Where Geology Meets Pedology:

Late Quaternary Tephras, Loess, and Paleosols in the Mamaku Plateau and Lake Rerewhakaaitu areas

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Field Trip 2

led by David Lowe, Kerri Lanigan & David Palmer

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Field Trip 2

Sunday, 25 November 2012

Where Geology Meets Pedology: Late Quaternary Tephras, Loess, and Paleosols in the Mamaku Plateau and Lake Rerewhakaaitu Areas

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Health and safety

Certain hazards will be encountered on this field trip. At all times, participants must heed and observe the warnings and directions of the leaders. High-visibility fluoro-vests must be worn by all participants throughout the trip. Stops 2, 3, and 4 are road-side cuttings and so traffic hazards are present. To help ensure these stops are low risk, we have a traffic safety manager, Chris McKinnon, accompanying us on the trip firstly to put out road signs and cones to warn and slow traffic, and secondly to flag down traffic approaching the sections at stops 2 and 3 especially. Please be aware at all times of the hazard posed by traffic.

Sturdy, enclosed, boot-like footwear are ideal (note we are at roadside sections except at stop 1 where we will have a short walk up a farm tanker road rising ~ 15 m). If using spades or the cutting tool 'Niwashi' please be careful of bystanders and watch out for fingers and toes.

We expect the weather to be warm and sunny, but participants also must be prepared for cold and wet conditions that can occur at this time of year. The weather during the week leading to the trip has ranged from cold, wet and windy to warm and sunny. In the afternoon we will be at ~450 m elevation at Lake Rerewhakaaitu and if a southerly gets up it can be cold. A sunhat, sunscreen, sweatshirt/jumper (i.e., have a warm top available in your day pack), and waterproof and windproof light jacket are essential. Please do not underestimate the potential to get sunburnt and dehydrated (or cold and wet if our luck turns!). Participants should carry their own sunscreen and insect repellent, and any personal medications for allergic reactions (e.g. insect stings, pollen, food allergies), and a water bottle is highly recommended.

A safety management plan is appended to the end of this guide.

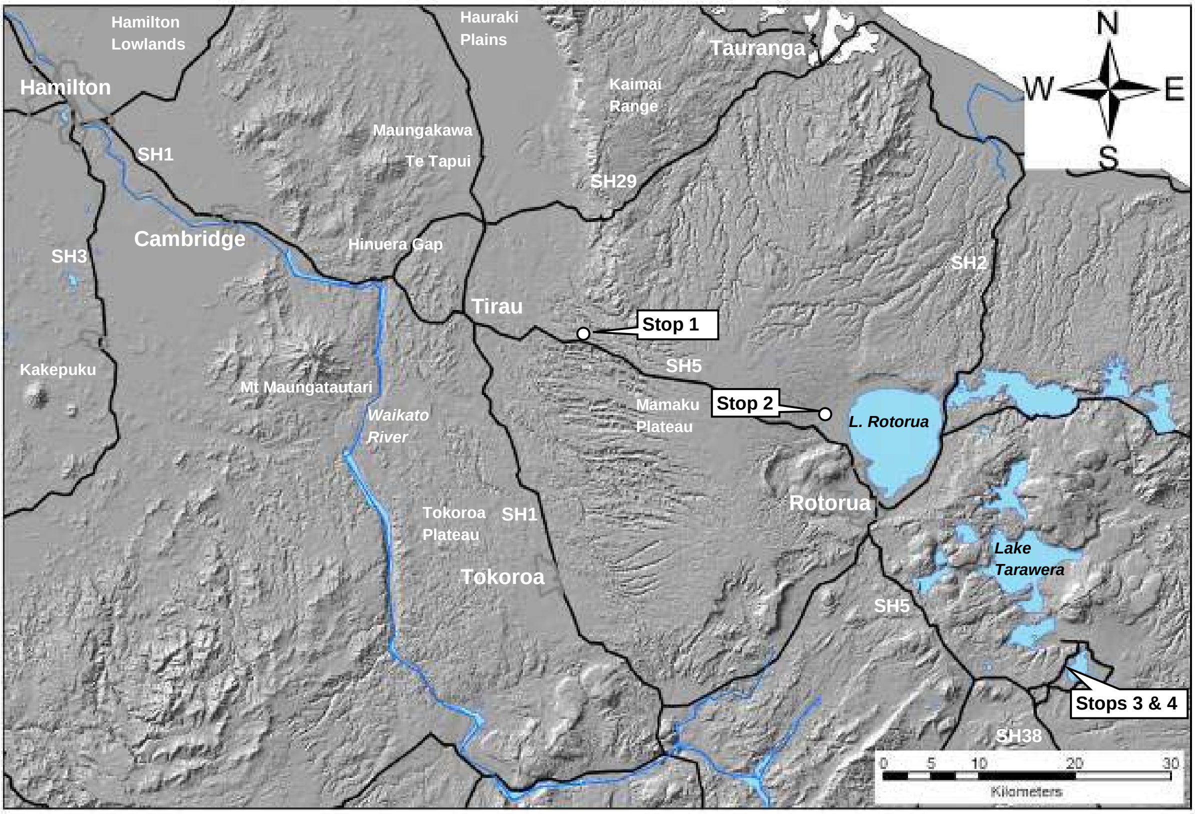


Fig. 1 Regional map showing geographical locations and some physiographic features.

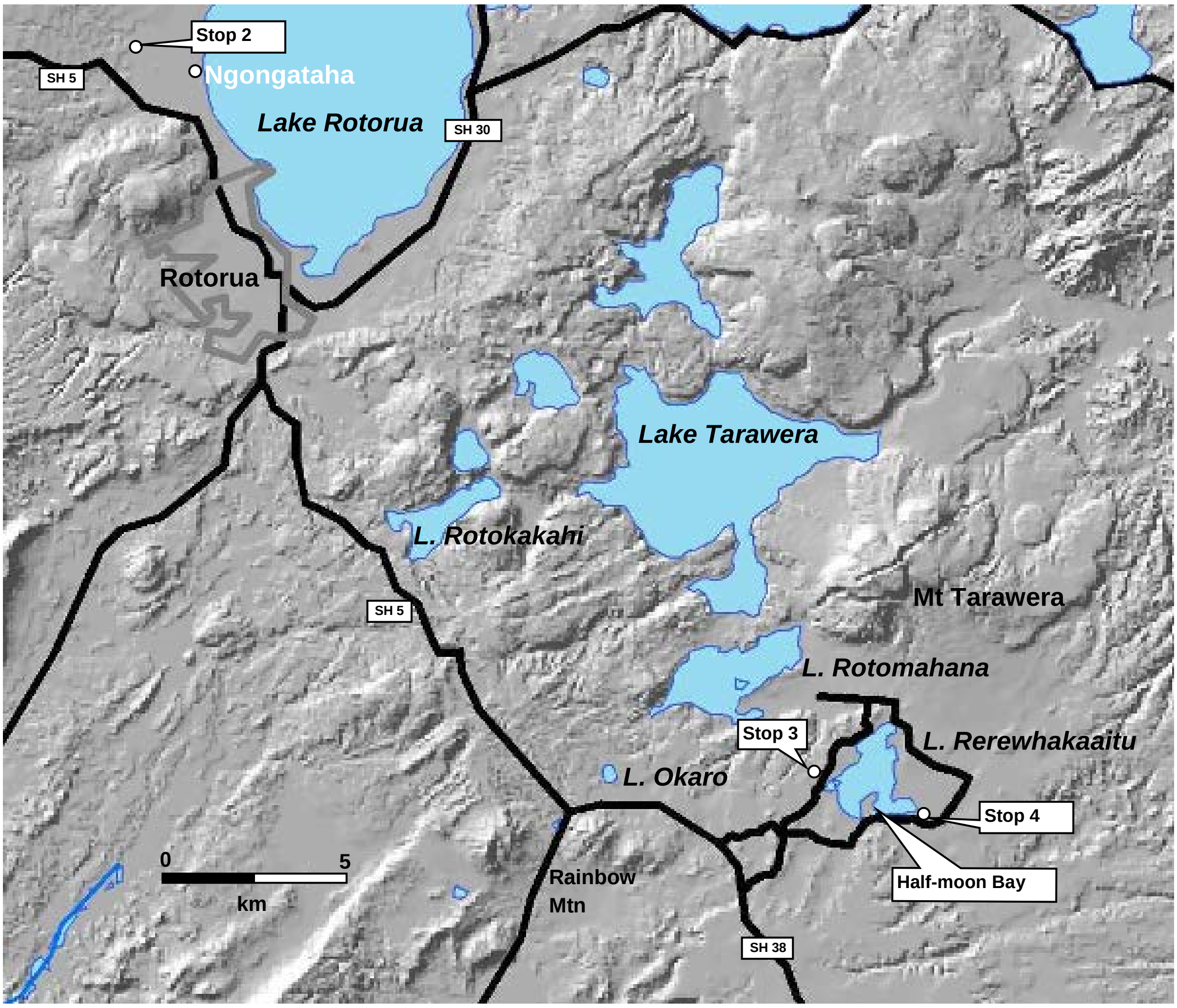


Fig. 2 Map of Rotorua lakes area within the Taupo Volcanic Zone, and locations of stops 2, 3, and 4.

Itinerary

8.00 am	Depart Univ. of Waikato, Student Village car park (adjacent to Knighton Rd)
9.00-10.00 am	STOP 1 Goodwin Farm section, Tapapa Rd (I hr)
10.05-10.25 am	Fitzgerald Glade café and toilets
10.50-11.30 am	STOP 2 Oturoa Rd section, Oturoa Rd (40 mins) *Extra care at this stop*
11.40-11.50 am	Ngongataha village centre and toilets (Hall St)
12.00-12.30 pm	LUNCH Ngongataha Lakeside Reserve, Lake Rotorua (Reeme St) (toilets)
1.10-2.10 pm	STOP 3 Brett Rd section, Lake Rerewhakaaitu (1 hr) *Extra care at this stop*
2.25-2.55 pm	STOP 4 Ash Pit Rd section, Lake Rerewhakaaitu (30 mins)
3.00-3.30 pm	Refreshments Half Moon Bay and toilets, Lake Rerewhakaaitu
3.30 pm	Return to Hamilton

Introduction

On this trip we focus on tephrostratigraphy and soil stratigraphy together with aspects of palaeoenvironmental reconstruction over long and short time-spans. We will examine the relationship between the deposition of tephras and tephric loess and the formation of soils in these deposits as they accumulate, either incrementally (millimetre by millimetre) or as thicker layers, in a process known as upbuilding pedogenesis. Development of age models for the eruption of marker tephras, and of the new climate event stratigraphy for New Zealand within the NZ-INTIMATE project (**Int**egration of **i**ce-core, **ma**rine, and **te**rrestrial records for New Zealand since 30,000 years ago), will also be touched upon.

A sequence comprising welded ignimbrite, tephras, loess, and buried soils dating back c. 230,000 years will be examined at Tapapa on the Mamaku Plateau at **stop 1**. Tephric loess deposited since c. 30,000 years ago (during the Last Glacial Maximum and afterwards), and interfingering tephra beds, will be seen at Oturoa Road near Ngongataha at **stop 2** (just inside the Rotorua caldera). After lunch at Ngongataha, a 'text book' sequence of Holocene tephras and buried soils dating back c. 9500 years on Brett Rd at Lake Rerewhakaaitu, near Mt Tarawera, will be examined at **stop 3**. This locality is also interesting for historical reasons relating to the development of tephra mapping and the establishment of Soil Survey Division of DSIR as a separate entity (1936), and military training activities during World War II. A nearby tephra-soil sequence at Ash Pit Rd (**stop 4**) dating to c. 14,000 years ago, and containing several buried podzol soils with distinctive morphological features, will complete the day (Figs. 1 & 2). More detailed notes about some of the stops, and an overview of Quaternary volcanism, tephras, and tephra-derived soils in North Island, and a history of the Rotorua basin and lake levels (Esler, 2010), are recorded in earlier guides (Lowe, 2008; Lowe et al., 2010). A review of volcanism of the central Taupo Volcanic Zone was published by Wilson et al. (2009). The Waikato and Rotorua sheets of the QMAP series were published by Edbrooke (2005) and Leonard et al. (2010), respectively, and Mt Tarawera and the Okataina Volcanic Centre were mapped by Nairn (1989, 2002). Lowe (2011) provided a comprehensive review of tephra studies and their application.

Geological vs pedological processes

Once we have established the stratigraphy (geological layering) of the sequences, we can then consider the interplay of topdown pedogenesis (soil formation) and 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 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)
- ***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 (see Fig. 32, p. 28).

In essence, the multisequal profiles represent the results of 'competition' between geological processes (eruption and deposition of tephras, deposition of loess) and pedological processes (topdown pedogenesis forming soil horizons) that has been played out over tens of thousands of years, i.e., where geology meets pedology.

Upbuilding pedogenesis

Two contrasting scenarios can be considered. In ***scenario 1***, successive thin tephra deposits (ranging from millimetres to centimetres in thickness) accumulate incrementally and relatively infrequently so that developmental upbuilding ensues. Such a situation occurs typically at distal sites. The thin materials deposited from each eruption become incorporated into the existing profile. Topdown pedogenesis continues as the tephras accumulate but its impacts are lessened because any one position in the sequence is not exposed to pedogenesis for long before it becomes buried too deeply for these processes to be effective as the land surface gently rises (Fig. 3). This history thus leaves the tephra materials with a soil fabric inherited from when the tephra was part of the surface A horizon or subsurface Bw horizon. Each part of the profile has been an A horizon at one point, as illustrated in Fig. 3 (Lowe and Tonkin, 2010; McDaniel et al., 2012).

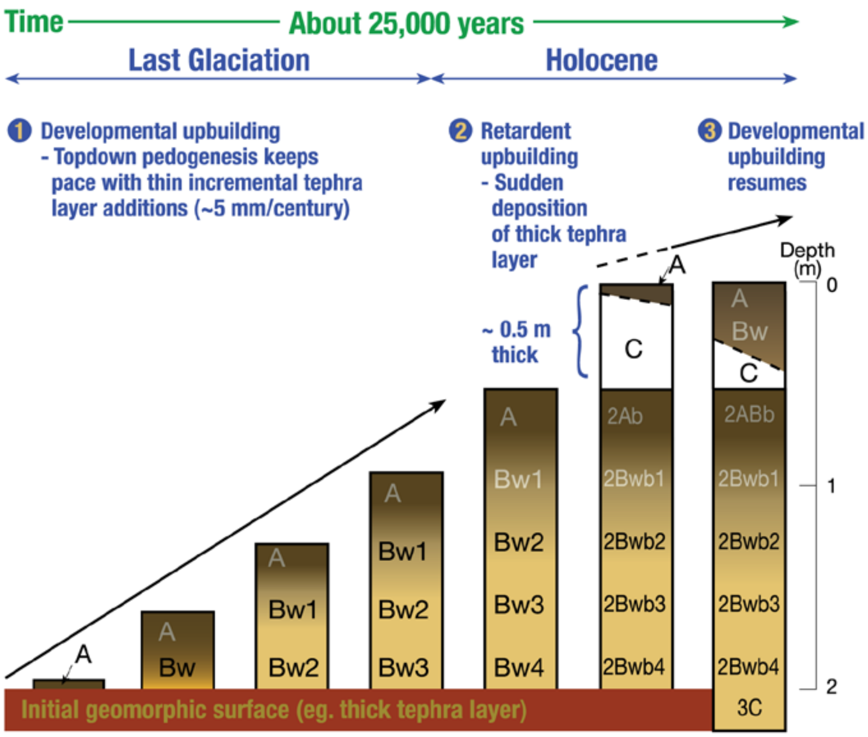


Fig. 3 Model of upbuilding pedogenesis in tephra deposits and the formation of a multisequal profile over c. 25,000 years in South Waikato. In phase 1, thin, distal tephras accumulate slowly whilst topdown processes imprint weak horizonation features on them as the land surface gradually rises. In phase 2, the sudden deposition of a tephra layer ~0.5 m thick (e.g., Taupo ignimbrite) 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. In phase 3, incremental tephra deposition on the new soil continues and developmental upbuilding resumes (from McDaniel et al., 2012).

In ***scenario 2***, tephra accumulation is more rapid, as occurs in locations close to volcanoes or when a much thicker layer (more than a few tens of centimetres) is deposited from a powerful eruption. In the latter case, the antecedent soil is suddenly buried and isolated beyond the range of most soil-forming processes (i.e., it becomes a buried soil horizon) (see Fig. 32, p. 28). A new soil will thus begin forming at the land surface in the freshly deposited material. This scenario typifies retardant upbuilding, which means that the development of the now-buried soil has been retarded or stopped, and the pedogenic 'clock' reset to time zero for weathering and soil formation to start afresh.

An example of a multisequal profile formed via retardant upbuilding pedogenesis since c. 9500 years ago is shown in Fig. 4 (this is the same sequence we will see at stop 3). Each of five successive tephra deposits (named Rotoma, Whakatane, Taupo, Kaharoa, and Tarawera) shows the imprint of topdown pedogenesis, as depicted by the *soil horizonation* indicated on the photo. But the sudden arrival of each new deposit buries and effectively isolates each of the weakly-developed 'mini' soil profiles as the land surface rises. Retardant and developmental upbuilding may both occur in the evolution of a single, deep profile. For example, in Fig. 3, topdown pedogenesis effectively keeps pace with incremental tephra additions (at c. 5 mm per century) until interrupted by deposition of a thick layer that overwhelms the pre-existing soil, leaving an abrupt, clear boundary.

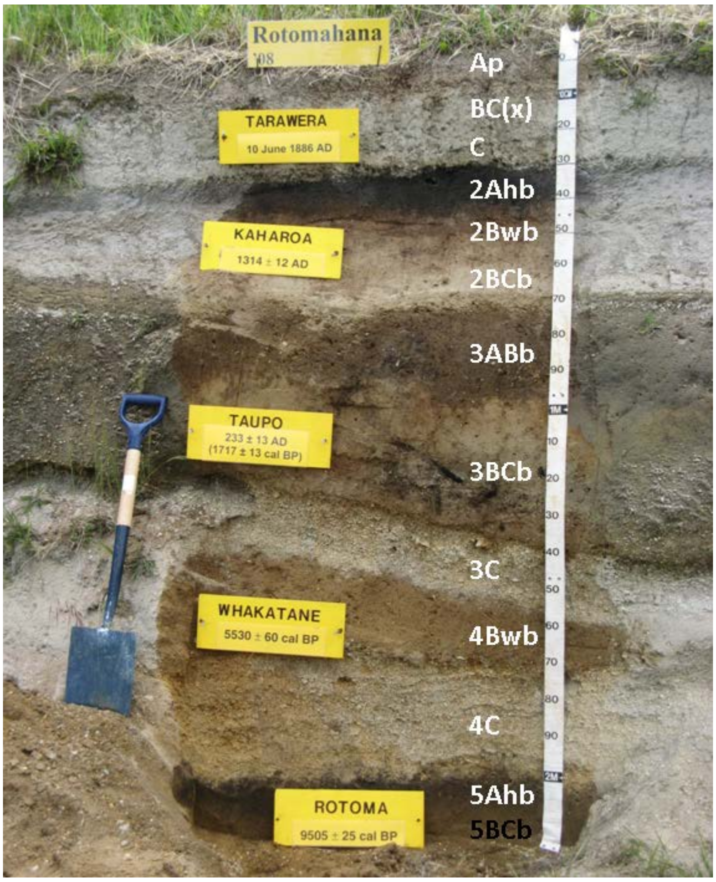


Fig. 4. Example of a multi-layered soil formed through retardant upbuilding. After each tephra is deposited, soil begins to develop until it is buried by another tephra and topdown pedogenesis begins operating in the fresh deposit. The buried 'mini' soil profile on Whakatane tephra (4Bwb, 4C) reflects ~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 ~126 years of pedogenesis on hydrothermally altered, mud-rich tephra deposited in AD 1886 by the Tarawera eruption. The black 2Ahb horizon reflects a high content of type-A humic acids and charcoal following invasion by bracken fern and grasses after Polynesian deforestation and probably ongoing burning (from McDaniel et al., 2012). Photo: R. MacEwan.

Andisols

These are one of 12 soil orders in the international soil classification system *Soil Taxonomy* (Soil Survey Staff, 1999, 2010). Andisols are often deep soils commonly with depositional stratification developing mainly from ash, pumice, cinders (scoria), or other explosively erupted, pyroclastic (fragmental) 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 above. 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. Understanding Andisol genesis in many instances thus requires a stratigraphic approach combined with an appreciation of buried soil horizons and polygenesis (McDaniel et al., 2012). In the *New Zealand Soil Classification* (NZSC, Hewitt, 2010), Andisols are split into Allophanic Soils and Pumice Soils (most Pumice Soils are classed as Vitrands in *Soil Taxonomy*, i.e., a slightly weathered, coarse-textured, glass-dominated Andisol).

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 (Figs. 5 & 6) (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) (see also Figs. 7−9). Some properties of buried soil horizons may have been altered via diagenesis.

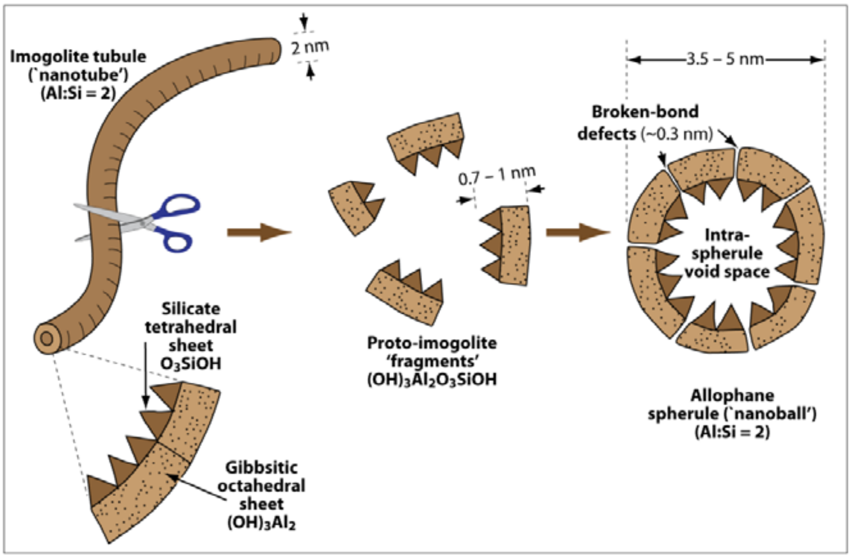


Fig. 5 Diagram of imogolite tubes and allophane spherules. 'Proto-imogolite' fragments have an imogolite atomic structure over a short range and link to form porous, hollow nanospheres with water molecules occupying the intra-spherule interior as well as being adsorbed to the outer AlOH surface (from McDaniel et al., 2012). Al: Si nomenclature refers to atomic ratios. Allophane content is estimated by analysing Al and Si dissolution in acid oxalate reagent and calculating the Al: Si atomic ratio (with corrections to account for Al-humus content) and then applying a multiplying factor (Parfitt, 2009; McDaniel et al., 2012).

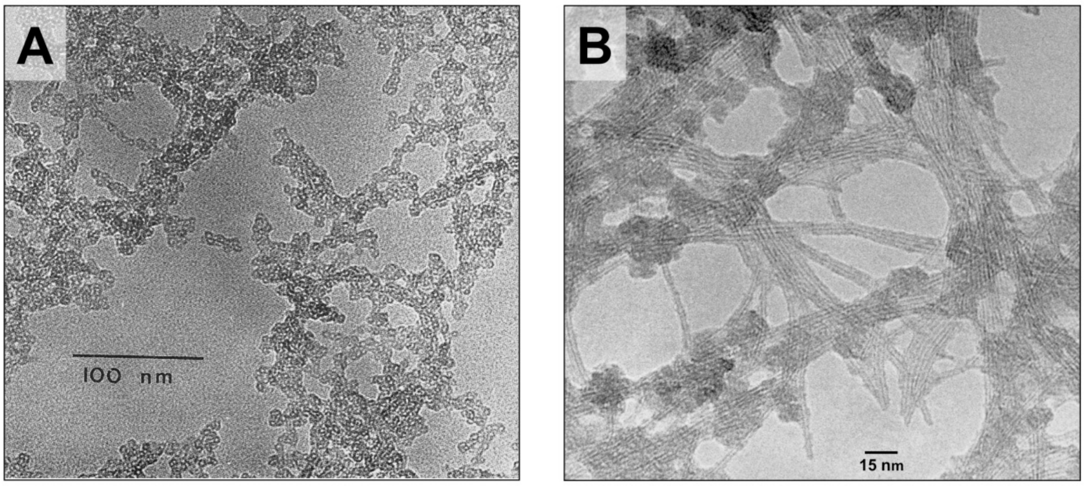


Fig. 6 Micrographs of (A) allophane and (B) imogolite (external diameter of nanotubes is ~2 nm) (from McDaniel et al., 2012).

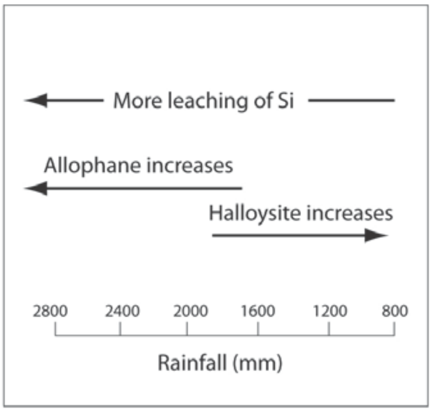


Fig. 7 Simplified allophane-halloysite rainfall leaching model (from McDaniel et al., 2012).

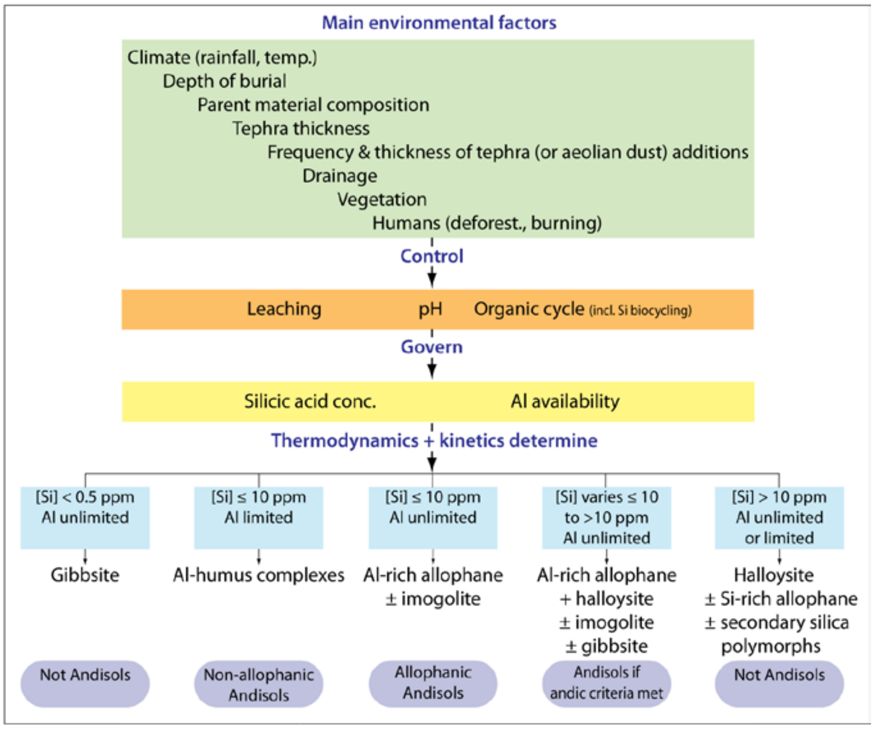


Fig. 8 Environmental influences and controls that govern the critical conditions leading to the formation of different clays from the weathering of tephras, and the likely occurrence or not of Andisols as a result (± indicates that the clay mentioned may also be present) (from Churchman and Lowe, 2012).

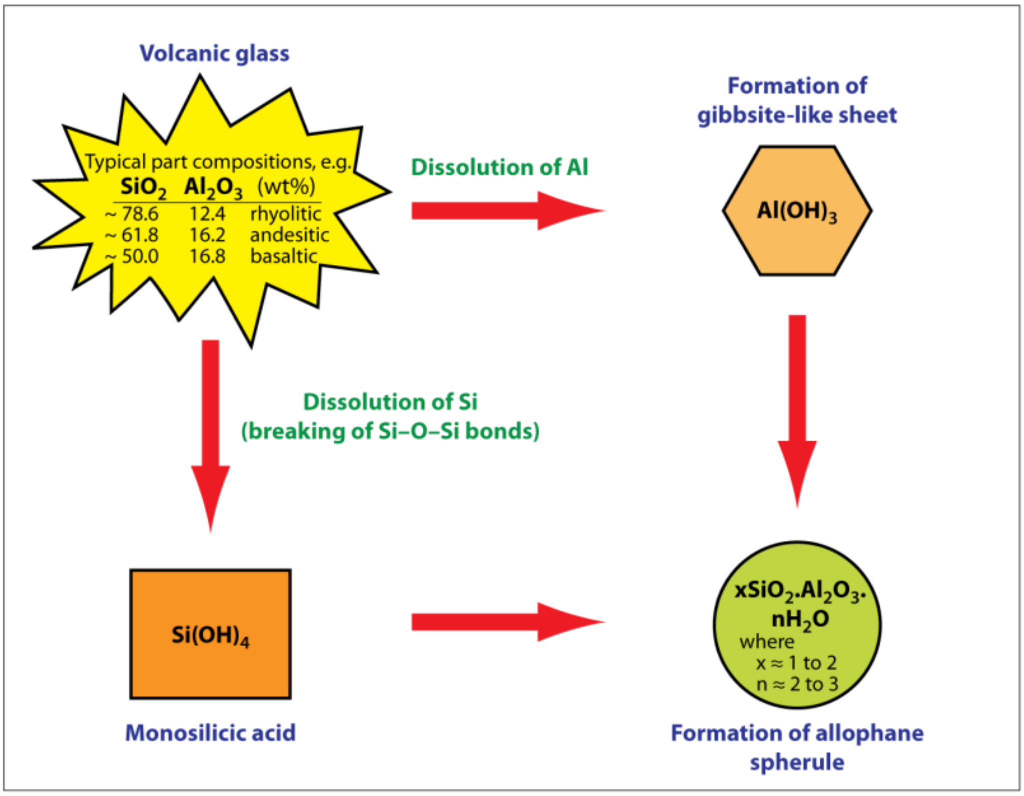


Fig. 9 Volcanic glass compositions and dissolution of Al and Si to form allophane (from McDaniel et al., 2012, based on Hiradate and Wada, 2005).

Climate change in the Rotorua area since c. 30 cal ka: summary of previous work

McGlone et al. (1984) carried out palynological studies in the Bay of Plenty to Gisborne area. They concluded that from the time of deposition of the Rotoehu ash (c. 45 cal ka) to Omataroa tephra (the uppermost unit of which is now designated Unit L, aged c. 33 cal ka), climate was dominated by cool interstadial conditions before a change at the time of the Omataroa or Kawakawa tephra (c. 25.4 cal ka) to much harsher conditions characterised by an unstable landscape which continued until the time of deposition of the Rerewhakaaitu (c. 17.5 cal ka) or soon after (as shown earlier by Vucetich and Pullar, 1969). Newnham et al. (2003) extended this work using a range of proxies to show that the landscape became stabilised in places by the time of deposition of Rotorua tephra (c. 15.6 cal ka). Much of that work was underpinned by palynological studies in the adjacent Waikato region by Newnham et al. (1989). For the period since c. 20,000 years ago, Newnham et al. (1989) recognised three main climatic phases: (1) last glacial phase, where the environment was mainly unforested; (2) late glacial transitional phase, beginning just after Rerewhakaaitu tephra, when forest quickly became re-established, and lasting until early post-glacial times, with climate continuing to become warmer and wetter; and (3) early post-glacial phase, where climate reached maximum warm wet conditions. Later during this phase the occurrence of frosts and or droughts became more common and the environment became drier (Newnham et al., 1989) (see also Alloway et al., 2007; Barrell et al., 2013).

Sase et al. (1988) and Kondo et al. (1994) studied phytoliths (siliceous plant cell remains) from tephra-loess-soil sequences and showed a change from grass-dominated to forest-dominated vegetation occurred at around the time of deposition of Waiohau tephra (c. 14 cal ka). That work was neatly married to the findings from analyses of clay mineral assemblages by Green (1987) and Hodder et al. (1990), as shown in Fig. 10. The Holocene record for the area has been examined by McGlone (1983) and by palaeolimnological work by Pickett (2008) from a core from Lake Rotorua.

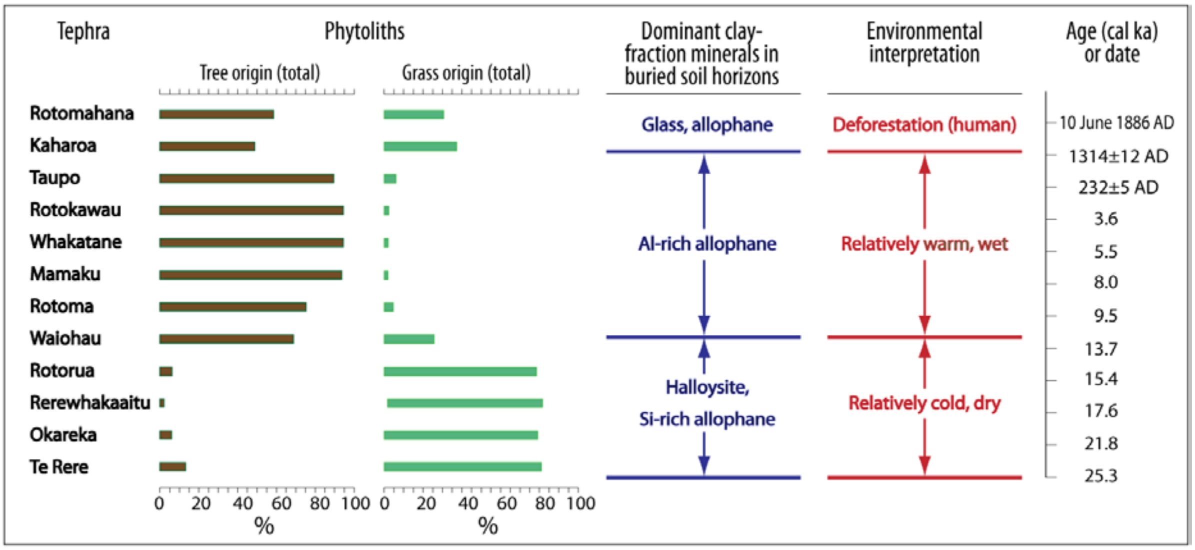


Fig. 10 Dominant phytoliths and clay minerals identified in buried soil horizons in a sequence of 11 rhyolitic tephras and one basaltic tephra (Rotokawau) deposited at Te Ngae near Rotorua, since c. 25 cal ka, showing the relationship between environment and clay mineral assemblages (from Churchman and Lowe, 2012).

Loess

The average rates of *loess accumulation* in New Zealand since deposition of the widespread marker bed, the Kawakawa tephra c. 25,400 cal yr BP (see Fig. 14, below), and before the Holocene, are about 3 to 10 mm per century on average (Eden and Hammond, 2003; Lowe and Tonkin, 2010). During periods when loess is accumulating, especially during the Last Glacial Maximum (see Lorrey et al., 2012), soil formation does not stop, but its effects are lessened as the upper soil horizons eventually become buried too deeply for topdown pedogenic processes to be effective, as described earlier. Soil formation thus occurs simultaneously with slow loess accumulation, forming a 'soil-sediment' via upbuilding pedogenesis (Fig. 11). In the eastern Waikato the intermittent fallout of thin, distal tephra deposits at about 1 to 5 mm per century is at a rate comparable to loess accretion during glacial periods (Lowe et al., 2008a).

Tephric loess in the Rotorua area

Lanigan (2012) examined tephric loess in the wider Rotorua area at 13 sites dating from c. 33 cal ka (marked by the uppermost Mangaone subgroup tephra known as Unit L: Jurado-Chichay and Walker, 2000; Smith et al., 2002) through to c. 9,400 cal yr BP (Rotoma tephra) and divided the loess deposits into six 'packets' based on bounding tephra layers (Fig. 12, Table 1). Unlike most previous studies, which suggested that loess accumulation had ceased around the time of deposition of the Rerewhakaaitu tephra (c. 17.5 cal ka) or the Rotorua tephra (c. 15.6 cal ka), Lanigan (2012) identified continuing loess deposition at some sites as young as c. 9,400 cal yr BP in the Rotorua region. In general, the tephric loess deposits are dominantly massive, mainly silty or very fine sand in grain size, and typically yellowish brown, dull yellowish brown, or dull yellow orange in colour (Munsell colour codes 10YR 5/4, 5/6, 5/8 or 6/4). The thickest (tephra-free) loess sequence occurs at Dansey Rd where a total of 4.3 m of loess was recorded between Unit L (c. 33 cal ka) and Rotoma tephra (c. 9.4 cal ka).

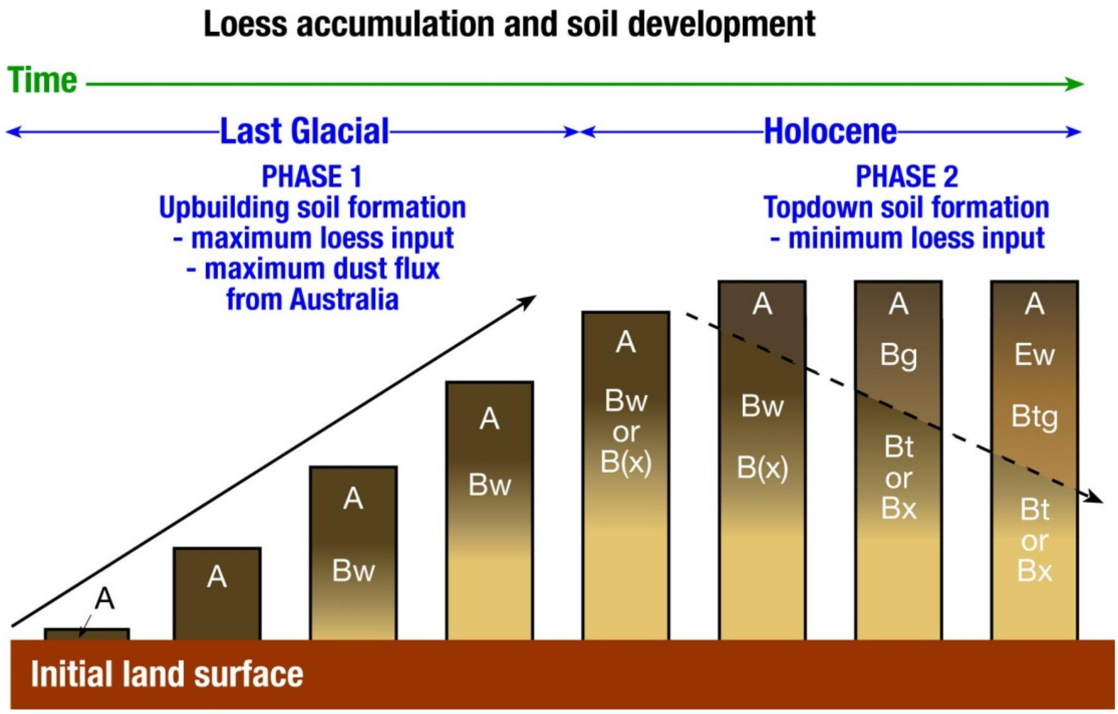


Fig. 11 General model of soil development in loess since c. 25,000 years ago in New Zealand. The initial geomorphic surface approximates the Kawakawa tephra. Phase 1 depicts upbuilding pedogenesis during maximum (but slow) loess accretion (OIS 2); phase 2 depicts topdown pedogenesis with minimal or zero loess accretion (OIS 1). Soil horizons show that the maximum development of subsurface features occurs in phase 2 with more strongly developed horizons evident (from Lowe and Tonkin, 2010).

On average, loess accumulation rates were relatively slow, about 23 mm per century on average throughout the field area, ranging from c. 5 mm/100 yrs on average (between the time of deposition of Unit L, c. 33 cal ka, and Kawakawa tephra, c. 25.4 cal ka) to c. 60 mm/100 yrs (between the time of deposition of Kawakawa and Te Rere tephras, although the imprecise age of Te Rere tephra, c. 25 ± 1 cal ka, makes this estimate of accumulation rate only approximate) (Fig. 13; Lanigan, 2012; Lowe et al., 2013). These slow rates of accumulation – only a few centimetres per century – as well as the presence of subtle changes in colour and other properties through the loess columns, indicate that these deposits were formed via developmental upbuilding (Fig. 11). Loess accumulation was interrupted intermittently by tephra deposition, which range in thickness from a few millimetres to greater than 1 m. Where these tephra layers were of substantial thickness (i.e., at least c. 20–30 cm), the antecedent soil/loess column was buried and isolated from surface soil-forming processes, causing retardant upbuilding, and hence loess accumulation and developmental upbuilding resumed at the new land surface in the freshly deposited materials (Lanigan, 2012).

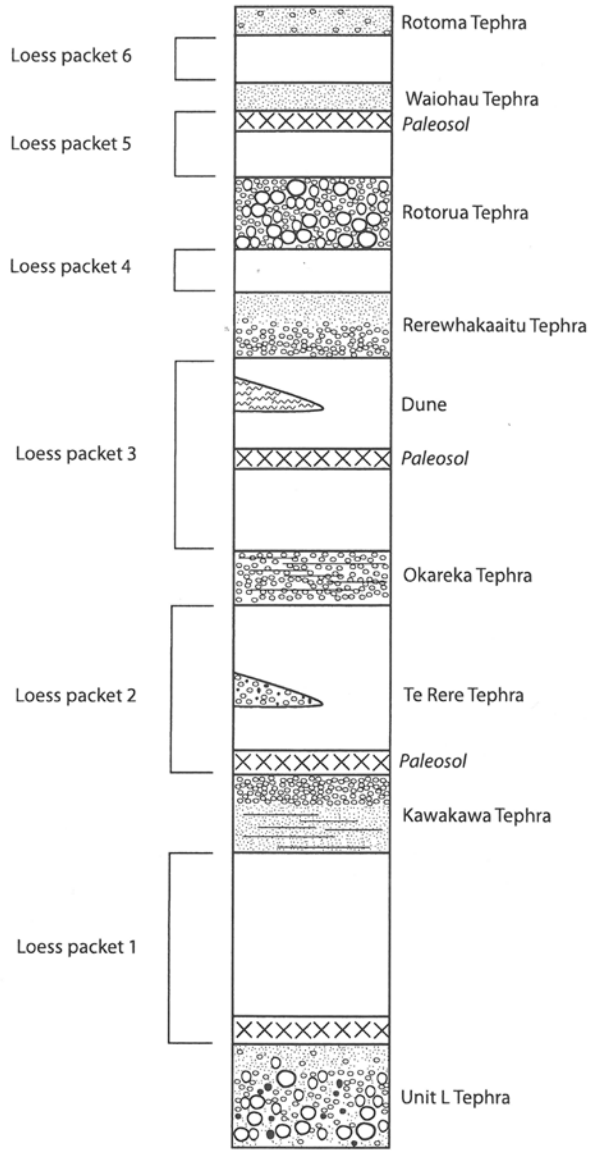


Fig. 12 Generalised composite stratigraphic column from Unit L (c. 33 cal ka) to Rotoma tephra (c. 9.4 cal ka) applicable for general Rotorua field area studied by Lanigan (2012). Note that there is usually a weak pedogenic imprint throughout the loess column but in some places enhanced imprints are recognised (labelled here 'paleosols'). Ages on tephras are given in Table 1; other tephras recorded in the area within this time span include Poihipi (c. 28.4 cal ka) and Okaia (c. 28.6 cal. ka) (Lowe et al., 2013).

Lanigan (2012) inferred that past climates and related factors have broadly controlled the production, deposition and rate of accumulation of tephric loess in her Rotorua field area (~45 km north to south and ~50 km west to east). Of the thirteen sites examined, Dansey Rd and Maniatutu Rd were selected as primary and secondary master sites, respectively, for detailed laboratory analysis of a number of properties which could be used as potential paleoclimatic proxies. These two sites were selected because they contained a large number of tephra marker beds and relatively thick loess deposits, thus providing a potentially high-resolution record of climatic change that could also be connected via tephrochronology to other records containing the same tephras. Properties analysed as climate proxies included loess grain-size, accumulation rate, phytoliths, magnetic susceptibility, total carbon content, carbon isotopes and potassium content.

The results from the proxies showed evidence of climatic variability and were summarised into a composite Rotorua climate event stratigraphy (RCES) spanning the period from c. 33 to 9.5 cal ka (Fig. 15).

Table 1 Summary of main rhyolitic tephras deposited in the Rotorua region during the last c. 25,400 cal years.

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) in 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 additionally received distal tephras from Taupo and Tuhua (Mayor Island) 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), 'present' being 1950 in the ^{14}C timescale (ages are based on Bayesian probability age modelling: Lowe et al., 2008b, 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)

Three broad *climat*e *periods* were recognised within the RCES:

(1) a warm interstadial period (c. 32.7−25.4 cal ka);
(2) a cold stadial/extended last glacial maximum period (c. 25.4−18.4 cal ka) with interstadials; and
(3) a warming/transitional period leading to an interglacial (c. 18.4−9.4 cal ka) but including a late-glacial reversal (c. 13.8−12.8 cal ka).

Within these three periods, nine shorter *climate phases* were recognised (Table 2).

Table 2 Climate change inferred from analyses of tephric loess in Rotorua area (Lanigan, 2012)

	phase 9 – warmer and wetter interglacial	c. 12.8−9.4 cal ka
Period 3	phase 8 – cold and dry late glacial reversal	c. 13.8−12.8 cal ka
	phase 7 – warm wet & less windy transition to interglacial	c. 18.4−13.8 cal ka
	phase 6 − cold, dry and partly windy stadial	c. 20.6−18.4 cal ka
	phase 5 – warmer and wetter interstadial	c. 21.2−20.6 cal ka
Period 2	phase 4 – cold, dry and windy stadial	c. 22.8−21.2 cal ka
	phase 3 – warmer and wetter interstadial	c. 23.4−22.8 cal ka
	phase 2 – cold, dry and generally windy stadial	c. 25.4−23.4 cal ka
Period 1	phase 1 – relatively warm and wet interstadial	c. 32.7−25.4 cal ka

Of the paleoclimatic properties measured, magnetic susceptibility, potassium content, and grain-size seem to have resulted in the most detailed records (including support for one or more of the nine recognised shorter climate phases from her study) in which trends were comparable with one another (Lanigan, 2012). The loess accumulation rate record shows general agreement with the three broad climate periods recognised as well as support in part for the late-glacial reversal phase (phase 8). However, the relatively low resolution of this record has prevented the detection of climatic variability at a finer scale. Phytoliths were analysed at a relatively low resolution by Lanigan (2012), and the resulting phytolith record shows some agreement with the previously mentioned records. Further phytolith analysis at a higher resolution and an increased number of sites may potentially prove a more useful proxy of paleoclimate in the Rotorua region. The record from carbon isotope analysis, although supporting the three broad climate periods recognised, did not strongly support the occurrence and timing of the shorter-lived climate phases. Also, the loess total carbon content record did not show evidence of fine-scale climatic variation. This lack of support and finer-scale variation may have been a result of the very low carbon content of the loess (range from 0.16% to 0.70 %).

The RCES was compared with other climate records (including both continuous and fragmentary records) in northern North Island. The RCES was also compared with the New Zealand climate event stratigraphy (NZ CES) of Barrell et al. (2013) (Fig. 16). In general, the three broad *climate periods* of the RCES were well supported by the occurrence of similar periods in the climate records from the North Island and the NZ CES, and there was reasonable correspondence of many of the *phases* with the NZ CES (although the timing of these periods were not always well synchronised) (Lanigan, 2012).

For example, RCES phase 1 approximately matches NZ CES events 11 and 10; RCES 2 matches NZ CES 9; RCES 3 matches NZ CES 8; RCES 4 matches NZ CES 7; RCES 5 and 6 match NZ CES 6; RCES 7 matches NZ CES 5 and 4; RCES 8 matches NZ CES 3; and RCES 9 matches NZ CES 2 and 1 (cf. Figs. 15 and 16).

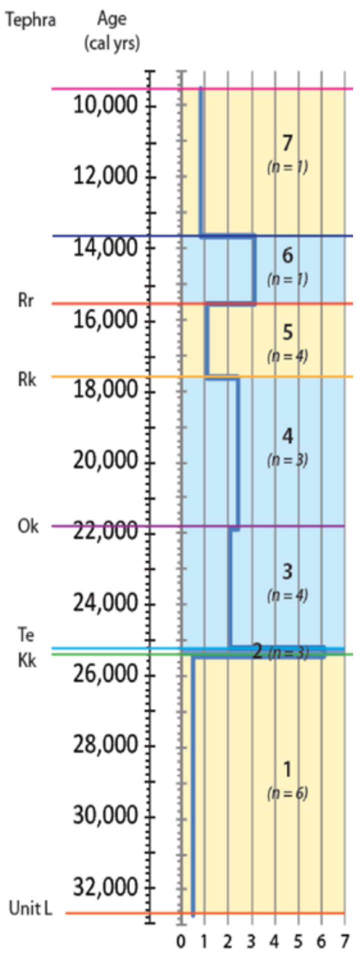


Fig. 13 Average loess accumulation rate in centimetres per century in the wider Rotorua area between c. 33 and 9.5 cal ka (rates shown at base of diagram). The bold numbers in each zone refer to the Rotorua CES (Fig. 15); *n* = number of sites measured for each loess zone. Tephra abbreviations as in Table 1 (from Lanigan, 2012).

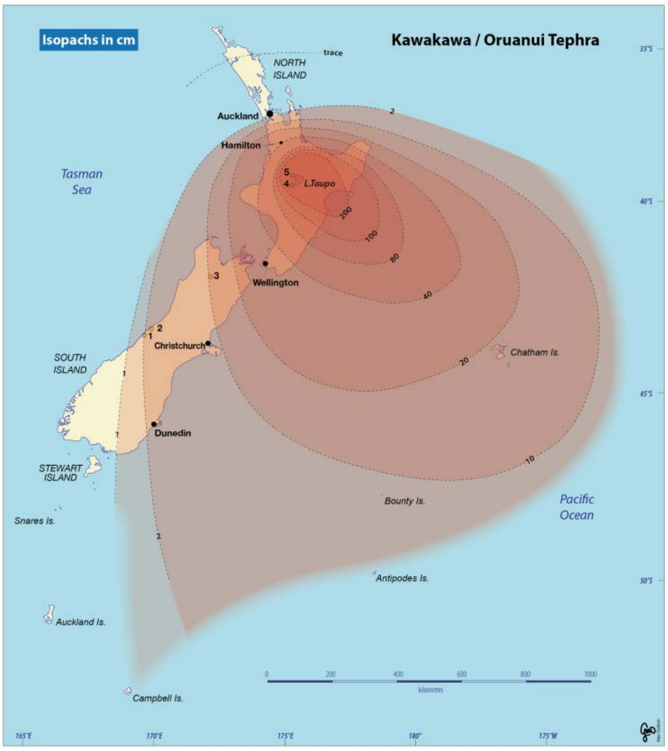


Fig. 14 Distribution of the Kawakawa tephra, a key marker bed for the LGM in the New Zealand region. Isopachs in cm. Numbers refer to sites where samples were taken to re-date the tephra recently (c. 25.4 cal ka) (from Vandergoes et al., 2013). See also Wilson (2001) for information about the eruption and its products.

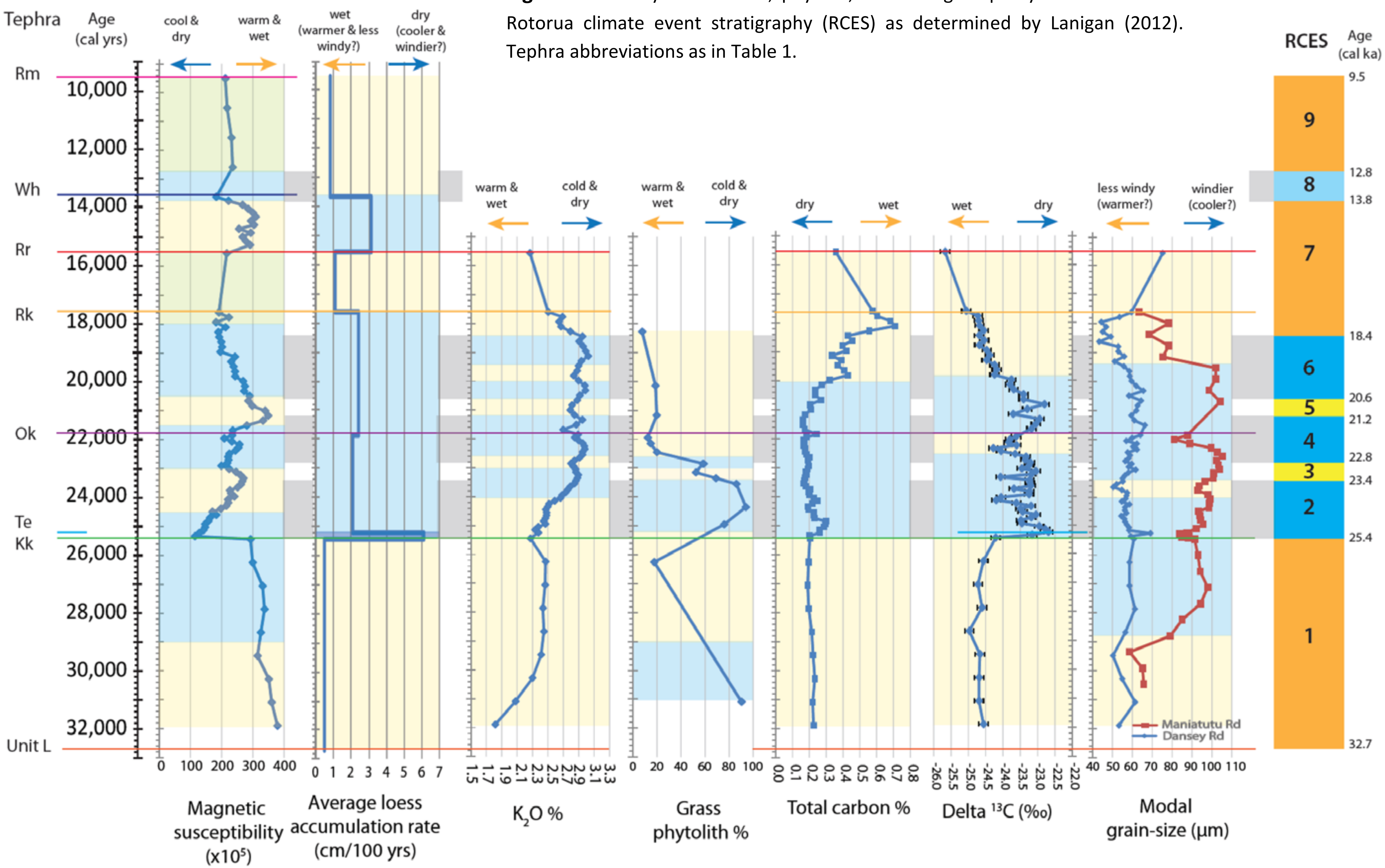


Fig. 15 Summary of chemical, physical, and biological proxy records and the Rotorua climate event stratigraphy (RCES) as determined by Lanigan (2012). Tephra abbreviations as in Table 1.

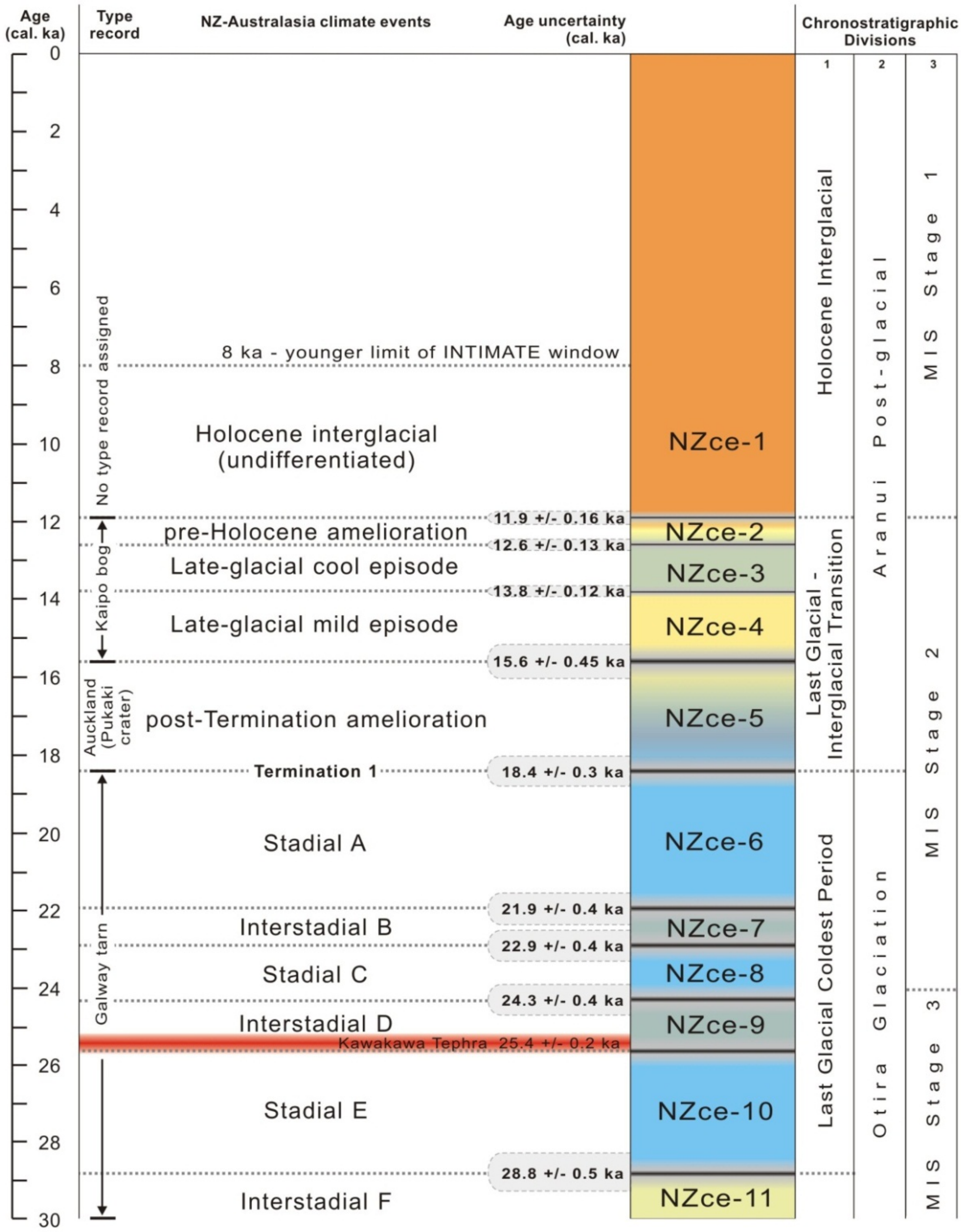


Fig. 16 The provisional NZ-INTIMATE* climate event stratigraphy based on boundaries derived from the composite stratotype (courtesy of David Barrell, from Barrell et al., 2013). The colour scheme schematically illustrates characteristic atmospheric temperatures (orange = warmest, blue = coldest). Chronostratigraphic schemes are (1) major climate phases in New Zealand (Alloway et al., 2007); (2) New Zealand climate-based timestratigraphic stages from Gage and Suggate (1958) and Suggate (1961), and (3) global marine-oxygen isotope scale (MIS) stages (Martinson et al., 1987). Note that errors on the ages for the boundaries of events (in 1000s of years BP, ka) will change slightly when this figure is revised during re-submission of Barrell et al. (2013). Tephras define the boundaries between NZce-10 and NZce-9 (Kawakawa tephra), NZce-5 and NZce-4 (Rotorua tephra), and NZce-2 and NZce-1 (Konini tephra [bed b], aged 11,888 ± 183 cal yr BP), which also defines the Pleistocene-Holocene boundary of the auxiliary stratotype for Australasia: Walker et al., 2009). Other tephras approximately mark the boundaries of events NZce-11 and NZce-10 (Poihipi tephra), NZce-7 and NZce-6 (Okareka tephra), NZce-6 and NZce-5 (Rerewhakaaitu tephra), and NZce-3 and NZce-2 (Waiohau tephra) (Barrell et al., 2013; Lowe et al., 2013).

*__INT__egration of __I__ce-core, __MA__rine, and __TE__rrestrial records for the period 30 to 8 cal ka

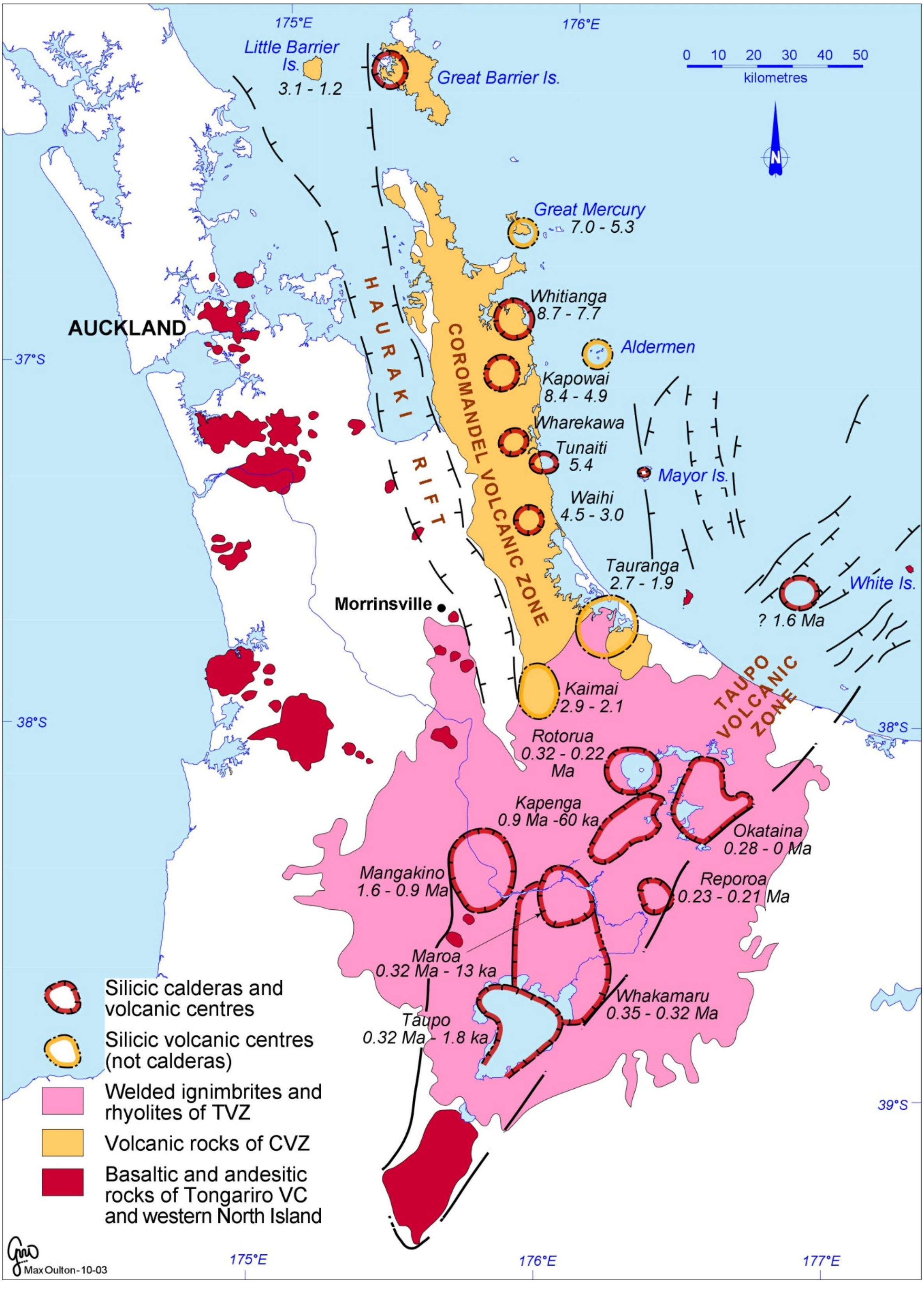


Fig. 17 Volcanic centres and the ages of activity and rocks (including welded ignimbrites) of central North Island (courtesy of Roger Briggs, after Briggs et al., 2005). See also Wilson et al. (2009).

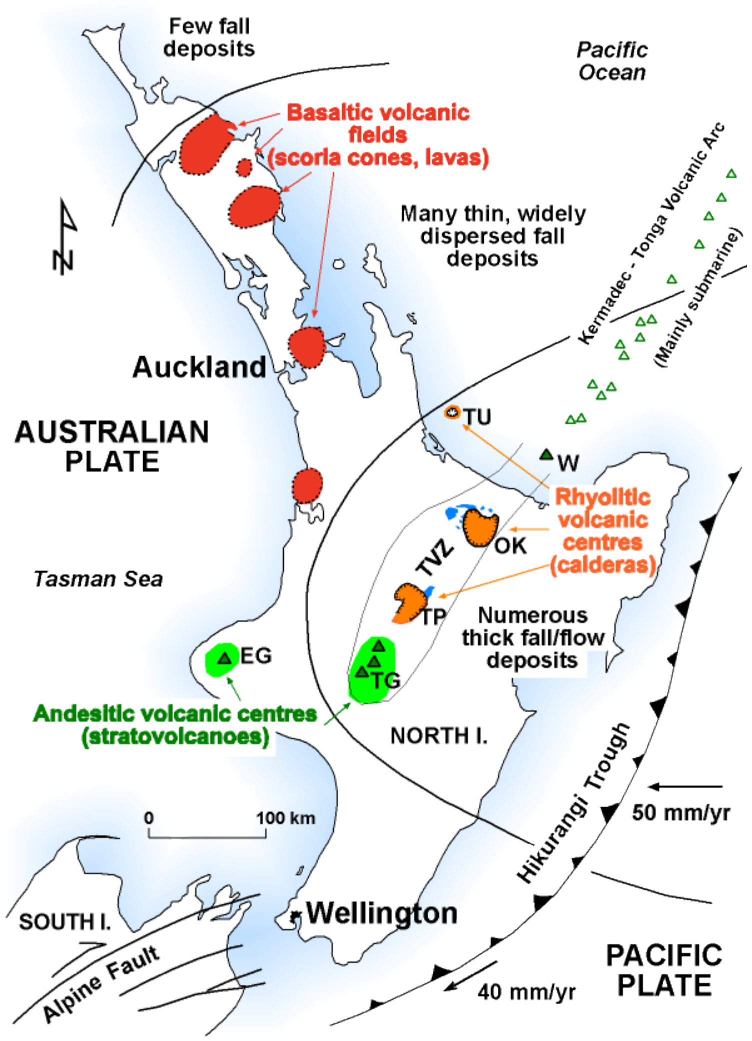


Fig. 18 Map showing plate tectonic setting, the main volcanic centres that produced parent materials for many tephra-derived soils, and the general dispersal of tephra on North Island (from Lowe and Palmer, 2005). EG, Egmont/Taranaki volcano; TG, Tongariro Volcanic Centre (includes Ngauruhoe, Tongariro, 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.

Table 3 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

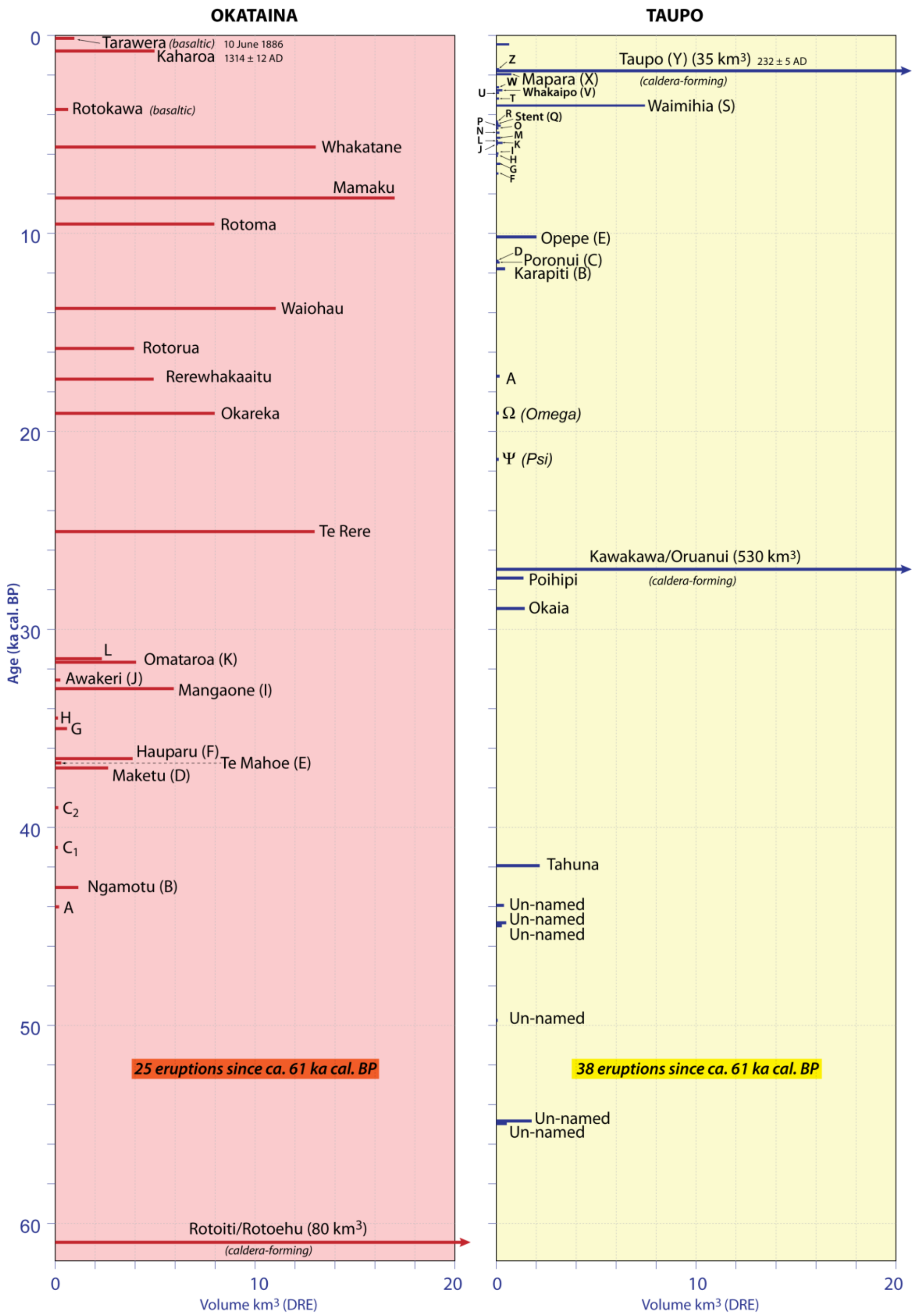


Fig. 19. Interfingering stratigraphic relationships, ages, and volumes (as non-vesiculated, void-free magma or dense-rock equivalent, DRE; multiply by ~3 to obtain approximate bulk volumes) of tephras erupted from Okataina and Taupo caldera volcanoes in North Island, New Zealand, since c. 61 ka cal BP (based on Wilson et al., 2009). Another significant unit (not depicted) is the rhyolitic Earthquake Flat tephra (EFT) (7 km^3 DRE), erupted from the Kapenga caldera volcano (adjacent to Okataina, Fig. 17) immediately after the Rotoiti/Rotoehu eruption. Note that since this diagram was published by Lowe (2011), Danišík et al. (2012) re-dated the Rotoiti/Rotoehu and EFT eruptives using (U-Th)/He and high-resolution ^{14}C dating to attain ages of c. 45-50 cal ka; Vandergoes et al. (2013) re-dated the Kawakawa/Oruanui eruptives using high-resolution ^{14}C dating on new, optimal sample materials to derive an age 25,358 ± 162 cal yr BP (2σ); and ages on around 20 other widespread tephras erupted since 30,000 cal yr BP were revised by Lowe et al. (2008b, 2013).

Stop 1 Goodwin Farm section, Tapapa Road, Mamaku Plateau

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), palaeomagnetic reversal/excursion, correlation with marine oxygen isotope stages.

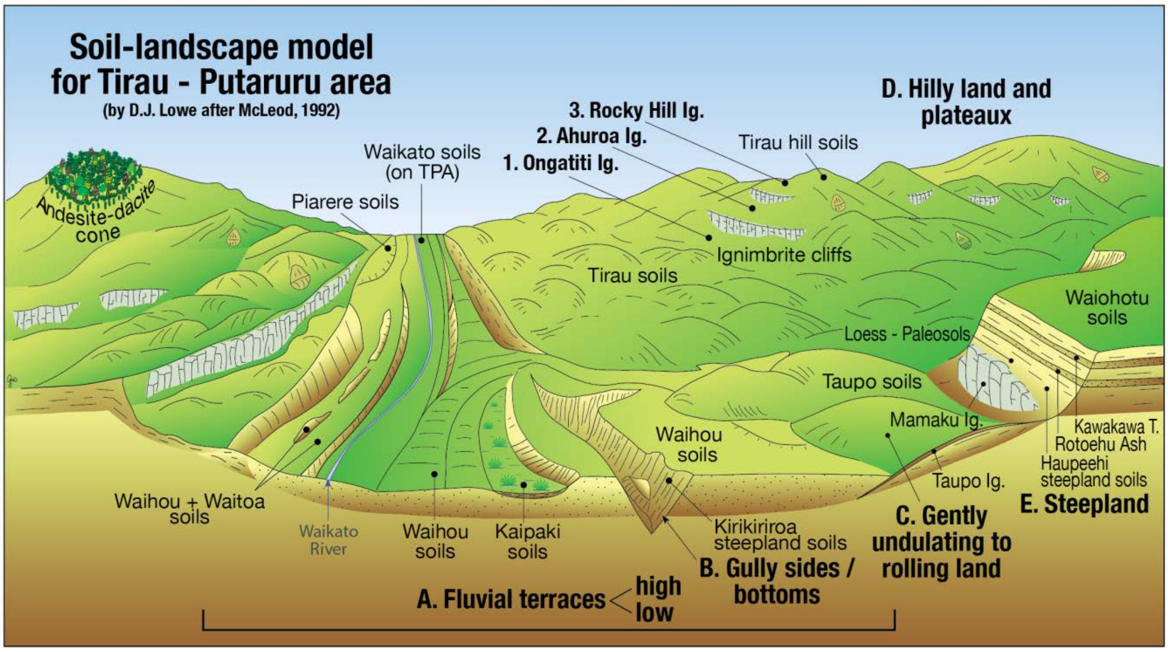


Fig. 20 Soil-landscape model for the Tirau-Putarura area and Tapapa. The three main welded ignimbrite units (~1.23 Ma to 0.9 Ma) form distinctive plateaux in the landscape and are mantled with tephra-fall deposits and subordinate tephric loess. Younger welded Mamaku Ignimbrite is present to the SE. Fluvial terraces are also mantled with tephras. TPA, Taupo Pumice Alluvium (c. 1.7 cal ka) (diagram by D.J. Lowe after McLeod, 1992).

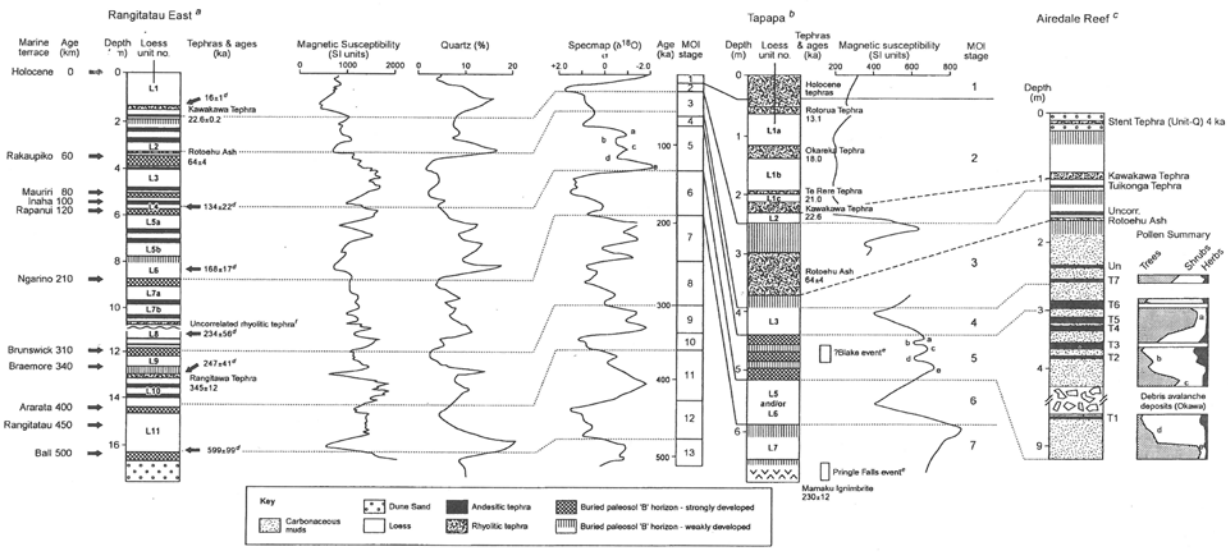


Fig. 21 Correlation of Tapapa section with Rangitatau East section near Wanganui, and Airedale Reef section near New Plymouth (from Newnham et al., 1999). The sections are connected using tephras common to each (tephrochronology). Magnetic reversals indicated at Tapapa are possibly equivalent to the Blake event (c. 120 ka) and Pringle Falls event (c. 220 ka).

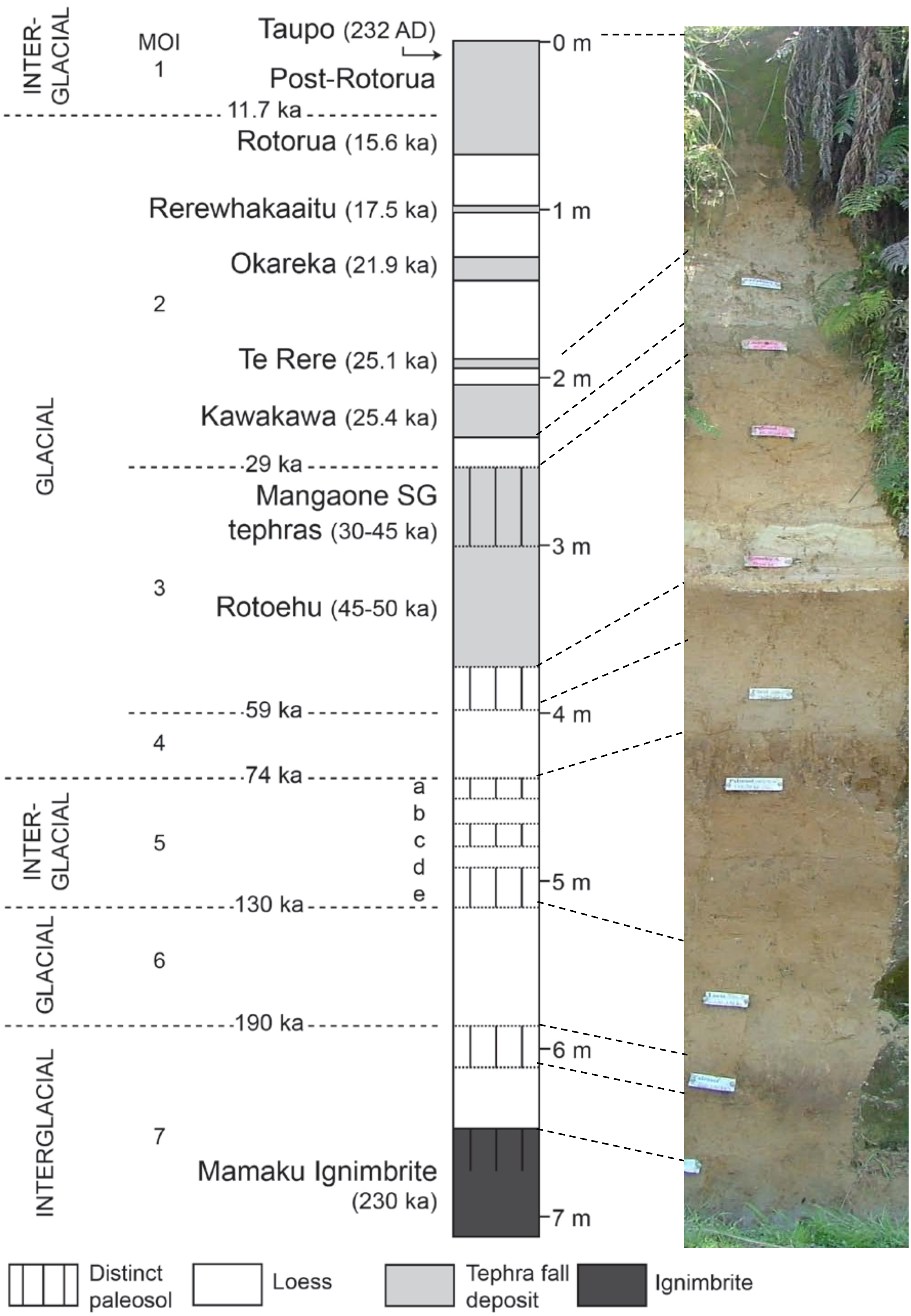
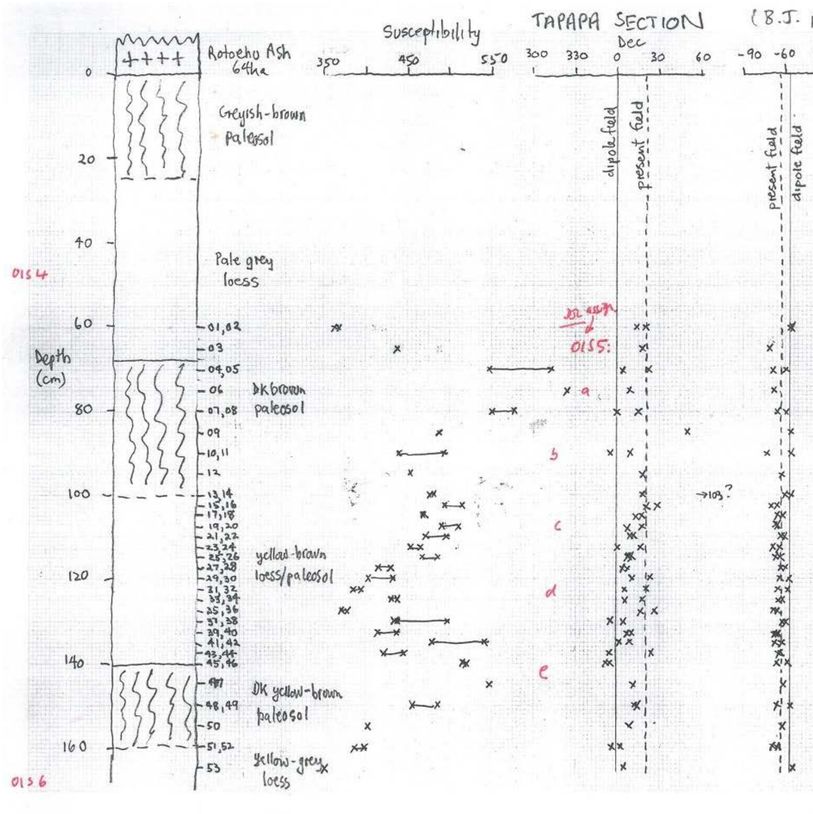


Fig. 22 Stratigraphy and chronology of Tapapa sequence and provisional correlation with marine oxygen isotope (MOI) stages (ages based on Froggatt, 1988; Kimber et al., 1994; Shane et al., 1994; Houghton et al., 1995; Lowe et al., 2008b, in press; Danišík et al., 2012). Unpublished data from D.J. Lowe, J.E. Begét, B.J. Pillans. Earlier work on uppermost part of the sequence was undertaken by Pullar and Birrell (1973). Soil series = Tirau.

Fig. 23 Tapapa section. Tephras preserved in nearby Lake Okoroire (~10 km NW of Tapapa; only Holocene tephras in core shown here) provide a record of tephra fall in the area since c. 20 cal ka (Lowe, 1986, 1988).



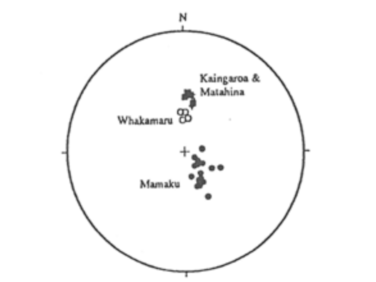
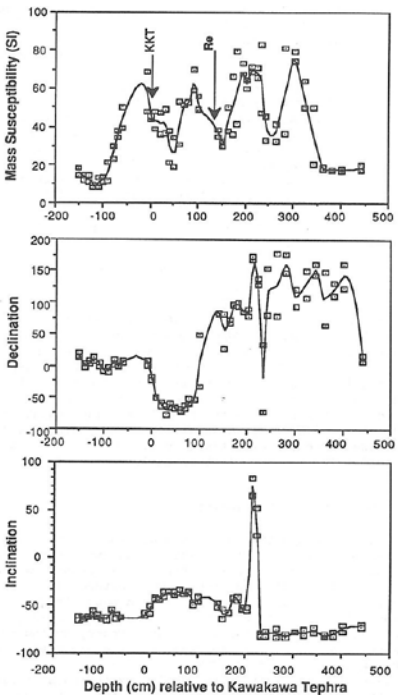


Fig. 25 Stereographic projection for 4 ignimbrites showing reversed signature for 230-ka Mamaku Ignimbrite (from Shane et al., 1994).

Fig. 24 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). The gritty base of Kawakawa/Oruanui tephra at Tapapa is unit 7 of Wilson (2001), with accretionary lapilli marking the top contact of this layer (C.J.N. Wilson pers. comm., 2008).



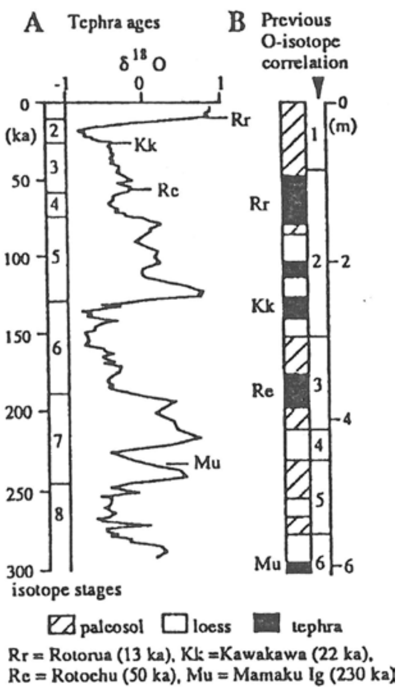


Fig. 26 (left) Paleomagnetic data for Tapapa section including possible Blake event c. 120 ka in ~MOIS 5d (from Froggatt, 1988). **Fig. 27** (right) Revised chronology of Tapapa sequence and correlation with MOI stages (from Shane et al., 1994). Ages on Mamaku Ignimbrite: 230 ± 12 ka (Shane et al., 1994); 220 ± 10 ka (Houghton et al., 1995); correlation to Pringle Falls event: 223 ± 4 ka (Shane et al., 1994; McWilliams, 2001).

Stop 2 Oturoa Road section, Mamaku Plateau

Location BE37 792845, 38° 02.643' S 175° 10.840' E; elevation ~380 m

Fig. 28 Oturoa Rd section (photographed 12 September, 2012). Rk, Rerewhakaaitu tephra; Kk, Kawakawa tephra (see Table 1 for ages). Note: A field test for Fe^{2+} in soil solution gave a positive reaction for the loess deposits between Rerewhakaaitu and Okareka tephras. Soil series = Ngakuru.

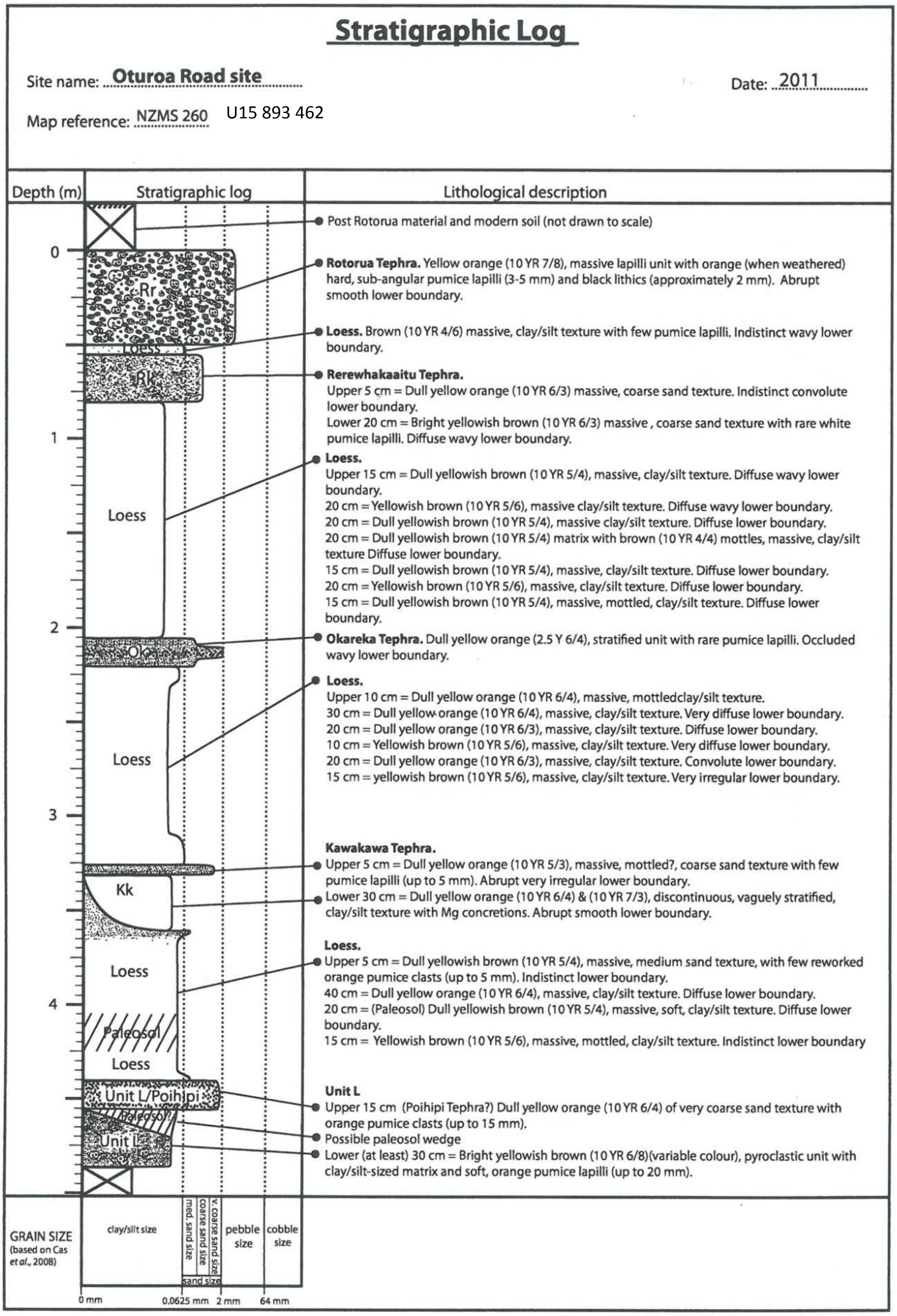


Fig. 29 Stratigraphic log of Oturoa Rd section (from Lanigan, 2012). Probable Poihipi tephra (28.4 cal ka) occurs at about 4.6 m depth, and the thin layer of coarse sand described at c. 5 m is probably tephric colluvium. Unit L is aged c. 33 cal ka. See Fig. 15 for a paleoclimatic interpretation relating to this and other sections in the Rotorua area.

Stop 3 Brett Road section, Lake Rerewhakaaitu

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

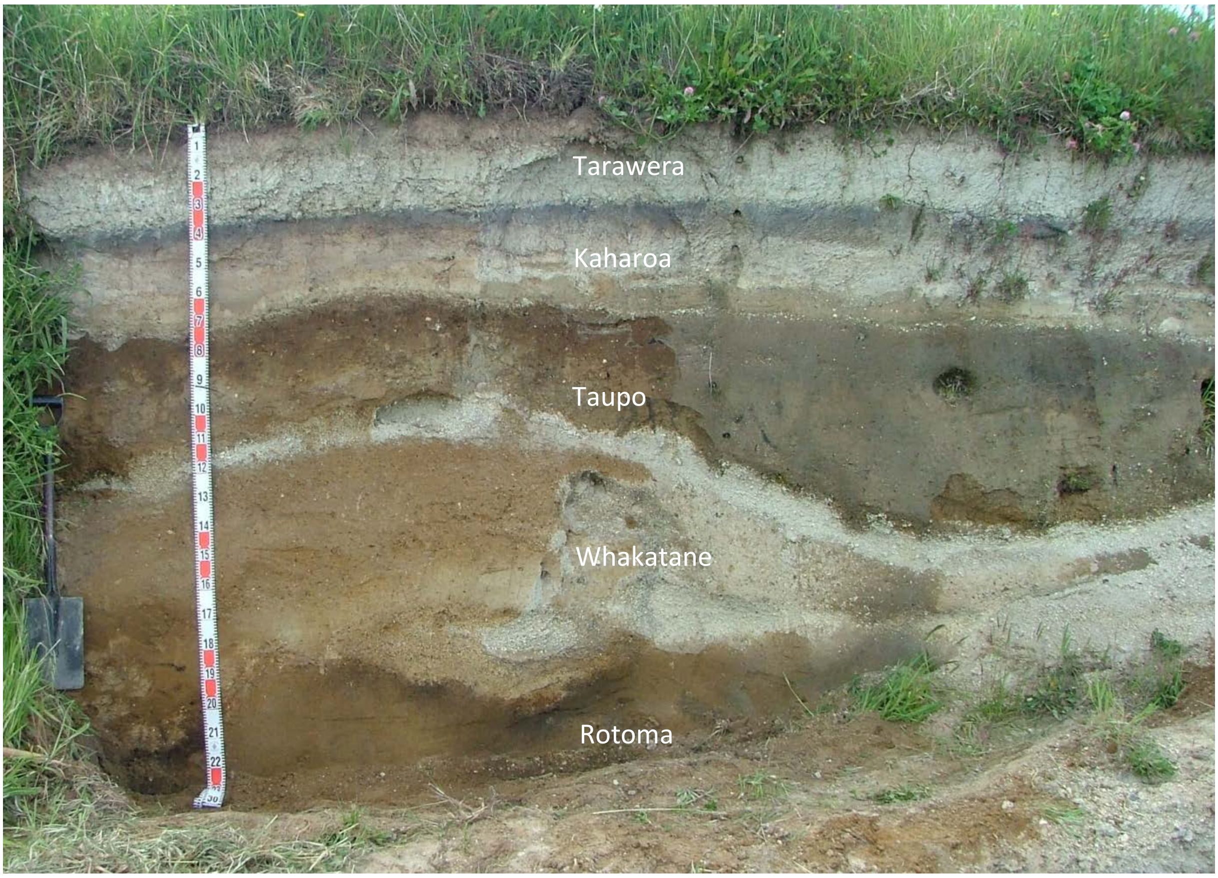


Fig. 30 Stratigraphy of the Brett Rd section (see also Fig. 4 which shows the soil horizonation at this section). Ages of tephras are given in Table 1. The uppermost 'mini' soil profile on Rotomahana Mud, containing ~20% clay, has a distinctive mineralogy including a zeolite, mordenite (e.g., Kirkman, 1976). Soil series = Rotomahana.

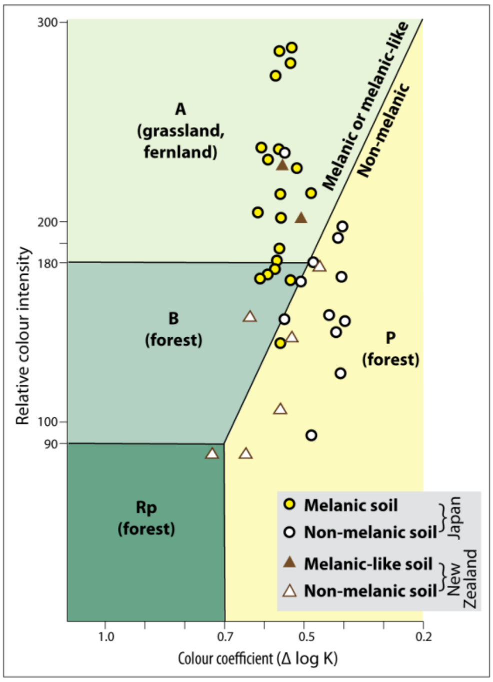


Fig. 31 Comparison of humic acids from volcanic ash-derived soils in Japan and New Zealand (after Watanabe and Sakagami, 1999). The buried soil on Kaharoa tephra is melanic-like and contains charcoal (probably from Polynesian burning; see text below).

Buried brown 'topsoil' horizons

Buried 'A' horizons in NZ on tephras tend to be brownish rather than dark or black (and hence often have AB or Bw 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 Andisols, 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. 32). Residual colours after removing organic matter from A horizons by H_2O_2 or burning are similar to those of buried horizons on the tephras (P.J. Tonkin pers. comm., 2006). Finally, 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.

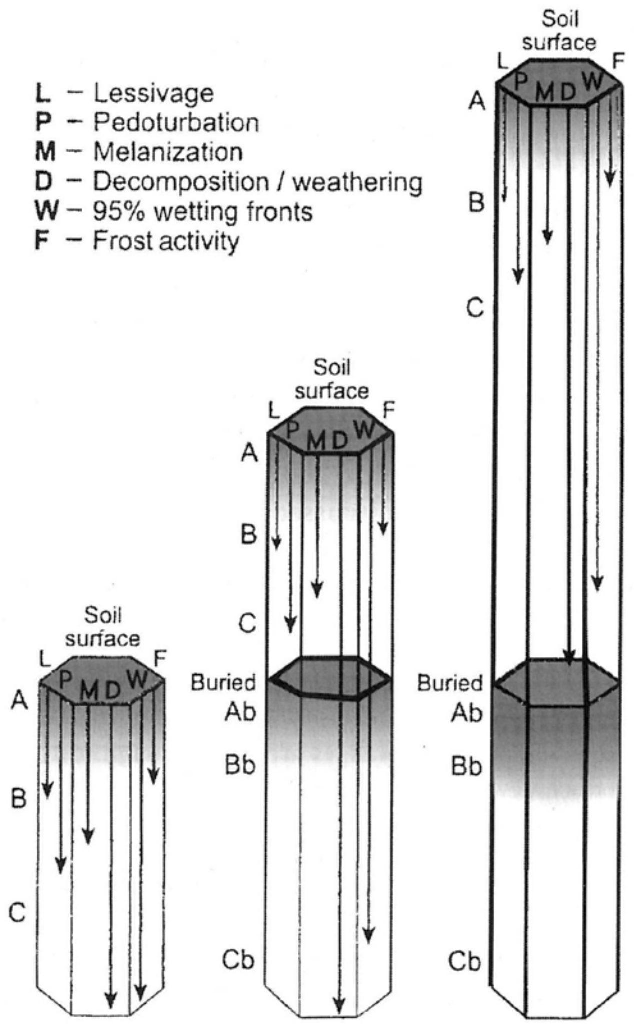


Fig. 32 Idealised model of buried soils at different depths and how they may be impacted by surficial (topdown) processes (from Schaetzl and Anderson, 2005).

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 4; 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 '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 Rerewhakaaitu area) showed that type-A humic acids predominated and that fernland and grassland had replaced the pre-existing forests (Fig. 31) (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). The repeated burning resulted in the formation of extensive fernlands (McGlone et al., 2005).

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.

Table 4 Bracken biomass comparisons – New Zealand and northern Idaho, USA*

	Rhizome biomass		**Frond biomass**	
Location	Mean	Range	Mean	Range
	(kg m^{-2})		(kg m^{-2})	
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 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 5), 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 5 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) (Fig. 31). 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).

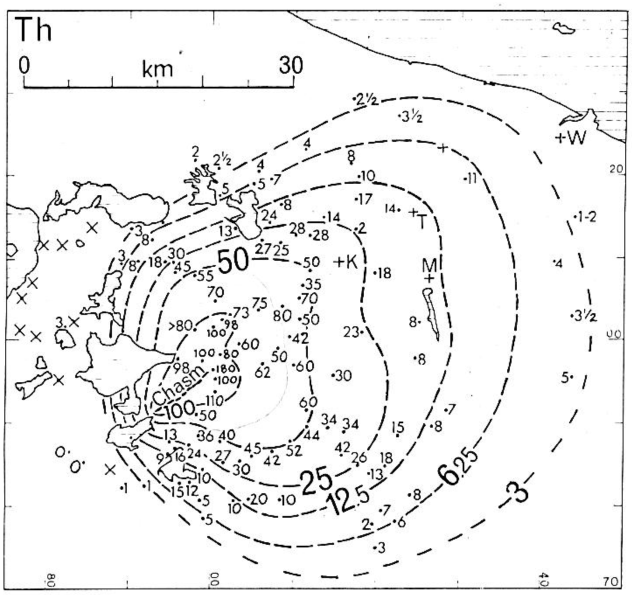


Fig. 33 Isopach map of 1886 Tarawera scoria fallout (in cm). x = location where scoria occurs mixed with Rotomahana Mud, but does not form a discrete layer (from Walker et al., 1984).

Tarawera eruption and catastrophic impacts

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.

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. 34). 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).

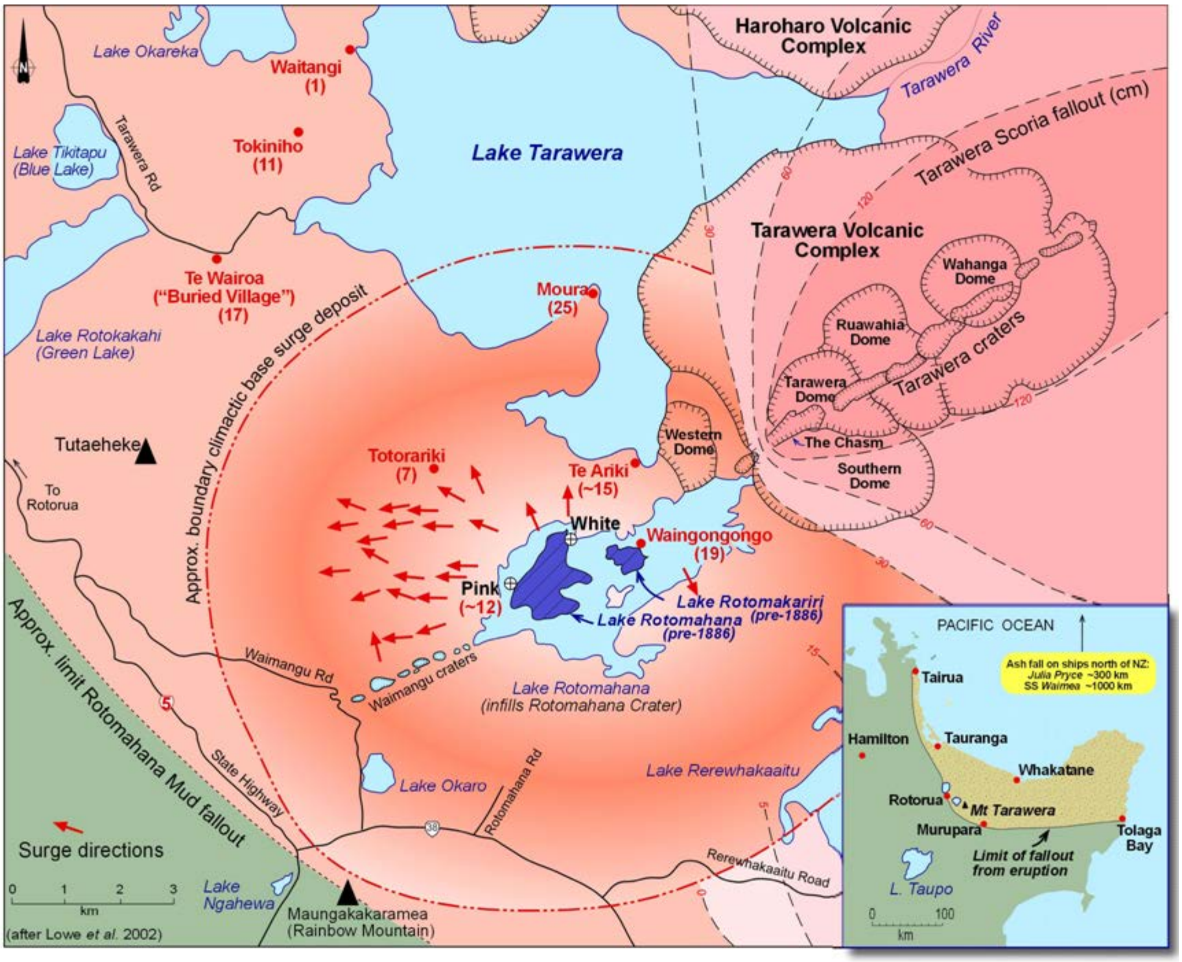


Fig. 34 Map of Tarawera area showing locations of the main craters of the 10 June 1886 fissure eruption across Tarawera Volcanic Complex, Rotomahana Crater (including pre-eruption lakes Rotomahana and Rotomakariri), and Waimangu craters (after Lowe et al., 2002). Locations of villages and associated 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).

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).

Stop 4 Ash Pit Rd section, Lake Rerewhakaaitu

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

Fig. 35 Section on Ash Pit Road with Mt Tarawera in background.

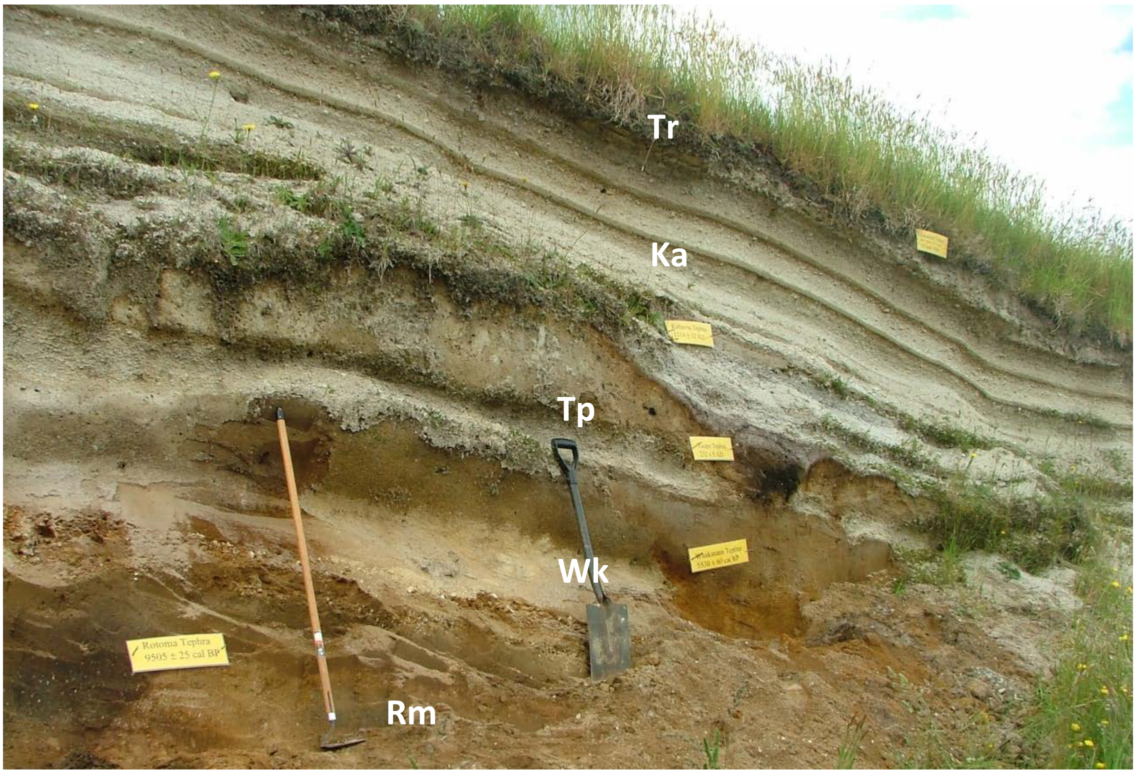


Fig. 36 Upper part of Ash Pit Rd sequence. Tr, Tarawera; Ka, Kaharoa (eruptive units A-H, 1st phase of eruption, emplaced in c. 27 hours: Nairn et al., 2004); Tp, Taupo; Wk, Whakatane; Rm, Rotoma. Ages are given in Table 1.

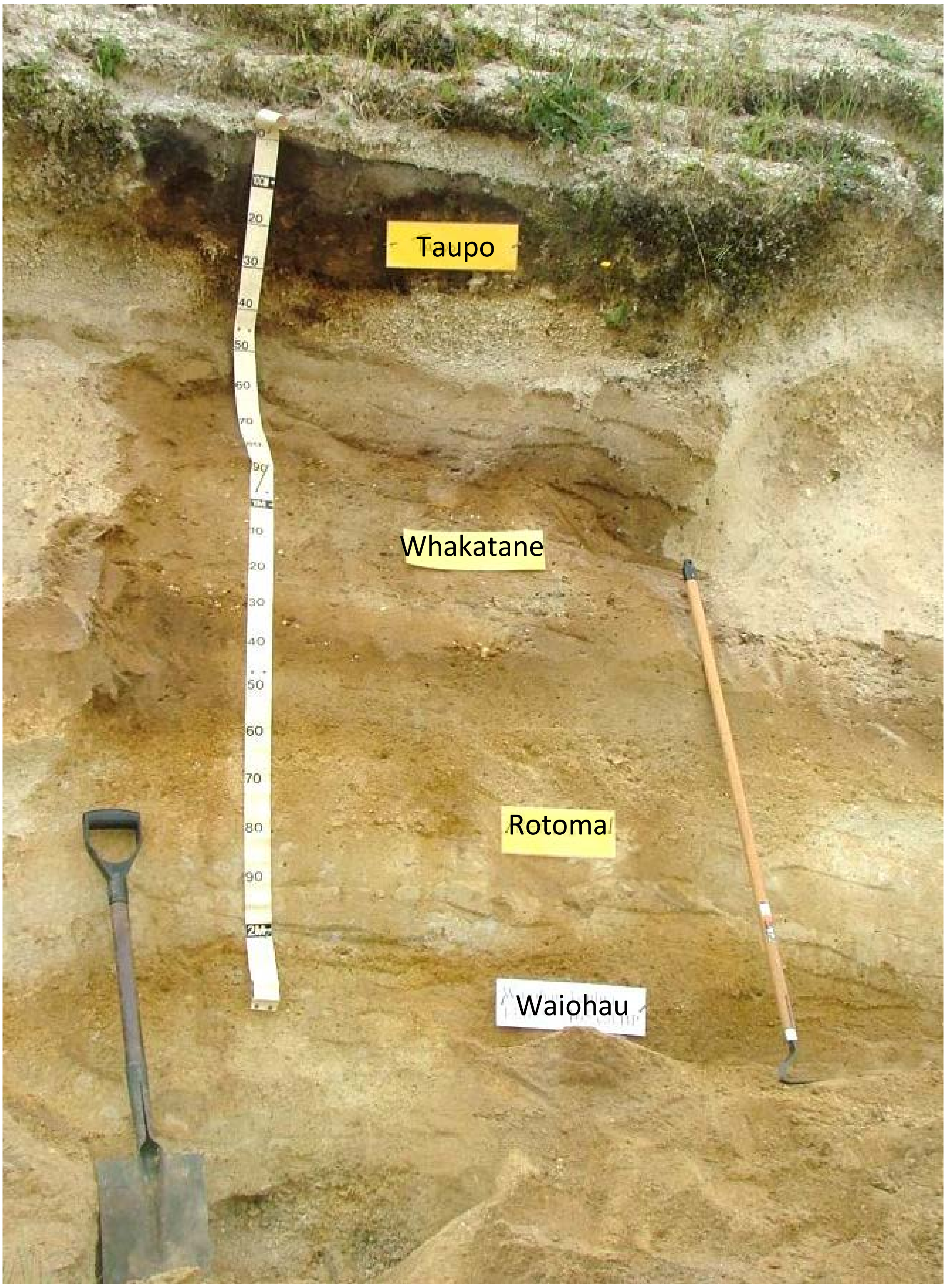


Fig. 37 Lower part of Ash Pit Rd sequence. Note the clear podzol-profile morphology (distinct E horizon on a Bh horizon, referred to as a spodic or podzolic-B horizon) evident on Taupo tephra, and another weak E horizon beneath Taupo on Whakatane tephra (see also Fig. 38). A blotchy E horizon also occurs 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. 39, below). 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 ('geology meets pedology').

On the topic of ashfall hazards relating to dairy farms in this area, see Wilson and Cole (2007).

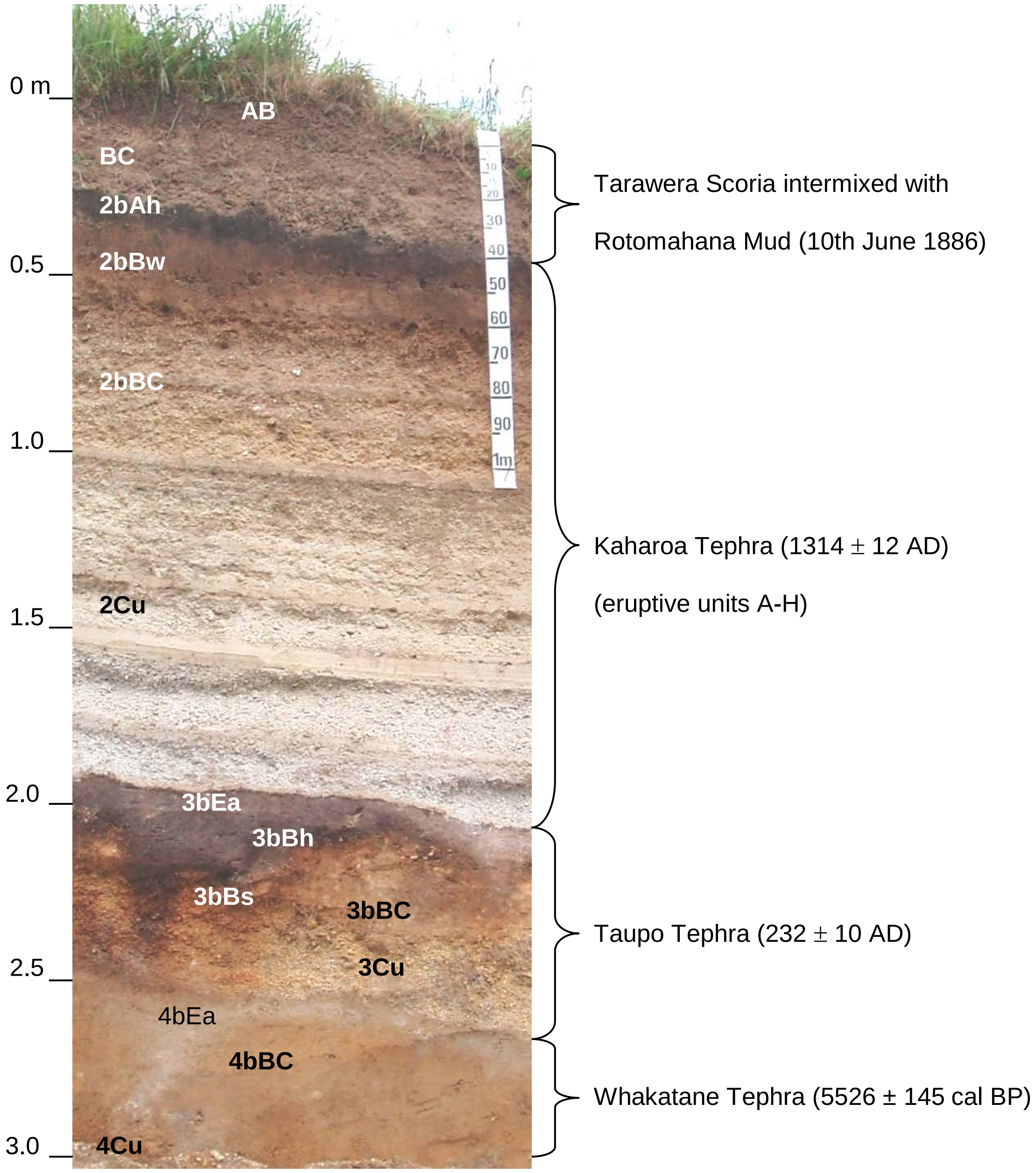


Fig. 38 Upper-part of Ash Pit Rd sequence showing the geological layers and the soil horizonation that has been developed in them (from H.S. Jones in Lowe et al., 2010). The podzol-profile morphology, notably the distinct 3bEa on 3bBh and 3bBs horizons, and 4bEa on 4bBC horizons below, on Taupo and on Whakatane tephras, respectively, probably follow a large root channel. Soil series = Matahina.

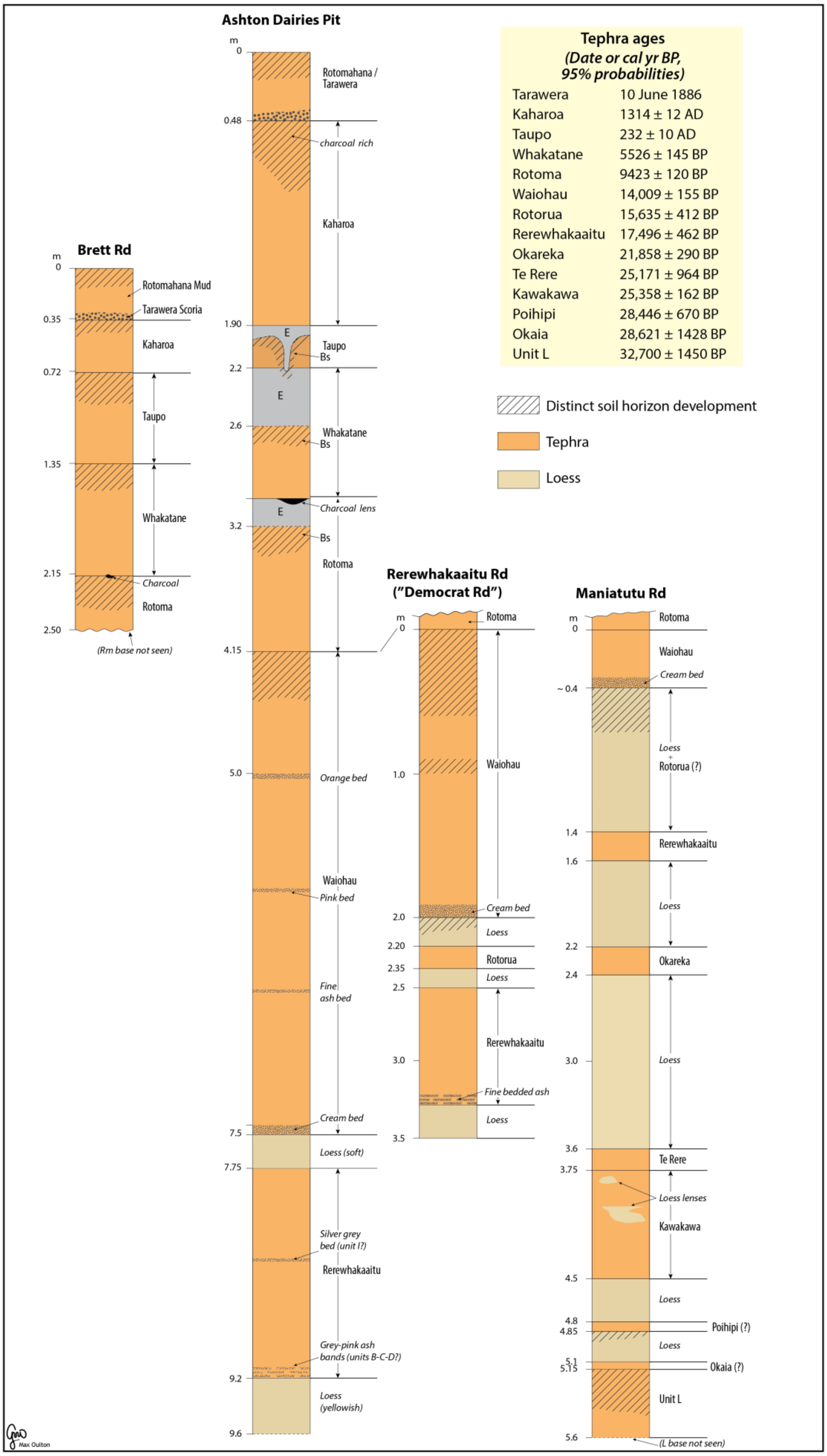


Fig. 39 Summary stratigraphy in the Lake Rerewkahaaitu area at Brett Rd, Ashton Dairies pit, and Rerewhakaaitu Rd sections, and a fourth sequence at Maniatutu Rd near Lake Rotoiti (D.J. Lowe unpublished, based on Marsden-funded research currently in progress "New views from old soils").

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Hazard Management Plan

Field trip 2 "Geology meets pedology" for Geosciences Society of NZ conference 2012

Date: Sunday 25 November 2012
Field trip leaders and van drivers: Prof David Lowe, Dr David Palmer
First aid: Appropriate first aid kits carried in vans
Mobile phone numbers: Prof David Lowe 021 027 727 07, Dr David Palmer 021 062 9509
Traffic safety manager: Chris McKinnon 027 246 6172
Please note: No smoking in vehicles or within 20 m of other field trip participants at stops
Route and main stops:
Hamilton-SH1-SH5-Tapapa Rd (Mamaku Plateau) to **stop 1 Goodwin Farm cutting**
SH5 Fitzgerald Glade café
SH5-Oturoa Rd **stop 2 Oturoa Rd section** (~1.5 km east of Fleming Rd junction)
SH 5 to Ngongataha village centre (Hall St) then lakeside reserve in Reeme St **Lunch**
SH 5 – Old Taupo Rd – SH5 – Waimangu Rd – SH 38 (Murupara Rd) – Rerewhakaaitu Rd-Brett Rd to **stop 3 Brett Rd cutting**
Brett Rd-Ash Pit Rd (towards Mt Tarawera) to **stop 4 Ash Pit Rd cutting**
Half Moon Bay, Lake Rerewhakaaitu
Return to Hamilton via SH38 and SH5
Transport arrangements: Vans depart and return to Student Village car park (Knighton Rd) (access via Gate 1, Knighton Rd)
Leave time: 8.00 am
Return time: approx 5.30 pm

Location 1: Tapapa Rd (stop 1)	**Time:** ~ 9.00-10.00 am
Hazard: Traffic on Tapapa Rd; walking up farm road (milk tanker access – tanker comes evenings)	
Mitigation: Cross road when all clear, wear boots to walk up farm road	
Hazard: Cleaning profile with spade or Niwashi: hazards include possibly injuring toes or fingers or muscle/back strain in digging	
Mitigation: Wear boots or sturdy footwear as instructed and always ask others in group to stand/move well clear when <u>any</u> digging with spade or trowel is occurring (use verbal warning). Digger to be cautious in operating spade to avoid overuse or strain of back, careful of toes etc and to take frequent rests	

Location 2: Fitzgerald Glade café	**Time:** ~ 10.05-10.25 am
Hazard: Traffic on main road/car park	
Mitigation: Don't go on main road, be aware of moving vehicles at all times in car park	

Location 3: Oturoa Rd section (stop 2)	**Time:** ~ 10.50-11.30 am
Hazard: Traffic on road from both directions. Be especially careful and alert at this stop.	
Mitigation: Vans to park on roadside east of cutting facing Lake Rotorua (hazard lights flashing) (i.e. *not* opposite cutting); all participants to wear fluoro vests; cones placed on roadway; warning signs to be placed on both sides of roadway approx 100 m to the west and to the east; participants to watch for traffic and traffic safety manager to station himself about 100 m west of cutting on Oturoa Rd and to flag down drivers as they approach from the west	

Location 4: Ngongataha village centre (Hall St)	**Time:** ~ 11.40 am-11.50 am
Hazard: Traffic in village centre	
Mitigation: Take care crossing road if necessary (use crossing)	

Location 5: Ngongataha lakeside reserve (Reeme St) (lunch)	**Time: ~**12.00 -12.30 pm
Hazard: Hyperthermia or drowning if enter lake	
Mitigation: Do not enter lake	

Location 6: Brett Rd section (stop 3)	**Time:** ~ 1.10 pm-2.10 pm
Hazard: Traffic on road	
Mitigation: Vans to park on roadside well north of cutting (same side as cutting) (hazard lights flashing); all participants to wear fluoro vests; cones placed on roadway; warning signs to be placed on both sides of roadway approx 100 m to the north and to the south; all participants to be extra careful here and to watch for traffic and traffic safety manager to station himself about 100 m west of cutting on Brett Rd and to flag down drivers as they approach from the south	
Hazard: Cleaning profile with spade or Niwashi: hazards include possibly injuring toes or fingers or muscle/back strain in digging	
Mitigation: Wear boots or sturdy footwear as instructed and always ask others in group to stand/move well clear when any digging with spade or trowel is occurring (use verbal warning). Digger to be cautious in operating spade to avoid overuse or strain of back, careful of toes etc and to take frequent rests	

Location 7: Ash Pit Rd section (stop 4)	**Time:** ~2.25-2.55 pm
Hazard: Traffic on road	
Mitigation: Vans to park off roadside adjacent to cutting (hazard lights flashing); all participants to wear fluoro vests; cones placed on roadway as warnings on cutting side. Cutting is off the road	

Location 8: Half-Moon Bay, L. Rerewhakaaitu	**Time:** ~3.00-3.30 pm
Hazard: Hyperthermia or drowning if enter lake	
Mitigation: Do not enter lake	

Emergency plan: Leaders and/or others provide first aid and seek emergency help via 111

Point of contact in Hamilton: Dr Adrian Pittari 021 025 38762

Local emergency agency: Police, fire, ambulance

Field trip 2 "Geology meets pedology", Sunday 25 November, 2012

My name:
My mobile phone number:
Emergency contact person (name):
Emergency contact person's relationship to me:
Emergency contact person's phone number:
Special requirements dietary and health:

I have been advised about the physical and safety requirements and the hazards and their mitigations of this field trip and have been given the opportunity to advise the field trip organisers of any special requirements I have. Under the Privacy Act 1993, I agree to the leader collecting and maintaining this information in strict confidence for the purposes of ensuring that information necessary for health and safety in an emergency is available. A copy of your contact details, and the tour hazard management plan, will be lodged with the conference convenor in Hamilton on the day of the trip as the trip's 'point of contact' in Hamilton for any emergency communications that may be needed. All information (originals and copies) will be destroyed after the trip.

Signed: _________________________

Date: ___________ November 2012

Please send this 'contact details' page to David Lowe via email (d.lowe@waikato.ac.nz) before Friday 23 November, 2012