INTRODUCTION TO TEPHRA-DERIVED SOILS, NORTH ISLAND, NEW ZEALAND

Post-conference Andisol excursion, Waikato-Bay of Plenty regions
University of Waikato, New Zealand, and University of Wisconsin-Platteville, USA
21-23 December 2016

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Provisional itinerary

Wednesday 21 December: Mamaku Plateau-Rerewhakaaitu-Lake Tarawera

8.00 am Departure

1 Goodwin Farm, Tapapa Rd, Tapapa: welded ignimbrite, tephras, loess, buried soils (Tirau soil)
- stratigraphy of sequence (230 ka and younger) and upbuilding pedogenesis
- Tirau silt loam
2 Brett Rd, Rerewhakaaitu: Holocene tephras and buried soil (Rotomahana soil)
- Volcanic landscape, historical importance of area for NZ soil survey
- Stratigraphy of sequence (~9.5 cal ka to 10 June 1886 Tarawera eruption) and upbuilding pedogenesis
- Rotomahana sandy loam
3 Ash Pit Rd, Rerewhakaaitu: tephras and buried soils (Matahina soil [only if time])
- Matahina gravel
- buried spodic/podzol soil features
4 Okareka Loop Rd tephra section with proximal Rotorua Tephra and buried soils, loess
Buried Village Museum, Te Wairoa
Lake Tarawera (Stoney Point)

Thursday 22 December: Otorohanga-Waitomo Caves -Pirongia Mountain

8.30 am Departure

1 Raynes Road section: Ultisol in composite tephra sequence (Kainui soil)
2 Otorohanga Kiwi House
3 Waitomo Caves
4 Pirongia Mountain: Mangakara forest walk
5 Evening meal on an Andisol

Friday 23 December: Hobbiton, Hamilton gardens including Te Parapara (ancient Maori garden)

9.00 am Departure

1. Hobbiton tour 10.15 am (2 hrs)
2. Hamilton Gardens incl. Te Parapara Garden and human-modified soils (Tamahere soil)

Ma = millions of years ago; ka = thousands of years ago; BP = before present, 'present' being defined as AD [CE] 1950 for radiocarbon-derived ages. Radiocarbon (^{14}C) ages are given in calendar or calibrated (cal) years BP unless noted otherwise, or as calendrical dates (e.g. AD 232). The Holocene encompasses the last 11,700 cal years (Walker et al., 2009).

Introduction to volcanism and its products

Volcanoes are not only conical mountains, but span a very wide range of landforms. A volcano is any landform that results from molten rock (magma) being erupted at the Earth's surface. The size and shape of a volcano reflect how often it erupts, the sizes and types of eruptions, and the composition of the magma it produces. Magmas contain almost all of Earth's known chemical elements but typically they comprise only nine – silicon, oxygen, aluminium, magnesium, iron, calcium, sodium, potassium and titanium – that sum 98% or more by weight. Oxygen and Si together are generally the most abundant elements, making up 48–76 % by weight of most magmas. The chemistry of magma, especially Si content, is important for influencing the way it erupts, and three main magma types, and resulting volcanic rocks, are identified on the basis of their chemical composition. A fourth type, dacite, is usually grouped with andesites but is intermediate between andesite and rhyolite in composition (Smith et al., 2007).

- *Basalt* is rich in Fe and Mg and low in Si and erupts at very high temperatures (~1100–1200 °C) as a very fluid magma. Basalt magma with very little gas cools to form dark black, dense lava, but where magma erupts with lots of gas it cools to form ragged scoria or ash.

- *Rhyolite* magma is rich in Si, K and Na and erupts at temperatures between 700–850 °C as an extremely viscous magma. Rhyolite magma containing lots of gas bubbles cools to form pumice, but if the magma contains little gas it may form obsidian glass.

- *Andesite* (also *dacite*) magma is intermediate in composition and physical properties. Erupting at ~800–1000 °C it is more viscous than basalt, but much less viscous than rhyolite. Andesite magma cools to form dark grey lava if gas-poor or scoria or ash if gas-rich.

Volcanic eruptions vary remarkably in style and size. The smallest may just dust the summit of a volcano with volcanic ash, whereas the largest are capable of creating entirely new landscapes across whole countries. Although there is great diversity of volcanic behaviour, eruptions can generally be classed as one of two broad types – either explosive or effusive.

Explosive eruptions

Explosive eruptions are caused by gases violently ripping apart and shattering magma into pieces which cool and solidify into pumice (if the magma is rhyolite), scoria (if the magma is andesite or basalt), and volcanic ash (sand and dust-sized fragments mainly of volcanic glass). Explosive eruptions take place in one of two ways. The first involves gas that is contained within the magma at depth. As magma rises to the surface the drop in pressure causes these gases to bubble and expand violently. Close to the surface magma becomes like the foam that explodes out of champagne or a can of fizzy drink when first opened. The second type of explosive eruptions occurs when magma contacts water, either beneath the ground (at an aquifer) or at the land surface (either a lake or the sea). The very high temperature of magma (700–1200 °C) means that it instantly boils the water, causing violent steam explosions, which blow apart the magma, eject liquid water and steam, and rip up the ground containing the water. These types of eruptions are called phreatomagmatic eruptions.

In both types of explosive eruptions, the shattered magma and other rock fragments are carried violently into the air by the uprush of expanding gases, before settling back to the ground to form a pyroclastic (literally 'fiery fragmental') deposit. The more explosive the eruption the more energetic this roaring stream of gas, and the higher the tephra and rock fragments will be carried into the air. The higher the material goes, the further from the volcano it will be blown by the wind, and so there is a close correlation or relationship between the energy of an eruption and how far the eruption products are spread (Smith et al., 2007).

Effusive eruptions

Effusive eruptions occur when magma contains little gas and so cannot behave explosively, but instead quietly extrudes at the surface forming flows of lava. The very fluid basalt lavas can flow long distances forming extensive, almost flat volcanoes, whereas very viscous rhyolite lava piles up around the vent, like toothpaste squeezed from a tube, forming large, steep-sided mounds called domes.

Three different types of volcanoes in North Island

Although North Island's active volcanoes look quite different from one another, all can be grouped into one of three main landform types:

- classic cones or stratovolcanoes (e.g. Mt Taranaki, Mt Ruapehu)
- volcanic fields (e.g. Auckland Volcanic Field, South Auckland Volcanic Field); and
- caldera collapse craters (e.g. Taupo caldera, Haroharo caldera)

Each of these has obvious landforms and the violence and styles of eruptions are unique to each. These differences reflect the type of magma erupted: basalt at the volcanic fields, andesite at the cone volcanoes, and rhyolite at the calderas. During our trip, we will see mainly rhyolitic or dacitic deposits and landforms

Caldera volcanoes and eruptions

A caldera is a large, deep crater resulting from the caving in of a rhyolite magma chamber. In places the caldera walls can be seen as steep cliffs, but many are difficult to observe in the landscape because they may be filled in with erupted material or covered by water. Calderas have extremely violent origins and form when a vast amount of viscous rhyolite magma, bubbling with gas, erupts explosively from a magma chamber that may only be a few kilometres beneath the ground. During these eruptions, so much magma is erupted that the chamber empties, leaving the ground above it unsupported. This area collapses, dropping like a piston, to form a wide, deep depression. Lake Taupo, the area to the east of Rotorua known as Okataina, and Mayor Island or Tuhua, are three examples of recently active caldera volcanoes in New Zealand. Some older calderas exist in the area between Taupo and Rotorua and on the Coromandel Peninsula (see Fig. 2 below).

Rhyolite calderas may be active for several hundred thousand years, but large eruptions are rare, with typically thousands of years between events. Caldera collapse is not the only effect on the landscape arising from these large explosive eruptions. Huge quantities of pumice, ash and gas are pumped into the atmosphere, and through a combination of heat and momentum, a roiling column of this material may rise to over 50 km above the caldera. From this height, ash and especially aerosols – gases and tiny drops of acid – can spread around the globe, affecting the world's climate for several years. Closer to the caldera the landscape may be buried by metres of pumice. The most devastating process, however, occurs when this column of material falls back to earth like a fountain, then surges out in all directions from the caldera as a hurricane-like billowing, ground-hugging flow of hot pumice, ash and gas. These pyroclastic flows or 'density currents' can travel over 100 km at the speed of a racing car, leaving behind a layer of volcanic (pyroclastic) debris that might be more than 100 metres deep. Some flows are so hot (600-700 °C) and thick that the ash and pumice fragments weld back together, forming solid rock known as partially or densely welded ignimbrite (Smith et al., 2007).

Dome building

Eruptions from rhyolite volcanoes are not always so explosively catastrophic. A small amount of rhyolite magma may remain after a caldera eruption, which is exhausted of all gas and so can only ooze from the volcano slowly, often along the faults and fissures opened up by earlier caldera collapse. The very high viscosity means the silica-rich rhyolite lava will not flow far, and instead, piles up around the vent, like toothpaste squeezed from a tube, to form a steep-sided dome or dome complexes. These domes are prominent landscape features amongst the caldera volcanoes of the Taupo Volcanic Zone (TVZ) (Fig. 1).

Mokoia Island and Mt Ngongataha are rhyolite lava domes erupted within Rotorua caldera, and Mt Tarawera comprises a collection of lava domes erupted c. AD 1314 within Haroharo/Okataina caldera.

Defining tephra, ash, and lapilli

'Tephra' comes from a Greek word *tephra* meaning ashes, and is an all-encompassing term for the explosively erupted, loose, pyroclastic (fragmental) products of volcanic eruptions (Lowe, 2011). It includes all grain sizes ranging from the finest dust to blocks the size of cars. 'Ash' is not a burnt residue. Rather, it consists of particles <2 mm in diameter including rock particles (lithics), pumice, mineral grains (crystals), and glass shards. Grains 2–64 mm in size are called lapilli (lapillus for single grain), and particles >64 mm are called blocks if they are sharp and angular in shape, or bombs if they are partly rounded or smooth in shape.

Ash

Photo: C. Wilson

Lapilli

Block

Table 1 Tephra-related nomenclature in brief (from Lowe, 2011).

Term	Definition
Tephra	All the explosively-erupted, unconsolidated pyroclastic products of a volcanic eruption (Greek *tephra*, 'ashes')
Cryptotephra	Tephra-derived glass-shard or crystal concentration, or both, preserved in sediment (including ice) or soil and not visible as a layer to the naked eye (Greek *kryptein*, 'to hide')
Tephrostratigraphy	Study of sequences of tephra layers and associated deposits, their distribution and stratigraphic relationships, and their relative and numerical ages. Involves defining, describing, characterizing, and dating tephra layers in the field and laboratory
Tephrochronology (*sensu stricto*)	Use of tephra layers as isochrons (time-parallel marker beds) to connect and synchronize sequences and to transfer relative or numerical ages to them using stratigraphy and other tools. An age-equivalent dating method
Tephrochronology (*sensu lato*)	All aspects of tephra studies and their application
Tephrochronometry	Obtaining a numerical age or date for a tephra layer

Quaternary volcanism in Taupo Volcanic Zone

The highest concentration of Quaternary volcanic activity in New Zealand occurs in the TVZ. This narrow band of cone and caldera volcanoes extends from Ruapehu in the south, over 240 kilometres to Whakaari (White Island) in the north, with the Taupo, Okataina, Rotorua and other calderas nestled between. Some of the planet's largest and most violent volcanic eruptions have occurred from this zone, as well as New Zealand's most recent small eruptions (Ruapehu 1995-1996, Whakaari 2000, Te Maari craters on Tongariro 2012). Volcanism occurs in the TVZ, and at Taranaki, because of subduction of the Pacific tectonic plate beneath the North Island. As this plate descends and is heated, water and other fluids are boiled off and stream into the mantle rocks under the North Island. These fluids cause chemical changes that enable the otherwise solid rock of the mantle to melt, forming basaltic magma. This magma rises until, because of its higher density, it gets trapped underneath the continental crust of the North Island. Here the very hot basalt magma acts like a gigantic blow-torch, melting the crust and mixing with it to form andesite magma, which is then erupted as cone volcanoes. Where enough melting of the continental crust occurs, rhyolite magma forms, generating caldera volcanoes (Smith et al., 2007).

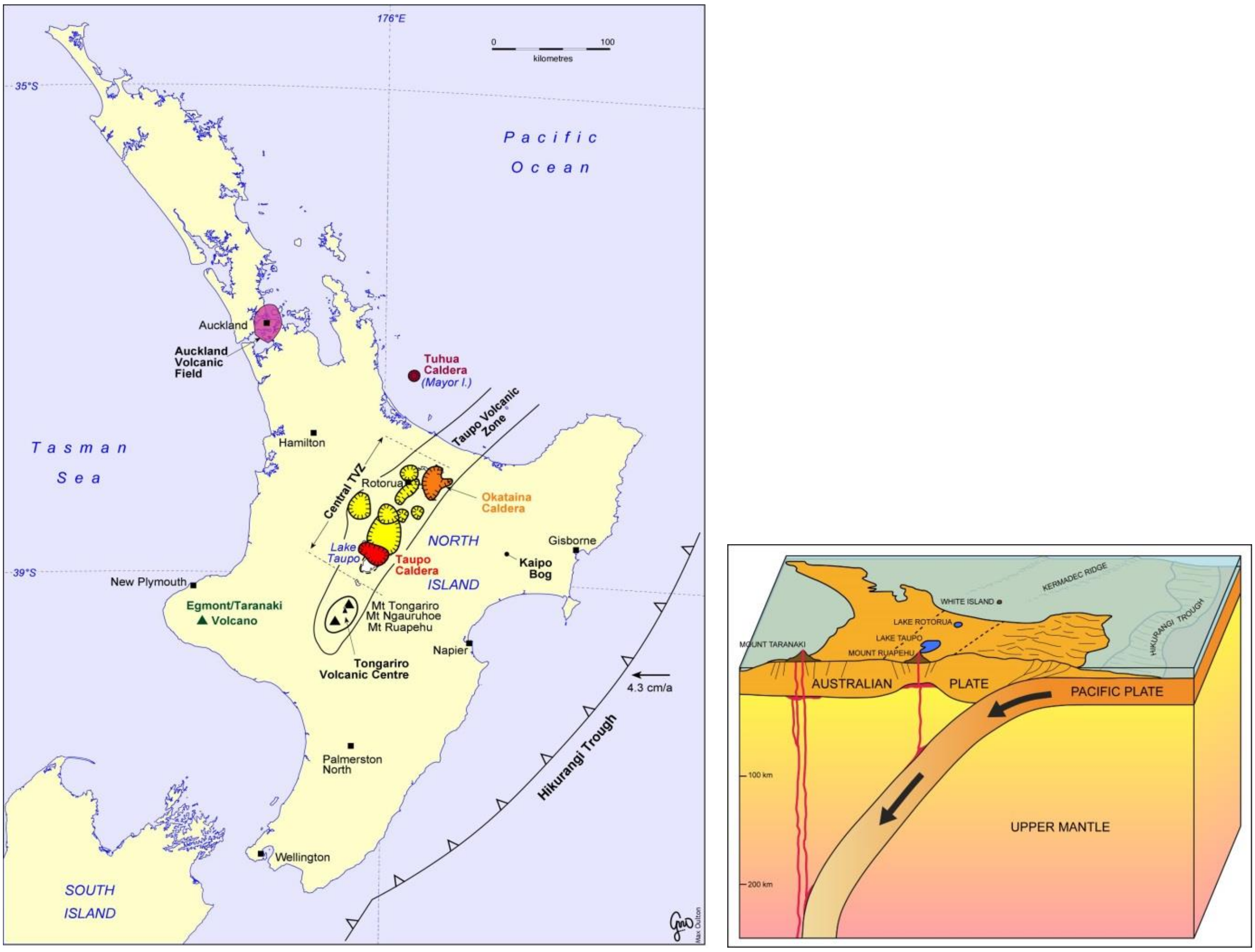


Fig. 1 Simplified North Island plate tectonic setting and main volcanic centres and caldera volcanoes active in the Quaternary (based on Leonard et al., 2010). North Island lies entirely on the Australian Plate. Diagram at right courtesy of Adrian Pittari.

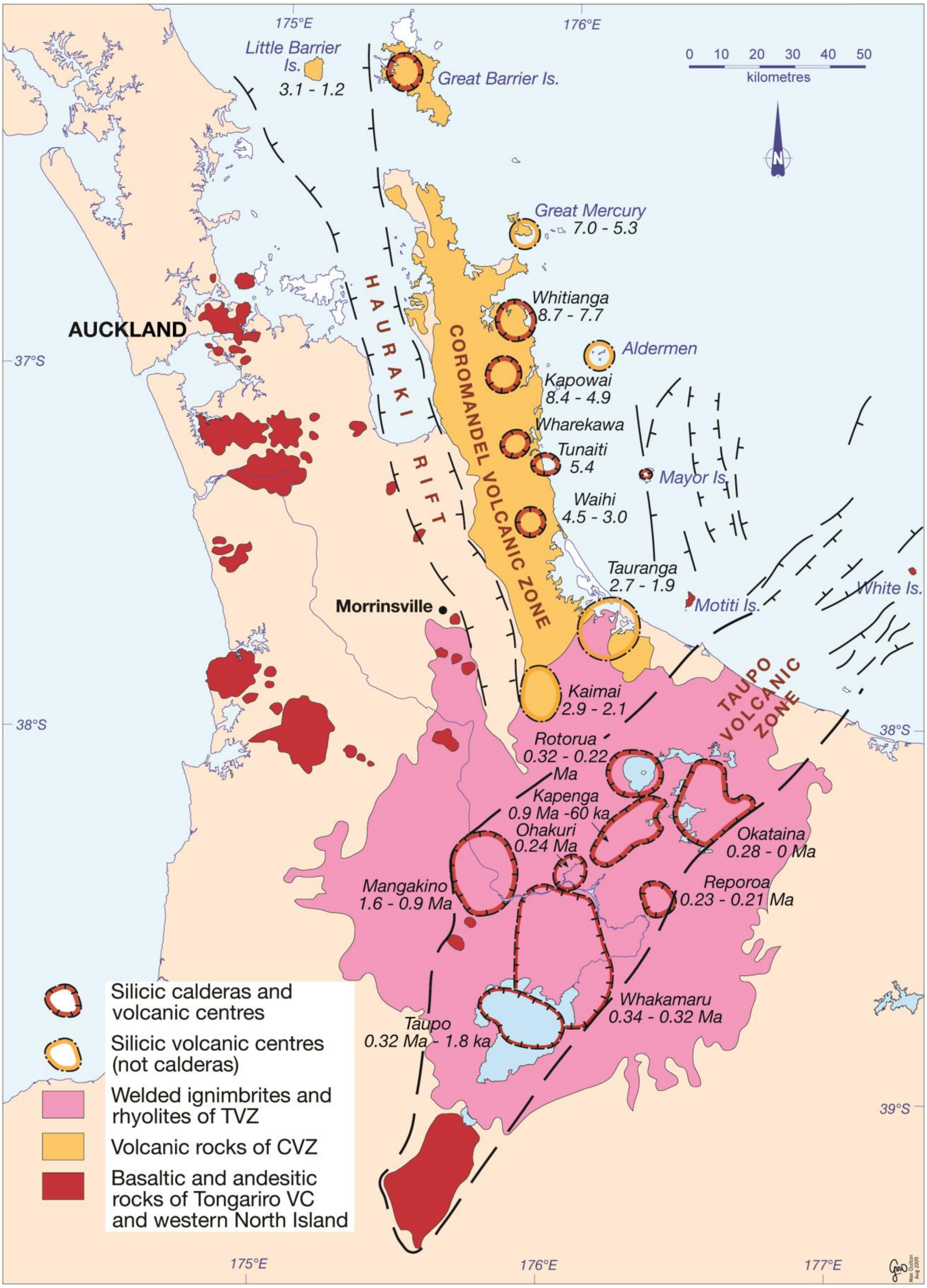


Fig. 2 Volcanic centres and the ages of activity and rocks (including welded ignimbrites) of central North Island.Diagram courtesy of Roger Briggs (after Briggs et al., 2005).

TVZ

The TVZ comprises three distinct parts (Fig. 1). A southern part, dominated by andesite cones, includes the active Ruapehu and Tongariro volcanoes and the probably extinct Pihanga and Tihia-Kakaramea cones. A northern part, which is also dominated by andesite stratovolcanoes, includes the active Whakaari (White Is.) and mid-Holocene Putauaki (Edgecumbe), and the much older, deeply eroded cones of Motuhora (Whale Is.) and Manawahe. These two stratovolcano clusters book-end the third and largest central part of the zone, extending from Turangi north to the Rotorua lakes district. This area is dominated by rhyolite calderas, including the highly active Taupo and Okataina volcanoes (Figs. 1-2), and older calderas including Mangakino, Kapenga, Whakamaru, Reporoa, Rotorua, and newly-identified Ohakuri caldera (Gravely et al., 2007). The origins and extent of Rotorua caldera are debated. Large explosive eruptions over the last 2 million years or so from this nested collection of rhyolite volcanoes have produced a huge volume of pyroclastic deposits, which when loose are called tephras (Table 1), and many of the older volcanoes cannot be seen in the landscape because of burial underneath hundreds of metres of volcanic material from more recent eruptions. The products of these caldera eruptions are most obvious as the extensive plateaux flanking the western and eastern sides of the TVZ, which erosion reveals to be made up of many layers or sheets of ignimbrite, pumice, and tephra fallout layers. However, caldera eruption products are found far beyond the more obviously volcanic landscape of the central North Island. If we consider a volcano as including all the material erupted from it, then in a sense the entire area from Auckland to Hawkes Bay is part of a huge caldera volcano centred on TVZ.

Introduction to Taupo Volcanic Centre and the Taupo eruption

Taupo volcano (Fig. 2) is the most frequently active and productive rhyolite volcano on Earth. Activity began after the eruption of the widespread and voluminous c. 340 ka Whakamaru group ignimbrites, including widespread Rangitawa tephra from Whakamaru caldera. Modern activity began c. 50 ka with nearly 40 eruptions recognised (Fig. 3). These were overwhelmingly pyroclastic (>95%) and from vents mostly now concealed beneath Lake Taupo (Wilson et al., 2006). Pyroclastic deposits exposed in the Taupo-Maroa area represent 11 eruptions from c. 50 ka to c. 25 cal ka, and then the phreatomagmatic Kawakawa/Oruanui eruption occurred at c. 25 cal ka. This super-eruption was extremely voluminous with a total dense-rock equivalent (DRE) volume of ~530 km^3 (equivalent to nearly 1200 km^3 as bulk pyroclastic material) (Wilson et al., 2006), and it generated one of the most widespread and stratigraphically useful tephra-fall deposits in the New Zealand region (Wilson, 2001; Wilson et al., 2006; Lowe et al., 2008, 2013; Holt et al., 2010). Caldera collapse associated with this eruption generated most of the modern outline of the basin now partly filled by Lake Taupo, and much of the central North Island landscape was changed as a consequence of the eruption (Manville, 2002; Manville and Wilson, 2004; Wilson et al., 2009).

Since the Kawakawa eruption (also known as the Oruanui eruption, hence now referred to as Kawakawa/Oruanui event), there have been a further 28 eruptions, all but three taking place in the last 12,000 cal years. The most recent (apart from lava extrusion of eruption Z) was the extremely powerful 'ultraplinian' caldera-forming Taupo eruption event (Wilson and Walker, 1985; Wilson, 1993) (Table 2). Wilson (1993) erected a volcanological nomenclature for these 28 events beginning with ψ (the oldest) followed by Ω, A, …, and Z. Other names are also used for some of them (Froggatt and Lowe, 1990).

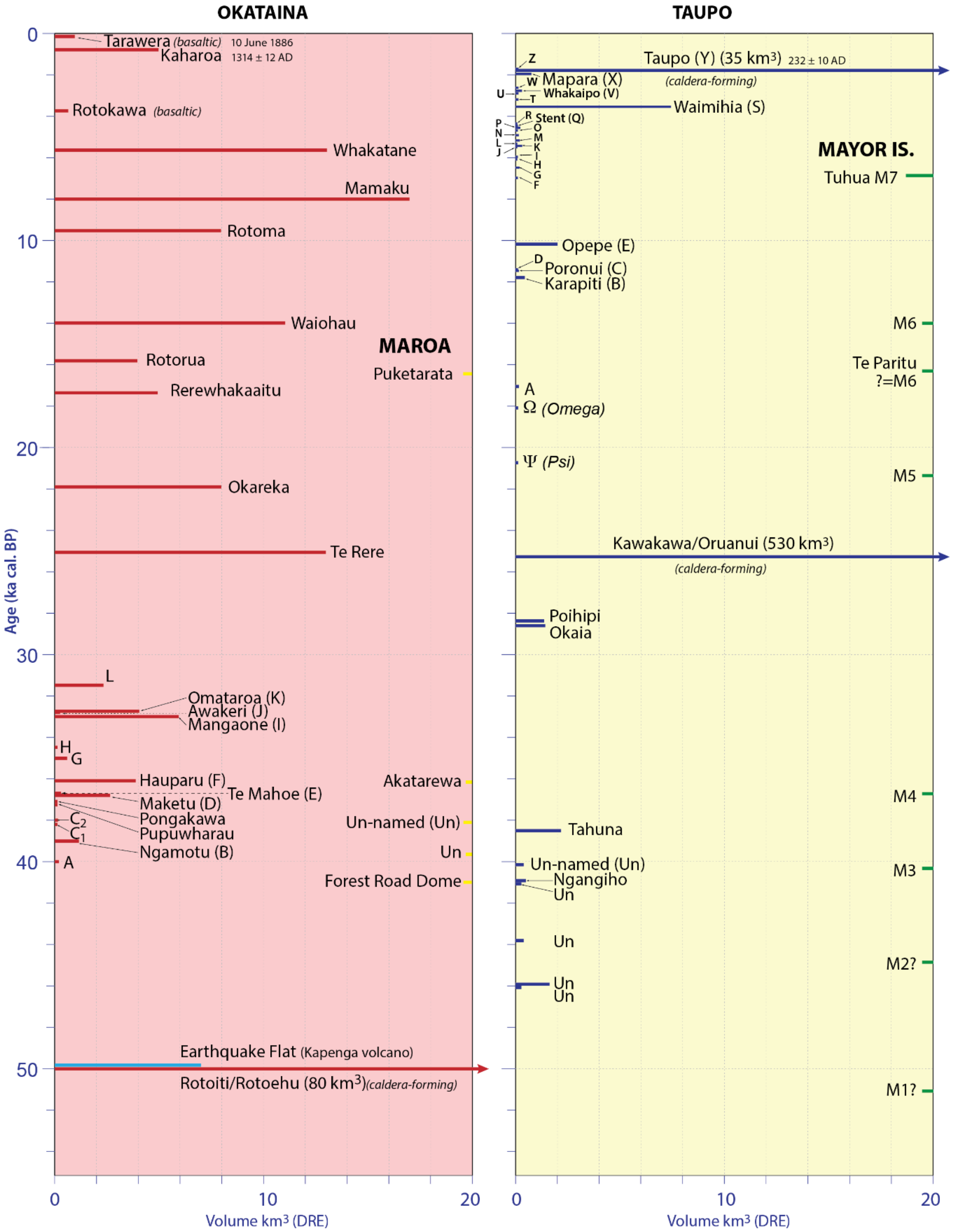


Fig. 3. Interfingering stratigraphic relationships, ages, and volumes (as non-vesiculated, void-free magma or dense-rock equivalent, DRE; multiply by ~3 to obtain approximate bulk volumes) of tephras erupted from Okataina and Taupo caldera volcanoes in North Island, New Zealand, since c. 50 cal ka (based on Wilson et al., 2009; Leonard et al., 2010; Danišík et al., 2012). Eruptions from Maroa and Mayor Island volcanic centres are also recorded (Lowe et al., 2015). Earthquake Flat tephra (EFT) (7 km^3 DRE) was erupted from the Kapenga caldera volcano immediately after the Rotoiti/Rotoehu eruption. Ages on around 20 other widespread tephras erupted since 30,000 cal yr BP were revised by Lowe et al. (2013) using a Bayesian age modelling approach.

Table 2 Summary of tephra names and ages and other information for 28 Taupo eruptives post-dating the Kawakawa/Oruanui eruption c. 25 cal ka (after Wilson, 1993, 1994). Note that ages for some eruptives have been modified since this table was published (Lowe et al., 2013)

Previous published tephra formation name	Volcanological name	Adopted age (years BP) ^{14}C time scale	Adopted age (years BP) calibrated timescale	Bulk volume in km^3 as used by Wilson (1993)	Other volume estimates, in km^3	Eruptive activity 'dry' fall	'wet' fall	Pyroclastic flow(s)	Lava extrusion
(not defined)	Eruption Z	-	1740	0.28	-	-	-	-	yes
Taupo Tephra	Unit Y	1850	1770	44.75	65, 105	yes	yes	yes	-
Mapara Tephra	Unit X	2150	2150	0.8	0.65, 2, 6	yes	yes	-	(possible)
(not recorded)	Unit W	(2650)	2750	0.023	-	-	yes	-	yes
Whakaipo Tephra	Unit V	2700	2800	0.8	0.8, 1.5, 2, 6	yes	yes	-	(possible)
	Unit U	(2750)	2850	0.2		-	yes	-	
(not recorded)	Unit T	(3000)	3200	0.08	-	-	yes	-	(possible)
Waimihia Tephra	Unit S	3300	3550	16.9	15, 17, 19, 29	yes	-	yes	-
Hinemaiaia Tephra	Unit R	3950	4450	0.05	(3)	yes	yes	-	-
	Unit Q	(4050)	4550	0.15		-	yes	-	(possible)
	Unit P	(4100)	4750	0.05		yes	yes	-	(possible)
	Unit O	(4150)	4800	0.05		yes	yes	-	(possible)
	Unit N	4200	4850	0.15		yes	yes	-	(possible)
	Unit M	(4500)	5250	0.2		yes	(possible)	-	(possible)
	Unit L	4550	5300	0.07		-	yes	-	yes
	Unit K	(4600)	5350	0.35		yes	yes	-	(possible)
	Unit J	(4620)	5370	0.015		-	yes	-	(possible)
	Unit I	(5200)	5950	0.02		-	yes	-	(possible)
Motutere Tephra	Unit H	(5300)	6050	0.2	(0.5, 1)	yes	yes	-	(possible)
	Unit G	(5800)	6650	0.5		yes	yes	-	(possible)
(not recorded)	Unit F	(6150)	7050	0.12	-	-	yes	-	yes
Opepe Tephra	Unit E	(9050)	9950	4.8	4, 5, 12	yes	yes	yes	-
Poronui Tephra	Unit D	(9780)	11 380	0.2	(3, 3.5, 7)	-	yes	-	yes
	Unit C	(9800)	11 400	0.75		yes	yes	-	(possible)
Karapiti Tephra	Unit B	10 100	11 800	1.4	2, 5, 6	yes	yes	-	-
(not recorded)	Unit A	(c. 14 200)	(c. 17 000)	(0.01)	-	-	yes	-	(possible)
(not recorded)	Unit Ω	(c. 15 600)	(c. 18 800)	0.1	-	yes	yes	-	-
(not recorded)	Unit Ψ	(c. 17 200)	(c. 20 500)	(0.05)	-	yes	yes	-	(possible)
Kawakawa Tephra	Oruanui ignimbrite	22 600	24 000-26 500	300				yes	-
	Oruanui fall deposit			c. 500		-	yes	-	-

Taupo eruption

The so-called Taupo eruption (eruption Y) took place in late summer to early autumn (typically late March to early April) on the basis of fruit and seeds preserved in a buried forest at Pureora (Fig. 4) and the lack of an outer latewood ring (Clarkson et al., 1988; Palmer et al., 1988; see Lowe and King, 2015). The eruption year was AD 232 ± 10 AD based on dendrochronology and wiggle-match dating by Hogg et al. (2012). A total eruptive bulk volume was estimated at ~105 km^3 (~30 km^3 DRE).

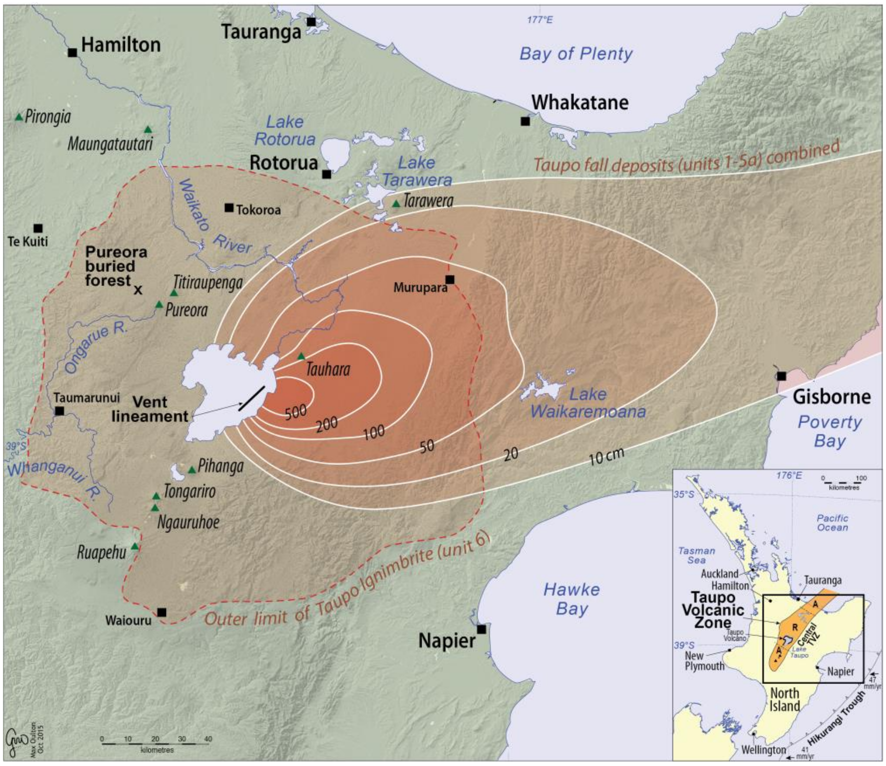


Fig. 4 Distribution of Taupo ignimbrite radially around Lake Taupo and tephra fallout isopachs (in cm) derived from the Taupo eruption (after Hogg et al., 2012; Houghton et al., 2014; Wilson and Leonard, 2015).

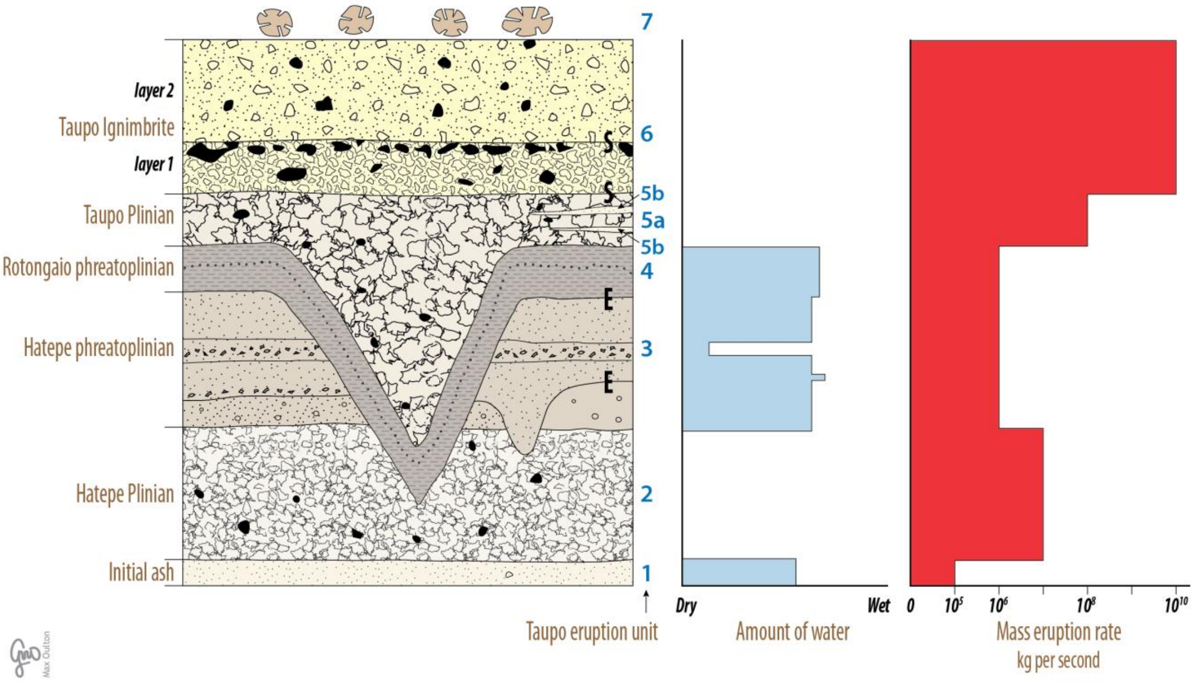


Fig. 5 Summary of the stratigraphy of pyroclastic deposits of the Taupo eruption (eruption Y of Wilson, 1993). Graphs at right indicate qualitative changes in the inferred degree of magma-water interaction and the magma discharge rate (which becomes 'extreme' during emplacement of Subunit Y6, Taupo ignimbrite) during the eruption. E = erosion horizons formed by running water; S = erosion horizons from shearing beneath the fast-moving pyroclastic flow that deposited the Taupo ignimbrite (after Houghton and Wilson, 1986; Houghton et al., 2014).

The eruption was complex, generating three phreatomagmatic ('wet') and two plinian ('dry') fall units, a multi-flow intraplinian ignimbrite, and at the eruption climax, the extremely violently emplaced Taupo ignimbrite (Subunit Y6) (Fig. 5). The duration of the entire eruption episode was of the order of tens of hours with a break after Y3 (probably < 3 weeks). The height of the main ultra-plinian phase (Subunit Y5) eruption column has been estimated at 50-55 km although Houghton et al. (2014) suggested that the eruption be 'downgraded' to a plinian event with an eruption column height ~35-40 km; this phase lasted for ~6 to 17 hours (Walker, 1980). The ignimbritic material was emplaced cataclysmically over about 400 seconds (~7 mins) by an extremely energetic pyroclastic flow (also called a pyroclastic density current or PDC) moving at 200-300 m/s over a near-circular area (~80 km radius) of c. 20,000 km^2 around the vents (Wilson, 1985, 1993; Wilson and Walker, 1985; Smith and Houghton, 1995). Its temperature was about 400-500° C at ~50 km from vent (within ~30-40 km of the vent it was 150-300° C) (McClelland et al., 2004; Hudspith et al., 2009). The non-welded ignimbrite was spread thinly over the landscape to generate an archetypal 'low aspect ratio' ignimbrite (Walker and Wilson, 1985). Ignimbrite-veneer deposits (IVD) are generally 0.5 to 1 m-thick and drape topographic highs; valley-pond ignimbrites (VPI) infill valleys and depressions to depths of 5 to 60 m (Manville, 2001a). Because of its extreme violence and energy release (≥150 ± 50 megaton TNT explosive yield, cf. Hiroshima bomb 0.015 Mt), and by analogy with the 1883 Krakatau event, it is likely that the ignimbrite-emplacement phase generated a volcano-meteorological tsunami that may have reached coastal areas worldwide (Lowe and de Lange, 2000). The emplacement of the ignimbrite destroyed all forests in its path (about 1 km^3 of timber), and then ignimbrite contains numerous charred logs and charcoal, many of the logs notably being orientated radially around the vents (Froggatt et al., 1981). Yet the forests recovered within 100-200 years (Clarkson et al., 1992, 1995; Wilmshurst and McGlone, 1996; Lowe and King, 2015).

The wide variation in eruption styles and dynamics relate to variations in discharge rate and the degree of interaction between the magma and water in the proto-Lake Taupo (Wilson and Walker, 1985; Wilson, 1993, 1994; Houghton et al., 2010). Much of Lake Taupo was expelled, evaporated, or drained into a caldera-collapse structure beneath the current lake floor during the eruption. Afterwards it refilled over approximately 15 to 40 years, reaching a height of ~400 m, about 30-40 m above its present level (357 m) to form a semi-continuous, wave-cut bench and highstand shoreline deposits (Manville et al., 1999, 2007, 2009). Catastrophic failure of a pumiceous pyroclastic dam led to the restablishment of the Waikato River and the release of ~20 km^3 of water in a single phase, the peak discharge being 20,000–40,000 m^3/sec, equivalent to the Mississippi River in flood (Manville et al., 1999). The break-out flood deposits can be traced 220 km downstream of Lake Taupo (Manville et al., 2007) including on the low terrace that supports the Hamilton Gardens.

Introduction to Okataina Volcanic Centre and Kaharoa and Tarawera eruptions

The Okataina Volcanic Centre (Figs. 1-2) comprises two main parts, the northern Haroharo Volcanic Complex (and Okareka embayment), and the southern Tarawera Volcanic Complex (centred on Mt Tarawera). Since c. 50 cal ka there have been at least 25 eruptions from Okataina (Fig. 4) and the most important tephras since c. 25,000 cal years ago are listed in Table 3 (below).

Kaharoa eruption

Most of us are aware of the basaltic Tarawera eruption on 10th June 1886: the high toll on life (~120 people), landscape devastation, and loss of the Pink and White Terraces. But this was not the first time that Mt Tarawera produced an eruption of importance both to volcanology and human history. The Kaharoa eruption occurred at Mt Tarawera in the winter of 1314 AD (± 12 years) (Hogg et al., 2003; Sahetapy-Engel et al., 2014). The importance of the Kaharoa eruption is at least threefold (Lowe and Pittari, 2014). (1) It is the most recent rhyolite eruption in New Zealand, and the largest New Zealand eruption volumetrically of the last millennium. (2) The Kaharoa tephra is an important marker horizon in late Holocene stratigraphy and geoarchaeology (Vucetich and Pullar, 1964; Lowe et al. 1998, 2000), and in particular helps to constrain the timing of settlement of early Polynesians in North Island, which occurred in c. AD 1280, a few decades before the eruption (Newnham et al. 1998; Wilmshurst et al., 2008). (3) There is a link between the soils that developed on the Kaharoa tephra, the animal 'wasting' disease known as 'bush sickness', and the birth of the government soil survey group as an independent organisation (Tonkin, 2012).

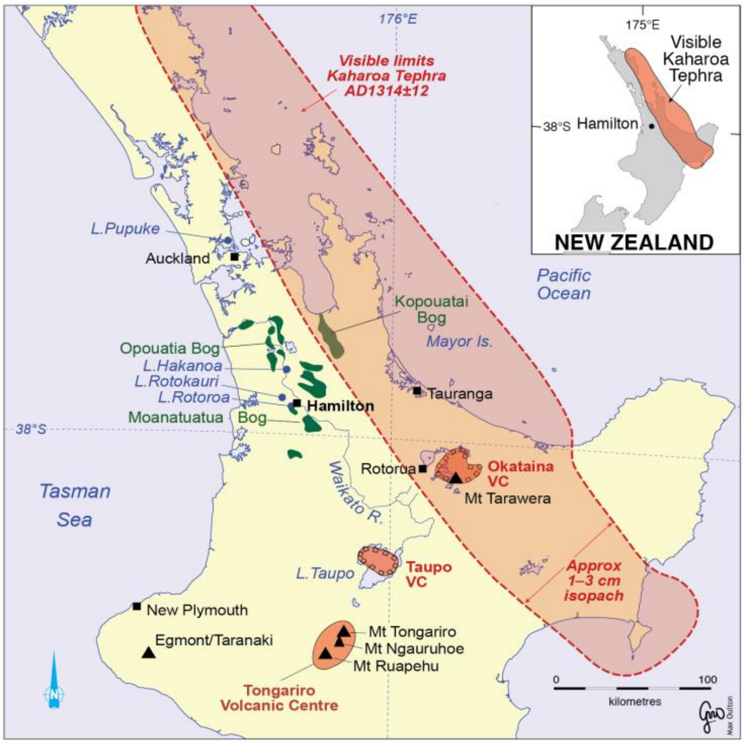


Fig. 6. Isopach map of Kaharoa tephra fallout blown firstly southeastward then northwestward to generate the lobate fallout pattern. The tephra isochron has been extended using cryptotephra occurrences in peats and lake sediments the Waikato and Auckland regions (after Lowe et al., 1998).

Table 3 Summary of main rhyolitic tephras deposited in the Rotorua-Galatea region since c. 25,400 cal yr BP.

Name (source)*	**Date or age¶**	**Description**
Tarawera Tephra (Tr) (Tarawera)	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) (Tarawera)	1314 ± 12 AD (636 ± 12 cal yr BP)	Fine to coarse white to grey ash, with occasional dense pumice, rhyolite, obsidian and basalt lapilli. Contains abundant biotite.
Taupo Tephra (also known as Unit Y) (Tp) (Taupo)	232 ± 10 AD (1718 ± 10 cal yr BP)	Creamy coloured coarse ash with plentiful shower-bedded pumice lapilli (crushable). Ignimbrite unit always associated with charcoal fragments.
Whakatane Tephra (Wk) (Haroharo)	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) (Haroharo)	7940 ± 257 cal yr BP	Loose, coarse yellowish-brown pumice ash grading into a weakly shower-bedded coarse ash/lapilli.
Rotoma Tephra (Rm) (Haraharo)	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) (Tarawera)	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) in NZ-CES§.
Rotorua Tephra (Rr) (Okareka embayment)	15,635 ± 412 cal yr BP	Shower-bedded pumiceous yellowish lapilli or blocks (gravel). Occasional rhyolitic lithics. Deposited at start of late-glacial mild episode (NZce-4) in NZ-CES§.
Rerewhakaaitu Tephra (Rk) (Tarawera)	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 occurred soon after deposition.
Okareka Tephra (Ok) (Tarawera)	21,858 ± 290 cal yr BP	Yellowish brown ash contains abundant biotite. Typically encased in yellowish to olive brown tephric loess. Deposited just before stadial A (NZce-6) NZ-CES§.
Te Rere Tephra (Te) (Haroharo/Okareka)	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) (Taupo)	25,358 ± 162 cal yr BP	Olive brown to pale yellowish brown ash (typically encased in yellowish to olive brown tephric loess). Deposited just before interstadial D (NZce-9) in NZ-CES§.

*Terminology is based mainly on Froggatt and Lowe (1990). Descriptions generalised because character may differ from proximal to distal locations and from site to site. The region has received additional distal tephras from Taupo and Tuhua volcanic centres, and has been dusted regularly with andesitic tephra fallout from numerous eruptions at Tongariro Volcanic Centre and Egmont/Taranaki Volcano, most recently in the 1995-96 Ruapehu eruptions.

¶Ages are given in calibrated or calendar (cal) years (95% probability range) before present (BP). Ages are based on Bayesian probability age modelling: Lowe et al. (2008, 2013). Calendar dates for the Kaharoa and Taupo eruptions have been determined by dendrochronology and ^{14}C wiggle-match dating (Hogg et al., 2003, 2012).

§NZ climate event stratigraphy of Barrell et al. (2013)

Tarawera eruption

The Tarawera eruption of 10 June, 1886, was the biggest and most destructive eruption in New Zealand during the historical (European) period. It was a basaltic rather than rhyolitic event, but was nevertheless very explosive: the resulting scoria fall ('Tarawera Scoria') has a dispersal similar in extent to that of the Vesuvius 79 AD pumice fall and is one of the few known examples of a basaltic deposit of plinian type from a fissure source (Walker et al., 1984). The eruption cored out a series of craters in a 7-km-long fissure through the antecedent rhyolite domes (including those emplaced during the Kaharoa event) of Mt Tarawera, and then generated more craters along an 8-km-long southwest extension of the fissure across the Rotomahana basin (which contained two shallow lakes and large silica sinter aprons, the 'Pink' and the 'White' terraces, asssociated with extensive hydrothermal activity) to Waimangu. Narratives (summarized authoritatively by Keam, 1988) indicate that after a series of precursory earthquakes from ~12.30 am, the eruption began at Ruawahia Dome at about 2.00 am on 10 June, 1886, and then gradually extended both northeastward and southwestward. At ~2.10 am the eruption intensified with the ascent of a tephra plume from the vicinity of Ruawahia Dome up to ~9.5 km. By 2.30 am craters along the whole length of the fissure were erupting, with the Rotomahana extension beginning to erupt possibly at ~3.20 am. By 3.30 am, craters along the entire 17 km-length of the fissure from Wahanga to Waimangu were in eruption. This paroxysmal stage of the eruption was over by 6.00 am when most activity ceased. See also recent papers by de Ronde et al. (2016a, 2016b), Keam (2016),

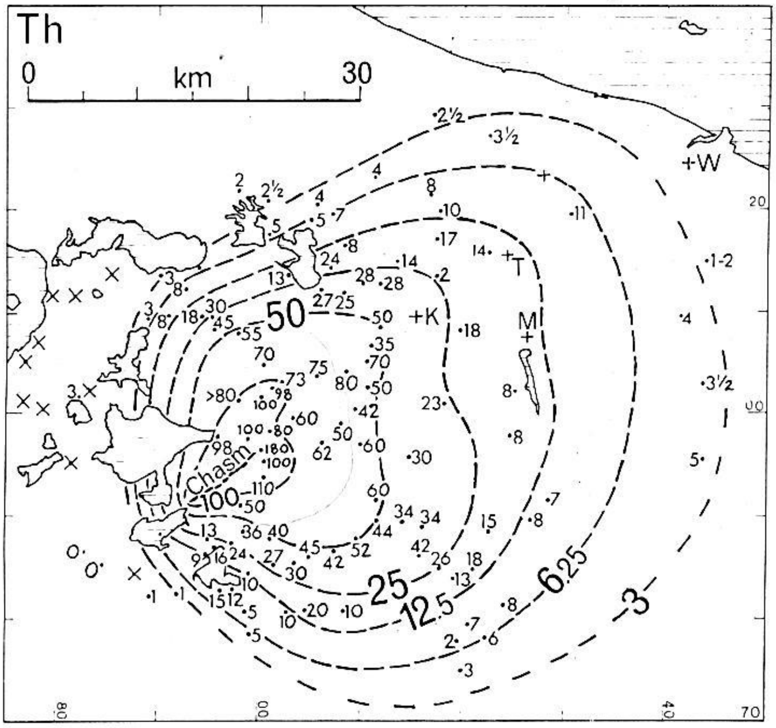


Fig. 7. Isopach map of 1886 Tarawera scoria fallout (in cm). x = location where scoria occurs mixed with Rotomahana Mud, but does not form a discrete layer (from Walker et al., 1984).

The erupted products were exclusively pyroclastic (no lava flows were generated, although basalt dikes were emplaced). The total volume (as deposited) of Tarawera Scoria is ~2 km^3 (Walker et al., 1984). The eruption along the Rotomahana and Waimangu extension was mainly phreatomagmatic (interaction between basalt magma and hydrothermal water) and phreatic. The explosive expansion of superheated water fragmented the country rock containing the hydrothermal system, plus subordinate lake sediment, to produce surge beds and fall deposits ('Rotomahana Mud') that rained out over much of the Bay of Plenty and beyond (~0.5 km^3 as deposited). Near Rotomahana, the surge beds were emplaced violently by hot and fast-moving turbulent pyroclastic surges or density currents up to ~6 km from source (Nairn, 1979) (Fig. 8).

Lightning during the eruption set fire to a house in Te Wairoa and to the forest on the north shore of Lake Tarawera; strong winds flattened many trees at Lake Tikitapu; and suffocating gases and falling mud and ash made breathing difficult at Te Wairoa, where most buildings were buried or collapsed under the weight of ~1 m of mudfall. A notable exception was *Hinemihi*, a large meeting house where most survivors were sheltered, because wooden forms for seating guests during Maori concerts were used to prop up the roof.

All but seven of the 108 known fatalities arising from the Tarawera eruption were Maori (the true number of deaths may have been ~120, but the oft-cited ~150 is erroneous: Lowe et al., 2001). The majority of deaths were the result of the Rotomahana explosions, especially the lethal, scorching pyroclastic surges and blasts. Clearly the event had a profound impact on Maori (and others) in the Te Wairoa and Rotomahana area especially, but trauma was felt throughout the extensive fallout zone in the Bay of Plenty and eastern North Island (Keam, 1988). For example, some groups of Maori in the region of the Rangitaiki and Tarawera rivers, north of Tarawera, became refugees at Matata. Although they had escaped with their lives and without serious injury, their possessions were buried by ~15–30 cm of tephra (some were retrievable by excavation), many potato pits were lost and those with livestock had no feed for them and so many starved (Keam 1988; Lowe et al., 2002). These people were eventually resettled in 1903–1905. The plight of these and other Maori seem minor in comparison with the difficulties of those from Te Wairoa-Rotomahana: apart from the lives lost, all possessions had been buried and many crushed. Among livestock, most smaller animals were killed, but dogs, pigs, cattle and horses that survived wandered loose and starving. The main livelihood of the region, tourism, had been destroyed, literally overnight. Whilst Maori continued to participate in the tourist trade, its control effectively moved into European hands from 1894 with the opening of the railway line to Rotorua. However, perhaps the biggest societal impact, according to Keam (1988), was the loss of land. For thirty years, Maori groups in the region had been generally secure in possession of their land and property. In previous times, under the old order, the prospect had always existed that a group might lose homes and land through warfare, but by the time of the Tarawera eruption, the people, long-established traders with European settlers, had become accustomed to a newfound security.

The eruption rather than warfare (against which there could at least be retaliatory or conciliatory action to make-good losses) had destroyed that security and dispossessed the people of the land, which they had prized most. Offers of resettlement for the surviving group, mainly the Tuhourangi subtribe or clan (*hapu*), were received from various parts of central and eastern North Island and beyond, but most settled at Whakarewarewa and Ngapuna, both near Rotorua. Eventually gifts of land were formally ratified and provided a home for most of the Tuhourangi people. Other Tuhourangi settled for a time in the Bay of Plenty and Coromandel. After 30-50 years almost all the refugees or their descendants had returned to Whakarewarewa or Ngapuna and the gifted land was returned to the donors (Keam, 1988; Lowe et al., 2002; see also Cashman et al., 2008).

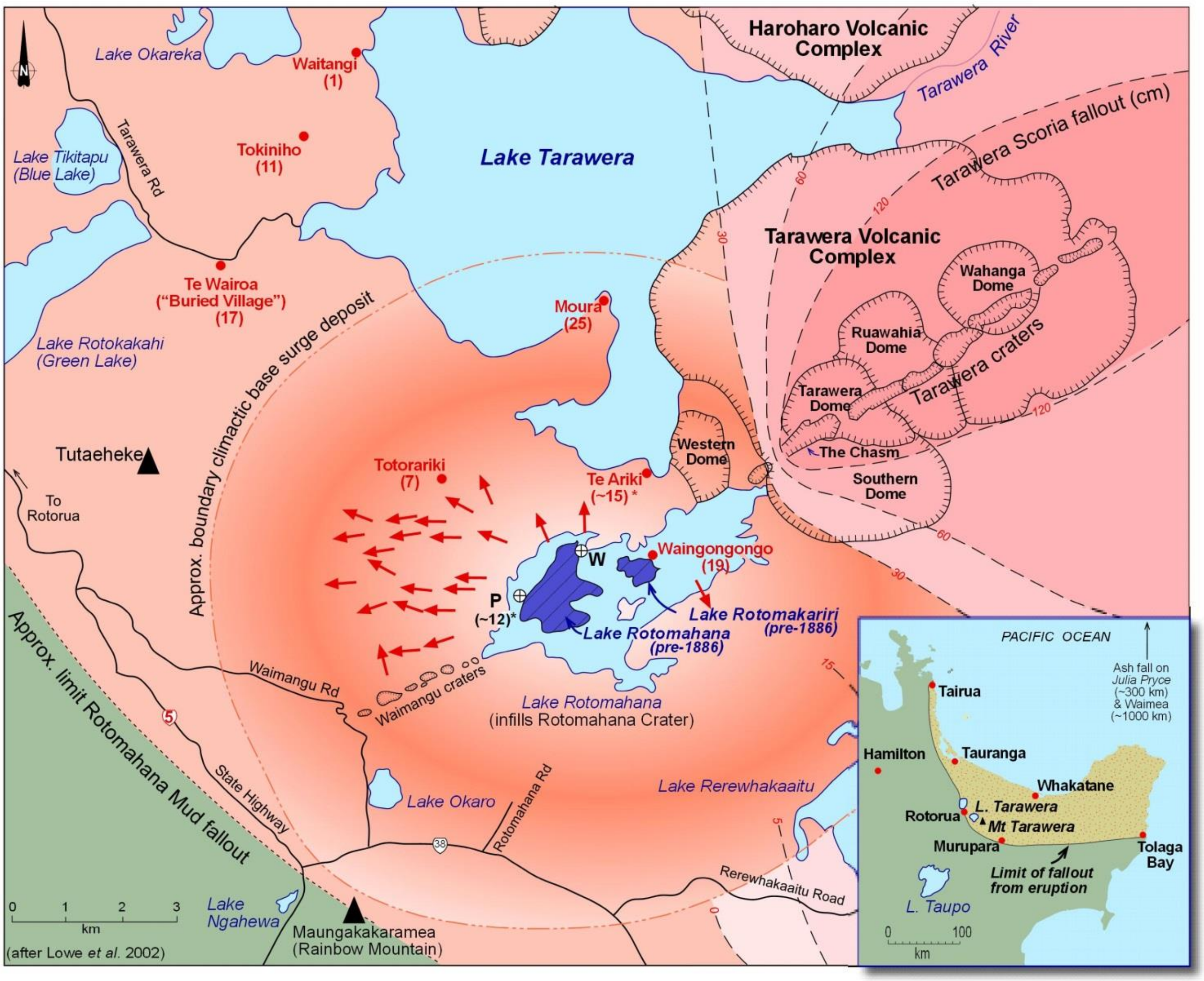


Fig. 8. Map of Tarawera area showing locations of the main craters of the 10 June 1886 fissure eruption across Tarawera Volcanic Complex, Rotomahana Crater (including pre-eruption lakes Rotomahana and Rotomakariri), and Waimangu craters (after Lowe et al., 2002). Locations of villages and associated fatalities (numbers in parentheses) are based on Keam (1988) (there was an additional death at an unknown locality). Fatalities were all Maori apart from six Europeans at Te Wairoa and one European and three (part) Maori at Waingongongo. On the night of the eruption nearly half of Te Ariki's 27 residents were camped at Pink Terrace (Otukapuarangi). Inset shows eastern North Island and documented limits of tephra fallout from the eruption (based on maps by A.P.W. 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).

Distribution of main soil-forming tephras

The thickest tephra sequences occur downwind of the TVZ in the Rotorua-Taupo area, Bay of Plenty, East Coast-Poverty Bay, and Hawke's Bay (Fig. 9). Moderately thick deposits are found in Wanganui-Taranaki, King Country-Waikato-Coromandel, and Auckland regions. Fewer tephra layers occur in other parts of the North Island. Only a handful of tephras has been recognised so far in the South Island. They include Rangitawa Tephra, erupted c. 340,000 years ago from Whakamaru volcano, and Kawakawa Tephra, erupted c. 25,400 cal years ago from Taupo volcano.

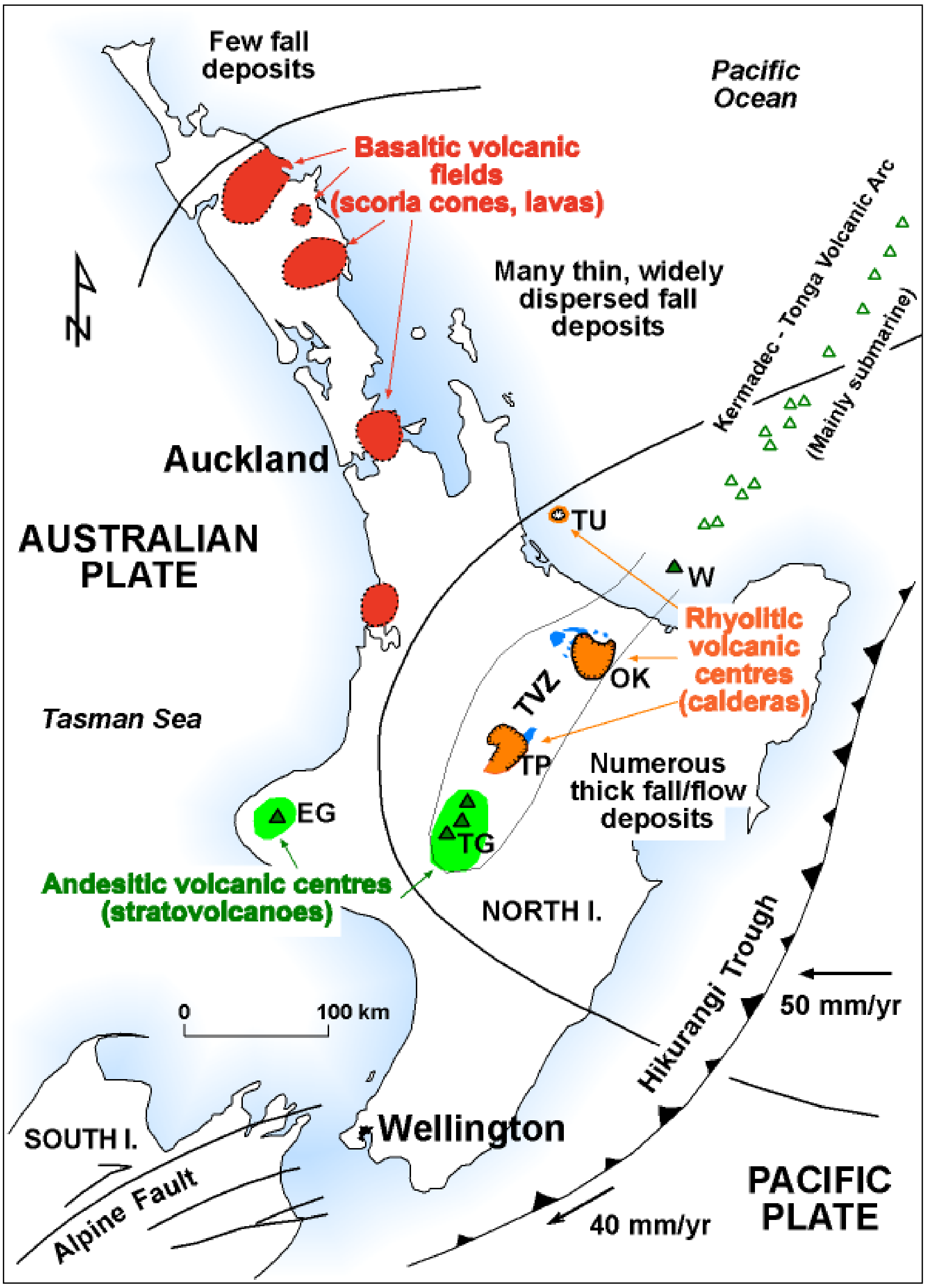


Fig. 9 Map showing plate tectonic setting, the main volcanic centres that produced parent materials for many tephra-derived soils, and the general dispersal of tephra on North Island. EG, Egmont/Taranaki volcano; TG, Tongariro Volcanic Centre; TP, Taupo Volcanic Centre; OK, Okataina Volcanic Centre (includes Mt Tarawera and Haroharo volcanic complexes); TU, Tuhua Volcanic Centre (Mayor Is.); W, Whakaari (White Is.) (from Lowe and Palmer, 2005).

Tephra-derived soils of New Zealand

The relatively young landscapes of much of central North Island, especially the Bay of Plenty-Taupo-Tongariro area, are predominantly of volcanic origin. Consequently, the nature and distribution of the soils contained in these landscapes are very strongly influenced by the volcanic history as well as faulting (tectonism) and reworking by water and wind. Variations in the age, thickness, and mineralogical composition of the tephra deposits in which the soils are forming have significantly contributed to the soil patterns. Post-depositional erosion and reworking of tephra deposits have helped to shape the landscape and, in turn, haves created 'genetic' links of varying strengths between the soils and landforms of the region. To some extent, climatic and indigenous vegetation gradients have also been imprinted upon the soils and their distribution pattern (Molloy and Christie, 1998).

Classification of tephra-derived soils

Soils formed from tephra deposits are represented by five orders of the New Zealand Soil Classification (*NZSC*) which reflect increasing age and development: (Tephric) Recent Soils (~1% of North Island soils), Pumice Soils (~15%), Allophanic Soils (~12%), and Granular Soils (~3%) and (rarely) Ultic Soils (Lowe and Palmer, 2005; Hewitt, 2010; see also table below for relative abundances of New Zealand soils).

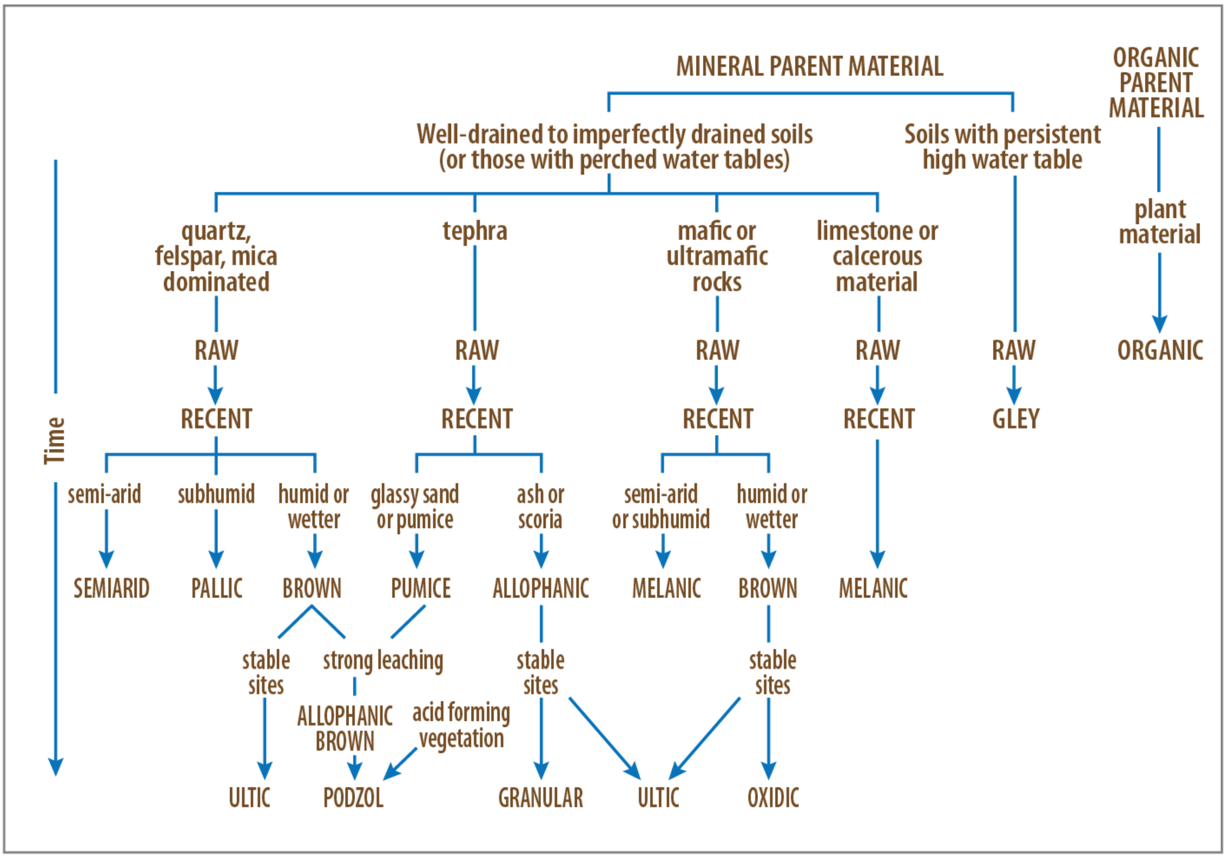


Fig. 10 Major taxonomic development paths of New Zealand soils (after A.E. Hewitt in Molloy and Christie, 1998).

Tephric Recent Soils (Entisols)

These soils occur on very young, mainly andesitic or basaltic eruptives (~100–600 years old) close to the volcanic centres of Taranaki, Tongariro-Ruapehu, Rangitoto Island, and Mt Tarawera. They are typically gravelly or sandy and have few nutrients – the result of insufficient time for weathering to release them – and cannot store much water.

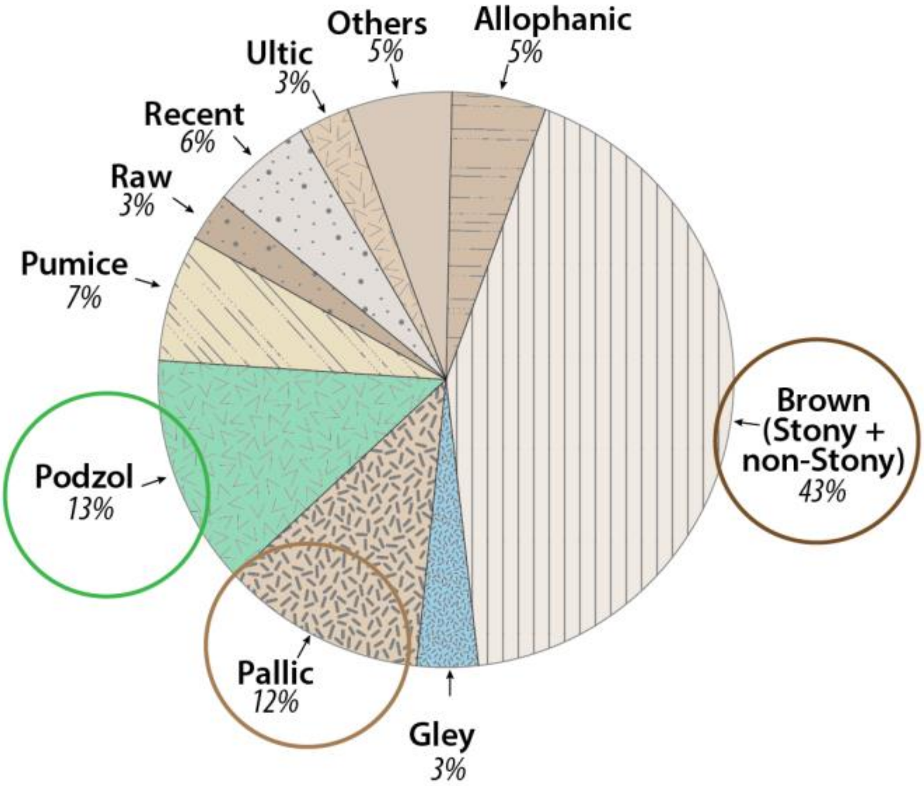


Fig. 11 Relative abundances of soil orders in New Zealand (after A.E. Hewitt in Molloy and Christie, 1998). Allophanic and Pumice Soils (Andisols) together cover about 25% of the North Island.

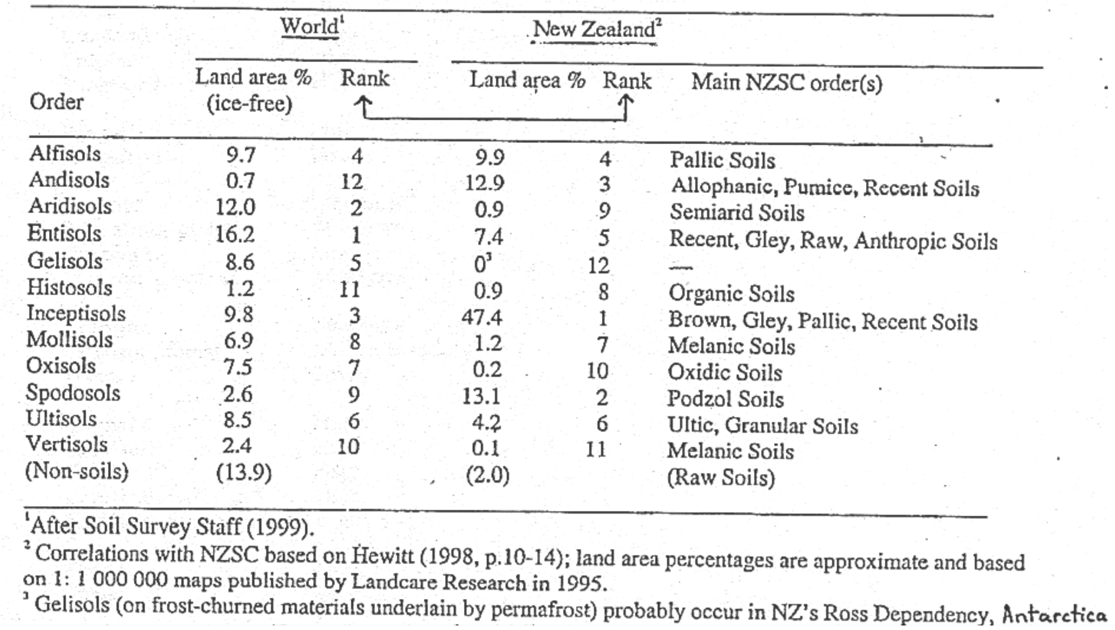
Pumice Soils (mainly Vitrands)

Covering a large swath of the central and eastern North Island, these shallow soils are made up of coarse rhyolitic pumice deposits derived mainly from the Taupo (c. 232 AD) and Kaharoa eruptions (c. 1314 AD). The young and weakly developed soils formed from these deposits (~700–1800 years old) are extremely deficient in many elements essential for animal health including copper, selenium, and (especially) cobalt. The Californian Monterey pine (*Pinus radiata*) grew fast and vigorously on the problematic Pumice Soils, partly by tapping into nutrients and moisture in the paleosols and soil horizons formed in tephras buried beneath them (see notes below about Co deficiency and plantation forestry).

Allophanic Soils (mainly Udands)

These deep, versatile soils are formed typically on accumulating sequences of thin, fine-grained interfingering tephra layers from both rhyolitic and andesitic volcanoes, and occur in the Ohakune-Waiouru area, Taranaki, King Country-Waikato, and western Bay of Plenty-Coromandel. Small patches are found on basaltic scoria cones in Auckland-Northland. Most Allophanic Soils have taken between 10,000 and 25,000 years to form, with some as old as c. 50,000 years, and clearly are irreplaceable, yet they are undervalued by most people. Their name comes from the tiny nanocrystalline clay mineral formed in them, allophane, which dominates their physical and chemical properties because of its positive charge and huge surface area: a single teaspoon (about 5 g) of allophane has the surface area of a rugby field (areas range from 250 $m^2\ g^{-1}$ to as much as 1125 $m^2\ g^{-1}$ (Lowe and Palmer, 2005; Neall, 2006; McDaniel et al., 2012; Huang et al., 2016a).

Table 4. Abundances of 12 soil orders of the world (of Soil Taxonomy) vs abundances in New Zealand (rank = relative abundance) (after Lowe et al., 2000a).



Order	World[1] Land area % (ice-free)	World[1] Rank	New Zealand[2] Land area %	New Zealand[2] Rank	Main NZSC order(s)
Alfisols	9.7	4	9.9	4	Pallic Soils
Andisols	0.7	12	12.9	3	Allophanic, Pumice, Recent Soils
Aridisols	12.0	2	0.9	9	Semiarid Soils
Entisols	16.2	1	7.4	5	Recent, Gley, Raw, Anthropic Soils
Gelisols	8.6	5	0[3]	12	—
Histosols	1.2	11	0.9	8	Organic Soils
Inceptisols	9.8	3	47.4	1	Brown, Gley, Pallic, Recent Soils
Mollisols	6.9	8	1.2	7	Melanic Soils
Oxisols	7.5	7	0.2	10	Oxidic Soils
Spodosols	2.6	9	13.1	2	Podzol Soils
Ultisols	8.5	6	4.2	6	Ultic, Granular Soils
Vertisols	2.4	10	0.1	11	Melanic Soils
(Non-soils)	(13.9)		(2.0)		(Raw Soils)

[1] After Soil Survey Staff (1999).

[2] Correlations with NZSC based on Hewitt (1998, p.10-14); land area percentages are approximate and based on 1: 1 000 000 maps published by Landcare Research in 1995.

[3] Gelisols (on frost-churned materials underlain by permafrost) probably occur in NZ's Ross Dependency, Antarctica

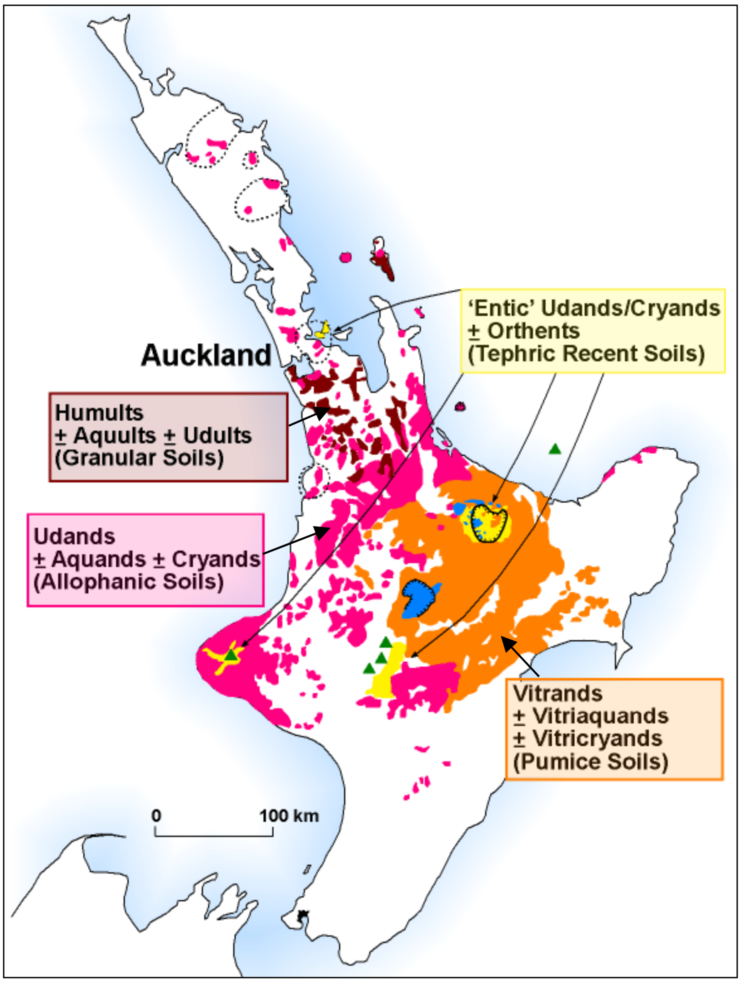


Fig. 12 Distribution of four main groupings of tephra-derived soils in North Island (after Kirkpatrick, 1999, based on Rijkse and Hewitt, 1995; modified from Lowe and Palmer, 2005).

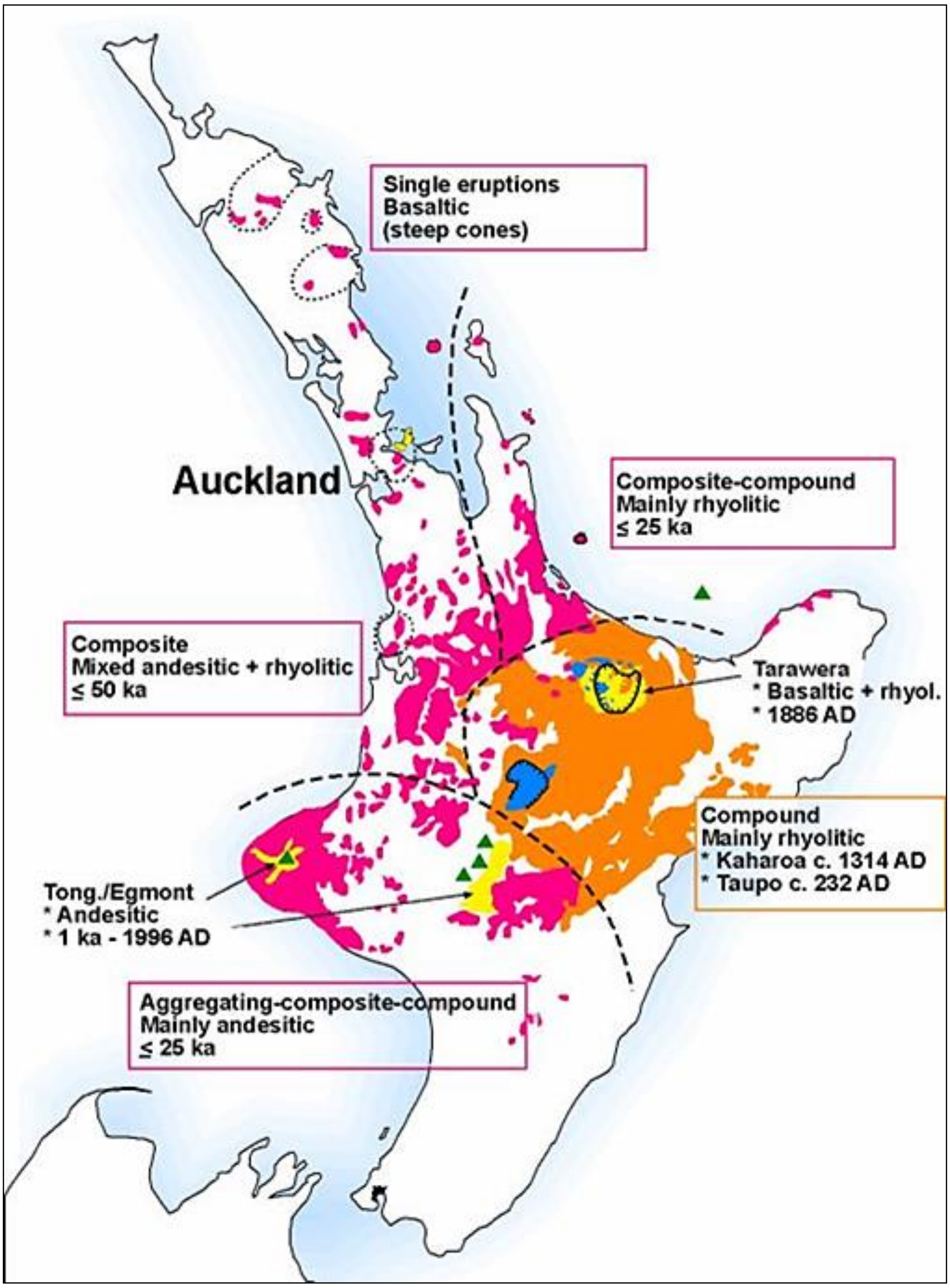


Fig. 13 General subdivision of the main groupings of Andisols in North Island into six zones according to their multisequal soil character (soil stratigraphy), the primary compositions of component tephras, and approximate ages of the 1-m deep soil profiles (from Lowe and Palmer, 2005). Ages on Kaharoa and Taupo tephras from Hogg et al. (2003, 2012). Note: 'Aggregating' should read 'Aggrading'.

Pumice Soils, "bush sickness", and plantation forestry

Inherently low in Co, these pumiceous parent tephras led to low Co levels in soils and herbage, and ultimately to a deficiency in ruminant animals (sheep and cows) that developed a serious and commonly fatal wasting disease known as "bush sickness" (Lowe and Palmer, 2005; Neall, 2006) (Fig. 14). This term referred to a variety of symptoms exhibited by livestock stemming from their inability to produce vitamin B_{12} (cobalamine, discovered in 1948), of which Co is an essential component for red blood cell production (Cornforth, 1998; Hendy, 2008).

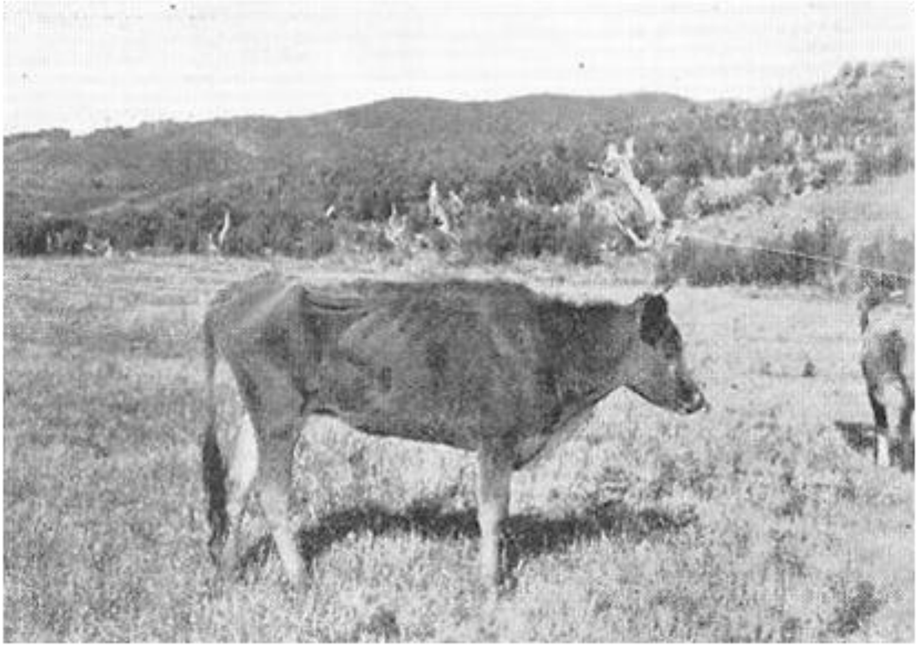


Fig. 14 ‘Bush-sick’ cow on Taupo soil at Ngaroma, South Waikato (from Grange and Taylor, 1932)

Identified in 1911, bush sickness became an increasingly urgent problem in the late 1920s when many farms on Pumice Soils, settled after WW I, were abandoned as the depression hit. The association of bush sickness with the Pumice Soils was recognized by Les Grange (who began mapping volcanic deposits in 1926) in the early 1930s (Grange and Taylor, 1932; Grange, 1937). Acquired Co deficiency also occurred in some other soils where high rainfall and strong leaching were the cause. Veterinarians were unable to diagnose any diseases, and it was thought that some property of the soil was responsible. Analytical techniques of the day (early 1900s) were too insensitive to show what this might be, but trial and error showed that iron ore (“limonite”) from some, but not all, sources provided relief as a stock ‘lick’ (Hendy, 2008). There was some rivalry in this work. Elsa Kidson (Cawthron Institute) and K.J. McNaught (Department of Agriculture) each developed essentially the same methods for finding trace amounts of cobalt. They published a series of papers on cobalt levels in rocks, soils, and pastures, while pointing out each other’s errors (Tonkin, 2012).

Initial research was directed at trying to supplement the animals’ diets with iron. In 1934, R.E.R. Grimmett and F.B. Shorland (senior chemists at the Department of Agriculture) found that the iron ore which gave the best results contained significant amounts of cobalt, and went against popular wisdom by dosing animals with cobalt, with spectacular results. Australians Underwood and Filmer (1935) confirmed the association. Grimmett and Shorland then developed cobaltised superphosphate fertiliser, which has been applied to the affected area ever since at a rate of a few grams per hectare, and has resulted in the addition of about 250,000 ha of productive farmland to New Zealand’s stock. Possibly, this one discovery has paid for all of the scientific research ever carried out in New Zealand (Hendy, 2008). In addition, Grange’s insight resulted in soil survey becoming a separate, independent branch of the Department of Scientific and Industrial Research (DSIR) in 1936 rather than effectively an ‘add-on’ to the Geological Survey Branch as it had been (Lowe, 1990; Tonkin, 2012). Grange was the first director of Soil Survey (and later a director of Geological Survey); it was renamed Soil Bureau in 1945 until morphing into Landcare Research in July, 1992.

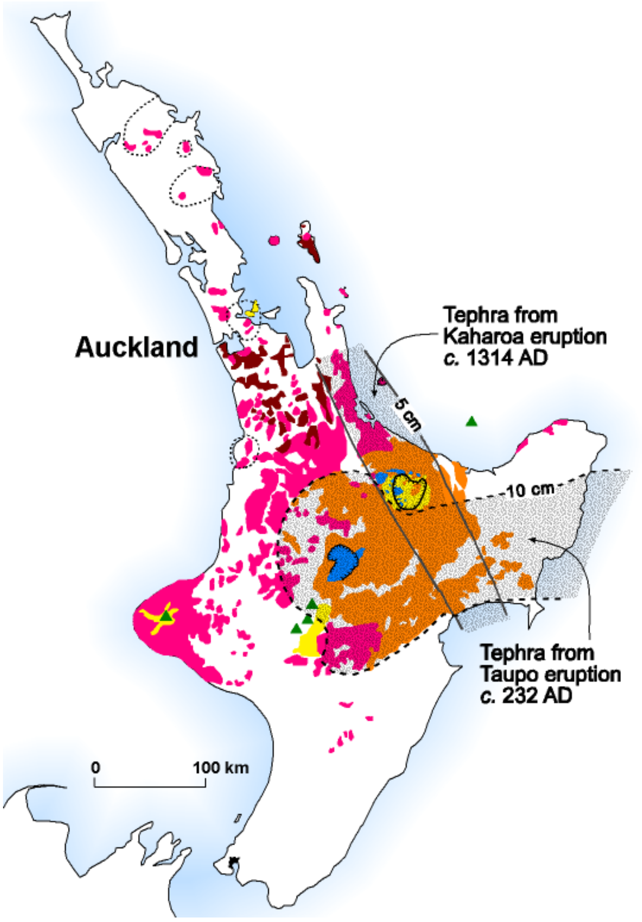


Fig. 15 Map of North Island showing single isopachs of tephras deposited from Taupo and Kaharoa eruptions, soils on which were deficient in Co which resulted in 'bush sickness' (from Lowe and Palmer, 2005). Co deficiency also occurred in soils in some other areas under high rainfall. Cartoon by geochemist Dr Nick Kim.

Fig. 16 Landscape at Litchfield, midway between Putaruru and Tokoroa, underlain by shallow Taupo soils on Taupo tephra. The Co deficiency here was the was first to be rectified – on the nearby farm of K.S. Cox.

Partly as a result of these agricultural problems, a forestry industry became established, the mainstay tree being *Pinus radiata* from California (known as Monterey pine). *P. radiata* has been very successful, it matures rapidly in about 25 years on average, and can grow on 'clapped out' soils with little problem. Its roots can easily punch through surficial pumice deposits to reach nutrients and water in buried soil horizons. The soils to the east of SH1 between Putaruru and Tokoroa are now growing their 5th crop (rotation) of *P. radiata*. Palmer et al. (2005) used a P-based nutrient model to establish that *P. radiata* was growing sustainably after two rotations on Podzol Soils (Andic Haplohumods) developed on Taupo tephra in elevated areas on the southern Mamaku Plateau to the east of Tokoroa. Models to predict *Pinus radiata* productivity throughout New Zealand were developed by Watt et al. (2010) and various spatial prediction techniques for developing *Pinus radiata* productivity surfaces across New Zealand were compared by Palmer et al. (2010).

Erodibility

The soils developed in loose Taupo tephra deposts around Lake Taupo are susceptible to severe gully erosion. The erodibility of the soils under three classes of vegetation – pasture grasses, ungrazed grass, and scrub – was assessed by Selby and Hoskins (1973) with the use of a specially designed flume that simulated gully erosion. Erosion was found to be significantly higher beneath scrub than beneath grass vegetation when the same erosive stress was applied in each case. Under natural conditions, however, greater runoff, and therefore greater erosive power, always occurs on pasture grasses than under scrub. In spite of the greater inherent erodibility of scrub, actual erosion is therefore greater on pasture lands (Selby and Hoskins, 1973). Under pasture grasses, plant roots and organic matter bind the soil particles and inhibit erosion. This effect is less under scrub. Gully erosion is attributable largely to the low density and easy entrainment of pumice particles. 'Retirement' of such gullies with tree planting has been successful in stabilising them.

Classification

Andisols are one of 12 soil orders in the international soil classification system *Soil Taxonomy* (Soil Survey Staff, 1999). They are often deep soils commonly with depositional stratification developing mainly from ash, pumice, cinders (scoria), or other explosively erupted, pyroclastic volcanic material (referred to collectively as tephra) and volcaniclastic or reworked materials. Andisols occur much less commonly on lavas. Unlike many other soils, Andisol profiles commonly undergo upbuilding pedogenesis as younger tephra materials are deposited on top of older ones, as described below. The resulting profile character is determined by the interplay between the rate at which tephras are added to the land surface and classical topdown processes that form soil horizons. Therefore, understanding Andisol genesis usually requires a stratigraphic approach combined with an appreciation of buried soil horizons and polygenesis (see notes below) (McDaniel et al., 2012). The *NZSC* splits Andisols into Allophanic Soils (mainly Udands) and Pumice Soils (mainly Vitrands). Vitrands are defined as slightly weathered, coarse-textured, glass-dominated Andisol with <15% 1500 kPa water retention on air-dried samples and <30% kPa water retention on undried samples (Soil Survey Staff, 2014).

Andisols are defined by characteristic andic soil properties that include physical, chemical, and mineralogical properties that are fundamentally different from those of soils of other orders (andic properties are termed allophanic soil materials in *NZSC*). The coarser fractions of Andisols are often dominated by volcanic glass. This glass weathers relatively quickly to yield a fine colloidal or nanoscale fraction (1–100 nm) dominated by short-range-order materials composed of 'active' Al, Si, Fe, and organic matter, especially humus. Previously described erroneously as 'amorphous', short-range order materials comprise extremely tiny but structured nanominerals, referred to nowadays as nanocrystalline, the main ones being allophane and ferrihydrite. Another colloidal constituent, imogolite, comprises long filamental tubes and therefore has both short- and long-range order (Churchman and Lowe, 2012). The nanominerals, chiefly allophane, ferrihydrite, and also Al- or Fe-humus complexes, are responsible for many of the unique properties exhibited by Andisols (McDaniel et al., 2012). The formation of allophane and other minerals including halloysite are described by Churchman and Lowe (2012). Some properties of buried soil horizons may be altered via diagenesis.

Allophane and its formation

Allophane is a nanocrystalline aluminosilicate comprising tiny spherules ~3.5 to 5.0 nm in diameter and with a chemical composition (1–2)$SiO_2 \cdot Al_2O_3 \cdot$(2–3)$H_2O$ (Abidin et al., 2007; Huang et al., 2016a) (Figs. 17-19). It provides many tephra-derived soils including Allophanic Soils and Pumice Soils with many of their unique chemical and physical properties (McDaniel et al., 2012; Yuan and Wada, 2012). With its small size, extreme surface area (up to ~1200 m^2 g^{-1}) (Allbrook, 1983, 1985; Parfitt, 2009; Yuan and Theng, 2012; Huang et al., 2016a), and variable surface-charge characteristics that arise via $(OH)Al(OH_2)$ groups at wall perforations of its outer gibbsitic octahedral sheet $[Al(OH)_3]$, allophane has strong affinity for water, metal cations, anions, organic molecules and DNA (Harsh, 2012; Huang et al., 2014, 2016a, 2016b).

The essential conditions for the formation of allophane are the activity of silicic acid in the soil solution, the availability of Al species, and the opportunity for co-precipitation (Fig. 21). These conditions are controlled largely by the leaching regime, the organic cycle, and pH, which, in turn, are potentially influenced by numerous environmental factors including rainfall, drainage, depth of burial, parent tephra composition and accumulation rate, dust accession, type of vegetation and supply of humic substances, and human activities (such as burning vegetative cover), together with thermodynamic and kinetic factors (McDaniel et al., 2012). Availability of Al, derived mainly from the dissolution of glass or feldspars, is assumed to be unlimited in this model, though potentially more is available from andesitic and especially basaltic tephras than rhyolitic tephras. In contrast, in pedogenic environments rich in organic matter and with pHs $\leq$5, humus effectively competes for dissolved Al, leaving little Al available for co-precipitation with Si to form allophane or halloysite. In these environments (such as in parts of Japan), Al-humus complexes are formed instead of allophane (McDaniel et al., 2012).

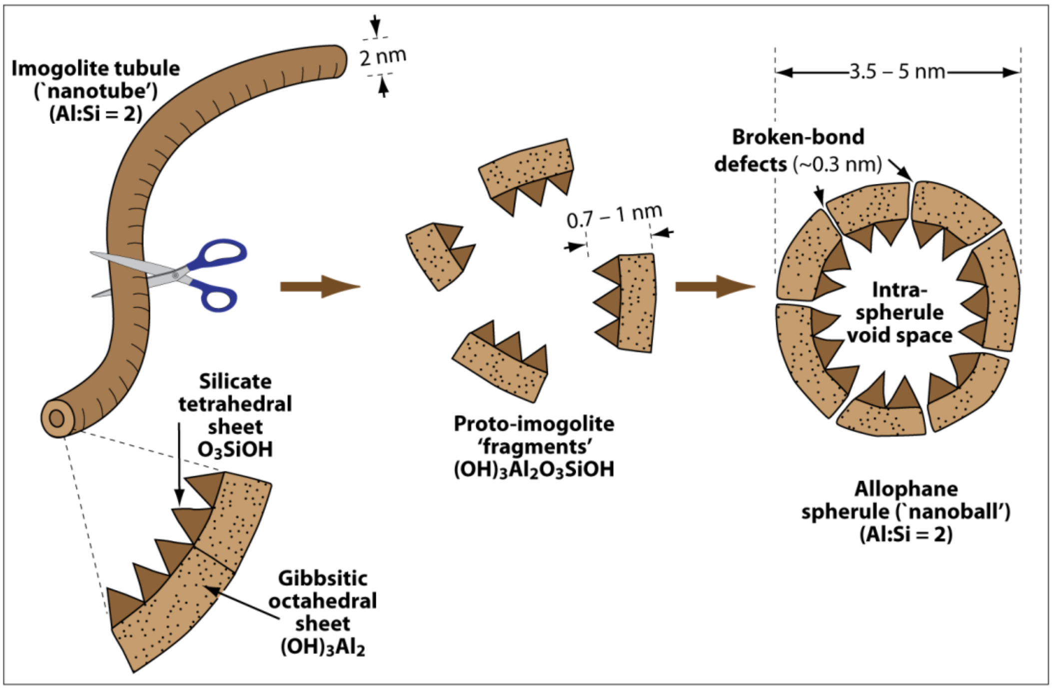


Fig. 17 Diagram of imogolite nanotubes and Al-rich allophane nanospheres, which have similar structures at the atomic scale (from McDaniel et al., 2012).

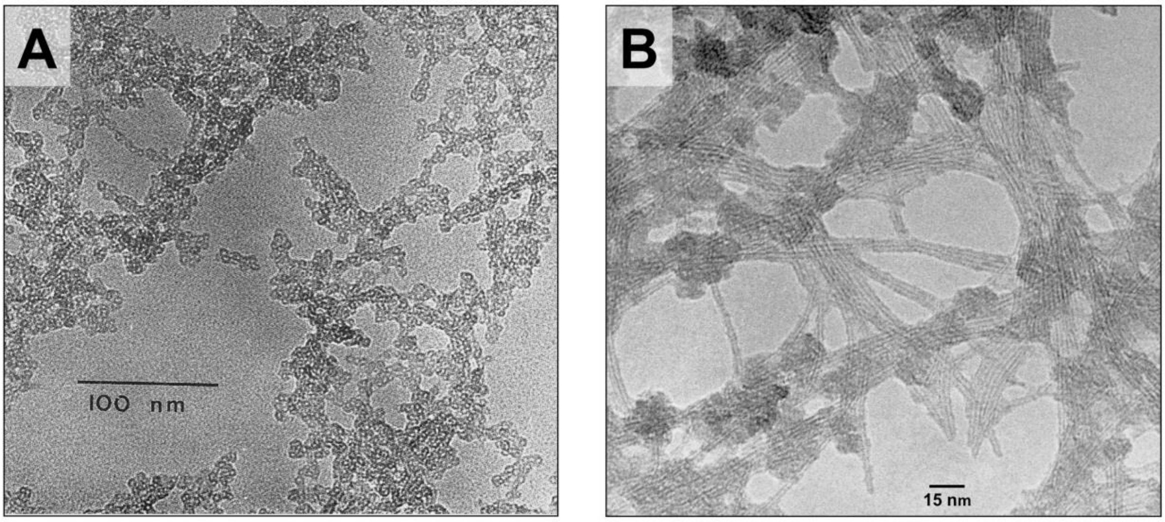


Fig. 18 Micrographs of (A) allophane and (B) imogolite (external diameter of nanotubes is ∼2 nm) (from McDaniel et al., 2012, after Parfitt, 1990).

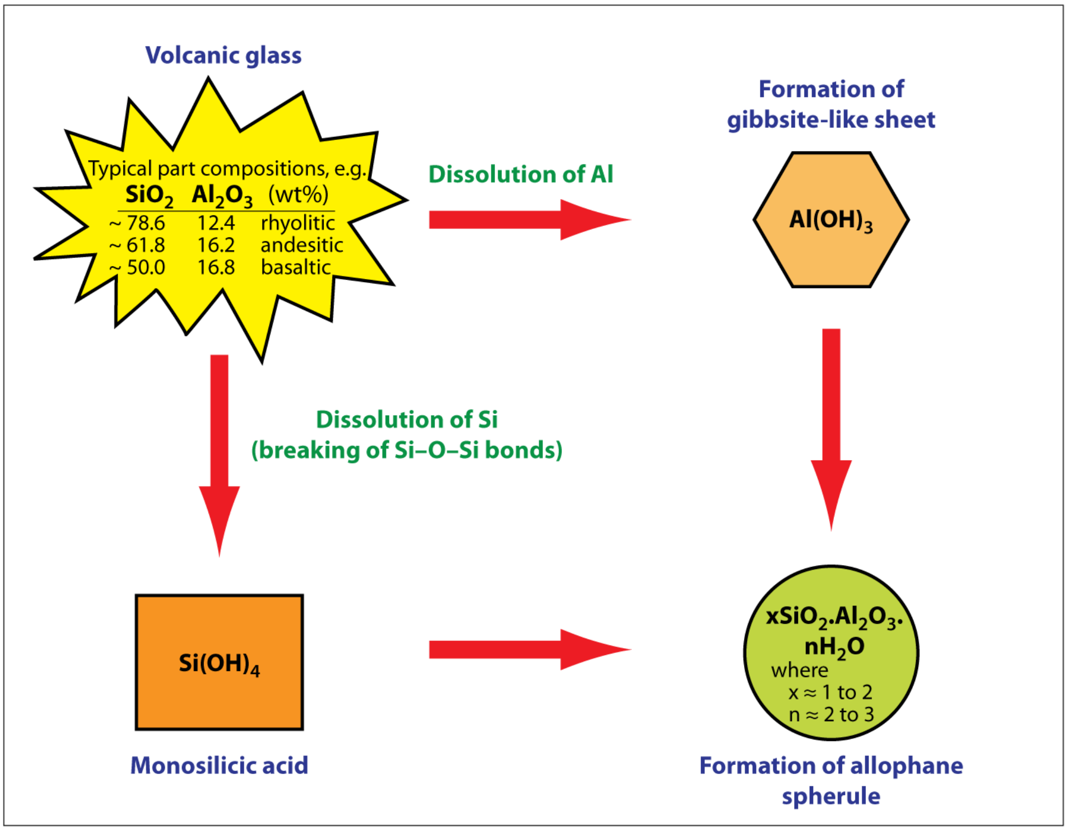


Fig. 19 Various volcanic glass compositions and dissolution of Al and Si and their reprecipitation to form allophane spherules or 'nanoballs' (from McDaniel et al., 2012, after Hiradate and Wada, 2005).

In New Zealand, both mineralogical and soil-solution studies on soils derived from tephras extending across a rainfall gradient showed that rainfall, coupled with through-profile drainage, helps govern Si concentration [Si] in soil solution and thus the likelihood of allophane being formed or not (Parfitt et al., 1983; Singleton et al., 1989; Parfitt, 1990, 2009; Churchman and Lowe, 2012). The Si leaching model is summarized as follows: where [Si] is less than ~10 ppm (mg l^{-1}), allophane is formed; where [Si] is greater than ~10 ppm, halloysite is formed. If [Si] is close to ~10 ppm then either allophane or halloysite may predominate. A profile throughflow threshold of approximately 250 mm per year of drainage water likely controls [Si] – less than ~250 mm means that the loss of Si is insufficient for Al-rich allophane to form and halloysite (or Si-rich allophane) forms instead (Parfitt et al., 1984; Lowe, 1986; McDaniel et al., 2012).

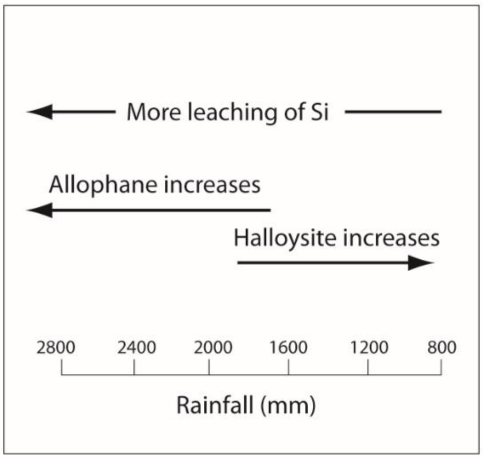


Fig. 20 Simplified allophane-halloysite rainfall Si-leaching model (from McDaniel et al., 2012).

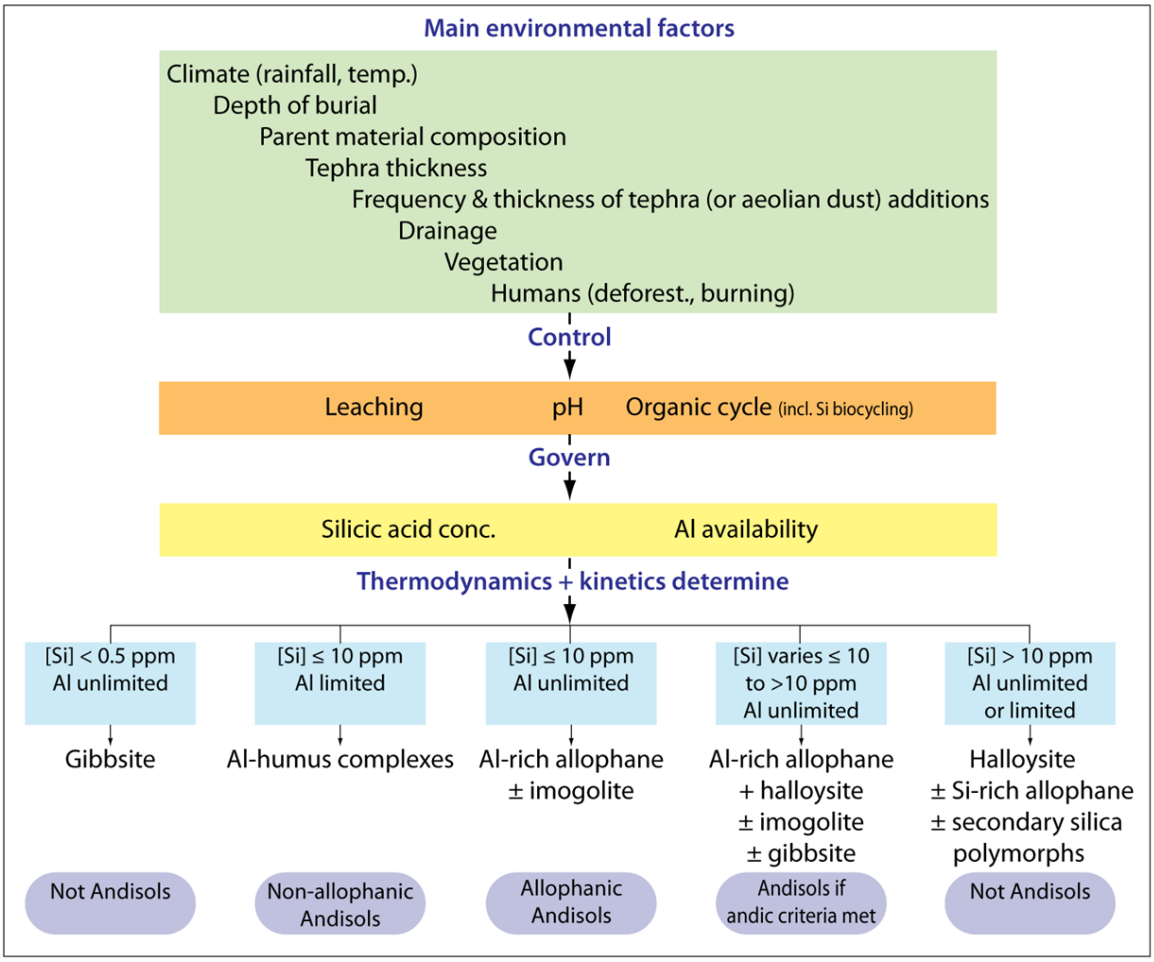


Fig. 21 Environmental influences and controls that govern the critical conditions leading to the formation of different clays from the weathering of tephras, and the likely occurrence, or not, of Andisols (mainly Allophanic and Pumice Soils in *NZSC*) as a result (from Churchman and Lowe, 2012). ± indicates that the clay mentioned may also be present.

Why Andisols (Allophanic Soils) are rich in carbon

Studies by Huang et al. (2016a) have determined, using an experimental approach with salmon-sperm DNA and artifical allophane, why Andisols may contain large amounts of organic matter (up to ~8–12% organic carbon). The formation of very stable allophane nanoaggregates and microaggregates (see Fig. 40) enables up to 28 µg mg^{-1} of DNA to be adsorbed (~80% of total) within tiny spaces (nanopores) between allophane spherules and allophane nanoaggregates (as "physical adsorption"), giving a total of 34 µg mg^{-1} of DNA adsorbed by the allophane. The stability of the allophane–DNA nano- and microaggregates likely prevents encapsulated DNA from exposure to oxidants, and DNA within small pores between allophane spherules and nanoaggregates may not be accessible to enzymes or microbes, hence enabling DNA protection and preservation in such materials. By implication, substantial organic carbon is therefore likely to be sequestered and protected in allophanic soils (Andisols) in the same way as demonstrated for DNA, that is, predominantly by encapsulation within a tortuous "nanolabyrinthic" network of nanopores and submicropores amidst stable nanoaggregates and microaggregates, rather than by chemisorption alone.

Forming a soil whilst tephras accumulate: geological vs pedological processes

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 tephras from numerous eruption. After establishing the stratigraphy (geological layering) of the sequences, the interplay of topdown pedogenesis (soil formation) and the accumulation to tephras on the land surface can be considered (upbuilding pedogenesis).

Topdown pedogenesis is 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. Soil formation proceeds by effectively modifying pre-existing parent materials to a greater or lesser extent according to a range of factors that dictate a range of processes. However, in many landscapes, such as those of alluvial plains, or where tephras or loess are deposited, aggrading parent materials are very common. The evolution of soils in such landscapes therefore has an additional complexity because the impact from topdown processes is modified by the rates at which new materials are added to the landsurface via geological processes (Almond and Tonkin, 1999). The resultant soils are formed by upbuilding pedogenesis.

Upbuilding pedogenesis is the ongoing formation of soil *via topdown processes* whilst tephras or loess (or alluvium, colluvium) *are concomitantly added* to the land/soil surface as normal geological processes (Lowe and Tonkin, 2010; McDaniel et al., 2012). The resultant soils may show distinctive layering and buried horizons (sometimes referred to as paleosols), forming *multisequal (multilayered) profiles*. The frequency and thickness of tephra accumulation (and other factors) determine how much impact topdown processes have on the ensuing profile character, and if *developmental* or *retardant* upbuilding, or both, will take place. These terms 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 Anderson, 2005).

- ***Developmental upbuilding*** occurs when the rate of addition of tephra or loess to the land is incremental and sufficiently slow so that topdown pedogenesis effectively keeps pace as the land gradually rises (a corollary is that each part of the profile has been an A horizon at one time) (Fig. 22).

- ***Retardant upbuilding*** occurs when a relatively thick layer of tephra (or alluvium, colluvium) is instantaneously added to the surface, or the rate of accumulation of thinner additions is fast, so that the original soil is rapidly buried (overwhelmed), and thus becomes a *buried horizon cut off and isolated* from the new land surface in which pedogenesis begins anew (Fig. 23).

We will see examples of soils dominated by developmental (Tirau) and retardant (Rotomahana) upbuilding.

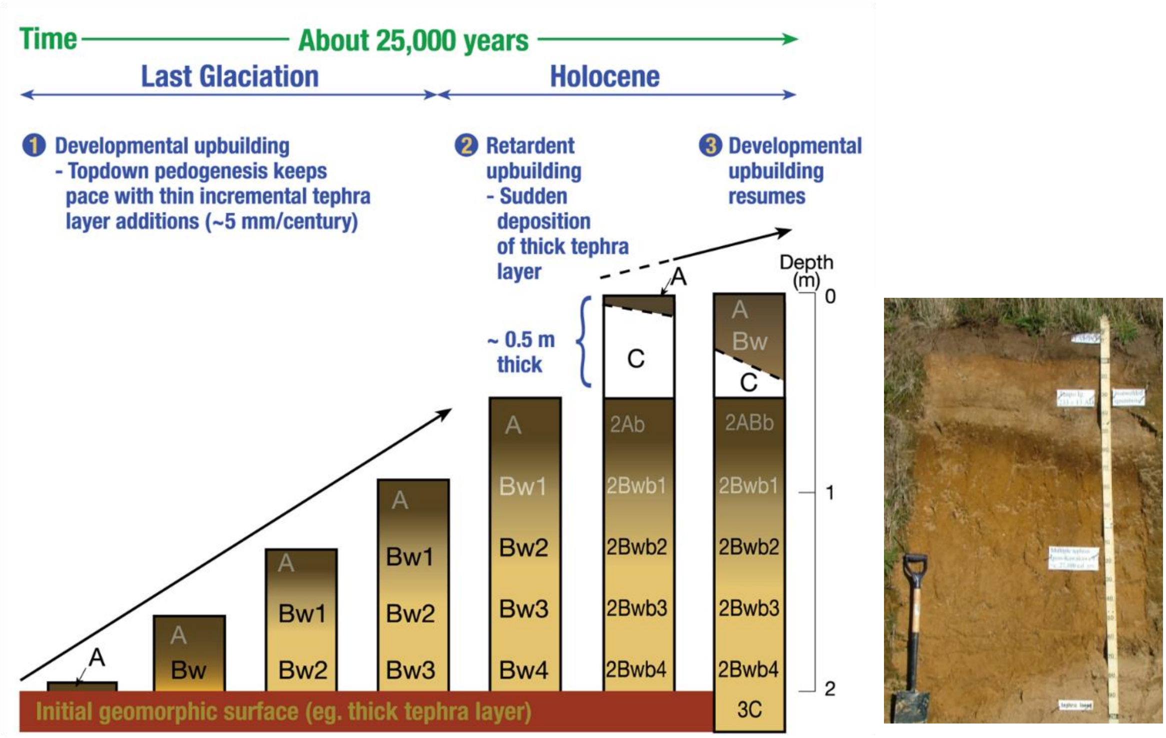


Fig. 22 Model of upbuilding pedogenesis in tephra deposits and the formation of a multisequal profile (photo at right) over c. 25,000 years in South Waikato. The underlying initial surface is marked here by a thick pinkish-grey layer of Kawakawa Tephra (c. 25,400 cal yr BP). In phase 1, thin, distal tephras accumulate slowly whilst topdown processes imprint weak horizonation features on them as the land surface gradually rises (developmental upbuilding). In phase 2, the sudden deposition of a tephra layer ~0.5 m thick, Taupo ignimbrite here (c. AD 232), from a particularly powerful eruption buries the antecedent soil, isolating it from most surface processes so that topdown processes begin anew on the freshly deposited tephra (retardant upbuilding). In phase 3, incremental tephra deposition on the new soil continues and developmental upbuilding resumes (from McDaniel et al., 2012).

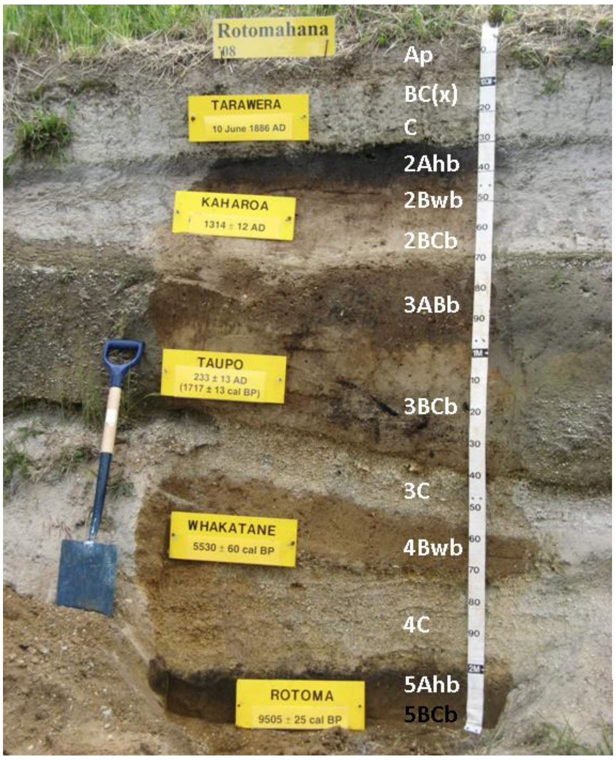


Fig. 23 Very clear example of a multilayered soil formed through retardant upbuilding at Brett Rd near Mt Tarawera. After each tephra is deposited, soil begins to develop until it is buried by another tephra and topdown pedogenesis begins operating in the fresh deposit. The buried 'mini' soil profile on Whakatane tephra (4Bwb, 4C horizons) reflects ~3800 years of pedogenesis, the amount of time it was at the land surface before burial by Taupo tephra; that on Taupo tephra (3ABb, 3BCb, 3C) reflects ~1100 years; that on Kaharoa tephra (2Ahb, 2Bwb, 2BCb) reflects ~570 years; and the topmost (surface) mini profile (Ap, BC(x), C) reflects ~120 years of pedogenesis on hydrothermally altered, mud-rich tephra deposited in AD 1886 by the Tarawera eruption (from McDaniel et al., 2012).

Buried brown rather than black ‘topsoil’ horizons

Buried ‘A’ horizons in New Zealand on tephras tend to be brownish rather than dark or black (and hence often have AB or Bw rather than Ah notations) and there is debate as to the reason for this. One suggestion is that in New Zealand they have largely been developed under podocarp-broadleaved forest until very recent times (last c. 700 years) and that such soils, especially Allophanic Soils, tend have brownish rather than dark A horizons anyway (this applies in USA for Andisols under conifers: P. McDaniel, pers. comm., 2008). Alternatively, or in addition, once ‘A’ horizons are buried then they may, depending on depth of burial, become isolated from the organic cycle and hence no longer receive new organic matter to maintain their darkness via melanisation (Fig. 25).

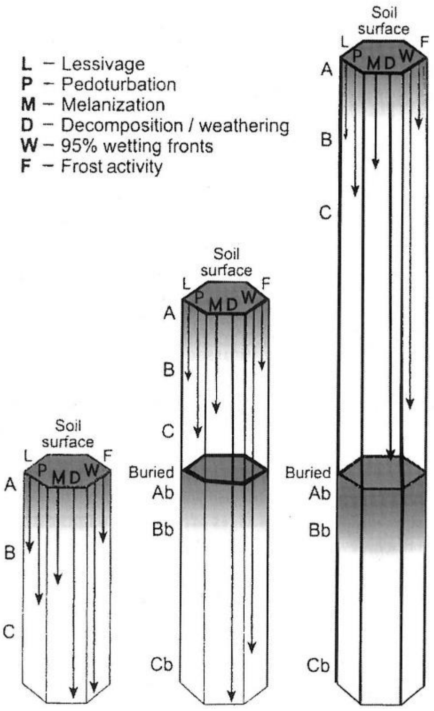


Fig. 24 Idealised models of buried soil horizons at different depths and how they may be impacted by surficial (topdown) processes (from Schaetzl and Thompson, 2015).

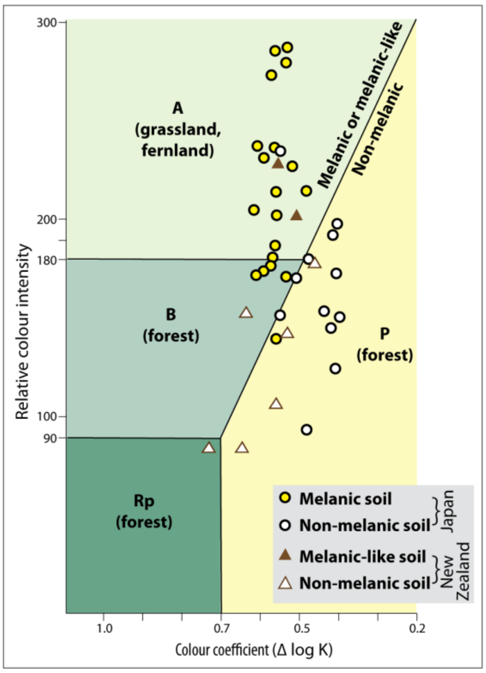


Fig. 25 Comparison of humic acids from tephra-derived soils in Japan and New Zealand (after Watanabe and Sakagami, 1999). The buried soil horizon on Kaharoa tephra is melanic-like and contains charcoal probably from Polynesian burning.

Residual colours after removing organic matter from A horizons by H_2O_2 or burning in the lab are similar to those of buried horizons on the tephras (P.J. Tonkin pers. comm., 2006). In some cases the depositional (burial) event may 'scalp' the topsoils (e.g., during emplacement of the Taupo ignimbrite), leaving effectively subsoils to represent the antecedent (now paleo) land surface. Forest fires following eruption events may also partially 'bleach' upper horizons (Wilson, 1994), and the effects of podzolisation (acid leaching), giving rise to bleached 'E' (albic) horizons over dark brown or reddish-brown podzolic-B (spodic) horizons are also evident in soils on Holocene tephras including on Taupo, Whakatane, and Rotoma tephras (Lowe et al., 2012).

Impacts of deforestation and burning, and the role of bracken fern, on the properties of surficial or buried soil A-horizons

Bracken fern (*Pteridium* spp.) is an aggressive plant that commonly invades disturbed sites. Its success as an invader is attributable, in part, to its ability to produce abundant growth, both below ground in the form of rhizomes and fine roots and above ground as fronds and stems (Table 5; Lowe and McDaniel, 2010). This biomass production has been shown to affect numerous soil properties. For many years, the black A horizons often found on Pumice Soils have been attributed 'to bracken fern, which replaced much of the forest'. Analyses of humus and phytoliths in the A horizons of soils developed especially on Kaharoa and Taupo tephras in central North Island (buried beneath 1886 Tarawera eruptives in the parts of Bay of Plenty) showed that type-A humic acids predominated and that fernland and grassland had replaced the pre-existing forests (Fig. 25) (Birrell et al., 1971; Sase et al., 1988; Hosono et al., 1991; Sase and Hosono, 1996). Pollen, phytolith and associated studies, together with tephrochronology, have shown that human-induced deforestation by burning began in New Zealand soon after Polynesian settlers arrived (Newnham et al., 1998; McGlone and Wilmshurst, 1999; McWethy et al., 2009, 2014). The repeated burning resulted in the formation of extensive fernlands (McGlone et al., 2005).

Table 5 Bracken biomass comparisons – New Zealand and northern Idaho, USA*

	Rhizome biomass		**Frond biomass**	
Location	Mean (kg m^{-2})	Range	Mean (kg m^{-2})	Range
Nelson, New Zealand	--	7.08 (max.)	--	1.41 (max.)
New Zealand (23 stands)	2.92	0.91-5.19	--	--
Idaho, USA (9 stands)	1.96	1.14-2.54	0.52	0.27-0.89

*From Lowe and McDaniel (2010)

In northern Idaho, USA, establishment of bracken is associated with the conversion of allophanic to non-allophanic Andisol mineralogy (Johnson-Maynard et al., 1997). These changes include increased soil carbon, darker soil colours, lower pH, and increased organic forms of active Al. In Japan, a major part of soil organic carbon in Andisols and associated soils comprises humic acids, which are characterized by their stability and aromatic (humified) structure (Shoji et al., 1993; Hiradate et al., 2004). These features arise from the presence of labile and active metals, chiefly Al and Fe, supplied by the weathering of glass and other tephric materials, which are able to bind humic substances through strong coordination bonding to form macromolecules of Al- and Fe-humic acid complexes very resistant to degradation or leaching (Hiradate et al., 2004).

The resultant very dark or commonly black A horizons, typically melanic horizons in *Soil Taxonomy* (Table 6), can contain up to 15% organic carbon (Hiradate et al., 2004). The Japanese pampas grass or 'susuki', *Miscanthis sinensis*, a C4 plant with large amounts of root residues, has been maintained artificially for millennia in ancient Japan to provide roofing material, straw bags, and fodder for grazing. Burning the grass in early spring before germination was common practice (buds of the pampas grass are several centimetres underground and so are not damaged) (Lowe and McDaniel, 2010). During burning, large amounts of very dark-coloured and charred microparticles were produced and these provided a second source of humic acids. The pampas grass has been regarded as a classic 'andisolizer' or 'melaniser' (Wada, 1986; Shoji et al., 1990, 1993; Hiradate et al., 2004).

Table 6 Main properties of melanic horizon*

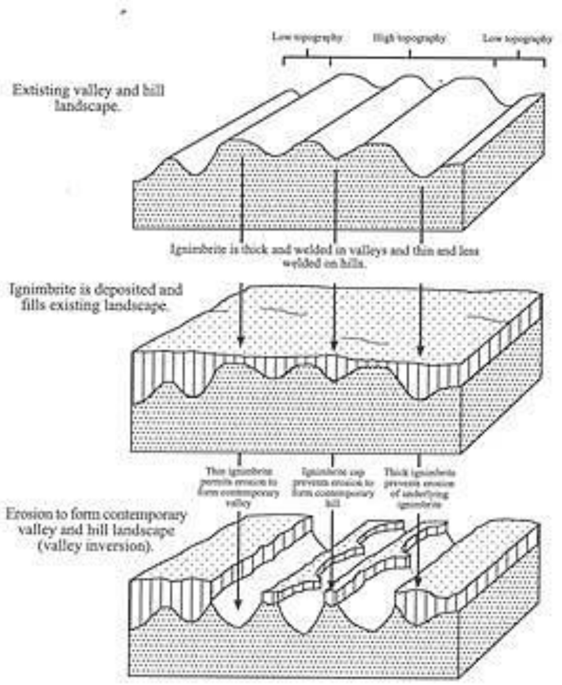
- Munsell colour values and chromas of ≤ 2 (dark) throughout
- Melanic index ≤ 1.70 throughout
- ≥ 6% organic C as weighted average
- Andic soil properties
- ≥ 30 cm thick

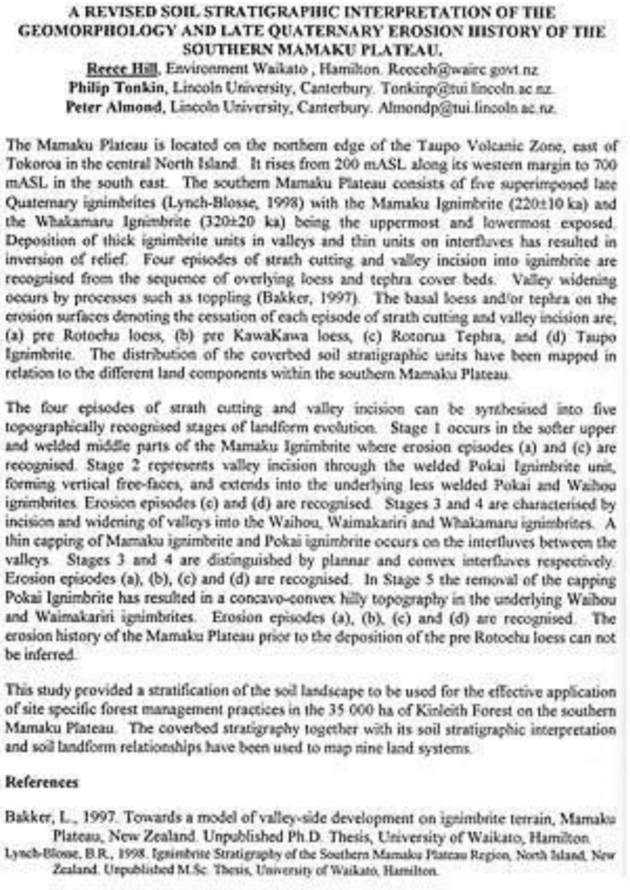
* After Soil Survey Staff (1999, p.23)

The relative importance of these two mechanisms – (1) stabilization of humic acids by complexing reactions with Al and Fe, or (2) cultivation of *M. sinensis* and its charred derivatives as a major source of carbon in humic acids – was evaluated by Hiradate et al. (2004) using $\delta^{13}C$ analyses of humic substances in a range of soils in Japan. Hiradate et al. (2004) were able to compare the contributions from C3- or C4-plant- derived carbon because *M. sinensis* was effectively the only C4 plant species in (traditional) Japan. They found that the contribution to humic and fulvic acids of carbon derived from *M. sinensis* ranged from 18 % to 52 %. Their conclusions were that although highly-humified, i.e. dark-coloured, humic acids tended to be derived from C4-plant-derived carbon (ultimately *M. sinensis*), the dominant source of carbon for humic and fulvic acids in many cases was from C3 plants (mainly forest vegetation). Consequently, the overriding importance of active Al and Fe especially on the formation and accumulation of the dark-coloured humic acids in *Kuroboku* soils (Andisols) was reinforced (Hiradate et al., 2004).

In New Zealand the 'black' A horizons generally have melanic properties, but do not meet the thickness criterion for melanic epipedons, and hence are regarded as 'melanic-like'. As noted above, they formed under fernland and tusssock grassland and most contain A-type humic acids (± charcoal). Non-melanic topsoils are formed under forest (most have non A-type humic acids, including Pg in P-type humic acids from deciduous trees) (Figs. 25, 32). Differences between New Zealand and Japan thus relate largely to differences in human settlement history and impacts, with New Zealand having an exceptionally short prehistory of only c. 700 years (since c. 1280 AD) in comparison with >10,000 years in Japan (Lowe and McDaniel, 2010).

Mamaku Plateau – model of its development





A REVISED SOIL STRATIGRAPHIC INTERPRETATION OF THE GEOMORPHOLOGY AND LATE QUATERNARY EROSION HISTORY OF THE SOUTHERN MAMAKU PLATEAU.

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The Mamaku Plateau is located on the northern edge of the Taupo Volcanic Zone, east of Tokoroa in the central North Island. It rises from 200 mASL along its western margin to 700 mASL in the south east. The southern Mamaku Plateau consists of five superimposed late Quaternary ignimbrites (Lynch-Blosse, 1998) with the Mamaku Ignimbrite (220±10 ka) and the Whakamaru Ignimbrite (320±20 ka) being the uppermost and lowermost exposed. Deposition of thick ignimbrite units in valleys and thin units on interfluves has resulted in inversion of relief. Four episodes of strath cutting and valley incision into ignimbrite are recognised from the sequence of overlying loess and tephra cover beds. Valley widening occurs by processes such as toppling (Bakker, 1997). The basal loess and/or tephra on the erosion surfaces denoting the cessation of each episode of strath cutting and valley incision are; (a) pre Rotoehu loess, (b) pre KawaKawa loess, (c) Rotorua Tephra, and (d) Taupo Ignimbrite. The distribution of the coverbed soil stratigraphic units have been mapped in relation to the different land components within the southern Mamaku Plateau.

The four episodes of strath cutting and valley incision can be synthesised into five topographically recognised stages of landform evolution. Stage 1 occurs in the softer upper and welded middle parts of the Mamaku Ignimbrite where erosion episodes (a) and (c) are recognised. Stage 2 represents valley incision through the welded Pokai Ignimbrite unit, forming vertical free-faces, and extends into the underlying less welded Pokai and Waihou ignimbrites. Erosion episodes (c) and (d) are recognised. Stages 3 and 4 are characterised by incision and widening of valleys into the Waihou, Waimakariri and Whakamaru ignimbrites. A thin capping of Mamaku ignimbrite and Pokai ignimbrite occurs on the interfluves between the valleys. Stages 3 and 4 are distinguished by plannar and convex interfluves respectively. Erosion episodes (a), (b), (c) and (d) are recognised. In Stage 5 the removal of the capping Pokai Ignimbrite has resulted in a concavo-convex hilly topography in the underlying Waihou and Waimakariri ignimbrites. Erosion episodes (a), (b), (c) and (d) are recognised. The erosion history of the Mamaku Plateau prior to the deposition of the pre Rotoehu loess can not be inferred.

This study provided a stratification of the soil landscape to be used for the effective application of site specific forest management practices in the 35 000 ha of Kinleith Forest on the southern Mamaku Plateau. The coverbed stratigraphy together with its soil stratigraphic interpretation and soil landform relationships have been used to map nine land systems.

References

Bakker, L., 1997. Towards a model of valley-side development on ignimbrite terrain, Mamaku Plateau, New Zealand. Unpublished Ph.D. Thesis, University of Waikato, Hamilton.
Lynch-Blosse, B.R., 1998. Ignimbrite Stratigraphy of the Southern Mamaku Plateau Region, North Island, New Zealand. Unpublished M.Sc. Thesis, University of Waikato, Hamilton.

Fig. 26 General model for landscape development of southern Mamaku Plateau involving emplacement and erosion of ignimbrites and tephrochronology for age control (from Hill et al., 1999).

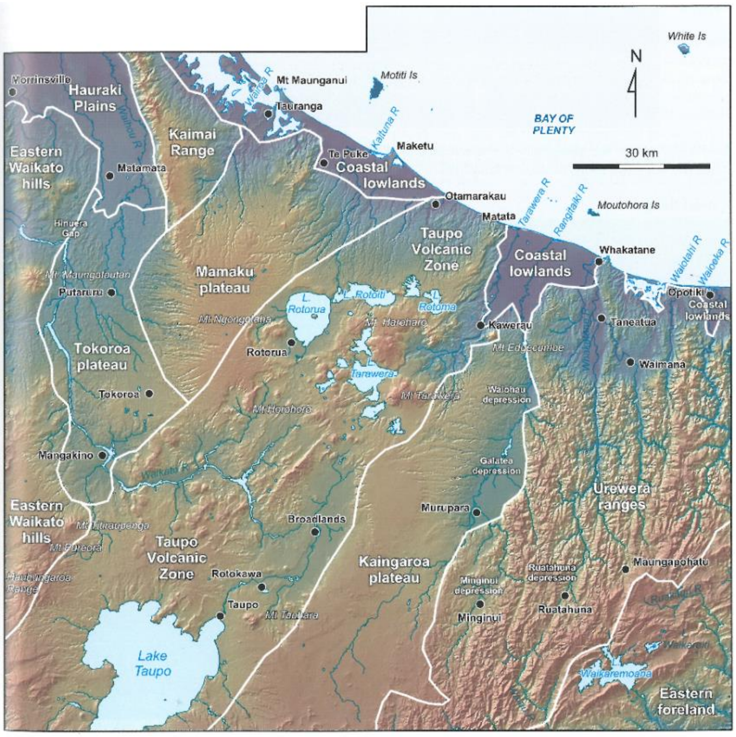


Fig. 27 Topographic relief model illustrating some of the physiographic regions covered partly on Wednesday 21 Dec 2016. The 'geomorphic' Taupo Volcanic Zone (TVZ) comprises an area of largely volcanic hills and lakes and covers a similar area (but not exactly equivalent) to the volcanological TVZ (defined by vent locations only) (from Leonard et al., 2010, p. 7).

STOP – TIRAU SILT LOAM, GOODWIN FARM, TAPAPA RD

Location BE36 534907, 37° 59′ 41″ S 175° 52′ 59″ E; elevation ~245 m

A feature of this site is that many different dating methods have been applied to the sequence, the ages being transferred here using tephrochronology: ^{14}C, ^{14}C-based wiggle-match dating with dendrochronology, amino acid racemisation, $^{40}Ar/^{39}Ar$, isothermal plateau fission-track dating on glass, U/Th(He), paleomagnetic reversal/excursion, correlation with marine oxygen isotope stages.

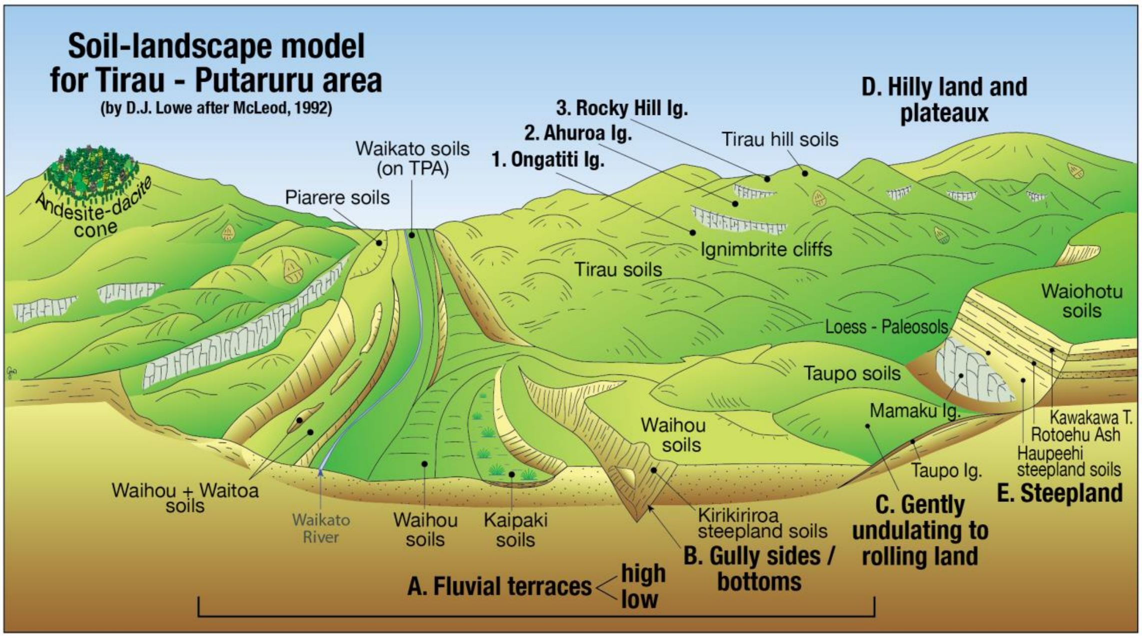


Fig. 28 Soil-landscape model for the Tirau-Putarura area and Tapapa. The three main welded ignimbrite units (~1.23 Ma to 0.9 Ma, erupted from Mangakino volcano) form distinctive plateaux in the landscape and are mantled with tephra-fall deposits and subordinate tephric loess. Fluvial terraces are also mantled with tephras. TPA, Taupo Pumice Alluvium (c. 1700 cal yr BP) (diagram modified from McLeod, 1992).

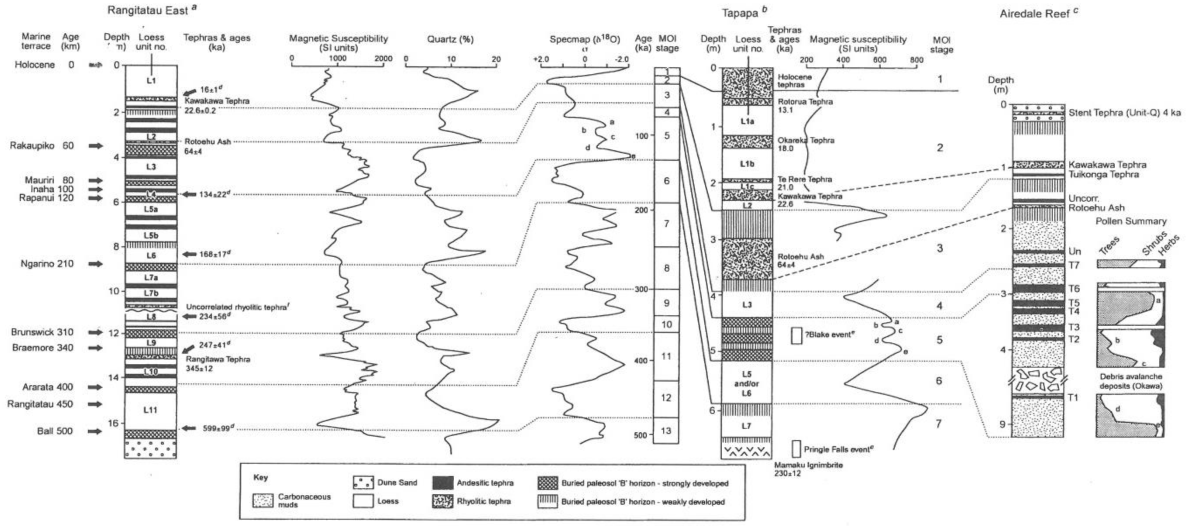


Fig. 29 Correlation of Tapapa section with Rangitatau East section near Wanganui, and Airedale Reef section near New Plymouth (from Newnham et al., 1999). The sections are connected using tephras common to each (tephrochronology). Magnetic reversals indicated at Tapapa are possibly equivalent to the Blake event (c. 120 ka) and Pringle Falls event (c. 220 ka) (from Lowe et al., 2012).

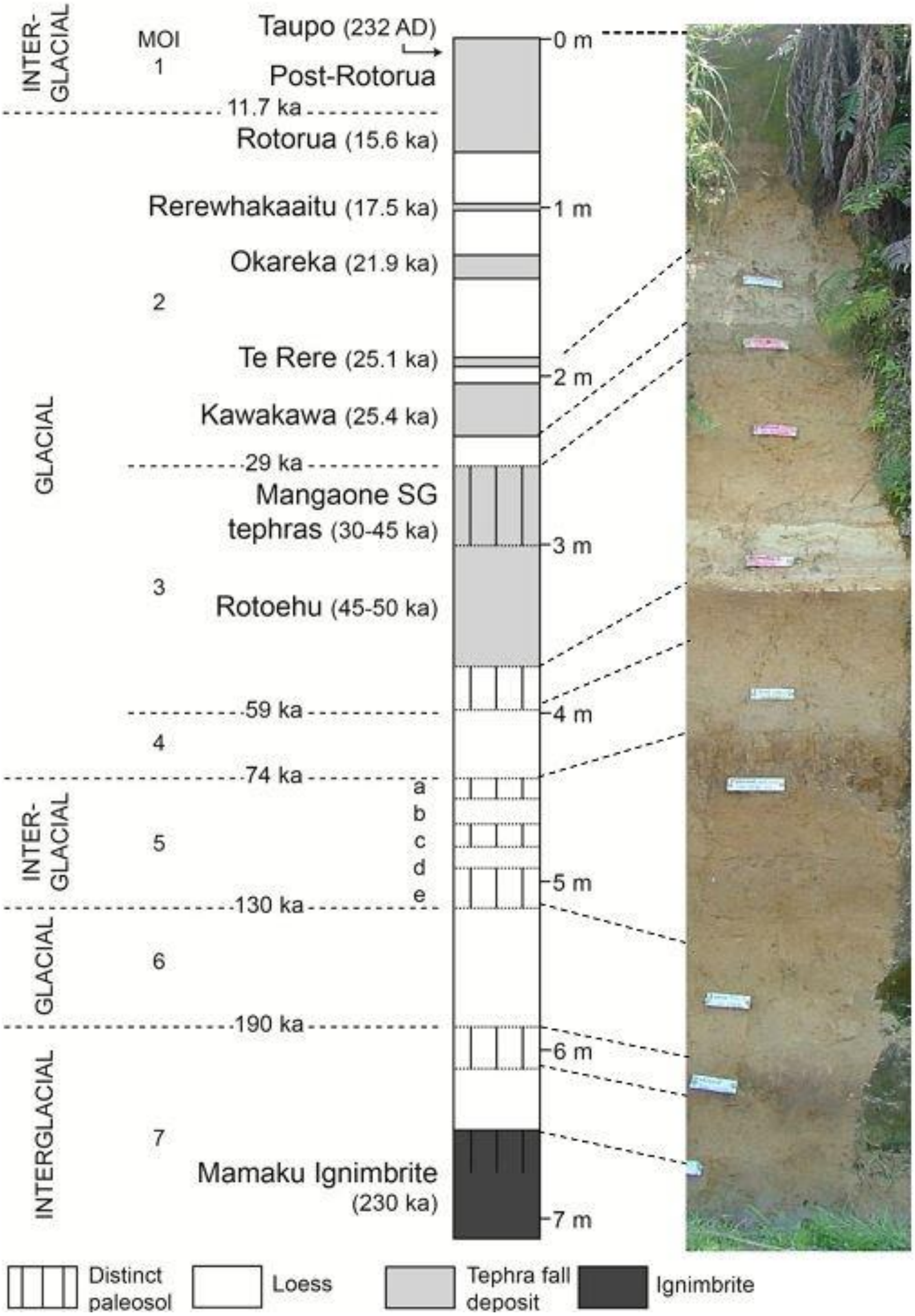
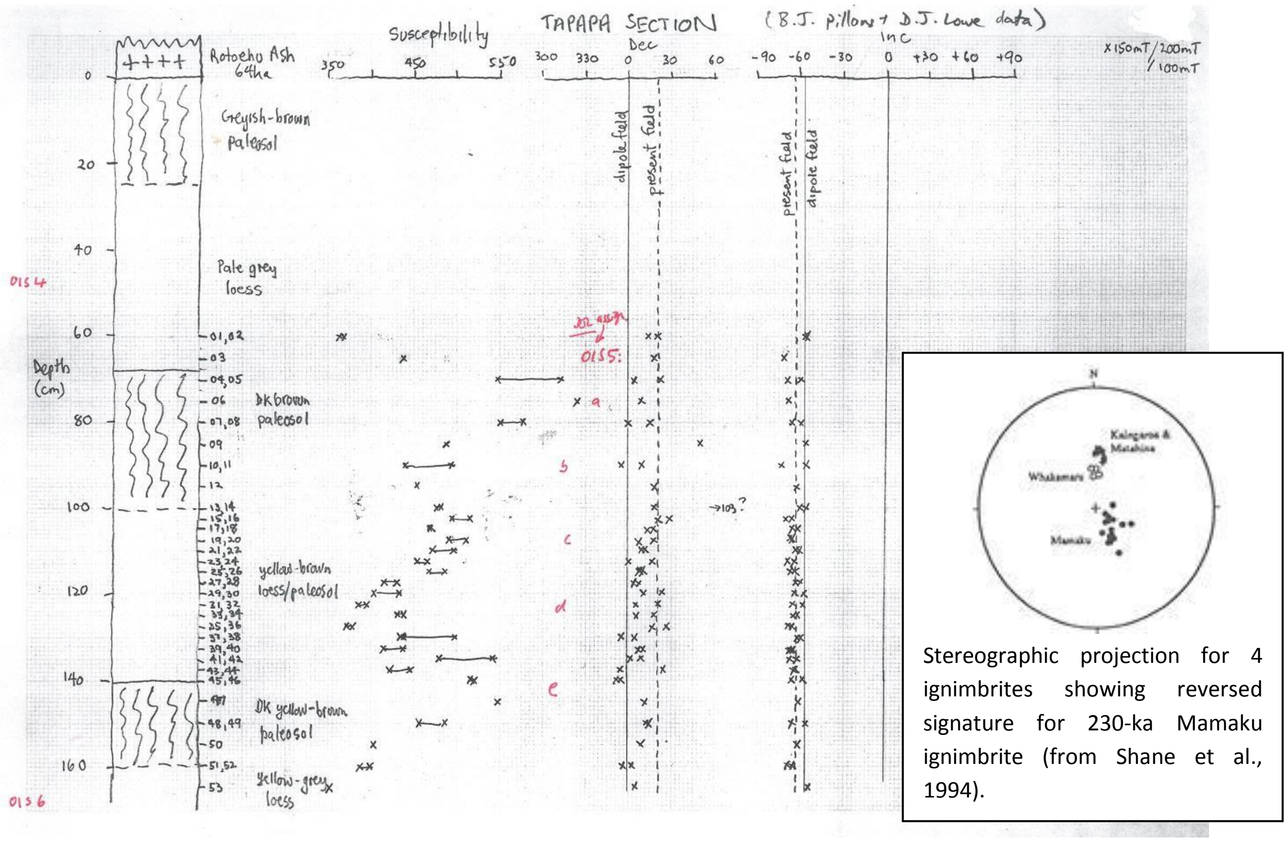


Fig. 30 Stratigraphy and chronology of Tapapa sequence and provisional correlation with marine oxygen isotope (MOI) stages (ages based on Froggatt, 1988; Kimber et al., 1994; Lowe and Briggs, 1994; Shane et al., 1994; Houghton et al., 1995; Lowe et al., 2008b, 2013; Danišík et al., 2012). Unpublished data from D.J. Lowe, J.E. Begét, B.J. Pillans. Earlier work on uppermost part of the sequence was undertaken by Pullar and Birrell (1973). The gritty base of cohesive, slightly weathered Kawakawa tephra = unit 7 of Wilson (2001); accretionary lapilli occur at the top of that layer. Soil series = Tirau.

Fig. 31 Photos of Tapapa section (upper, middle, lower). Tephras preserved in nearby Lake Okoroire (~10 km NW of Tapapa) provide a record of tephra fall since c. 20 cal ka (Lowe, 1986, 1988) (from Lowe et al., 2012).



Stereographic projection for 4 ignimbrites showing reversed signature for 230-ka Mamaku ignimbrite (from Shane et al., 1994).

Fig. 32 Magnetic susceptibility measurements and paleomagnetic data for the lower part of the Tapapa section (pre-Rotoehu Ash) (unpublished data of B.J. Pillans and D.J. Lowe)

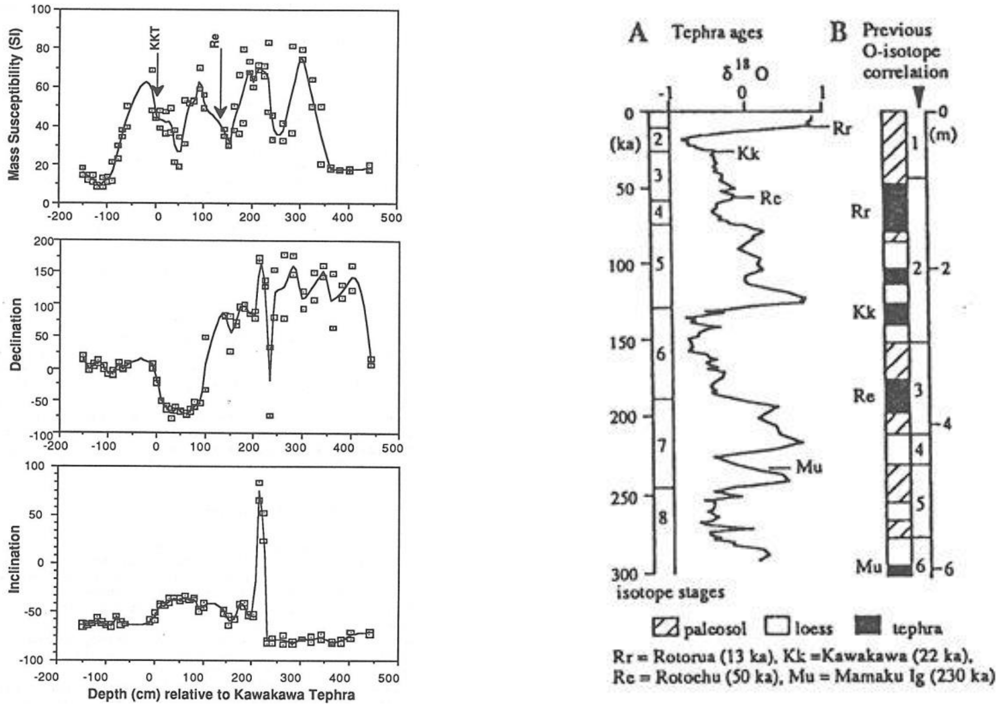
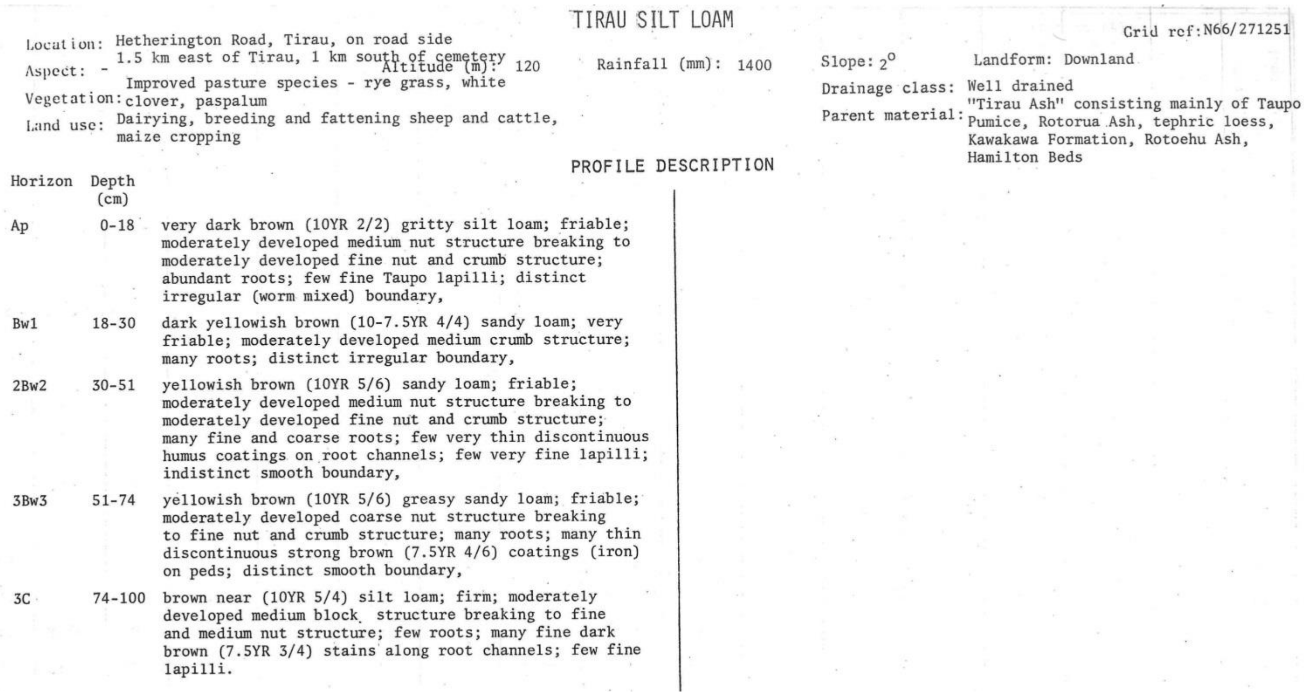


Fig. 33 Left: Paleomagnetic data for Tapapa section including possible Blake event c. 120 ka in ~MOIS 5d (from Froggatt, 1988). **Right**: Revised chronology of Tapapa sequence and correlation with MOI stages (from Shane et al., 1994). Ages on Mamaku Ig.: 230 ± 12 ka (Shane et al., 1994); 220 ± 10 ka (Houghton et al., 1995); correlation to Pringle Falls event: 223 ± 4 ka (Shane et al., 1994; McWilliams, 2001; Singer et al., 2013).



TIRAU SILT LOAM

Grid ref:N66/271251

Location: Hetherington Road, Tirau, on road side 1.5 km east of Tirau, 1 km south of cemetery

Aspect: -

Altitude (m): 120

Rainfall (mm): 1400

Slope: 2°

Landform: Downland

Vegetation: Improved pasture species - rye grass, white clover, paspalum

Land use: Dairying, breeding and fattening sheep and cattle, maize cropping

Drainage class: Well drained

Parent material: "Tirau Ash" consisting mainly of Taupo Pumice, Rotorua Ash, tephric loess, Kawakawa Formation, Rotoehu Ash, Hamilton Beds

PROFILE DESCRIPTION

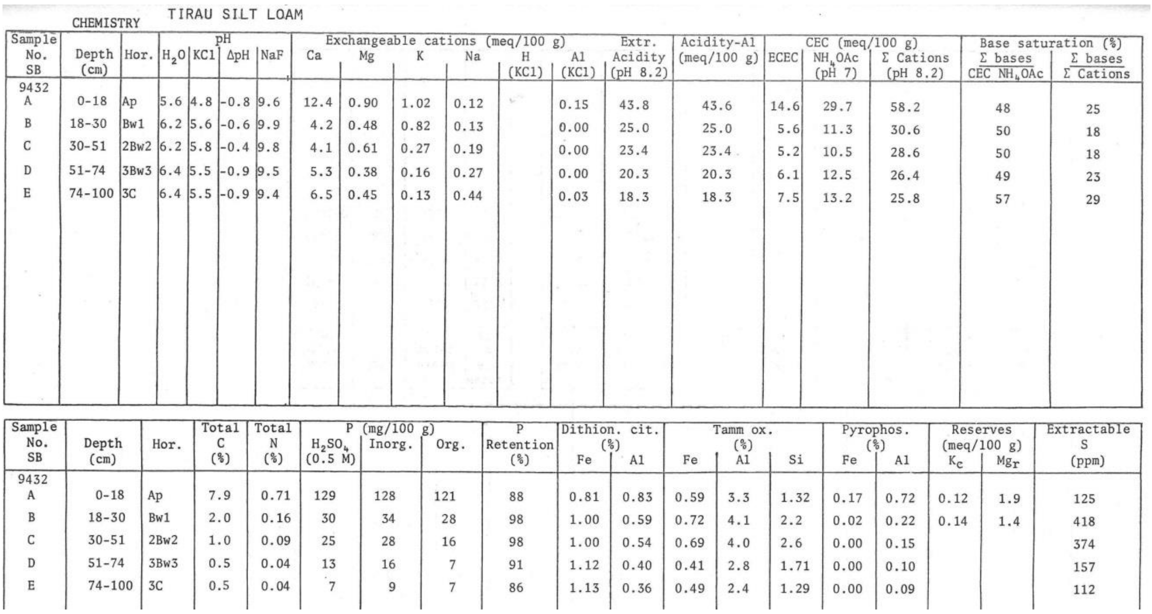
Horizon	Depth (cm)	
Ap	0-18	very dark brown (10YR 2/2) gritty silt loam; friable; moderately developed medium nut structure breaking to moderately developed fine nut and crumb structure; abundant roots; few fine Taupo lapilli; distinct irregular (worm mixed) boundary,
Bw1	18-30	dark yellowish brown (10-7.5YR 4/4) sandy loam; very friable; moderately developed medium crumb structure; many roots; distinct irregular boundary,
2Bw2	30-51	yellowish brown (10YR 5/6) sandy loam; friable; moderately developed medium nut structure breaking to moderately developed fine nut and crumb structure; many fine and coarse roots; few very thin discontinuous humus coatings on root channels; few very fine lapilli; indistinct smooth boundary,
3Bw3	51-74	yellowish brown (10YR 5/6) greasy sandy loam; friable; moderately developed coarse nut structure breaking to fine nut and crumb structure; many roots; many thin discontinuous strong brown (7.5YR 4/6) coatings (iron) on peds; distinct smooth boundary,
3C	74-100	brown near (10YR 5/4) silt loam; firm; moderately developed medium block structure breaking to fine and medium nut structure; few roots; many fine dark brown (7.5YR 3/4) stains along root channels; few fine lapilli.

Description of Tirau soil at Hetherington Rd, near Tirau (T15/546556) (~18 km from Tapapa) from Parfitt et al. (1981) (see also Bakker et al., 1996). At Tapapa the soil was mapped by McLeod (1992) as part of the Tirau series, which occur on rolling land grading to higher terraces (elevational range 70-400 m) and with a thermic temperature regime. However, Tirau soils have very similar parent materials to soils of the Waiohotu series that occur at usually higher elevations on high-level terraces (plateau surfaces) (elevational range 250-500 m) under higher rainfall (Waiohotu 2000-2400 mm pa, Tirau 1400-2000 mm pa) and mesic temperature regimes (see soil-landscape model p.10). The Waiohotu soils have slightly coarser textures (gritty silt loams vs silt loams), lower pHs (Waiohotu 4.5-5.9, Tirau 5.6-6.4), stronger leaching, and until recently have not normally been used for maize production (M. McLeod pers. comm., 2008). Tapapa is at the thermic/mesic boundary (Aldridge, 1982).

Classification of Tirau silt loam

NZSC: Acidic Orthic Allophanic; Mt; na (Rh and An fines), loamy; m

Soil Taxonomy: Medial, thermic/mesic Typic Hapludands



CHEMISTRY

TIRAU SILT LOAM

Sample No. SB	Depth (cm)	Hor.	pH H_2O	pH KCl	pH ΔpH	pH NaF	Exchangeable cations (meq/100 g) Ca	Mg	K	Na	H (KCl)	Al (KCl)	Extr. Acidity (pH 8.2)	Acidity-Al (meq/100 g)	ECEC	CEC (meq/100 g) NH_4OAc (pH 7)	Σ Cations (pH 8.2)	Base saturation (%) Σ bases / CEC NH_4OAc	Σ bases / Σ Cations
9432																			
A	0-18	Ap	5.6	4.8	-0.8	9.6	12.4	0.90	1.02	0.12		0.15	43.8	43.6	14.6	29.7	58.2	48	25
B	18-30	Bw1	6.2	5.6	-0.6	9.9	4.2	0.48	0.82	0.13		0.00	25.0	25.0	5.6	11.3	30.6	50	18
C	30-51	2Bw2	6.2	5.8	-0.4	9.8	4.1	0.61	0.27	0.19		0.00	23.4	23.4	5.2	10.5	28.6	50	18
D	51-74	3Bw3	6.4	5.5	-0.9	9.5	5.3	0.38	0.16	0.27		0.00	20.3	20.3	6.1	12.5	26.4	49	23
E	74-100	3C	6.4	5.5	-0.9	9.4	6.5	0.45	0.13	0.44		0.03	18.3	18.3	7.5	13.2	25.8	57	29

Sample No. SB	Depth (cm)	Hor.	Total C (%)	Total N (%)	P (mg/100 g) H_2SO_4 (0.5 M)	Inorg.	Org.	P Retention (%)	Dithion. cit. (%) Fe	Al	Tamm ox. (%) Fe	Al	Si	Pyrophos. (%) Fe	Al	Reserves (meq/100 g) K_c	Mg_r	Extractable S (ppm)
9432																		
A	0-18	Ap	7.9	0.71	129	128	121	88	0.81	0.83	0.59	3.3	1.32	0.17	0.72	0.12	1.9	125
B	18-30	Bw1	2.0	0.16	30	34	28	98	1.00	0.59	0.72	4.1	2.2	0.02	0.22	0.14	1.4	418
C	30-51	2Bw2	1.0	0.09	25	28	16	98	1.00	0.54	0.69	4.0	2.6	0.00	0.15			374
D	51-74	3Bw3	0.5	0.04	13	16	7	91	1.12	0.40	0.41	2.8	1.71	0.00	0.10			157
E	74-100	3C	0.5	0.04	7	9	7	86	1.13	0.36	0.49	2.4	1.29	0.00	0.09			112

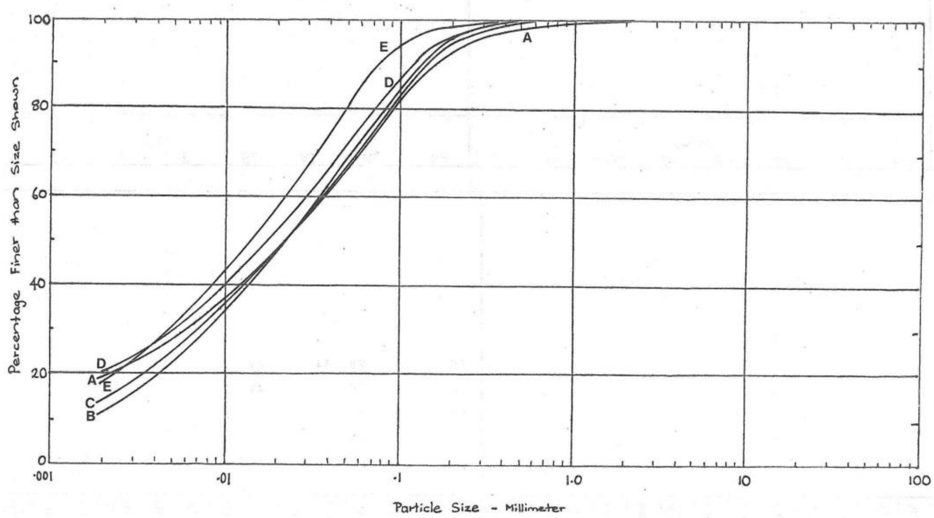
PHYSICS

Hor. Depth (cm)	Hor.	15 bar water Field moist (%)	15 bar water Air Dry (%)
0-18	Ap	31.1	23.3
18-30	Bw1	33.7	15.7
30-51	2Bw2	33.6	16.5
51-74	3Bw3	34.7	22.0
74-100	3C	33.9	20.4

Core Depth (cm)	Dry bulk density (T/m³)	Total porosity (%)	Large pores (%)	Field Cap. (at 0.2 bar) (% v/v)	Wilting Pt. (at 15 bar) (% v/v)	Available water (% v/v)
2-9	0.75					
20-27	0.71					
34-41	0.69					
58-65	0.79					
80-87	0.87					

PARTICLE SIZE DISTRIBUTION (<2 mm) TIRAU SILT LOAM

Sample No. SB	Depth (cm)	Hor.	Sand 2-0.1 mm (%)	Sand 0.1-0.05 mm (%)	Silt 0.05-0.002 mm (%)	Clay <0.002 mm (%)	Fine clay <0.0002 mm (%)	Fine clay / Total clay	Stones (%)
9432A	0-18	Ap	18	17	46	19			
B	18-30	Bw1	17	16	56	11			
C	30-51	2Bw2	17	16	54	13			
D	51-74	3Bw3	14	16	50	20			
E	74-100	3C	6	14	62	18			



SB 9432 Tirau Silt Loam

Mineralogy TIRAU

Sample No. SB	Depth (cm)	Hor.	Mica-Smectite	Mica-Vermiculite	Smectite	Vermiculite	Interlayered Hydrous Micas	Mica	Kaolinite	Halloysite	Gibbsite	Quartz	Cristobalite	Allophane	Feldspar	Anatase	Volcanic glass
			Clay Fraction (%)														
9432A	0-18									8				65			27
B	18-30									6				75			19
C	30-51									4				80			16
D	51-74									9	tr			55			36
E	74-100									21	tr		tr	48			31

Anthropogenic fluorine accumulation in the Waikato and Bay of Plenty regions of New Zealand: comparison of field data with projections

Nicholas D. Kim, Matthew D. Taylor, John J. Drewry

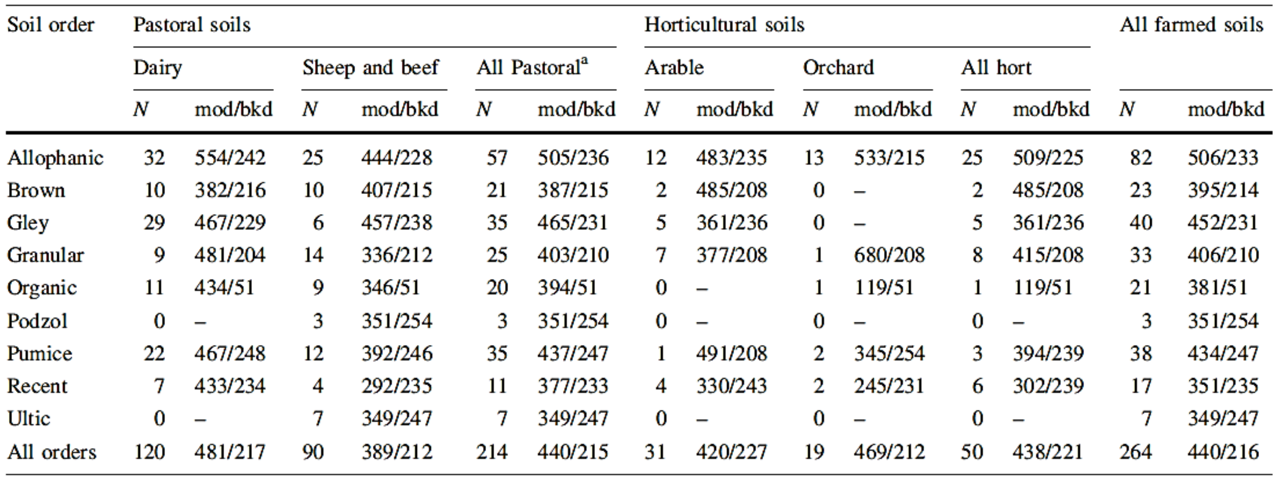
*Environmental Earth Sci*ences (2016) 75: 147 (DOI 10.1007/s12665-015-4897-2)

Long-term annual application of phosphate (P) fertilizers to farmland may be causing worldwide accumulation of fluorine (F) in productive soils, as F concentrations in rock phosphate and P fertilizers are typically ~75–150 times higher than those in recipient soils. Possible impacts of excess anthropogenic F in agricultural soils fall into three categories:

1. Toxicity, where concerns include toxicity to soil organisms and terrestrial wildlife, phytotoxicity, chronic fluorosis in grazing animals, and potential for aluminofluoride complexes to interfere with biochemical signalling pathways. AlF_x complexes are of toxicological interest because they act as phosphate analogues in a variety of enzymes.
2. Alterations of soil chemistry and function. Excess F may reduce organic matter turnover (Rao and Pal 1978) and phosphatase activity accelerate aluminosilicate weathering, induce formation of AlFx complexes in pore-water, and alter uptake of F, Al, AlF_x and other F-complexed elements in crops and animals.
3. Wider environmental impacts, including potential for contamination of ground-water, toxicity to aquatic ecosystems, and perturbation of the atmospheric F cycle from fluorinated gases released from treated soils or during fertilizer manufacture. Volatile F-containing species are effective greenhouse gases.

We report results of sampling across two large regions of New Zealand involving soils of 298 native and farmed properties. This has enabled the first wide-scale retrospective estimates of anthropogenic F enrichment in pastoral and horticultural soils. Results validate earlier projections: F accumulation in farmed soils has been comparatively rapid (mean increase 2.1 % per year) and widespread. Over 50 years, average total F concentrations in surface soils have doubled from ~220 to 440 mg/kg. Thresholds protective against chronic fluorosis in grazing animals are being substantively passed, indicating that land may be rendered unsuitable for pastoral production in the mid-term future: when sampled 44 % of dairy farm soil samples exceeded 500 mg/kg total F, and 10 % exceeded 650 mg/kg. Potential for F toxicity to plants and wildlife appear to be significant and marginal, respectively, at current soil F concentrations. Relationships between F and other elements suggest P fertilizers are also a source of several elements geochemically linked to F, and that anthropogenic F modifies soil aluminium (Al) chemistry, potentially opening a broad-scale Al exposure pathway to pollinating insects.

Table 3 Modern (mod) and estimated natural background (bkd) mean concentrations (mg/kg) of F ordered by soil order and land-use category



Soil order	Pastoral soils						Horticultural soils						All farmed soils	
	Dairy		Sheep and beef		All Pastoral[a]		Arable		Orchard		All hort			
	N	mod/bkd	N	mod/bkd	N	mod/bkd	N	mod/bkd	N	mod/bkd	N	mod/bkd	N	mod/bkd
Allophanic	32	554/242	25	444/228	57	505/236	12	483/235	13	533/215	25	509/225	82	506/233
Brown	10	382/216	10	407/215	21	387/215	2	485/208	0	–	2	485/208	23	395/214
Gley	29	467/229	6	457/238	35	465/231	5	361/236	0	–	5	361/236	40	452/231
Granular	9	481/204	14	336/212	25	403/210	7	377/208	1	680/208	8	415/208	33	406/210
Organic	11	434/51	9	346/51	20	394/51	0	–	1	119/51	1	119/51	21	381/51
Podzol	0	–	3	351/254	3	351/254	0	–	0	–	0	–	3	351/254
Pumice	22	467/248	12	392/246	35	437/247	1	491/208	2	345/254	3	394/239	38	434/247
Recent	7	433/234	4	292/235	11	377/233	4	330/243	2	245/231	6	302/239	17	351/235
Ultic	0	–	7	349/247	7	349/247	0	–	0	–	0	–	7	349/247
All orders	120	481/217	90	389/212	214	440/215	31	420/227	19	469/212	50	438/221	264	440/216

[a] Totals include four pastoral sites that are neither dairy nor sheep and beef (one brown, two granular, one pumice)

Comparing volcanic glass shards in unfertilised and fertilised Andisols derived from rhyolitic tephras, New Zealand: evidence for accelerated weathering and implications for land management

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Geoderma 271 (2016) 91–98 (http://dx.doi.org/10.1016/j.geoderma.2016.01.035)

Enhanced weathering associated with the use of phosphate fertilisers has been identified in some of the major farming areas of NZ and an evaluation of its effects on soil properties and the implications for soil management are needed. We assessed changes in the character of volcanic glass shards in topsoils (0−10 cm depth) of two tephra-derived Andisols of differing ages (Udivitrands, Hapludands), and with and without long-term fertilisation, to test if fertilising accelerates the weathering of soil constituents. Using visual assessment based on scanning electron microscopy and electron microprobe analyses of glass shards from samples from paired sites, we showed that the average sizes of the shards and the sharpness of the glass-shard edges (angularity) diminished with the age of the soil, and that these decreases were more marked in the soils that had been fertilised. Silica polymorphs were observed only in the older soil (Hapludand) that had been fertilised. The addition of phosphate-containing fertiliser enhanced the dissolution of volcanic glass, consistent with phosphoric acid and F^--induced dealumination and desilication, and thus soil weathering has been accelerated. The Al and Si may subsequently coprecipitate as secondary minerals, such as allophane. However, silica polymorphs may form where Al activity is low. The occurrence of neogenic silica in topsoils (despite high annual rainfall that should result in desilication of the topsoil and reprecipitation of silica deeper in the soil) is explained by the seasonality of fertiliser application and the spring–summer climate, where the soil remains moist for periods sufficiently long enough for the dissolution of volcanic glass (and possibly of other aluminosilicates), the formation of Al–humus complexes, and the subsequent precipitation of silica in dry periods.

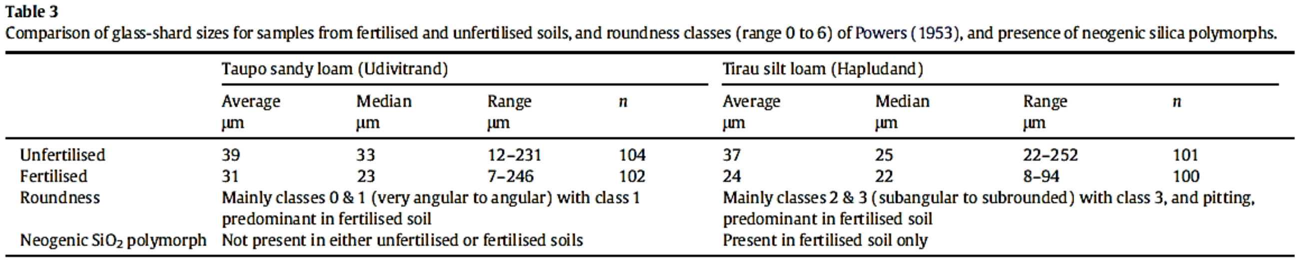

Table 3
Comparison of glass-shard sizes for samples from fertilised and unfertilised soils, and roundness classes (range 0 to 6) of Powers (1953), and presence of neogenic silica polymorphs.

	Taupo sandy loam (Udivitrand)				Tirau silt loam (Hapludand)			
	Average µm	Median µm	Range µm	*n*	Average µm	Median µm	Range µm	*n*
Unfertilised	39	33	12–231	104	37	25	22–252	101
Fertilised	31	23	7–246	102	24	22	8–94	100
Roundness	Mainly classes 0 & 1 (very angular to angular) with class 1 predominant in fertilised soil				Mainly classes 2 & 3 (subangular to subrounded) with class 3, and pitting, predominant in fertilised soil			
Neogenic SiO_2 polymorph	Not present in either unfertilised or fertilised soils				Present in fertilised soil only			

Implications for soil management and health emerge because of the accelerated weathering. Some trace elements, such as Co, are already at levels below optimum for animal health in these soils and increased leaching of these could reduce the efficiency of corrective fertiliser additions. Increased direct dosing of animals with essential trace elements may be required in the future. Other implications for soil management include changes in soil permeability and water storage capacity. Loss of mass may lead to increased porosity of the soil and enhanced permeability, if it is undisturbed by further cultivation. Conversely, precipitation of clays within pore spaces may reduce soil permeability but increase water storage. Changes in porosity are also likely to cause changes in surface area and capacity to store cations and anions. More broadly, there may be a significant feedback mechanism between climate and weathering processes. Enhanced weathering could result in enhanced removal of CO_2 from the atmosphere, as soil carbon derived ultimately from photosynthesis is converted into dissolved HCO_3^-.In addition, weathering releases divalent cations to the ocean via groundwater and riverine transport. Once there, divalent cations promoting the drawdown of CO_2 from the atmosphere by the precipitation and subsequent burial of carbonate mineral. If the enhancement of weathering is significant, it may provide some mitigation for climate change.

LAKE OKARO AND WETLANDS, OKARO RD

Location U16 177171, elevation 420 m asl, rainfall ~1500 mm pa

Geology and soils in Lake Okaro area

Lake Okaro was formed c. 700 years ago, probably during the Kaharoa eruption (1314 ± 12 AD), by a phreatic (i.e. steam) eruption (Lowe and Green, 1992; Lowe, 2006). The geology and soils of the area were described by Cross (1963), and soil units were recorded on the Rerewhakaaitu sheet (scale 1: 31,680) by Vucetich and Cross (1978) (also in Vucetich and Wells, 1978). Soils on the lake's western margins were mapped mainly as Rotomahana silt loam, mottled phase. Studies of rill erosion on the hills to the north of Lake Okaro, and on mechanisms and effects of the phreatic and secondary hydrothermal eruptions that formed the lake, were undertaken by Hardy (2005). The rilling, well exposed between Waimangu and Lake Okaro, is formed entirely in the ~1 m-thick mantle of Rotomahana Mud deposited in the area on 10 June 1886. The rill formation was rapid, beginning within days of the eruption and ending within a few years. The reason the rill erosion ceased is unknown but is possibly related to the permeability of underlying layers (Hardy, 2005). Rills are defined as centimetre to decimetre scale erosion channels cut by water running down a slope. Gullies are defined on a metre scale. In the USA, rills are described as small, runoff channels that can be obliterated by conventional tillage whereas gullies are large, runoff channels that cannot be obliterated by conventional tillage (Schoeneberger et al., 2002).

Lake Okaro and water quality (from Özkundakci et al. 2008)

Lake Okaro has an area of 0.28 km^2 and maximum depth of 18 m. It is monomictic and is typically thermally stratified for eight months of the year, from October until June. Limnological records for Lake Okaro extend back to 1955 (Jolly, 1977) when no cyanobacteria were observed in the lake. By contrast, a persistent cyanobacterial bloom was observed in 1963 (Forsyth et al., 1988). Today, Lake Okaro is the most eutrophic lake in the Rotorua region as a result of excess nutrients which promote primary production and algae growth. To meet statutory obligations, Environment Bay of Plenty, as part of its Land and Water Plan, planned the following restorative measures: (i) a phosphorus-absorbent lake-bed cap; (ii) a constructed wetland to remove primarily N from stream flows (iii); the protection of all riparian margins in the catchment; and (iv) the introduction of best management practices to reduce N leaching from land-use over time. The Regional Water and Land Plan for the Bay of Plenty sets water quality targets for the Rotorua lakes on the basis of trophic level index (TLI) (Burns et al., 1997). TLI values are determined annually from annual mean surface water concentrations of chlorophyll *a*, total nitrogen (TN), total phosphorus (TP), and Secchi-disk depth (SD). In the Lake Okaro Action Plan (2006), the TLI goal for the lake is 5.0. Between 1991 and 2008 the TLI of Lake Okaro ranged between 5.09 and 5.94, which classifies the lake as supertrophic (TLI 5.0–5.99). Considerable experimental work on lake restoration has been carried out on Lake Okaro (see LERNZ website and publications by Univ. of Waikato staff).

Fig. 34 Wetland soon after completion at Lake Okaro (2005) (LERNZ website)

STOP – ROTOMAHANA SILT LOAM, BRETT RD

Location V16 146168, 38° 17.905 S, 176° 28.823 E; elevation ~454 m

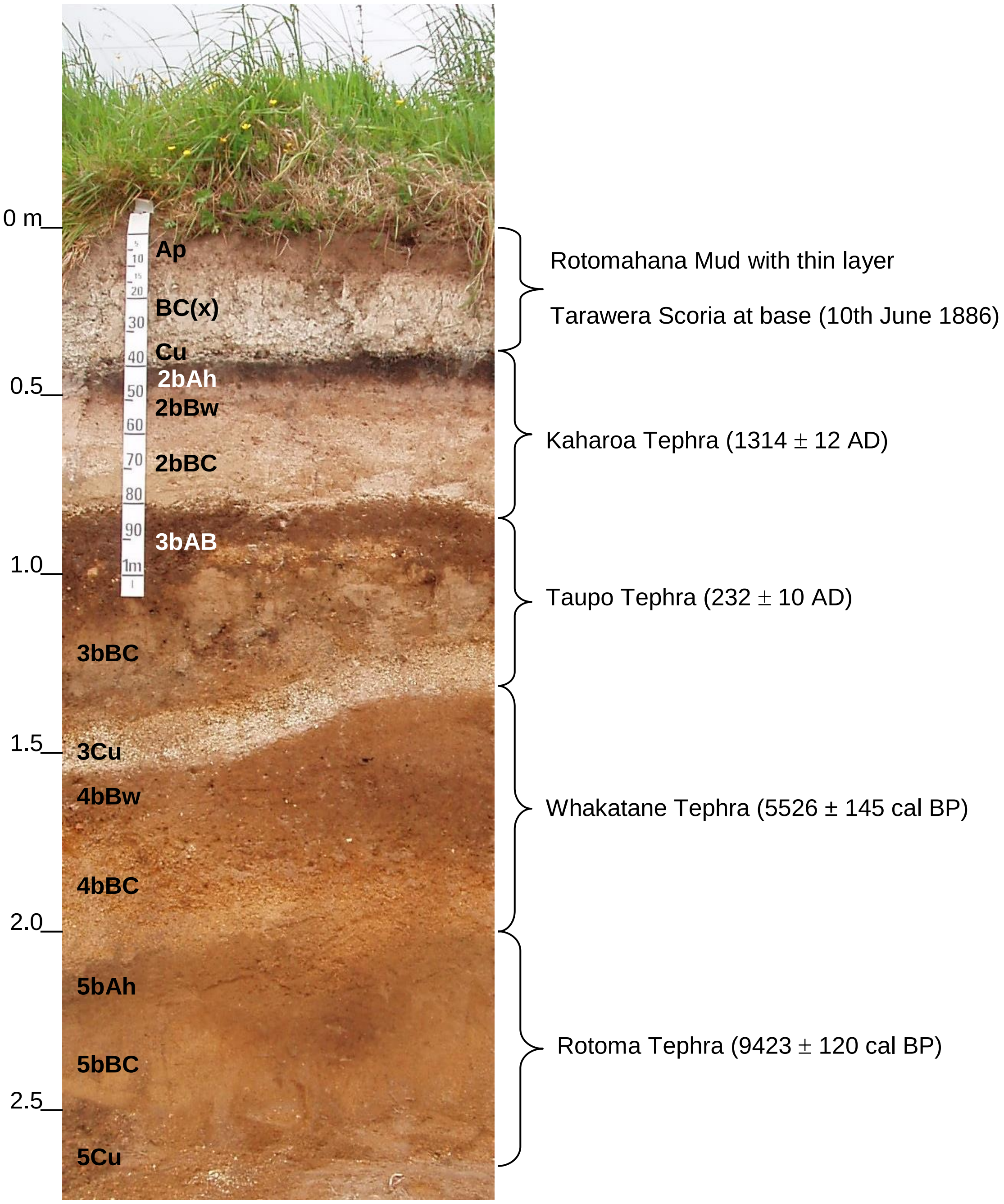

Fig. 35 Modern soil, buried soil horizons and tephra layers at Brett Rd section. Ages from Lowe et al. (2013). Rotomahana Mud was erupted from Rotomahana Crater and deposited through the air on 10 June 1886, i.e. it is a tephra-fall deposit, albeit an unusual one compositionally, containing ~20% clay with a distinctive mineralogy (Kirkman, 1976), described below.

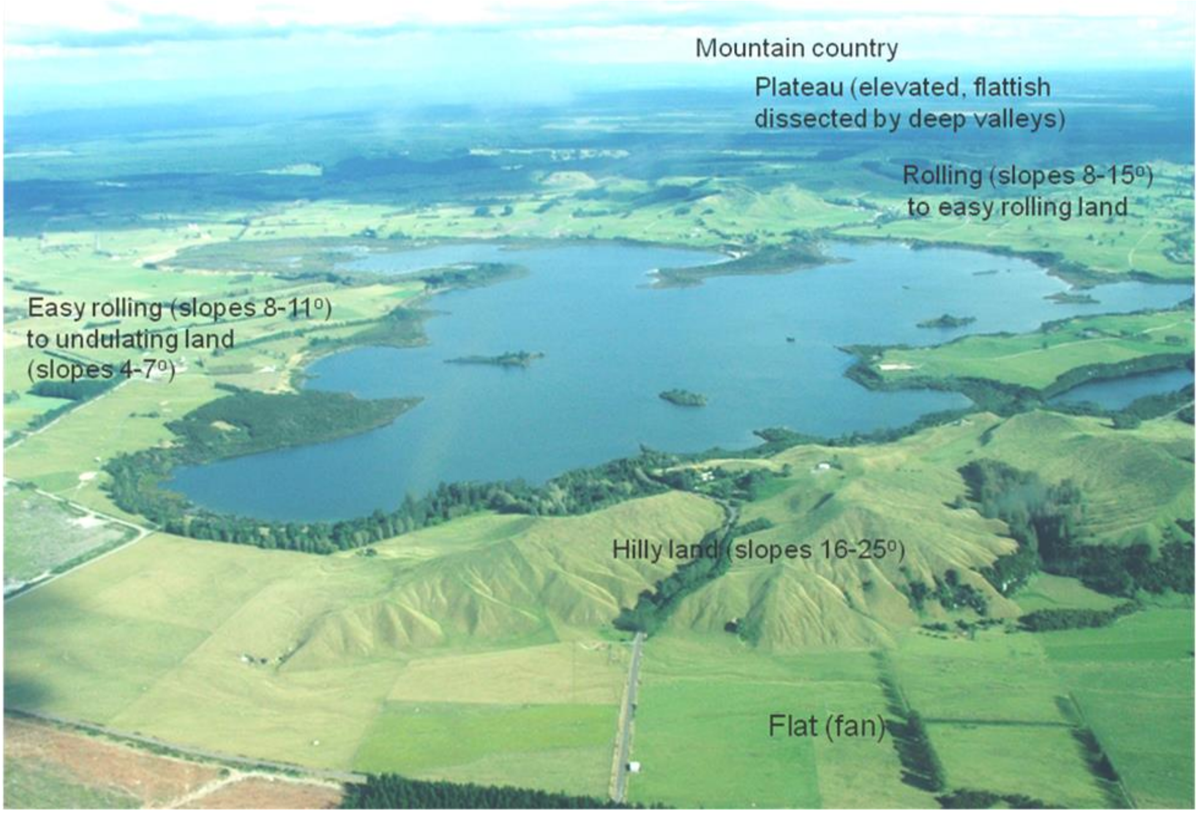

Fig. 36 Aerial view of landscape around Lake Rerewhakaaitu showing landforms. *Photo*: D.J. Lowe. Lake Rerewhakaaitu lies in a shallow basin impounded initially by pyroclastic deposits of the Waiohau eruption ca. 14,000 cal. yr BP, with further damming to present levels by Kaharoa pyroclastic deposits in ~1314 AD. It has an area of 7.4 km^2 and a maximum depth of 15 m. Awaatua basin is a small explosion crater ca. 10,000 years old (Nairn, 2002).

Soils and land use in the Waiotapu region (including Rerewhakaatiu district) were described by Vucetich and Wells (1978). The Rerewhakaaitu area was surveyed by Derek Cross (scale 1: 31,680). Analytical data for the Rotomahana soil are available in Parfitt et al. (1981; data below) and in Part 3 of 'Soils of New Zealand' (1968) (pp.122-123) from a site ~400 m west of the Waimangu Tearooms. Phytolith and humus analyses were undertaken at that site by Hosono et al. (1991); the clay minerals were examined by Kirkman (1976), who identified allophane, interstratified montmorillonite/mica, montmorillonite, mica, kaolinite, and a zeolite mineral, mordenite.

Notes from Mac Pacey, farmer on 'The Mud', *Tulachard Farm*, Brett Rd

Advantages: Naturally good fertility. High in Ca, Mg and K. Mainly fertilise with P and S. Good pH. Holds on better than surrounding country in dry periods. We stay green and do not have plant deaths in dry periods; therefore when it rains we recover quite quickly. When conditions are good we grow grass!

Disadvantages: When it rains and the soil is sodden the pasture can turn to mud very quickly. To overcome this we have built a feed pad to feed cows and stand them on in particularly wet conditions. Once it stops raining we can go back on the pasture within 24 hours with care. 'Mud' is high in Mb which causes Cu deficiency in the cattle so we have to supplement with Cu.

Note from soil surveyor Wim Rijkse

Rotomahana coarse sandy loam (near Waimangu Tearooms) is moderately to slightly acid and weakly leached (base saturations 71%, 65%, 94%). Exchangeable cations (Ca, Mg, K and Na) are of medium to high levels. Reserve potassium and magnesium of the Rotomahana Mud are of medium to high value. Extractable phosphorus is low.

Soil profile description by Haydon Jones

Waikato Regional Council, Hamilton

Rotomahana reference data

- Soil name:
  Series: Rotomahana
  Type: silt loam
- Soil classification:

***NZSC*:** Buried-pumice Tephric Recent; Mt; na (Rh fines and Ba ‘fines’/stones); loamy; m/r
Soil Taxonomy: Fine-loamy/medial, mixed/glassy, active, mesic Typic Udivitrands

Site data

- Location:
  - Map reference: NZMS 260 V16 2814530 6316815
  - Word description: road cutting on Brett Road (western side of Lake Rerewhakaaitu) about 215 m north of reserve/boat ramp
- Elevation: 450 m
- Rainfall: ~1500 mm pa
- Temperature:
- Geomorphic position: Profile on a 6° convex/linear slope with 125° aspect contained within a gentle slope in easy rolling country
- Erosion/deposition: Nil
- Vegetation: Pasture, grasses
- Parent material: Rotomahana Mud over a thin layer of Tarawera Scoria with underlying buried soil horizons formed in various tephra deposits (Kaharoa, Taupo, Whakatane, and Rotoma tephras) (see photos of stratigraphy for tephra ages or see summary p. 27)
- Drainage class: Well drained

Soil data

Note: “gravels” = “stones”.

Ap	
0-11 cm	Very dark greyish brown to dark brown (10YR 3/2.5) silt loam; slightly sticky; moderately plastic; peds weak and friable; weakly pedal; common fine polyhedral peds; non allophanic; abrupt smooth boundary. [Rotomahana]
BC(x)	
11-36 cm	Greyish brown (2.5Y 5/2) silt loam; very few extremely fine faint brown (7.5YR 5/4) mottles; slightly to moderately sticky; very plastic; peds slightly firm and brittle; very high penetration resistance; weakly pedal; common fine to coarse blocky peds; non allophanic; abrupt smooth boundary. [Rotomahana]
Cu	
36-39 cm	Greyish brown (2.5Y 5/2) extremely gravelly sand with fine to medium sub-rounded slightly weathered scoria gravels; non sticky; non plastic; apedal single grain; non allophanic; abrupt smooth boundary. [Tarawera]
2bAh	
39-46 cm	Black (2.5Y 2.5/1) sandy loam; slightly sticky; non plastic; peds weak and friable; apedal earthy; profuse very fine polyhedral peds; weakly allophanic; distinct smooth boundary. [Kaharoa]

2bBw 46-68 cm	Dark greyish brown to brown (10YR 4/2.5) very slightly gravelly loamy sand with fine sub-rounded slightly weathered pumice gravels; slightly sticky; non plastic; soil very weak and very friable; apedal single grain; moderately allophanic; indistinct wavy boundary. [Kaharoa]
2bBC 68-79 cm	Light olive brown to light yellowish brown (2.5Y 5.5/3) very slightly gravelly loamy sand with fine sub-rounded slightly weathered pumice gravels; very few extremely fine distinct brown (7.5YR 4/4) mottles; slightly sticky; non plastic; soil weak and friable; apedal massive; strongly allophanic; distinct wavy (occluded) boundary. [Kaharoa]
3bAB 79-101 cm	Very dark grey (2.5Y 3/1) very slightly gravelly sandy loam with fine sub-rounded slightly weathered pumice gravels; slightly sticky; slightly plastic; peds weak and friable; apedal earthy; profuse very fine polyhedral peds; strongly allophanic; distinct irregular (occluded) boundary. [Taupo]
3bBC 101-138 cm	Olive brown to light olive brown (2.5Y 4.5/3) very slightly gravelly (= not stony) loamy sand with fine sub-rounded slightly weathered pumice gravels; slightly sticky; non plastic; soil very weak and friable; apedal massive; strongly allophanic; distinct wavy boundary. [Taupo]
3Cu 138-151 cm	Pale yellow (2.5Y 7/3) extremely gravelly (= extremely stony*) sand with fine to medium sub-angular slightly weathered pumice gravels; non sticky; non plastic; apedal single grain; very weakly allophanic; distinct wavy boundary. [Taupo]
4bBw 151-173 cm	Very dark greyish brown to dark brown (10YR 3/2.5) slightly gravelly sandy clay loam with fine sub-rounded slightly weathered pumice gravels; moderately sticky; slightly plastic; peds weak and friable; apedal earthy; profuse very fine polyhedral peds; strongly allophanic; indistinct irregular (occluded) boundary. [Whakatane]
4bBC 173-199 cm	Yellowish brown (10YR 5/6) very gravelly sand with medium sub-rounded slightly weathered pumice gravels; non sticky; non plastic; apedal single grain; strongly allophanic; distinct irregular boundary. [Whakatane]
5bAh 199-225 cm	Dark greyish brown to brown (10YR 4/2.5) very slightly gravelly sandy loam with fine sub-rounded slightly weathered pumice gravels; slightly sticky; non plastic; peds very weak and friable; apedal earthy; profuse very fine polyhedral peds; moderately allophanic; indistinct wavy boundary. [Rotoma]
5bBC 225-255 cm	No data. [Rotoma]
5Cu 255 cm –on	No data. [Rotoma]

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* "Extremely gravelly or stony" implies the horizon is clast-supported hence there is no need to use term 'loose'.

ROTOMAHANA LOAM

Location: Waimangu Road, 400 m west along from tearoom, east side of road reserve

Grid ref: N85/845863

Aspect: West near top of ridge

Altitude (m): 400

Rainfall (mm): 125

Slope: 2°

Landform: Ridge

Vegetation: Bracken fern with mahoe, coprosma, kamahi, lupin

Drainage class: Moderately well drained

Land use: Dairying and semi-intensive sheep farming

Parent material: Rotomahana Mud, hydrothermally altered rhyolitic ejecta from Lake Rotomahana (erupted in 1886)

PROFILE DESCRIPTION

Profile	Depth (cm)	
Ah	0- 7	very dark brown (10YR 2/2) loam; slightly sticky non plastic; slightly greasy; friable; moderately developed fine nut structure; many fine and medium roots; distinct smooth boundary,
C1	7-50	light olive grey (5Y 6/2) silt loam; friable; sticky slightly plastic; weakly developed medium block structure breaking to crumb structure; few fine roots; indistinct irregular boundary,
C2	50-67	light olive grey (5Y 6/2) silt loam; slightly firm; slightly sticky non plastic; weakly developed medium block structure breaking to crumb structure; few fine grey (10YR 6/1) basaltic lapilli; few dark brown root channels; distinct regular boundary,
Cg	67-78	pale olive (5Y 6/3) sandy loam; slightly firm; weakly developed medium block breaking to crumb structure; many indistinct yellowish brown and dark yellowish brown (10YR 5/6 & 4/6) fine and medium mottles; few medium dark brown (7.5YR 3/2) root channels; sharp smooth boundary,
2Ah	78-87	black (7.5YR 2/0) sandy loam; friable; weakly developed medium nut structure; few roots; distinct smooth boundary,
2Bw	87-96	dark brown (10YR 3/3) sandy loam; friable; weakly developed fine nut and crumb structure; few medium (2-6 mm) lapilli; locally a 4 cm pale brown (10YR 6/3) gritty sandy loam layer (E hor.) overlies this horizon; distinct irregular boundary,
2Bs	96-105	strong brown (7.5YR 4/6) pumice gravel; loose; single grain; lapilli 2-10 cm; sharp smooth boundary,
3Ah	105+	*on* yellowish brown (10YR 5/4) sandy loam; friable; weakly developed nut and crumb structure; many fine (2-4 mm) lapilli; few fine roots.

CLASSIFICATION - N.Z. Genetic: Recent soil (ash)

Taxonomy: Typic Udorthent, fine loamy, mixed, mesic

CHEMISTRY ROTOMAHANA LOAM

Sample No. SB	Depth (cm)	Hor.	pH H_2O	pH KCl	pH ΔpH	pH NaF	Exchangeable cations (meq/100 g) Ca	Mg	K	Na	H (KCl)	Al (KCl)	Extr. Acidity (pH 8.2)	Acidity-Al (meq/100 g)	ECEC	CEC (meq/100 g) NH_4OAc (pH 7)	CEC Σ Cations (pH 8.2)	Base saturation (%) Σ bases / CEC NH_4OAc	Σ bases / Σ Cations
9581																			
A	0-7	Ah	5.7	4.7	-1.0	7.8	14.7	4.6	2.03	0.33		0.22	29.6	29.4	21.8	28.2	51.3	77	42
B	7-25	C1	6.0	4.5	-1.5	8.8	5.9	2.76	1.81	0.49		0.14	7.5	7.4	11.3	12.3	18.5	89	59
C	25-50	C1	6.7	4.8	-1.9	8.5	8.3	3.11	1.31	1.23		0.08	5.5	5.4	14.1	13.7	19.5	(100)	72
D	50-67	C2	6.9	5.0	-1.9	8.5	8.2	3.05	0.97	1.56		0.08	4.4	4.3	14.0	13.7	18.2	(100)	76
E	67-78	Cg	6.9	5.2	-1.7	8.5	10.2	3.6	1.40	2.13		0.10	5.6	5.5	17.4	17.2	22.9	(100)	76
F	78-87	2Ah	6.5	5.5	-1.0	8.8	37	6.6	0.40	0.42		0.31	27.8	27.5	44.7	46.2	72.2	96	61
G	87-96	2Bw	6.5	5.5	-1.0	10.2	11.0	2.11	0.21	0.24		0.49	16.4	15.9	13.8	15.1	30.0	90	46
H	96-105	2Bs	6.4	5.3	-1.1	10.6	7.3	1.24	0.25	0.52		0.81	17.9	17.1	9.3	12.2	27.2	76	34

Sample No. SB	Depth (cm)	Hor.	Total C (%)	Total N (%)	P (mg/100 g) H_2SO_4 (0.5 M)	Inorg.	Org.	P Retention (%)	Dithion. cit. (%) Fe	Al	Tamm ox. (%) Fe	Al	Si	Pyrophos. (%) Fe	Al	Reserves (meq/100 g) K_c	Mg_r	Extractable S (ppm)
9581																		
A	0-7	Ah	7.1	0.17	16	21	31	24	0.76	0.19	0.46	0.22	0.06	0.19	0.09	0.64	17	14
B	7-25	C1	0.6	0.12	17	23	6	17	0.77	0.19	0.34	0.14	0.10	0.05	0.01	0.73	26	3
C	25-50	C1	0.2	0.06	18	23	2	11	0.71	0.07	0.30	0.08	0.10	0.01	0.00	0.74	24	3
D	50-67	C2	0.2	0.05	18	24	1	10	0.72	0.07	0.27	0.08	0.09	0.01	0.00	0.81	22	2
E	67-78	Cg	0.3	0.06	18	24	2	13	0.99	0.14	0.35	0.10	0.09	0.03	0.00	0.72	19	7
F	78-87	2Ah	9.5	0.80	4	8	38	42	0.56	0.33	0.29	0.31	0.07	0.18	0.23	0.16	2.0	2
G	87-96	2Bw	3.7	0.41	4	11	26	45	0.58	0.37	0.32	0.49	0.04	0.25	0.31	0.12	1.1	4
H	96-105	2Bs	2.7	0.31	7	12	21	60	0.72	0.84	0.45	0.81	0.34	0.33	0.34	0.08	0.7	4

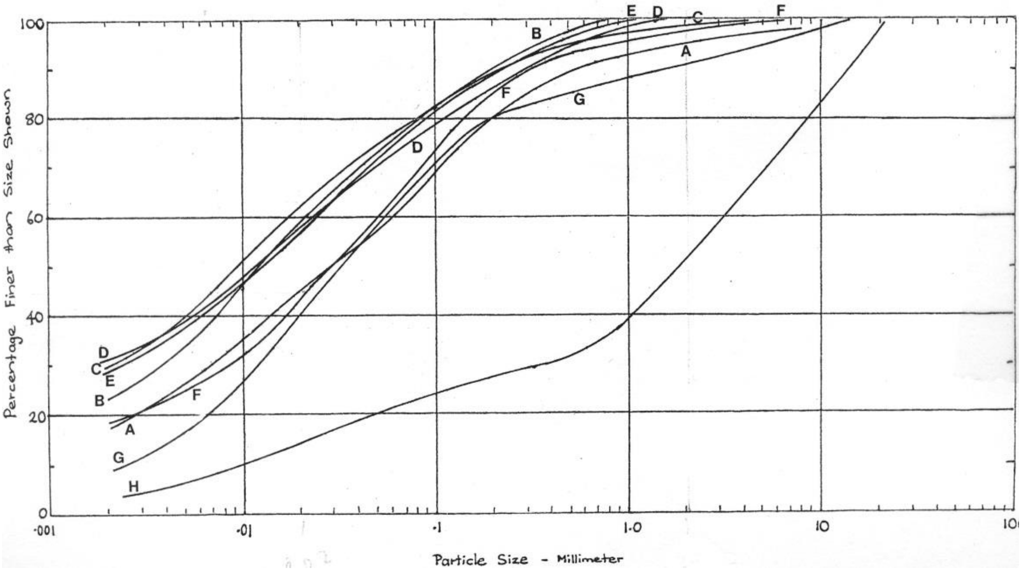
PARTICLE SIZE DISTRIBUTION (<2 mm) Rotomahana Loam

Sample No. SB	Depth (cm)	Hor.	Sand 2-0.1 mm (%)	Sand 0.1-0.05 mm (%)	Silt 0.05-0.002 mm (%)	Clay <0.002 mm (%)	Fine clay <0.0002 mm (%)	Fine clay / Total clay	Stones (%)
9581A	0-7	Ah	27	11	43	19			(4)
B	7-25	C1	18	10	48	24			(<1)
C	25-50	C1	16	8	46	30			(1)
D	50-67	C2	22	8	41	29			(<1)
E	67-78	Cg	18	11	42	29			
F	78-87	2Ah	25	14	45	16			2
G	87-96	2Bw	22	13	57	8			9
H	96-105	2Bs	50	11	34	5			50

PHYSICS

Hor. Depth (cm)	Hor.	15 bar water Field moist (%)	15 bar water Air Dry (%)
0-7	Ah	25.0	16.7
7-25	C1	14.0	12.1
25-50	C1	14.3	12.4
50-67	C2	14.0	12.3
67-78	Cg	15.0	12.8
78-87	2Ah	21.2	16.0
87-96	2Bw	15.5	7.3
96-105	2Bs	12.4	7.4

Core Depth (cm)	Dry bulk density (T/m^3)	Total porosity (%)	Large pores (%)	Field Cap. (at 0.2 bar) (% v/v)	Wilting Pt. (at 15 bar) (% v/v)	Available water (% v/v)



Mineralogy Rotomahana

Sample No. SB	Depth (cm)	Hor.	Clay Fraction (%) Mica-Smectite	Mica-Vermiculite	Smectite	Vermiculite	Interlayered Hydrous Micas	Mica	Kaolinite	Halloysite	Gibbsite	Quartz	Cristobalite	Allophane	Feldspar	Anatase	Volcanic glass	Sand Fraction (%) Quartz	Feldspar (acid)	Andesine	Glass	Muscovite	Biotite	Hornblende	Augite	Hypersthene	Epidote	Zoisite	Apatite	Magnetite	Plant opal
9581A	0-7	Ah			41	10		28	10			1		10																	
B	7-25	C1			40	6		26	17					11																	
C	25-50	C1			40	6		38	14					12																	
D	50-67	C2			41	4		24	16					15																	
E	67-78	Cg			56	4		14	11					10																	
F	78-87	2Ah			20				27					14			32														
G	87-96	2Bw			17				26					28			42														
H	96-105	2Bs							10								61														

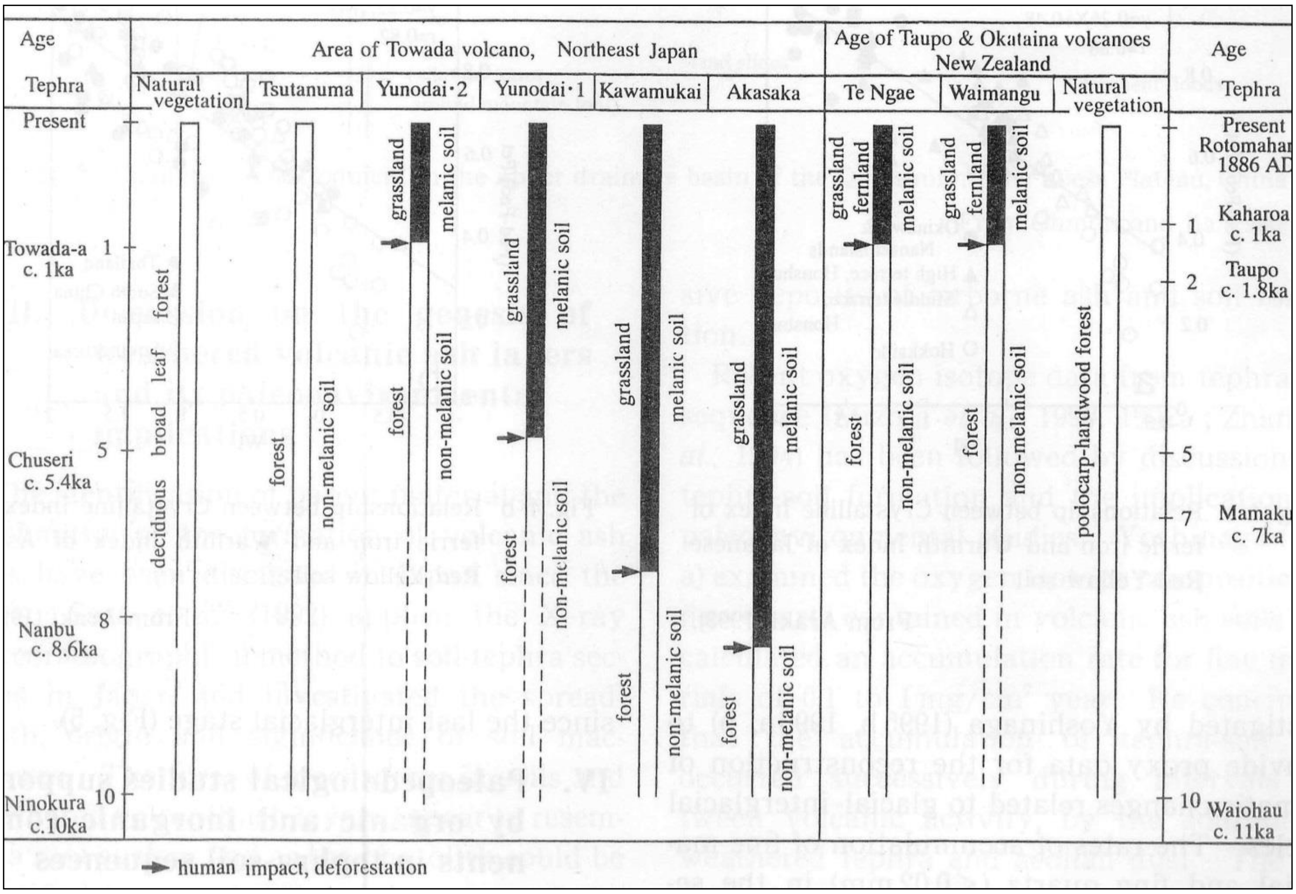


Fig. 37 Relationship between vegetation, tephra age (note ages are given in ^{14}C ka (not calibrated)) and human impact (from Watanabe and Sakagami, 1999 – after Sase and Hosono, 1996). Note dates for initial human impact vary in Japan. Initial settlement of New Zealand occurred c. 1280 AD, a few decades prior to the Kaharoa eruption.

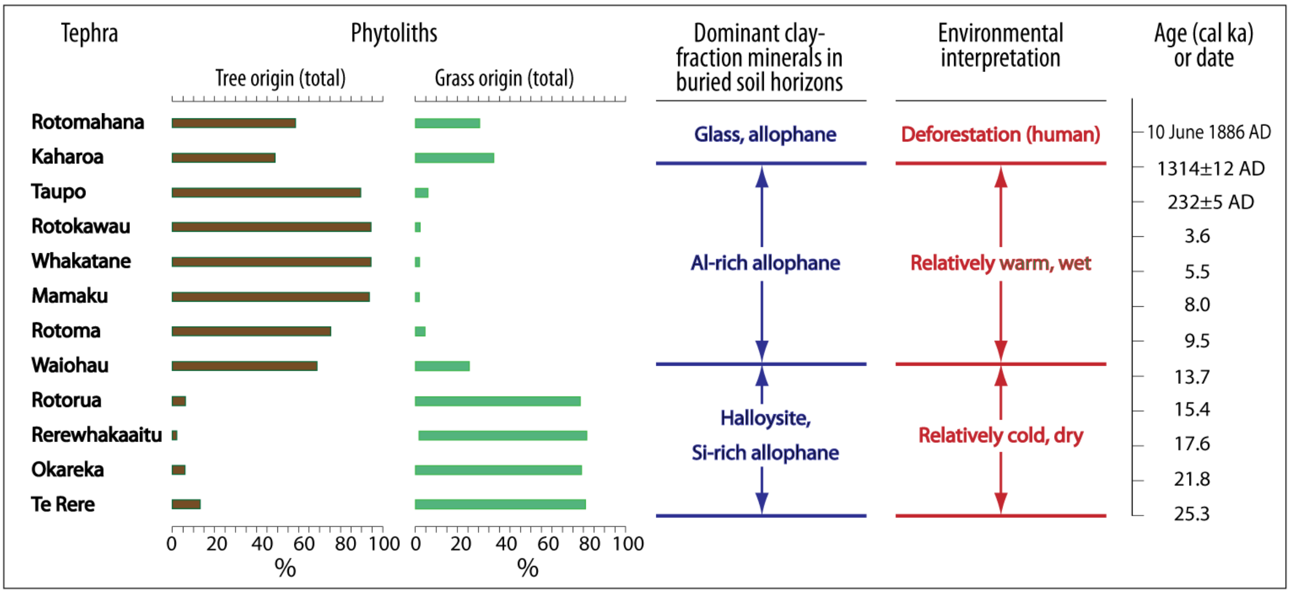


Fig. 38 Evidence of environmental change since c. 25,000 cal years BP based on phytolith and clay mineral data from analysis of buried soil horizons on rhyolitic tephras at Te Ngae, near Rotorua (from Churchman and Lowe, 2012, after Newnham et al., 1999: based on Green, 1987; Sase et al., 1988; Hodder et al., 1990; Kondo et al., 1994).

Extracting DNA from allophanic paleosols on tephras for paleoenvironmental reconstruction: new method and application, NZ

Huang, Y-T., Lowe, D.J., Zhang, H., Cursons, R., Young, J.M., Churchman, G.J., Schipper, L.A., Rawlence, N.J., Wood, J.R., Cooper, A. 2016. A new method to extract and purify DNA from allophanic soils and paleosols, and potential for paleoenvironmental reconstruction and other applications. *Geoderma* 247, 114-125.

Soils developed from late-Quaternary tephras are commonly dominated by the nanocrystalline aluminosilicate, allophane, and are called Andisols. They contain large stores of organic matter and are potential reservoirs for DNA. However, DNA recovery from Andisols has been difficult because of strong chemical bonding between DNA and allophane and organic matter, and also because up to 80% of DNA can be physically protected in nanolabyrinthic networks of nanopores in allophane nano/microaggregates. We have developed a new two-step DNA isolation method for Andisols and allophanic paleosols, including those low in clay, which circumvents these problems. The method centres on (1) using a buffer that releases mainly microbial/fungal DNA and unbound DNA and prevents re-adsorption of DNA on allophanic materials, and (2) novel application of acidified ammonium oxalate (Tamm's reagent) to dissolve the allophane and thus release DNA which had been both chemically-bound and encased within nanopores. Sequencing of PCR products obtained from a buried allophanic paleosol at 2.2-m depth on a Holocene tephra near Mt Tarawera yielded endemic and exotic plants that differed from the European grasses growing currently on the soil's surface. This difference suggests that the DNA extraction method is able to access (paleo)environmental DNA derived from previous vegetation cover. Our method hence may be applied to Andisols and allophane-bearing paleosols, offering (1) a means to isolate paleoenvironmental DNA and thus facilitate reconstruction of past environments in volcanic landscapes (datable using tephrochronology), (2) a new way to evaluate biodiversity in such soils/paleosols, and (3) possible application to soil forensic analysis.

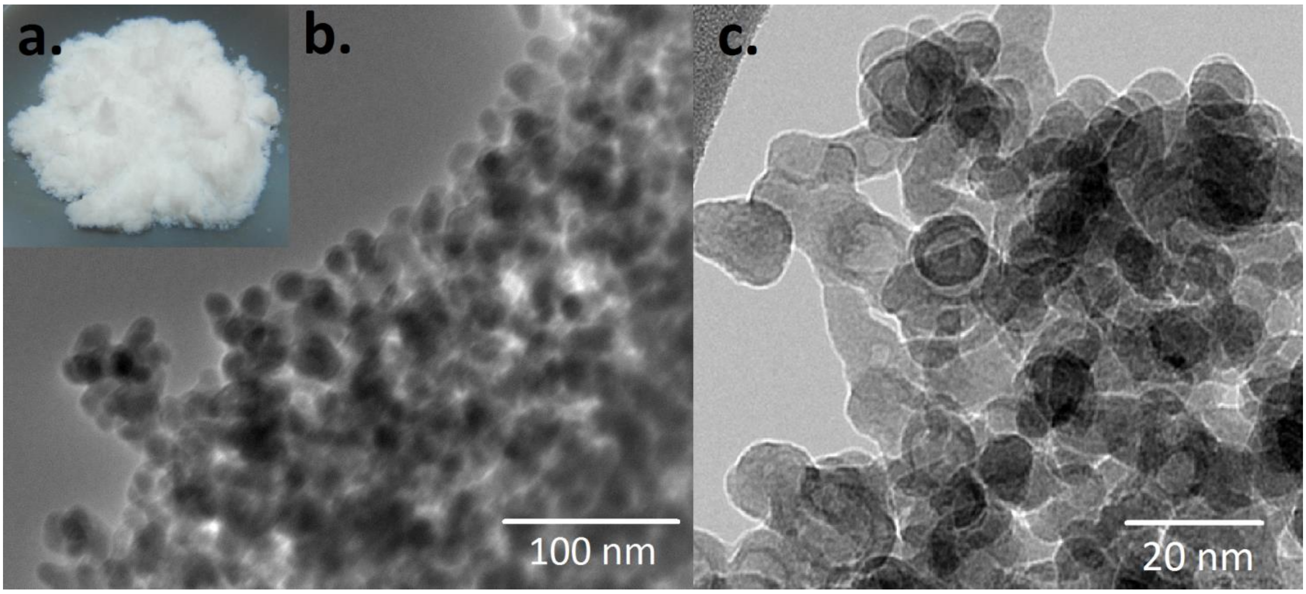


Fig. 39 (**a**) Synthetic allophane and (**b, c**) its spherical morphology seen using TEM (from Huang et al., 2016b)

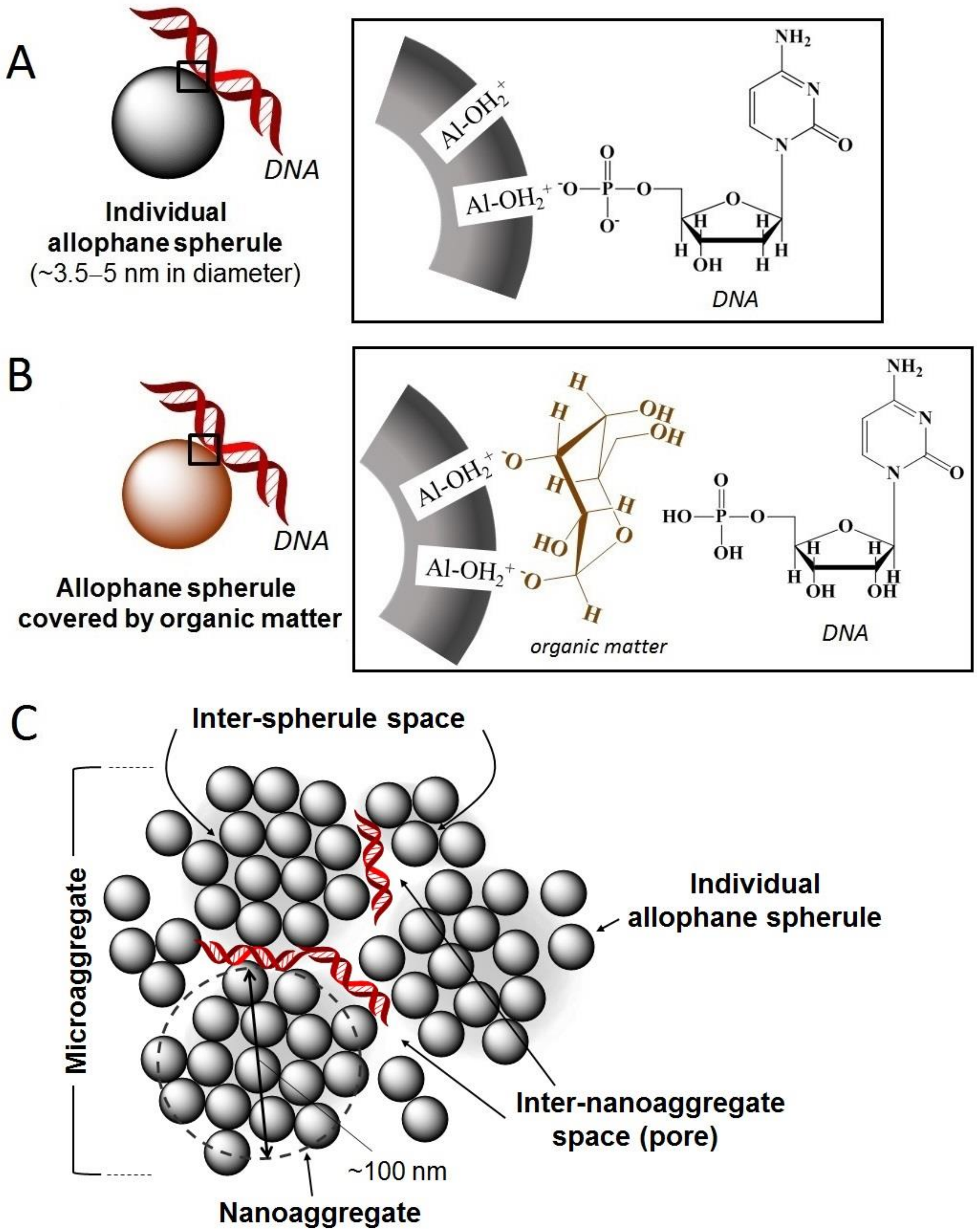


Fig. 40 A *Direct chemical adsorption* of DNA on allophane; **B** *indirect chemical adsorption* of DNA on organic matter-rich allophane; **C** '*physical' adsorption* of DNA (i.e. protection) in the nanopores of allophane nano- and micro-aggregates (from Huang et al., 2016a)

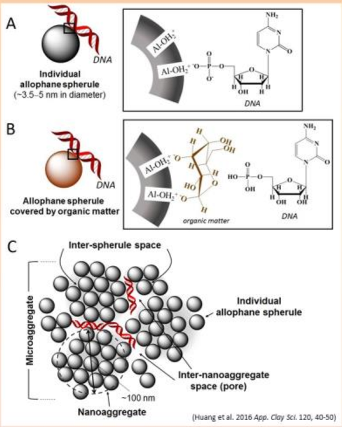
Extracting DNA from allophanic paleosols on tephras for palaeo-environmental reconstruction: new method and application, NZ

MARSDEN FUND
TE PŪTEA RANGAHAU A MARSDEN

David J. Lowe, Y.-T. Huang, H. Zhang, R. Cursons, J. Young, G.J. Churchman, L.A. Schipper, N.J. Rawlence, J.R. Wood, A. Cooper

1. Introduction: (dis)solving the almost impossible

- Ancient DNA (aDNA) is usually extracted from *discrete* fossil samples of bone, teeth, eggshell, leaves, etc, and **aDNA has become a powerful tool** for Quaternary studies including (e.g.) palaeoecology, archaeology, biogeography, and human evolution and disease
- *Disseminated* environmental DNA (e.g. from ice, sediment, soil, tephra, dental calculus), defined as **palaeoenvironmental DNA (PalEnDNA)**, is also used in Quaternary studies and archaeology (e.g. Rawlence et al. 2014, *J. Quat. Sci.* 29, 610-626).
- Allophanic paleosols on tephras sequester much carbon (incl. ~80% physically protected in stable nanoaggregates), hence provide a potential reservoir for PalEnDNA. But DNA extraction from such paleosols is very difficult because of (*i*) strong chemical bonding between allophane and DNA, and (*ii*) inaccessibility of DNA encased in nanoaggregates. **Our new method bypasses these difficulties.**



(Huang et al. 2016 *App. Clay Sci.* 120, 40-50)

Fig. 1 A *Direct chemical adsorption* of DNA on allophane; **B** *indirect chemical adsorption* of DNA on organic matter-rich allophane; **C** *'physical' adsorption* of DNA (i.e. protection) in the nanopores of allophane nano- and micro-aggregates

2. Objectives

- Develop an effective method for DNA extraction from (*i*) synthetic allophane and (*ii*) natural allophanic soils or paleosols
- Search for possible PalEnDNA from buried allophanic paleosols on Holocene tephras

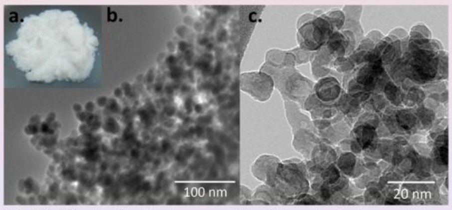


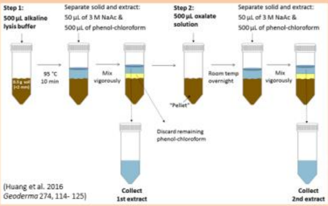
Fig. 2 (a) Synthetic allophane and **(b, c)** its spherical morphology seen using TEM

3. Results

- Synthetic allophane and salmon-sperm DNA provided proof-of-principle before trialling natural allophane; humic acids add complexity
- Our two-step method includes novel use of ammonium oxalate to *dissolve* allophane to release *all* DNA **including that entrapped in nanoaggregates** (unlike previous methods):

Step 1 releases microbial & unbound DNA (likely modern);
Step 2 releases chemically bound and physically adsorbed DNA (likely to be pre-modern, potentially aDNA)

3. Results contd.



(Huang et al. 2016 *Geoderma* 274, 114- 125)

Fig. 3 Summary of two-step DNA extraction from natural allophanic soils/paleosols

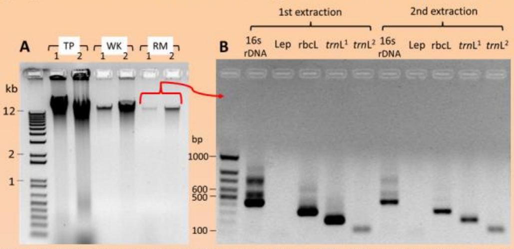


Fig. 4 A DNA extracted from paleosols on Taupo (TP), Whakatane (WK), Rotoma (RM) tephras; **B** amplifiable DNA fragments from Rotoma paleosol (Table 1) with bacterial, animal, and plant primers: 16s, bacterial; Lep, insect; rbcL, *trn*L, plant

Fig. 5 Sampling for possible PalEnDNA in buried allophanic paleosols on tephras deposited since ~12,000 yr BP

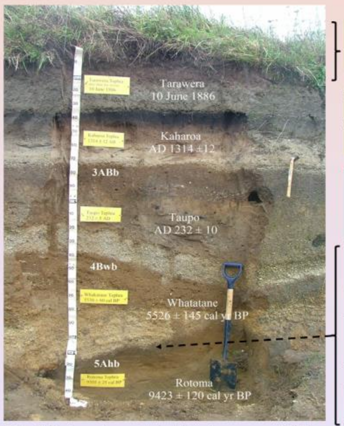


Fig. 6 Paleosols on dated tephras near Mt Tarawera

Modern plants at land surface = European grasses
Such vegetation at this site dates to c. 1900 AD or earlier

Table 1 New Zealand endemic plants detected in buried soil on Rotoma tephra using our extraction/purification protocols & polymerase chain reaction (PCR) with selected primers

Family	Plant taxa	Primer pair and % similarity to reference
Myrtaceae	*Leptospermum scoparium*	*trn*L g–h (98–99%) and *rbc*L (99%)
Araliaceae	*Hydrocotyle*	rbcL (97%)
	Other genera (multiple)	*trnL* c–h (99%) and *trn*L g–h (100%)
Griseliniaceae	*Griselinia lucida*	rbcL (98%)
Podocarpaceae	*Podocarpus*	*trn*L c–h (95–98%)

(Huang et al. 2016 *Geoderma* 274, 114- 125)

4. Conclusions

- Our two-step method enables previously inaccessible DNA to be extracted from allophanic soils by releasing DNA entrapped in stable nano/microaggregates
- Gel electrophoresis of extracted DNA, then gel purification, removes sufficient humic material for successful DNA amplification via PCR of multiple gene regions
- DNA extracted from a buried paleosol on Rotoma tephra (~9.4 cal ka) includes native NZ forest spp., different from European adventives on the land surface
- Thus DNA extraction from allophanic paleosols potentially offers a means to isolate PalEnDNA and hence facilitate reconstruction of past environments extensively in volcanic landscapes (datable using tephrochronology)
- Other potential applications include studies on soil biodiversity and soil forensics

Potential impacts of ash fall on dairy farms – Rerewhakaaitu case study by Wilson and Cole (2007)

Nat Hazards (2007) 43:103–128
DOI 10.1007/s11069-007-9111-8

ORIGINAL PAPER

Potential impact of ash eruptions on dairy farms from a study of the effects on a farm in eastern Bay of Plenty, New Zealand; implications for hazard mitigation

Thomas M. Wilson · James W. Cole

Abstract This paper investigates the impact ash fall would have on dairy farming, based on a study of 'Tulachard', a dairy farming operation at Rerewhakaaitu, North Island, New Zealand. It includes analysis of the potential effects on the dairy shed and milking machine, electrical supply and distribution, water supply and distribution, tractors and other farm vehicles, farm buildings (haysheds, pump sheds, implement sheds, etc.), milk-tanker access to the farm and critical needs of dairy cows and farm to keep milking. One of the most vulnerable areas identified in the study was the cooling of milk at the milking shed, pending dairy tanker pick-up. The cooling system's condenser is exposed to the atmosphere and falling ash would make it highly vulnerable. Laboratory testing with wet and dry ash was conducted to determine its resilience to ash ingestion. It was found to perform satisfactorily during dry testing, but during wet testing significant clogging/blocking of the condenser's radiator occurred, dramatically reducing airflow through the condenser. Specific mitigation recommendations have been developed that include cleaning with compressed air and adapting farm management techniques to lessen usage of the condenser during an ash-fall event. Specific recommendations for management of dairy farm operation are given to mitigate the effects of an ash-fall event.

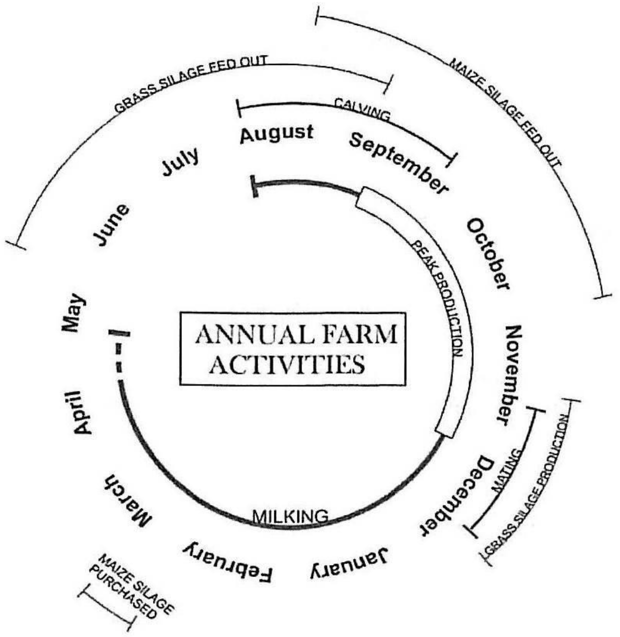


Fig. 2 The annual farm activities at the farm shows the key vulnerable periods during the year of farming operations. The farm's most important activities are closest to the centre, with activities of decreasing importance progressively further out from the centre

7 Recommendations

The effect of ash fall will depend on the magnitude, style of eruption, location of active vent zone, vent positions within the active vent zone, local topographic controls and wind directions. It is extremely hard to predict any of these factors for the next eruption, given the variety of styles of eruptions that have affected the farm during the last 22,000 years. Warning time is variable. There may be 1 year to 3 months warning for a rhyolitic eruption, while there may be only 3–4 h for a basaltic eruption.

Key recommendations to minimise the hazard are as follows:

(1) Long term planning (*periods of quiescence*)
  - Maintain power supply lines so they are in good order.
  - Develop a water supply with large tank storage capacity.
  - Develop a 'feed pad' that is easily cleared of ash for distributing supplementary feed.
  - Ensure roof pitches are greater than 30° and strengthened (perhaps to snow codes) on any new buildings.
  - Ensure the tractor is 4WD and has front bucket and blade attachments.

(2) Medium term planning (*12 to 3 months out from eruption*)
  - Conduct a vulnerability analysis of equipment and facilities to determine which would be the most affected by ash fall, and which are adequately and inadequately protected (http://volcanoes.usgs.gov).
  - Identify appropriate methods of protecting vulnerable equipment and facilities from ash.
  - Off load non-essential stock (i.e. beef cows, sick animals in the herd, dry milkers, old cows).
  - Increase reserves of supplementary feed (i.e. buy in or produce more; alternatively use less by off loading stock).
  - Ensure tractor and milking machine have been serviced recently.
  - Attempt to stockpile tractor engine and milking machine filters (air, oil, pulsators and milk), lubricating oil, brake and hydraulic fluids, and seals.
  - Purchase an air compressor or ensure it is in good working order.
  - Ensure diesel tank is maintained at a high level.
  - Have ladders and brooms (roof cleaning).
  - Ensure sump, drainpipes and drain grills are clear. Make sure sump pump is in good working condition.
  - Be prepared for false alarms; predicting a volcanic eruption is difficult.

(3) Short term planning (*immediately before an eruption*)
  - Cover all essential equipment (either within sheds or under a covering).
  - Move essential stock (milking herd) close to the milking shed.
  - Store transportable supplementary feed close to areas where it would be distributed (i.e. feed pad, paddocks close to the milking shed).
  - Ensure enclosed water storage tanks are at their maximum (especially if surface water is the farm's water supply).
  - Place ladders for access to key roofs in a secure way for easy safe cleaning. Plan to have a lot of time to clean roofs (prevent injury).
  - *Do not put stock onto the road* in the hope of finding somewhere better as they will hinder emergency service's and evacuee's mobility. They have a greater chance of survival on their farm (Neild et al. 1998).
  - Conduct any maintenance on tractor, milking machine and other key machinery (e.g. change filters). If there is time purchase new filters.

(4) During eruption
  - Keep ash out of buildings, machinery, vehicles, downspouts, water supplies and wastewater systems (e.g. dairy shed drains) as much as possible. The best way to prevent damage is to reduce machinery usage as much as possible, shutting down, closing off or sealing equipment. However, critical farm functions such as milking should be preceded by removal of as much ash as possible before operating equipment.
  - Minimize human exposure to airborne ash by using dust or filter masks and minimising travel.
  - Remove ash from roofs to prevent collapse and on going remobilisation. Take your time whilst cleaning roofs and wear a mask whilst doing so. Try to undertake the activity when you are alert and physically fresh.
  - Plan each day, in terms of what activities are critical, required and optional. These may change each day so be prepared to remain flexible. Develop a priority list of facilities that must be kept operative versus those that can be shut-down during and after ash falls.
  - Stay aware of the condition of your cows; they are the most important part of your farm.
  - Do not put stock onto the road in the hope of finding somewhere better as they will hinder emergency service's and evacuee's mobility. They have a greater chance of survival left on your farm.
  - Prioritize and sequence areas for cleanup (top to bottom).

TEPHRAS AND BURIED SOIL SEQUENCE, MATAHINA GRAVEL, ASH PIT RD

Location V16 188155, 38° 18.568 S, 176° 31.817 E; elevation ~448 m

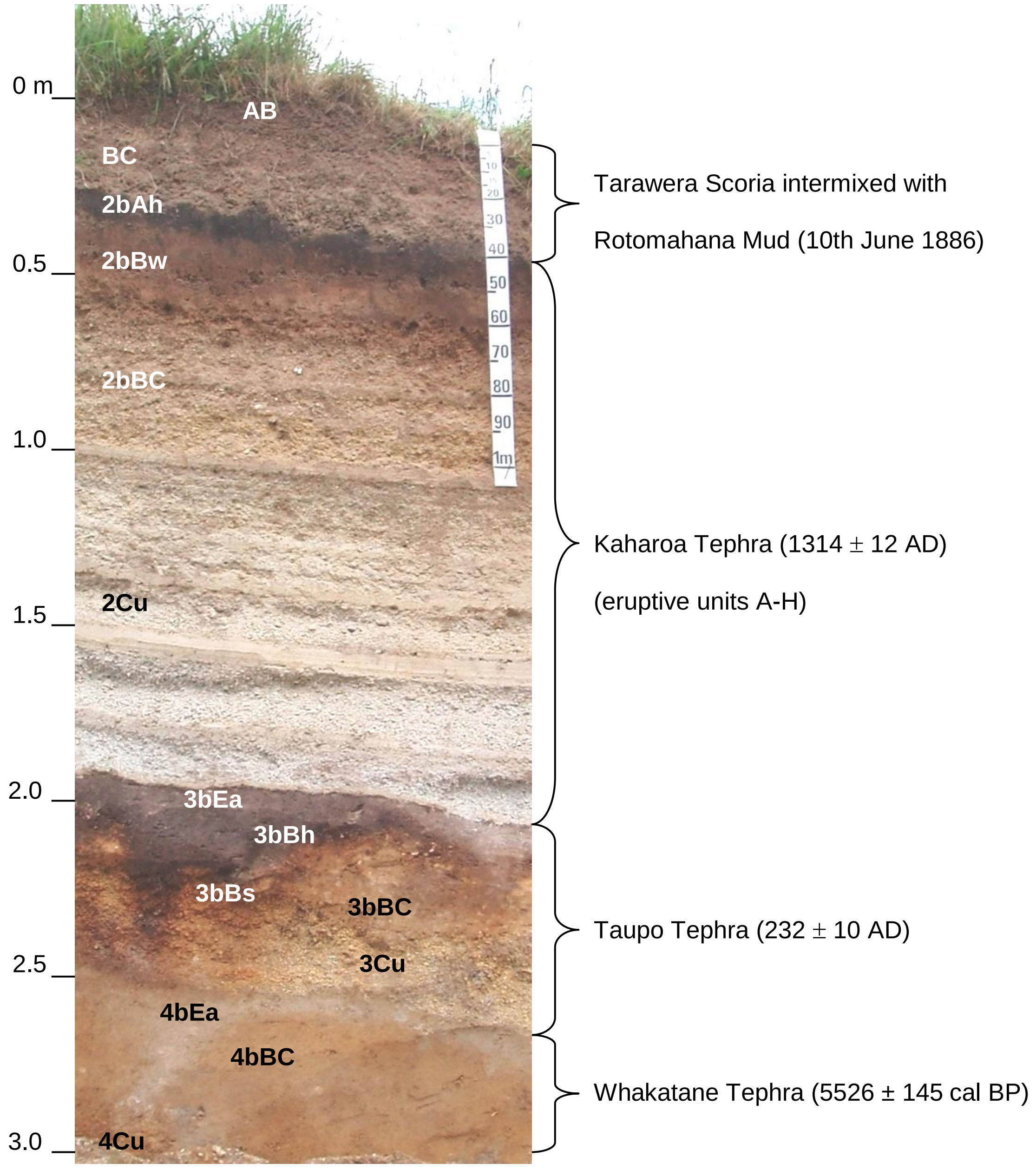


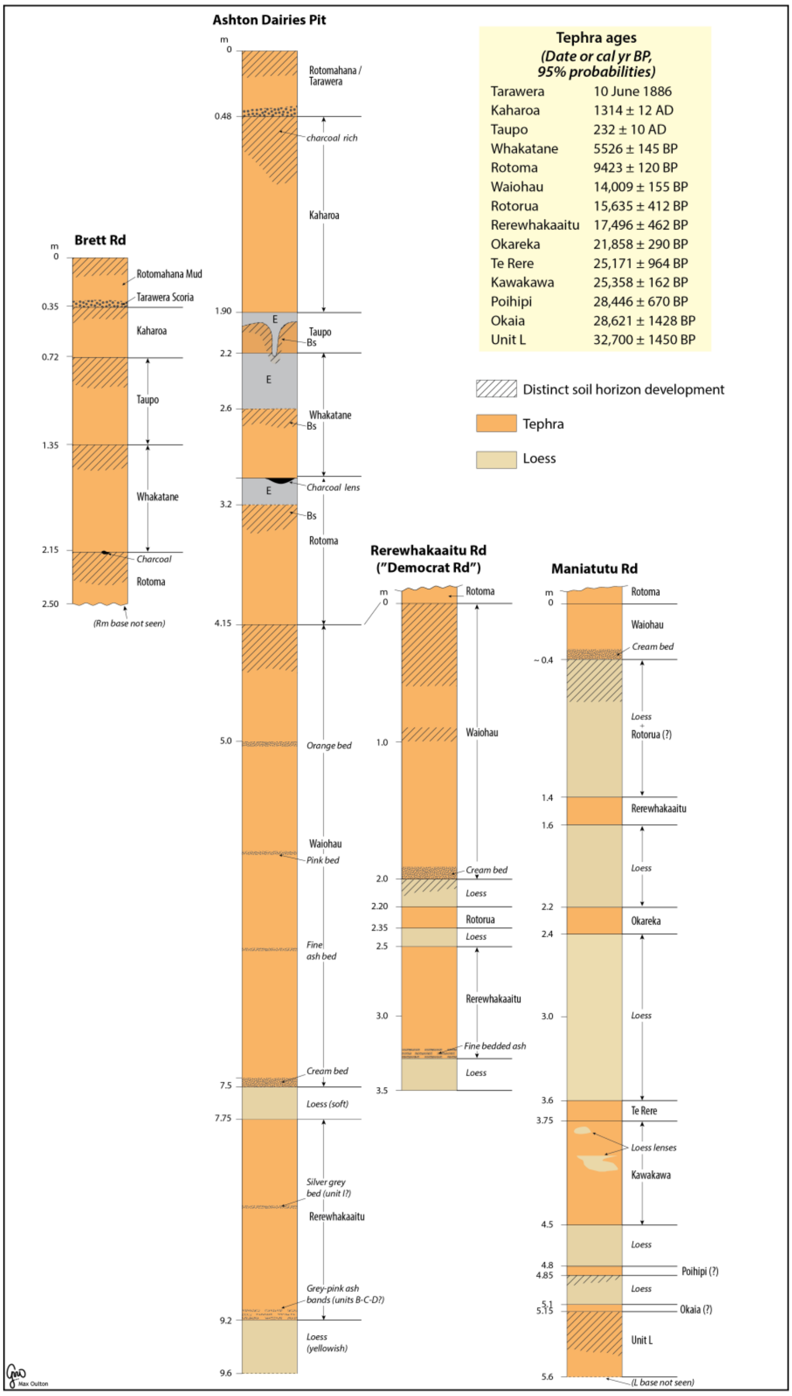
Fig. 41 Matahina gravel and associated buried soil horizons and tephra layers at Ash Pit Rd section. Ages from Lowe et al. (2013). Note the clear spodic-podzol-profile morphology (distinct E horizon on a Bh horizon, referred to as a spodic or podzolic-B horizon) evident on Taupo tephra, and another weak E horizon beneath Taupo on Whakatane tephra in this photo and one on page above. A blotchy E horizon also occurs beneath Whakatane tephra on Rotoma tephra. A similar sequence occurs at a nearby farm, 'Ashton Dairies', which shows three distinct podzol-profile morphologies (see Fig. 42). The grey 'E' horizons, and associated underlying Bh or Bs horizons, are pedogenic in origin and can easily be misidentified as separate pale tephra layers on buried soils (i.e., 'geology meets pedology') (Lowe et al., 2012).

Note from Wim Rijkse

Matahina gravel is a moderately leached soil with base saturations fluctuating from 71% in Tarawera Tephra, to 51% in the paleosol on Kaharoa Tephra, and 19% in Kaharoa lapilli, to finally 67% in the paleosol on Taupo Tephra ((Vucetich et al., 1960). Exchangeable cations are of low values except sodium which is medium. Available phosphorus presumably is low.

NZSC: Allophanic Orthic Pumice; Mt; na (Ba and Rh fines/stones); loamy/sandy; m

Soil Taxonomy: Ash-skeletal/pumiceous, mixed/glassy, subactive(?), mesic Vitrandic Udorthents



Tephra ages
(Date or cal yr BP, 95% probabilities)

Tarawera	10 June 1886
Kaharoa	1314 ± 12 AD
Taupo	232 ± 10 AD
Whakatane	5526 ± 145 BP
Rotoma	9423 ± 120 BP
Waiohau	14,009 ± 155 BP
Rotorua	15,635 ± 412 BP
Rerewhakaaitu	17,496 ± 462 BP
Okareka	21,858 ± 290 BP
Te Rere	25,171 ± 964 BP
Kawakawa	25,358 ± 162 BP
Poihipi	28,446 ± 670 BP
Okaia	28,621 ± 1428 BP
Unit L	32,700 ± 1450 BP

Fig. 42 Summary stratigraphy in the Lake Rerewkahaaitu area at Brett Rd, Ashton Dairies pit, and Rerewhakaaitu Rd sections, and a fourth sequence at Maniatutu Rd near Lake Rotoiti (from Lowe et al., 2012, based on Marsden-funded research "New views from old soils").

Military activities in the Rerewhakaaitu area

Military activities around Rerewhaakaaitu, documented by Mossop (1993), began with annual camps by New Zealand field artillery units in the 1920s-1930s. With the onset of World War II, the artillery units became established along the eastern shores of Lake Rerewhakaaitu and near Mt Tarawera. Batteries fired from escarpments along Northern Boundary Road into the lower slopes of Mt Tarawera. The New Zealand Tank Brigade (~1000 men and ~300 vehicles) trained there from May 1943. Three infantry divisions of the US Army (the 25th, 37th, and 43rd), comprising about 15,000 men in total, camped and trained in the area from 1942 to July 1944. The main units were the 43rd 'Winged Victory Division' and to a lesser extent the 25th 'Tropic Lightning Division'. The 25th Division was from Hawaii. It left New Zealand in February 1944. The 43rd Division was raised from Vermont, Connnecticut, and Maine. It began training at Rerewhakaaaitu on April 1944, and left New Zealand by the end of July. Winter in 1944 was very cold and snowfalls were recorded.

The main training area comprised land to the northeast of Lake Rerewhakaaitu bounded by Mt Tarawera in the north and the edge of the Kaingaroa forest in the south. The only other people living in the district were on Brett Rd, west of the lake, according to Mossop (1993). The main line of fire was towards the east, the so-called 'impact area' bounded today by eastern Ash Pit Rd. The camps were entirely tent-based with no wooden buildings. After the war ended, engineers from the New Zealand Army began the job of disposing of unexploded shells etc, completed by about 1950.

From the 1950s, the area on the northern shores of the lake was used as a camp for compulsory military training by the New Zealand Army (Steve Gilbert pers. comm., 2006). Gilbert also recorded that the road to the top of Mt Tarawera had been constructed by the US Army and lookouts posted there permanently during the war. Today, reminders of the USA presence in the area include Yankee Rd, Republican Rd, and Democrat Rd, although the last has been re-named Rerewhakaaitu Rd on the latest topographic maps. A trig point near the intersection of Ngamotu Rd and Okahu Rd is recorded as 'America NL' (506 m).

Captain Smith (left) and his cannoneers examine the effects of close range fire on a tree in the Rerewhakaaitu area.

Fig. 43 From Griffiths and Schuler (1993)

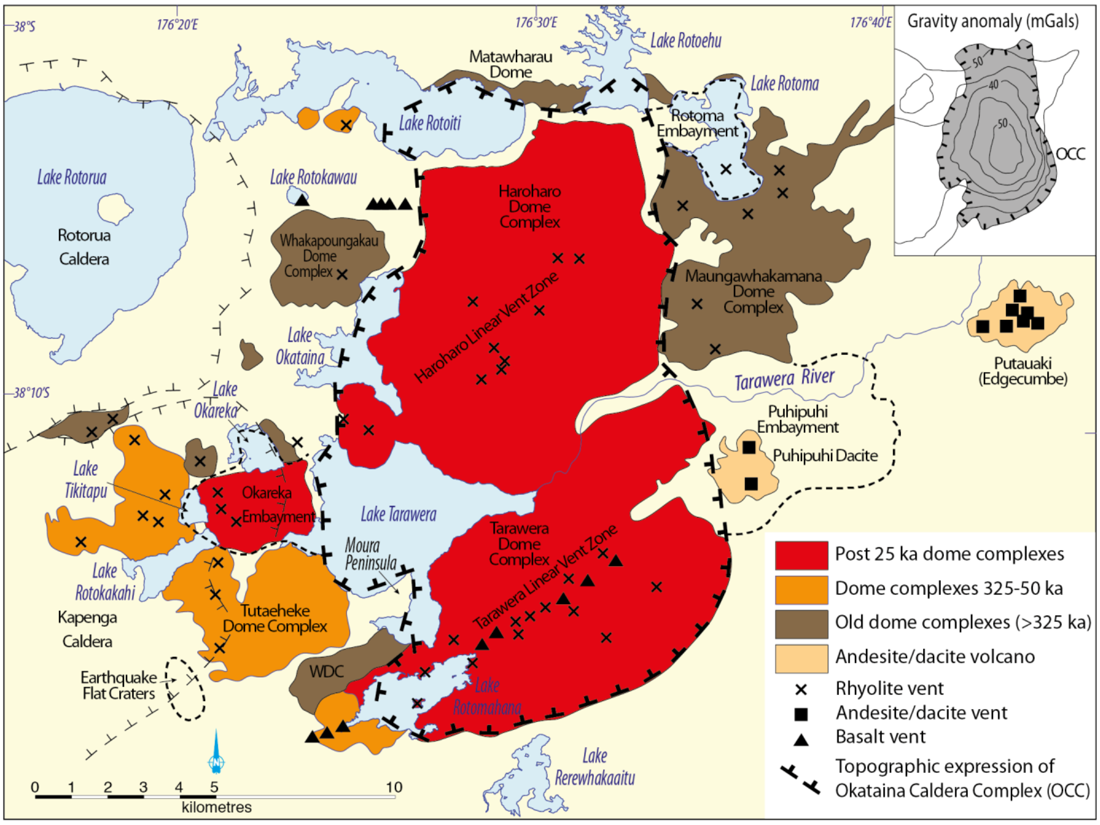


Fig. 44 (Top) Okataina Volcanic Centre, including the Okataina (or Haroharo) caldera complex, dome complexes and known volcanic vents (after Nairn, 2002; Cole et al., 2010, 2014). **Fig. 45** (**Bottom**) Rhyolite domes associated with the Okareka Embayment and their relationship to stops 4 and 5. Lake Tikitapu ('Blue Lake') lies directly to the south.

STOP – RNL Pumice Quarry: near-vent pumiceous tephra

Building the history of eruptions and landscape evolution

Sequence is as follows (Fig. 47):

(a) early tephras (Te Rere, 25.1 ka; Okareka, 21.8 ka) and thin interbedded loess within the remnant buried hill at the base of the sequence;
(b) the buried hill itself, which represents a period of erosion that occurred during the last glacial period, and remnants of a (reworked?) tephra draping the hillslope (Rerewhakaaitu, 17.6 ka);
(c) the thick, bedded pumice lapilli tephra mantling the hill (Rotorua, 15.6 ka), the top of which is modified to form a distinct orange-coloured soil; and
(d) younger tephras and soil horizons overlying the buried soil on the Rotorua tephra.

From distal to proximal – getting closer to the source

Three of the tephras that we observed at Tapapa Rd also feature in this outcrop: the Te Rere, Okareka and Rotorua tephras. The thick Rotorua tephra is particularly distinctive here. We have been tracking this tephra all the way from Tapapa Rd, 45 km from its source vent(s), to this site, only 4.5 km from its source vent(s). The source vent(s) lie to the southeast beneath the Trig7693 and Middle domes of the Okareka Embayment. We can see from the isopach map how the Rotorua tephra thickens closer to the vent(s), and also that much of it was dispersed towards the northwest. The tephra deposits to the northwest represent deposition from an early explosive phase of the Rotorua eruption sequence (phase 1 on isopach map Fig. 46) 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 second phase of the eruption sequence, which lasted for 3-6 years, involved the growth of the Trig7693 and Middle domes and intermittent explosive eruptions that seem to have generated thin tephra deposits blown to the southeast (denoted as phase 2 on the isopach map).

The Te Rere tephra also comes from nearby source vent(s) in the Okareka Embayment beneath the Northern and Eastern domes. Most of the remaining tephras seen here are from the Tarawera Volcanic Complex, 15 km to the southeast, except the Rotoma tephra, which was derived from the Rotoma Rhyolite Complex, 25 km to the northeast. The youngest tephra is Rotomahana Mud, deposited during the Tarawera eruption on 10 June 1886, at the land surface.

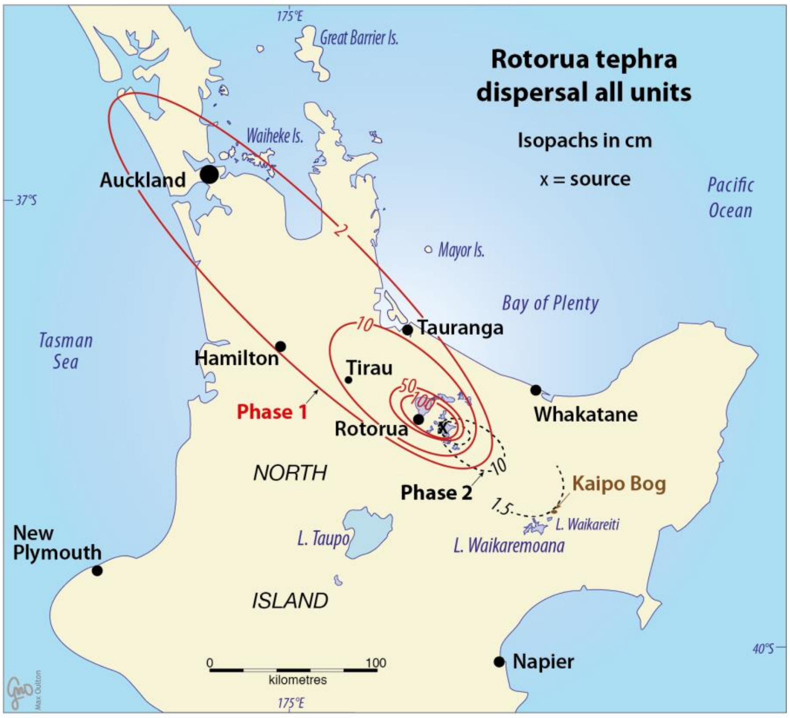


Fig. 46 Isopach map for the Rotorua tephra (modified from Kilgour and Smith, 2008; Shane et al., 2003) with thicknesses in centimetres. Compositional data are available in Smith et al. (2004).

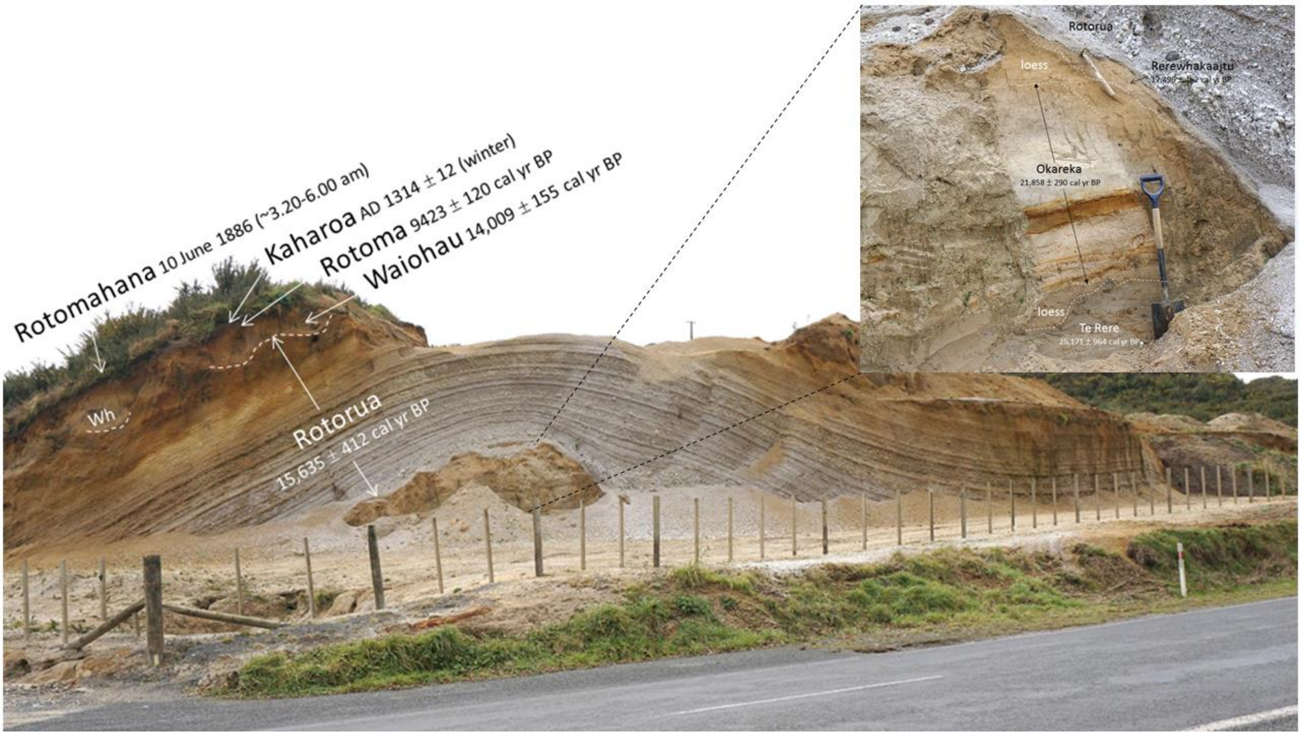


Fig. 47 Outcrop on Okareka Loop Rd by entrance to RNL Pumice Quarry (partly after Nairn, 1992). Ages on tephras from Lowe et al. (2013). 'Cal yr BP' refers to calendar (calibrated) years before present, 'present' taken as 1950 in radiocarbon-based timescale.

STOP – KAINUI SILT LOAM & NAIKE CLAY [GORDONTON RD]

Location S14 133859, elevation ~60 m asl, rainfall 1200 mm pa

At this stop are several remarkable features both stratigraphic and pedological, and a 'two-storied' soil, the Kainui silt loam alongside (in just a few places) the Naike clay. Both soils are Ultisols. The sequence of tephra beds and buried soil horizons spanning about 1 million years was exposed in 2007 by road works. We will not see this site; rather, an equivalent site on Raynes Rd south of Hamilton.

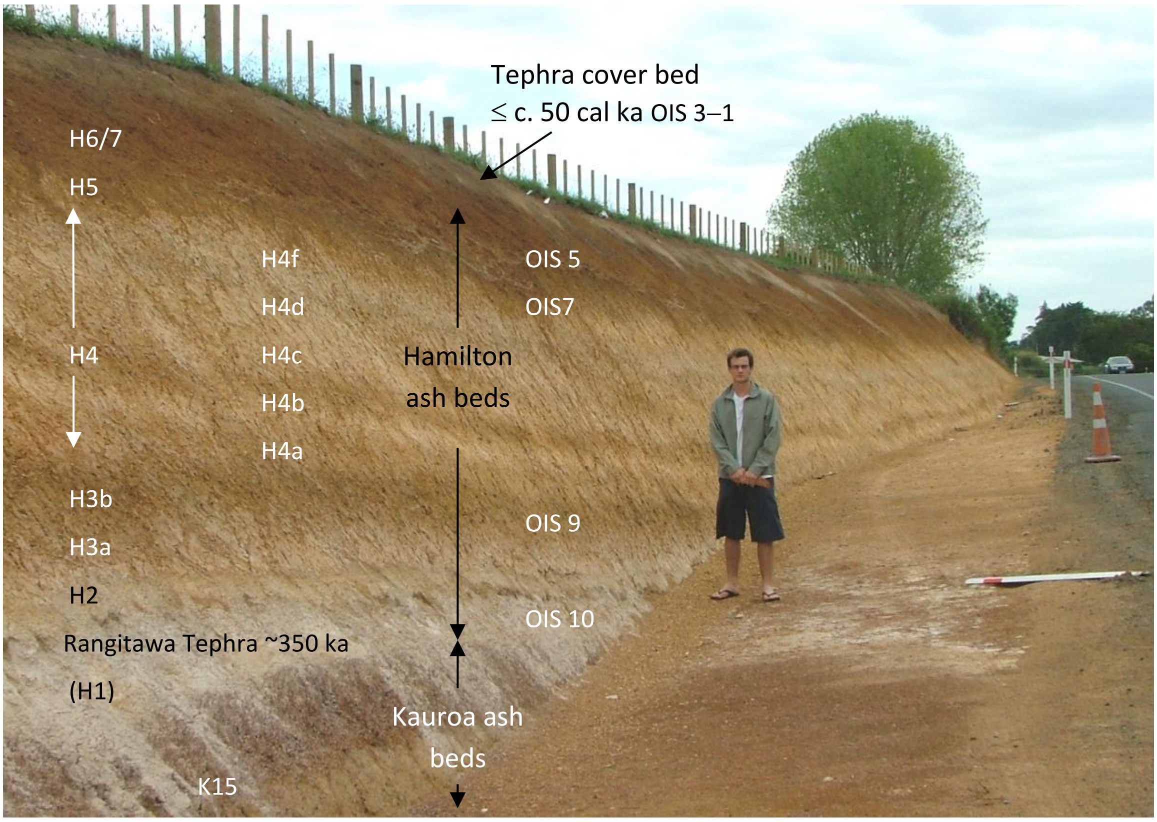


Fig. 48 Provisional stratigraphy of Gordonton Rd section. Seb provides the scale. *Photo*: David Lowe

Stratigraphy

(1) At the base of the section is the tiny remnant of an ancient landsurface represented by a buried, clay-rich soil >0.78 Ma on the basis of its reversed magnetism and other evidence (Horrocks, 2000; Lowe et al., 2001). Several undifferentiated beds visible beneath it are likely to be c. 1 Ma or older. These old tephra beds at the base of the Gordonton Rd section (northern end) are part of the so-called Kauroa ash bed sequence, the uppermost unit being the Waiterimu ash member or K15 (Ward, 1967; Lowe and Percival, 1993; Lowe et al., 2001).

(2) Overlying K15, with an unconformity, is the white ~0.5-m thick Rangitawa Tephra aged 0.35 Ma, one of the most widespread tephras in the southwest Pacific region that fell during Marine Oxygen Isotope (MOI) Stage 10. Rangitawa Tephra is overlain in turn by a ~3-m thick sequence of weathered, yellowish brown to brown to reddish brown clayey tephra beds and buried soils – the Hamilton ash beds – that represent MOI stages 9 to 5. The uppermost distinctive, dark reddish-brown buried soil, known as the Tikotiko ash member or bed H6/7 (Ward, 1967; see below), represents probably the Last Interglacial (OIS 5) paleo-landsurface.

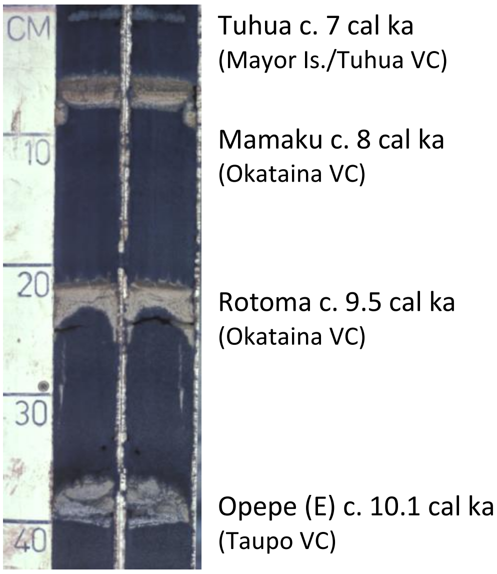
(3) At the top is a thin, silty cover bed mantle of intermixed late Quaternary tephras about 0.4-0.6 m thick, occasionally overthickened in hollows up to ~1.2 m in thickness, that have accumulated incrementally over the past c. 60,000 years (OIS 3–1). As at Pukekohe Hill, the base of the cover bed has been identified as Rotoehu Ash (c. 60 cal ka) but it is evident from detailed mineralogical and geochemical studies that the component tephras making up the composite mantle have been strongly intermixed during upbuilding pedogenesis (Lowe, 1981, 1986, 2000). Nearby lakes, formed c. 20–18 cal ka following deposition of the volcanogenic alluvium of the Hinuera Formation (see stops 3-4), have preserved >40 multiple, thin, visible tephra layers within their sediments (e.g. Green and Lowe, 1985; Lowe, 1988). These tephras each range in thickness from a few millimetres to several centimetres and in this area amount to an estimated ~37 cm in total thickness (Lowe, 1988). Together with tephras deposited between c. 60 and 20 cal ka, they form the parent material of the upper part of the Kainui soil (Lowe, 1986). The thin tephras preserved in the lake sediments are both rhyolitic (predominant) and andesitic and were derived from six volcanic centres 70 to 200 km away (Lowe, 1988). There are likely to be numerous very thin (< 1 mm) 'non-visible' tephras or sparse concentration zones of glass shards, known as cryptotephras (Alloway et al., 2007a), in the lake sediments as well as the visible layers. From recent work on lake cores and peat bogs, such cryptotephras are confirmed in the Waikato region (Gehrels et al., 2006, 2008) and thus probably were assimilated into the Kainui soil as 'dustings' from small-scale eruption plumes.

(Above)

Fig. 49 Lake Maratoto, south of Hamilton, was formed c. 20 cal ka. *Photo*: David Lowe

(Above right)

Fig. 50 The first core of 33 eventually taken from the lake (April 1979). Grey layer near base is alluvium overlying dark proto-lake lake sediment (near tape head) and pre-lake soil (Green and Lowe, 1985). Part core at right (from Lake Rotongata) shows 4 visible tephra layers preserved within dark organic-rich lake sediment



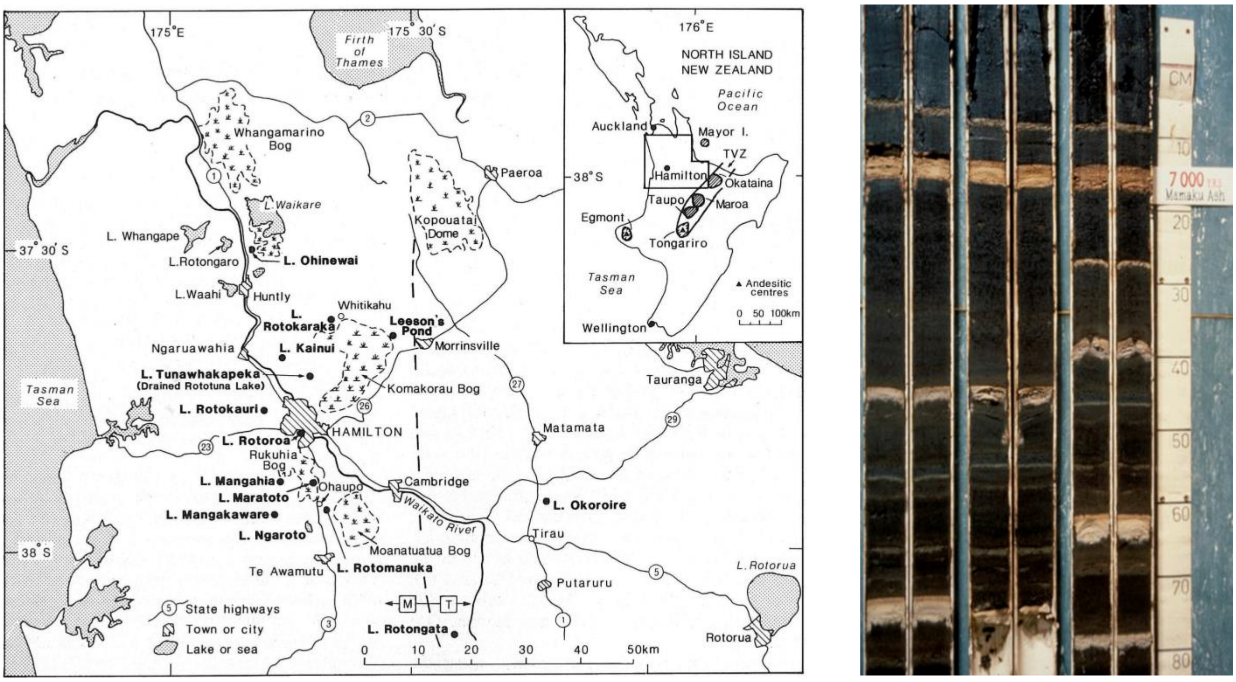


Fig. 51 Left) Central Waikato area showing locations of lakes cored to obtain detailed post-c. 20 cal ka tephra record. (Right) Cores from Lake Rotomanuka sliced open to show tephra layers preserved in dark lake sediments (from Lowe, 1988). We have recently re-cored three lakes (Kainui, Rotokauri, and Kainui for studies on cryptotephras (funded by EQC) and tephra 'seismites', i.e., tephra layers that have been liquefied by earthquake activity in the past 20,000 years.

Lake sites are: 1, L. Maratoto; 2, L. Rotomanuka; 3, L. Ngaroto; 4, L. Mangakaware; 5, L. Mangahia; 6, L. Rotoroa; 7, L. Rotokauri (thickness measurements do not include Rerewhakaaitu Ash); 8, L. Kainui; 9, L. Rotokaraka; 10, Leeson's Pond; 11, L. Okoroire; 12, L. Rotongata.

Fig. 52 Thickness and compositional relationships based on measurements of tephras in lake cores. Bars with hatching = total thickness of all tephras ≤ c. 20 cal ka; blank bars = rhyolitic tephras; stippled bars = andesitic tephra. Solid bars = actual measurements, dashed bars = thicknesses corrected for compaction and dissemination in sediment cores. Dashed lines = isopachs (in mm) of sum of tephras at subaerial sites deposited since c. 20 cal ka (from Lowe, 1988).

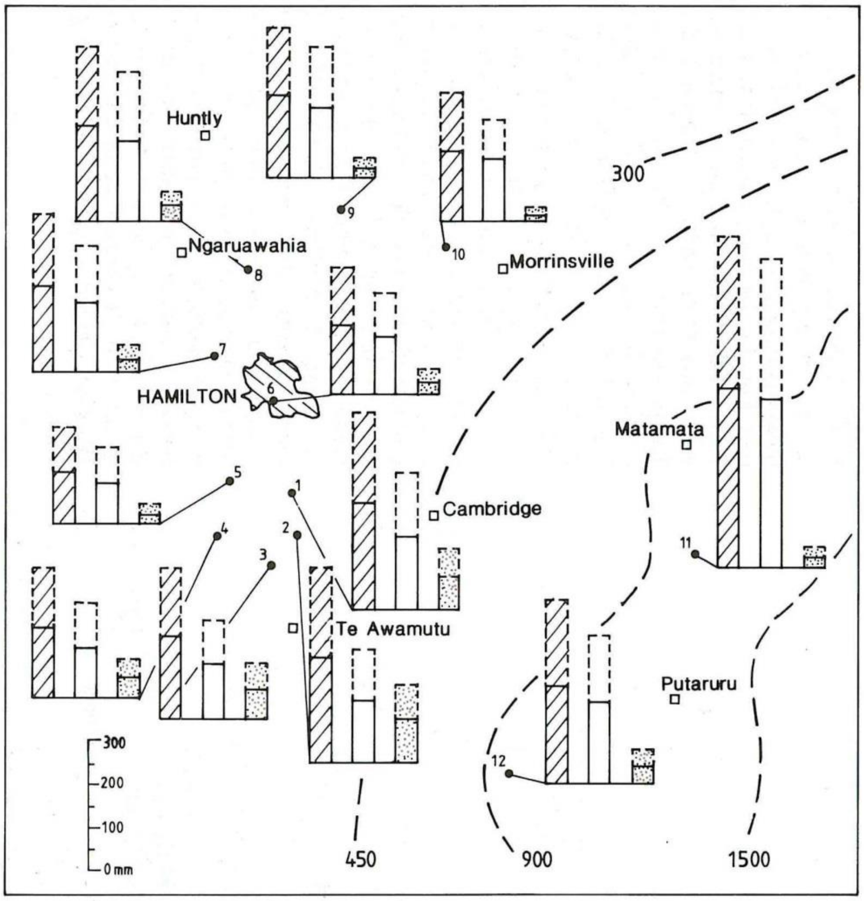
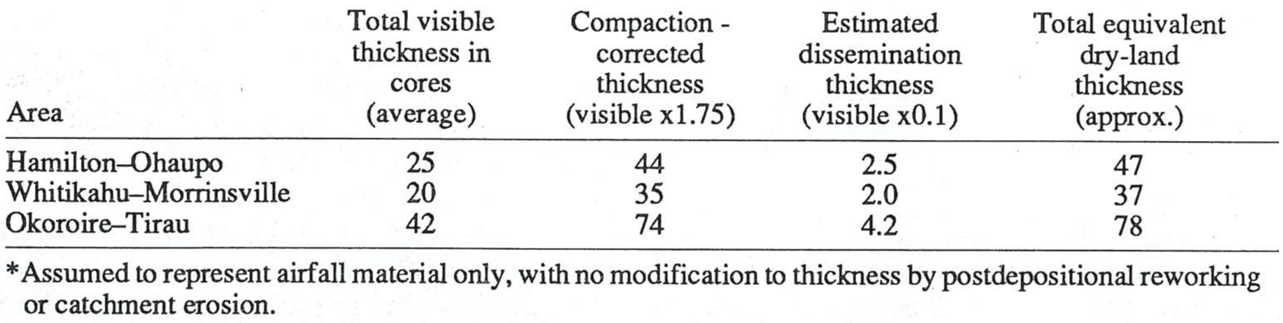


Table 7 Total thicknesses of tephras < c. 20 cal ka in central Waikato area based on lake core measurements and estimated 'dry-land' (subaerial) thicknesses (values in centimetres) (from Lowe, 1988)



Area	Total visible thickness in cores (average)	Compaction - corrected thickness (visible x1.75)	Estimated dissemination thickness (visible x0.1)	Total equivalent dry-land thickness (approx.)
Hamilton–Ohaupo	25	44	2.5	47
Whitikahu–Morrinsville	20	35	2.0	37
Okoroire–Tirau	42	74	4.2	78

*Assumed to represent airfall material only, with no modification to thickness by postdepositional reworking or catchment erosion.

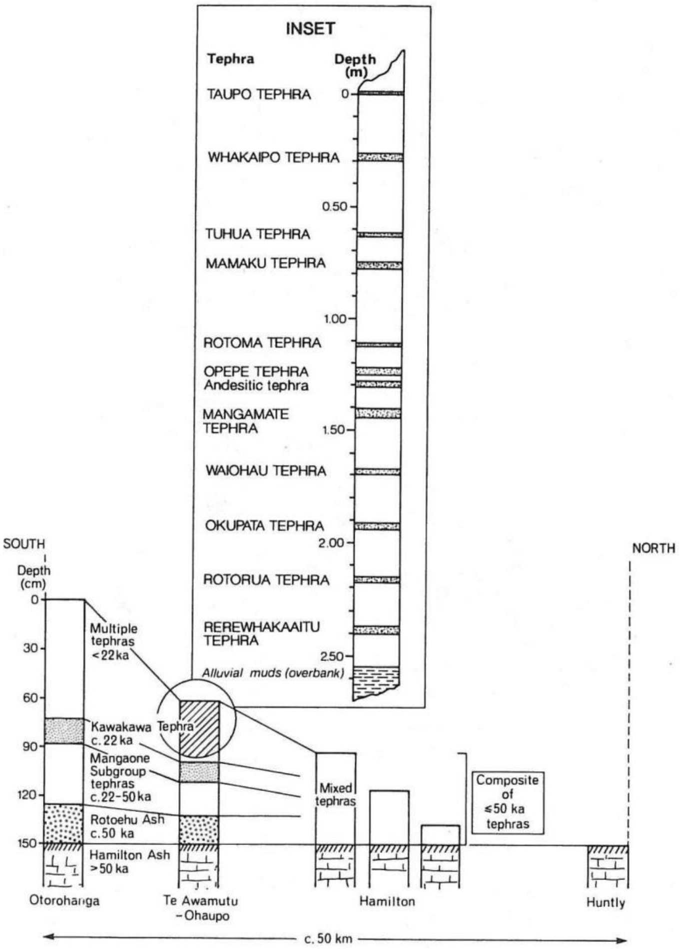
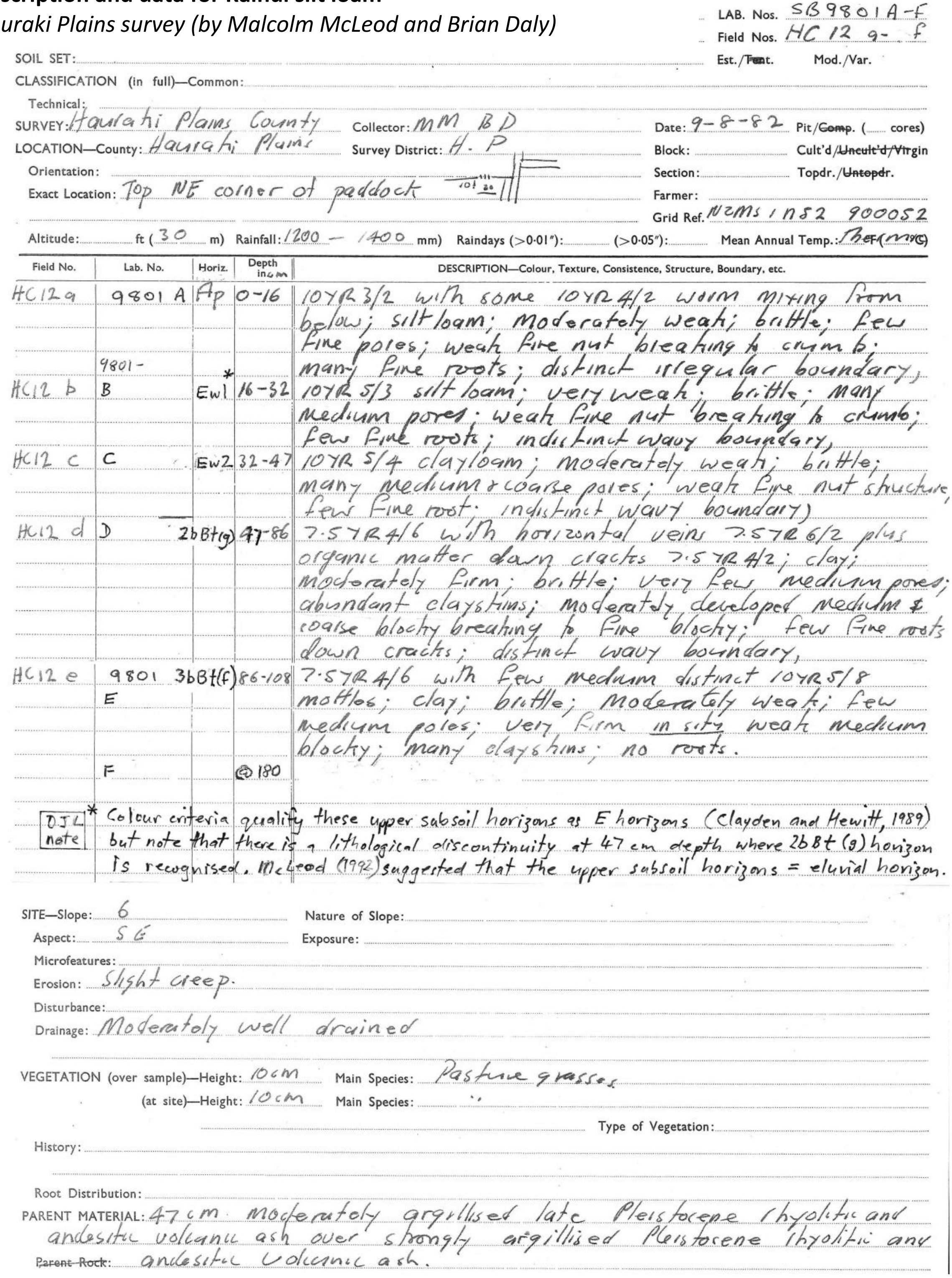


Figure 10.4 Transect across the Hamilton Basin showing the simplified stratigraphy and age of late Quaternary tephra deposits overlying Hamilton Ash on the low hills. Marker beds are distinguishable in the field in the south (Otorohanga and Te Awamutu-Ohaupo profiles) but around Hamilton the tephra deposits, thinning away from their sources, become intermixed to form a composite cover bed with no distinguishable marker beds. Where this cover bed is eroded, exhumed Hamilton Ash occurs at the surface, as for the Huntly profile, but thin late Quaternary tephras are present further north towards Auckland. The inset shows the stratigraphy of prominent tephra layers preserved in lake sediments in a core from Lake Maratoto, a 17 000-year-old peaty lake about midway between Ohaupo and Hamilton (see Figure 10.5). It indicates potential contributions of specific tephras as probable parent materials in the upper soil profile (hatching). ka = 1000 years BP. After Lowe (1986).

Fig. 53 Otorohanga and Ohaupo soils (Hapludands) occur at sites marked by columns 1 and 2; Kainui soils (Udults) at site marked by columns 3-5 ('Hamilton' ≅ Gordonton Rd); and Naike soils (Humults) at site marked by column 6 ('Huntly') (from Selby and Lowe, 1992). Ages in ^{14}C yr ka.

Description and data for Kainui silt loam

Hauraki Plains survey (by Malcolm McLeod and Brian Daly)



LAB. Nos. SB9801A-F
Field Nos. HC 12 a - f
SOIL SET:
Est./~~Tent.~~ Mod./Var.
CLASSIFICATION (in full)—Common:
Technical:
SURVEY: Hauraki Plains County
Collector: MM BD
Date: 9-8-82
Pit/~~Comp.~~ (...... cores)
LOCATION—County: Hauraki Plains
Survey District: H. P
Block:
Cult'd/~~Uncult'd/Virgin~~
Orientation:
Section:
Topdr./~~Untopdr.~~
Exact Location: Top NE corner of paddock
Farmer:
Grid Ref. NZMS 1 N52 900052
Altitude: ...... ft (30 m)
Rainfall: 1200 – 1400 mm)
Raindays (>0·01"): ...... (>0·05"): ......
Mean Annual Temp.: ~~°F~~ (°C)

Field No.	Lab. No.	Horiz.	Depth in cm	DESCRIPTION—Colour, Texture, Consistence, Structure, Boundary, etc.
HC12a	9801 A	Ap	0-16	10YR 3/2 with some 10YR 4/2 worm mixing from below; silt loam; moderately weak; brittle; few fine pores; weak fine nut breaking to crumb; many fine roots; distinct irregular boundary,
HC12 b	9801-B	Ew1*	16-32	10YR 5/3 silt loam; very weak; brittle; many medium pores; weak fine nut breaking to crumb; few fine roots; indistinct wavy boundary,
HC12 c	C	Ew2	32-47	10YR 5/4 clay loam; moderately weak; brittle; many medium & coarse pores; weak fine nut structure, few fine root; indistinct wavy boundary)
HC12 d	D	2bBt(g)	47-86	7·5YR 4/6 with horizontal veins 7·5YR 6/2 plus organic matter down cracks 7·5YR 4/2; clay; moderately firm; brittle; very few medium pores; abundant clayskins; moderately developed medium & coarse blocky breaking to fine blocky; few fine roots down cracks; distinct wavy boundary,
HC12 e	9801 E	3bBt(f)	86-108	7·5YR 4/6 with few medium distinct 10YR 5/8 mottles; clay; brittle; moderately weak; few medium pores; very firm <u>in situ</u> weak medium blocky; many clayskins; no roots.
	F		@ 180	

DJL note * Colour criteria qualify these upper subsoil horizons as E horizons (Clayden and Hewitt, 1989) but note that there is a lithological discontinuity at 47 cm depth where 2bBt (g) horizon is recognised. McLeod (1992) suggested that the upper subsoil horizons = eluvial horizon.

SITE—Slope: 6
Nature of Slope:
Aspect: SE
Exposure:
Microfeatures:
Erosion: Slight creep.
Disturbance:
Drainage: Moderately well drained

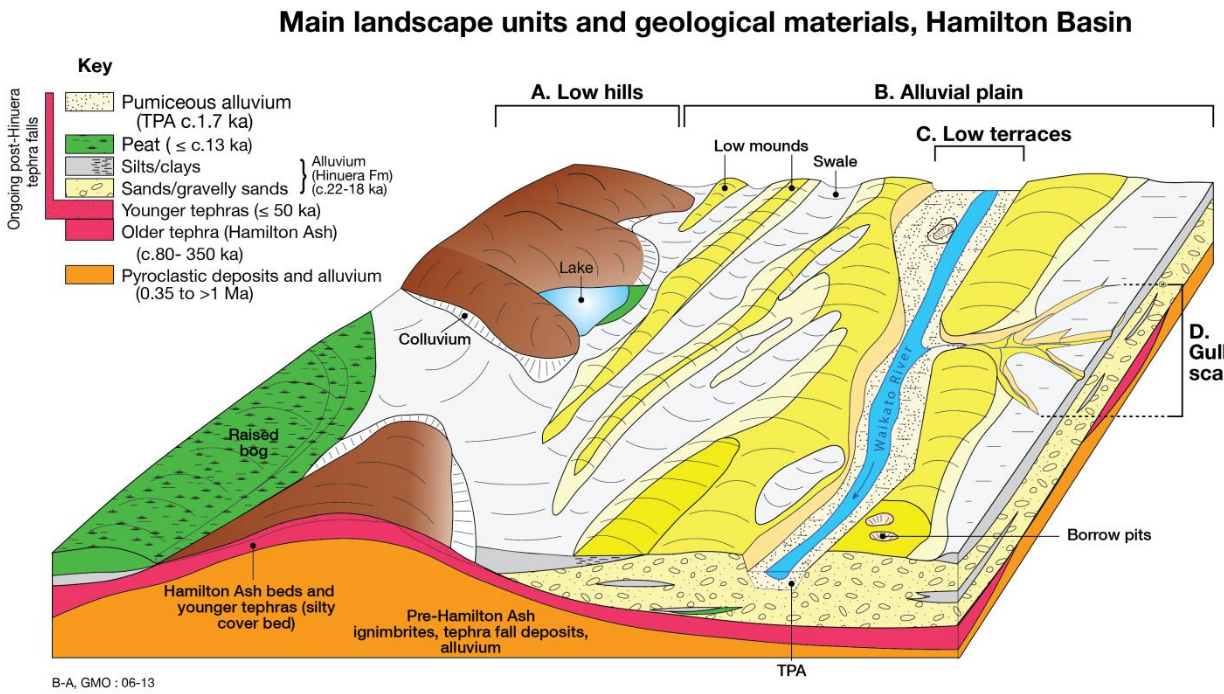
VEGETATION (over sample)—Height: 10 cm
Main Species: Pasture grasses
(at site)—Height: 10 cm
Main Species: "
Type of Vegetation:
History:
Root Distribution:
PARENT MATERIAL: 47 cm moderately argillised late Pleistocene rhyolitic and andesitic volcanic ash over strongly argillised Pleistocene rhyolitic and andesitic volcanic ash.
~~Parent Rock~~:

Classification Kainui silt loam

NZSC: Buried-granular Yellow Ultic Soils; Mt; na (Rh and An fines); silty/clayey; moderate/slow

Soil Taxonomy: Clayey, halloysitic, thermic Aquic [or Oxyaquic] Kandiudults

The 'organic matter down cracks' noted for 2bBt(g) in above description is likely to be MnO_2 (pyrolusite) coatings, abundant in lower subsoils (near boundary upper/lower parts of profile) of many Kainui soils. A 'Buried-granular' subgroup, rather than Podzolic subgroup, was adopted in 2010 to encompass widespread Kainui soils (Hewitt, 2010).



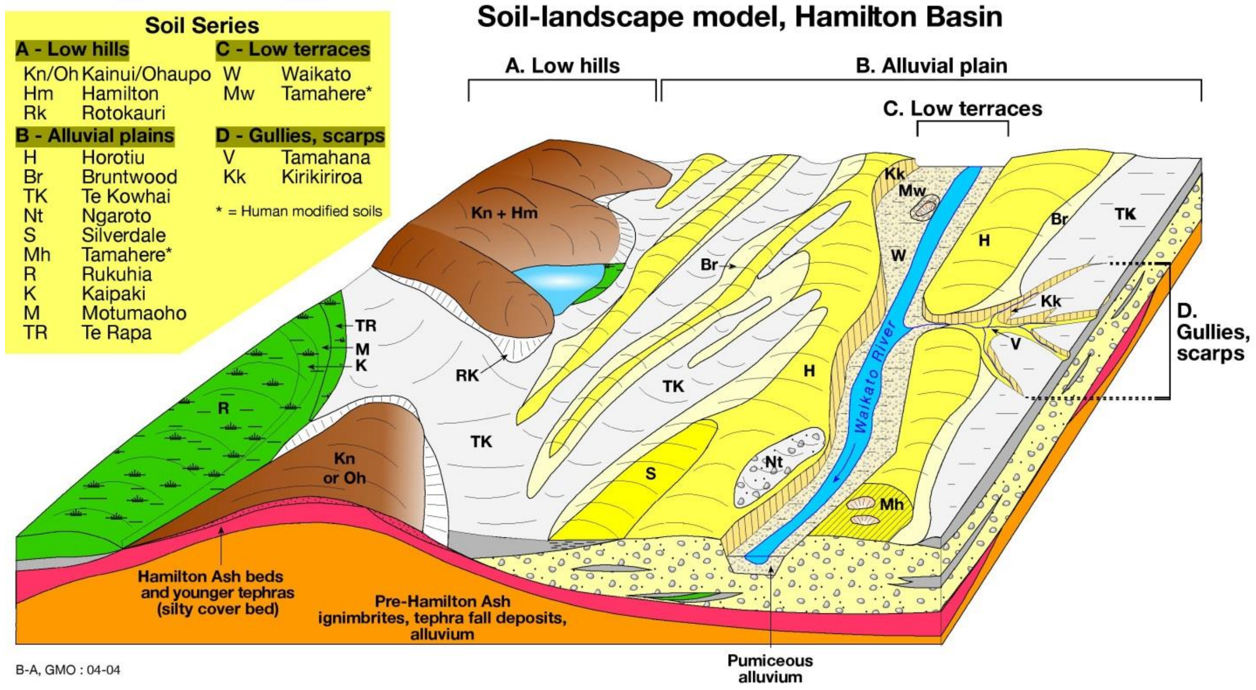


Fig. 54. Generalised geology-landform relationship (upper) and associated soil pattern (lower) in the Hamilton Basin

General landscape pattern

The Hamilton area is characterised by four main landscape units or landforms:

- Low rolling hills (e.g. University, Hospital, Hamilton East Cemetary, Wintec city campus) – the 'Hamilton hills'
- Flat alluvial plains (e.g. much Hamilton East) with micro-relief of low mounds (bars) and swales (depressions)
- Low terraces adjacent to the modern Waikato River (e.g. Lower Hamilton Gardens, Memorial Park)
- Gullies cut into the alluvial plain or low terraces (e.g. gully running through Hungerford Cresc into the Gardens)

1. The low rolling hills represent the remnants of a landscape dating back around more than a million years. A drill hole through a hill will typically show the following sequence of deposits (from top down):

- Silty cover bed of post-Hamilton-Ash tephra (volcanic ash) beds from multiple sources; ~0.5 m thick; ≤c. 50 ka
- Red-brown, clayey weathered tephra beds (Hamilton Ash); ~1–3 m thick; top bed c. 50–100 ka, basal c. 340 ka (dark red-brown uppermost buried soil horizon probably represents soil formation during the last interglacial)
- Orange/reddish/cream gravelly alluvial clays (Karapiro Formation); variable thickness (few metres); c. 500 ka
- Very dark reddish brown, clayey weathered tephra beds (part of Kauroa Ash Formation); patchy; c. 1 Ma
- Cream-coloured ignimbrite (deposits from hot, ground-hugging, fast moving pyroclastic flows, also called pyroclastic density currents); up to 10–20 m thick. Three main units: Ongatiti Ig., Rocky Hill Ig., Kidnappers Ig., aged from c. 1.2 to 0.9 Ma, respectively. The sculptures at Gate 1 (by Hungerford Cres/Cobham Drive) are made of Ongatiti Ignimbrite (c. 1.23 Ma) which is quarried as 'Hinuera Stone' in the Hinuera Valley between Piarere and Hinuera (near Matamata).

The earliest of these deposits, the ignimbrites, usually form the 'core' of the Hamilton hills. They and associated alluvium have been partly eroded to form a rolling landscape which has then been blanketed with subsequent tephra beds draping the hills and the valleys. So, the underlying hilly terrain is actually quite an old remnant landscape feature, one of the oldest in New Zealand. Buried soils or soil horizons are common and represent landscape surfaces of the past. The modern soils are developed largely in the uppermost deposits, namely the multiple tephra-derived cover bed and upper Hamilton Ash beds: the main soils, typically sticky and clayey, are referred to as the Kainui and Hamilton series (Kn + Hm). Hamilton soils tend to occur more commonly on shoulder slopes and are less common than soils of the Kainui series.

2. The plains represent alluvium derived ultimately from the mainly volcanic catchments of the central North Island and deposited by ancestral Waipa and then ancestral Waikato river system in a series of depositional episodes over the past *c*. 100 ka or so. These deposits swept around and over the pre-exisiting hilly landscape in the Waikato, partly burying it so that today we find just remnants of the hills protruding through the essentially flat-lying alluvial surface (the surface actually has slight surface features, a series of low ridges/bars and swales or depressions; it also slopes very gently in a fan form, the apex at Maungatautari and the toe at Taupiri, ~1 m vertically for every 1 km horizontally). The ancestral Waikato River was predominantly a high energy, braided system that until around 22,000 calendar (cal.) years ago flowed through the Hauraki Plains via the Hinuera Valley. It then switched (avulsed) at Piarere near Karapiro to flow into the Hamilton Basin. The name of the volcanogenic alluvium deposited by the ancient Waipa and Waikato rivers is the Hinuera Formation, and the surface of the plains is called the Hinuera Surface. The deposits of the Hinuera Formation are up to 60 m thick. The latest depositional episode in the Hamilton Basin was between *c*. 22,000 and 18,000 cal. years ago. Soon after, the ancestral Waikato River began to entrench into its modern channel, occasionally forming terraces at lower levels, as full forest vegetation was re-established over the landscape from c. 17,500 years ago. Thin but numerous tephra layers (each a few millimetres to a few centimetres in thickness) have blanketed much of the Hinuera Surface since it was abandoned *c.* 18,000 cal. years ago by the entrenching Waikato River. The tephra layers are well preserved in lake sediments (e.g. cores from Lake Rotoroa contain numerous tephra layers) and peat bogs that developed on or alongside the Hinuera deposits. The soil pattern on the ash-draped Hinuera Surface mimicks the alluvial depositional environments: well drained soils occur on the slightly raised channel/bar deposits (Horotiu series, H: ashes on coarse alluvium) and poorly drained soils occur on lower-lying overbank flood deposits (Te Kowhai series, TK; Ngaroto series, Nt). In between are the Bruntwood soils (Br, well drained upper, poorly drained lower horizons) and Silverdale soils (S, moderately well drained upper and poorly drained lower horizons).

3. The lowermost terraces adjacent to the modern Waikato River mark deposition from a dramatic breakout flood event about AD 250 AD ago following the latest eruption of Taupo Volcano (in AD 232 ± 10). Huge quantities of pumiceous deposits were swept down the Waikato River, which rose several metres to tens of metres, and then left stranded as terrace deposits adjacent to the main river channel and up tributary valleys or gullies that drained into it. The deposits are known as the Taupo Pumic Alluvium and are up to ~30 m thick. Soils developed on these materials (Waikato series, W) are weakly formed because of their relatively young age. The Cambridge Golf Course boasts that it was ‘sculptured by the Waikato River 15,000 years ago’. This is untrue: the course is dominated by deposits and paleochannels of the Taupo Pumice Alluvium of *c*. AD 250, only *c*. 1750 cal. years ago (the earlier Hinuera Formation materials are well buried underneath or were cannibalized during the Taupo break-out flood event).

4. Gullies are occasionally cut into the Hinuera Surface, usually draining towards the modern Waikato River. Soils of the gully sides, and terrace scarps, are Kirkiriroa series (Kk) and soils on the recent alluvium in gully bottoms are Tamahana series (V).

Past vegetation and climate

The first European descriptions of the central Waikato area noted that the landscape was covered largely in bracken and scrub. However, pollen and spore studies (palynology) of samples from cores taken from local lakes and peats demonstrated that the region was dominated by grassland from *c*. 20,000–17,500 cal. years ago when the climate was cool and dry. The region became forested from about 17,500 cal. years ago as climate became warmer and wetter, and forest cover persisted through to about AD 1300 when the prevalent podocarp-hardwood and kauri forests were partly destroyed by burning. Such burning is attributed largely to Polynesian activities. European settlers continued modifying the vegetation pattern.

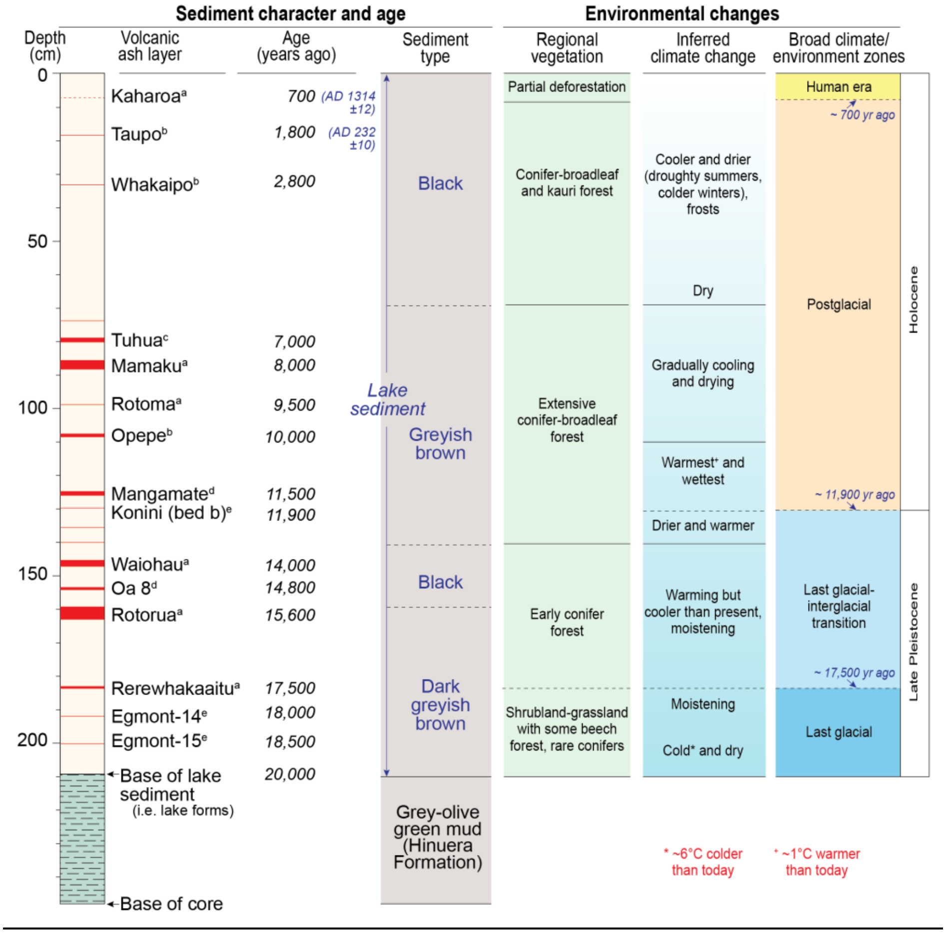


Fig. 55 Summary of inferred vegetation and climate since *c*. 20,000 cal. years ago in the Hamilton area, and volcanic ash layers in a core from Lake Rotoroa (from Lowe, 2014, after Newnham et al. 1989, 2013; Green and Lowe, 1994).

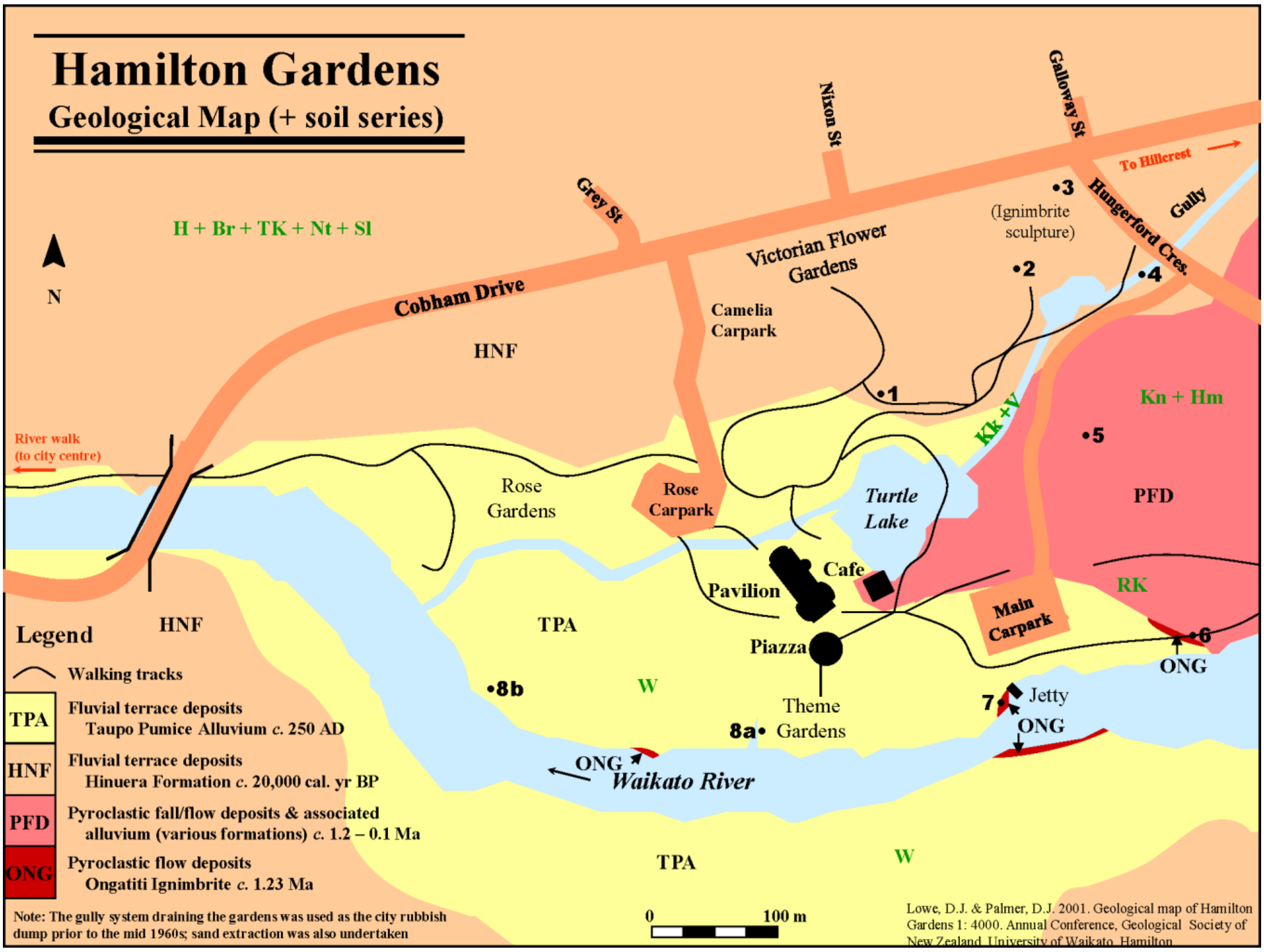


Fig. 56 Map of main geological units and associated soil series, Hamilton Gardens. See soil-landscape models above for key to abbreviations of names of soil series (H, Br, TK etc).

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