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Quaternary volcanism, tephras, and tephra-derived soils in New Zealand: an introductory review

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Introduction

This two-part article comprises brief introductions to (1) volcanism and its products in general and to the broad pattern of Quaternary volcanism and tephrostratigraphy in North Island, and (2) the ensuing tephra-derived soils of North Island. Part 1 derives mainly from Smith et al. (2006), Leonard et al. (2007), and Lowe (2008a). Other useful reviews include those of Neall (2001), Graham (2008: Chapter 7), Wilson et al. (2009), and Cole et al. (2010). Recent reviews on tephras include Shane (2000), Alloway et al. (2007), Lowe (2008b, 2011), and Lowe et al. (2008a, 2008b). A history of tephra studies in New Zealand was reported by Lowe (1990). Part 2 describes the distribution and character of the main tephra-derived soils, these being Entisols and Andisols (mostly Vitrands and Udands) and Ultisols (Lowe and Palmer, 2005). Books on these and other soils in New Zealand include NZ Soil Bureau (1968), Gibbs (1980), McLaren and Cameron (1996), Cornforth (1998), and Molloy and Christie (1998). An excellent overview is the web-based article by Hewitt (2008), and encyclopaedic reviews by Neall (2006) and McDaniel et al. (2011) include New Zealand examples. Tonkin (2007a, 2007b, 2007c) provided a history of soil survey and soil conservation activities in New Zealand. A quantitatively-based classification of New Zealand's terrestrial environments was published by Leathwick et al. (2003).

Volcanoes, volcanism, and tephras

Volcanoes, magmas, and types of eruptions

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 midway between andesite and rhyolite in composition.

- *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 splinters 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 (Smith et al., 2006).

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.

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

Although New Zealand’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 but some basaltic materials are also on show at the start (South Auckland Volcanic Field) and on Day 4 near Mt Tarawera.

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 map below) (Cole and Spinks, 2009).

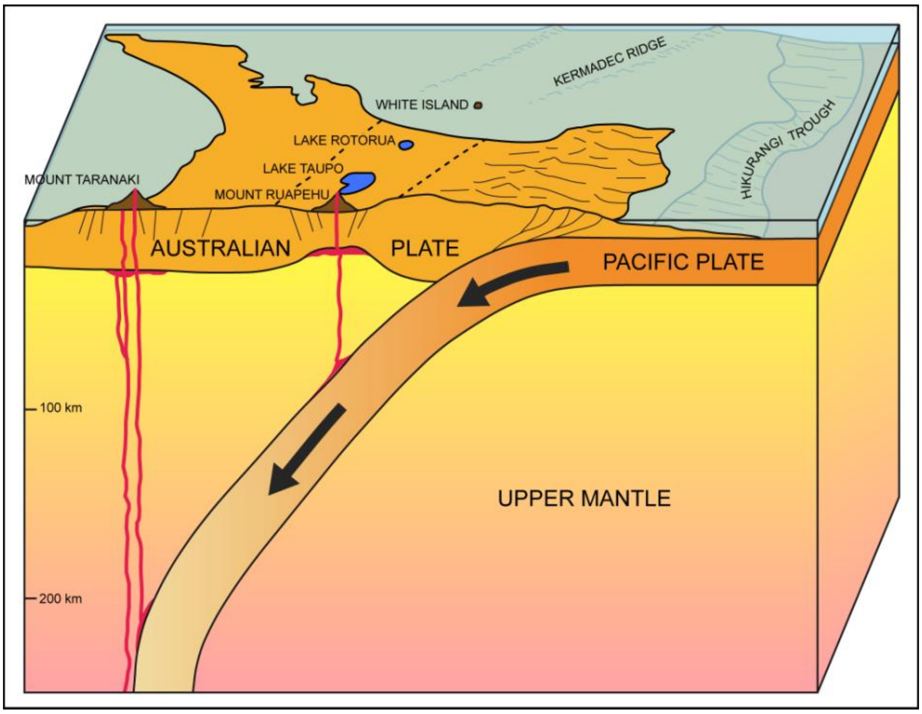
Rhyolite calderas may be active for several hundred thousand years, but large eruptions are rare, with typically thousands of years between events. Caldera collapse is not the only effect on the landscape arising from these large explosive eruptions. Huge quantities of pumice, ash and gas are pumped 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.

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

Quaternary volcanism in North Island

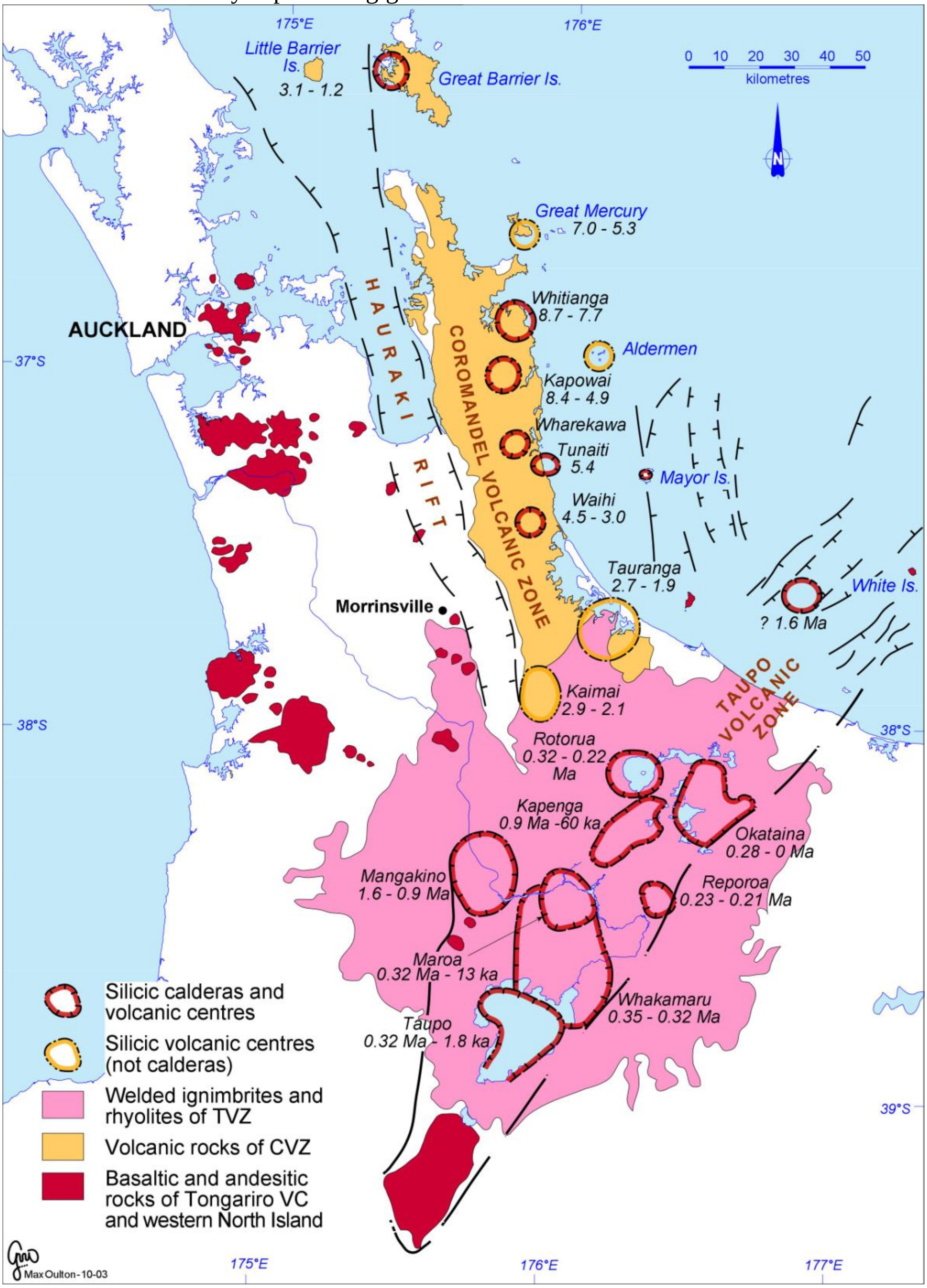
The highest concentration of Quaternary volcanic activity in New Zealand occurs in the area known as the Taupo Volcanic Zone (TVZ). This narrow band of cone and caldera volcanoes extends from Ruapehu in the south, over 240 kilometres to Whakaari (White Island) in the north, with the Taupo, Okataina, 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). 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., 2006).



Simplified North Island plate tectonic setting (diagram courtesy of Adrian Pittari)

Taupo Volcanic Zone

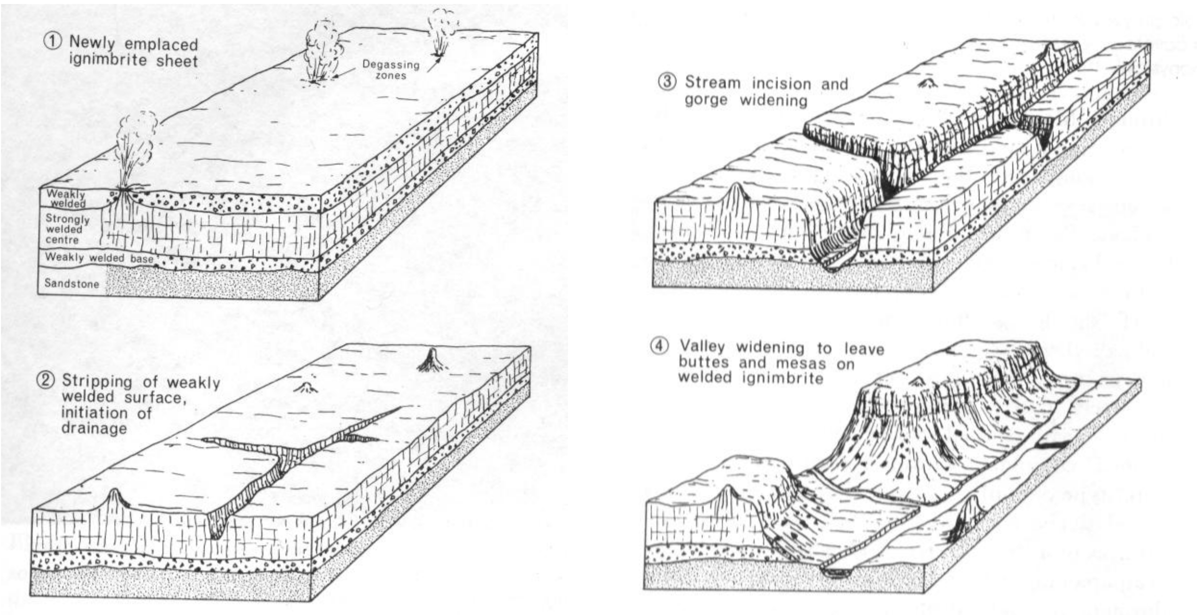
The TVZ can be thought of in three distinct parts. A southern part, dominated by andesite cones, includes the active Ruapehu and Tongariro volcanoes and the probably extinct Pihanga and Tihia-Kakaramea cones. A northern part, which is also dominated by andesite stratovolcanoes, includes the active Whakaari (White Is.) and the recently active 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, and seven older calderas including Mangakino, Kapenga, Whakamaru, Reporoa, Rotorua, Maroa, and the recently-recognised Ohakuri caldera (Spinks et al., 2004; Gravely et al., 2007). The origins and extent of Rotorua caldera are debated (see W.R. Esler, this volume). 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, 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. For instance, ignimbrite erupted from Mangakino about 1 million years ago is found 170 kilometres away in Auckland (up to 9 m thick) and rhyolite ash layers erupted from Whakamaru caldera c. 340,000 years ago are found under the seabed ~1200 km east of Napier (the Rangitawa Tephra). If we think of 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 gigantic caldera volcano centred on the TVZ.



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).

Volcanoes and landscapes

Volcanoes are both feared and revered for devastating eruptions that obliterate landscapes and terrestrial ecosystems, destroy buildings and other constructions, and injure or kill humans. Yet they provide benefits in many ways, including the formation of large areas of special, high-class soils, geothermal energy, lakes and other attractive landscape features favourable for healthy living, recreation and tourism, and materials for building and other purposes. Volcanic lakes form in calderas (e.g. Lake Taupo, Lake Rotoma), explosion craters (e.g. Lake Okaro), or in valleys dammed by lava flows (e.g. Lake Rotoehu) or pyroclastic flow deposits (e.g. Lake Rerewhakaaitu). They are especially attractive to people, and used for water supply and transport. Also appreciated are andesitic or dacitic stratovolcanoes, mountains or ranges known for their grandeur. Solitary or clustered steep-sided rhyolite domes and lava flows, and scoria cones and craters in basaltic volcanic fields (e.g. Auckland Volcanic Field), similarly provide landscape relief. Less dramatic but still impressive are the extensive layered landscapes of the central North Island and Arapuni-Putaruru, Mamaku-Rotorua, and Kaingaroa areas constructed from sheets of welded ignimbrites and characterised by cliffs and gorges, mesas and buttes (large and medium-sized flat-topped table lands), and thumb-shaped inselbergs (small steep-sided rocky mounds sometimes called tors). Draped with tephra-fallout layers and buried soil horizons (sometimes called paleosols), rolling land-surfaces have formed where the sheets become thinner.



Generalised development of land forms in an ignimbrite sheet emplaced over sandstone. In (2) the weakly welded upper part of the sheet has been stripped to leave tor-like features where, it has been suggested, fumarolic activity has caused strengthening by secondary mineral deposition (especially of silica) and alteration. However, simple erosion during glacials of softer materials is more likely and W.R. Esler (this volume) has suggested these landforms relate largely to 'topographic inversion' when former gorges are infilled with thick, welded, erosion-resistant ignimbrite. Many of the "isolated" tor-like features are part of distinct chains, probably defining ancient watercourses (diagram from Healy, 1992.)

What is/are 'tephra'?

'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. It includes all grain sizes ranging from the finest dust to blocks the size of sofas. The first recorded use of 'tephra' in Western literature was by Aristotle c. 350 BC who described an eruption on the island of Volcano (known as Hiera in Greek) in the Lipari (Aeolian) Islands near Sicily.

The first modern useage was by Sigurdur Thorarinsson of Iceland in 1944, who resurrected the term to fit with Greek words lava and magma and to link these with classical volcanology that derives from the Roman name for the island Vulcano, the southernmost of the Lipari Islands. Both 'tephra' and 'tephras' are acceptable plurals. Derivative terms are tephrostratigraphy, the study of sequences of tephra layers and associated deposis and their relative and numerical ages; and tephrochronology, the use of tephras to connect, synchronize, and date sequences from place to place, and thus a powerful, widely-applied age-equivalent dating tool. In recent times, glass-shard (and crystal) concentrations preserved within peats, lake and marine sediments, and ice cores, but not visible in the field as layers, have been recognised and the term 'cryptotephras' (from the Greek *kryptein*, to hide) has been applied to them (Lowe and Hunt, 2001; Lowe, 2008b, 2011).

What are 'ash' and 'lapilli'?

'Ash' is not ash in the sense of a burnt residue. Rather, it consists of pulverised, jagged rock particles including pumice, mineral grains (crystals), and glass shards, all defined as smaller than 2 mm in size. Generally, fine ash is <0.06 mm, medium ash is 0.06–0.5 mm, and coarse ash is 0.5–2 mm (see also White and Houghton, 2006). Grains 2–64 mm in size are called lapilli (lapillus for a single grain), and particles larger than 64 mm are called blocks if they are sharp and angular in shape, or bombs if they are partly rounded or smooth in shape as a result of being erupted through the air whilst still hot and semi-plastic.

Tephra layers blanket the landscape

As well as erupting lavas and other materials, and modifying or building landforms comparatively close to vents, North Island volcanoes have blasted huge volumes of tephra into the air to be blown over northern New Zealand and in some cases far out to sea, more than 1000 km from source. The accumulation of layer-upon-layer of tephra-fallout deposits has helped volcanologists work out the history of volcanism and the distribution of their far reaching airborne products. In many parts of North Island natural cliffs along terraces, river banks or at the coast, together with cuttings made during road construction or quarrying, reveal blanketing layers of tephra fallout from numerous eruptions. A feature of such layers is that they drape the landscape on which they fall, following the contours of hills, terraces and valleys, although they can also be washed into valleys by rain and rivers, slump off hillsides, and be blown by the wind if forest cover has been damaged or is missing, for example during glacial periods. Landscapes draped with tephras, such as in the Taranaki and Waikato regions, tend to have slopes generally smoother than those without tephra mantling.

Mapping tephras 'hand-over-hand'

A law in geology states that the oldest deposits in a layered sequence occur at the bottom and are overlain progressively by younger deposits, the most recent therefore being right at the top (Law of Superposition). This natural arrangement means that quite often only the youngest deposits are seen in a road cutting because the earlier layers are too deeply buried and therefore accessible only by drilling, especially near volcanoes where the deposits are very thick. Tephra layers are mapped by tracing each layer from cutting to cutting across the landscape and by drilling holes, digging pits, or coring lakes or peat bogs to fill any gaps. A tephra deposit from a single eruption may be tens of metres thick near its source but beyond about 100 km it thins quickly to only a few centimetres or millimetres. As well, the shattered rock fragments, crystals, and glass shards making up tephra layers are typically biggest near source but become finer with increasing distance away from it because smaller grains are able to be carried further by the wind. Consequently, mainly ash-size particles (<2 mm) are found in tephra deposits at localities several hundred kilometres or more from the source volcano.

Distribution of tephras in North and South islands

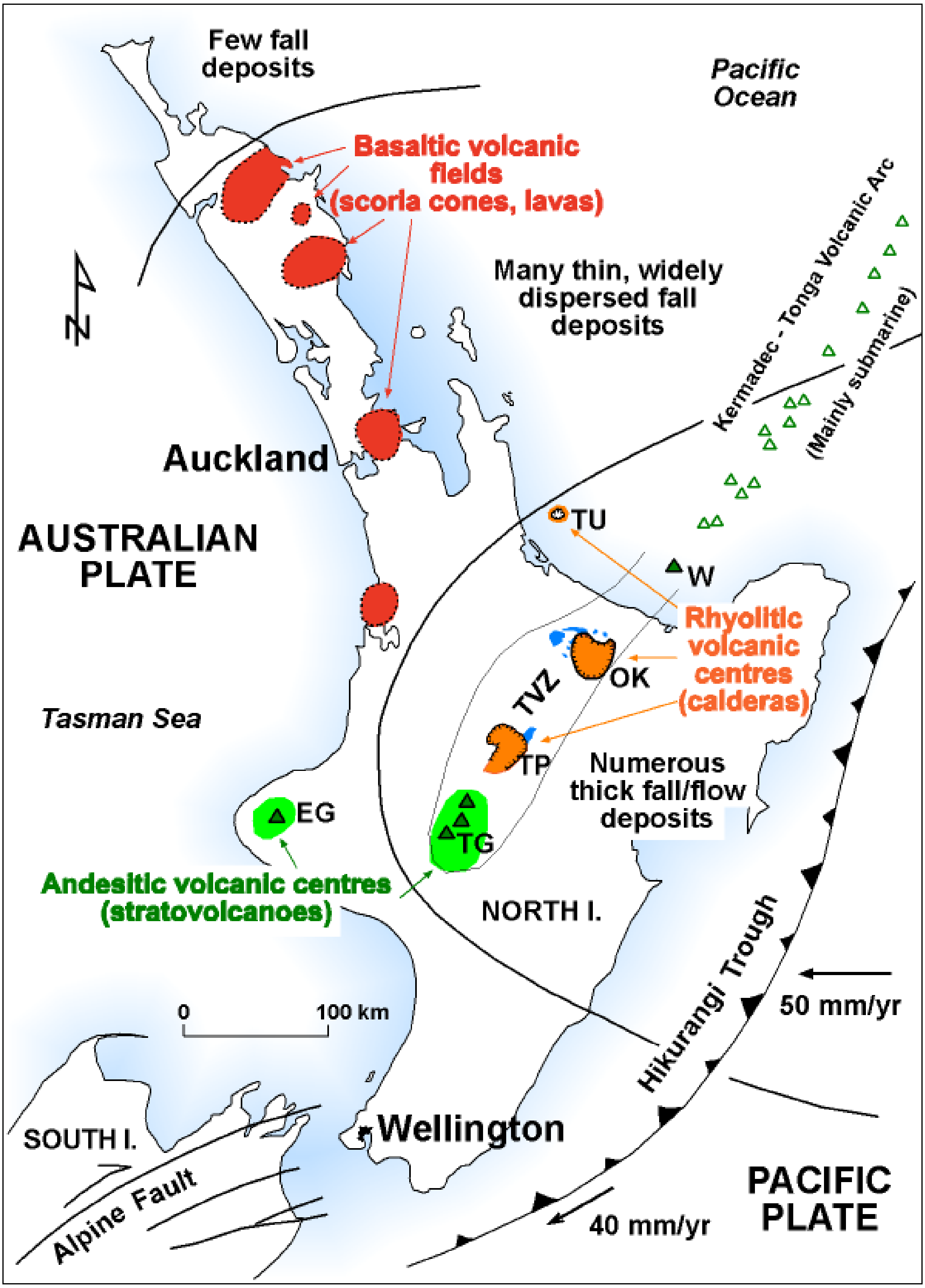
The thickest tephra sequences occur downwind of the TVZ in the Rotorua-Taupo area, Bay of Plenty, East Coast-Poverty Bay, and Hawke's Bay. Moderately thick deposits are found in Wanganui-Taranaki, King Country-Waikato-Coromandel and Auckland regions. Fewer tephra layers occur in other parts of the North 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. 27,100 cal. years ago from Taupo volcano.

Tephra as a unique dating tool (tephrochonology)

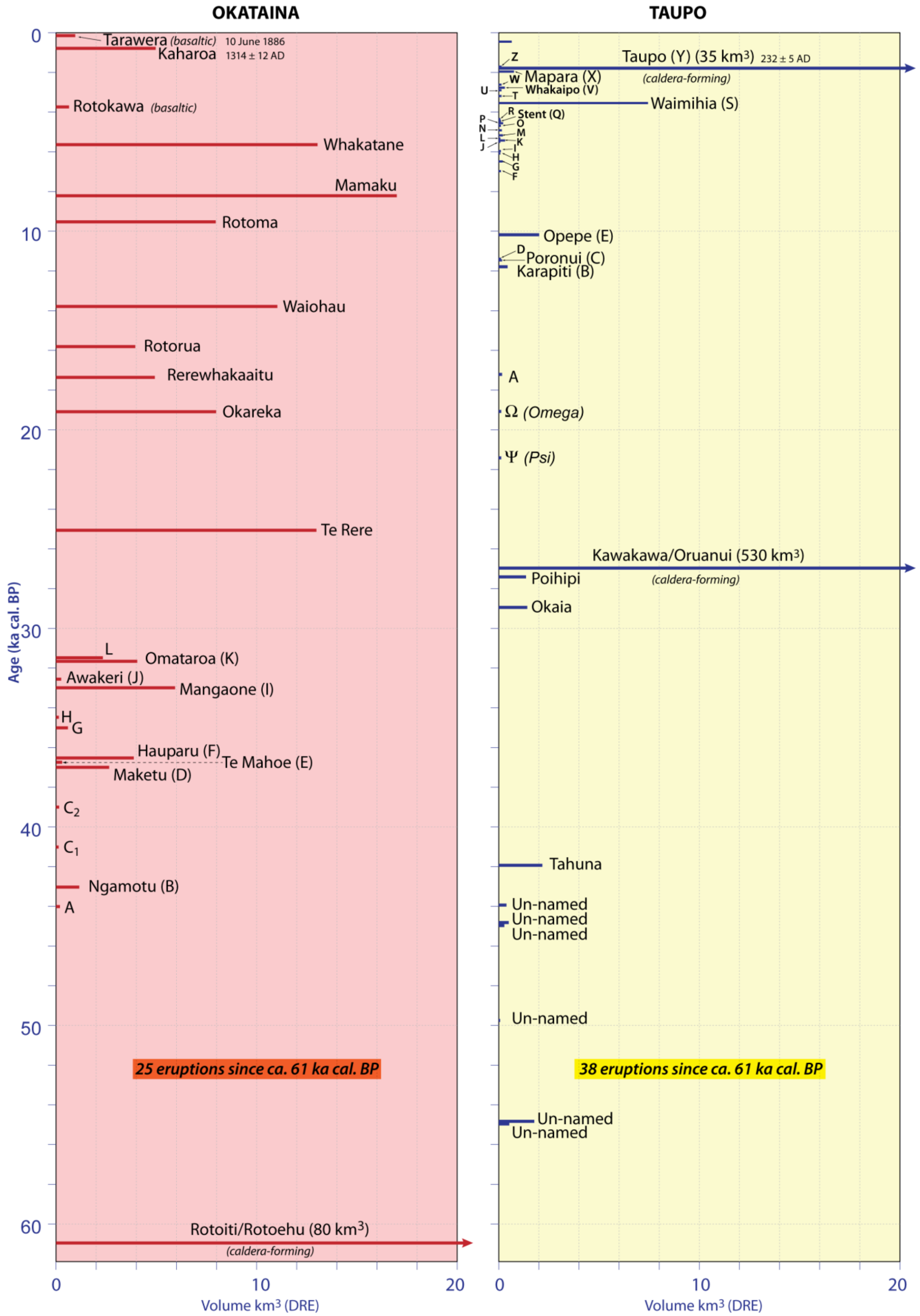
Tephra-fallout layers have two special features: (1) they are erupted over very short time periods, geologically speaking, usually a matter of only hours or days to a few weeks or months (Lowe, 2011); and (2) they can be spread widely over land and sea to form a thin blanket that has effectively the same age *wherever it occurs*. Therefore, once it is identified by mineralogical or geochemical analysis, a tephra layer provides a marker bed for an 'instant' in time (an isochron), that instant being the date of the eruption that produced the layer. In New Zealand and elsewhere many studies have used tephra layers or isochrons as a dating tool, a science called tephrochronology. These studies include examining climatic and environmental change during glaciations, sea-level changes, pre-historic earthquake events, flooding and landsliding history, and archaeology (for example, helping to answer the question of timing of Polynesian settlement in New Zealand; see D.J. Lowe, this volume).

Fingerprinting tephras

How can one tephra layer be distinguished from another? Tephrochronologists use many methods to characterise each layer, both in the landscape and laboratory. In the landscape, colour, thickness and position of the tephra in the sequence are important. The palaeoenvironmental or palaeoecological context in which a tephra occurs may also be useful for correlational purposes. Sometimes the type of pumice is useful in identifying it. For example, pumice from the Taupo eruption (c. 232 AD) is usually cream-coloured and relatively easy to crush between fingernails whereas pumice from the Kaharoa eruption (c. 1314 AD) is white, dense and hard to crush. In the lab, the types of minerals (crystals) present sometimes allow the tephra to be identified and matched to a source volcano. A widespread tephra erupted from Tuhua volcano (Mayor Is.) c. 7000 cal years ago (Tuhua Tephra), for example, contains very unusual minerals including aegirine that allow it to be identified instantly with a microscope, even if just a few grains are present. Chemical analysis of volcanic glass in tephra layers using the electron microprobe is perhaps the best way of fingerprinting them. This is because most tephras, except where strongly weathered and therefore altered to clay, contain abundant glass shards which can be analysed using the electron microprobe or laser ablation-mass spectrometry to provide a chemical signature. Another way of helping identify tephras is by dating them (see Lowe, 2011).



Map showing plate tectonic setting, the main volcanic centres that produced parent materials for many of todays' tephra-derived soils, and the general dispersal of tephra on North Island (from Lowe and Palmer, 2005). EG, Egmont or Taranaki volcano; TG, Tongariro Volcanic Centre (includes Ngauruhoe, Tongariro, and Ruapehu volcanoes); 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.); TVZ, Taupo Volcanic Zone.



Stratigraphic relationships, ages and volumes (as magma or dense-rock equivalent, DRE; multiply by ~3 to obtain approximate bulk volumes) of tephras erupted from Taupo and Okataina volcanic centres since c. 61,000 cal years ago (from Lowe, 2011, after Wilson et al., 2009).

Volcanic topdressing

The frequent but usually localised eruptions from the volcanoes of Tongariro Volcanic Centre and also Taranaki but less often, have added small but markedly beneficial amounts of many nutrients to soils downwind from the volcano. For example, the 1995-1996 eruptions of Mt Ruapehu added 30–1500 kg ha^{-1} of sulphur and small quantities of other useful elements (including cobalt) to large areas of land in central and eastern North Island. By coring lakes and bogs in Waikato, Auckland and Hawke's Bay regions and identifying many thin tephras preserved within them (and, most recently, cryptotephras expressed typically as glass-shard concentrations), it has become clear that such topdressing by andesitic tephras has continued over tens of thousands of years in the past, helping to maintain soil fertility in northern and eastern North Island.

Painting with *kokowai*

Early Maori used yellowish to reddish iron oxides called kokowai, or 'red ochre', derived from seepages and stream beds in volcanic areas as a pigment or paint. The most important site was Kokowai Springs, Mt Taranaki. Kokowai was used for facial or body decorations, paint for buildings and canoes, and as an insect repellent. Its colours could be altered by heating over several steps, becoming bright red after strong heating (to form haematite). Kokowai has been identified as ferrihydrite, a tiny clay mineral with a huge surface area (200-500 m^2/g) and strong 'pigmenting power' (i.e. it permanently stains clothing or other surfaces). Haematite, another iron oxide from red scoriaceous soils, was also an important ceremonial pigmenting agent used mainly for facial decorations on high-ranking chiefs (Lowe et al., 2002).

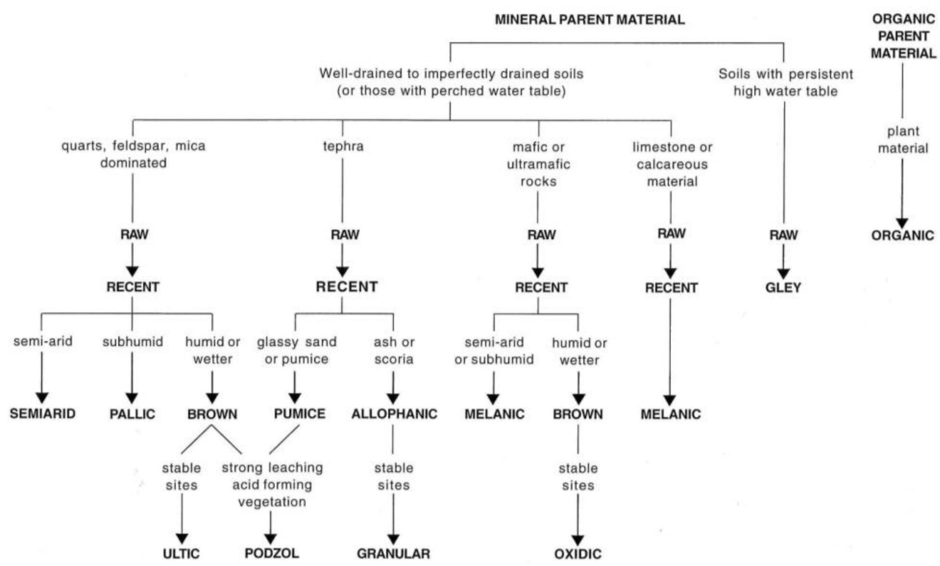
Photo (left) shows ferrihydrite seepage near Waikato River, Hamilton (see Lowe and Percival, 1993). Photo: David Lowe

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. 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 evident today. Post-depositional erosion and reworking of tephra deposits have helped to shape the landscape and, in turn, has created 'genetic' links of varying strengths between the soils and landforms of the region. To a certain extent, climatic and indigenous vegetation gradients have also been imprinted upon the characteristics of the soils and their patterns of distribution (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 (Hewitt, 1998; Lowe and Palmer, 2005; see also table below for relative abundances of New Zealand soils).



Major taxonomic development paths of New Zealand soils (from A.E. Hewitt in Molloy and Christie, 1998, p.235).

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.

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 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.

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. 60,000 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 (400-900 m^2/g) (Lowe and Palmer, 2005; Neall, 2006; McDaniel et al., 2011).

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

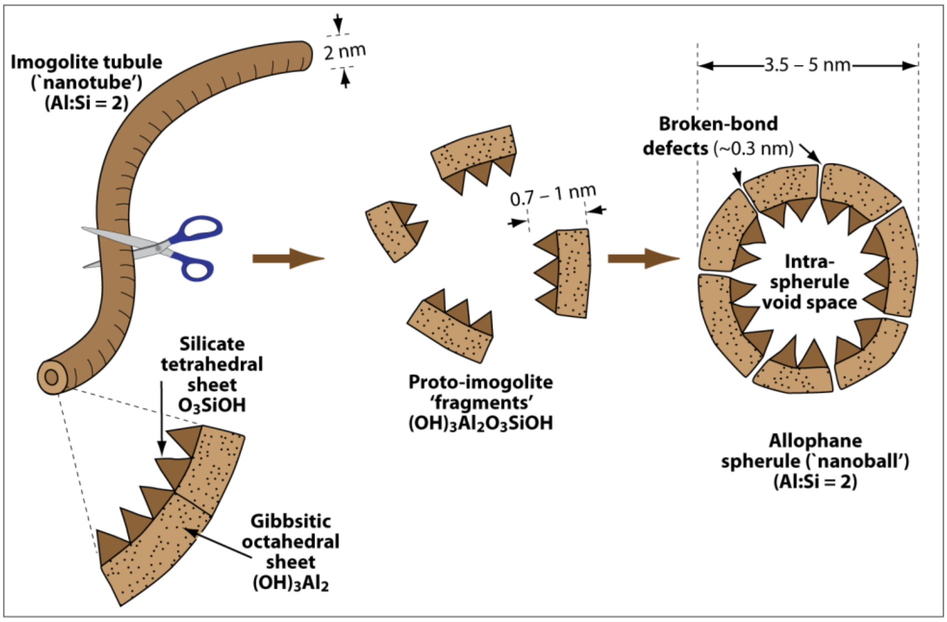
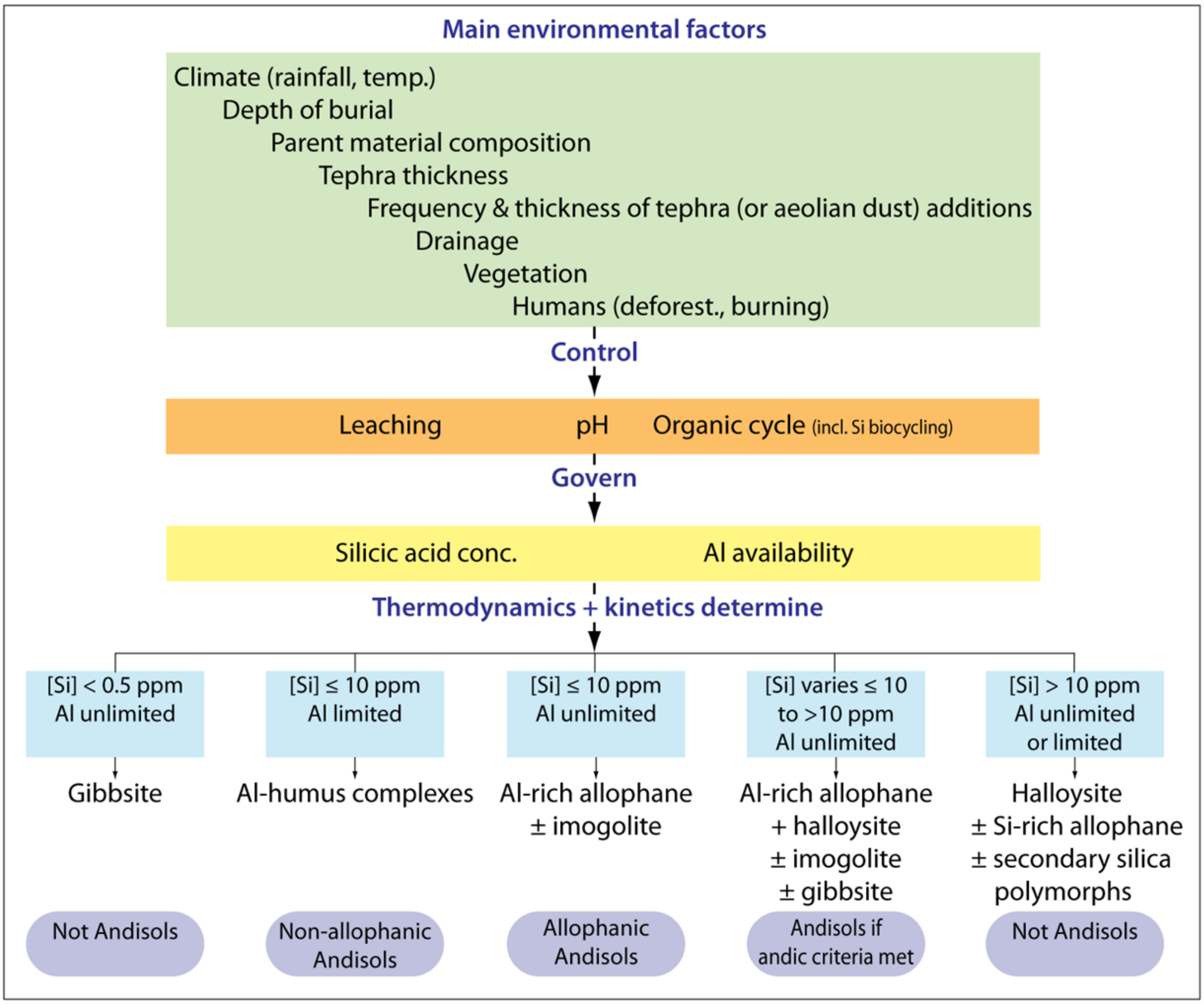


Diagram of imogolite nanotubes and Al-rich allophane nanospheres, which have similar structures at the atomic scale (from McDaniel et al., 2011, after Lowe, 1995).

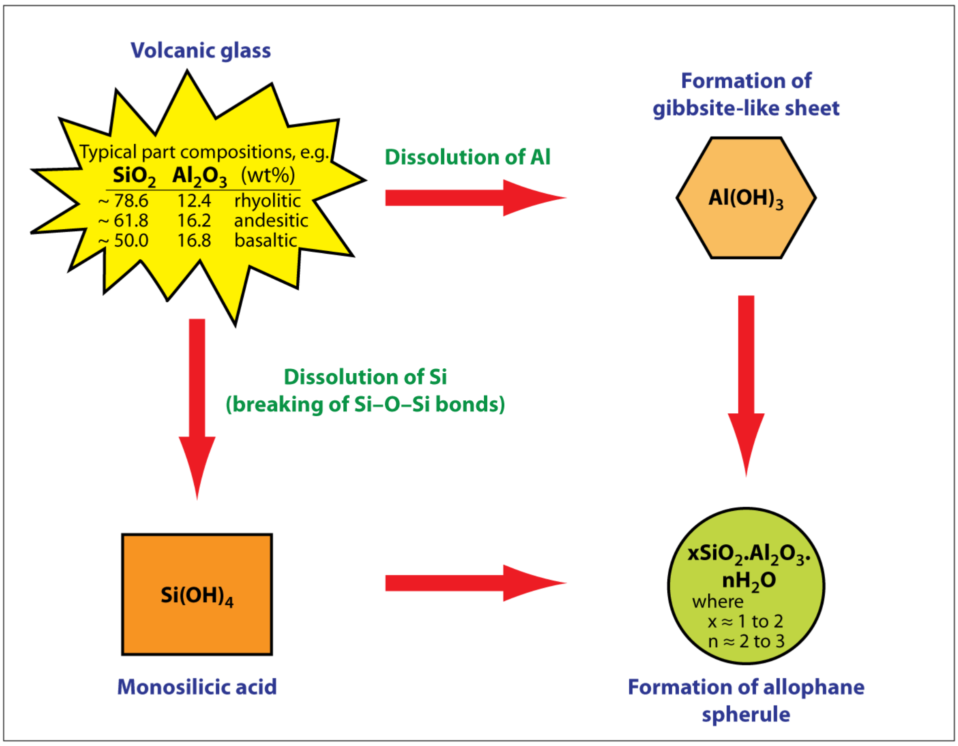
Forming allophane

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 (see figure below). 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 (Lowe, 1986; Parfitt, 2009; McDaniel et al., 2011). 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., 2011).



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 as a result (from Churchman and Lowe, 2011, modified after Lowe, 1986, 1995). ± indicates that the clay mentioned may also be present.

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). 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, 1995; McDaniel et al., 2011).

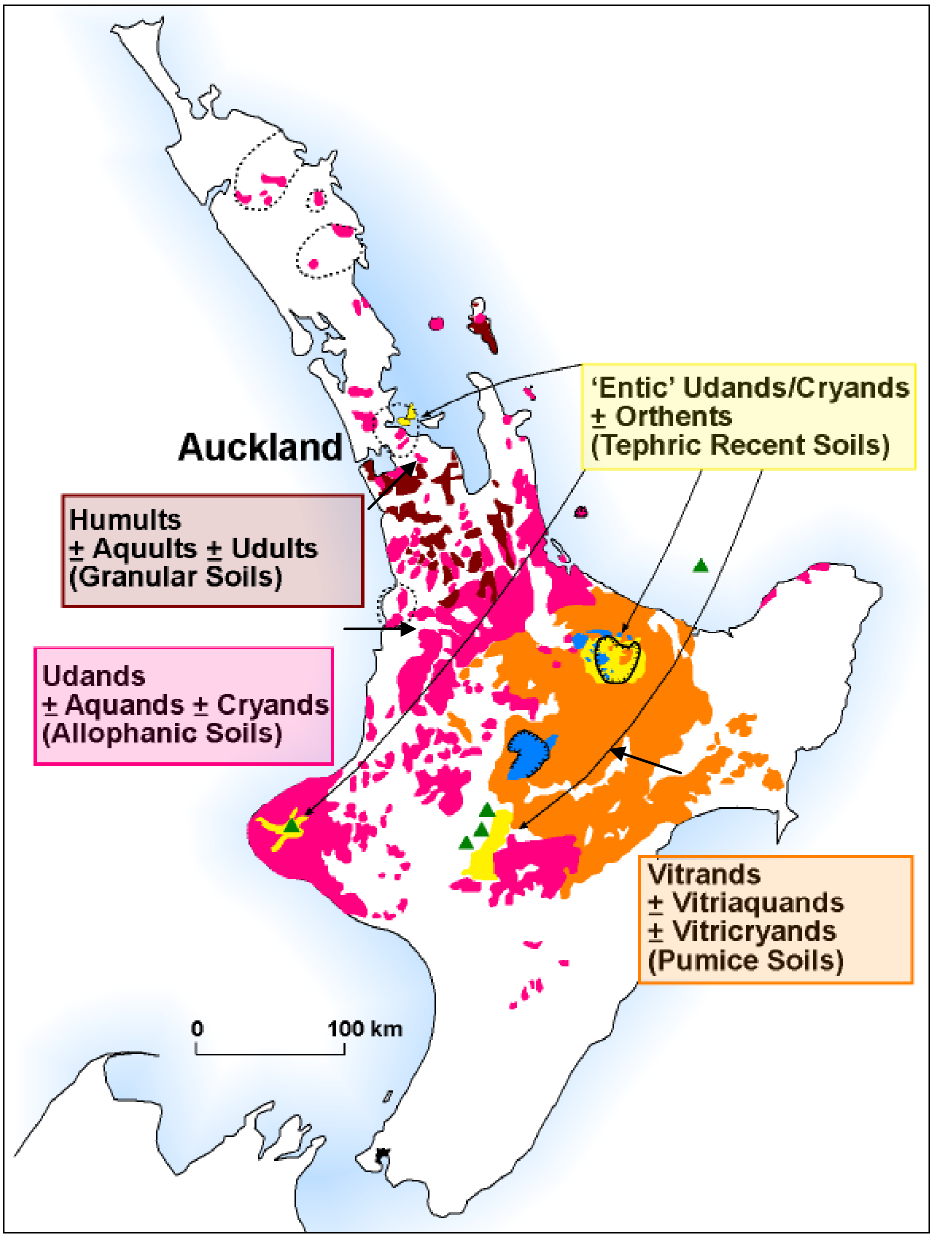


Various volcanic glass compositions and dissolution of Al and Si and their reprecipitation to form allophane spherules or 'nanoballs' (from McDaniel et al., 2011, after Hiradate and Wada, 2005; see also Theng and Yuang, 2008).

Allophanic Soils are supreme in New Zealand for food, fibre, and water production because of their outstanding physical properties. Friable and free draining, even after heavy rain, yet resilient to repeated cropping or stock treading, they have good aeration and very stable soil aggregates, a high organic carbon content, and they can store large amounts of water (Molloy and Christie, 1998). These features and their distribution on smooth, easily manageable tephra-mantled landscapes make them ideal for pasture production and grazing in humid climates. Allophanic Soils are unmatched for almost any land-use: cropping, horticulture, effluent irrigation, forestry, and sports fields. However, contrary to popular opinion, these soils (especially those more siliceous) are not normally 'rich and fertile' – many have low natural fertility, and need regular 'topping up' with various nutrients especially phosphorus (because of P fixation) and potassium to maintain high productivity (Lowe and Palmer, 2005). Sensitivity and thixotropy, properties that cause them to behave in a fluid-like manner when loading pressures are applied, can also pose engineering problems (Neal, 2006).

Granular Soils (mainly Udults, Humults)

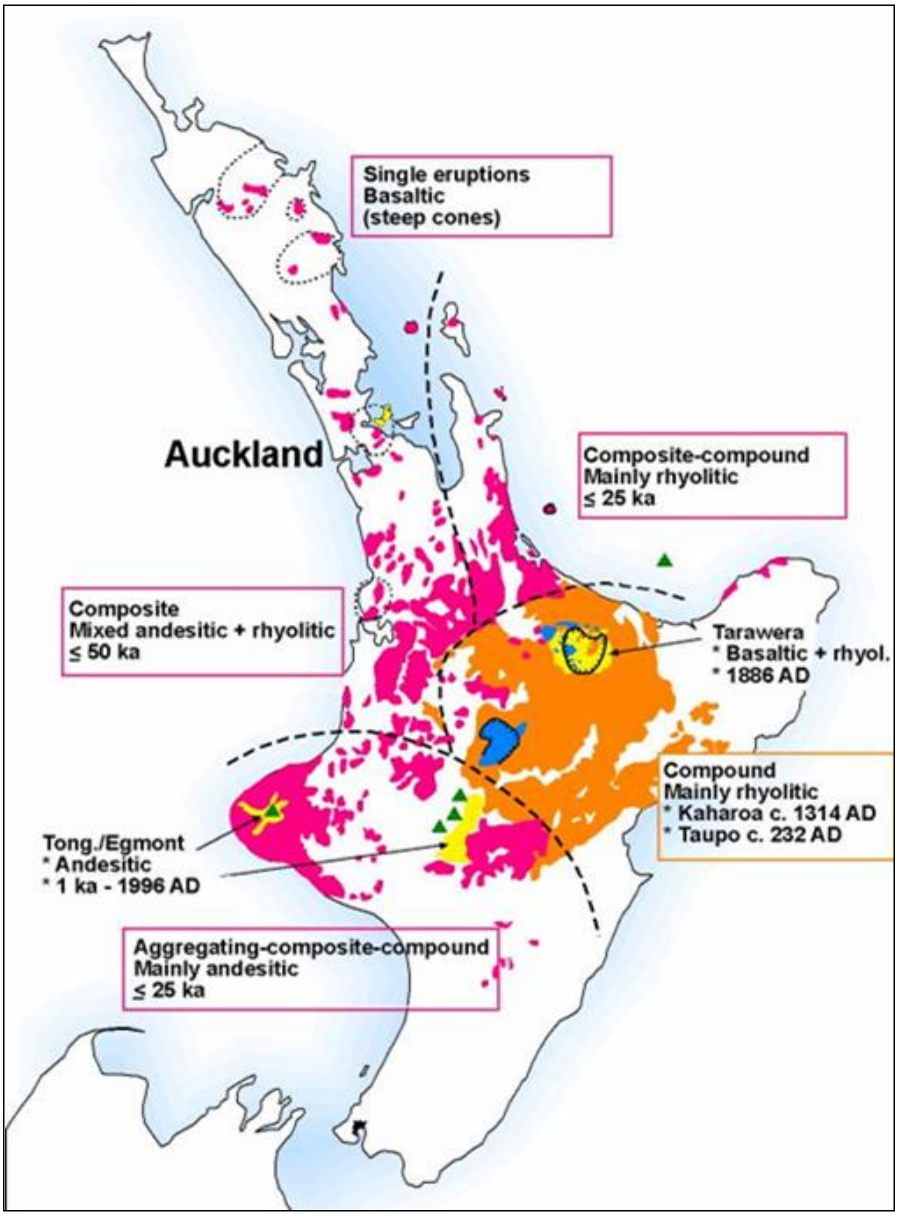
These sticky and clayey but well-structured soils have formed on older, strongly weathered tephra layers erupted from central TVZ between about 100,000 and 350,000 years ago (Lowe et al., 2001). They occur in the northern Waikato and South Auckland regions – for example in the Pukekohe-Bombay Hills area – where the younger mantling tephra layers so predominant in central North Island have become sufficiently thin to allow these older deposits to emerge at the land's surface. The clay mineral dominant in these soils (halloysite) has proven suitable for cricket pitches in the northern North Island partly because it dries out and shrinks relatively quickly in humid climates. An example of these soils will be seen at Stop 1 on Day 1 of the tour and along road cuts in the Hamilton Basin.



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).

Upbuilding pedogenesis

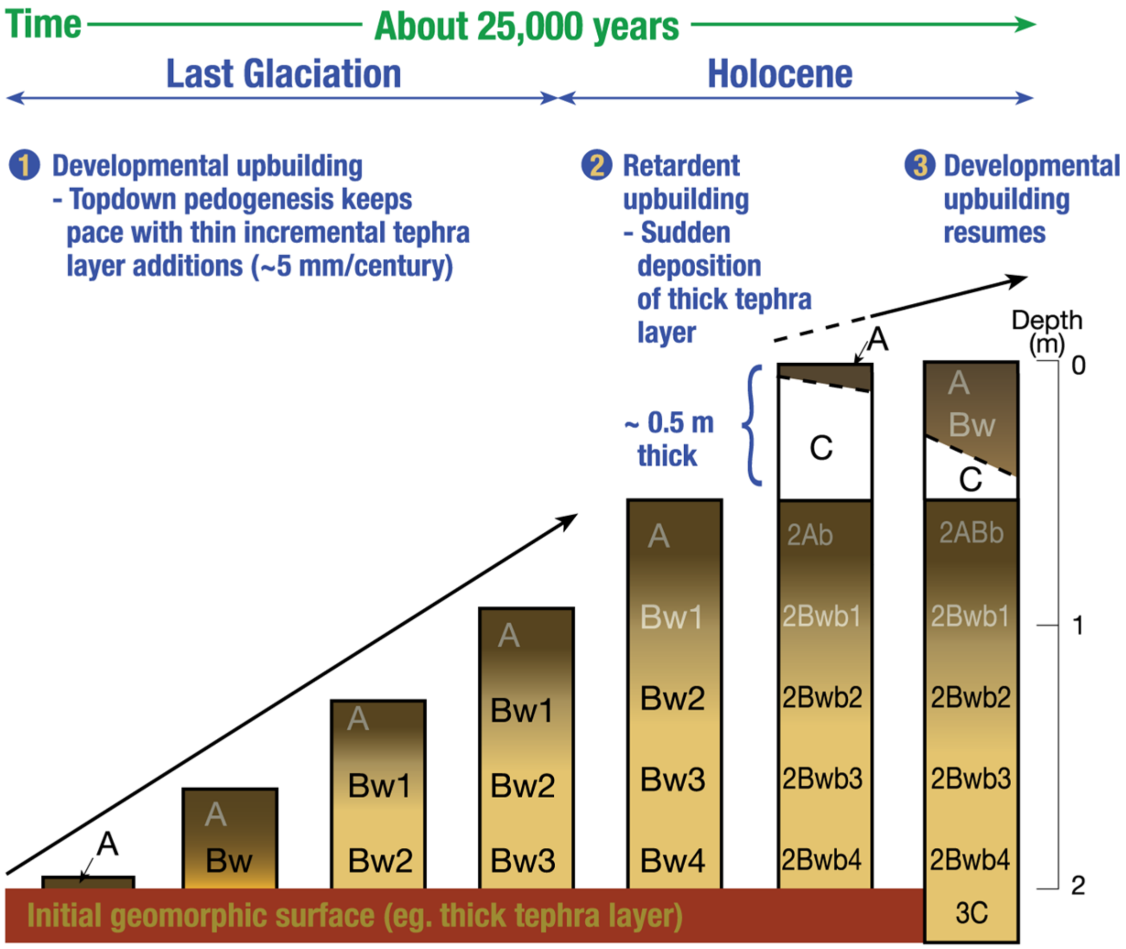
A distinctive feature of many volcanic ash-derived soils is the 'multisequel' or layered nature of their profiles which attests to the up-building of the landscape via the deposition of tephras from numerous eruptions. During periods of quiescence between major eruptions, soil formation takes place, transforming the characteristics of the unmodified tephra via *topdown pedogenesis* (Almond and Tonkin, 1999). Soil processes alter the underlying material in a downward-moving front, forming generally well-developed subsoil horizons – i.e., classical pedogenesis. However, where tephras are added to the land surface, *upbuilding pedogenesis* takes place and the rate of upbuilding determines the rate and impact of pedogenesis. Two scenarios can be considered: (1) tephra accumulation is incremental or relatively slow, leading to 'developmental upbuilding'; (2) tephra accumulation is rapid, e.g. burial by a thick deposit (which may become a stratigraphic marker bed), leading to 'retardant upbuilding' (Lowe and Tonkin, 2010; McDaniel et al., 2011).



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, 2009). Note: 'Aggregating' should read 'Aggrading'.

Scenario 1 Where successive tephra deposits are thin and accumulate relatively frequently (e.g. at distal locations), the material deposited from each eruption will become incorporated into the existing soil via soil mixing and other process. When tephras (and tephric loess) are accumulating incrementally, topdown soil formation does not stop, but its effects are lessened because any one position in the tephra deposits is not exposed to soil processes for long before it becomes buried too deeply for these processes to be effective as the land surface gently rises. Nonetheless, this upbuilding history leaves the tephra deposit with a soil fabric inherited from when the tephra was part of the surface A horizon or subsurface Bw horizon. The maximum development of subsurface soil horizons occurs when soil formation has a greater impact during phases of topdown pedogenesis. In developmental upbuilding, subsurface horizons are typically weakly expressed.

Scenario 2 Where a tephra deposited on the land surface surface is of sufficient thickness, or more rapid, to quickly bury the antecedent soil below the range of soil forming processes (i.e., it becomes isolated), the buried soil becomes part of the underlying regolith and is recognised as a buried paleosol (a soil of a landscape or environment of the past) or more typically a buried soil horizon. A new soil will begin forming at the new land surface in the freshly deposited material. Thus, retardant upbuilding recognises that the development of the newly-buried soil has been stopped or retarded, and the pedogenic 'clock' reset to zero for soil formation to start on the new land surface.



Model of upbuilding pedogenesis and evolving horizonation over ~25,000 years in the Waikato region, North Island, with contrasting developmental and retardant upbuilding episodes (from Lowe and Tonkin, 2010)

The terms 'developmental upbuilding' and 'retardant upbuilding' were used by Johnson and Watson-Stegner (1987) and Johnson et al. (1990) as part of their dynamic-rate model whereby soils evolve by 'ebb and flow' through time (Schaetzl and Anderson, 2005). A complication is that loess (wind-blown sediment) was widely generated in the central North Island during glacial periods. Unstratified tephric loess deposits of about three metres thickness (e.g. on Mamaku Plateau – see Stop 5, Day 4) were derived largely from thick rhyolitic tephra-fall and ignimbrite deposits, which eroded during glacial periods to form valley fill and fan deposits. These were supplemented probably by glassy dust blown directly from primary tephra fall deposits. Tephric loess deposition slowed and petered out generally at around the time of deposition of Rerewhakaitu tephra (c. 17,600 cal years ago) after which climate began ameliorating and full forest cover returned (Vucetich and Pullar, 1969; Newnham et al., 2003). Today tephric loess is found as subsurface layers in tephra-soil sequences, being buried by tephra deposition during the Holocene. The fastest rates of loess accretion in New Zealand were during the cold glacial periods and especially during marine oxygen isotope stage 2, when rivers aggraded very rapidly (Lowe et al., 2008c). The fastest rates were 0.15–0.23 millimetres per year (15-23 mm/century) where deposition was enhanced by turbulence and the slowest was less than 0.01 mm per year (<1 mm/century). Accretion rates for tephric loess in the Waikato region, ~0.03–0.08 millimetres per year (3-8 mm/century), are similar to those for loess in south Westland, 0.04–0.12 mm per year (4-12 mm/century). In an 'upbuilding' phase, soil formation thus occurs simultaneously with slow loess accumulation, forming a 'soil-sediment' (Lowe et al., 2008c).

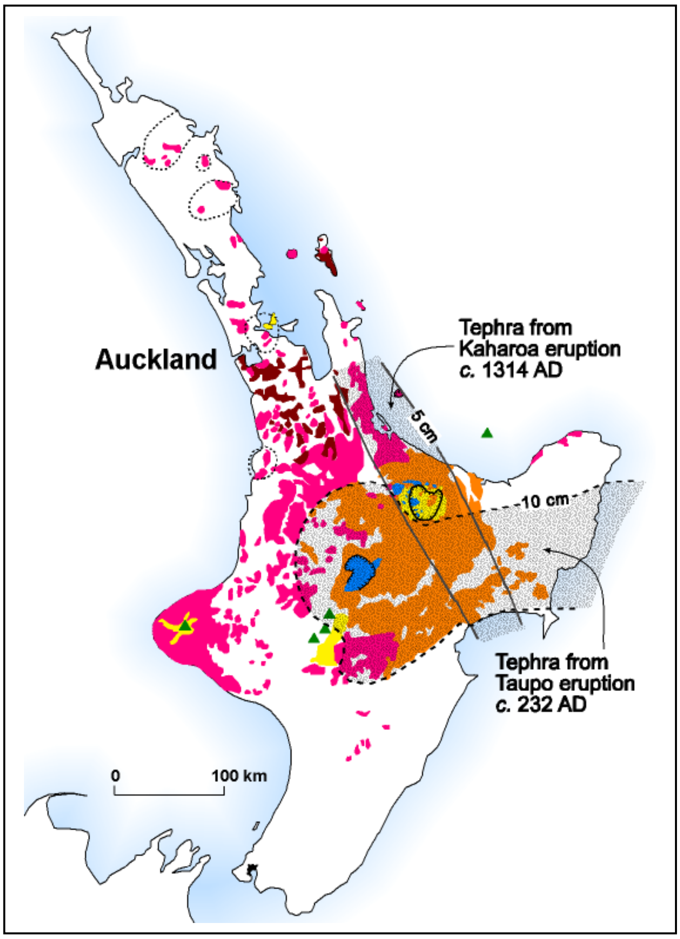
Ages and rates of soil formation can be assessed for the tephra-derived soils through tephrochronology, the use of tephra layers to link and date sequences (Lowe and Tonkin, 2010). Where Allophanic or Pumice soils (Andisols) comprise upbuilding sequences of tephras and soil horizons, the maximum age of the soil profile constituents depends on the depth at which the profile 'base' is drawn. In considering the uppermost 1 to 2 m of Andisols, some generalizations about their composite ages can be made. In situations where just a single eruption event has taken place to produce a parent deposit, then Andisols developed in that material have the same age as the eruption. In New Zealand, there is a wide range of ages on Andisols depending on location (see figure above). Most of the Pumice Soils (Vitrands) are between ~700 and ~1800 cal years old; extensive Allophanic Soils (Udands) date back ~20,000–25,000 cal years and some are as old as ~60,000 years.

Tephra-derived soils and land use

Although many of the tephra-derived soils are of supreme quality, some are not. In the early part of the 20th century – at a time when large tracks of land were being prepared for pastoral agriculture – many of the soils on the central plateau were found to be deficient in trace elements crucial for animal health (i.e. cobalt, copper, and selenium), causing the so-called "bush sickness" problem. Early surveys of soils and tephra deposits ("soil-forming ash-showers") showed a link between Kaharoa and Taupo deposits and the occurrence of bush sickness, but it was not recorded on Tarawera eruptives. The worst bush-sick area was on Kaharoa Tephra and the soils were regarded (even into the 1950s) as 'despised soils' (Vucetich and Wells, 1978). Note that some other areas of New Zealand also had bush sickness, typically under high rainfall, but that was a deficiency acquired from leaching rather than inherent. Ironically, the cobalt deficiency led to the development of the large pine forest plantations of central North Island. These forests were to become the foundation of New Zealand's exotic timber industry (Molloy and Christie, 1998). The land-use debate has been recently renewed with substantial areas of forest land being converted to dairy pastures and concerns being raised regarding the impacts of the land use change on the soils and water quality (see Day 4).

Soil classification

Soil classifications throughout this guide are given in terms of both the *New Zealand Soil Classification* (NZSC) by Hewitt (1998) and Clayden and Webb (1994), and *Soil Taxonomy* by Soil Survey Staff (1999, 2010).



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). Cartoon from Nick Kim, Environment Waikato.

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