Curl tephras and of fall deposits associated with basal Whakamaru Ignimbrite (Kamp & Lowe, 1981; D.J. Lowe, unpublished data).

[4] Total Fe as FeO

[5] Difference between original analytical total and 100

***Table 1.** Major element composition of glass[1] of Rangitawa Tephra and its correlatives.*

Method and age (Ma ± 1σ)			Reference[2]
***Fission track**[3]*			
0.35 ± 0.02	(n = 4)	Isothermal plateau (glass)	1, 2, 3
0.35 ± 0.04	(n = 5)	External detector (zircon)	2, 3
0.345 ± 0.012	(n = 9)	Mean FT age	3
Marine oxygen isotope stratigraphy (astronomical timescale)[3]			
0.340 ± 0.007	(n = 2)		3, 4
$^{40}Ar/^{39}Ar$ (single-crystal laser fusion)[4]			
0.302 ± 0.008	(n = 4)		3

[1] Hendy *et al.* (1980) reported a corrected U-Th disequilibria age on Fe-Ti oxide phases (magnetite, ilmenite) extracted from H1 (Ohinewai Ash) of 0.200 + 0.120 – 0.045 Ma (n = 2). Using SHRIMP $^{238}U/^{206}Pb$, Brown & Fletcher (1999) derived a minimum spot age of 346 ± 21 ka on zircon from Whakamaru Ignimbrite, consistent with an ignimbrite eruption age of *c.* 340 ka (Houghton *et al.*, 1995; Wilson *et al.*, 1995a).

[2] 1, Alloway *et al.* (1993); 2, Kohn *et al.* (1992); 3, Pillans *et al.* (1996); 4, Nelson (1988).

[3] Weighted mean ages for n determinations that are considered reliable by Kohn *et al.* (1996), Pillans *et al.* (1996) and Pillans & Kohn (1998).

[4] This age is significantly younger than the FT and Ar/Ar mean ages (Pillans *et al.*, 1996).

***Table 2.** Summary of previous radiometric ages on Rangitawa Tephra and correlatives[1].*

surfaces, and polished using alumina slurry followed by 1-µm diamond powder. Etching of spontaneous tracks in the zircon crystals took place in molten KOH-NaOH eutectic solution at *c.* 205° C for about 50 hours until all spontaneous tracks intersecting the polished surface were revealed. After etching, zircon mounts were cleaned by immersion in dilute HF for 10 minutes.

Low-uranium mica external detectors were sealed in contiguous contact with the mounts using envelopes of heat-shrink plastic. The mounts, together with uranium dosimeter glass CN1, were irradiated in the X-7 facility of the HIFAR reactor, New South Wales, Australia. Nominal fluences of 3 x 10^{15} neutrons cm^{-2} for zircons were used.

After irradiation, the mica detectors were etched in 40% HF for 24 minutes at 24° C. FT density determinations were undertaken using a Zeiss Axioplan™ optical microscope (x1250, dry). Tracks were counted independently by two operators (JMT, IJL) and the zeta calibration method applied throughout (Hurford & Green, 1983; Green, 1985; Hurford & Watkins, 1987; see also Tippett & Kamp, 1993). Weighted mean zeta values (CN1) on zircon determined by JMT and IJL are reported in Table 3.

Because of anisotropic etching, only zircons with well-etched tracks in all orientations were counted. Seward & Kohn (1997) recommended that, ideally, 15–20 crystals should be counted when dating Quaternary-aged tephras using the ZFT method. These limits were met in six of the nine individual assessments that were made (Table 3), and so they are likely to provide realistic 'stable' ages. Ages calculated for the remaining three assessments (in which 9–13 crystals were counted) are statistically identical to those of the replicates. The final error-weighted mean ages (pooled data) are all based on >20 crystals (Table 3).

3.2. Results

Analytical data are reported in Table 3. FT ages were calculated using the standard FT-age equation (Hurford & Green, 1983) with conventional errors (Green, 1981) quoted at $\pm 1\sigma$, as used by Kohn *et al.* (1992). The probability of grains counted in a sample belonging to a single population of ages is assessed by a chi-square statistic (Galbraith, 1981). A probability of less than 5% may indicate that the grains represent a mixed population. Where $P(\chi^2) < 5\%$, a central age (Galbraith & Green, 1990) is quoted in Table 3.

Samples 9202-03, 9202-01/02/03, 9202-05, 9202-06, and 9202-07 all yielded track-density data with high chi-square values, indicating the probability of unimodal populations of ages. The duplicate age assessments for each sample are statistically indistinguishable from each other and hence were able to be pooled to provide error-weighted mean ages (Table 3). (All assessments of age homogeneity using the test statistic T' are at the 5% level, P 0.05.) Sample 9202-08 'failed' the chi-square test suggesting that there may be two populations of zircon grains. The single grain ages ranged from 0.6 ± 0.5 to 4.9 ± 1.4 Ma. There is no legitimate reason to exclude either the low- or high-age crystals, and therefore the mean age is reported. The source of the larger-than-expected single-grain age variation could originate from geological mixing processes either in the section or during the eruption process, or (less likely) from contamination in the laboratory. The exclusion of the apparently 'too young' or 'too old' grains does not significantly affect the sample mean, and is within the error estimates quoted.

Comparisons using the test statistic T' of the ZFT ages show that the ages are consistent with the stratigraphy: H1 (0.38 ± 0.04 Ma) is significantly younger than ages on the underlying Kauroa Ash members; K12 (1.28 ± 0.11 Ma) is significantly younger than K3 (1.68 ± 0.12 Ma), but not K2 (1.43 ± 0.17 Ma) (though K2 and K3 ages themselves are statistically indistinguishable); and K1 (2.24 ± 0.29 Ma) is significantly older than ages on the overlying Kauroa Ash members.

4. Discussion

4.1. Ages of Kauroa Ash beds

The ZFT age obtained on the basal member of the Kauroa Ash Formation, K1, is identical to the age obtained by Briggs *et al.* (1989) on the equivalent unit using tephrochronology (Fig. 3), thus supporting its validity. It is also consistent with polarity measurements that show K1 is reversely magnetised and thus younger than 2.6 Ma (the age on the Gauss-Matuyama transition: Naish *et al.*, 1998) (Horrocks, 2000). The error-weighted mean of all ages now available for K1 is 2.26 ± 0.06 Ma ($n = 3$). Although members K2 and K3 are not separable by ZFT ages alone, K3 stratigraphically overlies K2 with an intervening paleosol and therefore must be younger by possibly some tens-of-thousands of years. The older end (*c.* 1.7 Ma) of the ZFT age-range for members K2 and K3 suggests that one or other might fall within the Olduvai (or Gilsá) Subchron, which has normal polarities within the Matuyama reversal. The age determinations are thus testable by palaeomagnetic measurement.

Member K12 of the Kauroa Ash Formation is considered equivalent to the Oparau Tephra, which in turn is probably a correlative of the Ongatiti Ignimbrite (Pain, 1975; Salter, 1979; Fergusson, 1986; Horrocks *et al.*, 1999). Ongatiti Ignimbrite, derived from the Mangakino Volcanic Centre (Fig. 1; Briggs *et al.*, 1993; Wilson *et al.*, 1995a), has been well dated at 1.21–1.25 Ma using several independent techniques (Table 4). Shane *et al.* (1996a) suggested that Mangatewaiiti tephra (dated at 1.23 ± 0.09 and 1.24 ± 0.07 Ma) may be a distal tephra-fall correlative of Ongatiti Ignimbrite. The ZFT age of 1.28 ± 0.11 Ma obtained for K12 is consistent with all these ages (they are statistically indistinguishable) and hence with the proposed correlations. Assuming that member K12 is a correlative of the Ongatiti Ignimbrite (and Maungatewaiiti tephra), then the error-weighted mean of all available ages on this deposit is 1.231 ± 0.016 Ma ($n = 8$).

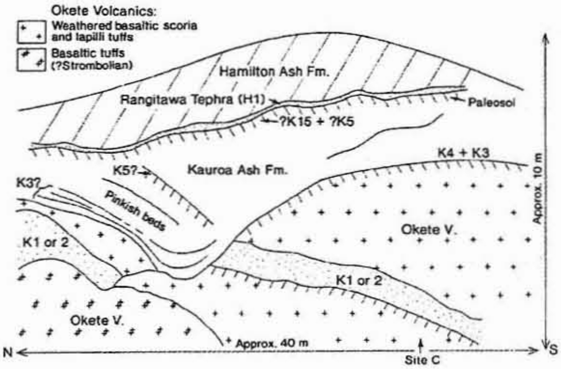

***Figure 3**. Sketch of section at Ohiapopoko cone (R14/787722), Maungatawhiri centre, showing stratigraphic inter-relationships of Kauroa and Hamilton Ash beds and eruptives of the Okete Volcanics (Marumaruaitu Member: Goles et al., 1996) dated at 2.25 Ma. Section is oriented North–South as indicated. 'Site C' is described in Briggs et al. (1989). From Briggs et al. (1994, p. 30).*

The ZFT age on K12 is consistent also with the stratigraphic relationships described by Briggs *et al.* (1989) from Foxs centre which indicate that members K12 and K15 are <1.81 Ma in age. Furthermore, palaeomagnetic polarity measurements on K12 and K15 show them to be reversed (Horrocks, 2000), thus indicating an age older than 0.78 Ma (the age on the Matuyama-Brunhes transition: Naish *et al.*, 1998). On this basis, members K13–K15 of the Kauroa Ash Formation are aged between *c.* 1.2 and 0.78 Ma (cf. Ward, 1972).

Members of the Kauroa Ash Formation occur intercalated with distal laharic deposits of the Karioi Formation at a number of sections along the flanks of Mt Karioi volcano

Stratigraphic unit	Sample No.	No. crystals	Spontaneous		Induced		$P\chi^2$,%	ρd	Nd	Operator	Age (Ma) ± 1σ	Weighted mean age (Ma) ±1σ
			ρs	Ns	ρi	Ni						
Hamilton Ash Formation[2]												
H1	9202-03	25	0.063	35	10.903	6060	89.8	1.054	2503	JMT	0.41 ± 0.07	
	9202-01/02/03	18	0.045	25	7.865	4387	99.0	0.907	2240	IJL	0.35 ± 0.07	**0.38 ± 0.04**
Kauroa Ash Formation												
K12[3]	9202-05	20	0.108	122	5.464	6171	10.8	1.068	2537	JMT	1.41 ± 0.13	
	9202-05	9	0.063	25	3.974	1588	32.0	0.928	2294	IJL	0.99 ± 0.20	**1.28 ± 0.11**
K3	9202-06	24	0.265	124	11.246	5261	29.4	1.075	2564	JMT	1.70 ± 0.16	
	9202-06	13	0.228	61	8.716	2336	37.8	0.935	2312	IJL	1.65 ± 0.22	**1.68 ± 0.12**
K2	9202-07	18	0.125	51	6.045	2457	83.6	1.082	2581	JMT	1.50 ± 0.22	
	9202-07	10	0.127	22	6.067	1050	96.8	0.942	2329	IJL	1.33 ± 0.29	**1.43 ± 0.17**
K1	9202-08	17	0.311	137	10.830	4777	0.4	1.089	2598	JMT	**2.24 ± 0.29**	

[1] Track densities (ρ) are x 10^6 tracks cm^{-2}. All analyses are by the external detector method using 0.5 for the $4\pi/2\pi$ geometry correction factor. Zircon ages are calculated using dosimeter glass CN1; zeta-CN1 = 133.9 ± 1.4 for JMT, 135.1 ± 2.8 for IJL. $P(\chi^2)$ is the probability of obtaining χ^2 value for v degrees of freedom (where v is the number of crystals -1). Central age (Galbraith & Green, 1990) is reported for 9202-08 as $P(\chi^2)$ value is <5%.

[2] Ohinewai Ash Member (Ward, 1967), equivalent to Rangitawa Tephra (Kohn *et al.*, 1992).

[3] Probable correlative of Oparau Tephra (Pain, 1975) and Ongatiti Ignimbrite (Horrocks *et al.*, 1999; Horrocks, 2000).

Table 3. *Zircon fission-track data*[1] *for selected beds within Kauroa and Hamilton Ash formations.*

Method and age (Ma ± 1σ)	Material	Reference[2]
Fission-track		
1.25 ± 0.12	Isothermal plateau on glass	1
1.23 ± 0.09	Isothermal plateau on glass[3]	2
K/Ar		
1.25 ± 0.09	Hornblende separate	3
^{40}Ar/ ^{39}Ar (single-crystal laser fusion)		
1.251 ± 0.060	Feldspar separate	4
1.23 ± 0.02	Feldspar separate	5
1.21 ± 0.04	Feldspar separate	6
1.24 ± 0.07	Feldspar separate[3]	2
Palaeomagnetic timescale		
>0.780 (Matuyama Chron)		1, 3

[1] Error-weighted mean radiometric age for all samples, including ZFT age on K12 (sample 9202-05, Table 3) is 1.231 ± 0.016 Ma ($n = 8$).
[2] 1, Black *et al.* (1996); 2, Shane *et al.* (1996a); 3, Soengkono *et al.* (1992); 4, Pringle *et al.* (1992); 5, Briggs *et al.* (1993); 6, Houghton *et al.* (1995).
[3] Maungatewaiiti tephra (Hawke's Bay) – provisionally correlated with Ongatiti Ignimbrite by Shane *et al.* (1996a).

Table 4. *Summary of previous radiometric ages on Ongatiti Ignimbrite and possible correlatives*[1]*.*

near Raglan (Fig. 1A; Briggs *et al.*, 1994; Goles *et al.*, 1996). At one such section (Fig. 5), the age of *c.* 1.2 Ma on K12 provides a minimum age for the underlying laharic deposits, which represent the late cone-building stage of the volcano's history (Goles *et al.*, 1996). Similarly, the newly-dated members of the Kauroa Ash sequence help provide age constraints where they occur interbedded with defined units of the Tauranga Group or Kaihu Group in the Waikato–South Auckland regions (e.g. Kear & Schofield, 1978; Kamp & Lowe, 1981; Nelson *et al.*, 1988, 1989; Stokes, 1988; Waterhouse & White, 1994).

4.2. Possible sources and correlatives of Kauroa Ash beds

The source(s) of the Kauroa Ash Formation is unknown but various options have been considered (e.g., Briggs *et al.*, 1989, 1994). On the basis of the age range established here, from *c.* 2.25 Ma to 0.78 Ma, and assuming that the beds are predominantly rhyolitic, the formation may relate to either 'late' CVZ or 'early' TVZ eruptions, or both.

The youngest caldera centres of southern CVZ (Skinner, 1986) are not well defined and are poorly dated but possible calderas <*c.* 2.5 Ma in age (Fig. 1) have been inferred at Katikati (Brathwaite & Christie, 1996), Te Puna (Briggs *et al.*, 1996), and Kaimai summit (Wilson *et al.*, 1995a) on the basis of negative gravity anomalies and associated volcanic evidence. Some of the ignimbrites mapped in the Tauranga region (in southern CVZ) may represent proximal correlatives of several Kauroa Ash beds (e.g., Waiteariki Ignimbrite, aged *c.* 2.15 Ma; Te Puna Ignimbrite, aged between *c.* 1.2 and 0.78 Ma; Briggs *et al.*, 1996).

The oldest caldera centres of the TVZ are the Mangakino and Kapenga centres, dating ostensibly from *c.* 1.6 Ma (Fig. 1; Houghton *et al.*, 1995). However, Mangakino activity is probably older than 1.6 Ma because Krippner *et al.* (1998) demonstrated that there are earlier inaccessible (buried) rhyolitic eruptive products. Moreover, if the earliest member of the Kauroa Ash sequence is TVZ-derived, then the age we obtained here on K1 (2.25 Ma) suggests that explosive rhyolitic TVZ volcanism may date from around this time. We note that the 'blurred' distinction between the cessation of CVZ volcanism and the initiation of TVZ volcanism may be ultimately clarified by analysis of ODP Leg 181 deep-sea cores, including that from Site 1124 (Fig. 1) in which at least *c.* 140 macroscopic layers of tephra up to 0.9 m thick and dating back to *c.* 11 Ma have been preserved (Hayward, 1998; Carter *et al.*, 1999).

Notwithstanding the question of timing of initial rhyolite volcanism in TVZ, numerous ignimbrites and associated fall deposits have erupted from Mangakino since *c.* 1.6 Ma, including Ongatiti Ignimbrite (1.23 Ma) which we correlated with member K12 of the Kauroa Ash Formation. In addition to Ongatiti, the most voluminous Mangakino-derived eruptives include Ngaroma (1.6 Ma), Ahuroa (1.2 Ma), Kidnappers (Unit 'E') (1 Ma), Rocky Hill (0.95 Ma), and the Marshall 'A' and 'B' ignimbrites (0.9 Ma) (e.g., Grindley & Mumme, 1991; Briggs *et al.*, 1993; Houghton *et al.*, 1995; Wilson *et al.*, 1995a, 1995b). Any of these may relate to the Kauroa Ash sequence on the basis of age.

Various distal, silicic pyroclastic deposits with ages in the *c.* 2.3 to 0.8 Ma range have been documented at widely-

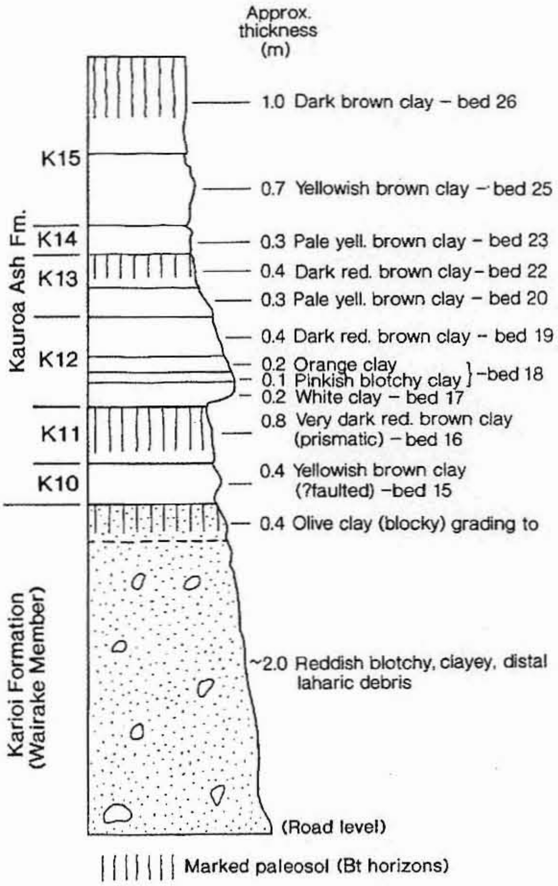

Figure 5. *Stratigraphic inter-relationships of upper Kauroa Ash beds and laharic deposits of the Karioi Formation (Goles et al., 1996) at Bryant Home section, Manu Bay (R14/705737). The sequence is overlain by thin Hamilton Ash and younger tephra deposits. After Briggs et al. (1994, p. 36). Yell. = yellowish; red. = reddish.*

spaced locations throughout North Island (see Fig. 1), including Ohinewai (Nelson *et al.*, 1988), Port Waikato (Nelson *et al.*, 1989), Cape Kidnappers (Shane *et al.*, 1996b), Rangitikei River (Naish *et al.*, 1996), Te Muna (Shane *et al.*, 1995, 1996a), and Patiki Road and elsewhere in Auckland (Moore, 1991; Newnham & Grant-Mackie, 1993; Alloway & Newnham, 1995; Newnham *et al.*, 1999b), and in offshore cores (Carter *et al.*, 1999). Although a few of these distal deposits have been correlated with the proximal units (e.g., Potaka Tephra and Kidnappers Ignimbrite/Unit 'E': Wilson *et al.*, 1995b), most have yet to be firmly linked to one another. It is likely that some of the widespread distal deposits are co-eval with members of the Kauroa Ash Formation. Well-dated, named distal eruptives in the target age range include Ohingaiti (2.17 Ma), Waipuru (1.85 Ma), Vinegar Hill (1.75 Ma), Pakihikura (1.65 Ma), Mangapipi (1.6 Ma), Rewa (1.3 Ma), and Kaukatea (0.87 Ma) (Alloway *et al.*, 1993; Naish *et al.*, 1996, 1998; Shane, 1994; Shane *et al.*, 1996a, 1996b; Seward & Kohn, 1997; Shane, 2000).

A submarine caldera feature identified off the Bay of Plenty coast (Fig. 1) may have an age similar to that of the Mangakino centre (Davey *et al.*, 1995). It is therefore another potential source for some of the Kauroa Ash beds.

4.3. Ages of Hamilton Ash beds

The ZFT age obtained on the basal member of the Hamilton Ash Formation, H1 (Ohinewai Ash), is statistically indistinguishable from the fission-track and astronomical ages obtained for its proposed correlative, Rangitawa Tephra and other deposits (Table 2; Pillans *et al.*, 1996). Our age of 0.38 ± 0.04 Ma therefore supports this correlation (cf. McCraw, 1975). It is clearly inconsistent, however, with much younger ages of *c.* 0.23–0.24 Ma derived previously for Rangitawa Tephra and its correlatives that were considered unreliable by Kohn *et al.* (1992, 1996), Pillans *et al.* (1996) and Pillans & Kohn, (1998), but favoured by Vella & Vucetich (1995, 1996) and Vella (1997).

Because this tephra is known to have been deposited near the end of MOI Stage 10 (Kohn *et al.*, 1992; Pillans *et al.* 1996; Pillans & Kohn, 1998), and from application of a Si-leaching model relating clay mineralogy and palaeoclimate (Stevens & Vucetich, 1985; Lowe, 1986, 1995; Lowe & Percival, 1993; Shepherd, 1994), we suggest that the paleosols developed on Hamilton Ash members H1 and H3 were developed during MOI Stage 9 (*c.* 0.34–0.30 Ma), member H4 (comprising multiple units) was deposited during MOI Stage 8 (*c.* 0.29–0.25 Ma), the (allophanic) paleosol on member H5 was developed during MOI Stage 7 (*c.* 0.24–0.19 Ma), and members H6 and H7 (Tikotiko Ash) relate to MOI stages 6 (*c.* 0.18–0.13 Ma) and 5 (*c.* 0.13–0.08 Ma), respectively (approximate age ranges for MOI stages are after Martinson *et al.*, 1987). Development of the paleosol on member H7 during interglacial MOI Stage 5e and the 5d–5a transition is consistent with it being overlain unconformably by the Rotoehu Ash (64 ± 4 ka or younger), which was deposited probably early in MOI Stage 3 (Berryman, 1992; Wright *et al.*, 1995; Cronin *et al.*, 1996; Palmer & Pillans, 1996; Newnham *et al.*, 1999a).

More dating and tephrochronological work is needed to test and refine this provisional chronology for members of the post-H1 Hamilton Ash sequence.

4.4. Possible sources and correlatives of Hamilton Ash beds

The source(s) of the Hamilton Ash sequence is unknown except that member H1 (Ohinewai Ash) is now established as a correlative of Rangitawa Tephra and Whakamaru-group ignimbrites, which have been ascribed a source in the Whakamaru caldera volcano (Kohn *et al.*, 1992). Shepherd & Gibbs (1984) suggested from geochemical analysis of Fe-Ti oxides that the Hamilton Ash sequence originated from 'two or more vents in the Taupo–Maroa volcanic centres'. However, many ignimbrite-generating volcanic centres were active in TVZ in the post-0.35 Ma period. These include Kapenga, Rotorua, Okataina, Reporoa, and Taupo in addition to Whakamaru (Fig. 1), and all provide potential sources of Hamilton Ash beds that were emplaced subsequent to member H1. At least five or six major ignimbrites, some imprecisely dated, were erupted from these centres between *c.* 0.34 and 0.20 Ma, including Matahina (0.34–0.28 Ma), Waimakariri (between *c.* 0.32 and 0.22 Ma), Kaingaroa (0.31–0.23 Ma), and Mamaku (0.22 Ma) (Houghton *et al.*, 1995; Wilson *et al.*, 1995a; Black *et al.*, 1996; Briggs *et al.*, 1996; Brown *et al.*, 1998; Beresford & Cole, 2000). A few studies have identified distal, rhyolitic tephra-fall deposits pre-dating Rotoehu Ash and post-dating Rangitawa Tephra in eastern North Island (Iso *et al.*, 1982; Froggatt, 1983; Manning, 1996) and in Lake Omapere in Northland (Lowe, 1987), and some of these tephras may prove to be correlatives of members of the Hamilton Ash sequence.

5. Conclusions

Using the zircon fission-track method, we have obtained five ages on members of two strongly-weathered, Pliocene-Pleistocene tephra sequences, the Kauroa and Hamilton Ash formations, in western North Island.

Of the Kauroa Ash sequence, member K1 (basal unit) was dated at 2.24 ± 0.29 Ma, confirming a previous age of *c.* 2.25 Ma obtained using tephrochronology and K/Ar ages on basalt, and consistent with palaeomagnetic polarity measurements. Members K2 and K3 gave indistinguishable ages between 1.68 ± 0.12 and 1.43 ± 0.17 Ma. Member K12, a correlative of Oparau Tephra and probably also Ongatiti Ignimbrite, was dated at 1.28 ± 0.11 Ma, consistent with a previous K/Ar-based age estimate of <1.81 Ma (Briggs *et al.*, 1989). It is also consistent with an age of 1.23 ± 0.02 Ma obtained by various methods on Ongatiti Ignimbrite (Table 4). On the basis of palaeomagnetic measurements, members K13 to K15 (top unit, Waiterimu Ash) are aged between *c.* 1.2 Ma and 0.78 Ma (Horrocks, 2000).

Of the Hamilton Ash sequence, member H1, defined as Ohinewai Ash, was dated at 0.38 ± 0.04 Ma. This age matches those obtained by various methods on Rangitawa Tephra of 0.34–0.35 Ma (Table 2; Pillans *et al.*, 1996), supporting correlation with this deposit. Member H5 is estimated to be *c.* 0.24–0.19 Ma in age, and the youngest members of the sequence, H6–H7 (Tikotiko Ash), are estimated to be *c.* 0.18–0.08 Ma in age.

Possible sources of the Kauroa Ash Formation include younger volcanic centres in the southern Coromandel Volcanic Zone or older volcanic centres in the Taupo Volcanic Zone, or both (Fig. 1). Various widespread silicic pyroclastic deposits in North Island, and in deep-sea cores, may be co-eval with members of the Kauroa Ash Formation on the basis of their age. Member H1 (Rangitawa Tephra) of the Hamilton Ash Formation evidently originated from the Whakamaru caldera in the TVZ (Froggatt *et al.*, 1986; Kohn *et al.*, 1992). Other members have unknown origins but various younger volcanic centres in TVZ provide potential sources.

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References

ADAMS, C.J., GRAHAM, I.J., SEWARD, D. & SKINNER, D.N.B., 1994 – Geochronological and geochemical evolution of late Cenozoic volcanism in the Coromandel Peninsula, New Zealand. *New Zealand Journal of Geology and Geophysics*, 37: 359-379.

ALLOWAY, B.V. & NEWNHAM, R.M., 1995 – A preliminary assessment of the threat posed by distal silicic volcanism based on the Middle–Late Quaternary tephrostratigraphic record. *Geological Society of New Zealand Miscellaneous Publication*, 81B: 73-83.

ALLOWAY, B.V., PILLANS, B.J., SANDHU, A.S. & WESTGATE, J.A., 1993 – Revision of the marine chronology in the Wanganui Basin, New Zealand, based on isothermal plateau fission-track dating of tephra horizons. *Sedimentary Geology*, 82: 299-310.

BAKKER, L., LOWE, D.J. & JONGMANS, A.G., 1996 – A micromorphological study of pedogenic processes in an evolutionary soil sequence formed on late Quaternary rhyolitic tephra deposits, North Island, New Zealand. *Quaternary International*, 34-36: 249-261.

BERESFORD, S.W. & COLE, J.W., 2000 – Kaingaroa Ignimbrite, Taupo Volcanic Zone, New Zealand: evidence for asymmetric caldera subsidence of the Reporoa Caldera. *New Zealand Journal of Geology and Geophysics*, 43: 471-481.

BERRYMAN, K.R., 1992 – A stratigraphic age of Rotoehu Ash and late Pleistocene climate interpretation based on marine terrace chronology, Mahia Peninsula, North Island, New Zealand. *New Zealand Journal of Geology and Geophysics*, 35: 1-7.

BIRRELL, K.S., STEVENS, K.F. & VUCETICH, C.G., 1981 – Late Quaternary sections containing tephra and loess in the Te Kuiti district, New Zealand. *Geology Department, Victoria University of Wellington Publication*, 20: 5-10.

BLACK, K.P., NELSON, C.S. & HENDY, C.H., 1988 – A spectral analysis procedure for dating Quaternary deep-sea cores and its application to a high-resolution Bruhnes record from the southwest Pacific. *Marine Geology*, 83: 21-30.

BLACK, T.M., SHANE, P.A.R., WESTGATE, J.A. & FROGGATT, P.C., 1996 – Chronological and palaeomagnetic constraints on widespread welded ignimbrites of the Taupo volcanic zone, New Zealand. *Bulletin of Volcanology*, 58: 226-238.

BRATHWAITE, R.L. & CHRISTIE, A.B., 1996 – Geology of the Waihi area, part sheets T13 and U13, scale 1: 50,000. *Institute of Geological and Nuclear Sciences Geological Map*, 21, 1 sheet, 64p.

BRIGGS, R.M., ITAYA, T., LOWE, D.J. & KEANE, A.J., 1989 – Ages of the Pliocene–Pleistocene Alexandra and Ngatutura Volcanics, western North Island, New Zealand, and some geological implications. *New Zealand Journal of Geology and Geophysics*, 32: 417-427.

BRIGGS, R.M., GIFFORD, M.G., MOYLE, A.R., TAYLOR, S.R., NORMAN, M.D., HOUGHTON, B.F. & WILSON, C.J.N., 1993 – Geochemical zoning and eruptive mixing in ignimbrites from Mangakino volcano, Taupo Volcanic Zone, New Zealand. *Journal of Volcanology and Geothermal Research*, 56: 175-203.

BRIGGS, R.M., LOWE, D.J., GOLES, G.G. & SHEPHERD, T.G., 1994 – Intra-conference tour day 1: Hamilton–Raglan–Hamilton. In Lowe, D.J. (ed), *Conference Tour Guides*, Inter-INQUA Field Conference on Tephrochronology, Loess, and Palaeopedology, University of Waikato, Hamilton: 24-44.

BRIGGS, R.M., HALL, G.J., HARMSWORTH, G.R., HOLLIS, A.G., HOUGHTON, B.F., HUGHES, G.R., MORGAN, M.D. & WHITBREAD-EDWARDS, A.R., 1996 – Geology of the Tauranga area, sheet U14, scale 1: 50,000. *Department of Earth Sciences, University of Waikato, Occasional Report*, 22, 1 sheet, 57p.

BROWN, S.J.A. & FLECHTER, I.R., 1999 - SHRIMP U-Pb dating of the preeruption growth history of zircons from the 340 ka Whakamaru Ignimbrite, New Zealand: Evidence for > 250 k.y. magma residence times. *Geology*, 27: 1035-1038

BROWN, S.J.A., WILSON, C.J.N., COLE, J.W. & WOODEN, J., 1998 – The Whakamaru group ignimbrites, Taupo Volcanic Zone, New Zealand: evidence for reverse tapping of a zoned silicic magma system. *Journal of Volcanology and Geothermal Research*, 84: 1-37.

CARTER, L., NELSON, C.S., NEIL, H.L. & FROGGATT, P.C., 1995 – Correlation, dispersal, and preservation of the Kawakawa Tephra and other late Quaternary tephra layers in the southwest Pacific Ocean. *New Zealand Journal of Geology and Geophysics*, 38: 29-46.

CARTER, L., CARTER, R.M., MCCAVE, N. & SHIPBOARD SCIENTISTS, 1999 – You don't know what's there until you drill: initial results from Leg 181 – SW Pacific gateway. *NIWA Water and Atmosphere*, 7: 14-16.

CRONIN, S.J., NEALL, V.E. & PALMER, A.S., 1996 – Investigation of an aggrading paleosol developed into andesitic ring-plain deposits, Ruapehu volcano, New Zealand. *Geoderma*, 69: 119-135.

DAVEY, F.J., HENRY, S.A. & LODOLO, E., 1995 – Asymmetric rifting in a continental back-arc environment, North Island, New Zealand. *Journal of Volcanology and Geothermal Research*, 68: 209-238.

FERGUSSON, D.A., 1986 – *Geology of inland Kawhia: emphasis on Te Kuiti Group stratigraphy and sedimentation.* Unpublished M.Sc. thesis, University of Waikato, Hamilton.

FROGGATT, P.C., 1983 – Toward a comprehensive Upper Quaternary tephra and ignimbrite stratigraphy in New Zealand using electron microprobe analysis of glass shards. *Quaternary Research*, 19: 188-200.

FROGGATT, P.C., NELSON, C.S., CARTER, L., GRIGGS, G. & BLACK, K.P., 1986 – An exceptionally large late Quaternary eruption from New Zealand. *Nature*, 319: 578-582.

FROGGATT, P.C. & LOWE, D.J., 1990 – A review of late Quaternary silicic and some other tephra formations from New Zealand: their stratigraphy, nomenclature, distribution, volume, and age. *New Zealand Journal of Geology and Geophysics*, 33: 89-109.

GALBRAITH, R.F., 1981 – On statistical models for fission-track counts. *Mathematical Geology*, 13: 471-478.

GALBRAITH, R.F. & GREEN, P.F., 1990 – Estimating the component ages in a finite mixture. *Nuclear Tracks and Radiation Measurements*, 17: 197-206.

GOLES, G.G., BRIGGS, R.M. & ROSENBERG, M.D., 1996 – Late Pliocene stratigraphic succession and volcanic evolution of Karioi volcano, western North Island, New Zealand. *New Zealand Journal of Geology and Geophysics*, 39: 283-294.

GREEN, P.F., 1981 – A new look at statistics in fission track dating. *Nuclear Tracks*, 5: 77-86.

GREEN, P.F., 1985 – Comparison of zeta calibration baselines for fission track dating of apatite, zircon and sphene. *Chemical Geology*, 58: 1-22.

GRINDLEY, G.W. & MUMME, T.C., 1991 – Magnetic stratigraphy and correlation of ignimbrite eruptions of the Mangakino Basin and Tokoroa Plateau. *New Zealand Geological Survey Record*, 43: 25-36.

HAYWARD, B.W., 1998 – Ocean Drilling Programme comes down under: ODP Leg 181. *Geological Society of New Zealand Newsletter*, 117: 5-9.

HENDY, C.H., HOGG, A.G. & VAN DER LEE, T., 1980 – The prospect of dating tephra and other pyroclastics from the central North Island by uranium-thorium disequilibria. *Abstracts*, 'Tephra Workshop', Geology Department, Victoria University of Wellington, 30 June-1 July 1980, 2p.

HESSE, P.P., 1994 – The record of continental dust from Australia in the Tasman Sea sediments. *Quaternary Science Reviews*, 13: 257-272.

HORROCKS, J.L., 2000 – *Stratigraphy, chronology, and correlation of the Plio-Pleistocene (c. 2.2 - 0.8 Ma) Kauroa Ash sequence, western central North Island, New Zealand.* Unpublished Ph.D. thesis, University of Waikato, Hamilton.

HORROCKS, J.L., LOWE, D.J., NELSON, C.S. & BRIGGS, R.M., 1999 – Characterising weathered tephras: microprobe analysis of glass inclusions in quartz grains. *Geological Society of New Zealand Miscellaneous Publication*, 107A: 72.

HOUGHTON, B.F., WILSON, C.J.N., MCWILLIAMS, M.O., LANPHERE, M.A., WEAVER, S.D., BRIGGS, R.M. & PRINGLE, M.S., 1995 – Chronology and dynamics of a large silicic magmatic system: Central Taupo Volcanic Zone, New Zealand. *Geology*, 23: 13-16.

HURFORD, A.J. & GREEN, P.F., 1983 – The zeta age calibration of fission-track dating. *Isotope Geology*, 1: 285-317.

HURFORD, A.J. & WATKINS, R.T., 1987 – Fission track age of the tuffs of the Bulnk Member, Bakate Formation, northern Kenya: a suitable fission track age standard. *Chemical Geology*, 66: 209-216.

ISO, N., OKADA, A., OTA, Y. & YOSHIKAWA, T., 1982 – Fission-track ages of late Pleistocene tephra on the Bay of Plenty coast, North Island, New Zealand. *New Zealand Journal of Geology and Geophysics*, 25: 295-303.

KAMP, P.J.J. & LOWE, D.J., 1981 – Quaternary stratigraphy, landscape and soils of the Hamilton Basin. *Geological Society of New Zealand Miscellaneous Publication*, 29B: 14-28.

KAMP, P.J.J., GREEN, P.F. & WHITE, S.H., 1989 – Fission track analysis reveals character of collisional tectonics in New Zealand. *Tectonics*, 8: 169-195.

KEAR, D. & SCHOFIELD, J.C., 1978 – Geology of the Ngaruawahia Subdivision. *New Zealand Geological Survey Bulletin*, 88, 168p.

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., PILLANS, B.J. & MCGLONE, M.S., 1992 – Zircon fission track age for middle Pleistocene Rangitawa Tephra, New Zealand: stratigraphic and palaeoclimatic significance. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 95: 73-94.

KOHN, B.P., PILLANS, B.J. & ALLOWAY, B.V., 1996 – Fission track age estimates for Mount Curl Tephra – reply. *New Zealand Journal of Geology and Geophysics*, 39: 333-335.

KRIPPNER, S.J.P., BRIGGS, R.M., WILSON, C.J.N. & COLE, J.W., 1998 – Petrography and geochemistry of lithic fragments in ignimbrites from the Mangakino Volcanic Centre: implications for the composition of the subvolcanic crust in western Taupo Volcanic Zone, New Zealand. *New Zealand Journal of Geology and Geophysics*, 41: 187-199.

KYLE, P.R. & SEWARD, D., 1984 – Dispersed rhyolitic tephra from New Zealand in deep-sea sediments of the Southern Ocean. *Geology*, 12: 487-490.

LIAN, O.B. & SHANE, P.A.R., 2000 – Optical dating of paleosols bracketing the widespread Rotoehu tephra, North Island, New Zealand. *Quaternary Science Reviews*, 19: 1649-1662.

LOWE, D.J., 1986 – Controls on the rates of weathering and clay mineral genesis in airfall tephras: a review and New Zealand case study. In Colman, S.M. and Dethier, D.P. (eds), *Rates of Chemical Weathering of Rocks and Minerals*, Academic Press, Orlando: 265-330.

LOWE, D.J., 1987 – *Studies on late Quaternary tephras in the Waikato and other regions in northern North Island, New Zealand, based on distal deposits in lake sediments and peats.* Unpublished Ph.D. thesis, University of Waikato, Hamilton.

LOWE, D.J., 1988a – Late Quaternary volcanism in New Zealand: towards an integrated record using distal airfall tephras in lakes and bogs. *Journal of Quaternary Science*, 3: 111-120.

LOWE, D.J., 1988b – Stratigraphy, age, composition, and correlation of late Quaternary tephras interbedded with organic sediments in Waikato lakes, North Island, New Zealand. *New Zealand Journal of Geology and Geophysics*, 31: 125-165.

LOWE, D.J., 1995 – Teaching clays: from ashes to allophane. In Churchman, G.J., Fitzpatrick, R.W. and Eggleton, R.A. (eds), 'Clays: Controlling the Environment'. *Proceedings 10th International Clay Conference, Adelaide (1993)*. CSIRO Publishing, Melbourne, 19-23.

LOWE, D.J., 2000 – Upbuilding pedogenesis in multisequal tephra-derived soils in the Waikato region. Proceedings, Australian and New Zealand Second Joint Soils Conference, Lincoln University, 2: 183-184.

LOWE, D.J. & HOGG, A.G., 1995 – Age of the Rotoehu Ash - Comment. *New Zealand Journal of Geology and Geophysics*, 38: 399-402.

LOWE, D.J. & PERCIVAL, H.J., 1993 – Clay mineralogy of tephras and associated paleosols and soils, and hydrothermal deposits, North Island. *Guide Book for New Zealand Pre-Conference Field Trip F1*, 10th International Clay Conference, Adelaide, Australia, 110 p.

MANNING, D.M., 1996 – Middle-Late Pleistocene tephrostratigraphy of the eastern Bay of Plenty, New Zealand. *Quaternary International*, 34-36: 3-12.

MARTINSON, D.G., PISIAS, N.G., HAYS, J.D., IMBRIE, J., MOORE, T.C. & SHACKELTON, N.J., 1987 – Age dating and the orbital theory of the ice ages: development of a high resolution 0–300,000 year chronostratigraphy. *Quaternary Research*, 27: 1-29.

MCCRAW, J.D., 1975 – Quaternary airfall deposits of New Zealand. *Royal Society of New Zealand Bulletin*, 13: 35-44.

MOORE, C.L., 1991 – The distal record of explosive rhyolitic volcanism: an example from Auckland, New Zealand. *Sedimentary Geology*, 74: 25-38.

NAISH, T.R., KAMP, P.J.J., ALLOWAY, B.V., PILLANS, B.J., WILSON, G.S. & WESTGATE, J.A., 1996 – Integrated tephrochronology and magnetostratigraphy for cyclothemic marine strata, Wanganui Basin: implications for the Pliocene-Pleistocene boundary in New Zealand. *Quaternary International*, 34-36: 29-48.

NAISH, T.R., ABBOTT, S.T., ALLOWAY, B.V., BEU, A.G., CARTER, R.M., EDWARDS, A.R., JOURNEAUX, T.D., KAMP, P.J.J., PILLANS, B.J., SAUL, G. & WOOLFE, K.J., 1998 – Astronomical calibration of a Southern Hemisphere PlioPleistocene reference section, Wanganui Basin, New Zealand. *Quaternary Science Reviews*, 17: 695-710.

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.

NELSON, C.S., HENDY, C.H., CUTHBERTSON, A.M. & JARRETT, G., 1985 – Late Quaternary carbonate and isotope stratigraphy, subantarctic site 594, southwest Pacific. In Kennett, J.P. and von der Borch, C.C. (eds), *Initial Reports of the Deep Sea Drilling Project*, 90: 1425-1436.

NELSON, C.S., MILDENHALL, D.C., TODD, A.J. & POCKNALL, D.T., 1988 – Subsurface stratigraphy, palaeoenvironments, palynology and depositional history of the late Neogene Tauranga Group at Ohinewai, Lower Waikato Lowland, South Auckland, New Zealand. *New Zealand Journal of Geology and Geophysics*, 31: 21-40.

NELSON, C.S., KAMP, P.J.J. & MILDENHALL, D.C., 1989 – Late Pliocene distal silicic ignimbrites, Port Waikato, New Zealand: implications for volcanism, tectonics, and sea-level changes in South Auckland. *New Zealand Journal of Geology and Geophysics*, 32: 357-370.

NEWNHAM, R.M. & GRANT-MACKIE, J.A., 1993 – Palynology of a peat layer interbedded with rhyolitic tephra layers at Bucklands Beach, Auckland: a preliminary investigation. *Tane*, 34: 133-140.

NEWNHAM, R.M., LOWE, D.J. and WILLIAMS, P.W., 1999a – Quaternary environmental change in New Zealand: a review. *Progress in Physical Geography*, 23: 567-610.

NEWNHAM, R.M., LOWE, D.J. & ALLOWAY, B.V., 1999b – Volcanic hazards in Auckland, New Zealand: a preliminary assessment of the threat posed by central North Island silicic volcanism based on the Quaternary tephrostratigraphical record. In Firth, C. and McGuire, W.J. (eds), 'Volcanoes in the Quaternary'. *Geological Society, London, Special Publications*, 161: 27-45.

PAIN, C.F., 1975 – Some tephra deposits in the south-west Waikato area, North Island, New Zealand. *New Zealand Journal of Geology and Geophysics*, 18: 541-550.

PALMER, A.S. & PILLANS, B.J., 1996 – Record of climatic fluctuations from ca. 500 ka loess deposits and paleosols near Wanganui, New Zealand. *Quaternary International*, 34-36: 155-162.

PILLANS, B.J. & KOHN, B.P., 1981 – Rangitawa Pumice: a widespread(?) Quaternary marker bed in Taranaki-Wanganui. *Geology Department, Victoria University of Wellington Publication*, 20: 94-104.

PILLANS, B.J. & KOHN, B.P., 1998 – The age of the Rangitawa Tephra: *Geological Society of New Zealand Newsletter*, 115: 45-52.

PILLANS, B.J., KOHN, B.P. & MCGLONE, M.S., 1992 – Rangitawa Tephra: the zircons tell their tale at last. *Geological Society of New Zealand Newsletter*, 95: 42-46.

PILLANS, B.J., MCGLONE, M.S., PALMER, A.S., MILDENHALL, D., ALLOWAY, B.V. & BERGER, G.W., 1993 – The Last Glacial Maximum in central and southern North Island, New Zealand: a palaeoenvironmental reconstruction using the Kawakawa Tephra Formation as a chronostratigraphic marker. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 101: 283-304.

PILLANS, B.J., KOHN, B.P., BERGER, G.W., FROGGATT, P.C., DULLER, G., ALLOWAY, B.V. & HESSE, P., 1996 – Multi-method dating comparison for mid-Pleistocene Rangitawa Tephra, New Zealand. *Quaternary Science Reviews*, 15: 1-14.

PRINGLE, M.S., MCWILLIAMS, M.O., HOUGHTON, B.F., LANPHERE, M.A. & WILSON, C.J.N., 1992 – ^{40}Ar/^{39}Ar dating of Quaternary feldspar: Examples from the Taupo Volcanic Zone, New Zealand. *Geology*, 20: 531-534.

PULLAR, W.A., BIRRELL, K.S. & HEINE, J.C., 1973 – Age and distribution of late Quaternary pyroclastic and associated cover deposits of central North Island, New Zealand [with accompanying explanatory notes]. *New Zealand Soil Survey Report*, 2, 4 sheets, 32p.

SALTER, R. T., 1979 – *A pedological study of the Kauroa Ash Formation at Woodstock*. Unpublished M.Sc. thesis, University of Waikato, Hamilton.

SELBY, M.J. & LOWE, D.J., 1992 – The middle Waikato Basin and hills. In Soons, J.M. and Selby, M.J. (eds), *Landforms of New Zealand (2nd edn)*, Longman Paul, Auckland, 233-255.

SEWARD, D. & KOHN, B.P., 1997 – New zircon fission-track ages from New Zealand Quaternary tephra: an interlaboratory experiment and recommendations for the determination of young ages. *Chemical Geology*, 141: 127-140.

SHANE, P.A.R., 1994 – A widespread, early Pleistocene tephra (Potaka tephra, 1 Ma) in New Zealand: character, distribution, and implications. *New Zealand Journal of Geology and Geophysics*, 36: 25-35.

SHANE, P.A.R., 2000 – Tephrochronology: a New Zealand case study. *Earth-science Reviews*, 49: 223-259.

SHANE, P.A.R., FROGGATT, P.C., BLACK, T.M. & WESTGATE, J.A., 1995 – Chronology of Pliocene and Quaternary bioevents and climatic events from fission-track ages on tephra beds, Wairarapa, New Zealand. *Earth and Planetary Science Letters*, 130: 141-154.

SHANE, P.A.R., BLACK, T.M., ALLOWAY, B.V. & WESTGATE, J.A., 1996a – Early to middle Pleistocene tephrochronology of North Island, New Zealand: Implications for volcanism, tectonism, and palaeoenvironments. *Geological Society of America Bulletin*, 108: 915-925.

SHANE, P.A.R., ALLOWAY, B.V., BLACK, T.M. & WESTGATE, J.A., 1996b – Isothermal plateau fission-track ages of tephra beds in an early-middle Pleistocene marine and terrestrial sequence, Cape Kidnappers, New Zealand. *Quaternary International*, 34-36: 49-53.

SHANE, P.A.R., BLACK, T.M., EGGINS, S. & WESTGATE, J.A., 1998 – Late Miocene marine tephra beds: recorders of rhyolitic volcanism in North Island, New Zealand. *New Zealand Journal of Geology and Geophysics*, 41: 165-178.

SHEPHERD, T.G. 1984 – *A pedological study of the Hamilton Ash Group at Welches Road, Mangawara, north Waikato*. Unpublished M.Sc. thesis, University of Waikato, Hamilton.

SHEPHERD, T.G., 1994 – Palaeoclimatic implications of clay minerals and paleosols within strongly weathered Plio-Pleistocene tephras of the Waikato region, central North Island, New Zealand. In Lowe, D.J. (ed), *Programme and Abstracts*, Inter-INQUA Field Conference on Tephrochronology, Loess, and Palaeopedology, University of Waikato, Hamilton: 52.

SHEPHERD, T.G. & GIBBS, H.S., 1984 – Mineralogical and chemical composition of the Hamilton Ash in the Waikato Basin. *New Zealand Soil News*, 32: 182.

SKINNER, D.N.B., 1986 – Neogene volcanism of the Hauraki Volcanic Region. *Royal Society of New Zealand Bulletin*, 23: 21-47.

SOENGKONO, S., HOCHSTEIN, M.P., SMITH, I.E.M. & ITAYA, T., 1992 – Geophysical evidence for widespread reversely magnetised pyroclastics in the western Taupo Volcanic Zone (New Zealand). *New Zealand Journal of Geology and Geophysics*, 35: 47-55.

STEVENS, K.F. & VUCETICH, C.G., 1985 – Weathering of Upper Quaternary tephras in New Zealand, 2. Clay minerals and their climatic interpretation. *Chemical Geology*, 53: 237-247.

STOKES, S., 1988 – *The Kaihu Group: a review and reassessment of aspects of late Neogene stratigraphy, sedimentation and related events in coastal northwestern North Island, New Zealand.* Unpublished M.Phil. thesis, University of Waikato, Hamilton.

TAYLOR, N.H., 1933 – Soil processes in volcanic-ash beds. *New Zealand Journal of Science and Technology*, 14: 193-202, 338-352.

TIPPETT, J.M. & KAMP, P.J.J., 1993 – Fission track analysis of the late Cenozoic vertical kinematics of continental Pacific Crust, South Island, New Zealand. *Journal of Geophysical Research*, 98: 16119-16148.

TONKIN, P.J. 1970 – Contorted stratification with clay lobes in volcanic ash beds, Raglan-Hamilton region, New Zealand. *Earth Science Journal*, 4: 129-140.

VELLA, P., 1997 – How good are Quaternary tephra correlations? *Geological Society of New Zealand Newsletter*, 114: 37-40.

VELLA, P. & VUCETICH, C.G., 1995 – Comments on the numerical age of the Mt Curl-Rangitawa Tephra. *Geological Society of New Zealand Newsletter*, 106: 44-45.

VELLA, P. & VUCETICH, C.G., 1996 – Fission track age estimates for Mt Curl Tephra – comment. *New Zealand Journal of Geology and Geophysics*, 39: 333.

VUCETICH, C.G., BIRRELL, K.S. & PULLAR, W.A., 1978 – Ohinewai Tephra Formation; a *c.* 150,000-year-old tephra marker in New Zealand. *New Zealand Journal of Geology and Geophysics*, 21: 71-73.

VUCETICH, C.G., KOHN, B.P. & PULLAR, W.A., 1981 – Correlation of Aratora Tephra, Ahuroa cover bed type section, Te Kuiti. *Geology Department, Victoria University of Wellington Publication*, 20: 116-130.

VUCETICH, C.G., VELLA, P. & WARNES, P.N., 1996 – Antepenultimate glacial to last glacial deposits in southern Wairarapa, New Zealand. *Journal of the Royal Society of New Zealand*, 26: 469-482.

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.

WARD, W.T., 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. & WHITE, P.J., 1994 – Geology of the Raglan-Kawhia area, sheets R14CD, R15, and part R16, scale 1: 50,000. *Institute of Geological and Nuclear Sciences Geological Map*, 13, 1 sheet, 48p.

WILSON, C.J.N., HOUGHTON, B.F., LANPHERE, M.A. & WEAVER, S.D., 1992 – A new radiometric age estimate for the Rotoehu Ash from Mayor Island, New Zealand. *New Zealand Journal of Geology and Geophysics*, 35: 371-374.

WILSON, C.J.N., HOUGHTON, B.F., MCWILLIAMS, M.O., LANPHERE, M.A., WEAVER, S.D. & BRIGGS, R.M., 1995a – Volcanic and structural evolution of Taupo Volcanic Zone, New Zealand: a review. *Journal of Volcanology and Geothermal Research*, 68: 1-28.

WILSON, C.J.N., HOUGHTON, B.F., KAMP, P.J.J. & MCWILLIAMS, M.O., 1995b – An exceptionally widespread ignimbrite with implications for pyroclastic flow emplacement. *Nature*, 378: 605-607.

WRIGHT, I.C., MCGLONE, M.S., NELSON, C.S. & PILLANS, B.J., 1995 – An integrated latest Quaternary (Stage 3 to present) paleoclimatic and paleoceanographic record from offshore northern New Zealand. *Quaternary Research*, 44: 283-293.