Supplementary notes

2024 MOANA OCEANIA
SOIL JUDGING COMPETITION

28 NOVEMBER – 1 DECEMBER 2024
ROTORUA, New Zealand

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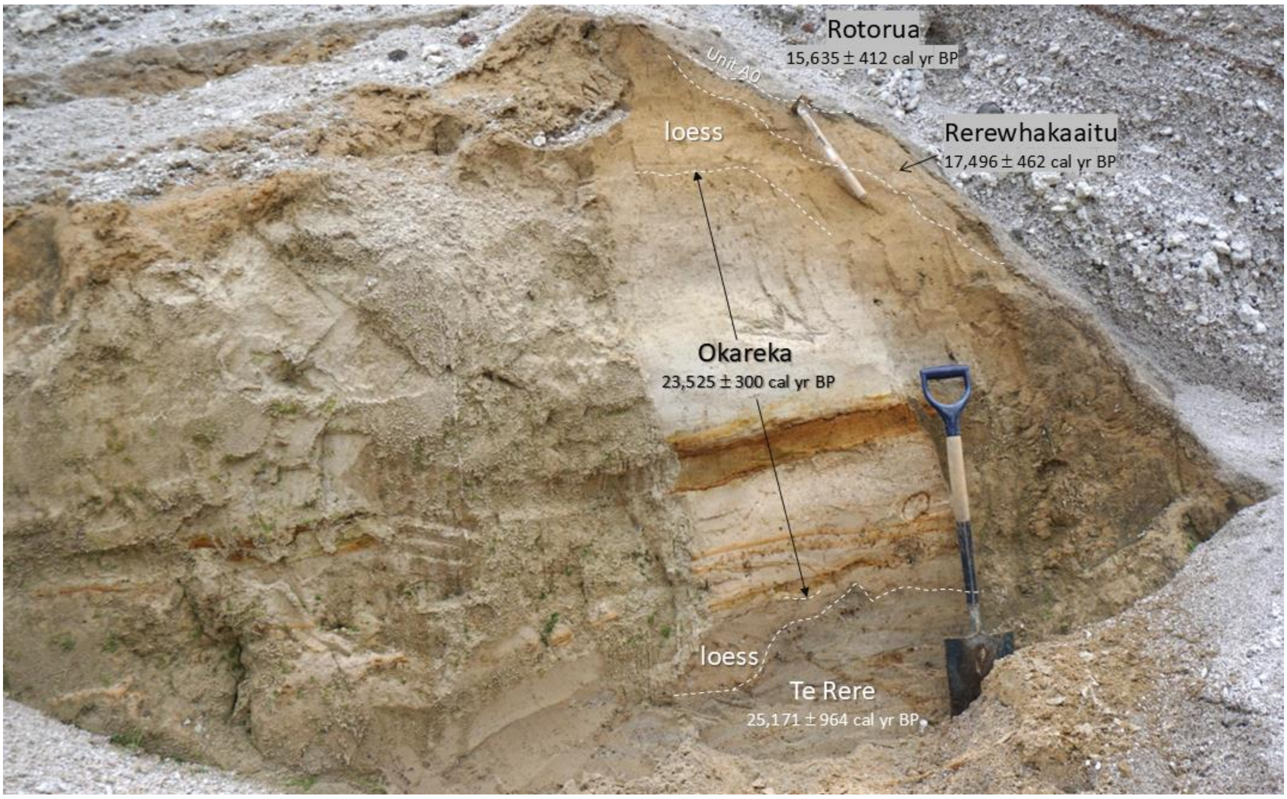


Frontispiece: explaining the imagery used for the "SOILS ROTORUA 2024" conference

Section on Okareka Loop Road near Rotorua showing stratigraphy and ages of tephra deposits, (minor) loess, and soils/paleosols dating back to c. 25,200 years BP (from Lowe and Ilanko, 2023; partly after Nairn, 1992). The photo shows the distinctive lapilli- and block-dominated Rotorua tephra-fall deposits mantling an antecedent small hill. In lower image, note thin iron pans and redox segregations (Fe-Mn oxides), including blue-black pyrolusite, and redox depletions (low chroma colours, i.e. pale grey–white colours), as secondary reductimorphic/redoximorphic features (Hewitt et al., 2021). Photos: D.J. Lowe

Figure S1 Map of North Island showing the locations and ages of most of the main tephra-producing calderas, volcanic centres, fields, or stratovolcanoes (cones) active during the Quaternary or shortly before (from Hopkins et al., 2021). The calderas in central Taupō Volcanic Zone (TVZ) are overwhelmingly rhyolitic with Mangakino, Whakamaru, Taupō, and probably Tauranga being supervolcanoes (Prentice et al., 2022); Taranaki Maunga and Tongariro Volcanic Centre are andesitic; Tuhua (Mayor Island) is peralkaline rhyolite; and the locally distributed tephras from Auckland Volcanic Field are basaltic. The plate tectonic setting (Leonard et al., 2010) and various other features are also shown, including marine core locations in which tephra-fall deposits (including some cryptotephras) have been recorded. BF, buried forest (see Figure S5); H, Haroharo Volcanic Complex; T, Tarawera Volcanic Complex.

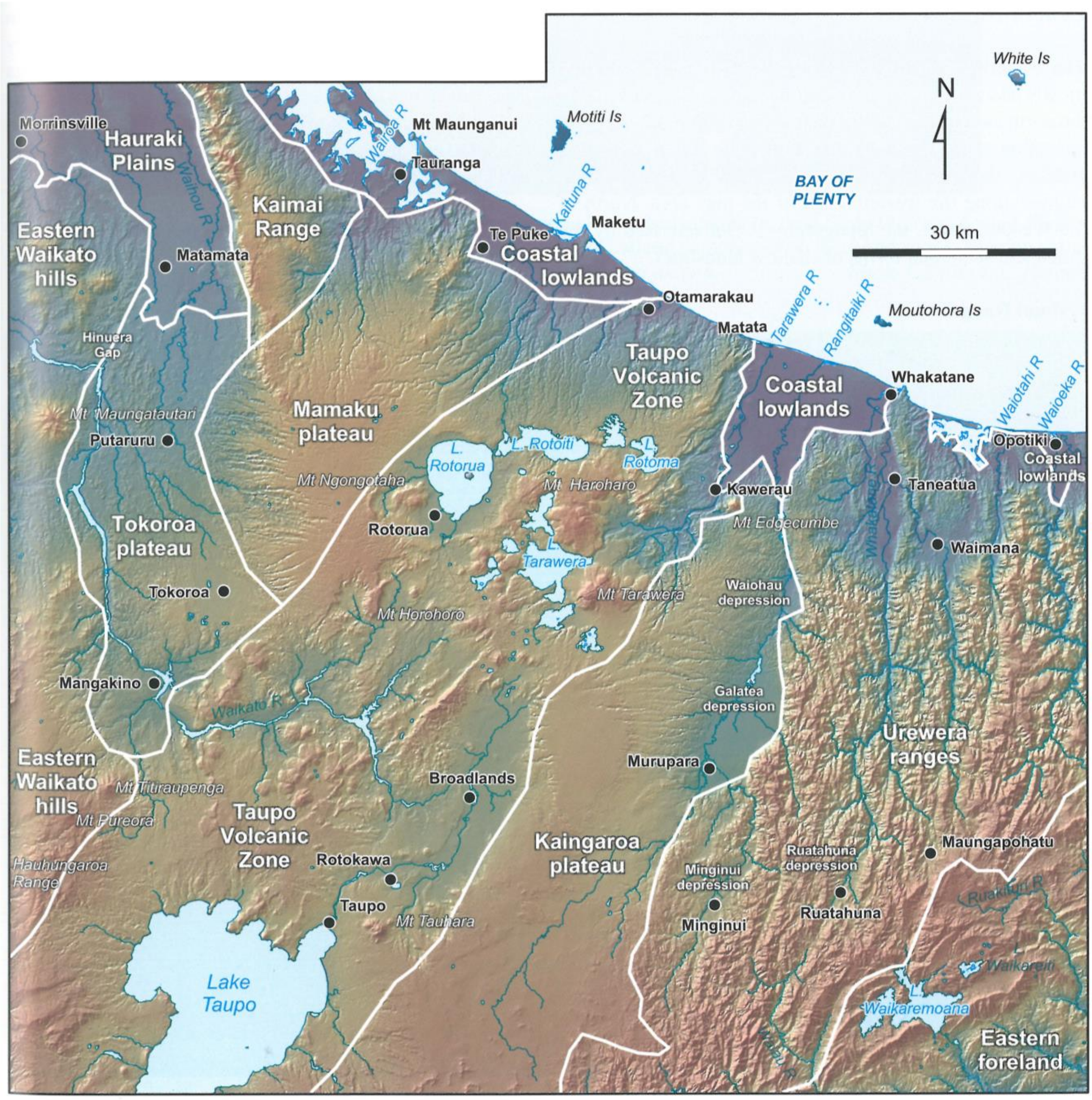


Figure S2 Topographic relief model illustrating the broad physiographic regions in the Bay of Plenty-Rotorua-Taupō region. The 'geomorphic' Taupō Volcanic Zone (TVZ) comprises an area of largely volcanic hills and lakes and covers a similar area (but not exactly equivalent) to the 'volcanologic' TVZ (defined by vent locations only) (from Leonard et al., 2010). The sections and pits for the soil judging exercises are located on the Mamaku Plateau and in the TVZ to the southeast of Rotorua and near Mt Tarawera.

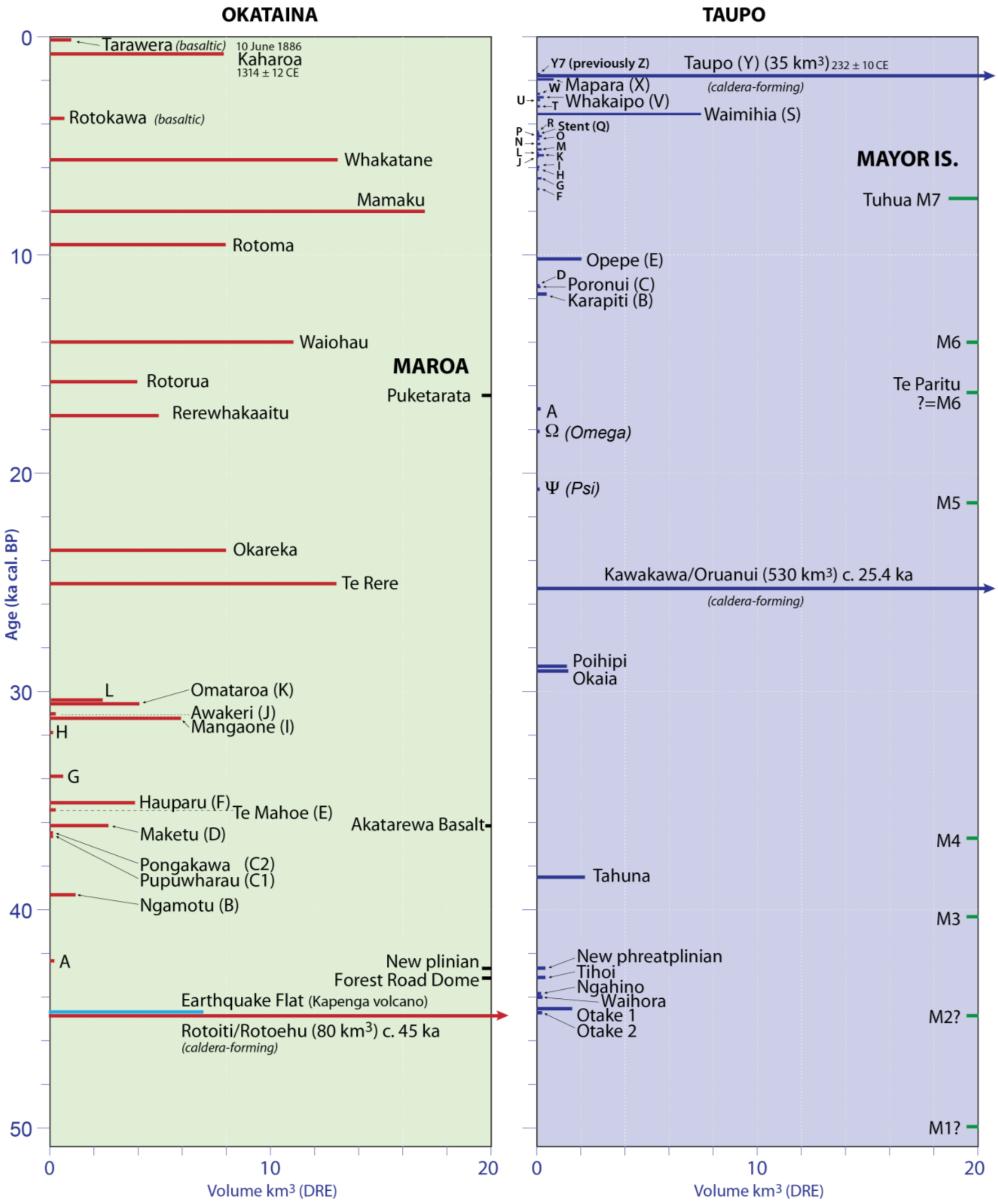
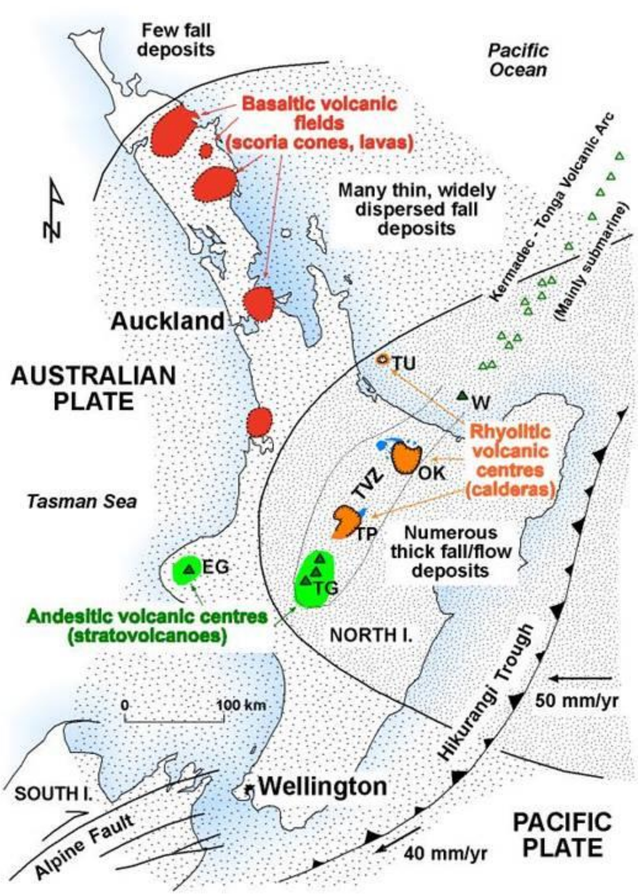


Figure S3. Stratigraphy, ages, and volumes (dense-rock equivalent, DRE) of eruptives derived from three rhyolitic centres in central Taupo Volcanic Zone (Okataina, Taupō, Maroa), and from Mayor Island (Tuhua), since ~50 cal ka. One eruptive (Earthquake Flat) from Kapenga Volcanic Centre (see Figure S1) is additionally depicted within the early eruptives of the Okataina sequence (from Hopkins et al., 2021; some ages from Danišík et al., 2012, 2020).

Table S1 Summary of main rhyolitic tephras deposited in the Rotorua-Tarawera region during the last c. 25,400 cal years and their generalised physical properties.

Name* (*source volcano*)	**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. See maps below.
Kaharoa Tephra (Ka) (*Tarawera*)	1314 ± 12 CE/AD (636 ± 12 cal yr BP)	Fine to coarse white to grey ash, with occasional dense (hard, hard-to-crush) pumice, rhyolite, obsidian and basalt lapilli. Contains abundant biotite. Distinctive black A horizon (contains charcoal from Polynesian and/or early European burning). Provides datum for early Polynesian settlement, northern New Zealand.
Taupo Tephra (also known as Unit Y) (Tp) (*Taupo*)	232 ± 10 CE/AD (1718 ± 10 cal yr BP)	Creamy coloured coarse ash with plentiful shower-bedded pumice lapilli (crushable). Non-welded ignimbrite unit always associated with charcoal fragments.
Whakatane Tephra (Wk) (*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)[§].
Rotorua Tephra (Rr) (*Okareka embayment*)	15,635 ± 412 cal yr BP	Shower-bedded pumiceous yellowish lapilli or blocks (gravel/cobbles). Occasional rhyolitic lithics. Deposited at start of late-glacial mild episode (NZce-4).
Rerewhakaaitu Tephra (Rk) (*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 of region occurred soon after deposition.
Okareka Tephra (Ok) (*Tarawera*)	23,535 ± 300 cal yr BP	Yellowish brown ash contains abundant biotite. Typically encased in yellowish to olive brown tephric loess.
Te Rere Tephra (Te) (*Okareka embayment*)	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), always fine grained and somewhat 'sticky' in situ. Deposited just before interstadial D (NZce-9). Product of a supereruption (Barker et al., 2021).

*Terminology after Froggatt and Lowe (1990) and Wilson (1993, 2001). See Figure S1 for source volcanoes. Bayesian-modelled ages from Lowe et al. (2013), Vandergoes et al. (2013), and Peti et al. (2021). The region has additionally received distal tephras from Taupō and Tuhua (Mayor Island) volcanic centres and has been 'dusted' regularly with andesitic tephra fallout from numerous eruptions at Tongariro Volcanic Centre and Egmont Volcano (Taranaki Maunga), most recently 1995-96 Ruapehu eruptions. Ages are given in calibrated or calendar (cal) years (95% probability range) before present (BP), 'present' being 1950 in the ^{14}C timescale. Calendar dates for the Kaharoa and Taupō eruptions have been determined by ^{14}C wiggle-match dating using dendrochronology (Hogg et al. 2003, 2012, 2019). An *ag*e is reported in years BP (e.g. 14,000 cal yr BP) whereas a *date* is a calendrical date (e.g. 1314 CE/AD). *Note*: ka = x1000 years BP (e.g. 14 cal ka = 14,000 cal yr ago). [§]NZ climate event stratigraphy of Barrell et al. (2013).



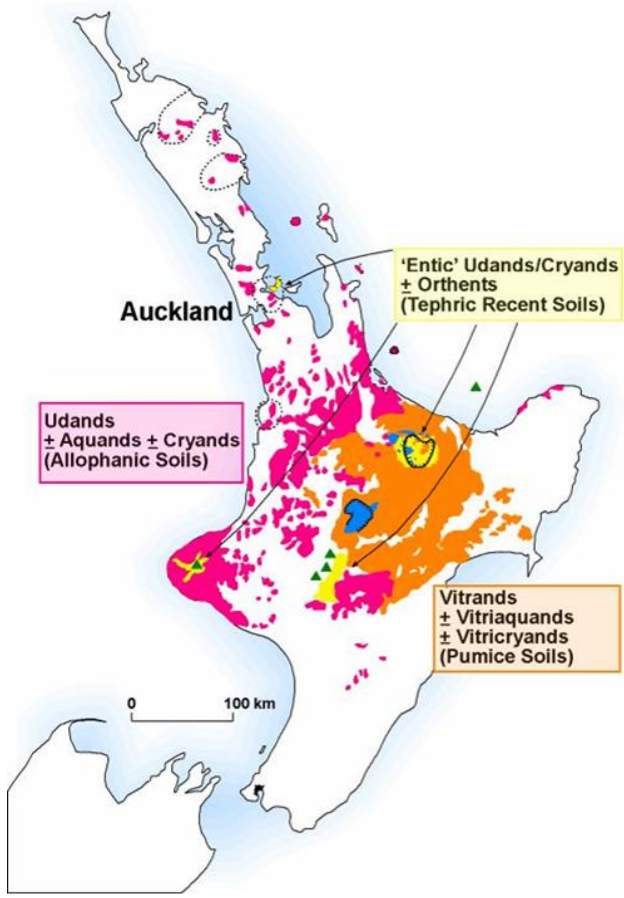


Figure S4 (**Left**) Map showing plate tectonic setting, the main volcanic centres that produced parent materials for many tephra-derived soils, and the general dispersal of tephra on North Island (from Lowe and Palmer, 2005). (**Right**) General distribution of three main groupings of tephra-derived soils in North Island (collectively termed Andisols in "Soil Taxonomy": Soil Survey Staff, 1993, 2022), namely Tephric Recent Soils (a group in NZSC), Pumice Soils (order in NZSC), and Allophanic Soils (order in NZSC) (Hewitt, 2010) (after Rijkse and Hewitt, 1995; see also Hewitt et al., 2021).

EG, Egmont/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. Other eruptive centres in TVZ include Mangakino (~2.0−0.9Ma), Whakamaru (0.35−0.32 Ma), Kapenga (0.9 Ma−50 ka), Rotorua (0.32−0.22 Ma, Maroa (0.32 Ma−13 ka), and Reporoa (0.23−0.21 Ma) (see Wilson et al., 2009; Pittari et al., 2021). Ma = millions of years ago; ka = thousands of years ago.

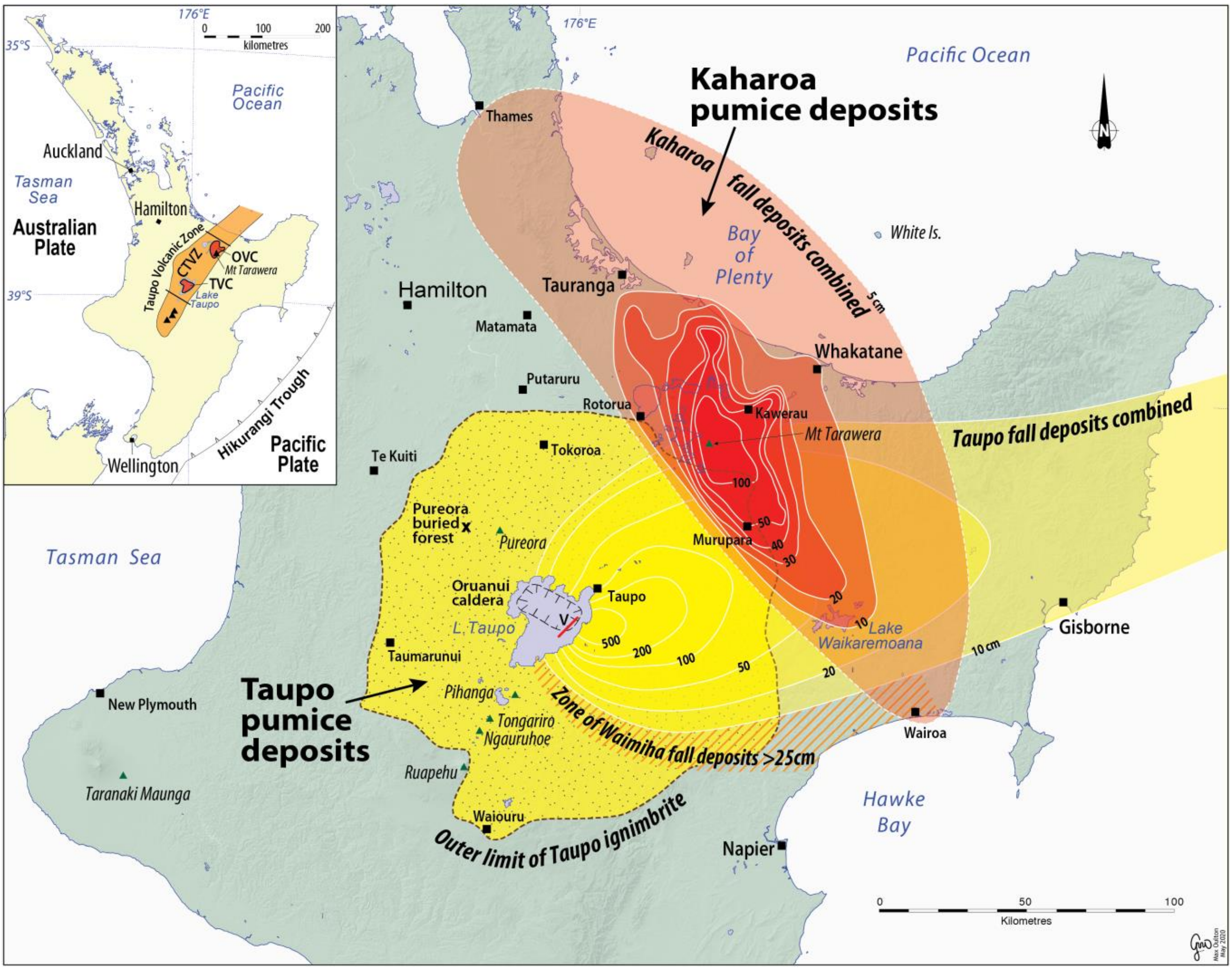


Figure S5 Distribution of the products of the Taupo (AD/CE 232 ± 10) and Kaharoa (AD/CE 1314 ± 12) eruptions in central North Island on which almost all of the Pumice Soils are formed (Hewitt et al., 2021). The Taupo eruptives (yellow) include the area covered by (i) ashfall to a depth of 10 cm or more shown with thickness contours (isopachs) in centimetres (directed strongly eastward), and (ii) the non-welded Taupo ignimbrite that was emplaced radially around Lake Taupo by an extremely energetic pyroclastic flow, the deposit covering all peaks except Ruapehu (Lowe and Pittari, 2021). Vents for the eruption occurred on a fissure along the eastern side of the lake (marked with the symbol V). The Kaharoa ash-fall eruptives (red) are depicted by isopachs (in cm) with only a small area comprising pyroclastic flow deposits within about 5 km of source Mt Tarawera (not shown; see Todde et al., 2024). Both Taupo and Kaharoa tephras lack cobalt, and hence soils formed from the are deficient in this trace element, which led to what is now recognised as a vitamin B12 deficiency, known as 'bush sickness' (see chapter on Pumice Soils in Hewitt et al., 2021; Lowe et al., 2023). The Kaharoa tephra provides a datum for earliest Polynesian settlement in North Island (approximately AD/CE 1250–1275: Bunbury et al., 2022), some decades before the Kaharoa eruption (see Newnham et al., 1998; Lowe et al., 2002; Hogg et al., 2003; Lowe and Newnham, 2004; Wilmshurst et al., 2008; Lowe and Pittari, 2014; Alloway et al., 2025). Inset map shows the plate tectonic setting of North Island. CTVZ = central Taupo Volcanic Zone, OVC = Okataina Volcanic Centre, and TVC = Taupo Volcanic Centre. From Hewitt et al. (2021) (redrawn after Wilson and Walker, 1985, Walker, 1981, and Sahetapy-Engel et al., 2014).

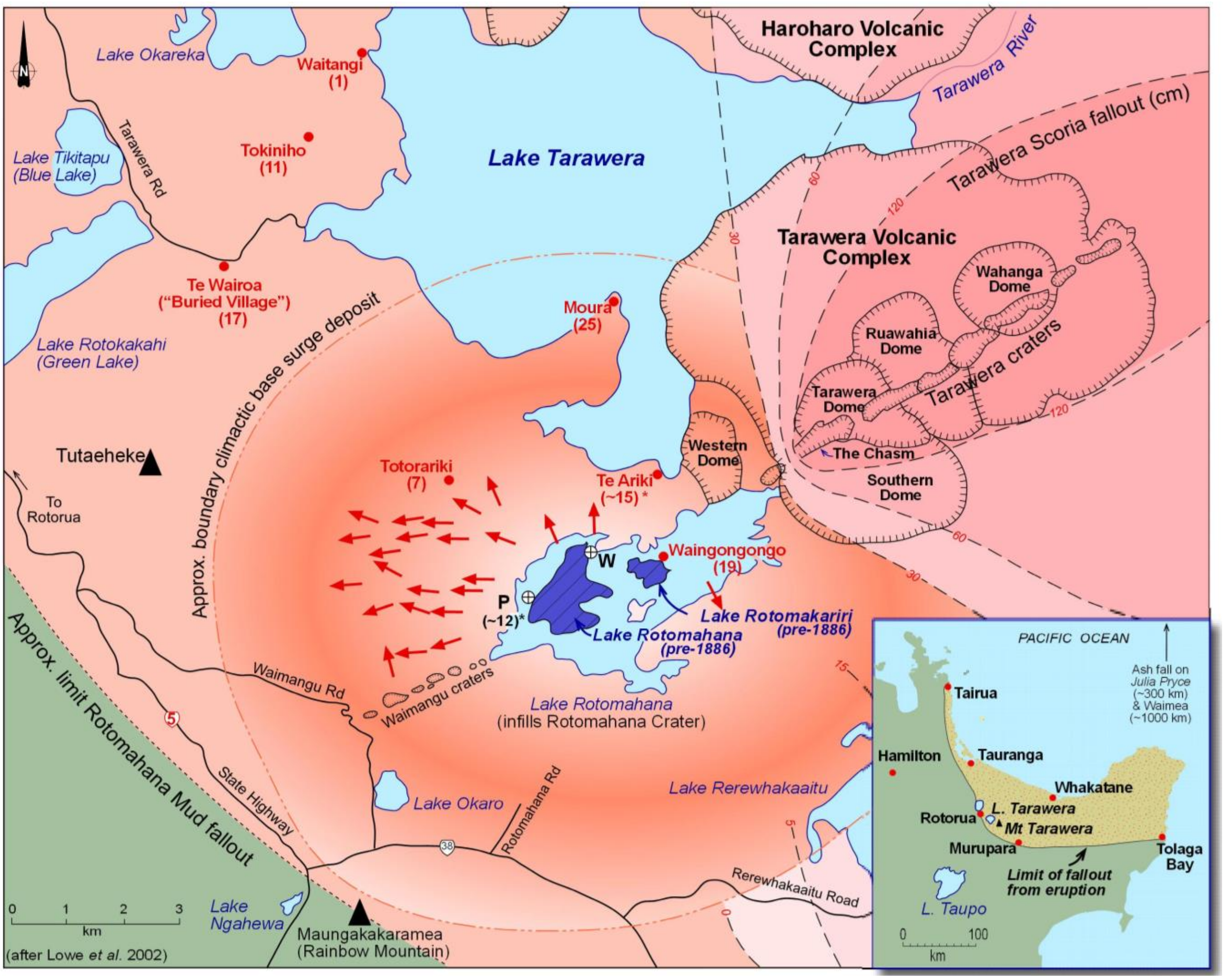


Figure S6 Map of Tarawera area showing locations of the main craters of the 10 June 1886 fissure eruption across Tarawera Volcanic Complex, Rotomahana Crater (including pre-eruption lakes Rotomahana and Rotomakariri), and Waimangu craters (after Lowe et al., 2002). Locations of villages and associated fatalities (numbers in parentheses, total ~120) are based on Keam (1988) and Lowe et al. (2001) (there was an additional death at an unknown locality). Fatalities were all Māori apart from six Europeans at Te Wairoa and one European and three Māori at Waingongongo. On the night of the eruption nearly half of Te Ariki's 27 residents were camped at Pink Terrace (Te Otukapuarangi). Inset shows eastern North Island and documented limits of tephra fallout from the eruption (based on maps by Thomas, 1888). Ash fell on several ships at sea, the farthest being *Julia Pryce* (c. 300 km) and S.S. *Waimea* (c. 1000 km) north of North Island (Keam, 1988). Lorrey and Wolley (2018) used historic data recorded during Ferdinand Hochstetter's 1859 survey to locate the sites of Lake Rotomahana's former sinter terraces (see also de Ronde et al. 2016, 2019; Keam, 2016; Keir, 2019).

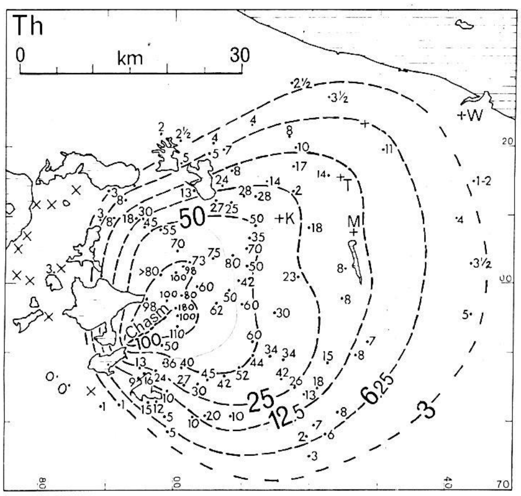


Figure S7 Isopach map of 1886 Tarawera scoria fallout (in cm). x = location where scoria occurs mixed with Rotomahana Mud but does not form a discrete layer (from Walker et al., 1984). See also Rowe et al. (2021).

Mamaku Plateau – development of an ignimbrite plateau landscape

Ignimbrites typically infill pre-existing valleys forming *valley-pond ignimbrites*, often densely welded and hard. They also spread thinly over hills forming *veneer ignimbrites*, typically weakly or non-welded and 'soft' (Figure S8; Lowe and Pittari, 2021).

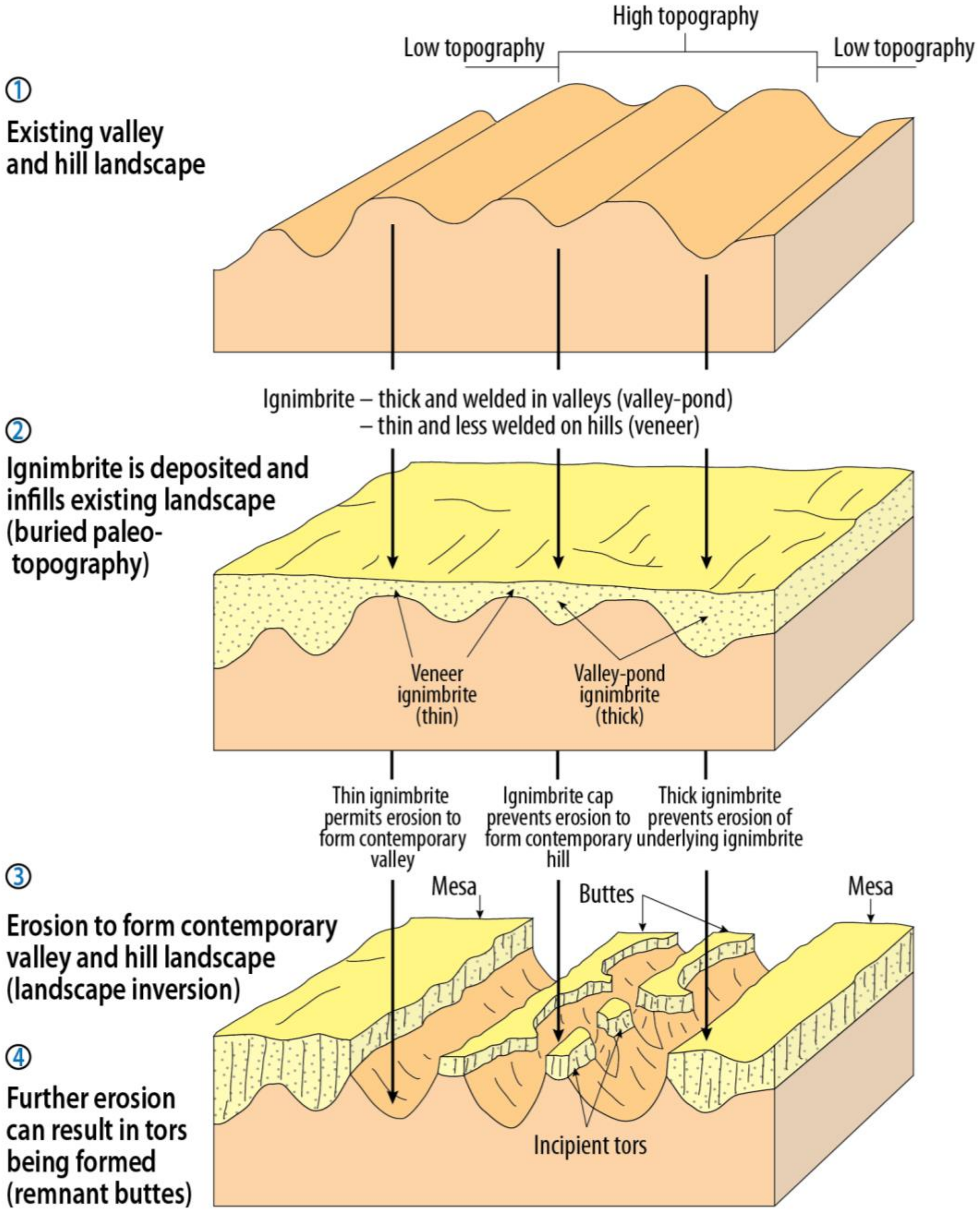


Figure S8 General model for landscape inversion in an ignimbrite terrain involving the emplacement of an ignimbrite as valley-pond and veneer deposits, and the subsequent erosion of the ignimbrite to form wide mesas and narrow buttes, and smaller tors, alongside deep valleys (modified after Hill et al., 1999).

The soft, veneer ignimbrites are easily eroded and so these high points can subsequently become valleys, whereas the hard, valley-pond ignimbrites form resistant, isolated hills with flat tops and steep sides known as *buttes* and *mesas* (butte means 'small hill' in French, mesa means 'table' in Spanish), effectively individual landforms within a broader *ignimbrite plateau* landscape. The process whereby valleys become hills, and hills become valleys, is referred to as landscape inversion (Figure S8).

Some of the multiple ignimbrite sheets on the Mamaku Plateau have been deeply eroded to form gorges and valleys, visible on either side of the main state highway, with cliffs of jointed ignimbrite and toppled blocks and colluvium at their margins (Figure S9). At the crest of the plateau, isolated conical hills called *tors* (a Celtic word for 'tower' or 'conical hill') are evident. These are hardened parts of the ignimbrite that are more resistant to erosion than the surrounding flatter, lower areas. They may represent the eroded remains of buttes or zones of former fumarolic activity that has caused strengthening by deposition of secondary minerals (Figure S9), or both.

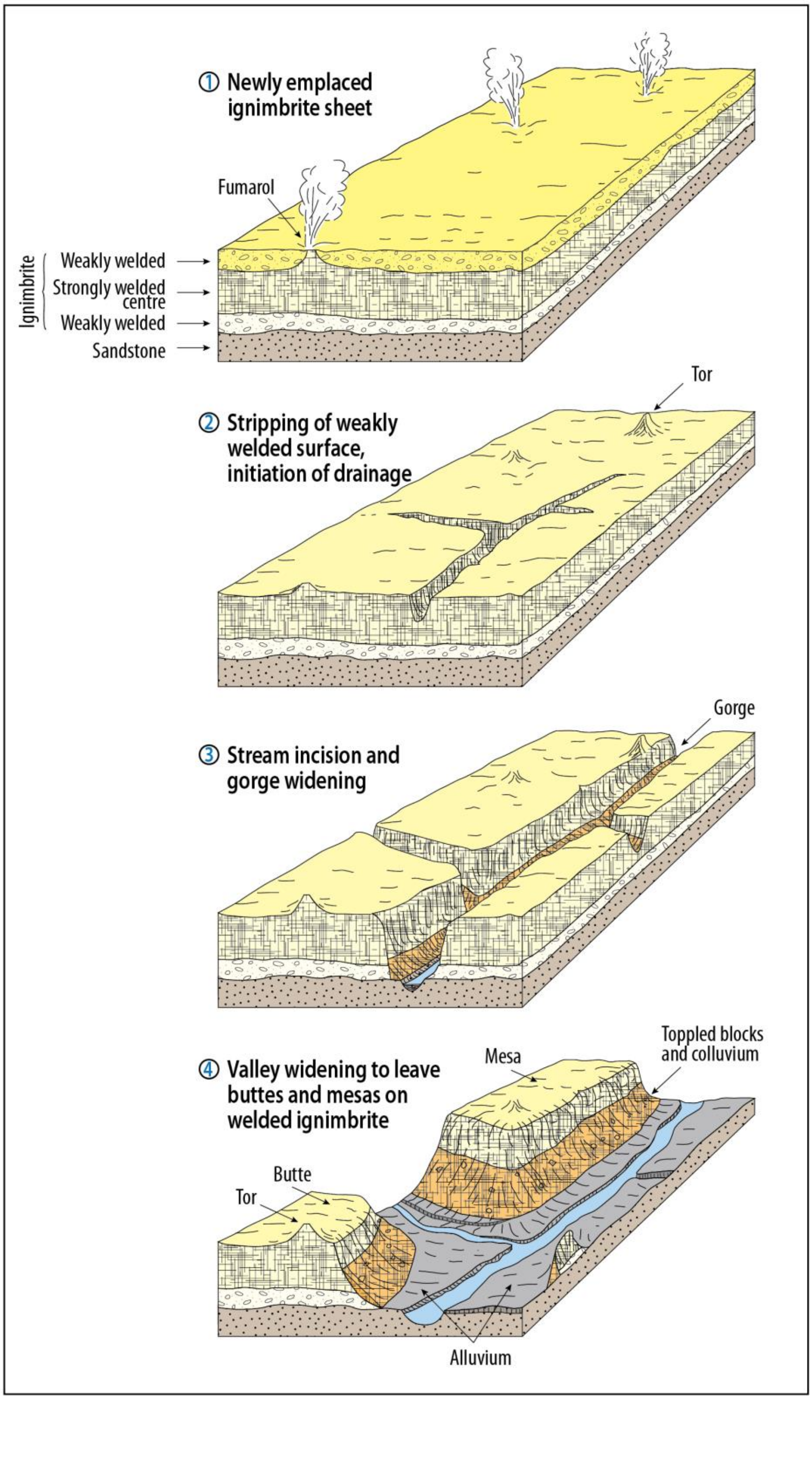


Figure S9 General development of landforms in an ignimbrite sheet comprising three units with different degrees of welding, forming gorges then widened valleys flanked by mesas and buttes. Tors may originate where fumarolic activity has caused strengthening by secondary mineral deposition and alteration. Modified after M.J. Selby in Healy (1992, p. 261).

Notes about allophane and its genesis and importance

Allophane is an Al-rich nanocrystalline aluminosilicate clay 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)$H_2O$ (Figure S10). It provides Allophanic Soils and Pumice Soils with many of their unique chemical and physical properties (e.g. Nanzyo, 2002; Harsh, 2012; McDaniel et al., 2012; Yuan and Wada, 2012). With its small size, extreme surface area (up to 1200 m^2 g^{-1}) 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 (Huang et al., 2016a). The high surface area and formation of allophanic nano- and micro-aggregates enable it to adsorb much soil organic matter to help stabilize soil organic carbon and preserve pre-modern DNA, as described below (Huang et al., 2016b). The similar but Fe-rich nanocrystalline ferrihydrite, formula $Fe_5HO_8.4H_2O$, is also present in most Allophanic Soils but typically in much smaller quantities than allophane unless on basaltic parent tephras in which it is relatively abundant (Huang et al., 2021).

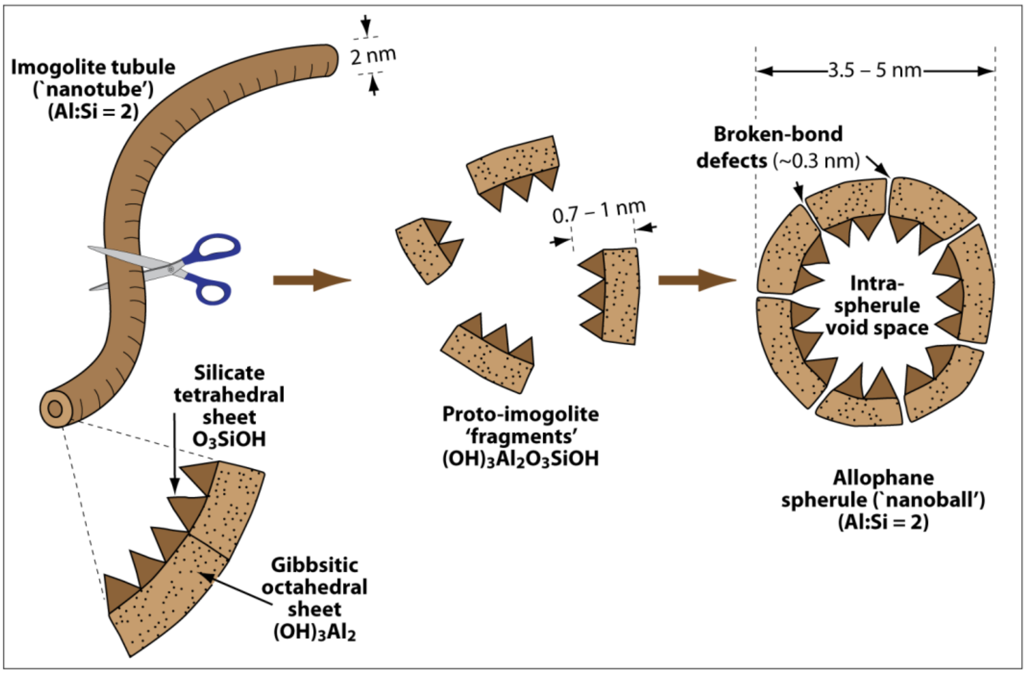


Figure S10 Diagram of imogolite nanotubes and Al-rich allophane nanospheres, which have similar structures at the atomic scale (from McDaniel et al., 2012, after Lowe, 1995).

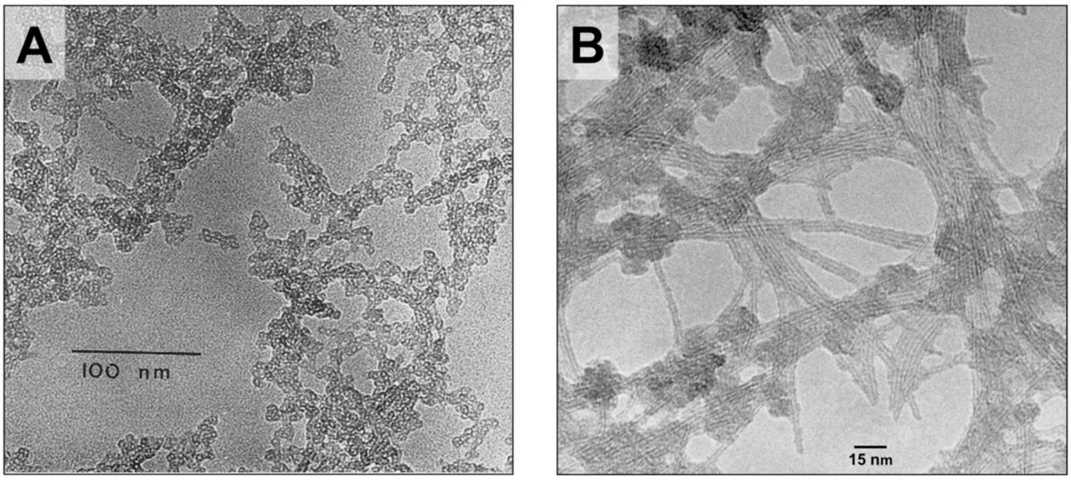


Figure S11 Micrographs of (A) allophane and (B) imogolite (external nanotube diameter is ~2 nm) (from McDaniel et al., 2012, after Parfitt, 1990, 2009).

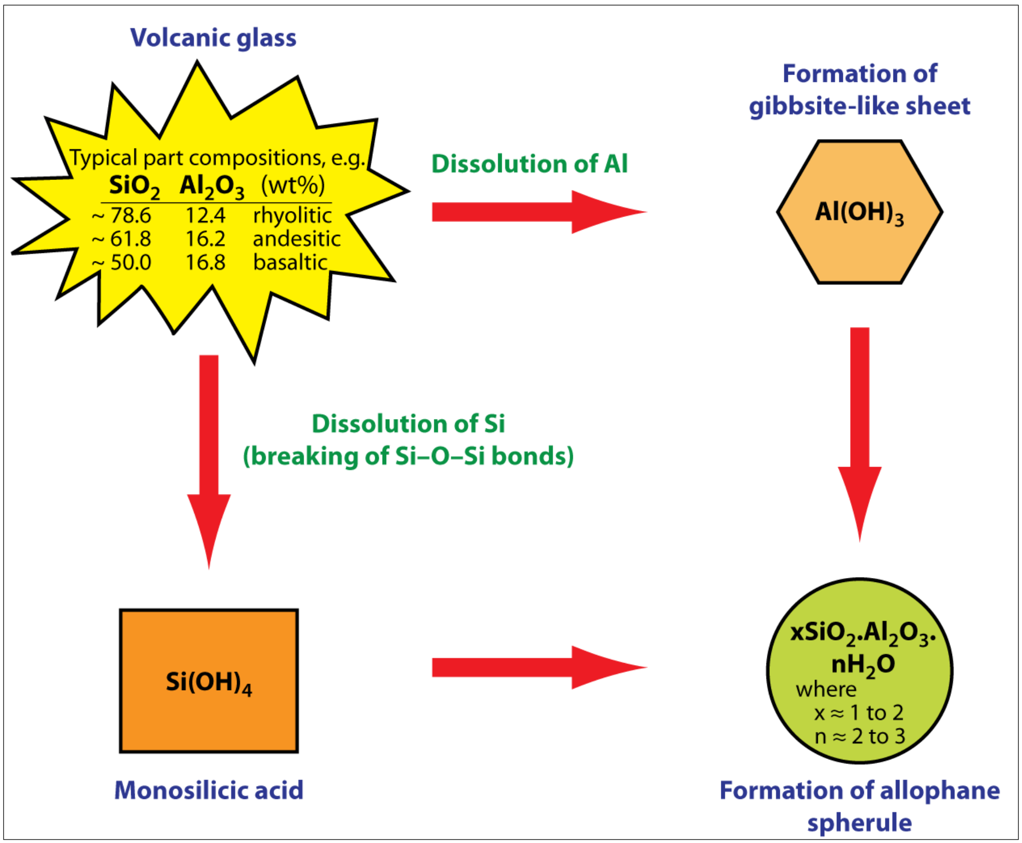


Figure S12 Dissolution of volcanic glass by hydrolysis, releasing Al and Si to precipitate into allophane spherules (nanoballs). From McDaniel et al. (2012) after Hiradate et al. (2005). See also Hodder et al. (1990).

The essential conditions for the formation of allophane are the concentration of silicic acid in the soil solution, the availability of Al species, and the opportunity for co-precipitation (Churchman and Lowe, 2012). 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 New Zealand (and in the rare Andisols of southeast South Australia formed on basaltic Holocene tephras at Mts Gambier and Schank: Lowe and Palmer, 2005), 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). The *silicon leaching model* (Figure S13) is summarized as follows: where [Si] is less than ~10 ppm, 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 depending on profile soil moisture conditions at a particular time. 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 and Palmer, 2005; Churchman and Lowe, 2012; McDaniel et al., 2012) (Figure S13).

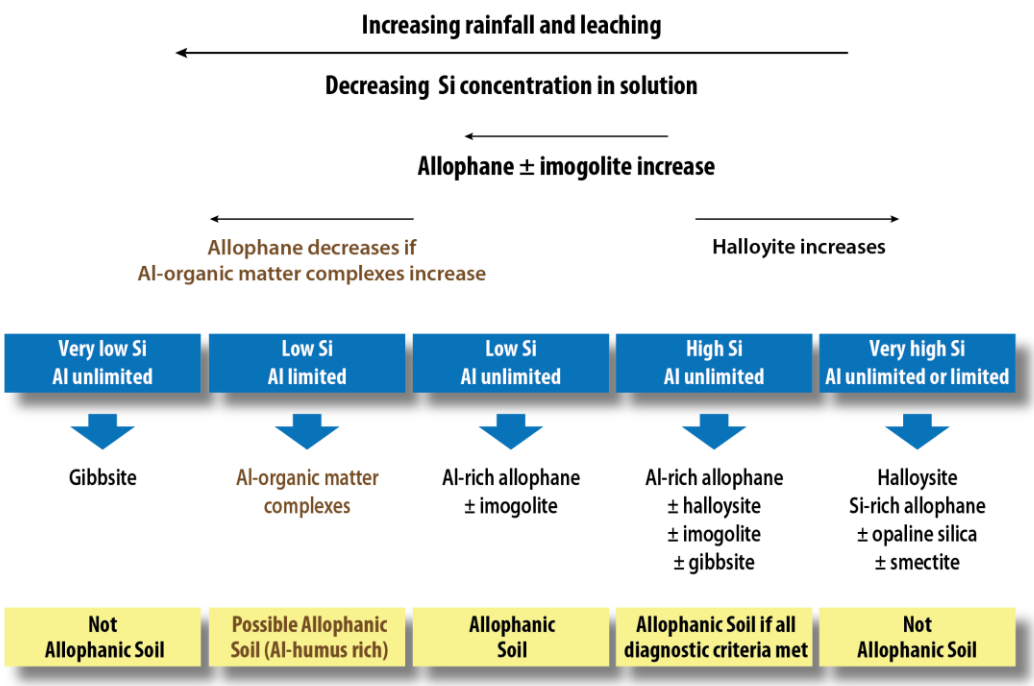


Figure S13. Relationship between environmental conditions and the formation of allophane and other minerals on tephra deposits (and some other materials) according to the silicon-leaching model and the availability of aluminium (from Hewitt et al., 2021, after Churchman and Lowe, 2012). The notation ± indicates that the clay mentioned may also be present. Very low [Si] <0.5 ppm; low [Si] ≤10 ppm; high [Si] varies ≤10 ppm to >10 ppm; very hi [Si] >10 ppm.

Extracting DNA from allophanic paleosols on tephras

Soils developed from late-Quaternary tephras are commonly dominated by the nanocrystalline aluminosilicate clay mineral, allophane, as described above. Allophane-dominated soils contain large stores of organic matter and are potential reservoirs for DNA. However, DNA recovery from them 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 (Huang et al., 2016a). Based on experimental work, the formation of very stable allophane nanoaggregates and microaggregates (Figure S14) 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 (Huang et al., 2016a). The stability of the allophane–DNA nano- and micro-aggregates 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.

Huang et al. (2016b) 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 (i.e. preserved) within nanopores as noted above. Sequencing of PCR products obtained from a buried allophanic paleosol at 2.2-m depth on an early Holocene tephra (9.4 cal ka Rotoma tephra) near Mt Tarawera yielded endemic and exotic plants that differed from the European grasses growing currently on the soil's surface. This difference shows that the DNA extraction method is able to access (paleo)environmental DNA derived from previous vegetation cover. The 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.

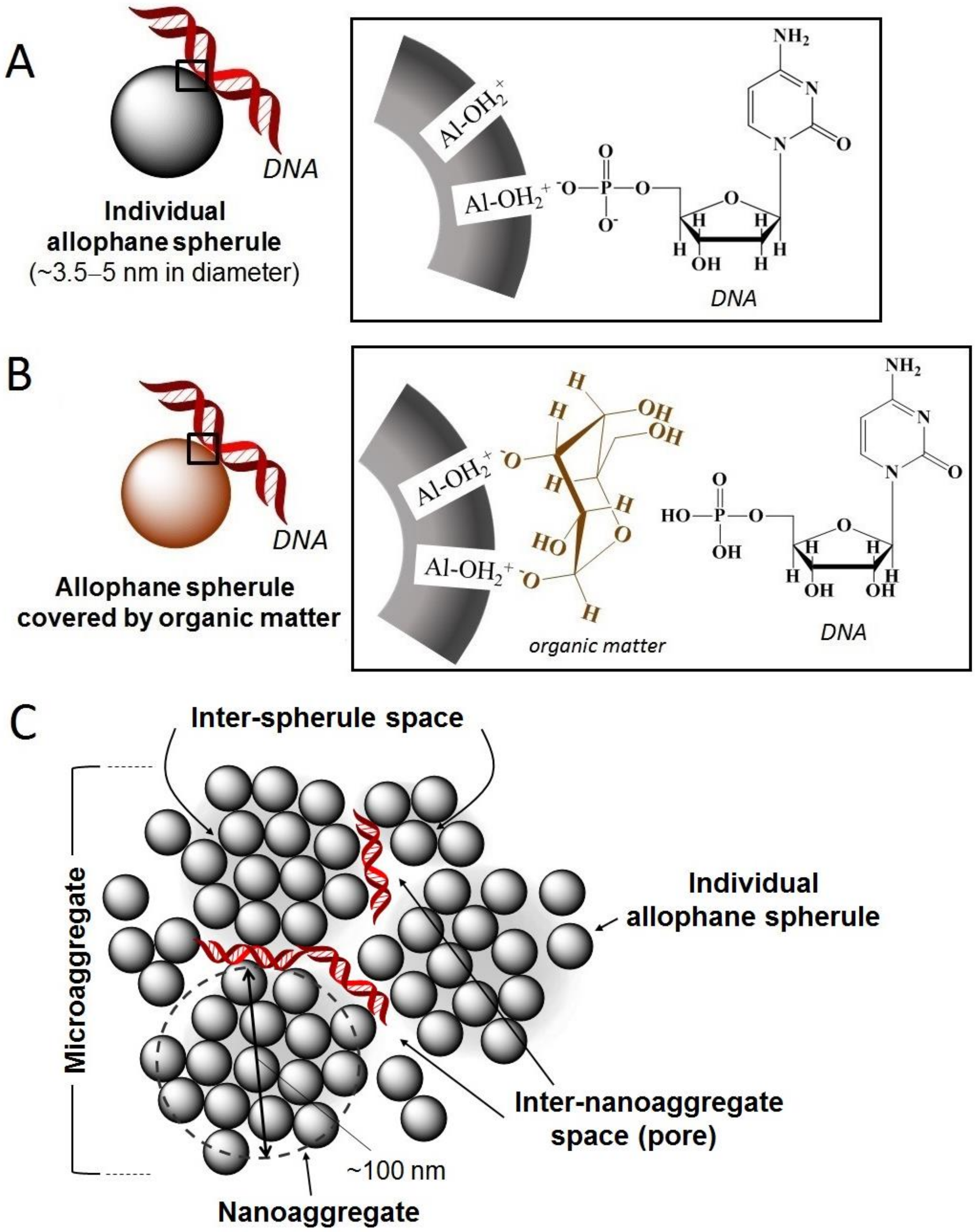


Figure S14 (A) Direct chemical adsorption of DNA on allophane; (**B)** indirect chemical adsorption of DNA on organic matter-rich allophane; (**C)** 'physical' adsorption of DNA (i.e. protection) in the nanopores of allophane nano- and micro-aggregates (from Huang et al., 2016a).

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