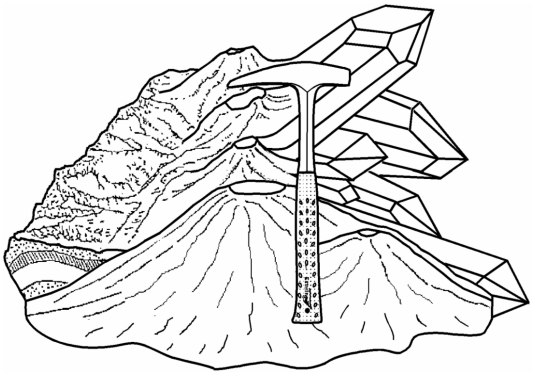


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Contributions about the geology of New Zealand (particularly northern New Zealand) from members are welcome. Articles are lightly edited but not refereed.

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BASIS FOR MODIFIED AGES OF AUCKLAND VOLCANOES IN "VOLCANOES OF AUCKLAND: A FIELD GUIDE, 2019"

Bruce W. Hayward and Jenni Hopkins

In Volcanoes of Auckland: The Essential Guide (Hayward *et al*., 2011, p. 25) BWH listed known or estimated ages of 32 of Auckland's volcanoes (Table 1, Fig. 1), mostly based on the summary document by Lindsay *et al*. (2011). Nine of these age assessments were simply that the volcano was older than a certain age based on its stratigraphic relationship with nearby volcanoes, or on the oldest known sediment or tephra cored in its crater-filling sediment.

Since 2011, there have major advances in the understanding of the eruption sequence and ages of Auckland's volcanoes through two major research initiatives (Ar–Ar dating and geochemical fingerprinting of ash layers):

Ar-Ar dating
This initiative has been spearheaded by GNS volcanologist, Graham Leonard, using modern argon-argon radiometric dating methods (Leonard *et al*., 2017). Leonard *et al.* (2017)'s work produced new Ar–Ar ages for 23 volcanoes (Table 2). They argue that careful selection of fresh, non-glassy, non-vesicular samples of basalt from the centre of flows, coupled with separation techniques to use only the groundmass, result in reliable age determinations. In a few instances the Ar–Ar age is inconsistent with the sequence and age determined from fingerprinting (Hopkins *et al*., 2017) (see Table 2). In these instances, we have usually favoured the fingerprinting age. Where there are no other age determinations, we have accepted the Ar–Ar ages at face value so long as they are consistent with any other evidence.

Fingerprinting basaltic tephra
This initiative has been the PhD research (at Victoria University) of the second author of this note, JH (Hopkins *et al*., 2015, 2017). JH used geochemical fingerprinting of basaltic tephra in crater sediment cores (Figs 2–5) to correlate the tephra (ash layers) back to their source volcanoes. Hopkins *et al*. (2017) produced a sequence and calibrated sediment accumulation rate ages for 27 volcanoes (Table 2). Correlating distal tephra in the cores with their source volcano using geochemistry is not without its difficulties. The distal tephra is usually produced by early phreatomagmatic eruptions and these products are often buried beneath the source volcano (e.g. most volcanoes with large scoria cones). Additionally, detailed geochemical studies on products from the full sequence of eruptions from some larger volcanoes (e.g. Motukorea, Mt Wellington, Rangitoto) have shown considerable temporal geochemical change through time (e.g. Needham *et al*., 2011; Shane & Zawalna-Geer, 2011; McGee *et al*., 2013; Linnell *et al*., 2016). Hopkins *et al*. (2017) rated the confidence levels of their correlations of basaltic tephra layers (Fig. 5) with source volcanoes on a scale of 1 (high) to 3 (lower) (Table 2).

Adopted volcano age assignments that differ from those given from fingerprinting or Ar–Ar methods
All adopted ages follow those from fingerprinting, sometimes rounded off to the nearest thousand or hundred years (Hopkins *et al*., 2017), except for those discussed below. All volcanoes with ash layers deeper (= older) than Rotoehu Tephra have been recalibrated using a more precise and a now more probable younger age for Rotoehu (see below). If there are no radiocarbon ages, fingerprinting ages or stratigraphic constraints for a volcano then the Ar–Ar age determinations (Leonard *et al*., 2017) have been adopted (with some rounding).

Most reliable ages
Volcanoes dated by fingerprinting correlation with confidence levels of 1 or 2 (Hopkins *et al.* (2017) have been accepted and bolded (with minor rounding) as most reliable, except Three Kings and Pukeiti (see below). Those volcanoes identified as having a paleomagnetic signature consistent with the Mono Lake excursion have all been bolded as having reliable ages.

Paired volcano ages
Examination of exposures of the contacts between the volcanic material erupted from one volcano and another close by suggests that some erupted at the same time as, or soon after, their neighbour, with no time in between for any forest to become established nor soil develop (Hayward *et al*., 2011; Hopkins, 2018). The possible paired eruptions include (in younging order): Grafton–Auckland Domain (~100 ka), Māngere Lagoon–Māngere Mt (~50 ka), Ash Hill–Wiri (~30 ka), Te Pou Hawaiki–Maungawhau (28 ka), Green Mount–Styaks Swamp (~20 ka), Pukeiti–Otuataua (~15 ka), Purchas Hill–Maungarei (~10 ka), early Rangitoto–late Rangitoto (~620, 600 yrs), Hampton Park–Ōtara Hill (?age). The Maungawhau–Te Pou Hawaiki pair is more uncertain than the others. Each volcano in a pair has been given approximately the same age estimate (Tables 1, 2), although often only one of the volcanoes has been dated. Pupuke–Onepoto–Te Kopua-o-Matokamokamo/Tank Farm erupted close together, but how long the gap was between them is not well constrained (see below).

Age of Rotoehu Tephra used in calibrating ages of basaltic tephra in cores
To obtain an age estimate for each of the basaltic tephra (numbered with prefix of AVF) in the sediment cores, Hopkins *et al*. (2017) first had to determine an age model going down each core (in Pukaki Lagoon, Te Hopua, Orakei Basin, Glover Park, Onepoto, Pupuke) using the well-determined ages of a number of geochemically distinct rhyolitic tephra (Fig. 4) (Lowe *et al*., 2013) that occurred within their sequences (updated from Shane and Hoverd, 2002 and Molloy *et al*., 2009). Lacustrine

Table 1. Ages of Auckland volcanoes (in thousands of years) given by BWH in the Essential Guide (2011, p. 25) and the newly updated ages given by BWH in the Field Guide (2019), determined by the methods given below with slight modifications (see later):

[A] Ar–Ar radiometric dating (from Leonard *et al*., 2017);
[B] breached by Last Interglacial high sea level, 120,000-130,000 years ago (Fig. 6);
[C] radiocarbon dating (14C) of wood, peat or shell (from Lindsay *et al*., 2011);
[L] geochemical correlation of basaltic tephra in lake sediment cores with source volcanoes (from Hopkins *et al*., 2017);
[M] paleomagnetic method (from Cassidy, 2006; Cassata *et al*., 2008);
[R] relative age based on stratigraphic relationship with other volcanoes of known age;
[S] minimum age based on the oldest lake sediment recovered from their explosion craters;
± = plus and minus limits of accuracy; > = older than; ~ = approximately.

Bolded ages are considered to be the most reliable.

	2011 preferred age	2019 preferred age
Albert Park		~145 [A]
Ash Hill	32 [C, M]	~30.5 [C]
Boggust Park		>130 [B]
Cemetery Crater		No data
Crater Hill	32 [M]	**~30.5** [A,C,M,S]
Grafton	>45 [R]	~100 [L,R]
Hampton Park	20 [A]	? [M]
Kohuora	>32 [S]	**34±1** [C,L,S]
Māngere Lagoon		**~50** [L]
Matanginui/Green Mount	11-29 [C]	~20 [A]
Matukutūreia/McLaughlins Mountain		~50 [A]
Maungakiekie/One Tree Hill	>28.5 [R]	**~60** [L]
Maungarahiri/Little Rangitoto		**~24.5** [A,L]
Maungarei/Mt Wellington	10-10.5 [C]	**10±0.2** [C,L]
Maungataketake/Elletts Mountain	91 [A]	~90 [A]
Maungauika/North Head		~90 [A]
Maungawhau/Mt Eden	28 [C]	**~28** [C,L]
Motukorea/Browns I.		**24.4±0.5** [L]
Mt Robertson/Sturges Park		~24 [L]
O Huiarangi/Pigeon Mt		24.5±0.5 [L]
Ōhinerangi/Mt Hobson/Ōhinerau	>28.5 [R]	**34±1** [L]
Ōrākei Basin	85 [S]	~120 [L]
Otahuhu/Mt Richmond	32 [M]	**~30** [L,M]
Otuataua		~15 [L]
Puhinui Craters		~50 ?
Pukekawa/Auckland Domain	>45 [C, S]	~100 [L]
Puketāpapa/Pukewīwī/Mt Roskill		~105 [A]
Pukewairiki/Highbrook Park	>130 [B]	>130 [B]
Pupuke Moana/Lake Pupuke	193-208 [A]	~190 [A]
Rangitoto	0.55-0.65 [C]	**0.62-0.60** [C,L]
Rarotonga/Mt Smart		**20±0.1** [L]
Styaks Swamp		~20±3 [A]
Takaroro/Mt Cambria		~40 [A]
Takarunga/Mt Victoria		35±2 [L]
Taurere/Taylors Hill	32 [M]	**~30** [L,M]
Te Ahi-kā-roa-a-Rakataura/Mt Albert	>40-50 [C]	~120 [A]
Te Apunga-o-Tainui/McLennan Hills	39-41 [M]	**41±1** [A,C,M]
Te Hopua-a-Rangi/Gloucester Park	29 [S]	>30 [S]
Te Kopua Kai-a-Hiku/Panmure Basin	18 [S]	**25±1** [L]
Te Kopua-o-Matakamokamo/ Tank Farm/Tuff Crater		~180 [L]
Te Kopua-o-Matakarepo/Onepoto	150-220 [S]	~185 [L]
Te Kōpuke/Tītīkōpuke/Mt St John	>28.5 [R]	~75 [A]
Te Manurewa o Tamapahore/ Wiri Mountain	32 [M]	**~30** [A,C,M]
Te Motu a Hiaroa/Puketūtū	32 [M]	**~30** [A,C,L,M]
Te Pane-o-Mataaho/Māngere Mountain		**~50** [L]
Te Pou Hawaiki		~28 ? [C]
Te Pukaki Tapu-o-Poutukeka/ Pūkaki Lagoon	65 [S]	>54 [S]
Te Puke-o-Taramainuku/Ōtara Hill	20 [M]	?
Te Puketapapatanga a Hape/Pukeiti		~15 [A]
Te Tātua-a-Riukiuta/Three Kings	28.5 [C]	**28.5±0.5** [C,L]
Te Tauoma/Purchas Hill	11 [C]	**~10±0.2** [C,L]
Waitomokia/Moerangi/Mt Gabriel	>16 [S]	**20.3±2** [L]
Whakamuhu/Glover Park	>45 [S]	160±20 [S]

The volcano names used here are the officially accepted Maori names (where known) with their most used European alternatives (used in Hayward, 2019).

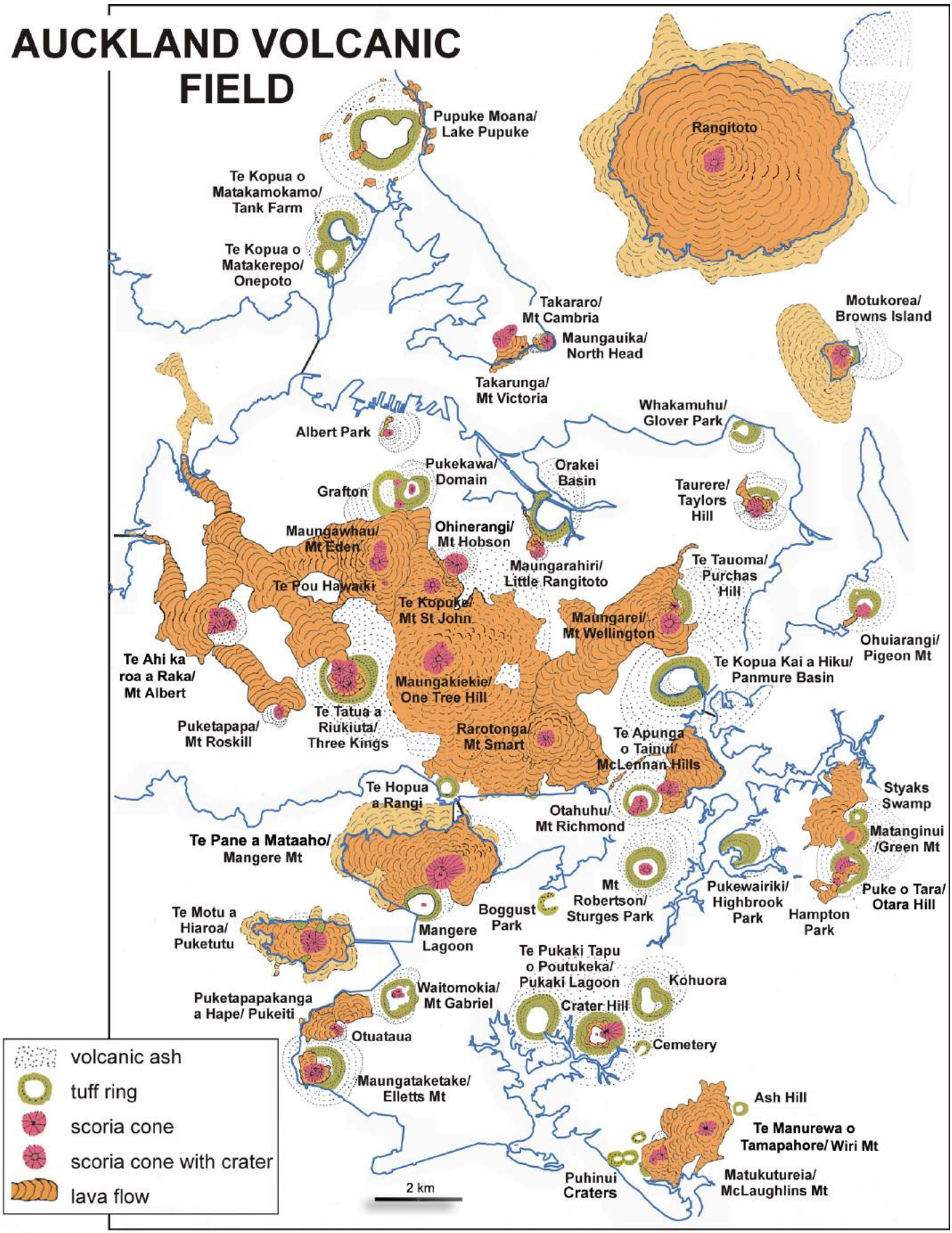


Fig. 1. Volcanoes in the Auckland Volcanic Field.

Table 2. Recent assessment of the most likely age estimate of Auckland's volcanoes, in thousands of years (Hayward, 2019) allowing for confidence limits (±) of instrumental measurements and sedimentation rates. Age determinations by the following methods are given for each volcano: radiocarbon dating (^{14}C); Ar–Ar radiometric dating; paleomagnetic method; the minimum age based on the oldest lake sediment recovered in crater cores; or by the geochemical correlation of basaltic tephra in cores with source volcanoes. Dates have been sourced, with minor modifications, from Hopkins *et al*. (2017), Leonard *et al*. (2017) and Lindsay and Leonard (2009). (± = plus and minus limits of accuracy; > = older than). **Bolded ages** are considered to be the most reliable. Hopkins *et al*. (2017) assessed confidence of their basalt tephra correlations and therefore ages are given on their scale of 1 (high) to 3 (low) in square brackets.

	14C dates	Ar–Ar dates	Paleo-magnetic	Oldest cored lake sediment	Ash correlation & sed. rate	Most likely age
Albert Park		144-150			145±2 [2]	~145
Ash Hill	32					~30.5[3]
Boggust Park						>130
Cemetery Crater						No data
Crater Hill	30-34	29-35	30-31		30.4±0.4 [2]	~30.5
Grafton					100±5*	~100[1]
Hampton Park		37-73	?			?
Kohuora	32-36			>32 (8 m)	33.7±1.2 [2]	34±1
Māngere Lagoon						~50[2]
Matanginui/Green Mt	11-29	16-23				~20[5]
Matukutūreia/McLaughlins Mt		45-51				~50
Maungakiekie/One Tree Hill		49-56			61±3* [1]	~60
Maungarahiri/Little Rangitoto		18-23			24.6±0.3 [1]	~24.5
Maungarei/Mt Wellington	10				10±0.2 [1]	10±0.2[7]
Maungataketake/Elletts Mt	>30-50	87-92				~90
Maungauika/North Head		80-95				~90
Maungawhau/Mt Eden	28	18-25			28±0.3 [1]	~28[4]
Motukorea/Browns I.		8-20			24.4±0.3 [2]	24.4±0.5
Mt Robertson/Sturges Park					24.3±0.4 [3]	~24
Ōhinerangi/Mt Hobson/Ōhinerau		51-62			34.2±0.9 [3]	34±1
Ōrākei Basin				120 (100 m)	119±3* [2]	~120
Otahuhu/Mt Richmond		30-39	30-31		30.2±2 [3]	~30
Otuataua					24.2±1 [3]	~15[6]
Pigeon Mt/O Huiarangi					24.35±0.4 [3]	24.5±0.5
Puhinui Craters				>15		~50?
Pukekawa/Auckland Domain	>40-50			>45 (10 m)	100±5* [3]	~100[1]
Puketāpapa/Pukewīwī/Mt Roskill	102-108					~105
Pukewairiki/Highbrook Park						>130
Pupuke Moana/Lake Pupuke	>40-50	190-196		>45 (73 m)		~190
Rangitoto	0.5-0.55				0.6 [1]	0.62-0.60[8]
Raratonga/Mt Smart		15-18			20.1±0.1 [2]	20±0.2
Styaks Swamp		~20?				~20[5]
Takaroro/Mt Cambria		31-53				~40
Takarunga/Mt Victoria		50-65			34.8±2 [3]	35±2
Taurere/ Taylors Hill		26-29	30-31		30.2±0.1 [2]	~30
Te Ahi-kā-roa-a-Rakataura/Mt Albert	>40-50	116-122				~120
Te Apunga-o-Tainui/McLennan Hills	39-46	32-37	41-42			41±1
Te Hopua-a-Rangi/Gloucester Park				29 (49 m)		>30
Te Kopua Kai-a-Hiku/Panmure Basin	32			18 (43 m)	25.2±0.9 [1]	25±1
Te Kopua-o-Matakamokamo/Tank Farm					181±1 [1]	~180
Te Kopua-o-Matakarepo/Onepoto	>40-50	220-276		150-220 (61 m)	>181	~185
Te Kōpuke/Mt St John		74-77				~75
Te Manurewa o Tamapahore/Wiri Mountain	32-34	28-33	30-31			~30[3]
Te Motu a Hiaroa/Puketūtū	25-37	31.5-36	30-31		30±2 [2]	~30
Te Pane-o-Mataaho/Māngere Mountain	67-74				50±2* [2]	~50[2]
Te Pou Hawaiki					~28?	~28? [4]
Te Pukaki Tapu-o-Poutukeka/Pūkaki Lagoon				>45 (62 m)		>54
Te Puke-o-Taramainuku/Ōtara Hill	37-73	?				?
Te Puketapapatanga a Hape/Pukeiti	8-15				15±0.7 [2]	~15[6]
Te Tātua-a-Riukiuta/Three Kings	28.5				31±0.9 [1]	28.5±0.5
Te Tauoma/Purchas Hill	11					~10±0.2[7]
Waitomokia/Moerangi/Mt Gabriel				>16 (10 m)	20.3±0.2 [2]	20.3±2
Whakamuhu/Glover Park				161±18		160±20

* Sediment core ages recalculated from Hopkins *et al*. (2017) using revised age for Rotoehu Tephra (±).

[1-8] Paired volcanoes given approximately same age.

sediment accumulation rates (with ~instantaneously deposited volcanic ash thicknesses excluded) could then be calculated between each of the dated rhyolitic tephra layers and used to date the basaltic tephra layers erupted from nearby Auckland volcanoes. Hopkins *et al.* (2017) used a scientifically more robust method for doing this. They modelled basaltic tephra horizons as a function of deposit depth, interpolating ages using Monte Carlo simulations. This technique was employed for all the cores in the Auckland Volcanic Field, and where correlated tephra were found in multiple cores, ages assigned are calculated as means from each core. The uncertainty in the age assigned to a tephra horizon in the individual core coupled with the variability of the ages across the cores were used to calculate the overall uncertainties.

The oldest distinctive and dated rhyolitic tephra in each core is Rotoehu Tephra and its age was used to provide an estimate of ages for all tephra deeper and older than Tahuna Tephra (39.3±1.2 ka). Hopkins used an age estimate of 52±7 ka for Rotoehu Tephra. This resulted in fingerprinting age estimates for most of the older basalt tephra having large uncertainties (Hopkins *et al*., 2017). This age determination is highly conservative and encompasses the wide range of ages that has been determined for Rotoehu Tephra by many different methods over the past 50 years. Most of the methods that gave older age determinations are radiometric with no independent way of assessing how accurate they are. In the opinion of BWH, the most reliable ages are those obtained from (1) recent AMS radiocarbon dating of wood above and below the tephra (between 47.5±2.1 and 44.8±0.3 ka, Danisik *et al*., 2012); (2) orbitally-tuned sedimentation rates in ODP 1123 (45.1 ka, Allan *et al*., 2008) and from (3) marine sedimentation rates in 4 cores in the Bay of Plenty calibrated by the depths of other distinctive, well-dated rhyolitic tephra (43.8-47.7 ka, Shane *et al*., 2006). If one uses the average lacustrine sediment accumulation rates above the Tahuna Tephra in each of four Auckland crater lake cores, they give an age for Rotoehu Tephra of 42.2-43.5 ka (Pukaki Lagoon), 43-43.5 ka (Onepoto), 40.3-44.3 ka (Orakei Basin) and 42.5-44.8 ka (Pupuke). It could be argued that the sedimentation rates were lower before 40 ka in all these crater lakes but this does not explain the other younger dates above. Most recently, Peti and Augustinus (2019) have adopted an age of 45.1±1.65 ka for Rotoehu Tephra in their Orakei Basin studies (based on the results of Danisik *et al*., 2012). Thus for the new field guide an age for Rotoehu Tephra of ~45.5±2 ka has been used to recalculate the sedimentation rates in the lower parts of the crater lake cores. By doing this, the ages of the four basalt tephras that are older than 40 ka are a bit younger than estimated by Hopkins *et al.* (2017)(Table 3).



Fig. 2. Barge with small drill rig used to core Orakei Basin in 2007. Photo by Phil Shane.

Table 3. Comparison of fingerprinting age determinations using an age for Rotoehu Tephra of 52±7 ka (Hopkins *et al.*, 2017) and of 45.5±2 ka (Hayward, 2019).

Volcano	from 52±7 ka	from 45.5±2 ka
Mangere Mt and Lagoon	59±10	50±2
Maungakiekie/One Tree Hill	67±6	61±3
Domain/Grafton	106±4	100±10
Orakei	126±3	119±3

Age of the Mono Lake magnetic excursion

Five of Auckland's volcanoes (Crater Hill, Mt Richmond, Taylors Hill, Puketutu, and Wiri Mt) have been shown by aeromagnetic survey to have negative residual magnetic anomalies due to eruption during a short-lived geomagnetic excursion (called Mono Lake) (Cassidy, 2006). This excursion has been recognised in a number of places outside of New Zealand where it has been imprecisely dated within the period 27.3–35.5 ka (Laj *et al.*, 2014). Leonard *et al*. (2017, Table 2) used this age range to show that all the Ar–Ar dates from these five volcanoes lay within the Mono lake excursion, as did Ash Hill, Kohuora, Three Kings, and possibly McLennan Hills. But all these latter four have positive magnetic anomalies (Cassidy and Locke, 2010, Table 1) and lie outside the boundaries of the excursion, which could not have lasted more than 2000 years at most.



Fig. 3. Core being extruded from the core barrel during coring at Auckland Domain crater, 2006.



Fig. 4. Split Orakei Basin core showing a distinctive cream-coloured rhyolitic tephra used to calibrate the age of the sequence of laminated diatomite maar-lake sediment. Photo by Elaine Smid.



Fig. 5. Split Orakei Basin core showing a distinctive dark-coloured basalt tephra from an Auckland Volcano within the sequence of laminated diatomite maar-lake sediment. Photo by Elaine Smid.

Studies in the Auckland Volcanic Field provide the most precise dating on the Mono Lake excursion. It has been dated by Cassata *et al*. (2008) at 31.6±1.8 ka based on Ar–Ar ages of Crater Hill, Puketutu and Wiri. This is consistent with radiocarbon dating of Wiri Mt but also Ash Hill and Kohuora (all 34–32 ka) (Lindsay *et al.*, 2011). The fingerprinting correlations of Hopkins *et al*. (2017,) provide even higher resolution and probably the most accurate age constraints on the Mono Lake excursion, which must have occurred between ~29 ka (between Puketutu and Maungawhau) and 30.4±0.4 ka (Crater Hill), although there is no fingerprinting constraints on Wiri Mt, which has not been recognised in any cores so far. Each of the four Mono Lake volcanoes recognised in cores from fingerprinting erupted separately at least a few hundred years between each (Hopkins *et al*., 2017). In the preferred age estimates in the book (Tables 1, 2), BWH has assigned Ash Hill an age of ~30.5 ka because of its identical radiocarbon age to Wiri Mt, but Ash Hill must have just preceded the excursion.

Using all dating methods available to us, we have listed the Auckland volcanoes in age order (Fig. 7).

Comments on some individual volcano ages

Glover Park (preferred age assessment 160±20 ka). The original >45 ka age quoted by Hayward *et al*. (2011) was based on the presence of Rotoehu Tephra in two cores in the lake and swamp sediment (Hoverd *et al*., 2005). The age adopted now comes from fingerprinting that has correlated the deepest basaltic tephra in the core to Albert Park Volcano (145 ka)(Hopkins *et al*., 2017).



Fig. 6. Oblique aerial from northeast showing Boggust Crater in 1949 before suburbia engulfed it and before mangroves filled the tidal inlet. The only age limits we have on this volcano is that it appears to have been breached by high sea levels of ~5 m above present, during the Last Interglacial, 120–130 kyrs ago. Photo by Whites Aviation.

Hampton Park and Otara Hill (preferred age assessment = ?). Believed to have erupted close together because of

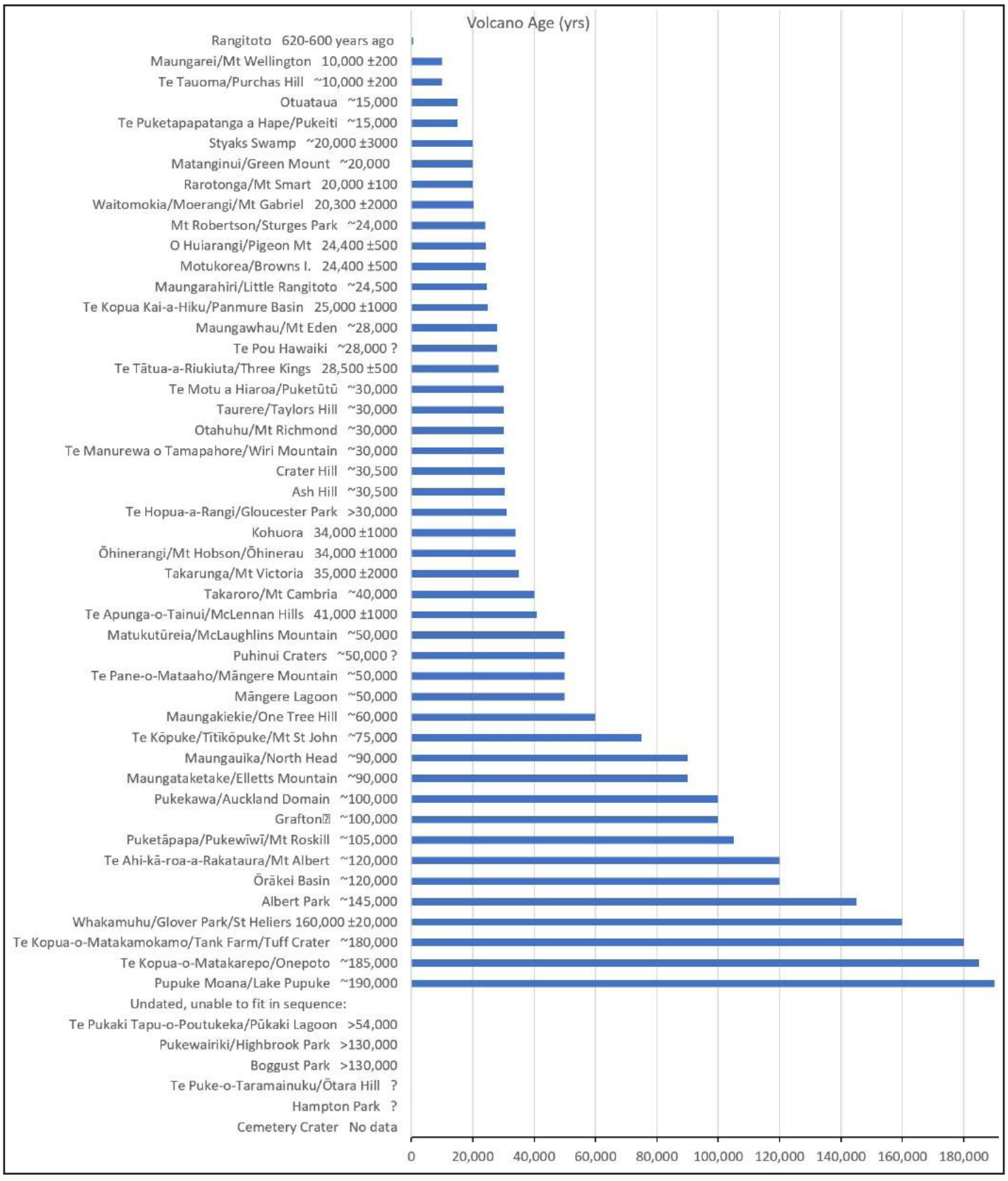


Fig. 7. Ages of Auckland volcanoes in age order.

similar unusual paleomagnetic signature (Cassata *et al*., 2008) but the Ar–Ar age range is so wide (37–73 ka) as to be of minimal value.

Otuataua and Pukeiti (preferred age assessment ~15 ka)
Searle (1959) observed that Otuataua lava flows overlie those from adjacent Pukeiti. We observe that Pukeiti flows are mantled in ash and some of Otuataua's are not. These suggest that Otuataua is younger than Pukeiti, which is the reverse of the fingerprinting age determinations of 15±0.7 ka [2] for Pukeiti and 24.2±1 ka [3] for Otuataua. The confidence level of the fingerprinting correlation is higher (2) for Pukeiti and it also has a consistent Ar–Ar age (8–15 ka) and thus the ~15 ka has been adopted as the preferred age estimate in the book for both, as they are likely an example of two adjacent volcanoes erupting at or close to the same time (Hopkins, 2018).

Pukaki Lagoon (preferred age assessment >54 ka)
The oldest rhyolitic tephra in Pukaki cores is Rotoehu at 62 m with 3 m of lake sediment below (Shane, 2005). The background sedimentation rate above the Rotoehu is 1 m per 3 ka, so we assess Pukaki Lagoon to be older than 54 ka (using the 45.5 ka age for Rotoehu Tephra). Hopkins *et al*. (2017) gave >52 ka based on the presence of Rotoehu Tephra.

Three Kings (preferred age assessment 28.5 ka)
The age of Three Kings volcano is controversial. It has been determined by fingerprinting as AVF7 dated at 31.0±0.9 ka (pre-Mono Lake excursion) (Hopkins *et al*. 2017). This is inconsistent with the firmly established age by radiocarbon dating of charred wood and twigs beneath Three Kings lava flows from six boreholes at 28.6±0.2 ka (Eade, 2009, Lindsay *et al*., 2011).

Three Kings has long been known to have produced the most voluminous tephra eruptions of the volcanoes on the central Auckland isthmus (e.g. Kermode *et al.*, 1992; Kereszturi *et al.*, 2014; Hayward, 2019). The thickest basalt tephra in the central maar lake cores, Orakei and Te Hopua, at 0.4 m in Orakei and Te Hopua, is AVF12, which is reliably dated at 28.03±0.26 ka (Hopkins *et al*., 2017). Trace element chemistry, however, suggests that AVF12 is quite different from the whole rock chemistry of Three Kings lava flows and scoria and more likely correlative with the whole rock chemistry of lava flows and scoria of Mt Eden (Hopkins *et al.*, 2017). Additionally, the trace element chemistry of AVF7, a much thinner basaltic tephra occurring in all cores and dated at 31.04±0.9 ka (Hopkins *et al*., 2017), was an excellent match for the whole rock chemistry of Three Kings and this age was adopted by Hopkins *et al*. (2017). It seems, however, that the chemistry of earlier phreatomagmatic eruptions from Three Kings, which have recently been analysed (e.g. Brenna, 2018) may be a good correlation with AVF12 and therefore give an age consistent with the radiocarbon dates and known volume of Three Kings phreatomagmatic eruptions.

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QUIZ Know your maars.

Match photos A – G with names 1 – 7.

Names to choose from are:
1. Boggust Park
2. Lake Pupuke
3. Mangere Lagoon
4. Orakei Basin
5. Onepoto Basin
6. Pukewairiki
7. Styaks Swamp

(Answers on last page)















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THE SCORIA CONES OF PUKETONA/PUKETUTU VOLCANO, BAY OF ISLANDS

Bruce W. Hayward

In May 2019, Auckland Geoclub members obtained permission from the owner to visit the two scoria cones on the north side of Puketona Rd. These lie within the mid-late Pleistocene Kaikohe-Bay of Islands basaltic Volcanic Field in Northland (Fig. 1). We had viewed the cones from the road on several occasions, but they merely appeared to be two mounds of scoria with pre-European defensive earthwork modifications. The surrounding low-lying lava flows near the road are covered in heaps of stones that are clear indication of the area's extensive use by the pre-European Maori for growing kumara and other crops.

The first European to have commented upon the volcanic origin of the Puketona cones was geologist Charles Darwin, who used a Maori trail to get from Waitangi Falls to Waimate North mission station and back in December 1835 (Hayward, 2017a). On the walk, Darwin (1839) noted that the "soil is volcanic; in several parts we passed over shaggy lavas, and craters could clearly be distinguished on several of the neighbouring hills."

Name and age

Geologists have usually referred to this cluster of basalt cones as Puketutu Volcano (e.g. Kear, 1961) or Puketutu (Puketona) Volcano (e.g. Kermode *et al*., 1992). Ferrar (1925) labelled the larger cone north of Puketona Rd as Puketutu Pa and labelled a high greywacke peak south of the road as Puketona Pa. The official NZMS 260 map marks the larger cone on the north side of the road as Puketona Pa and for this reason I usually refer to this volcano as Puketona. Puketona has a single K-Ar date – a method that gives dates of questionable accuracy especially in the Quaternary. The age is 100,000 years +/- 60, 000 years (Smith *et al*., 1993).

How many cones or vents?

It has always been difficult to determine precisely where, and how many cones or vents there are in the Puketona Centre. This has not been made any easier by the extensive quarrying of both basalt and greywacke in Puketona Quarry since the late 1950s. Ferrar (1925) described them as "a group of well-preserved scoria cones, but did

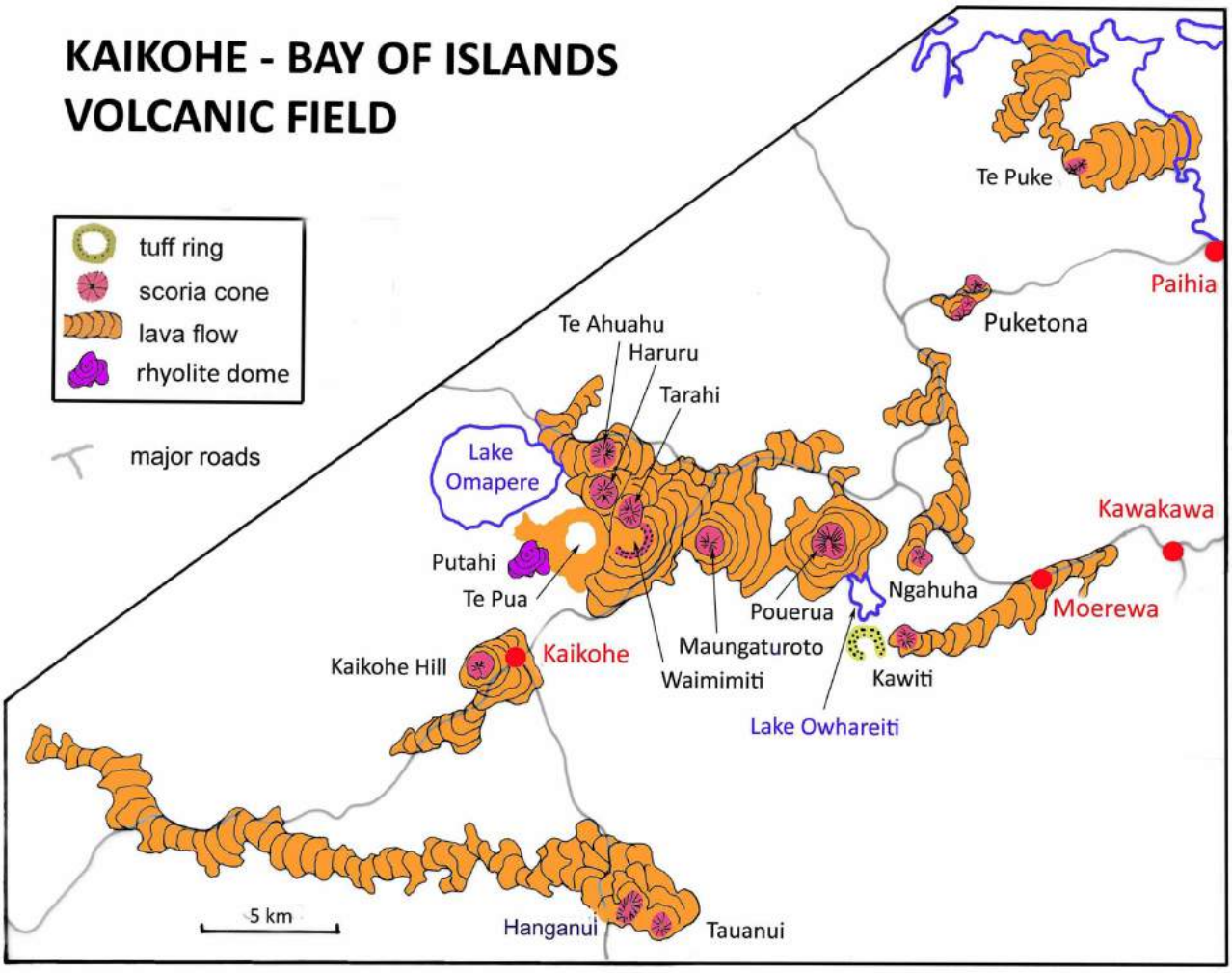


Fig. 1. Map of the young Kaikohe-Bay of Islands Volcanic Field showing the location of Puketona Volcano centre in the northeast.



Fig. 2. Google earth showing locations of the line of small Puketona scoria cones.

not delineate the cones from the young basalt flows on his map. Kear (1961) described the centre as containing "a number of scoria mounds" with no craters north of the road and several south of it. Kermode *et al*. (1992) say "there were two small cinder cones, one on either side of the road." Two years ago (Hayward, 2017b) I wrote that I thought there were six small scoria cones aligned along a small fault (Fig. 2).

Cones north of Puketona Road

The large, extensively terraced scoria cone on the north side of Puketona Rd (scoria cone 1) rises to 98 m above sea level (Fig. 3). During our visit, we determined that there is a small breached crater on the northwest side that has been slightly enlarged with a small quarry pit (Figs 4, 5). An elongate mound of scoriaceous basalt, located 50 m north of the U-shaped crater, would appear



Fig. 3. View NE from Puketona Rd to the two scoria cones on the north side of the road (peaks labelled 1 and 2).



Fig. 4. Oblique aerial view from the west over the two scoria cones north of Puketona Rd with the craters of the two cones labelled 1 and 2.

to be part of the cone that has been rafted away on the lava flow that formed the breach (Fig. 6). Southwest of the main scoria cone there is a second, smaller cone (2), which rises to 69 m above sea level. This has a perfectly circular, 2–3 m deep, 30 m-diameter crater (Figs 3, 6, 7) with the high point of the cone on the east side of the crater. Within the crater, there are several large volcanic bombs, including a 2 m-long spindle bomb (Fig. 8).

Cones south of Puketona Road

I have viewed this area from the road and by helicopter, but have not been able to ground truth my observations. From scoria cone 1 and from the air, a shallow vegetated crater of scoria cone 3 is visible on a north-facing slope south of Puketona Rd (Fig. 9). On the Lidar contour map (Fig. 10), it is 2–3 m deep and surrounded to the south by a high, arcuate ?scoria cone. The remains of a small quarry pit is present on the lower northeast side of this cone. Overlapping with scoria cone 3 on its southwest margin, is another small cone (4) which has had its lower western flanks quarried by Puketona Quarry. A semi-circular depression filled with trees is possibly this cone's crater (Fig. 9).

A large area of red scoria in the centre of the mouth of Puketona Quarry and 100 m south of the road indicates the site of scoria cone 5, where quarrying began in the late 1950s. A late 1950s air photograph (Kear, 1961, figure 8) shows this was a perfect small cone topped with an unbreached circular crater. On the southeast side of this quarried cone is a classic, small, unquarried, U-shaped scoria cone (6) with a breached crater facing out towards the road (northwest).

The six scoria cones are roughly aligned in a northeast–southwest direction (Figs 2, 11, 14). At the south end of this line and adjacent to cone 6 is a relatively high, grassed, conical peak. On google earth, it can be seen to be terraced around the upper parts. Is this peak made of greywacke or scoria? It needs to be ground checked. Ferrar (1925) mapped what appears to be this peak in red (= basalt). It is labelled pa on his map. There is no evidence on Ferrar's map, however, that he actually visited the cone, as there are no exposure observation crosses anywhere south of the road in this vicinity. Whether or not there is indeed a seventh small scoria cone at Puketona is still unknown.



Fig. 5. Ground level view from the NW into the breached crater of scoria cone 1 on the north side of Puketona Rd.

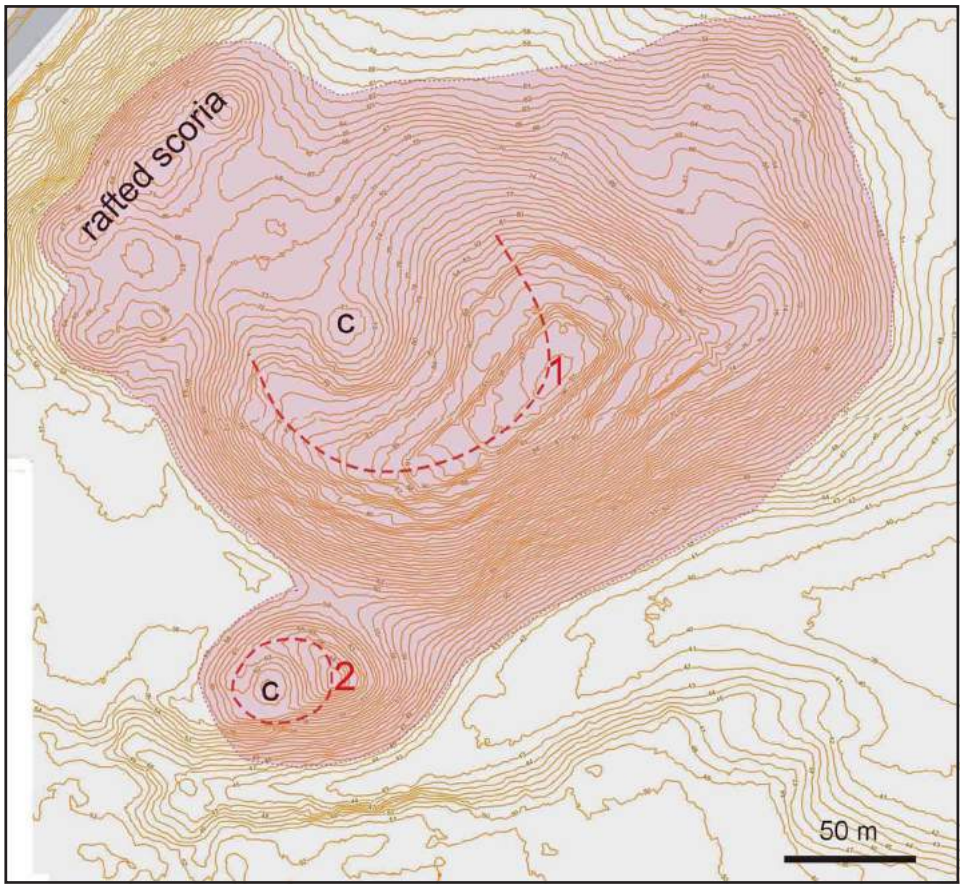


Fig. 6. Lidar map with 1 m contours showing the shapes of scoria cones 1 and 2 (peaks labelled) with their respective craters (c). The extent of the scoria cones is shaded pink.



Fig. 7. Geoclub members explore the crater of small scoria cone 2, north of Puketona Rd.



Fig. 8. Large volcanic bomb in the crater of scoria cone 2.



Fig. 9. Oblique aerial view over the entrance to Puketona Quarry to scoria cone 3 with its vegetation-filled crater (c) and cone 4 with its red quarried scoria on its lower western flank (right).

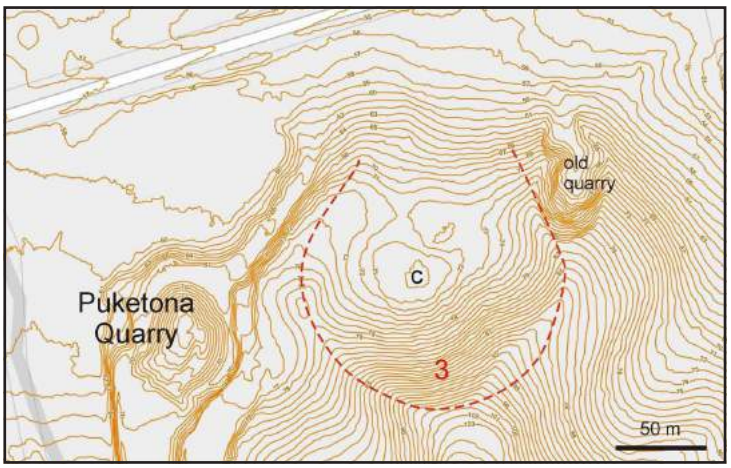


Fig. 10. Lidar map with 1 m contours showing the shape of scoria cone 3 with its crater labelled (c).



Fig. 11. View southwest across the middle part of Puketona Quarry showing the locations of scoria cones 4–7. Greywacke face in upper left.



Fig. 12. U-shaped scoria cone 6 with its breached crater, as seen from Puketona Rd.



Fig. 13. Oblique aerial view from the SW over U-shaped scoria cone 6 and the quarried site of cone 5 beyond.



Fig. 14. View SW from the top of cone 1 showing the crater of cone 3 and the conical hill that may be scoria cone 7.

Conclusion

Puketona (Puketutu) Volcanic centre comprises a northeast–southwest alignment of six, or possibly seven, small scoria cones. Vents 1–6 all have craters preserved. This northeast–southwest alignment likely reflects an upper crustal fault up which the basalt magma rose. On this same alignment to the northeast is Te Puke Volcano (with its four, northeast–southwest, small scoria cones) and to the southwest is large Pouerua Volcano (Fig. 1).

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OREWA DEEP DRILLHOLE, 1978

Bruce W. Hayward and Barrie C. Waterhouse (deceased)

The second author, Barrie Waterhouse, died in 2014 (Isaac and Hayward, 2014) and the first author was invited to help go through several boxes of Barrie's geological records with a view to determining what was worth keeping and what could be binned. One manila folder caught my attention. It was labelled "Orewa Deep Drillhole" and this brought back memories of my examining foraminiferal samples for Barrie soon after it was drilled in 1978. Sure enough, inside the folder I found a copy of my report (Hayward, 1978) and the original geological report by Barrie (Waterhouse, 1978).

The Orewa Deep Drillhole is significant because of the information it provides about the thickness of the Waitemata Group sequence that underlies the Auckland region. The thickness of Waitemata Group in this drillhole has been reported by Schofield (1989) and information on the basal Waitemata sequence encountered near the base has been given in Hayward and Brook (1984) and Hayward and Triggs (2016). The drillhole was put down by Drillwell Exploration in September and October 1978 in an attempt to get hot water, similar to that at Waiwera nearby to the north. The drillhole was drilled for Mr L. Harvey, the owner of a property he had recently acquired on the banks of Nukumea Stream at the north end of the Holocene flat behind Orewa Beach, North Shore (Fig. 1).

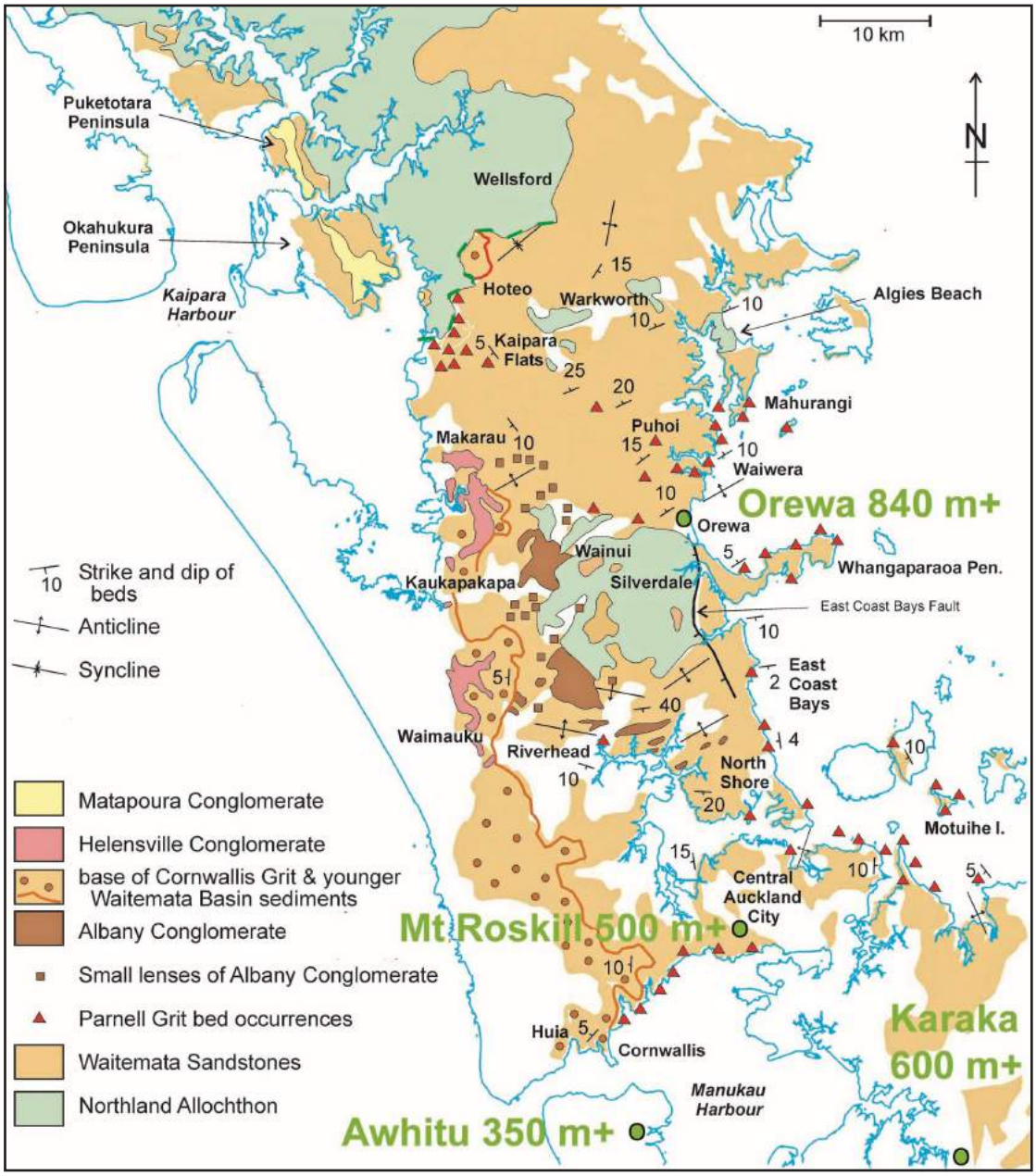


Fig. 1. Map of the early Miocene Waitemata Group geology of the Auckland region showing the location of the four drillholes that have penetrated the greatest thickness of Waitemata Group strata sitting on top of greywacke basement. The Waitemata Group thickness is shown. Modified from Hayward (2017).

Drillhole sequence (Waterhouse, 1978; Hayward, 1978)

0–801 m of alternating sandstone and mudstone (Waitemata Group, East Coast Bays Formation) with a microfossil fauna (R10/f13) containing 90–95% planktic foraminifera and benthic foraminifera, indicating deposition of these turbidite deposits at about lower bathyal depths (1000–2000 m) during the Otaian stage (Early Miocene).

801–811 m limestone and sandstone (Waitemata Group, Kawau Subgroup, Papakura Limestone) containing sparse recrystallised benthic foraminifera of the genus *Amphistegina* indicating high energy, inner shelf depths (0–50 m) of initial deposition. The deposit is inferred to have slumped into deeper water within the early Waitemata Basin.

811–827 m shelly grey siltstone (Waitemata Group, Kawau Subgroup, Tipakuri Sandstone) containing 15-20 % planktic foraminifera and a benthic foraminiferal fauna indicative of deposition at mid shelf depths (50–100 m).

827–839 m calcareous fine sandstone and siltstone (Waitemata Group, Kawau Subgroup, Tipakuri Sandstone) containing no planktic foraminifera and a sparse benthic foraminiferal fauna indicative of shallow inner shelf or beach deposition (0–20 m).

839–860 m quartz pebbly sandstone and calcareous sandstone with no microfossils. Possibly a non-marine deposit of the basal Waitematas (Kawau Subgroup).

860–875 m hard grey green greywacke (Waipapa Terrane basement).

This transgressive (deepening) sequence deposited during subsidence of the Waitemata Basin is similar to that observed in outcrop in places like Waiheke and Motuihe islands (Hayward and Brook, 1984, 1994). The sequence differs from that inferred nearby around Silverdale by Waterhouse (1966) and Schofield (1989), who believed that the Waitemata Group strata in this area were separated from the underlying greywacke basement by in-situ Oligocene deep-water Mahurangi Limestone and in-situ or displaced Cretaceous-Eocene sedimentary rocks. It is consistent, however, with the sequence inferred by Hayward (1982, 1993, 2017) with the Cretaceous-Oligocene deep-water rocks believed to be part of a large subseafloor landslide deposit sourced from the north that occurred within the Waitemata Basin and is located above the top of the Orewa drillhole sequence.

Thickness of Waitemata Basin sedimentary sequence

The thickness of 839–860 m of early Miocene near flat-lying Waitemata Group strata in the Orewa Deep Drillhole is the thickest sequence so far penetrated in the Waitemata Basin (Fig. 1). It is almost double the thickness of Waitematas then known (1978) from a Waiwera drillhole, (3.5 km to the north), which reached basement greywacke at 424 m depth (Waterhouse, 1968). It is thought that a northeast-southwest North Orewa Fault (Mansergh in Mansergh and Schofield, 1990) may separate these two drillholes with considerable uplift on the northwest side. Other drillholes that have drilled through Waitemata Group strata into basement and give a minimum depth of the basin-fill sequence have been at Awhitu (350 m; Waterhouse, 1989) on an upfaulted block (Kenny *et al*., 2012); Mt Roskill (500 m; Edbrooke *et al*., 1998); and Karaka (600 m; Hayward and Hornibrook, 1982).

The thickness of 860 m in the Orewa Drillhole is consistent with the results of apatite fission track and vitrinite reflectance studies on surface samples of Waitemata Group strata that indicate only shallow burial with temperatures no more than 60 degrees C and overlying sediment thickness of ≤ 1000 m (Raza *et al.*, 1999). Raza's samples were from the north Manukau coast and around St Heliers, and had an unknown thickness of Waitemata sedimentary rocks beneath, probably between 200 and 400 m (BWH inference). Thus a total thickness in the vicinity of Auckland Isthmus of no more than 1200–1400 m is indicated.

Orewa is about 25 km north of the isthmus and closer to the inferred northwest source of the turbidites and therefore the submarine fan could have had a slightly thicker sedimentary sequence than further south. At the south end of Orewa Beach, the Waitemata sequence is overlain in drillholes by displaced Cretaceous-Oligocene rocks (Onerahi Chaos Breccia of Kear and Waterhouse, 1967; Mansergh and Schofield, 1990) in addition to deformed Paremoremo Formation and Albany Conglomerate near Silverdale (Schofield, 1989). The thickness of this unit of displaced blocks and mélange (inferred seafloor landslide deposit of Hayward, 1982) is unknown and potentially highly variable, possibly 150–500 m thickness. Unconformably overlying these displaced rocks and outcropping to the west are about 400 m of proximal turbidite beds, conglomerate and deep-water mudstone (Cornwallis Formation, Helensville Conglomerate, Swanson Mudstone of Schofield, 1989) (Fig. 1). Combining these thicknesses gives a total Waitemata Basin fill in the vicinity of Orewa of 1400–1750 m (850 m + 150–500 m + 400 m). This is somewhat thicker than the 800–1000 m thickness for Waitemata Group strata that has usually been cited (e.g. Hayward, 2017) since the study of Raza *et al*. (1999).

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QUIZ ANSWERS

Know your maars.

1. Styaks Swamp
2. Boggust Park
3. Mangere Lagoon
4. Pukewairiki
5. Lake Pupuke
6. Onepoto Basin
7. Orakei Basin

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