Origin and classification of Kainui silt loam: update on the leopard that changed its spots*

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Introduction

Around 30 years ago, the editors of *New Zealand Soil News* (Val Orchard and Lee Searle at the time) invited members to contribute short articles on their 'pet profiles' – that is, on a representative soil of their favourite series, describing key morphological and other features and explaining why the soil is important. I wrote such an article in 1991 on the Kainui silt loam (Lowe, 1991), a soil on which I had worked for part of my masterate research. Funnily enough, my article, number 11, was the last 'pet profile' to be published (Table 1). I have always wondered why. Perhaps the answer lies with the massive upheaval of science in New Zealand that occurred on 1 July 1992, when the CRIs came into existence. Possibly no one had time thereafter for 'frivolities' such as writing simple, short articles of interest to a wide readership? All the pet profiles provide useful information, unique insight, passion, and humour in just a page or two. We should resurrect the series.

Table 1. Pet profiles published in *NZ Soil News* 1988–1991

Author	Profile no.	Soil (series)	Year
David Lowe	11	Kainui	1991
Peter Singleton	10	Hauraki	
Wim Rijkse	9	Katikati	
Ian Smalley	8	Timaru	
Geoff Mew	7	Mahinapua	1990
Bob Lee	6	Addison	
Wim Rijkse	5	Opotiki	
Roger Parfitt	4	Egmont	
Michael Leamy	3	Conroy	
Wim Rijkse	2	Taupo	1988
Peter McIntosh	1	Otama	

Why Kainui? To paraphrase Churchill, it is a riddle wrapped in a mystery inside an enigma. No other soil provides such interest at the heart of pedology: puzzling origins, perplexing mineralogy, and problematic classification. Summarised below are some of the advances since 1991 regarding the Kainui silt loam and its genesis and classification. I have published a more detailed account elsewhere (Lowe, 2019).

Origin of Kainui silt loam: key features

Key points about the Kainui silt loam (Kainui soil hereafter) are many, perhaps the critical one being the need to appreciate that soil stratigraphy – the interplay between geological deposition, soil formation, buried soils, and their chronological relationships, sometimes called pedostratigraphy (e.g. Palmer, 2013) – is central to understanding the soil's genesis, character, and classification. An Ultisol, the Kainui soil occurs widely on near-level summits, shoulders, and upper-middle backslopes of low rolling hills, and old terraces, of Mid-Quaternary age in and north of Hamilton city in the northern Hamilton lowlands, and in parts of the Piako and Hauraki areas to the north and northeast of Hamilton (McCraw, 1967; Bruce, 1979; Wilson, 1980; McLeod, 1984a, 1992; see also S-map online). It is essential to be aware of this distribution and realise that south of Hamilton (between Hamilton and Ohaupo), the Kainui soil morphs into soils of the Ohaupo and Otorohanga series, both of which are Andisols, mainly on rolling hills and hills in the Waipa area (Barrratt, 1981; Orbell, 1983; McLeod, 1984b). Reasons for differences between the Kainui and Otorohanga soils are described in Lowe (2019).

(1) The Kainui soil is a two-storeyed soil, the upper storey c. 0.4 to 0.7 m thick (c. 0.6 m on average) comprising a composite silt-rich coverbed of multiple, thin tephra layers deposited incrementally since c. 50,000 years ago (commonly denoted 'late Quaternary') overlying a buried paleosol on older, strongly weathered clay-rich Hamilton Ash beds (the lower storey) (Fig. 1). The profile *in toto*, extending to a metre in depth, thus encompasses two main 'units' easily seen in road cuts when the profile is dry because of the contrasting colours and textures.

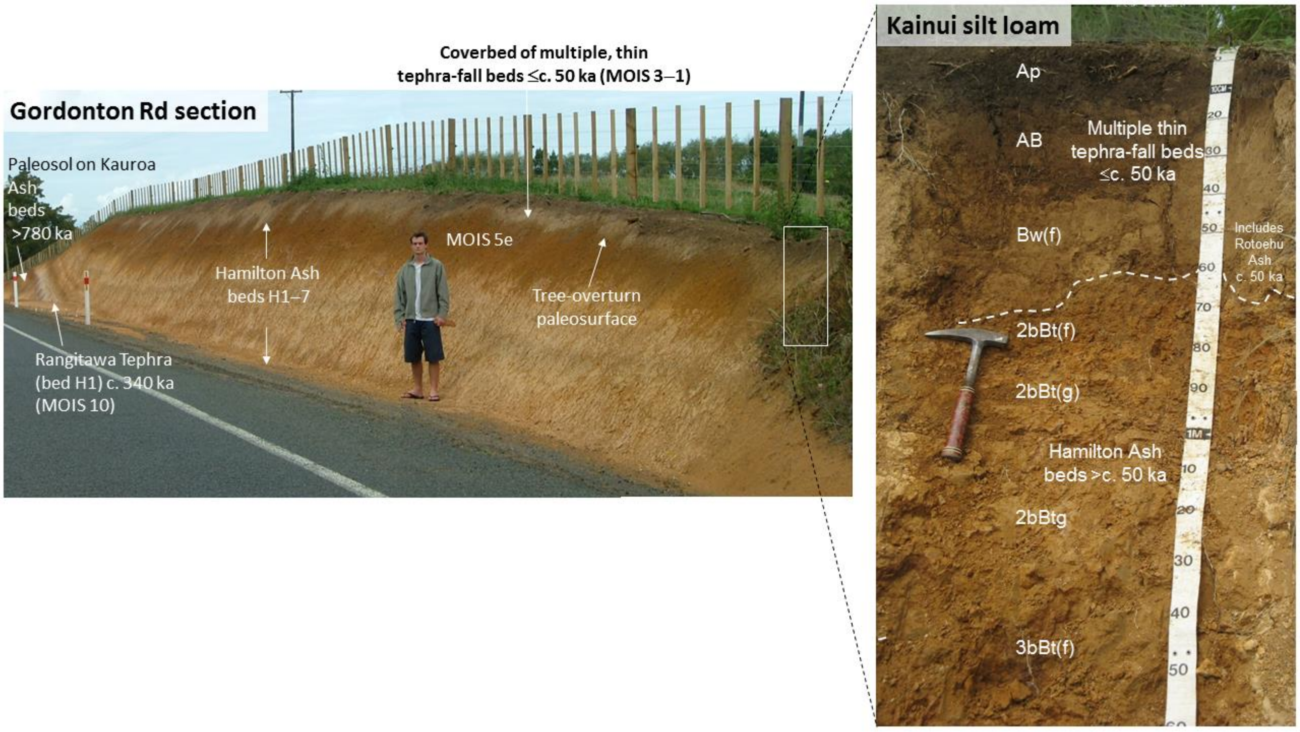

Figure 1. **Left:** A long section exposing weathered tephras, including the Hamilton Ash beds, in a road cut on Gordonton Road about 3 km north of Hamilton (37°42'21" S, 175°18'14" E) (very near Zealong Tea Plantation). The dark reddish-brown soil horizons on the upper Hamilton Ash probably represent a paleosol dating back to the Last Interglacial, or Marine Oxygen Isotope Stage (MOIS) 5e. On top is the thin, silty coverbed of multiple late Quaternary tephras that have accreted one-by-one over the past c. 50,000 years. The paleosurface boundary, a lithological discontinuity, is distinctly wavy or irregular and marks tree-overturn hollows and mounds. The coverbed deposits are occasionally overthickened in the hollows that can be up to c. 1.2 m deep locally. In such deep hollows (>c. 0.8 m), upper profiles sporadically can be allophanic rather than halloysitic (Lowe, 1986). Near the base of the section is Rangitawa Tephra, aged c. 340 ka (pale bed at far left). It overlies unconformably a tiny remnant of a truly ancient landsurface represented by a buried, extremely clay-rich soil on bed K15, or Waiterimu Ash, of the Kauroa Ash sequence (Ward, 1967; Lowe et al., 2001). K15 is aged >c. 780 ka. Seb Lowe provides the scale. Photo: D.J. Lowe. **Right:** Profile of the Kainui soil at Gordonton Road comprising two distinctive parts separated by the lithological discontinuity (dashed line). Formed by developmental upbuilding pedogenesis, each component of the upper profile has previously been an 'A' horizon whilst the land surface has risen slowly since c. 50 ka as thin tephras were accreted at the site. Redoximorphic features in the Bw(f) horizon (>2% Mn-Fe concretions with some mangans) indicate prolonged periods near to saturation because of perching on the buried paleosol marked by the 2bBt(f) horizon. Consequently, the entire soil is dominated by halloysite, not allophane, because of limited desilication (Lowe, 2019). Photo: R. McEwan.

The soil looks much like the 'strong texture-contrast' or 'duplex' soils that are especially common in Australia (e.g. McKenzie et al., 2004) but it has quite different origins. Earlier ideas of the coverbed comprising loess (McCraw, 1967) were discounted because the mineralogy of the mantle is pyroclastic in origin (although the clay minerals did not seem 'to fit' that origin, as discussed below), and because adjacent 22,000-year-old (22 ka) lakes in the Hamilton lowlands contained in their organic-rich sediments many thin but well-preserved visible tephra-fall layers (Lowe, 1985, 1988, 2002).

These lacustrine tephra deposits (in the millimetre- to centimetre-thickness range) therefore provided an integrated 'dossier' of tephra fallout over the landscape since c. 22 ka. Equivalent thin, subaerial (dryland) tephra deposits make up the upper part of the coverbed (Lowe, 1986). Older, pre-22-ka tephras, include Kawakawa tephra (c. 25.4 ka), Okaia Tephra (c. 28.6 ka), Tāhuna Tephra (c. 39.3 ka), and Rotoehu Ash (c. 50 ka) (Lowe, 2019). The last three tephras were discovered well preserved beneath lake sediments at Lake Maratoto (Green and Lowe, 1985), which is about 7.5 km south of Hamilton (near Hamilton Airport). Earlier mapping of named (correlated) tephras in the Waikato region had been limited to the eastern margins (Pullar, 1967; Pullar and Birrell, 1973) because most of the tephra layers as such effectively petered out as they became thinner farther away (and 'upwind') from their main volcanic sources in the central Taupo Volcanic Zone. They also became shallower and increasingly altered within the soil-forming environment so that their diagnostic physical properties became more difficult to discern (e.g. Hodder and Wilson, 1976; Hogg and McCraw, 1983; Lowe, 1988). These pre-22-ka tephras, dominated by Rotoehu Ash, make up the lower half of the coverbed (Fig. 2), although there has been considerable intermixing throughout the coverbed because of upbuilding pedogenesis, discussed below. The basal age (c. 50 ka) of the coverbed in the Kainui soil stems from the identification of Rotoehu Ash (not 100% pure, but overwhelmingly predominant) in the basal deposits. Rotoehu Ash has been re-dated recently at about 50 ka (Danišík et al., 2012; Flude and Storey, 2016). From the proportions of diagnostic cummingtonite in the ferromagnesian mineral fractions, Rotoehu Ash is estimated to be c. 25 ± 10 cm thick at Rototuna in northern Hamilton, and 30 cm thick at Lake Maratoto.

(2) One of the biggest advances since 1991, when I wrote that the thin multiple tephra layers had been "weathered and blended by soil forming processes", thereby masking their origin, is the recognition that these profile features reflect upbuilding pedogenesis. Upbuilding pedogenesis is the ongoing formation of soil *via topdown processes* whilst tephras or loess (or alluvium, colluvium) are *simultaneously* added to the land/soil surface as a consequence of normal geological processes. The frequency and thickness of tephra accumulation (and other factors) determine how much impact topdown soil-forming processes have on the ensuing profile character, and if either developmental or retardant upbuilding, or both, prevail (Lowe and Tonkin, 2010). Upbuilding pedogenesis is readily envisaged as an ongoing 'competition' between *geology* (e.g. tephra or loess deposition) and *pedology* (transformation of tephra or loessic material into soil horizons). Topdown pedogenesis comprises multiple processes operating mainly from the land surface, driven by the organic and water cycles, that result in the gradual deepening of the profile as a downward moving front in pre-existing parent materials (Almond and Tonkin, 1999). That is, 'classical' soil formation proceeds by effectively modifying a (static) parent material to a greater or lesser extent according to a range of factors that dictate an ensemble of soil processes. Such classical soil formation is thus seen as a two-step process (step 1: parent material emplacement or exposure; step 2: its transformation into soil horizons), whereas steps 1 and 2 occur together, not sequentially, in upbuilding pedogenesis. It is important to appreciate that topdown pedogenesis occurs, nevertheless, during upbuilding pedogenesis, but its effectiveness is lessened as the land rises either gradually (developmental upbuilding) or abruptly when thick deposits are emplaced (retardant upbuilding).

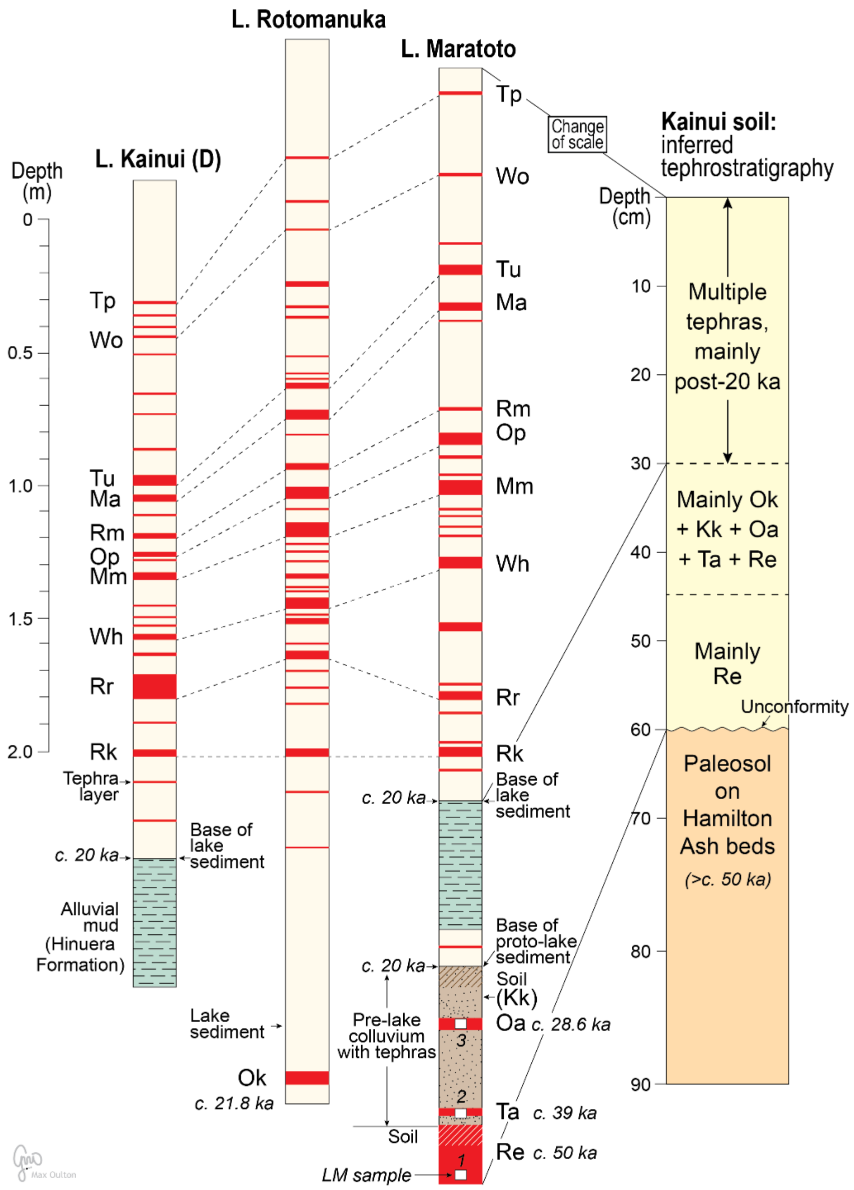

Figure 2. Stratigraphy and correlation of tephra layers in lake sediment cores from c. 20- to 22-ka-aged lakes Kainui, Rotomanuka and Maratoto and underlying pre-lake lithologies and buried soils (from Lowe, 2019). Lake Kainui is within c. 7.5 km of the Gordonton Road site shown in Fig. 1. Named tephras and approximate calendrical ages are: Tp, Taupō (1.7 ka or 232 ± 10 AD); Wo, Whakaipo (2.8 ka); Tu, Tuhua (7.5 ka); Ma, Mamaku (8.0 ka); Rm, Rotoma (9.4 ka); Op, Opepe (10.0 ka); Mm, Mangamate (11.3 ka); Wh, Waiohau (14.0 ka); Rotorua (15.6 ka); Rk, Rerewhakaaitu (17.6 ka); Ok, Okareka (21.8 ka); and Kk, Kawakawa (25.4 ka) (not visible as layer). In the lower Lake Maratoto core, the older tephras (ages shown) are Oa, Okaia; Ta, Tāhuna; and Re, Rotoehu. The two buried soil horizons represent disconformities. The column at far right depicts the inferred stratigraphy of the Kainui soil. The boundaries of the coverbed tephrostratigraphy are notional because of continuous tephra admixing during upbuilding pedogenesis. The figure shows that the parent materials of the Kainui soil (to c. 1 m depth) are time-transgressive, spanning an age range that could be as much as c. 125,000 years if the upper Hamilton Ash (which is undated) is as old as c. 125 ka in age (MOIS 5e). To convey the soil's two-storeyed, upbuilding-derived, diachronous character, the age of the parent materials cannot be enunciated by a single number. Instead, they may be described, for example, as 'a composite of multiple tephras younger than c. 50 ka over strongly weathered tephra considerably older than c. 50 ka', or as 'a composite of late Quaternary tephras on a buried paleosol on older tephras (Hamilton Ash)'.

The terms developmental and retardant upbuilding were coined by Johnson and Watson-Stegner (1987) and Johnson et al. (1987, 1990). To reiterate, retardant upbuilding occurs when a relatively thick layer of tephra (or alluvium or colluvium) is instantaneously added to the land surface, or where the rate of accumulation of many thin deposits is so fast that the original soil is rapidly overwhelmed, and thus becomes a buried horizon cut off and isolated from the new land surface in which topdown pedogenesis begins anew. Developmental upbuilding, represented well by the Kainui soil (Fig. 1), and by most loess-derived soils, occurs when the rate of addition of tephra (or loess) to the land surface is incremental and sufficiently slow to enable topdown pedogenesis to keep pace as the land gradually rises (e.g. Kemp, 1999; Alloway et al., 2018). At Gordonton Road, the rate of accumulation of tephras in the upper profile averages c. 1.2 mm per century, about the same rate as very slow loess accumulation on the West Coast, South Island.

These concepts of upbuilding pedogenesis form part of the dynamic-rate model of soil evolution whereby soils are envisaged to evolve by 'ebb and flow' through time (Johnson et al., 1990; Schaetzl and Thompson, 2015). A corollary associated with developmental upbuilding is that each part of the profile has, at one time, been an 'A' horizon, which helps explain the pedogenic fabric evident in the horizons making up the upper 'storey' of the Kainui soil.

(3) That the boundary between the upper and lower storeys is a lithologic discontinuity (unconformity) is an important conclusion because it negates several other ideas of genesis that had been invoked previously. One hypothesis was that the buried soil horizon (2bBtg) on the upper Hamilton Ash (Fig. 1) was an argillic horizon (it is, but as a relict feature in a paleosol); another was that it was a podzolic-B horizon. Both hypotheses assume the 2bBtg horizon to be genetically connected by the eluviation of clays, or by the eluviation of Fe, Al, and Si, from the upper to lower parts of the soil, forming a sequum. But the upper and lower profiles are probably not directly connected genetically (or they have been connected for only a limited period): the buried soil has properties (including features that qualify as kandic and argillic horizons) that relate to its formation at an earlier time, probably during the Last Interglacial (Bakker et al., 1996).

(4) The clay fraction of the weathered mantle of late Quaternary tephras is dominated by halloysite, not allophane. Earlier, this had been a major puzzle because the formation of halloysite was erroneously thought to follow, by some ~10,000 to ~15,000 years, the formation of allophane (Lowe, 1986, 2002). However, the development of the Si-leaching model explained that the formation of allophane or halloysite depended in part on the amount of silicon in soil solution, which was in turn controlled by rainfall, drainage, depth to slowly permeable layer, and other factors (Parfitt et al., 1983, 1984; Parfitt and Wilson, 1985; Singleton et al., 1989), age being indirect and subordinate (Lowe, 1986, 2002). This is another key finding: that 'young' tephras could weather directly to halloysite, exemplified in the Kainui soil, was the 'leopard that changed its spots'. In fact, the inverse atomic structures of allophane and halloysite preclude the possibility of allophane transforming to halloysite other than by completely dissolving and reforming (Churchman and Lowe, 2012). The presence of redox segregations, especially MnO_2-concretions towards the base of the late Quaternary tephra mantle, supported the Si-leaching model because these wet-dry features show that desilication has been limited to some degree (Lowe, 2008, 2019).

Classification

The classification of the Kainui has been troublesome in that the soil, despite its 'young' tephra-derived origins, did not fit into the Yellow-brown loams of the earlier *New Zealand Genetic Soil Classification* because it was clearly non-allophanic (Taylor and Pohlen, 1962, 1968). Nor did it sit well in the Brown-granular loams (typically formed on weathered Hamilton Ash beds) because the 'granular' fabric associated with this group was at a depth of ~0.5 m or more. Instead, the two-storeyed character of the Kainui soil was suitably reflected by its classification as a composite Yellow-brown earth on (pre-weathered) Brown-granular loam (McCraw, 1967; Wilson, 1980; McLeod, 1992). In the *New Zealand Soil Classification* (NZSC), the Kainui soil was initially placed in the Granular Soils (first and second editions) but I thought the earlier composite classification was more appropriate because it fitted the whole (c. 1-m deep) profile morphology better. The Kainui soil has also been characterized previously as having an eluvial and illuvial couplet, namely a pale E horizon over a (translocated clay-enriched) Bt (argillic/kandic) horizon, forming a sequum. However, the soil stratigraphic evidence shows that the Bt horizon is a buried soil, hence is classed as a 2bBt horizon, with the upper boundary representing a lithologic discontinuity. Therefore the sequum is illusory because the E and (2b)Bt horizons are (largely) not connected genetically and are some tens of thousands of years apart in age. Clayden and Hewitt (1989) suggested that the E horizon in such cases should be designated an EBw horizon. Most if not all of the clay skins in the 2bBt horizon are relict. Hence in the third edition of NZSC, the Kainui soil is now, uniquely, a Buried-granular Yellow Ultic Soil; tephric; not applicable (mixed rhyolitic >> andesitic fines); silty/clayey; moderate/slow (Hewitt, 2010; Webb and Lilburne, 2011). The 'ultic' character is well expressed in *Soil Taxonomy*: the soil depicted in Fig. 1 is a Typic Kandiudult; fine-silty over clayey, halloysitic, thermic (Soil Survey Staff, 2014).

What about the buried soil on the upper Hamilton Ash beds?

Athough we now understand the origins and character of the upper storey to a better extent than before, the buried paleosol on the upper Hamilton Ash beds (the lower storey) remains enigmatic, partly because it is so weathered and altered. Of the entire Hamilton Ash sequence, only the basal unit, H1, which is also known as Rangitawa Tephra, has been dated directly (Fig. 1; Lowe et al., 2001). The white, ~0.5-m-thick Rangitawa tephra is c. 340 ka in age and it fell late in MOIS 10 (Pillans et al., 1996). Rangitawa tephra is overlain in turn by the ~3-m thick sequence of weathered, yellowish brown to brown to reddish brown clayey tephra beds and buried soils – the Hamilton Ash beds – that must represent MOI stages 9 to 5. Partly on the basis of the colours of the beds in the sequence and the climatic associations developed by other workers in similar materials elsewhere in central North Island (e.g. Stevens and Vucetich, 1985; Alloway et al., 1992), the uppermost distinctive, dark reddish-brown buried soil, known also as the Tikotiko Ash or bed H6/7, probably represents MOIS 5e with an age of c. 125 ka (as noted earlier). Following Stage 5e and subsequent interstadials (5c, 5a) and stadials (5d, 5b), marked cooling into the Last Glaciation began at c. 74 ka. Therefore, the pit-mound windthrow features (Fig. 1) on the paleo-surface on the upper Hamilton Ash allow an approximate minimum age of c. 74 ka to be inferred for this surface because forest cover, almost certainly very extensive during MOIS 5e and prevalent during MOIS 5d-5a, was likely reduced to remnant status in the central Waikato after c. 74 ka with shrubland-grassland being predominant during the Last Glacial Maximum (c. 30–18 ka). Such an age for the paleo-surface could be tested using several radiometric dating methods provided suitable zircons could be extracted, by undertaking paleomagnetic measurements to try to identify the Pringle Falls excursion/event at c. 220 ka and the Blake excursion/event at c. 120 ka, and by extracting quartz grains containing melt inclusions (i.e. glass), which could be analysed by electron microprobe as a compositional ''fingerprinting' tool (Lowe, 2019).

Micromorphology

Clay coatings and other micromorphological features in the (now buried) horizons in the weathered upper Hamilton Ash beds match those identified by Bakker et al. (1996) in the Naike clay loam, which is an equivalent (paleo)soil formed on Hamilton Ash that has been exhumed (Lowe, 2008). Bakker et al. (1996) wrote that the laminated character of the clay coatings in the Bt horizons of the Naike soil indicates clay illuviation, and that the fine-clay/total-clay ratios for the Naike soil are consistent with this interpretation. The clay skins, infilling pores, then led to the formation of iron (hypo) coatings. The question then arises as to the source of the translocated clays in the 2bBt horizons because, as has been discussed, the upper late Quaternary tephra mantle accumulated only during the past c. 50 kyr, meaning that overlying soil materials that potentially provide an eluvial source of fine clays were absent, or relatively thin for much of the time as the tephras accumulated incrementally. Also, the upper mantle can comprise Bw(f) and Bw(g) horizons that are pale because of seasonal gleyisation rather than because of eluviation (which could still occur) (see section 5, "Caught in the act", in Lowe, 2019, p. 17). Could additional tephras covering the 2bBt horizons at the time of the Last Interglacial have been eroded, possibly in MOIS 4, and then effectively replaced during MOIS 3 by the Rotoehu Ash and ensuing younger coverbed tephras we see today?

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