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Commission on Tephrochronology (COT)

**Pre-conference Tephra Data Workshop**

**Hands-on session II:**

**Tephra excursion, Okareka Loop Road**

Sunday 29 January, Rotorua, New Zealand

**Excursion leaders**

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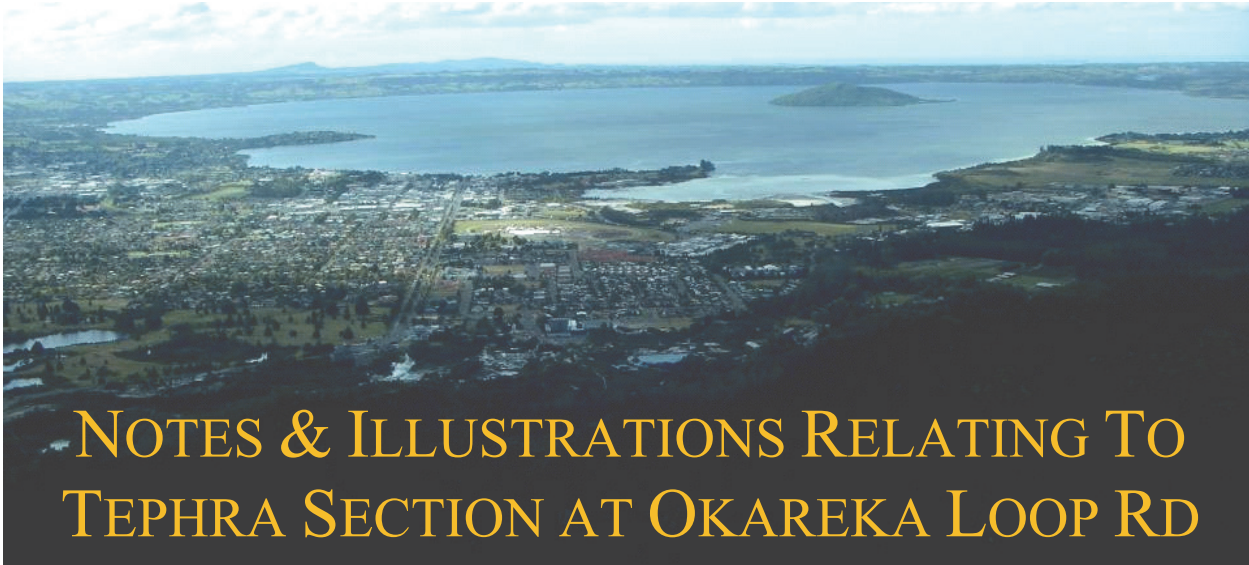


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## TephraSeismites

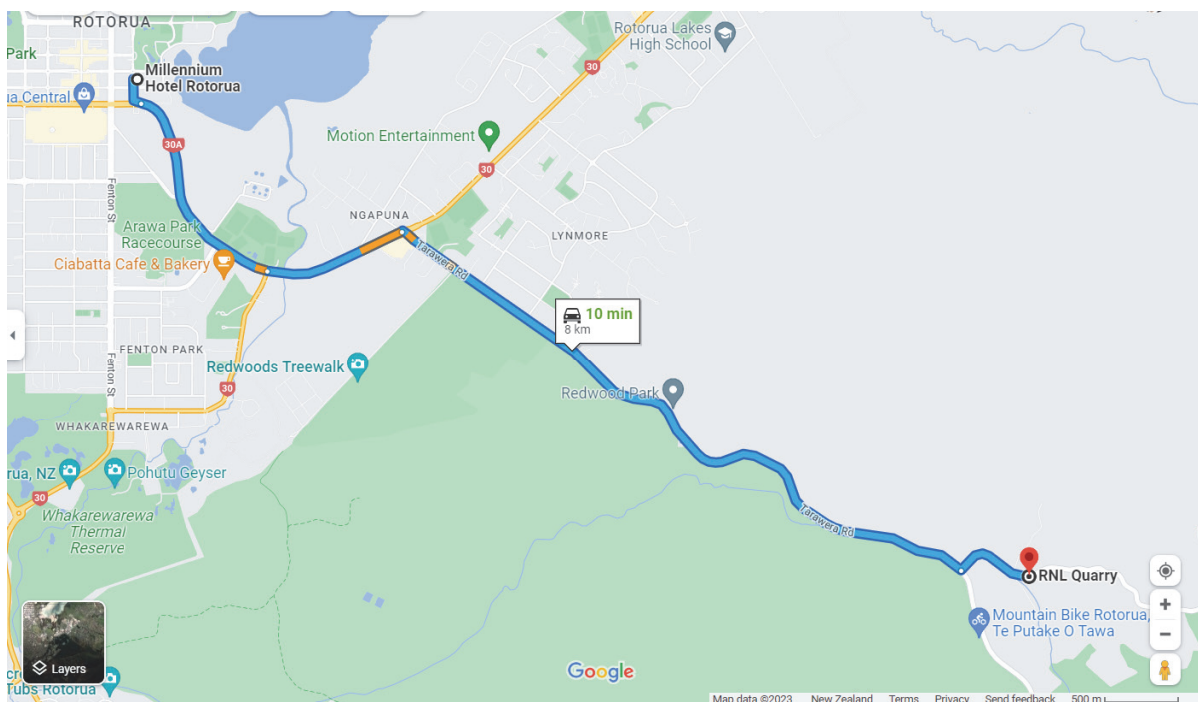
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### Itinerary and NZ tephra studies

We will travel to a section adjacent to the driveway of a pumice quarry (RNL Quarry) on Okareka Loop Rd. It is about 8 km from the Millennium Hotel in Rotorua (Figs. 1–3). Departure is at 8.15 am from the hotel; we aim to return by 1.00 pm. We have allowed 3–3.5 hours at the section, which is fenced off from the adjacent roadway. We have a mid-morning refreshment and toilet break scheduled at nearby Redwood Forest Visitor Centre (at the site marked “Redwoods Treewalk” on Fig. 1 below). Lunch location/timing to be advised.

A review of tephra studies in New Zealand has been prepared for the conference by Hopkins et al. (2021a). The first comprehensive modern tephra database for New Zealand was developed by Hopkins et al. (2021b). A review of global tephra studies, centred on the role and importance of the “Commission on Tephrochronology”, and including aspects of New Zealand work, is provided by Lowe et al. (2022). Ages and compositions of the main rhyolitic tephras in New Zealand younger than c. 50,000 cal yr BP are covered by (e.g.) Smith et al. (2005), Lowe et al. (2008, 2013), Danišik et al. (2020), and Hopkins et al. (2021a, b). A climate event stratigraphy – from the NZ-INTIMATE Project – is reported by Barrell et al. (2013). See also tables and diagrams later in the field guide.



**Fig. 1.** Main route for today’s excursion to RNL Quarry entrance, Okareka Loop Rd.



**Fig. 2.** Topographic map of the landscape southeast of Lake Rotorua (NZ Topo Map online). Arrow indicates field site.

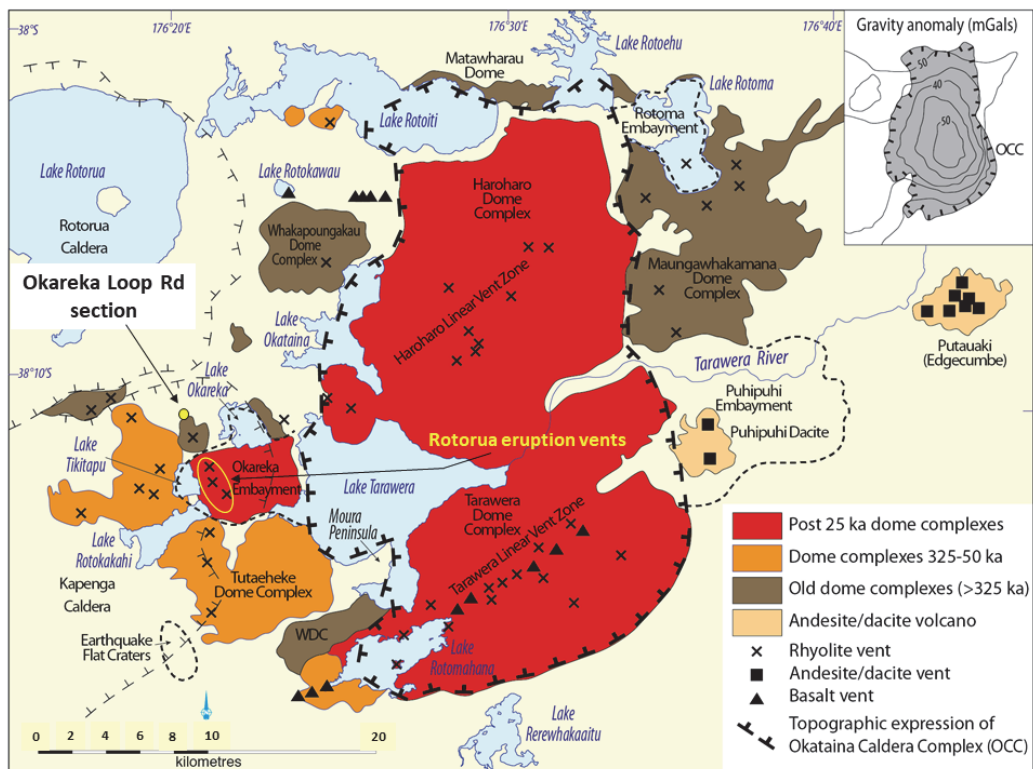


**Fig. 3.** Google Earth image showing Okareka Loop Rd and location of section at RNL quarry. The site is located at  $38^{\circ}10'7.19''$  S  $176^{\circ}19'29.25''$  E and is at  $\sim 450$  m asl. Modelled mean annual rainfall is from 1525 to 1654 mm.

At the section, we will see tephras derived from vents centres associated with the Okareka Embayment rhyolite domes (Fig. 4), as well as from the Tarawera Dome Complex and Rotomā Embayment (Fig. 5). These tephras (eight in total) are shown in Figure 6.



**Fig. 4.** Rhyolite domes associated with the Okareka Embayment and their relationship to ‘stop 4’ = entrance to RNL quarry. See map below for references.



**Fig. 5.** Okataina Volcanic Centre, including the Okataina (Haroharo) caldera complex, dome complexes and known volcanic vents including those for the Rotorua tephra as indicated in yellow (after Nairn 2002; Cole et al. 2010, 2014).



a



**Fig. 6.** Annotated photographs (a–c) showing the stratigraphy and ages of units at the Loop Rd section. The stratigraphy of pre-Rotorua tephra deposits (6c) partly follows Nairn (1992). In Fig. 6c, an angular unconformity lies at the base of the loess on the paleoslope alongside subhorizontal Okareka tephra. Within Okareka and Te Rere tephtras, thin iron pans and redox concentrations or segregations (Fe, Mn oxides), including blue-black pyrolusite, and redox depletions (low chroma colours, i.e. pale grey–white colours), are secondary redoximorphic features (Hewitt et al. 2021). The shower bedding in the Rotorua tephra contains numerous diastems (very short breaks in deposition). Photos: D.J. Lowe.

### General stratigraphy of Okareka Loop Rd section

The following units are evident in the sequence (Fig. 6) from the base upwards:

- (1) early tephras (Te Rere, 25.1 cal ka; Okareka, 23.5 cal ka) and thin interbedded loess within the remnant top of a small, buried hill-top at the base of the sequence;
- (2) the buried hill itself, the formation of which represents a period of erosion that occurred during the last glacial period, and remnants of a (reworked?) tephra draping the (paleo)hillslope (Rerewhakaaitu, 17.6 cal ka);
- (3) the thick (~4.5 m), bedded pumice lapilli tephra (with lithics) mantling the hill (Rotorua, 15.6 cal ka), the top of which is pedogenically modified to form a distinct orange soil (this orange soil material is evident throughout Rotorua basin and in road cuttings such as along SH 5 to the west of Rotorua); and
- (4) at least four younger tephras and soil horizons overlying the buried soil on the Rotorua tephra: Waiohau (14.0 cal ka), Rotomā (9.4 cal ka), Kaharoa (c. 1314 ± 10 CE/AD), and Rotomahana Mud (of the Tarawera eruption, 10 June 1886).

The thick Rotorua tephra is particularly distinctive here. The source vent(s) lie to the southeast beneath the Trig 7693 and Middle domes of the Okareka Embayment (Fig. 4). The isopach map (Fig. 7) shows how Rotorua tephra thickens closer to the vent(s), and also that much of it was dispersed towards the northwest (Nairn 1980). The tephra deposits to the northwest represent deposition from an early explosive phase of the Rotorua eruption sequence (phase 1 on the isopach map) involving a ~20-km-high plinian eruption plume that must have lasted for at least 3.5 hours, but no more than 3-4 days (Kilgour and Smith 2008). The unit A0 represents the phreatomagmatic, initial ash that is locally dispersed and not found beyond 5 km from the inferred vent area. The second phase of the eruption sequence, which lasted for 3–6 years, involved the growth of the Trig 7693 and Middle domes and intermittent explosive eruptions that seem to have generated thin tephra deposits blown to the southeast (denoted as phase 2 on Fig. 7) (Kilgour and Smith 2008).



**Fig. 7.** Isopach map for the Rotorua tephra (modified from Kilgour and Smith 2008; Lowe et al. 1999; Shane et al. 2003 and various references for the Waikato and Auckland regions) with thicknesses in centimetres.

The Te Rere tephra also derives from nearby source vent(s) in the Okareka Embayment (Fig. 4) beneath the Northern and Eastern domes (Nairn 1992). The remaining tephtras seen at the Loop Rd section are from the Tarawera Volcanic Complex, 15 km to the southeast, except the Rotomā tephra, which was derived from the Rotomā Rhyolite Complex, 25 km to the northeast (Fig. 5). The youngest tephra is Rotomahana Mud, deposited during the later part of the short-lived Tarawera eruption on the morning of 10 June 1886, that forms the land surface (see Rowe et al. 2021).

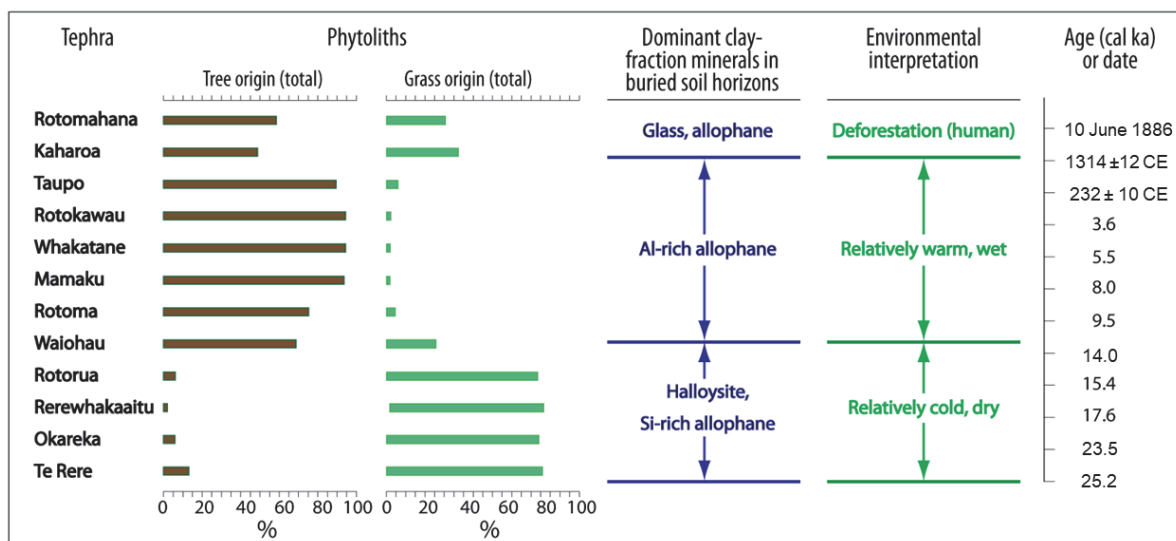
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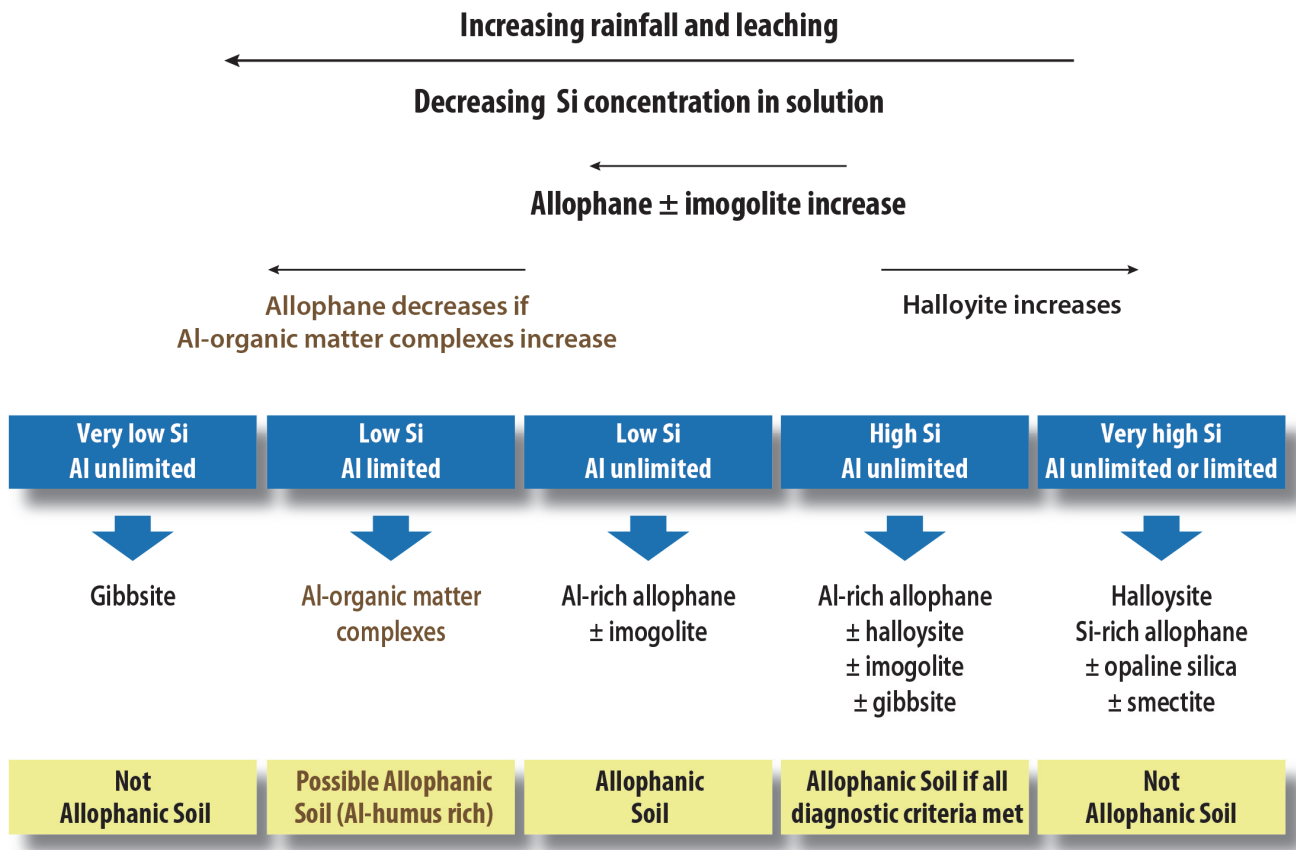
### Note about soil formation (pedogenesis) on tephra deposits, and stratigraphic importance

A distinctive feature of many tephra-derived soils is the multilayered nature of their profiles which attests to building up the landscape via the deposition of tephtras from numerous eruptions. The notes below mainly follow Hopkins et al. 2021a (p. 178–180).

Soils of the region are described by Rijkse (1979) and S-MAP ONLINE (<https://smap.landcareresearch.co.nz/>). The dominant weathering product in them is the nanocrystalline mineral, allophane ( $\pm$  ferrihyrite), together with halloysite formed under drier climates on older deposits (Churchman and Lowe 2012; McDaniel et al. 2012; Hewitt et al. 2021) (Figs. 8 and 9). Where allophane predominates, Allophanic Soils (*New Zealand Soil Classification*: Hewitt et al. 2010, 2021) or Andisols (*Soil Taxonomy*: McDaniel et al. 2012; Soil Survey Staff 2022) are the usual high-level classifications (orders).



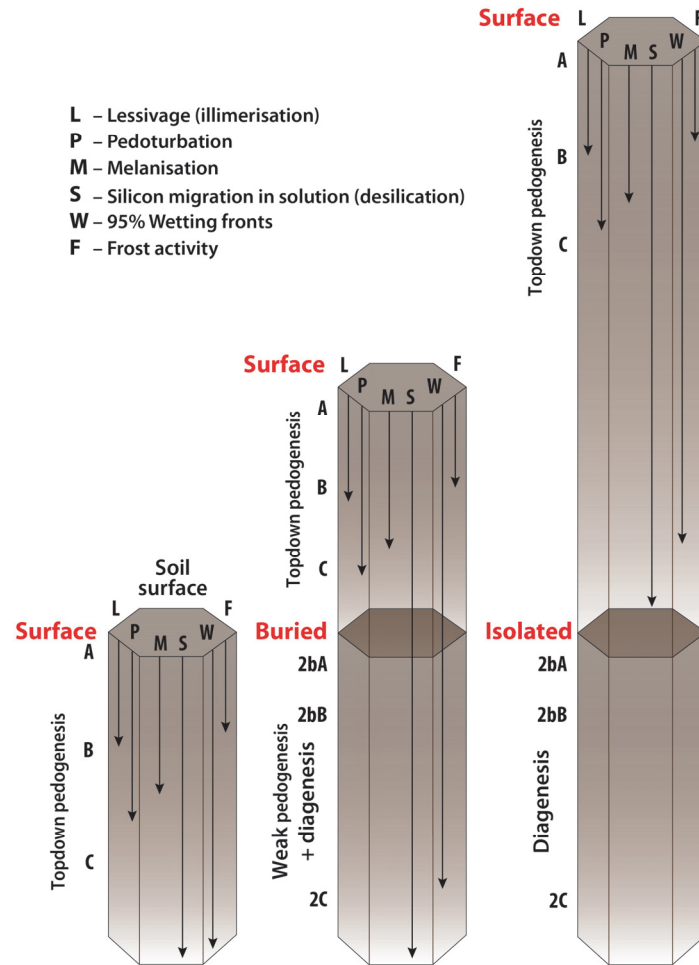
**Fig. 8.** Evidence of environmental change since c. 25 cal ka based on phytolith and clay mineral data from analyses of buried soil horizons on rhyolitic tephtras at Te Ngae, near Rotorua (after Churchman and Lowe 2012).



**Fig. 9.** Relationship between environmental conditions and the formation of allophane and other minerals on tephra deposits (and some other materials) according to the silicon-leaching model and the availability of aluminium (from Hewitt et al. 2021, after Churchman and Lowe 2012).

Almost all soil textbooks describe only the ‘classical’ formation of soil horizons in a profile through various processes that gradually deepen the profile as a downward moving ‘front’ on a pre-existing parent material on a stable land surface with nil (or negligible) additions to the surface. Such soil formation, referred to as *topdown pedogenesis*, proceeds by effectively modifying a pre-existing parent material to a greater or lesser extent according to a range of factors that dictate a range of processes and their impacts. In such a scenario, the soil profile originates via a two-step process: step 1, accumulation (or exhumation) of a ‘new’ parent material at the land surface, followed by step 2, the modification of the parent material by soil-forming processes and weathering, the latter mainly involving the dissolution of glass and crystals by hydrolysis and precipitation of the dissolution products as clays (Fig. 9) (e.g., Hodder et al. 1990; Churchman and Lowe 2012) to form soil horizons, thus generating a soil profile.

However, in North Island landscapes where tephra have been repeatedly deposited, many of the soils are formed by *upbuilding pedogenesis*. This is the ongoing formation of soil via topdown processes whilst tephra (or loess, alluvium, etc) are simultaneously added to the land surface. In this scenario, step 1 and step 2 occur together (not sequentially) so that the soil profile deepens as the land surface rises concomitantly over time. The profiles become multi-layered soils that reflect this interplay of geological versus pedological processes (Cronin et al. 1996; Lowe and Tonkin 2010; McDaniel et al. 2012; Hewitt et al. 2021). The frequency and thickness of tephra accumulation, and other factors, determine how much impact topdown processes have on the ensuing soil-horizon development and profile character. Where a thick tephra layer is deposited (e.g., ~50 cm or more), or the rate of accumulation of multiple thin additions is exceptionally rapid, the antecedent soil is suddenly buried and isolated at depth (becoming a buried paleosol) (Fig. 10), and soil formation begins again on the fresh materials at the new land surface. This process is *retardant upbuilding pedogenesis* (because the original soil’s development has been permanently ‘retarded’ by its sudden/rapid burial).



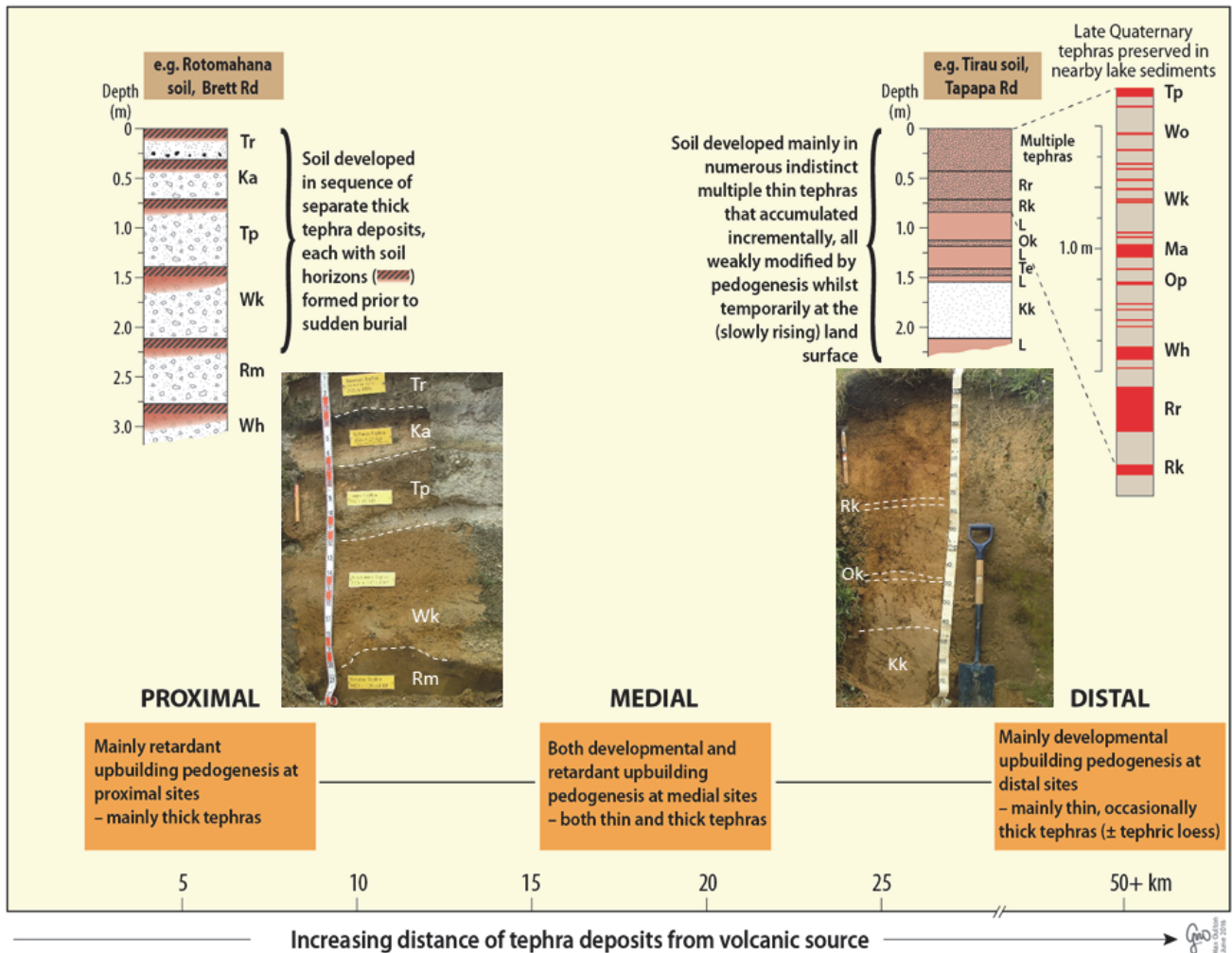
**Fig. 10.** Idealized model of the relative depth of burial of paleosols and their alteration by pedogenic processes acting from the surface downwards (arrows). Once a paleosol is isolated by relatively deep burial, any changes may be regarded as largely diagenetic, not pedogenic (Churchman and Lowe 2012) (modified after Schaetzl and Sorenson 1987).

In other situations, typically at distal sites where individual tephra-fall beds are usually thin (a few millimetres or centimetres in thickness), the rate of accumulation is incremental and sufficiently slow to allow topdown pedogenesis to keep operating as the land slowly rises. This process is *developmental upbuilding pedogenesis*. Figure 11 illustrates these two ‘end members’ (retardant vs developmental) of upbuilding pedogenesis.

The pivotal concept – concurrent deposition and pedogenesis – was originally proposed by Taylor (1933, p. 195), who stated that ‘soil-forming processes are continuous’ during the ‘slow addition of dust from eruptions of the intermittent type’. Thus, topdown pedogenesis continues whilst thin tephra and cryptotephra accumulate but its impacts are lessened because any one position in the sequence is not exposed to surface-dominated pedogenesis for long before it becomes buried too deeply for these processes to be effective (Hewitt et al. 2021). Thin tephra layers preserved in sediments of nearby lakes or bogs provide unequivocal evidence of persistent incremental tephra accretion to adjacent soil/land surfaces (Fig. 11, far right) (e.g., Alloway et al. 1992; Selby and Lowe 1992; Damaschke et al. 2017; Lowe 2019). This history thus leaves the profile with a weakly-weathered soil fabric inherited from when the tephra deposits were being modified at the surface as part of an A and/or upper subsoil (AC, AB, or Bw) horizon. The terms ‘developmental’ and ‘retardant’ upbuilding were coined by Johnson and Watson-Stegner (1987) and Johnson et al. (1990) as part of their dynamic-rate model of soil evolution whereby soils are envisaged to evolve by ‘ebb and flow’ through time (Schaetzl and Thompson 2015).

Note that buried soil horizons, even when only very weakly weathered, mark soil formation that took place when the tephra was at the land surface and stratigraphically represent a *disconformity*; the boundary between the top of a buried soil and the succeeding tephra deposit is a *paraconformity* that marks a period of non-deposition (Neall 1972; Howorth 1975; Hopkins et al. 2021a).

Can you see how the Okareka Loop Rd sequence displays the impacts of upbuilding pedogenesis, and how the buried soil horizons mark the passage of time and thus represent unconformities?



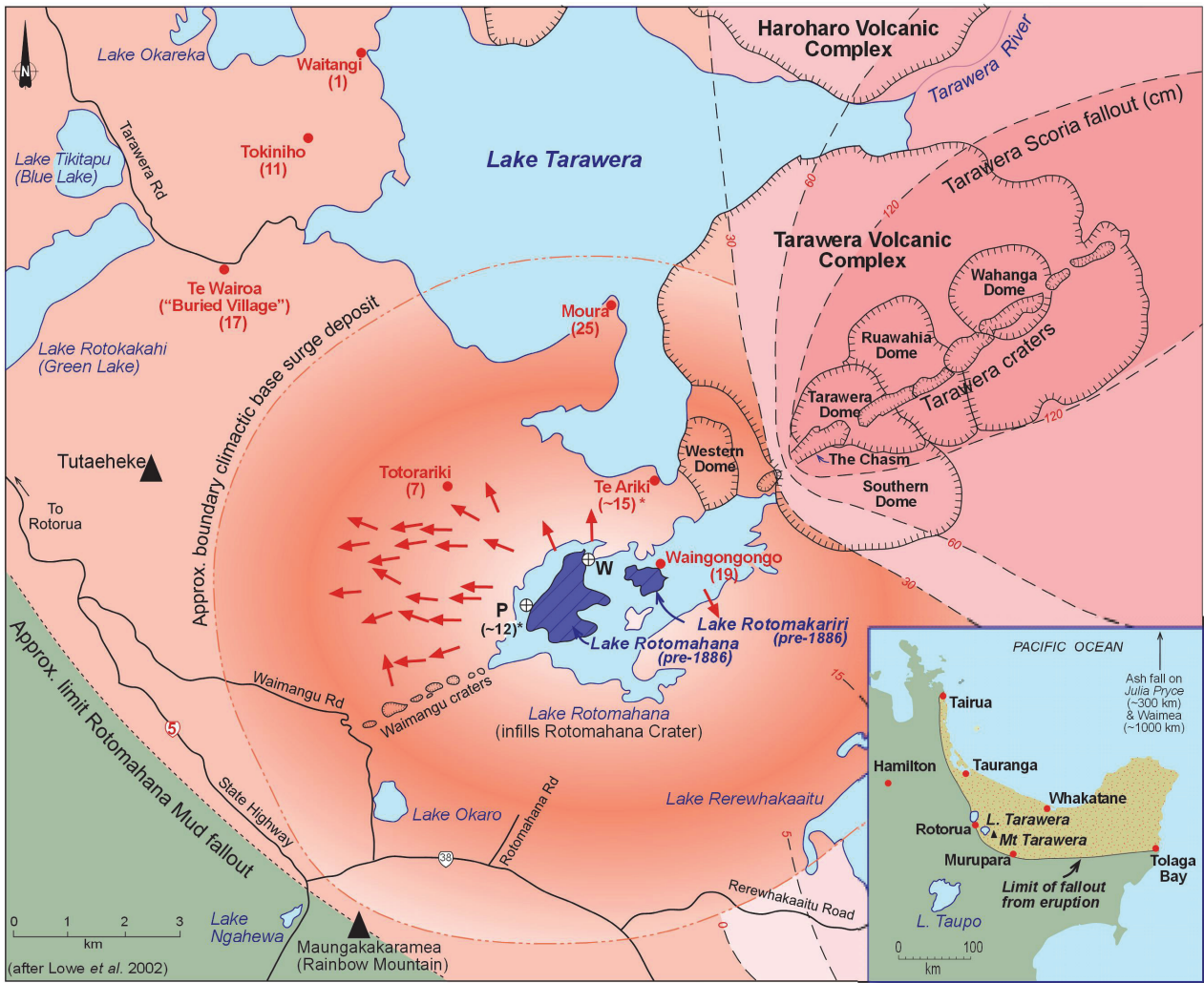
**Fig. 11.** Diagram illustrating the difference between retardant upbuilding pedogenesis (*Rotomahana soil* at left) at Brett Rd versus mainly developmental upbuilding pedogenesis (*Tirau soil* at right) at Tapapa Rd, and how these differences relate generally to tephra thickness and distance of site from volcanic sources. Tephra thicknesses usually decline exponentially away from source. Stratigraphy is after Huang et al. (2021). Core depicted at far right represents tephra layers (some of which are named) preserved in Lake Okoroire, which is ~10 km from the Tapapa Rd profile (Lowe 1988). Tephra abbreviations: Tr, Tarawera (Rotomahana Mud); Ka, Kaharoa; Tp, Taupo; Wo, Whakaipo (c. 2.8 cal ka); Wk, Whakatane; Ma, Mamaku; Op, Opepe (c. 10.0 cal ka); Rm, Rotomā; Wh, Waiohau; Rr, Rotorua; Rk, Rerewhakaaitu; Ok, Okareka; Kk, Kawakawa (Oruanui) (see Table 1). L = loess.

#### *Mainly retardant upbuilding pedogenesis*

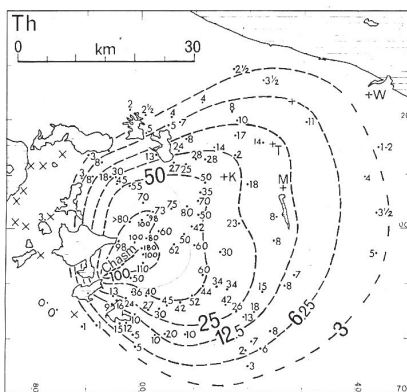
The Rotomahana soil at Brett Rd, which is adjacent to Lake Rerewhakaaitu near Mt Tarawera, represents essentially a stack of 'mini' soil profiles (each a buried paleosol), one atop the other. Five such 'mini soil profiles' are evident in the photo as indicated.

#### *Mainly developmental upbuilding pedogenesis*

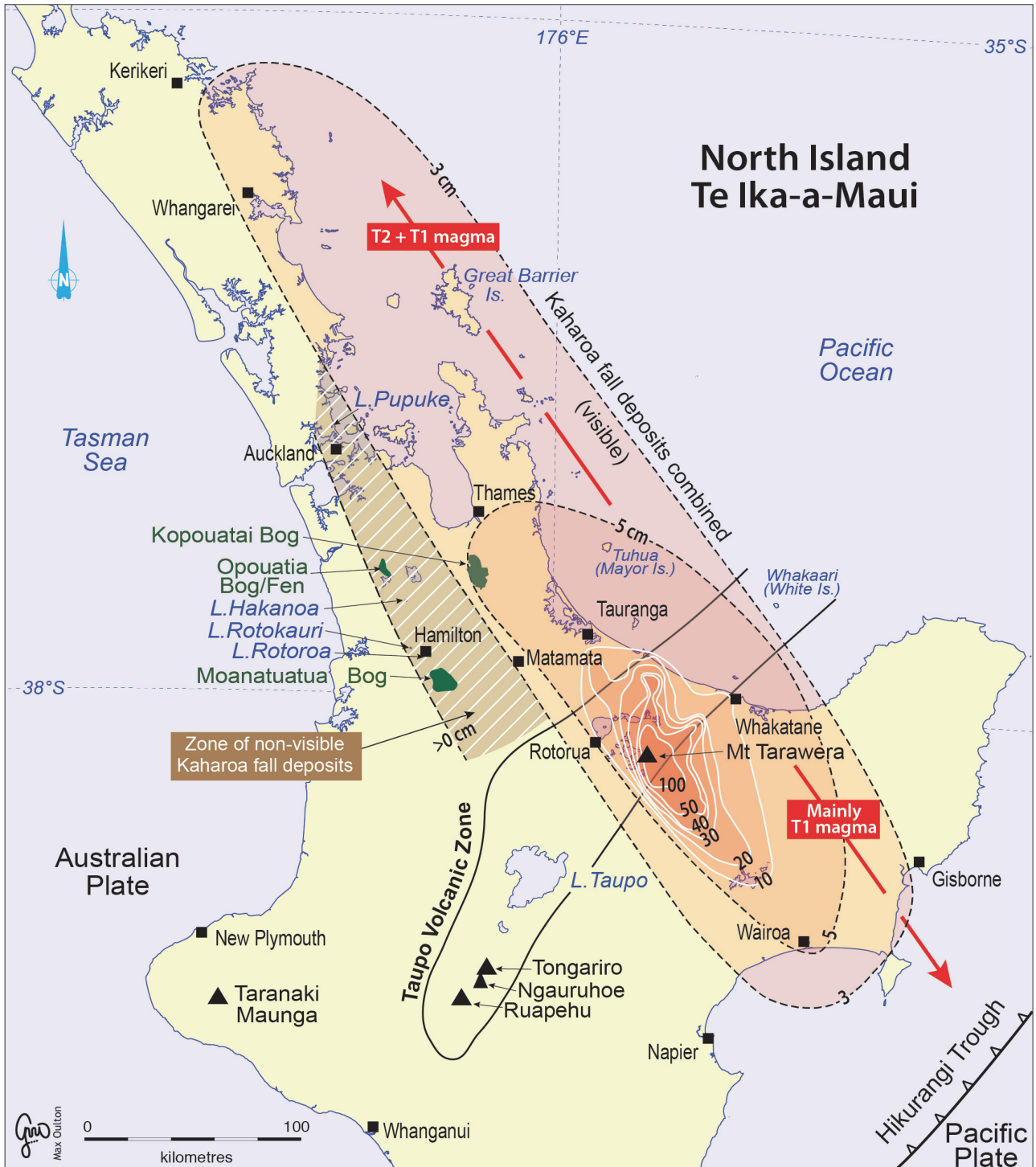
The Tirau soil at Tapapa Rd, which is in the eastern Waikato region and 'upwind' of the main tephra source volcanoes, represents mainly incremental, slow additions of tephra and/or loess to the land surface so that (weak) topdown pedogenesis has effectively kept pace as the land gradually rises. The rate of addition of tephra and loess to the land surface since Kawakawa tephra (Kk) was deposited averages ~6 mm per century (i.e. ~1500 mm in 25,400 cal yrs), comparable to slow loess deposition in some parts of New Zealand. A corollary is that every part of the profile (above Kk) has been a soil A horizon at one time.



**Fig. 12a.** Map of Tarawera area showing locations of the main craters of the 10 June 1886 fissure eruption across Tarawera Volcanic Complex, Rotomahana Crater (including pre-eruption lakes Rotomahana and Rotomakariri), and Waimangu craters (after Lowe et al. 2002). Locations of villages and associated fatalities (numbers in parentheses, total ~120) are based on Keam (1988) and Lowe et al. (2001) (there was an additional death at an unknown locality). Fatalities were all Māori apart from six Europeans at Te Wairoa and one European and three Māori at Waingongongo. On the night of the eruption nearly half of Te Arika's 27 residents were camped at Pink Terrace (Te Otukapuarangi). Inset shows eastern North Island and documented limits of tephra fallout from the eruption (based on maps by Thomas 1888). Ash fell on several ships at sea, the farthest being *Julia Pryce* (c. 300 km) and *S.S. Waimea* (c. 1000 km) north of North Island (Keam 1988). Lorrey and Wolley (2018) used historic data recorded during Ferdinand v. Hochstetter's 1859 survey to locate the sites of Lake Rotomahana's former sinter terraces (see also de Ronde et al. 2016, 2019; Keir 2019).



**Fig. 12b.** Isopach map of 1886 Tarawera scoria fallout (in cm). x = location where scoria occurs mixed with Rotomahana Mud but does not form a discrete layer (from Walker et al. 1984). See also Rowe et al. (2021).



**Fig. 13.** Isopach map of Kaharoa tephra fallout blown firstly southeastward then northwestward to generate the elongated lobate fallout pattern (after Pullar et al. 1977; Lowe et al. 1998; Sahetapy-Engel et al. 2014; Ratcliffe et al. 2020). Magma types based on Smith et al. (2005) and Shane et al. (2008) (see Table 3). The tephra isochron has been extended using cryptotephra occurrences in peats and lake sediments in the Waikato and Auckland regions (Gehrels et al. 2010; Newnham et al. 2018; unpublished data). The Kaharoa tephra provides an approximate settlement datum in northern New Zealand for early Polynesian arrival in the late 13<sup>th</sup> century CE (Newnham et al. 1998; Hogg et al. 2003; Lowe and Newnham 2004; Hopkins et al. 2021a).

**Table 1** Summary of main rhyolitic tephtras deposited in the Rotorua-Tarawera region during the last c. 25,400 cal years and their general physical properties.

Name* ( <i>source volcano</i> )	Date or age <sup>†</sup>	Description
Tarawera Tephra (Tr) ( <i>Tarawera</i> )	10 June 1886	Comprises basaltic scoria (Tarawera Scoria) with occasional rhyolite clasts and/or fine greyish brown ‘muddy’ ash (Rotomahana Mud). Mud was dispersed more widely than the scoria.
Kaharoa Tephra (Ka) ( <i>Tarawera</i> )	1314 ± 12 CE/AD (636 ± 12 cal yr BP)	Fine to coarse white to grey ash, with occasional dense (hard, hard-to-crush) pumice, rhyolite, obsidian and basalt lapilli. Contains abundant biotite. Black A horizon (contains charcoal from Polynesian and/or early European burning)
Taupo Tephra (also known as Unit Y) (Tp) ( <i>Taupo</i> )	232 ± 10 CE/AD (1718 ± 10 cal yr BP)	Creamy coloured coarse ash with plentiful shower-bedded pumice lapilli (crushable). Non-welded ignimbrite unit always associated with charcoal fragments.
Whakatane Tephra (Wk) ( <i>Haroharo</i> )	5526 ± 145 cal yr BP	Shower-bedded pale yellow coarse ash, overlying a fine to coarse rhyolitic (pale grey) ash. Rich in cummingtonite. Reddish-brown uppermost horizon (sometimes with basaltic Rotokawau tephra c. 4 cal ka).
Mamaku Tephra (Ma) ( <i>Haroharo</i> )	7940 ± 257 cal yr BP	Loose, coarse yellowish-brown pumice ash grading into a weakly shower bedded coarse ash/lapilli.
Rotoma Tephra (Rm) ( <i>Haraharo</i> )	9423 ± 120 cal yr BP	Shower-bedded fine grey to yellowish brown ash with coarse ash layers, cummingtonite. Marked by a dark Ah horizon at top, sometimes with charcoal, or podzolised.
Waiohau Tephra (Wh) ( <i>Tarawera</i> )	14,009 ± 155 cal yr BP	Grey fine and coarse shower-bedded ash. Distinctive v. fine cream ash layer at the base. Usually has well developed yellowish-brown or greyish upper soil horizon. Deposited a few centuries before late-glacial cool episode (NZce-3) <sup>§</sup> .
Rotorua Tephra (Rr) ( <i>Okareka embayment</i> )	15,635 ± 412 cal yr BP	Shower-bedded pumiceous yellowish lapilli or blocks (gravel/cobbles). Occasional rhyolitic lithics. Deposited at start of late-glacial mild episode (NZce-4).
Rerewhakaaitu Tephra (Rk) ( <i>Tarawera</i> )	17,496 ± 462 cal yr BP	Yellowish-brown ash grading down into tephric loess. Contains abundant biotite. Marks transition from Last Glacial to post-glacial conditions (Termination I); reafforestation of region occurred soon after deposition.
Okareka Tephra (Ok) ( <i>Tarawera</i> )	23,535 ± 300 cal yr BP	Yellowish brown ash contains abundant biotite. Typically encased in yellowish to olive brown tephric loess.
Te Rere Tephra (Te) ( <i>Okareka embayment</i> )	25,171 ± 964 cal yr BP	Yellowish-brown ash (typically encased in yellowish to olive brown tephric loess).
Kawakawa Tephra (Kk) (also known as Oruanui) ( <i>Taupo</i> )	25,358 ± 162 cal yr BP	Olive brown to pale yellowish-brown ash (typically encased in yellowish to olive brown tephric loess), always fine grained and somewhat ‘sticky’ in situ. Deposited just before interstadial D (NZce-9). Product of a supereruption (Barker et al. 2021).

\*Terminology is based mainly on Froggatt and Lowe (1990) and Wilson (1993, 2001). Bayesian-modelled ages mainly from Lowe et al. (2013), Vandergoes et al. (2013), and Peti et al. (2021). Descriptions generalised because character may differ from proximal to distal locations and from site to site. The region has additionally received distal tephtras from Taupō and Tuhua (Mayor Island) volcanic centres (Fig. 13) and has been ‘dusted’ regularly with andesitic tephra fallout from numerous eruptions at Tongariro Volcanic Centre and Egmont Volcano (Taranaki Maunga), most recently in the 1995-96 Ruapehu eruptions.

Ages are given in calibrated or calendar (cal) years (95% probability range) before present (BP), ‘present’ being 1950 in the <sup>14</sup>C timescale. Calendar dates for the Kaharoa and Taupō eruptions have been determined by dendrochronology and <sup>14</sup>C wiggle-match dating (Hogg et al. 2003, 2012, 2019). An *age* is reported in years BP (e.g., 14,000 cal yr BP) whereas a *date* is a calendrical date (e.g., 1314 CE/AD). *Note*: ka = x1000 years (e.g., 14 cal ka = 14,000 cal yr ago).

<sup>§</sup>NZ climate event stratigraphy of Barrell et al. (2013)

**Table 2** Ferromagnesian mineralogical assemblages and magma temperatures and oxygen fugacities of 22 marker tephras erupted since c. 30,000 cal. yr BP in New Zealand (from Lowe et al. 2008).

Tephra name	Relative abundances of ferromagnesian minerals <sup>a</sup>	Eruption temperature <sup>b</sup> (° C)	Oxygen fugacity $fO_2$ (NNO) <sup>c</sup>
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***Taupo Volcanic Centre (rhyolitic)*** (see Fig. 6)

Taupo (Unit Y)	Opx >> Cpx	862 ± 17	-0.17 ± 0.11
Whakaipo (Unit V)	Opx	785 ± 10	-1.06 ± 0.12
Waimihia (Unit S)	Opx >> Hbe	816 ± 10	-0.72 ± 0.08
Unit K	Opx	822 ± 16	-0.59 ± 0.11
Opepe (Unit E)	Opx >> Cpx	812 ± 18	-0.54 ± 0.17
Poronui (Unit C)	Opx >> Cpx		
Karapiti (Unit B)	Opx >> Cpx + Hbe	788 ± 33	-0.75 ± 0.24
Kawakawa/Oruanui	Opx > Hbe	774 ± 12	-0.14 ± 0.10
Poihipi	Opx > Hbe > Bio	771 ± 6	0.07 ± 0.10
Okaia	Opx > Hbe	789 ± 17	0.21 ± 0.09

***Okataina Volcanic Centre (rhyolitic)***

Kaharoa	T1 <sup>d</sup>	Bio >> Hbe >> Cgt ± Opx	731 ± 10	0.09 ± 0.14
	T2	Bio >> Cgt > Hbe ± Opx		
Whakatane	T1	Hbe > Cgt > Opx	746 ± 13	0.33 ± 0.09
	T2	Hbe > Cgt > Opx	737 ± 9	0.29 ± 0.11
	T3	Opx > Hbe > Cgt	770 ± 5	0.52 ± 0.05
Mamaku		Hbe > Opx >> ± Cgt	735 ± 19	0.18 ± 0.13
Rotoma	T1	Cgt > Hbe > Opx	752 ± 19	0.47 ± 0.12
	T2	Hbe > Opx > Cgt	752 ± 19	0.47 ± 0.12
	T3	Opx > Hbe > Cgt	752 ± 19	0.47 ± 0.12
Waiohau		Opx > Hbe	762 ± 23	0.36 ± 0.22
Rotorua	T1	Opx > Hbe >> Cpx	871 ± 10	1.11 ± 0.13
	T2	Bio > Hbe >> Opx	745 ± 30	0.17 ± 0.20
Rerewhakaaitu	T1	Opx > Hbe	721	-0.31
	T2	Hbe + Bio >> Opx	750 ± 18	0.43 ± 0.14
	T3	Opx > Hbe		
Okareka	T1	Opx + Hbe >> Cgt	759 ± 20	0.30 ± 0.20
	T2	Hbe + Bio >> Opx	724 ± 14	0.05 ± 0.15
	T3	Opx > Hbe	794 ± 12	0.82 ± 0.08
Te Rere	T1	Opx + Hbe	801 ± 24	1.43 ± 0.16
	T2	Opx + Hbe + Bio > Cpx	708 ± 3	-0.07 ± 0.01
	T3	Opx + Hbe		

***Tuhua Volcanic Centre (peralkaline rhyolitic)***

Tuhua		Aeg > Cpx > Opx ± Aen ± Rie ± Hbe ± Olv(fa) ± Tuh		
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***Tongariro Volcanic Centre (andesitic)***

Okupata		Opx > Cpx >> ± Olv(fo) ± Hbe	~900-1100	
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***Egmont Volcano (Taranaki Maunga) (andesitic)***

Konini		Hbe > Cpx >> ± Opx	~950	
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## Footnotes Table 2

<sup>a</sup>Opx, orthopyroxene (mainly hypersthene); Cpx, clinopyroxene (mainly augite); Hbe, hornblende; Cgt, cummingtonite; Bio, biotite; Aeg, aegirine; Aen, aenigmatite; Rie, riebeckite; Olv, olivine (fa, fayalite; fo, forsterite); Tuh, tualite.

<sup>b</sup>Pre-eruption temperature data (mean  $\pm$  1 standard deviation).

<sup>c</sup>Oxygen fugacity data reported in NNO units relative to the NiNiO buffer.

<sup>d</sup>T1–T3 represent separate magma types (early to late eruptive phases, respectively) identified by Smith et al. (2005) for some Okataina eruptive episodes.

**Table 3** Glass major element compositions of 22 tephras erupted since c. 30 cal ka (from Lowe et al. 2008).

	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	TiO <sub>2</sub>	FeO	MnO	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	Cl	H <sub>2</sub> O	<i>n</i>
<i>Taupo Volcanic Centre (rhyolitic)<sup>b</sup></i>												
Taupo (Unit Y)	75.04 0.19	13.45 0.12	0.30 0.04	1.99 0.08	0.07 0.03	0.22 0.10	1.47 0.05	4.49 0.12	2.85 0.07	0.19 0.01	4.63 1.85	19
Whakaipo (Unit V)	76.89 0.14	12.43 0.12	0.22 0.08	1.54 0.07	0.07 0.04	0.11 0.05	1.07 0.04	4.37 0.11	3.15 0.06	0.16 0.02	6.10 1.71	10
Waimihia (Unit S)	75.58 0.18	13.11 0.08	0.24 0.05	1.92 0.09	0.08 0.04	0.17 0.05	1.32 0.04	4.48 0.10	2.92 0.10	0.19 0.02	3.25 0.66	11
Unit K	75.83 0.32	12.81 0.11	0.26 0.08	1.64 0.16	0.03 0.03	0.14 0.05	1.30 0.07	4.86 0.13	2.98 0.08	0.16 0.03	5.63 1.05	9
Opepe (Unit E)	75.38 0.50	13.06 0.37	0.24 0.06	1.74 0.10	0.08 0.06	0.11 0.10	1.60 0.08	4.66 0.15	2.97 0.11	0.17 0.03	5.93 1.42	22
Poronui (Unit C)	76.26 0.30	12.91 0.16	0.19 0.04	1.57 0.12	0.03 0.02	0.16 0.04	1.45 0.16	4.14 0.15	3.15 0.15	0.15 0.03	2.92 0.94	10
Karapiti (Unit B)	76.16 0.33	12.75 0.12	0.20 0.06	1.57 0.12	0.06 0.05	0.11 0.08	1.42 0.10	4.42 0.15	3.14 0.08	0.16 0.03	6.26 1.88	18
Kawakawa/Oruanui	77.46 0.41	12.37 0.26	0.19 0.07	1.23 0.12	0.07 0.05	0.11 0.08	1.13 0.10	4.14 0.17	3.16 0.15	0.19 0.04	7.45 1.78	40
Poihipi	77.39 0.34	12.26 0.30	0.15 0.07	0.91 0.15	0.08 0.07	0.06 0.04	0.81 0.14	3.97 0.14	4.16 0.21	0.20 0.03	3.95 1.13	10
Okaia	77.50 0.34	12.42 0.21	0.18 0.06	1.29 0.10	0.04 0.04	0.10 0.06	1.20 0.09	3.90 0.14	3.28 0.10	0.19 0.02	5.99 2.36	19
<i>Okataina Volcanic Centre (rhyolitic)<sup>b</sup></i>												
Kaharoa												
T1 <sup>c</sup>	77.61 0.19	12.39 0.11	0.12 0.06	0.79 0.07	0.08 0.05	0.05 0.04	0.51 0.05	4.04 0.12	4.26 0.08	0.15 0.03	4.93 1.80	84
T2	77.75 0.18	12.32 0.07	0.13 0.05	0.82 0.07	0.07 0.05	0.05 0.04	0.58 0.05	4.01 0.13	4.13 0.05	0.15 0.03	1.83 0.50	30
Whakatane												
T1	77.84 0.20	12.24 0.11	0.16 0.07	0.85 0.09	0.07 0.05	0.09 0.06	0.77 0.05	4.22 0.13	3.67 0.08	0.16 0.04	2.94 1.48	98
T2	77.83 0.23	12.19 0.10	0.17 0.07	0.82 0.09	0.07 0.07	0.09 0.06	0.69 0.05	4.12 0.15	3.87 0.08	0.17 0.04	3.99 1.71	53
T3	77.83 0.27	12.19 0.07	0.19 0.07	0.88 0.15	0.07 0.04	0.12 0.06	0.85 0.05	4.17 0.12	3.52 0.09	0.15 0.04	2.43 0.73	19
Mamaku	78.15 0.15	12.15 0.08	0.16 0.02	0.89 0.06	0.06 0.02	0.01 0.01	0.76 0.07	4.03 0.09	3.69 0.16	0.13 0.01	na na	34
Rotorua												
T1	77.84 0.22	12.23 0.09	0.16 0.07	0.86 0.10	0.09 0.06	0.11 0.07	0.80 0.07	4.28 0.16	3.57 0.19	0.15 0.03	2.77 1.31	39
T2	77.76 0.21	12.30 0.10	0.18 0.07	0.90 0.08	0.07 0.05	0.14 0.07	0.83 0.05	4.26 0.23	3.45 0.08	0.16 0.04	3.06 2.07	38
T3	77.73 0.18	12.24 0.10	0.18 0.06	0.94 0.10	0.06 0.04	0.13 0.07	0.93 0.05	4.29 0.18	3.36 0.08	0.15 0.04	2.99 1.53	32
Waiohau	78.11 0.28	12.15 0.13	0.19 0.06	0.98 0.15	0.08 0.06	0.04 0.04	0.91 0.07	4.02 0.17	3.39 0.11	0.14 0.03	3.68 2.08	97
Rotorua												
T1	76.50 0.29	12.77 0.23	0.29 0.08	1.29 0.13	0.07 0.06	0.23 0.08	1.35 0.08	4.33 0.12	3.02 0.09	0.15 0.03	5.74 1.65	55
T2	77.34 0.20	12.32 0.06	0.14 0.12	0.87 0.12	0.09 0.07	0.08 0.05	0.76 0.11	4.03 0.11	4.26 0.16	0.15 0.03	4.82 1.52	34

	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	TiO <sub>2</sub>	FeO	MnO	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	Cl	H <sub>2</sub> O	<i>n</i>
<b>Rerewhakaaitu</b>												
T1	77.73 <i>0.22</i>	12.16 <i>0.11</i>	0.18 <i>0.07</i>	0.96 <i>0.09</i>	0.07 <i>0.05</i>	0.11 <i>0.07</i>	0.92 <i>0.06</i>	4.27 <i>0.12</i>	3.44 <i>0.09</i>	0.17 <i>0.04</i>	5.80 <i>1.47</i>	69
T2	77.36 <i>0.32</i>	12.27 <i>0.18</i>	0.13 <i>0.07</i>	0.91 <i>0.10</i>	0.06 <i>0.05</i>	0.10 <i>0.08</i>	0.82 <i>0.07</i>	3.96 <i>0.13</i>	4.21 <i>0.10</i>	0.18 <i>0.04</i>	6.07 <i>1.72</i>	66
T3	77.37 <i>0.31</i>	12.38 <i>0.15</i>	0.20 <i>0.08</i>	1.05 <i>0.10</i>	0.05 <i>0.04</i>	0.15 <i>0.06</i>	0.99 <i>0.08</i>	4.62 <i>0.12</i>	3.14 <i>0.06</i>	0.15 <i>0.07</i>	8.00 <i>0.49</i>	10
<b>Okareka</b>												
T1	77.81 <i>0.23</i>	12.31 <i>0.11</i>	0.18 <i>0.07</i>	0.90 <i>0.11</i>	0.08 <i>0.05</i>	0.11 <i>0.06</i>	0.76 <i>0.09</i>	3.87 <i>0.14</i>	3.81 <i>0.15</i>	0.17 <i>0.04</i>	6.88 <i>1.07</i>	27
T2	77.67 <i>0.21</i>	12.28 <i>0.08</i>	0.15 <i>0.07</i>	0.86 <i>0.08</i>	0.09 <i>0.04</i>	0.10 <i>0.05</i>	0.77 <i>0.05</i>	3.76 <i>0.09</i>	4.16 <i>0.05</i>	0.15 <i>0.02</i>	4.12 <i>1.75</i>	13
T3	77.76 <i>0.19</i>	12.20 <i>0.09</i>	0.21 <i>0.07</i>	1.02 <i>0.10</i>	0.07 <i>0.05</i>	0.18 <i>0.05</i>	1.02 <i>0.06</i>	3.97 <i>0.10</i>	3.43 <i>0.07</i>	0.14 <i>0.03</i>	3.76 <i>2.05</i>	37
<b>Te Rere</b>												
T1	77.37 <i>0.35</i>	12.48 <i>0.16</i>	0.21 <i>0.07</i>	1.03 <i>0.13</i>	0.09 <i>0.06</i>	0.17 <i>0.07</i>	1.00 <i>0.07</i>	4.30 <i>0.17</i>	3.19 <i>0.11</i>	0.16 <i>0.05</i>	3.99 <i>2.12</i>	209
T2	77.60 <i>0.30</i>	12.12 <i>0.21</i>	0.15 <i>0.06</i>	0.86 <i>0.10</i>	0.08 <i>0.05</i>	0.07 <i>0.04</i>	0.64 <i>0.12</i>	3.84 <i>0.35</i>	4.47 <i>0.24</i>	0.18 <i>0.05</i>	5.43 <i>1.36</i>	33
T3	77.22 <i>0.18</i>	12.53 <i>0.09</i>	0.30 <i>0.09</i>	1.00 <i>0.15</i>	0.06 <i>0.07</i>	0.19 <i>0.06</i>	1.23 <i>0.07</i>	4.20 <i>0.11</i>	3.15 <i>0.06</i>	0.12 <i>0.03</i>	1.89 <i>0.42</i>	11
<b>Tuhua Volcanic Centre (peralkaline)<sup>a</sup></b>												
Tuhua	73.40 <i>0.42</i>	9.57 <i>0.29</i>	0.26 <i>0.05</i>	5.89 <i>0.17</i>	0.15 <i>0.06</i>	0.05 <i>0.04</i>	0.25 <i>0.04</i>	5.94 <i>0.30</i>	4.28 <i>0.08</i>	0.25 <i>0.04</i>	4.14 <i>1.30</i>	58
<b>Tongariro Volcanic Centre (andesitic)<sup>c</sup></b>												
<b>Okupata</b>												
Hydro Access Rd	67.52 <i>1.00</i>	16.14 <i>1.08</i>	0.79 <i>0.19</i>	3.86 <i>0.66</i>	0.20 <i>0.06</i>	0.78 <i>0.14</i>	4.10 <i>0.59</i>	3.57 <i>0.27</i>	2.86 <i>0.21</i>	0.24 <i>0.04</i>	1.40 <i>1.30</i>	10
Kaipo bog	68.71 <i>1.23</i>	15.61 <i>0.84</i>	0.79 <i>0.11</i>	3.41 <i>0.25</i>	0.15 <i>0.09</i>	0.90 <i>0.10</i>	3.37 <i>0.69</i>	3.93 <i>0.16</i>	2.97 <i>0.16</i>	0.16 <i>0.04</i>	3.19 <i>2.21</i>	11
<b>Egmont Volcano (andesitic)<sup>f</sup></b>												
<b>Konini</b>												
Kaipo bog	65.24 <i>0.34</i>	17.40 <i>0.50</i>	0.72 <i>0.09</i>	3.25 <i>0.51</i>	0.21 <i>0.04</i>	1.03 <i>0.25</i>	2.79 <i>0.46</i>	4.97 <i>0.34</i>	4.23 <i>0.21</i>	0.19 <i>0.04</i>	2.16 <i>0.75</i>	8
Pukaki crater	64.31 <i>0.66</i>	17.02 <i>0.26</i>	0.73 <i>0.06</i>	4.03 <i>0.23</i>	0.20 <i>0.08</i>	1.32 <i>0.10</i>	2.86 <i>0.22</i>	4.58 <i>0.38</i>	4.72 <i>0.29</i>	0.21 <i>0.04</i>	0.70 <i>0.60</i>	10

<sup>a</sup>Analyses recalculated to 100% on a volatile-free basis and expressed as a mean and standard deviation (italics) in wt%. Total Fe as FeO, water by difference from original analytical total, *n* = number of shards analysed, na = not available. Analytical methods for rhyolitic and peralkaline tephra were described in Smith et al. (2005).

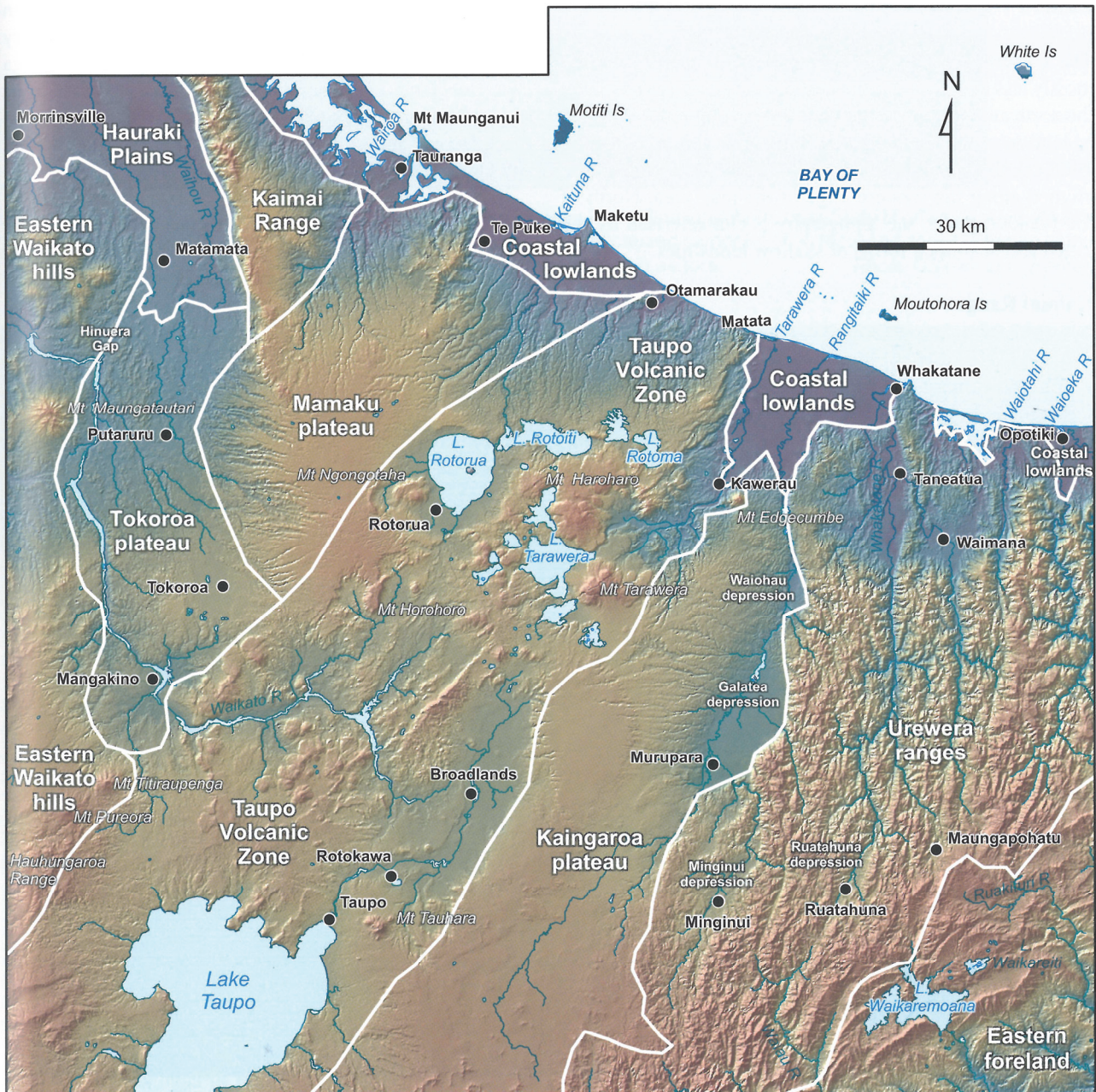
<sup>b</sup>Data for rhyolitic tephra all from Smith et al. (2005) except Okareka, Kawakawa/Oruanui, Okaia from P.A.R. Shane (unpubl. data). See also Smith et al. (2006) for data on Rotoma, Mamaku and Whakatane eruptions.

<sup>c</sup>T1–T3 represent separate magma types (early to late eruptive phases, respectively) identified by Smith et al. (2005).

<sup>d</sup>Data from P.A.R. Shane (unpubl.).

<sup>e</sup>Data from Donoghue et al. (1999) (Hydro Access Rd sample 10) and Lowe et al. (1999) (Kaipo bog, anal. 18).

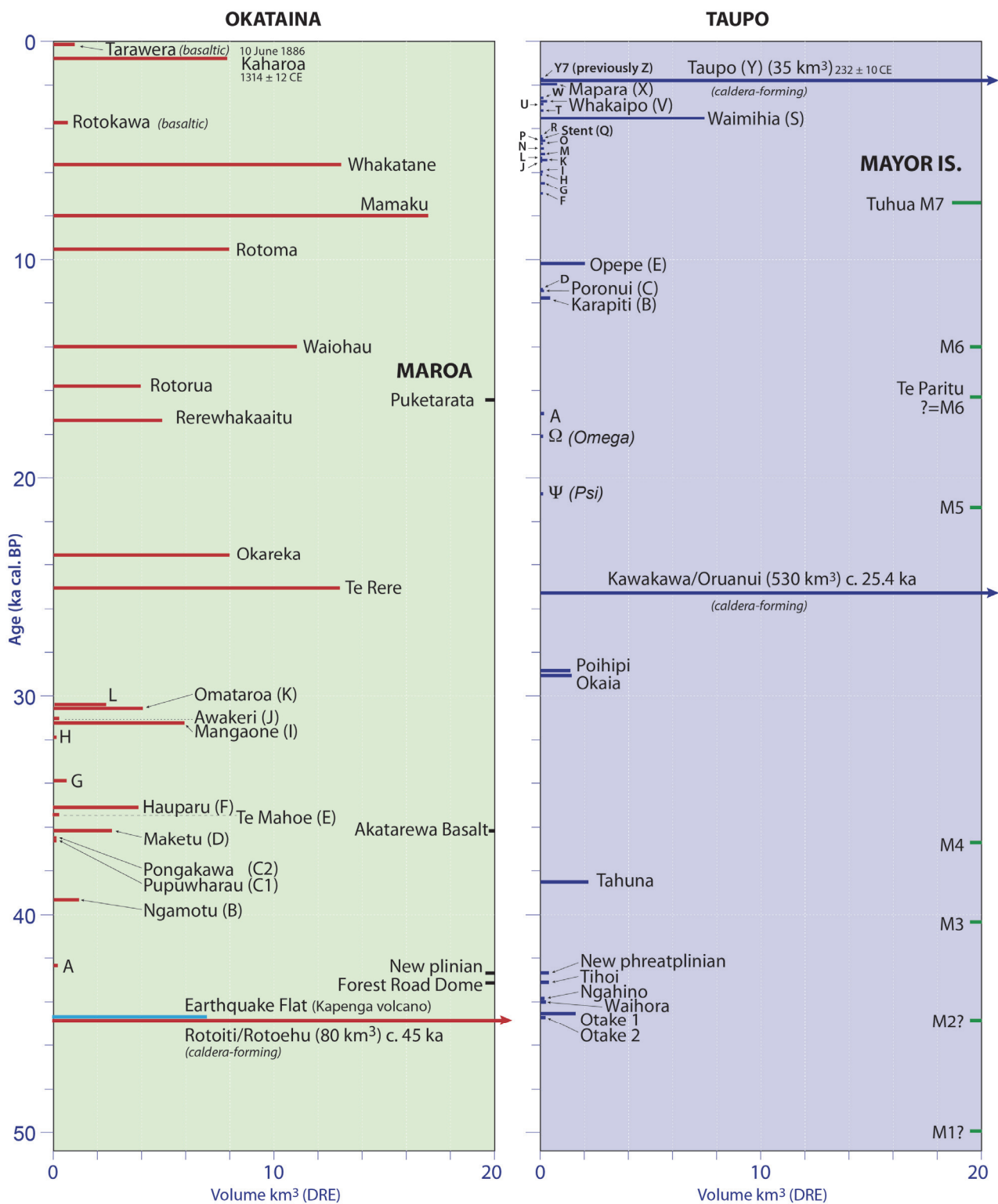
<sup>f</sup>Data after Lowe et al. (1999) (Kaipo bog, anal. 19a) and Sandiford et al. (2001) (Pukaki crater, anal. AT191).



**Fig. 14.** Topographic relief model illustrating the broad physiographic regions in the Bay of Plenty-Taupō region. The 'geomorphic' Taupō Volcanic Zone (TVZ) comprises an area of largely volcanic hills and lakes and covers a similar area (but not exactly equivalent) to the 'volcanologic' TVZ (defined by vent locations only) (from Leonard et al. 2010).



**Fig. 15.** Map of North Island showing the locations and ages of most of the main tephra-producing calderas, volcanic centres, fields, or stratovolcanoes (cones) active during the Quaternary or shortly before (from Hopkins et al. 2021a). The calderas in central Taupō Volcanic Zone (TVZ) are overwhelmingly rhyolitic with Mangakino and Taupō being supervolcanoes; Taranaki Maunga and Tongariro Volcanic Centre are andesitic; Tuhua (Mayor Island) is peralkaline rhyolite; and the locally distributed tephra from Auckland Volcanic Field are basaltic. The plate tectonic setting (Leonard et al. 2010) and various other features are also shown, including marine core locations in which tephra-fall deposits (including some cryptotephra) have been recorded. BF, buried forest at Pureora (see Hogg et al. 2012, 2019; Lowe and Pittari 2021); H, Haroharo Volcanic Complex; T, Tarawera Volcanic Complex.



**Fig. 16.** Stratigraphy, ages, and volumes (dense-rock equivalent, DRE) of eruptives derived from three rhyolitic centres in central TVZ (Okataina, Taupō, Maroa), and from Mayor Island (Tuhua), since ~50 cal ka. One eruptive (Earthquake Flat) from Kapenga Volcanic Centre is additionally depicted within the early eruptives of the Okataina sequence. From Hopkins et al. (2021a).



**Fig. 17.** Grey loess deposits ~4 m thick on Oturoa Road near Ngongatahā that were deposited in the last glacial coldest period between c. 31,500 and c. 15,600 years ago. Such loess is widespread around the Rotorua region. Named tephra layers provide ages (in thousands of years ago) for New Zealand climate events (NZce) 10, 8, and 6, being the coldest periods or stadials (Barrell et al. 2013). From Lowe et al. (2012, 2015). Age on Okareka tephra from Peti et al. (2021). Rerewh. = Rerewhakaaitu.

Based on calculations from 18 sites throughout New Zealand, and assuming minimal loss by erosion or dissolution, net accretion rates of loess since the eruption of Kawakawa (Oruanui) tephra c. 25,400 cal yr BP, and prior to the Holocene, have mostly been c. 3–10 mm per century (Lowe et al. 2015). The fastest rates are 15–25 mm per century where deposition was enhanced by turbulence, and the slowest is <1 mm per century (Eden and Hammond 2003). Rates of incremental loess accumulation – during which topdown pedogenesis continues – at this site and others in the Rotorua basin range from an average 5 mm per century (between Unit L and Kawakawa tephra), to 20–25 mm per century (from Kawakawa to Rerewhakaaitu tephra). At other sites loess deposition continued until the Holocene at an average of 10 mm per century (after Rerewhakaaitu tephra) (Lowe et al. 2012). These rates (~5–25 mm per century) are sufficiently slow for topdown soil-forming processes to continue to operate as the land surface gradually rises ‘millimetre by millimetre’, generating subsoil features that are only weakly developed. Such loess is thus a sediment-soil (Lowe and Tonkin 2010).

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