Unravelling upbuilding pedogenesis in tephra and loess sequences in New Zealand using tephrochronology

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Abstract
The genesis of soils developed in either tephra or loess on stable sites differs markedly from that of soils developed on rock because classical topdown processes operate in conjuction with geological processes whereby material is added to the land surface so that the soils form by upbuilding pedogenesis. Understanding the genesis of such soils (typically Andisols and Alfisols, respectively) often requires a stratigraphic approach combined with an appreciation of buried soil horizons and polygenesis. In New Zealand, calendrically-dated tephras provide an advantage for assessing rates of upbuilding through chronostratigraphy. Many Andisol profiles form by upbuilding pedogenesis as younger tephra materials are deposited on top of older ones. The resultant profile character reflects interplay between the rate at which tephras are added to the land surface and topdown processes that produce andic materials and horizons. In loess terrains, upbuilding pedogenesis since c. 25,000 years ago is associated with maximum rates of loess accumulation c. 3—10 mm per century, sufficiently slow for soil-forming processes to continue to operate as the land surface gradually rises. Thus, Alfisol subsoil features are only weakly developed and Bw or B(x) horizons typically are formed. In contrast, topdown pedogenesis is associated with minimal or zero loess accumulation, the land surface elevation remains essentially constant, and subsoil features become more strongly developed and Bg, Bt, or Bx horizons typically are formed.

Key Words
Soil-sediment, tephrochronology, chronostratigraphy, pedostratigraphy

Introduction
Most text books describe pedogenesis in terms of classical 'topdown' processes that progressively modify a stable, pre-existing parent material. Indeed, modelling of such processes in the context of explaining soil development in time and space is almost invariably restricted to soils formed on rock, that factor being 'constant' apart from change resulting from in situ weathering (e.g., Minasny *et al*., 2008). However, in many landscapes, such as those of alluvial plains or where tephras or loess have been 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. The resultant soils are formed by upbuilding pedogenesis instead of topdown pedogenesis (Johnson *et al*., 1987; Almond and Tonkin, 1999; Schaetzl and Anderson, 2005). They may show distinctive layering and buried horizons, forming multisequal profiles. In this paper we use tephrochronology to examine the rates and processes involved in the evolution of late Quaternary soils via upbuilding pedogenesis from tephras (typically forming Andisols) and from loess (typically forming Alfisols) in New Zealand. Such application has been enhanced by the development of new calibrated age models for tephras erupted in the past c. 30,000 years (Lowe *et al*., 2008a).

Upbuilding pedogenesis on tephra
The accumulation at a particular site of numerous tephra deposits from sequential eruptions from one or more volcanoes leads usually to the formation of Andisols with distinctive layered profiles and buried soil horizons. Such layered profiles, together with their andic soil properties and glass content, are key features of Andisols. Study of the layers and attaining ages for them (tephrostratigraphy) is an important aspect of understanding Andisol formation. During periods of quiescence between major eruptions, soil formation takes place, transforming the unmodified tephra materials via normal topdown pedogenesis in a downward-moving front to form subsoil horizons. However, when new tephras are added to the land surface, upbuilding pedogenesis takes place. The frequency and thickness of tephra accumulation (and other factors) determine how much impact the topdown processes have on the ensuing profile character, and if 'developmental' or 'retardant' upbuilding, or both, will take place. 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 (Figure 1). 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 (Lowe and Palmer, 2005; McDaniel *et al*., in press). Each part of the profile has been an A horizon at one point, as illustrated in Figure 1.

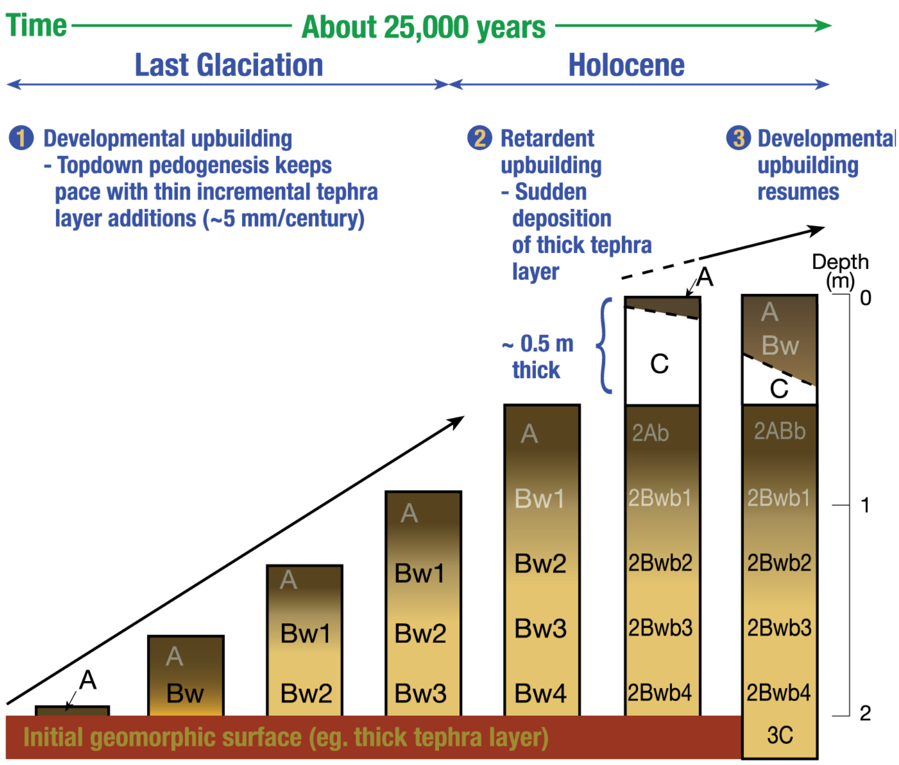

Figure 1. Model of upbuilding pedogenesis in tephra deposits and the formation of a multisequal Andisol over c. 25,000 years. In phase 1 (developmental upbuilding), thin, distal tephras accumulate slowly whilst topdown processes imprint weak horizonation features on them as the land surface gradually rises. In phase 2 (retardant upbuilding), the sudden deposition of a tephra layer ~0.5 m thick 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 (after McDaniel *et al*., in press).

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/buried soil horizons). 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 Andisol profile formed via retardant upbuilding pedogenesis since c. 9500 years ago is shown in Figure 2. Each of five successive tephra deposits (named Rotoma, Whakatane, Taupo, Kaharoa, and Tarawera) shows the imprint of topdown pedogenesis, as depicted by their soil horizonation. 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. The soil in Figure 2 (Rotomahana series) is an Udivitrand in North Island, New Zealand. Retardant and developmental upbuilding may both occur in the evolution of a single Andisol profile. For example, in Figure 1, 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.

Upbuilding pedogenesis in loess

As recognised c. 120 years ago by James Hardcastle in the South Island of New Zealand, loess deposits commonly comprise multiple sheets with buried soils, formed during phases of very slow or zero loess deposition, marking the boundaries between sheets. In some areas, the loess-buried soil horizon sequences have been considered to represent cold-warm climates, respectively, with the change from one to the other analogous to an on/off switch.

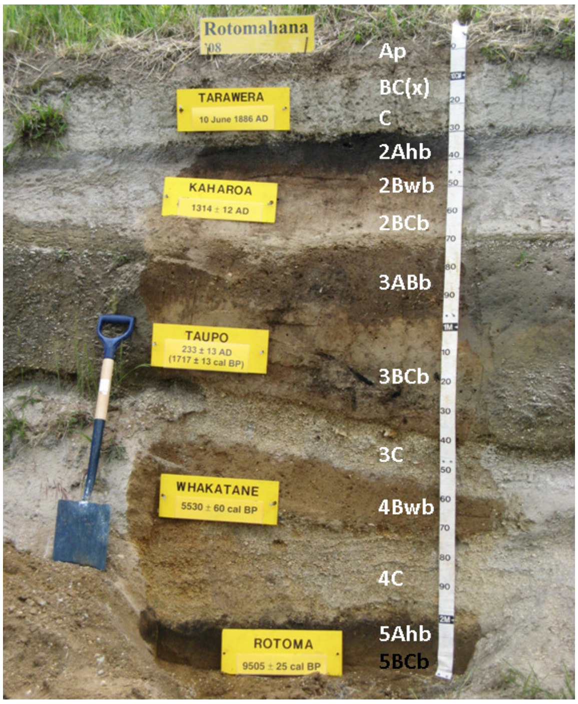

Figure 2. Example of a multi-layered Andisol formed through retardant upbuilding in New Zealand. After each tephra is deposited, soil begins to develop until it is buried by another tephra and topdown pedogenesis begins operating in the fresh deposit. The buried 'mini' soil profile on Whakatane tephra (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 ~125 years of pedogenesis on hydrothermally altered, mud-rich tephra deposited in AD 1886 by the Tarawera eruption. Some properties of the buried soil horizons may have been altered via diagenesis. 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 (after McDaniel *et al*., in press). Photo: R. McEwan.

This model applied to the southern North Island area where cold climatic conditions (e.g., oxygen isotope stages [OIS)] 2, 6, 8) corresponded to maximum loess accumulation and relatively slow pedogenesis, and warm climatic conditions (e.g., OIS 1, 5, 7) to relatively fast pedogenesis and no loess accumulation (Palmer and Pillans, 1996). Where loess accumulation is minimal or nil, soil development operates as a classical topdown process to form the distinctive subsoil (i.e. B horizon) features used to identify buried soils and to subdivide the loess column into sheets or soil stratigraphic units. But, as for distal tephra fallout sequences, most loess deposits have features indicative of continual pedogenesis. During periods when loess is accumulating, soil formation does not stop, but its effects are lessened as it eventually becomes buried too deeply for these topdown processes to be effective (Lowe *et al*., 2008b). This upbuilding history leaves the loess deposit with a soil 'vermiform' fabric inherited from when the loess was at the land surface and represented by soil A horizons. These vermiform features include fragipans, the interiors of which have a soil fabric throughout comprising traces of faunal activity such as back-filled burrows and root traces. The latter are very obvious where secondary $CaCO_3$ in the loess has formed root pseudomorphs. (The vermiform fabric is one of the signatures used to distinguish loess from other silty sediments such as weathered siltstones.) Soil formation thus occurs simultaneously with slow loess accumulation, forming a 'soil-sediment' via upbuilding pedogenesis (Figure 3). In New Zealand, the average rates of net loess accumulation since deposition early in OIS 2 of the widespread marker bed the Kawakawa tephra c. 27,100 years ago, and before the Holocene, are only about 3 to 10 mm per century (Eden and Hammond, 2003; Lowe *et al*., 2008a, 2008b). When loess accumulation slows further or ceases altogether, topdown soil formation takes over. The imprint of topdown pedogenesis is more marked in the long run, forming the distinctive buried soil features – not simply because of 'improved' climatic conditions but because the rate of loess accumulation is so reduced that pedogenic processes and weathering effectively operate for longer periods. This model of alternate upbuilding pedogenesis and topdown pedogenesis phases applies widely to loess sequences in the South Island and probably in most of southern North Island (Lowe *et al*., 2008b).

In landscapes upwind from the main tephra sources in central North Island, the intermittent fallout of thin, distal tephra deposits at about 1 to 5 mm per century is at a rate comparable to slow loess accretion during glacial periods. Hence, for almost all of the time, upbuilding pedogenesis predominates in many distal-tephra-derived Andisol profiles because the accretion of tephra – together with tephric loess during glacials – is effectively continual. Typically, a few millimetres or centimetres of ash are deposited every few hundred years on the average, more frequently if cryptotephras (glass-shard concentrations not visible as layers in the field) are considered. The topdown-dominant phase only comes into play when a thicker tephra layer (approximately 20–30 cm or more) is emplaced so that the antecedent soil is effectively buried and sealed off. But in time, upbuilding pedogenesis will gradually resume as the ongoing eruptions of wind-borne (hence loess-like) tephras continue to 'dust' the imperceptibly rising land surface over thousands of years.

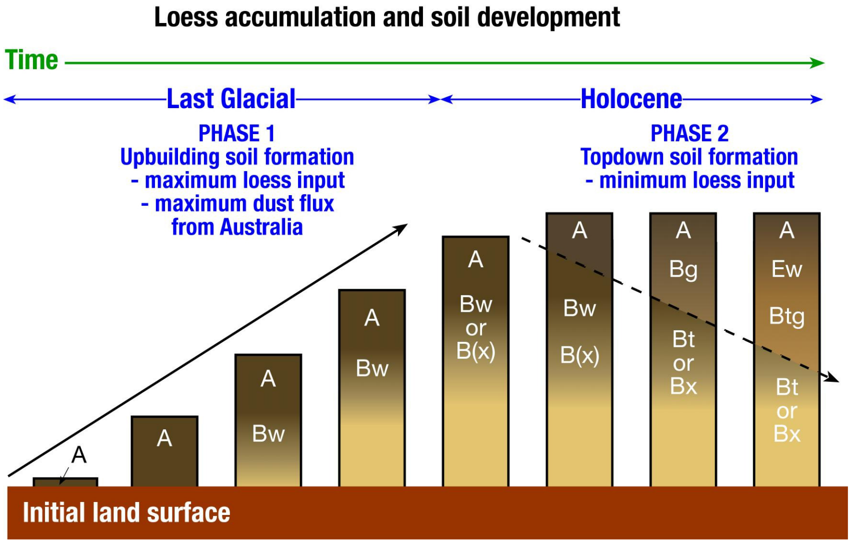

Figure 3. Model of soil development in loess since c. 25,000 years ago. The inital geomorphic surface approximates the Kawakawa tephra. Phase 1 depicts upbuilding pedogenesis during maximum (but slow) loess accretion (OIS 2); phase 2 depicts topdown pedogenesis with minimal or zero loess accretion (OIS 1). Soil horizons show that the maximum development of subsurface features occurs in phase 2 with more strongly developed horizons evident (after Lowe *et al*., 2008b).

Conclusion

Andisol profiles commonly have distinctive layering and buried soil horizons and form by upbuilding pedogenesis as younger tephra materials are deposited on top of older ones. The resultant profile character is determined by the interplay between the rate at which tephras are added to the land surface and topdown processes that produce andic materials and horizons. Understanding Andisol genesis thus often requires a stratigraphic approach combined with an appreciation of buried soil horizons and polygenesis. In loess terrains, upbuilding pedogenesis is associated with maximum rates of loess accumulation (during cold climates) but these rates are sufficiently slow for soil-forming processes to continue to operate as the land surface gradually rises 'millimetre by millimetre'. Thus, subsoil features are only weakly developed and Bw or B(x) horizons are formed. In contrast, topdown pedogenesis is associated with minimal or zero loess accumulation (during warm climates), the land surface elevation remains essentially constant, and subsoil features become more strongly developed so that Bg, Bt, or Bx horizons are formed. Loess accumulation and soil formation may be envisaged as 'competing' processes (e.g., see Muhs *et al*., 2004), but the former seldom exceeds the latter. Quantitative modelling of soil development should incorporate soils developed via upbuilding pedogenesis as well as those that evolve through topdown pedogenesis.

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