Andisols of New Zealand and Australia

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ABSTRACT

During the Quaternary, much of central North Island, New Zealand, was repeatedly overwhelmed or modified by emplacement of ignimbrites and especially by multiple rhyolitic and andesitic tephra fallout deposits, and reworked derivatives, that successively mantled landsurfaces forming buried paleosols in multisequal profiles. Relatively thick proximal deposits buried and isolated antecedent soils, forming compound soil profiles, whereas relatively thin tephra fallout at medial and distal sites resulted in composite or aggrading profiles, their character determined by the interplay of upbuilding and topdown pedogenesis. Scoriaceous basaltic tephras erupted in northern North Island were locally distributed. Andisols, of the 'allophanic' type with andic soil properties dominated by short-range-order (SRO) clays rather than Al-humus complexes, cover ~32,100 km² and comprise about 12.5% of New Zealand soils. They consist of three groups : (1) 'Entic' Udands or Cryands occur on mainly andesitic eruptives <1000 years old near recently active volcanoes (Tephric Recent Soils in New Zealand Soil Classification; ~1200 km², ~0.5%); (2) Vitrands occur in central-eastern North Island on glassy, rhyolitic pumiceous deposits mainly from the Taupo eruption *c.* 232 AD and the Kaharoa eruption *c.* 1314 AD (Pumice Soils; ~17,200 km², ~6.5%); and (3) Udands occur typically on composite, multiple tephra deposits of varying ages in Taranaki (mainly andesitic tephras), King Country-western Waikato (mixed andesitic-rhyolitic), eastern Waikato-western Bay of Plenty-Coromandel (mainly rhyolitic), and Auckland-Northland (basaltic), the age span of sola increasing towards distal sites as constituent tephra layers become thinner and shallower (Allophanic Soils; ~13,700 km², ~5.5%). Moisture and temperature regimes are mainly udic and mesic, thermic, or cryic. Udands are pre-eminent among New Zealand's most versatile, high-quality soils because they provide valuable soil ecosystem services including sorption, water storage and supply, natural fertility, and foundation support.

Andisols are currently known only in the Mt Gambier area of southeast South Australia, and comprise ~85 km² (~ 0.001%) of Australian soils. Intraplate basaltic volcanoes at Mts Gambier and Schank erupted *c.* 5000 years ago and the resultant localised tephras contain both exotic crystalline material, derived from underlying limestone and calcareous dunes, and juvenile basaltic material. Sand fractions at Mt Gambier are dominated by exotic, silicic crystalline material (≥80%) and relatively little glass (<20%) but at Mt Schank unaltered Al-rich glass predominates (≥50%). Vitrixerands and Haploxerands with pHs 6.4–8.0 have been formed under xeric moisture and mesic temperature regimes (Andic, Chernic Tenosols in Australian Soil Classification). The parent mineralogies have influenced clay mineral formation : SRO clays at Mt Schank (up to 20% allophane, 7% ferrihydrite, fine-earth basis) are more abundant than at Mt Gambier (≤12% allophane, 4% ferrihydrite) because the glass at Mt Schank weathers more rapidly than the Al-poor crystalline material at Mt Gambier, releasing Al. Seasonal Si-leaching has also been influential : where leaching is sufficient to remove silica, and $CaCO_3$ content is low (in upper soil horizons at Mt Gambier; in most horizons at Mt Schank), Al-rich allophane has formed; where leaching is weak (intermediate horizons), Si-rich allophane and layer silicate minerals (but not halloysite) have formed; and where leaching barely occurs (in lowest horizons), smectite has formed. The Xerands are versatile soils.

INTRODUCTION

Although making up only about 1.24 million km^2, or approximately 1% of the global land area (Kimble et al., 2000; Takahasi and Shoji, 2002), Andisols have long been regarded as special soils because of their distinctive or unique morphological, mineralogical, physical, and chemical properties and generally high productivity. They were included in Soil Taxonomy in 1990 as the eleventh order (Parfitt and Clayden, 1991) following recommendations of the International Committee on the Classification of Andisols chaired by the late Dr Michael L. Leamy of New Zealand (Parfitt et al., 1988). Since then, numerous excellent reviews of the genesis, nature, and environmental and agricultural significance of Andisols have been published, including those of Shoji et al. (1993a), Kimble et al. (2000), Ping (2000), Nanzyo (2002), Shoji and Takahashi (2002), Takahashi and Shoji (2002), Ugolini and Dahlgren (2002), Dahlgren et al. (2004), and Qafoku et al. (2004).

Andisols (approximately equivalent to Andosols in the World Reference Base for Soil Resources : Spaargaren, 2000) are defined essentially by the presence of andic soil properties, these being attributable to significant amounts of short-range-order (SRO) (i.e. allophane, ferrihydrite) or paracrystalline (i.e. imogolite) minerals or Al-humus complexes (Soil Survey Staff, 1999; Kimble et al., 2000). These and other materials are commonly formed during weathering and mineral transformations of tephra – the unconsolidated, primary pyroclastic products of a volcanic eruption (Lowe and Hunt, 2001) – and other parent materials with a significant content of volcanic glass, the processes being known collectively as andisolization (Shoji et al., 1993b; Lowe, 1995; Ugolini and Dahlgren, 2002). Although volcanic glass is a common component in many Andisols (Lowe and Green, 1992), it is not a requirement of the Andisol order and some soils develop andic properties without the influence of volcanic glass (Soil Survey Staff, 1999). The concept of Andisols includes weakly weathered soils with much volcanic glass as well as more strongly weathered soils dominated by (1) SRO minerals and imogolite, the so-called 'allophanic Andisols', or by (2) Al/Fe-humus complexes, typically with 2 : 1 layer silicates, the so-called 'non-allophanic Andisols' (Dahlgren et al., 2004).

Translocation within Andisols is normally minimal (Soil Survey Staff, 1999; Ugolini and Dahlgren, 2002). However, Bakker et al. (1996) demonstrated that micro-laminated, anisotropic, clay coatings had been illuviated into lower horizons of a Typic Placudand/Vitric Hapludand (Horotiu series) in New Zealand (cf. Jongmans et al., 1994).

In New Zealand, Andisols are found only in the North Island, as described in the next part of this paper, and at around 12.5% (approximately 32,100 km^2) of the total area comprise the third-most extensive soil order in New Zealand after Inceptisols (~47.4%) and Spodosols (~13.2%) (Lowe et al., 2000a; Table 1). However, significant areas of soils containing Al-rich allophane are recognised in extensive upland or 'high country' regions of inland South Island (Parfitt and Webb, 1984; Parfitt, 1990a). They are mainly Andic Dystrudepts in Soil Taxonomy (Soil Survey Staff, 1999) and Allophanic Brown Soils in the New Zealand Soil Classification (NZSC) (Hewitt, 1998). An 'Andisol-like' soil (Venlaw series : Wallace et al., 2000), dominated by Al-humus complexes, has been reported in southern South Island (Saigusa and Matsuyama, 2004; R.L. Parfitt pers. comm., 2004) and warrants further investigation.

Soils formed either from very young, little-weathered tephra deposits or from older, strongly-weathered tephra and other volcanic deposits, but lacking sufficient andic properties to qualify as Andisols, also occur in New Zealand (Gibbs, 1968; Hewitt, 1998; Molloy and Christie, 1998). Such volcanogenic soils are mostly Entisols or Ultisols, respectively, but Oxisols and other orders (rare) occur as well (Hewitt, 1995, 1998; Rijkse and Hewitt, 1995; Bakker et al., 1996; Lowe et al., 2001).

In Australia, Andisols have been identified only in the southeastern part of South Australia (Lowe et al., 1996; Table 1), and these are described later in this paper.

VOLCANISM AND TEPHRA DISTRIBUTION IN NORTH ISLAND

Because New Zealand bisects an obliquely convergent plate boundary, tectonism and volcanism, together with Quaternary environmental change, have been the dominant influences on its soil pattern (Molloy and Christie, 1998; Lowe et al., 2000a).

Volcanism in the North Island since *c.* 2.5 million years ago can be classed into three main types (Fig. 1), each generating characteristic pyroclastic products from which Andisols have been formed.

(1) Intraplate basaltic volcanic fields, largely monogenetic, have erupted locally distributed basaltic (scoriaceous) tephra-fall deposits in northern North Island.

(2) Subduction-related volcanic centres, forming andesitic stratovolcanoes, especially Egmont/Taranaki and Tongariro, Ngauruhoe, and Ruapehu volcanoes, have erupted local to widespread but generally thin andesitic tephra-fall deposits very frequently, and localised pyroclastic density current or flow deposits (including block-and-ash flow deposits).

(3) Crustal-derived and explosive rhyolite volcanic centres include the large, active Taupo and Okataina calderas in the central part of the Taupo Volcanic Zone from which voluminous pyroclastic density current or flow deposits (ignimbrites) and widespread silicic tephra-fall deposits have been erupted moderately frequently to infrequently. Another type of rhyolite has been erupted from the offshore peralkaline Tuhua caldera volcano (Fig. 1) (Froggatt and Lowe, 1990; Houghton et al., 1992; Wilson et al., 1995; Shane, 2000).

Thus most parts of the central North Island landscape especially have been repeatedly overwhelmed or modified by the catastrophic emplacement of ignimbrites and the widespread fall of numerous rhyolitic and andesitic tephra deposits, and reworked derivatives that include volcanogenic alluvium, colluvium, and subsurface tephric loess (Cowie and Milne, 1973; Pullar and Birrell, 1973; Soil Bureau Staff, 1973; McCraw, 1975). The tephra-fall deposits have successively mantled rolling and flattish landsurfaces forming multisequal soils comprising repetitions of soil horizons and buried paleosols within the vertical profile. Similarly layered soils comprising multiple sequences of buried horizons and tephra deposits are recognised in other volcanic terrains (e.g. Ping et al., 1988; Shoji et al., 1993c; Kimble et al., 2000).

Relatively thick proximal deposits have buried and isolated antecedent soils, forming compound soil profiles (e.g. see Fig. 5 below), whereas fallout at medial/distal sites of relatively thin, multiple tephra deposits from successive eruptions has resulted in composite or aggrading (accretionary) profiles, the ensuing soil character being determined by the interplay of upbuilding and topdown pedogenesis (Hill, 1999; Hill et al., 1999; Lowe, 2000) (e.g. see Fig. 6 below). Soils on such aggrading landscapes have undergone 'developmental upbuilding' (progressive pedogensis) if the rate of addition of tephras allowed assimilation of the deposits and profile deepening, or 'retardant upbuilding' (regressive pedogenesis) if the rates were so rapid that horizonation was prevented (Johnson and Watson-Stegner, 1987; Lowe, 2000). In upbuilding soils, each increment of soil below the A horizon has experienced processes that are characteristic of all horizons above it (Almond and Tonkin, 1999).

Many of the major tephra deposits in the North Island, mainly rhyolitic, have been dated and mapped (Froggatt and Lowe, 1990), thereby providing time-stratigraphic frameworks for studies on soils, paleosols, and paleoclimates (e.g. Parfitt et al., 1983; Alloway et al., 1992; Bakker et al., 1996; Cronin et al., 1996; Newnham et al., 1999; Lowe et al., 2001), on their rates of weathering and clay mineralogy (Neall, 1977; Lowe, 1986; Hodder et al., 1990, 1996; Parfitt, 1990a; Lowe and Percival, 1993), and on the interaction of volcanism with humans in antiquity (Lowe et al., 2000b, 2002).

DISTRIBUTION AND CHARACTER OF ANDISOLS IN NORTH ISLAND

Most North Island Andisols have developed under udic moisture regimes (some are perudic, e.g. in elevated parts of Mt Egmont/Taranaki region) and thermic, mesic, or cryic temperature regimes. Isofrigid temperature regimes were reported by Suryaningtyas (1998). The Andisols may be classed into three main groups of increasing age (Table 1; Fig. 2).

(1) Weakly developed or 'Entic' Cryands or Udands, typically integrading to Vitrandic Cryorthents/Udorthents, occur adjacent to Egmont volcano and Tongariro Volcanic Centre on very weakly weathered, coarse-grained, glassy andesitic tephras <1000 years old (zone 1a, Fig. 3), near Mt Tarawera in the Okataina Volcanic Centre on basaltic scoria and fine-grained hydrothermally altered rhyolite and sediment from the 1886 AD Tarawera eruption (zone 1b), and on basaltic ashfall on Motutapu Island from the Rangitoto eruption

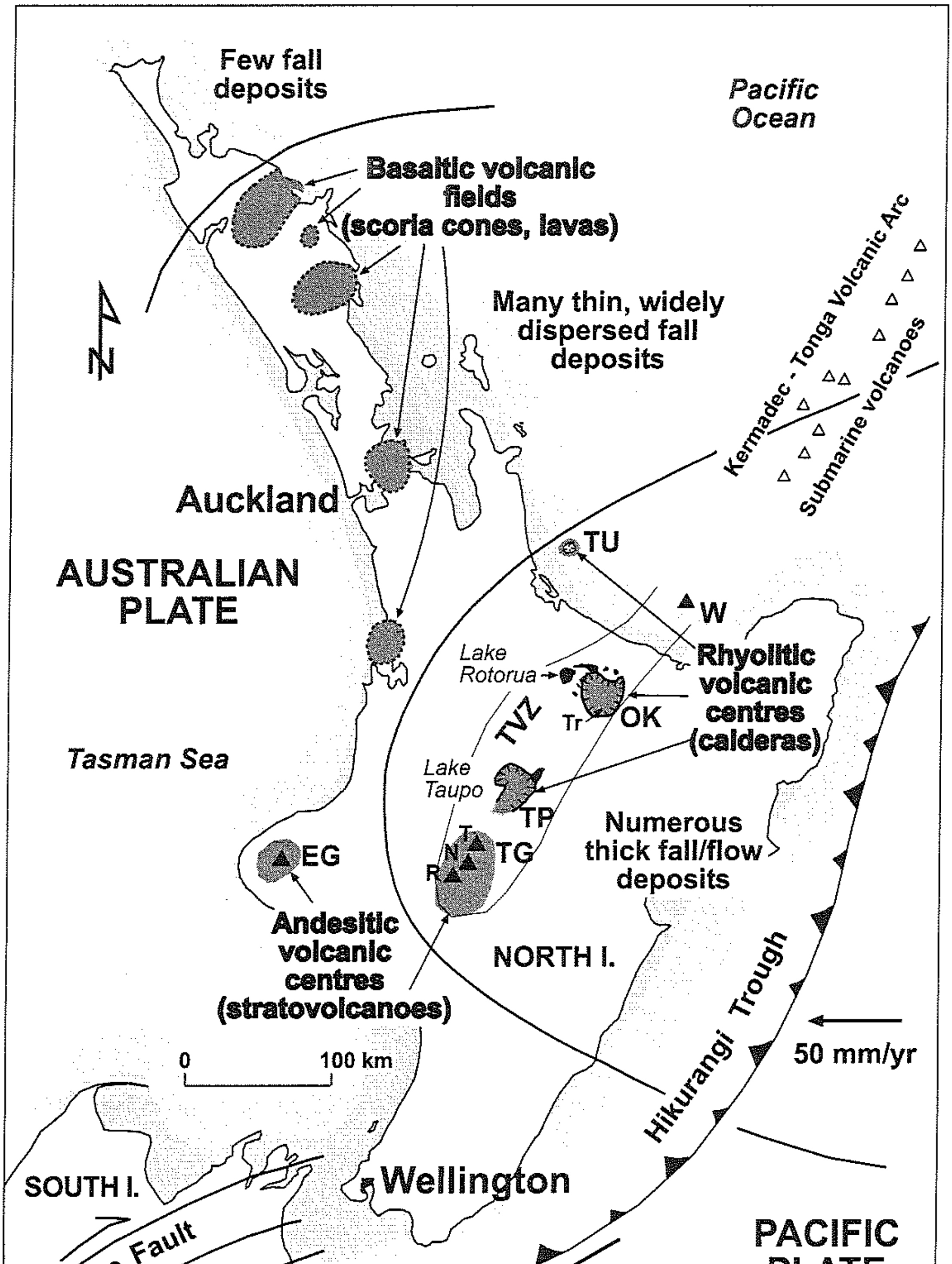

Fig. 1. Plate tectonic setting and the main volcanic centres that have erupted Andisol–forming tephra deposits, and the general dispersal of tephra in North Island (after Shane, 2000; Lowe et al., 2002). EG, Egmont volcano (also known as Mt Taranaki); TG, Tongariro Volcanic Centre (T, Tongariro volcano; N, Ngauruhoe volcano ['Mt Doom']; R, Ruapehu volcano); TP, Taupo Volcanic Centre; OK, Okataina Volcanic Centre (Tr, Mt Tarawera); TU, Tuhua Volcanic Centre (Mayor Island); W, Whakaari (White Island); TVZ, Taupo Volcanic Zone. Distribution of submarine volcanoes after Wright et al. (2004).

near Auckland *c.* 1400 AD (zone 1c). These soils are classed mainly as Tephric Recent Soils in NZSC (Clayden et al., 1997; Hewitt, 1998).

(2) Vitrands (also Vitriaquands and Vitricryands) occur in central-eastern North Island on weakly weathered, relatively coarse textured, glassy and pumiceous rhyolitic deposits (zone 2) derived from the Taupo eruption in *c.* 232 AD ± 15 and the Kaharoa eruption in *c.* 1314 AD ± 12 (Fig. 4). Small areas of Vitrands in eastern North Island were also formed on rhyolitic pumiceous deposits from the Waimihia eruption (from Taupo caldera) *c.* 3500 calendar years ago.

All these Vitrands are classed as Pumice Soils in NZSC and an example is shown in Fig. 5. This Humic Udivitrand has been formed on a layer of Taupo Ignimbrite about 80 cm thick that was emplaced instantaneously as a single unit around 1770 years ago. At higher elevations and with increasing leaching and podzolization, soils on similar materials grade to Andic Haplohumods (Parfitt and Saigusa, 1985; Molloy and Christie, 1998; Palmer et al., in press).

(3) Udands (also Aquands and Cryands) occur largely as multisequal soils on composite, weakly to moderately weathered, relatively fine textured, multiple tephra deposits of varying ages derived from eruptions from either the andesitic or rhyolitic volcanic centres (Fig. 1), typically both (Fig. 3), hence are time transgressive. The Udands occur in the Taranaki-Ruapehu region (comprising mainly andesitic tephras, zone 3), King Country-western Waikato (mixed andesitic-rhyolitic, zone 4), eastern Waikato-western Bay of Plenty-Coromandel Peninsula (mainly rhyolitic, zone 5), and Auckland-Northland (basaltic, zone 6), the age span of sola increasing towards distal sites as constituent tephra layers become thinner and shallower and increasingly intermixed with one another (Fig. 3).

All these Udands are grouped as Allophanic Soils in NZSC. An example is given in Fig. 6, which shows a Typic Hapludand formed on a composite of multiple, pedogenically intermixed and moderately weathered, thin tephras that have accumulated since about 26,500 years ago (this arbitrary 'starting' point is marked stratigraphically by Kawakawa Tephra, also known as Oruanui or Aokautere tephra : Froggatt and Lowe, 1990). Individual tephra layers preserved in nearby 20,000 year-old lakes (see inset) allow likely constituent parent tephras in the upper soil profile, each a few millimetres to centimetres thick, to be identified (Lowe, 1988, 2000; Selby and Lowe, 1992). At this site in the southern part of zone 5 (Fig. 3), most of the tephra layers are rhyolitic (~94%) but very thin andesitic tephras, identified on the basis of mineralogical and geochemical analyses of the soil materials and the tephras in the lake cores (Lowe, 1986, 1988), are also present (~6%). The rate of tephra accumulation since Kawakawa Tephra was deposited has been about 50 mm ka^{-1}, sufficiently slow for andisolization to take place concomitantly with upbuilding (and about the same rate as quartzofeldspathic loess accumulation in Westland, New Zealand : Almond and Tonkin, 1999). Earlier episodes of tephra and loess deposition and generally slower soil formation are evident below Kawakawa Tephra, and these lower horizons are typically halloysitic rather than allophanic because of resilication at depth or because of drier and colder climatic conditions, or both (Parfitt et al., 1983; Lowe, 1986; Singleton et al., 1989; Dahlgren et al., 1993; Lowe and Percival, 1993).

On a global basis, Vitrands (30.8%) and Udands (30.6%) are the two most common Andisol suborders, followed by Cryands (28.0%) (Wilding, 2000). These suborders similarly predominate in North Island : Vitrands ≥Udands >>Cryands, Aquands.

In contrast to Japan and some other long-settled volcanic countries (e.g. Ecuador), epipedons on Andisols in North Island generally do not meet thickness or other requirements for melanic horizons in Soil Taxonomy because New Zealand's Polynesian settlement history, and thus change from forest cover to fern and tussock grassland and scrub, dates from only *c.* 1250–1300 AD (Newnham et al., 1998; Hogg et al., 2003; Table 1). However, some A horizons, typically ≤20 cm thick and under bracken fern and native grasses or scrub, are black or very dark, have high organic carbon contents, and contain type-A humic acids that are characteristic of melanic horizons (Birrell et al., 1971; Birrell and Pullar, 1973; Hosono et al., 1991; Sase and Hosono, 1996; see also Nanzyo et al., 1993).

Utilization and management

High-quality, versatile soils are of very limited extent in New Zealand (~5.4% : Singleton, 1999)

Table 1. Classes, general features and approximate extent of Andisols in New Zealand and Australia (Japan and Iceland for comparison)

Andisol suborder (± great group)	National soil classification [h]	General parent material composition	Vegetation	Climate [m]	Area [n] km²	%
		New Zealand				
'Entic' Udands/Cryands [a]	Tephric Recent Soils	Andesitic	Dense podocarp–	Ud, Me–Cr	1,200	0.5
Vitrands [b]	Pumice Soils	Rhyolitic	broadleaf forest	Ud, Me–Cr	17,200	6.5
Udands [c]	Allophanic Soils	Andesitic to rhyolitic [i]	(bracken, grass/ shrubland) [k]	Ud, Me–Th	13,700	5.5
Total New Zealand [d]					32,100	12.5
As global percentage of Andisols						~2.7
	Australia					
Xerands [e]	Andic, Chernic Tenosols	Basaltic [j]	Dense to semi–	Xe, Me	85	0.001
Total Australia			open woodland & grassland/shrubs [l]		85	0.001
As global percentage of Andisols						~0.007
Japan						
Total Japan [f]					69,000	18.0
As global percentage of Andisols						~5.8
Iceland						
Total Iceland [g]					80,000	80
As global percentage of Andisols						~6.7

[a] Weakly developed Udands or Cryands usually marginal to Orthents.
[b] Includes small areas of Vitriaquands and Vitricryands as well as Udivitrands.
[c] Mainly Hapludands but Hydrudands also occur (Suryaningtyas, 1998). Includes small areas of Aquands (Epi/Endoaquands) and Cryands (Haplocryands).
[d] Areas estimated using Parfitt et al. (1988), Rijkse and Hewitt (1995), Hewitt (1998), and Kirkpatrick (1999, p.11).

Table 1 contd

[e] Approximate area estimated from ~50-cm isopach in Fig. 7, which is based on Blackburn (1959), Hutton et al. (1959), Sheard (1986, 1990), and field work; small areas of soils with andic properties, and possibly Andisols, occur in the 'Newer Volcanics' province of western Victoria (e.g. Tower Hill, Mt Eccles, Red Rock, or Mt Porndon volcanic complexes) (Hamblin and Greenland, 1972; Lowe et al., 1996).

[f] Includes Hapludands, Udivitrands, Melanudands, Fulvudands, Hydrudands; area is maximum estimate (Otawa, 1986; Takahashi and Shoji, 2002).

[g] Mainly Vitricryands; area is maximum estimate (Arnalds and Kimble, 2001).

[h] From New Zealand Soil Classification (Hewitt, 1998) and Australian Soil Classification (Isbell, 2002).

[i] Small local areas of Udands are formed also in free-draining scoriaceous basaltic tephra deposits in northern North Island (Fig. 3).

[j] Eruptions also incorporated exotic calcareous and siliceous material (see text) (after Lowe et al., 1996). The eruptions *c.* 5000 years ago were evidently recorded in Aboriginal oral tradition (Sheard, 1990).

[k] Most soils developed under dense native forest but repeated burning by early Polynesians (Maori) in parts of North Island from *c.* 1250–1300 AD resulted in many being developed under bracken fern, shrubland and native grasses (McGlone, 1989; Newnham et al., 1998; McGlone and Wilmshurst, 1999; Hogg et al., 2003). Many of the soils have been under introduced grasses (together with bracken and scrub) since European settlement from the mid-1800s.

[l] European accounts from the early–mid-1800s described the volcanic soils beyond the craters generally as heavily timbered with dense to semi-open woodland and some open grassy meadows with ferns, whereas the crater interiors were sparsely treed with grasses and shrub cover on the steeper slopes (M.J. Sheard, pers. comm. 2004; see also Dodson, 1975). Plants fossilized by the volcanic ash include common tree or shrub species and grasses (Sheard, 1978, 1983). The impact of Aboriginal 'fire-stick' burning after the eruptions was probably limited to understorey firing in cooler times to avoid deforestation (M.J. Sheard, pers. comm., 2004). The area has been under introduced grasses and bracken fern since extensive European clearance from the mid-1800s (Blackburn, 1959).

[m] Soil moisture and temperature regimes from Soil Survey Staff (1999): Ud, udic; Xe, xeric; Me, mesic; Cr, cryic; Th, thermic; local aquic moisture regimes and conditions gave rise to Aquands and Vitriaquands in New Zealand.

[n] Globally, Andisols cover about 1.24 million km^2 (Soil Survey Staff, 1999; Kimble et al., 2000), around 0.84% of the world's land surface (Takahashi and Shoji, 2002).

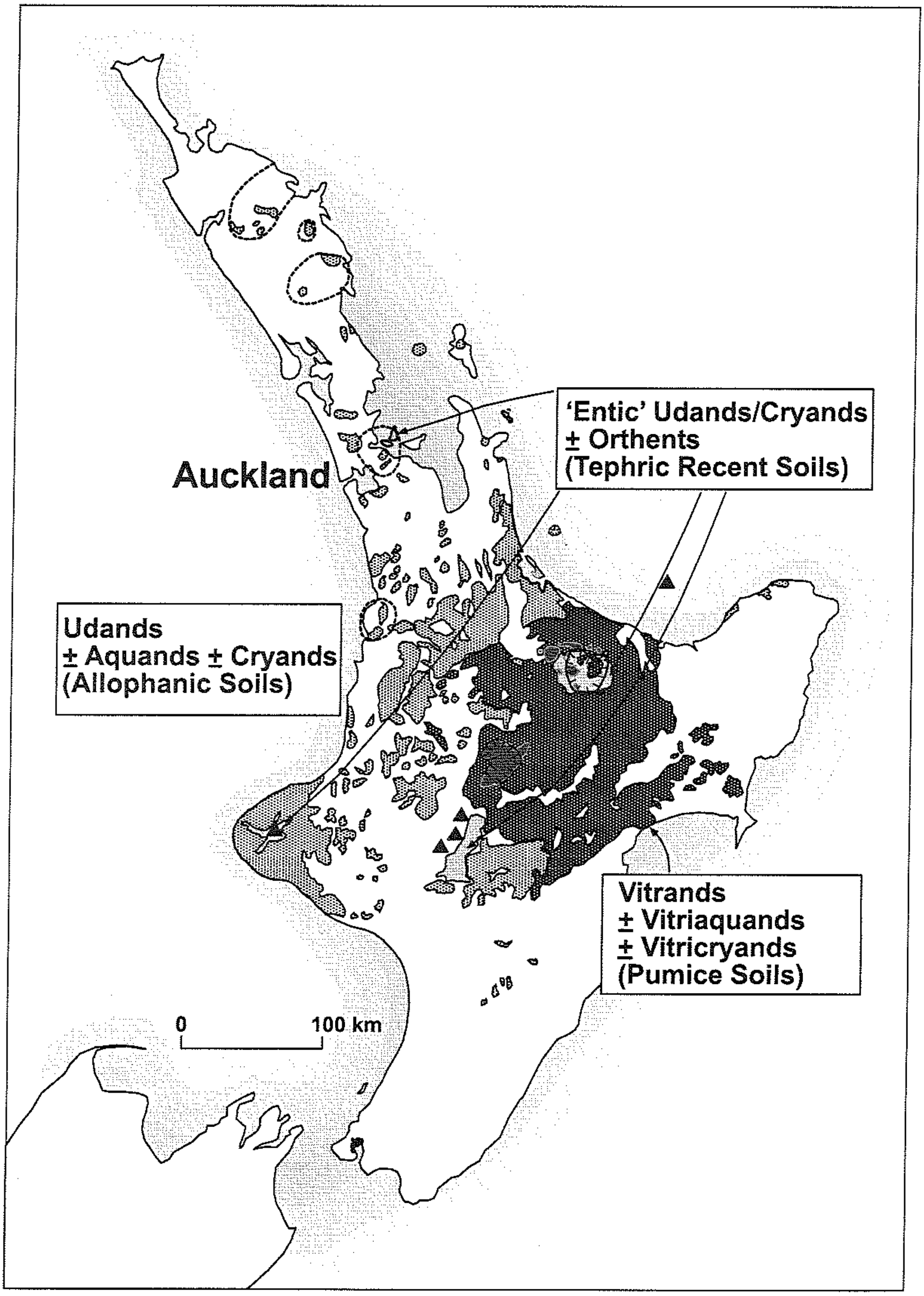

Fig. 2. Distribution of three main groupings of Andisols in North Island (after Kirkpatrick, 1999, based on Rijkse and Hewitt, 1995). Classifications according to NZSC are given in parentheses (Hewitt, 1998).

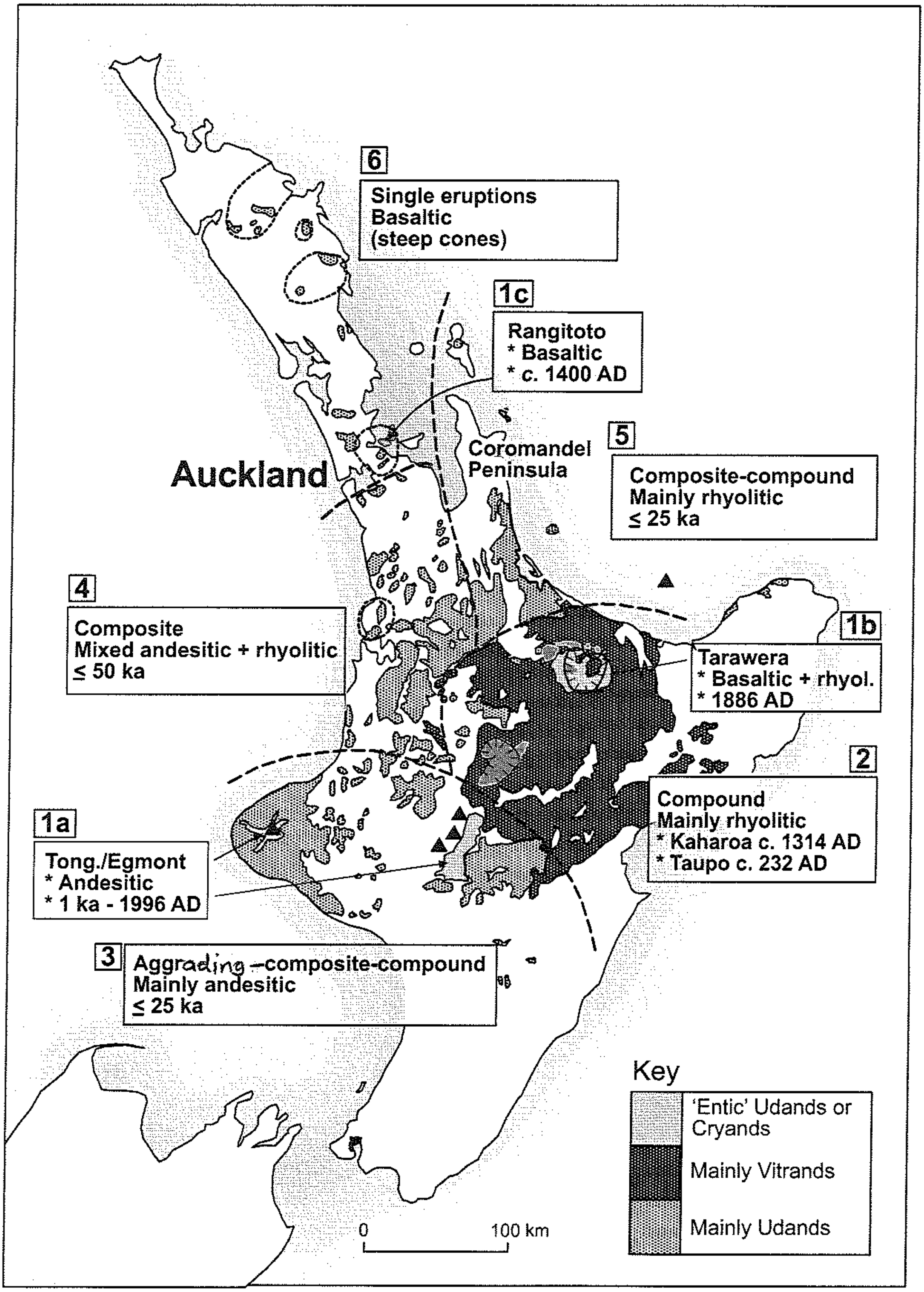

Fig. 3. Generalised subdivisions of the main groupings of Andisols in North Island into six zones according to their multisequal soil character (soil stratigraphy), the primary composition(s) of component tephras, and approximate ages of the soil profiles (ka, thousands of years).

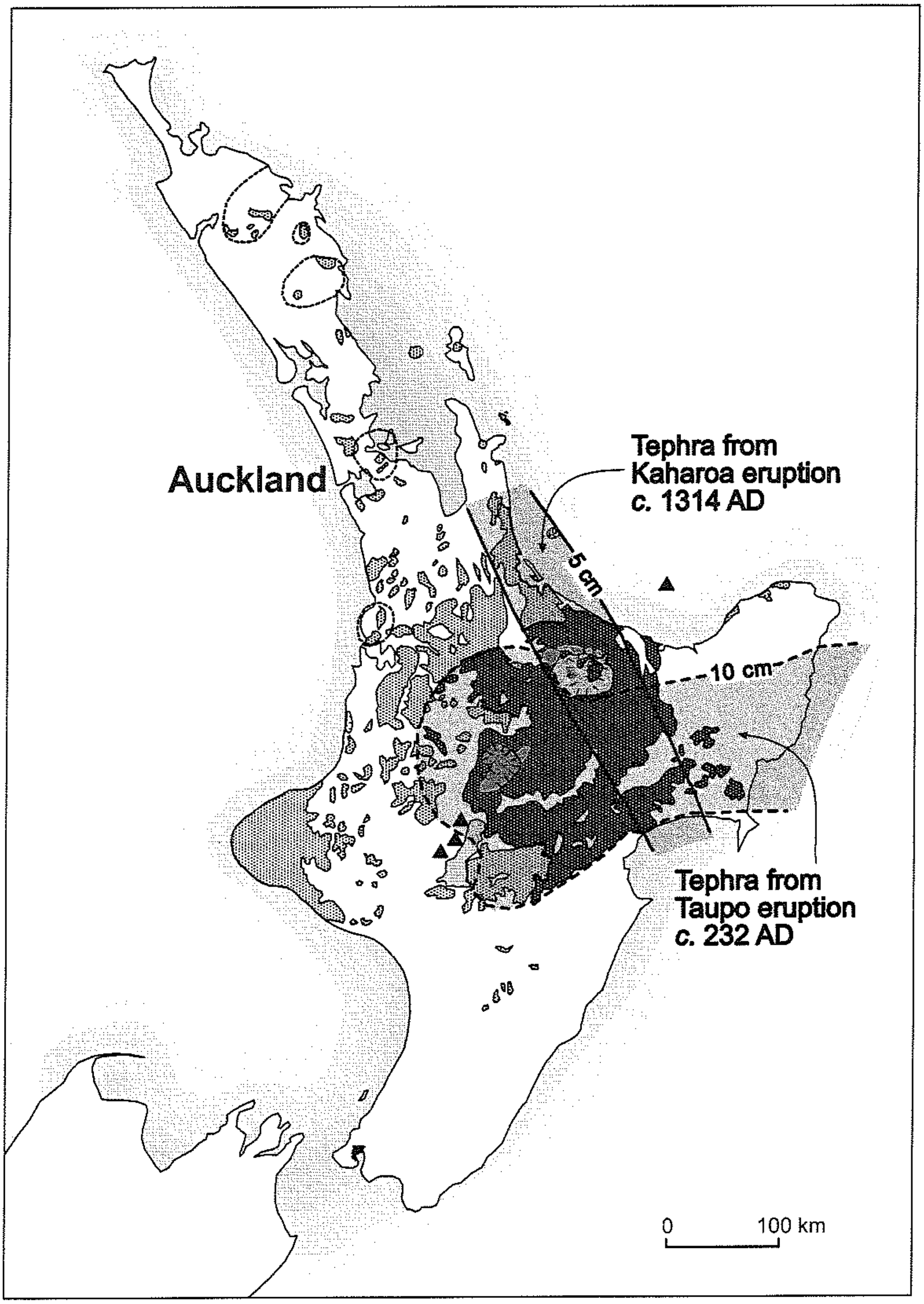

Fig. 4. Approximate single isopach distributions of tephra deposited from the two most recent rhyolitic eruptions in North Island: the Taupo eruption *c.* 232 AD ± 15 from Taupo Volcanic Centre (after Wilson and Walker, 1985; Sparks et al., 1995; Lowe and de Lange, 2000), and the Kaharoa eruption *c.* 1314 AD ± 12 from Mt Tarawera in Okataina Volcanic Centre (after Lowe et al., 1998; Hogg et al., 2003). Key for shading as in Fig. 3.

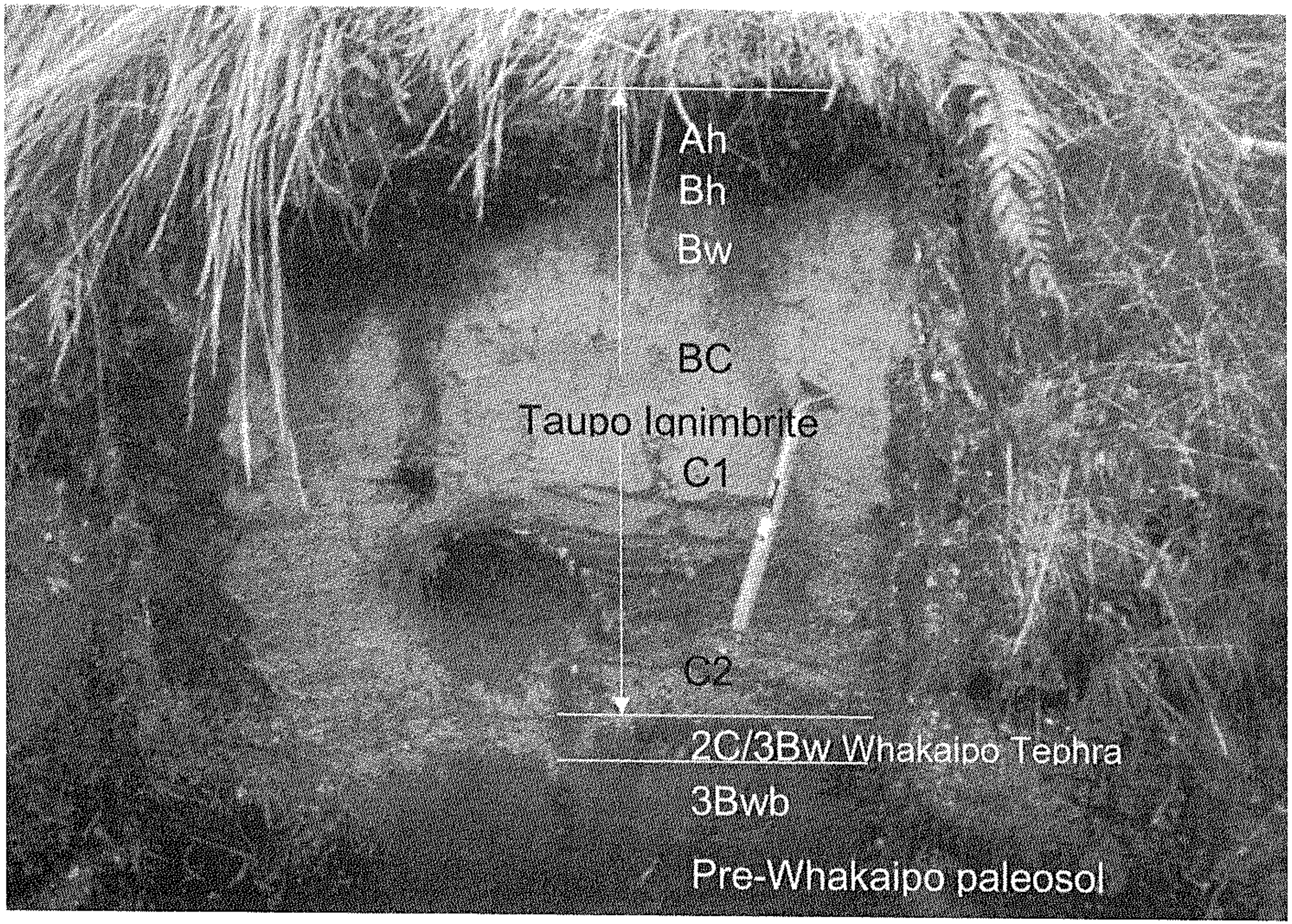

Fig. 5. Humic Udivitrand developed on Taupo Ignimbrite (unconsolidated pyroclastic density current deposit from phase Y6 of Taupo eruption *c.* 232 AD), on Mamaku Plateau east of Tokoroa (New Zealand Map Series 260 grid reference U16/745313). In NZSC, this soil is a Podzolic Orthic Pumice Soil (Hewitt, 1998), a member of the Oruanui series (Rijkse, 1979; Hill, 1999). Whakaipo Tephra (Unit V) was erupted from Taupo Volcanic Centre *c.* 2800 years ago (Wilson, 1993). Horizonation is based on Schoeneberger et al. (2002). Photo: D.J. Lowe.

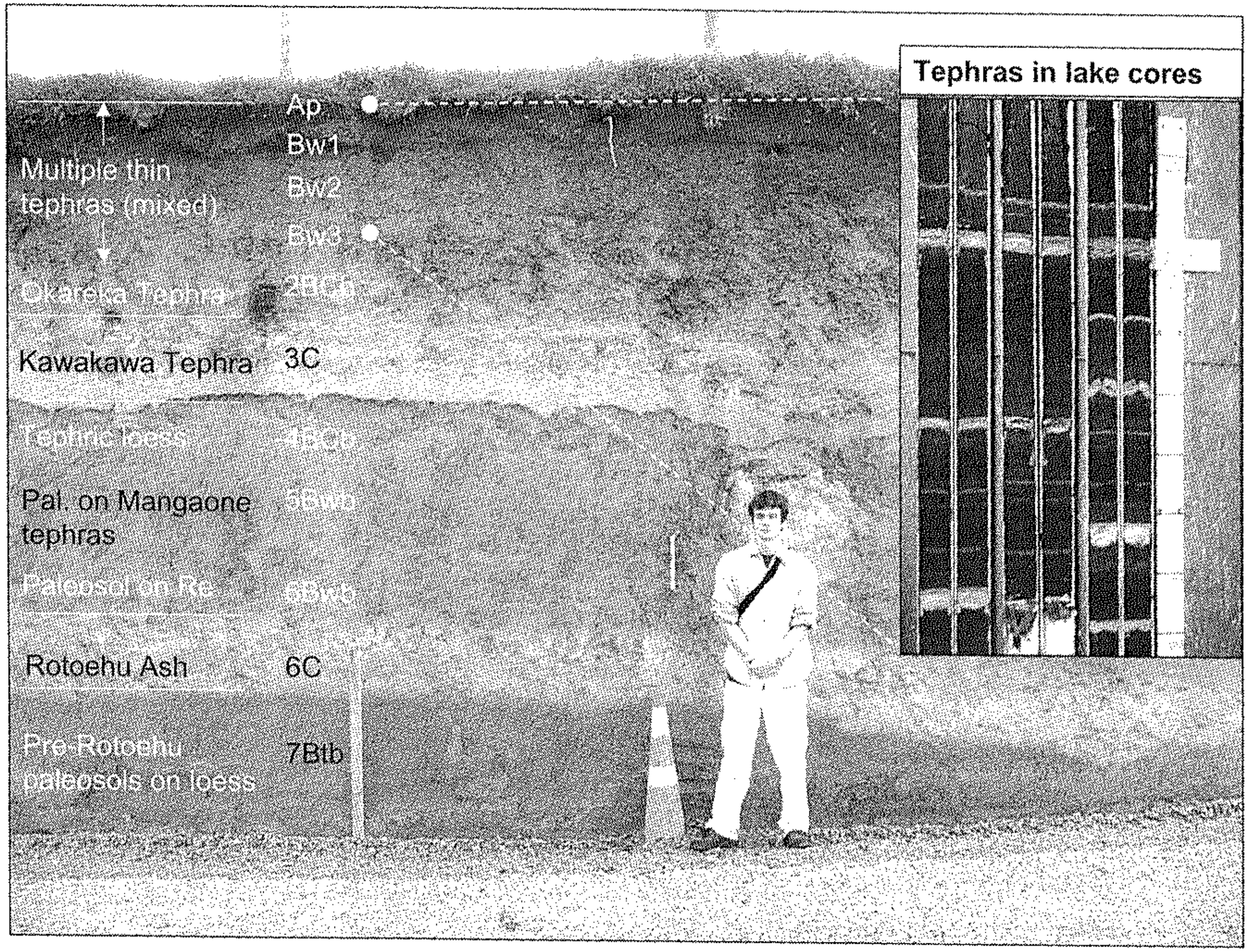

Fig. 6. Typic Hapludand developed on a composite of multiple tephras overlying Okareka Tephra (*c.* 22,500 years old, Newham et al., 2003) and earlier eruptives and tephra loess deposits and associated paleosols, near Putaruru (T15/575498) in southeastern Waikato region. Kawakawa Tephra (from Taupo VC) is *c.* 26,500 years old (Wilson, 2001), Rotoehu Ash (from Okataina VC) is *c.* 55,000 years old (Newnham et al., 2004). In NZSC, the modern soil is a Typic Orthic Allophanic Soil (Hewitt, 1998), a member of the Tirau series (McLeod, 1992). Horizonation is based on Schoeneberger et al. (2002). Inset shows Holocene tephra layers preserved in organic lake sediment (after Lowe, 1988). Main photo: D. J. Lowe

and Andisols, covering ~29% of the North Island, are pre-eminent among them, especially Udands, because of important soil ecosystem services they provide including sorption, water storage and supply, natural fertility (with regular maintenance dressings of potassic superphosphate and other fertilisers), and foundation support (Leamy et al., 1980; Hewitt, 2001).

The Vitrands (Pumice Soils in NZSC) are extremely deficient in phosphorus, potassium, sulphur, nitrogen and magnesium and typically deficient also in micronutrients such as cobalt (especially), selenium, copper, boron, iodine and molybdenum (Cornforth, 1998; Hewitt, 1998; Molloy and Christie, 1998). Because of their coarse textures and low strength, they tend to be easily depleted of nutrients, readily eroded, and droughty (Gibbs, 1968; Selby and Hosking, 1973). On the credit side, however, shifting nutrient balances by fertilizer management of Vitrands is much easier than in other soils of greater weathering and clay content, and they respond well to fertilizer inputs (Gibbs et al., 1968; Molloy and Christie, 1998). Occasional 'dustings' by andesitic tephra fallout from eruptions of volcanoes in the Tongariro Volcanic Centre have generally added small but beneficial amounts of nutrients to Vitrands (and some Udands), such as from the 1995–1996 eruptions of Mt Ruapheu that added between 30–1500 kg ha^{-1} sulphur, as well as small quantities of selenium, potassium and magnesium, to substantial land areas (Cronin et al., 1998). The young age of the Vitrands also means that soil nutrients are potentially available from ongoing weathering by carbonic acid of the easily-weatherable fine pumice fragments in the parent material (Bakker et al., 1996; Dahlgren et al., 2004; Zabowski et al., in press).

Vitrands are generally well suited to deep-rooting plants such as lucerne (alfalfa) and exotic pine plantations, which are dominated by *Pinus radiata* in central North Island (Molloy and Christie, 1998; Palmer et al., in press), and also for forest farming (Tustin et al., 1979). Except where subsoils are compact, trees are usually able to develop extensive, deep root systems very rapidly and hence tap and exploit reserves of nutrients and moisture in buried soils (Gibbs, 1970; Knight and Will, 1970; Will, 1974). In addition, the very fine vesicularity of the pumice particles in the Vitrands confers a high water storage capacity (20–30% of soil volume) yet the soils are highly porous, drain readily, and have good infiltration characteristics (Jackson, 1974; Molloy and Christie, 1998). Edaphic factors relating to plantation forestry on Vitrands have been the focus of considerable study (e.g. Madgwick et al., 1990; Beets et al., 2004), and research into sustainable forest practices has increased markedly since the Resource Management Act was enacted in 1991 and New Zealand became a signatory to the Montreal Process (e.g. Murphy et al., 1997; Richardson et al., 1999; Simcock et al., 2003; Oliver et al., 2004; Palmer et al., in press).

The Udands (Allophanic Soils in NZSC), like their counterparts beyond New Zealand, are generally of high value for food production because they are deep and have outstanding physical properties including free drainage and high porosity and hence good aeration, high friability and good tilth, low bulk densities, stable aggregates, and high plant-available moisture retention (Gibbs et al., 1968; Soil Bureau Staff, 1968; Fletcher and Jessen, 1982; Allbrook, 1983; Molloy and Christie, 1998). These features thus provide a high rate of seedling emergence, excellent rooting characteristics, and strong resistance to drought stress (Dahlgren et al., 2004), ideal for plant production and grazing in udic climates because the upper soil profiles are not sticky and when moist absorb large amounts of water without swelling (Gibbs et al., 1968). On the other hand, the Udands have high maintenance requirement for phosphorus, potassium and magnesium for dairying, and they respond to regular additions of these and also to lime where pHs are <5.5 (Gibbs et al., 1968; Cornforth, 1998; Hewitt, 1998). Sulphur retention is also high (Cornforth, 1998) and cobalt is marginally deficient in more strongly leached Udands (Hewitt, 1998). However, the Udands are unmatched with regard to versatility for pasture growth (16–18 tonnes dry matter/ha in the Taranaki and Waikato regions), cropping (maize in thermic parts of the Waikato region), horticulture (including nurseries, kiwifruit, tamarillos, berry fruit, pip and stone fruit, citrus, asparagus, feijoas, and avocados, especially in the Bay of Plenty and in Northland for warmth-requiring crops), and sports fields (Molloy and Christie, 1998). Although under growing pressure from much more intense cropping and grazing, North Island Udands are proving to be remarkably resilient soils (e.g. Cotching et al., 1979; Magesan et al., 1999; Shepherd et al., 2001; Parfitt et al., 2002), but in some cases properties have deteriorated as a consequence of such intensification (e.g. Singleton and Addison, 1999). Udands and some Vitrands are being used successfully for effluent (wastewater) irrigation and the disposal of biosolids (Cameron et al., 1997; Degens et al, 2000; Speir, 2002; Magesan and Wang, 2003; Barton et. al., 2005), and they are proving to be generally effective at pesticide sorption (Baskaran et al., 1996).

HOLOCENE VOLCANISM AND ANDISOLS IN SOUTHEAST SOUTH AUSTRALIA

Origin, age and composition of Holocene volcanoes and eruptives

The volcanoes of southeast South Australia form the western extension of the Newer Volcanics Province of western Victoria (Sheard and Nicholls, 1989) and comprise two distinct groups : a northern Pleistocene group in the Mount Burr range (not considered further) and a southern Holocene group of two isolated basaltic eruption centres at Mounts Gambier and Schank (Fig. 7; Sheard, 1978, 1983, 1990, 1992). About 10 km apart, Mounts Gambier and Schank are both aged about 5000 years old on the basis of a combination of radiocarbon, thermoluminescence and palaeomagnetic dating, and are the youngest volcanoes on the Australian mainland (Barton and McElhinny, 1980; Barbetti and Sheard, 1981; Smith and Prescott, 1987; Sheard, 1990). Leaney et al. (1995) suggested that the Mount Gambier complex was considerably older, at least 28,000 years old, but this older age has been disputed (M.J. Sheard, pers. comm. 2004).

Mounts Gambier and Schank comprise unusual complex maar and cone structures built over eruptive fissures and, strongly influenced by the presence of abundant groundwater, erupted mainly tephra including scoria, lapilli and ash that was dispersed to a thickness of about 5 cm or less at around 10–12 km from source (Fig. 7; Hutton et al., 1959; Hutton, 1974); lava is less common and rarely soil-forming.

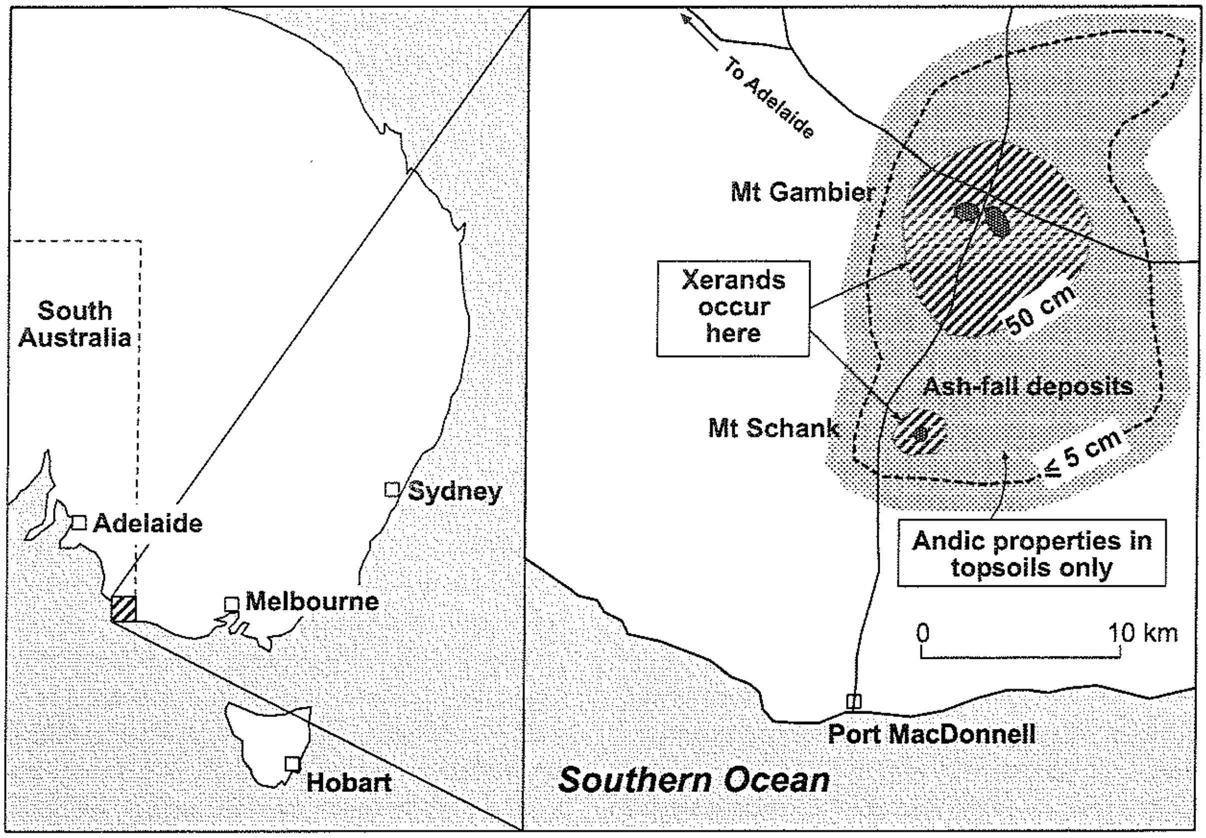

Fig. 7. Location of Mts Gambier and Schank in southeastern South Australia and generalised distribution of ash-fallout from these volcanoes and associated soils with andic properties.

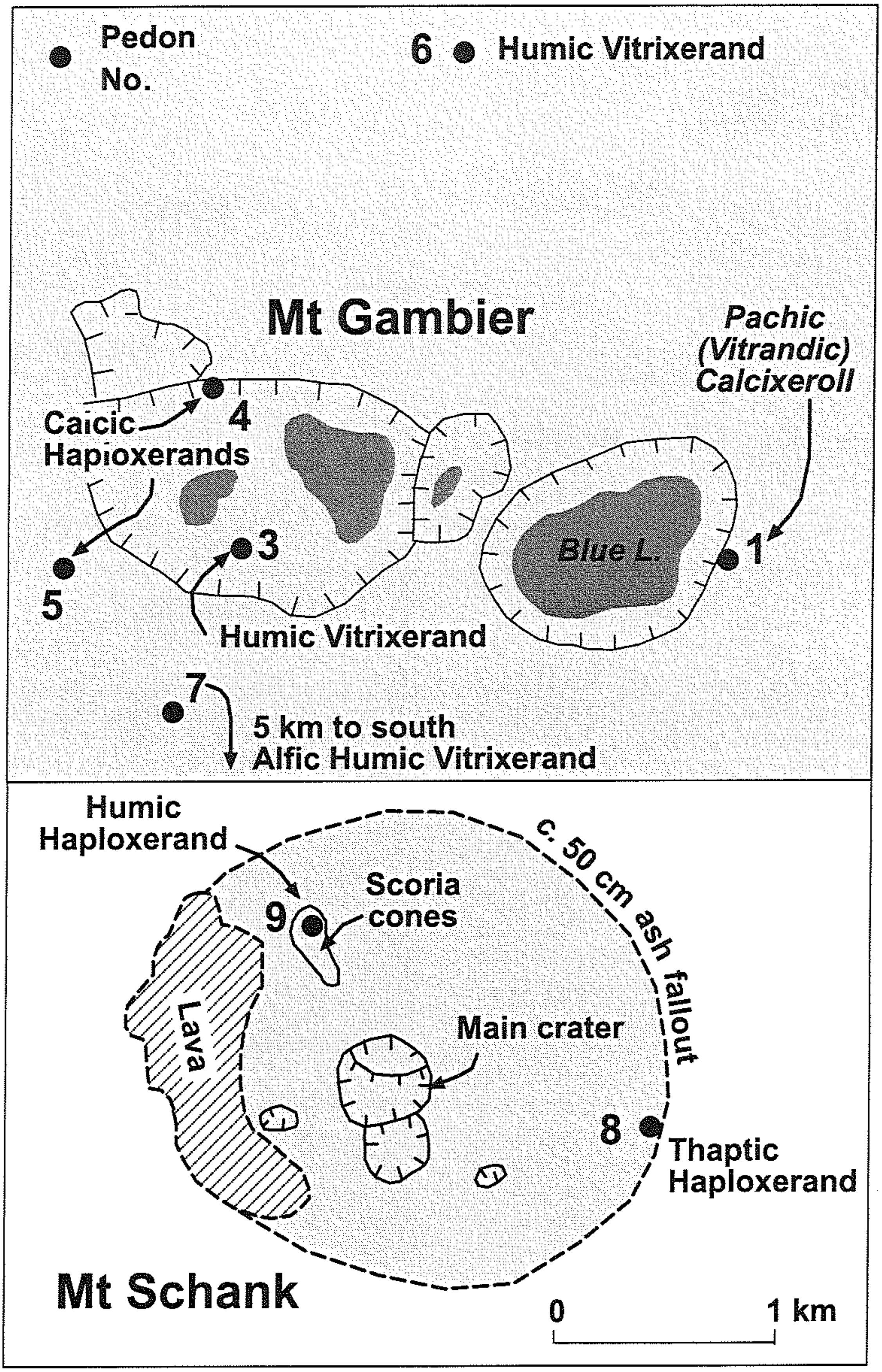

Fig. 8. Locations of pedons studied at Mts Gambier and Schank and subgroup classifications (Soil Survey Staff, 1999). In upper panel, Mt Gambier township lies mainly on the northern slopes of the cones/crater features, and ashfall thickness is ≥~50 cm throughout. Grey areas represent crater lakes.

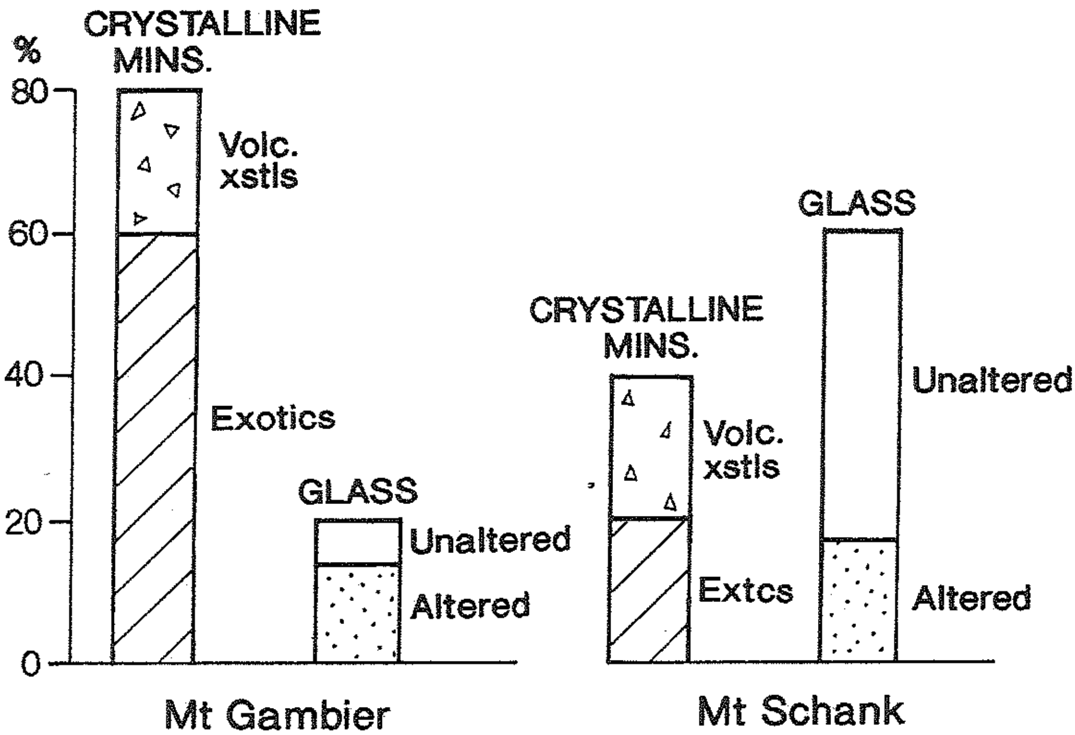

Fig. 9. Mineralogy of sand fractions of tephra–derived soils in the Mt Gambier region, showing contrast between Mt Gambier and Mt Schank. Juvenile volcanic crystals include olivine, labradorite, titanaugite, and Fe–Ti oxides; exotic minerals include quartz, chert, sponge spicules. After Sheard et al. (1993) and Lowe et al. (1996).

Both volcanic complexes stratigraphically overlie consolidated, calcareous aeolian sands (Bridgewater Formation) and Oligocene–Miocene limestone (Gambier Limestone) (Sheard, 1986, 1990, 1992), and therefore the resultant pyroclastic deposits, and hence soils, may contain large proportions (up to 60%, see below) of exotic, non–volcanic material including limestone fragments as well as basaltic material (Lowe et al., 1996).

Five pedons were studied by Lowe (1992) and Lowe et al. (1996) at Mount Gambier, two at Mount Schank, and one mid–way (pedon 7) between the two centres (Fig. 8). Sand fractions of the Mount Gambier soils, acid–treated to remove $CaCO_3$ and analysed using optical ~~mineralogy~~ microscopy and an electron microprobe, are dominated by crystalline minerals (≥80%) including substantial exotic, silicic minerals (quartz, chert, sponge spicules), magma–derived crystals of forsteritic olivine, labradorite, titanaugite, and Fe–Ti oxides, and little volcanic glass (<20%), most of which is altered (Fig. 9). In contrast, the acid–treated sand fractions of the Mt Schank soils contain abundant glass (≥50%), most of which is unaltered, fewer exotic minerals (quartz, sponge spicules), and magma–derived crystals of titanaugite, olivine, labradorite, and Fe–Ti oxides (Fig. 9). The volcanic glass shards from Mts Gambier and Schank are basaltic (mean SiO_2 content = 48–50%) and Al–rich (mean Al_2O_3 = 16.3%), the two centres being indistinguishable on the basis of glass major oxide compositions (Sheard et al., 1993).

Soil physical and chemical properties and clay mineralogy

Profile morphologies of the pedons at four of the sites are illustrated in Fig. 10. At sites close to source, the soils are developed entirely within pyroclastic eruptives from Mt Gambier or Mt Schank (e.g. Fig. 10A, B) but at the more distant sites (pedons 7 and 8) the ashfall of ~60 cm thickness has buried and isolated the pre–existing soils, forming compound, multisequal soil profiles containing buried paleosols (Fig. 10C, D).

The soils were formed under xeric moisture and

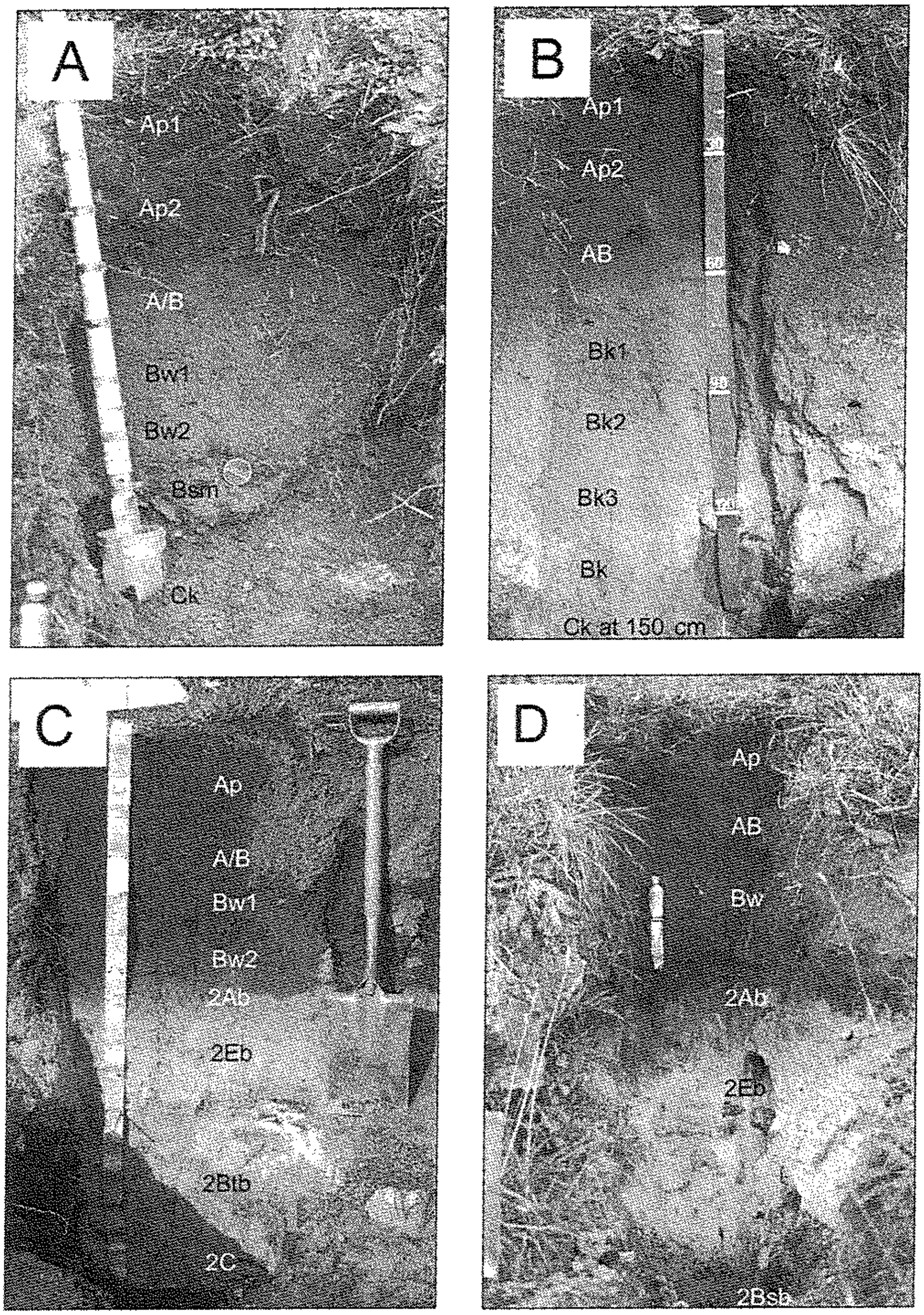

Fig.10. Profiles of four Xerands in the Mt Gambier region at sites indicated in Fig. 8. Soils and locations are described in Lowe (1992). Horizonation is based on Schoeneberger et al. (2002). All photographs by D.J. Lowe.

A. Humic Vitrixerand at site 3 (Brownes Lake; see also McKenzie et al., 2004, p.346) developed in coarse, basaltic lava spatter and ashfall deposits. In the Australian Soil Classification, this soil is a Humose, Andic, Chernic Tenosol (Isbell, 2002). Marks on auger at 10–cm intervals.
B. Calcic Haploxerand at site 4 (Potters Point) developed in fine basaltic lava spatter (above ~65 cm) over basaltic ash and lapilli fall deposits. In ASC, this soil is a Humose–Calcareous, Andic, Chernic Tenosol. Scale in cm.
C. Alfic Humic Vitrixerand at site 7 (Louden Hill Quarry) developed in basaltic ashfall deposits overlying a buried soil on aeolian sand. In ASC, this soil is a Melanic, Andic, Chernic Tenosol *on* Bleached, Dystrophic, Yellow Chromosol. Scale in cm.
D. Thaptic Haploxerand at site 8 (Laslett Rd) developed on basaltic ashfall deposits overlying a buried soil on aeolian sand. In ASC, this soil is a Humose, Andic, Chernic Tenosol *on* Fragic, Sesquic, Aeric Podosol. Knife is 25 cm long.

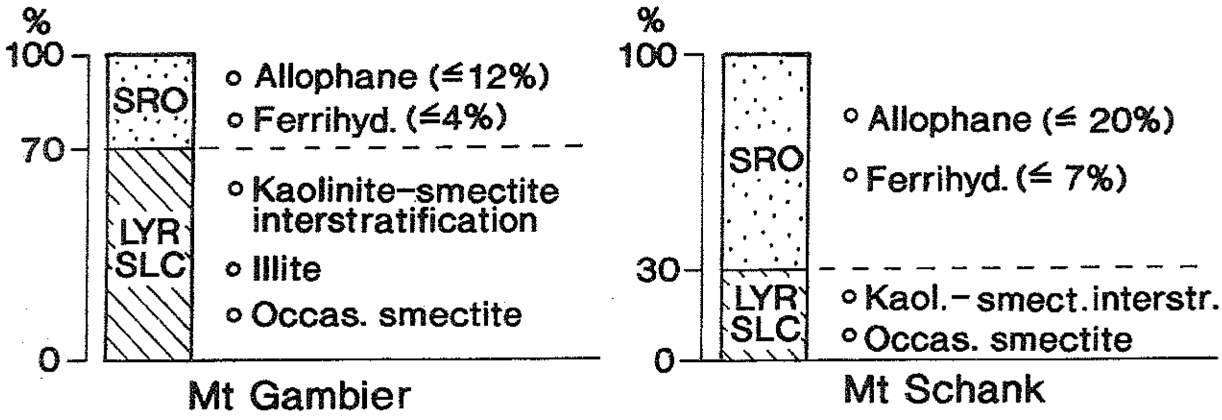

Fig. 11. General distribution of clays (percentages on fine-earth basis) in profiles in the Mt Gambier region, contrasting the differences between Mt Gambier and Mt Schank (after Lowe et al., 1996; see also Churchman, 2000). SRO = short-range-order clays, LYR SLC = layer silicate clays.

mesic temperature regimes characterised by moist (drizzly), cool winters and very warm, dry summers (Table 1). Although the annual rainfall at Mt Gambier is around 700 mm, water balance studies show that usually about 280 mm of water drains through upper soil profiles over a period of three to ten weeks in winter and early spring (Allison and Hughes, 1978).

At both Mts Gambier and Schank, the soils are generally weakly weathered and have deep, black to dark brown, very friable, polyhedral or apedal earthy A horizons with gritty silt loam textures (mean <2 µm-clay contents = 11-22%) and a mean of 5.5 ± 1.0 % organic carbon (range 3.7-6.9%). Subsoils comprise mainly brown or yellowish to greyish-brown, friable Bw horizons with textures of loamy sands or sandy or silt loams (mean <2 µm-clay contents = 2-15%), usually with gravel (e.g. Fig 10B). Visible or HCl-reactive accumulations of $CaCO_3$, up to 38 wt%, are common at Mt Gambier, forming Bk and Ck horizons (e.g. Fig. 10A, B). The soils to 60 cm depth have generally low bulk densities (mean = 0.84 ± 0.13 Mg m^{-3}, range 0.68-1.17 Mg m^{-3}), high acid-oxalate extractable Al_{ox} and Fe_{ox} (both 4%) if $CaCO_3$ is low and vice versa, P retentions that exceed 50% (highest when Al_{ox} is high), 1.5 MPa water from 7 to 26%, and pH_{water} values from 6.4 to 8.0 (Lowe et al., 1996).

Clay fractions (<2 µm) at Mt Gambier are dominated by layer silicate minerals including kaolinite interstratified with smectite, illite and sometimes discrete smectite (Churchman and Lowe, 1993; Lowe et al., 1996). No halloysite was detected by the formamide expansion test (Churchman et al., 1984). Substantial allophane (up to ~12% on a fine-earth basis, FEB) and ferrihydrite (up to ~4%, FEB) occur in some horizons (Fig. 11).

Clay fractions of the soils at Mt Schank contain substantial allophane (up to ~20%, FEB) and ferrihydrite (up to 17%, FEB) in most horizons, with some layer silicates (not illite) found in the lowest horizons (Fig. 11). The greater abundance of SRO minerals at Mt Schank than at Mt Gambier may reflect the contrast in proportions of glassy and xenolithic materials making up the parent materials (Fig. 9), with the abundant basaltic glass at Mt Schank weathering more readily to release Al (Churchman and Lowe, 1993; Lowe et al., 1996).

For each of the pedons, the ratio of Al to Si of the allophane (Al_{ox}-Al_{py}/Si_{ox}) tends to diminish with increasing depth (Churchman and Lowe, 1993; Churchman, 2000). It averages~1.8 in upper horizons, dropping to 1.5 and then 1.2 in intermediate horizons; there is little or no allophane in lowermost horizons that are usually calcareous. These trends imply that 'imogolite-like' Al-rich allophane is forming in the upper horizons whereas 'halloysite-like' Si-rich allophane is forming at intermediate depths lower in the profiles, consistent with a general Si-leaching model (Parfitt et al., 1983; Lowe, 1986, 1995). It was suggested by Lowe et al. (1996) that the formation of the Al-rich allophane in the upper horizons was probably the result of frequent seasonal leaching (consistent with low $CaCO_3$ content) during winter or early spring when rainfall is highest and evapotranspiration lowest. The drainage of ~280 mm of water through the upper profile each year on average matches or just exceeds the threshold of about 250 mm needed for Al-rich allophane to form, based on New Zealand models (Parfitt et al., 1984; Lowe, 1995; Churchman, 2000). In contrast, the formation of the Si-rich allophane in the intermediate horizons is probably the result of weaker leaching, the net rainfall being insufficient to penetrate to such depths very often because only about 100 mm of water drains through the intermediate horizons each year at Mt Gambier (Allison and Hughes, 1982), and thus silica levels remain relatively high. The silicic components derived from the limestones have provided an additional potential source of silica (Fig. 9). The lack of allophane, together with the presence of smectite, in the lowest horizons is consistent with minimal leaching or possibly silica accumulation, or both. The absence of halloysite is surprising because previous work on soils formed in dry (or calcareous) regimes suggested that this was likely to be the main clay mineral formed (e.g. Mizota and van Reeuwijk, 1989; Parfitt, 1990b; Takahashi et al., 1993; Silber et al., 1994; Qafuka et al., 2004).

Thus clay mineral formation, especially allophane, is affected partly by leaching and partly by the parent material composition. The Mt Gambier sand fractions are dominated by exotic, silicic crystalline minerals and the clays comprise mainly layer silicates with some allophane in upper horizons, whereas the Mt Schank clay fractions are dominated by Al-rich basaltic glass and the clays consist of mainly allophane with minor layer silicates.

Classification

Most of the pedons studied at Mts Gambier and Schank are Vitrixerands or Haploxerands (Figs. 8, 10), all but one qualifying by exceeding required glass contents >5% to >12% (Soil Survey Staff, 1999). Pedon 1 failed because it contained too little glass (>21% glass required), and instead is a Pachic Calcixeroll. This subgroup keys out just before Vitrandic Calcixerolls. An alternative classification – 'Vitrandic Pachic' Calcixeroll – would encapsulate both the thick mollic epipedon and (weak) andic properties of the soil (Lowe et al., 1992; Fitzpatrick et al., 1992).

Xerands, making up only 3.5% of the Andisols (Wilding, 2000), are comparatively rare on a global basis because andisolization processes that form SRO clays (or Al/Fe-humus complexes), and hence andic soil properties, tend to be favoured by strong leaching in cool, udic moisture regimes (Mizota and van Reeuwijk, 1989; Parfitt and Kimble, 1989; Parfitt, 1990b; Kimble et al., 2000; Dahlgren et al., 2004). Moreover, the South Australian Xerands have evidently formed quite rapidly, in only 5000 years, assuming the ages for the volcanoes are accurate. They are the only Andisols currently identified in Australia, but small patches of soils with andic properties probably occur on younger volcanoes in the Newer Volcanics Province in western Victoria such as at the Tower Hill volcanic complex, and possibly elsewhere (Table 1).

In the Australian Soil Classification (Isbell, 2002), the pedons are all classed as Andic, Chernic Tenosols, this great group being erected specifically by the late Ray F. Isbell to accommodate the Xerands first identifed at Mts Gambier and Schank by Lowe et al. (1992) (Isbell et al., 1997). Most of the characteristic thick topsoils, which gave rise to their classification previously as Chernozems (e.g. Blackburn, 1959; Stace et al., 1968), qualify in Isbell (2002) as Humose horizons (e.g. Fig. 10A, B, D) but pedon 7, with less organic carbon, has a Melanic horizon[1] (Fig. 10C).

Why do the Xerands around Mts Gambier and Schank tend to have such thick A horizons? One suggestion is that Aboriginal 'fire-stick' farming (see Mckenzie et al., 2004, p.112), although probably limited to understorey burning in cooler times to avoid deforestation (M.J. Sheard, pers. comm. 2004), has led to partial 'melanisation' of the ash-derived soils in areas where semi-open woodland and open grassy meadows with ferns prevailed (Table 1). Alternatively, the Al-rich nature of the readily weatherable basaltic glass at Mt Schank may have helped stabilise humus accumulation via Al-humus complexing in addition to forming allophane.

Utilization and management

The Xerands in the Mt Gambier region are regarded as valuable, versatile soils that have been used for agriculture (dairying) and horticulture (especially vegetables chiefly potatoes, onions, and also cut flowers) since the 1850s. They are essentially

[1] Note : The Melanic horizon of Isbell (2002) differs from that of Soil Survey Staff (1999).

free of micro-element deficiencies and have relatively high levels of P, N, K, and S (Blackburn, 1959; Hutton, 1974). However, extended periods of cutting lucerne hay have resulted in the development of potassium deficiency where the volcanic-ash derived soils are shallow (less than ~50 cm thick) over limestone or calcareous aeolian sand. Although naturally high in total phosphorus, a small response was obtained to this element at such sites (R. Merry, pers. comm. 2004). Some soils near Mt Schank have been used for effluent irrigation.

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REFERENCES

Allbrook, R.F. 1983. Some physical properties of allophane soils from the North Island, New Zealand. New Zealand Journal of Science 26 : 481-492.

Allison, G.B., and M.W. Hughes. 1978. The use of environmental chloride and tritium to estimate total recharge to an unconfined aquifer. Australian Journal of Soil Research 16 : 181-195.

Alloway, B.V., M.S. McGlone, V.E. Neall, and C.G. Vucetich. 1992. The role of Egmont-sourced tephra in evaluating the paleoclimatic correspondence between the bio- and soil-stratigraphic records of central Taranaki, New Zealand. Quaternary International 13-14 : 187-194.

Almond, P.C., and P.J. Tonkin. 1999. Pedogenesis by upbuilding in an extreme leaching and weathering environment, and slow loess accretion, south Westland, New Zealand. Geoderma 92 : 1-36.

Arnalds, O., and J. Kimble. 2001. Andisols of deserts in Iceland. Soil Science Society of America Journal 65 : 1778-1786.

Bakker, L., D.J. Lowe, and A.G. Jongmans. 1996. A micromorphological study of pedogenic processes in an evolutionary soil sequence formed on Late Quaternary rhyolitic tephra deposits, North Island, New Zealand. Quaternary International 34-36 : 249-261.

Barbetti, M., and M.J. Sheard. 1981. Palaeomagnetic results from Mounts Gambier and Schank, South Australia. Journal of the Geological Society of Australia 28 : 385-394.

Barton, C.E., and M.W. McElhinny. 1980. Ages and ashes in lake floor sediment cores from Valley Lake, Mt Gambier, South Australia. Transactions of the Royal Society of South Australia 104 : 161-165.

Barton, L., L.A. Schipper, G.F. Barkle, M. McLead, T.W. Speir, M.D. Taylor, A.C. McGill, A.P. van Schaik, N.B. Fitzgerald, and S.P. Pandey. 2005. Land application of domestic effluent on to four soil types. Journal of Environmental Quality 34 : 635-643.

Baskaran, S., N.S. Bolan, A. Rahman, and R.W. Tilman. 1996. Pesticide sorption by allophanic and non-allophanic soils of New Zealand. New Zealand Journal of Agricultural research 39 : 297-310.

Beets, P.N., G.R. Oliver, M.O. Kimberley, S.H. Pearce, and B. Rodgers. 2004. Genetic and soil factors associated with variation in visual magnesium deficiency symptoms in *Pinus radiata.* Forest Ecology and Management 189 : 263-279.

Birrell, K.S., and Pullar, W.A. 1973. Weathering of paleosols in Holocene and late Pleistocene tephras in central North Island, New Zealand. New Zealand Journal of Geology and Geophysics 16 : 687–702.

Birrell, K.S., W.A. Pullar, and J.C. Heine. 1971. Pedological, chemical, and physical properties of organic horizons of paleosols underlying the Tarawera Formation. New Zealand Journal of Science 14 : 187–218.

Blackburn, G. 1959. The soils of County Grey, South Australia. CSIRO Soils and Land Use Series 33. 51p.

Cameron, K.C., Di, H.J., and McLaren, R.G. 1997. Is soil an appropriate dumping ground for our wastes? Australian Journal of Soil Research 35 : 995–1035.

Churchman, G.J. 2000. The alteration and formation of soil minerals by weathering. In : Sumner, M.E. (ed-in-chief) Handbook of Soil Science. CRC Press, Baca Baton : F3–76.

Churchman, G.J., and D.J. Lowe. 1993. Poorly crystalline clay minerals in soils from Holocene basaltic tephra in a calcareous environment and xeric moisture regime in South Australia. Abstracts, 10th International Clay Conference, Adelaide : P-30.

Churchman, G.J., J.S. Whitton, G.G.C. Claridge, and B.K.G. Theng. 1984. Intercalation method using formamide for differentiating halloysite from kaolinite. Clays and Clay Minerals 32 : 241–248.

Clayden, B., A.E. Hewitt, M. McLeod, W. Rijkse, H. Wallace, and R.H. Wilde. 1997. North Island soil surveys : classification of named soils by subgroups of the New Zealand Soil Classification. Landcare Research, Lincoln. 149p.

Cornforth, A. 1998. Practical Soil Management. Lincoln University Press, Whitireia Publishing, and Daphne Brasell Associates, Canterbury. 248p.

Cotching, W.E., R.F. Allbrook, and H.S. Gibbs. 1979. Influence of maize cropping on the soil structure of two soils in the Waikato district, New Zealand. New Zealand Journal of Agricultural Research 22 : 431–438.

Cowie, J.D., and J.D.G. Milne. 1973. Maps and sections showing the distribution and stratigraphy of North Island loess and associated cover deposits, New Zealand. New Zealand Soil Survey Report 6.

Cronin, S.J., V.E. Neall, and A.S. Palmer. 1996. Investigation of an aggrading paleosol developed into andesitic ring-plain deposits, Ruapehu volcano, New Zealand. Geoderma 69 : 119–135.

Cronin, S.J., M.J. Hedley, V.E. Neall, R.G. Smith. 1998. Agronomic impact of tephra fallout from the 1995 and 1996 Ruapehu Volcano eruptions, New Zealand. Environmental Geology 34 : 21–30.

Dahlgren, R., S. Shoji, and M. Nanzyo. 1993. Mineralogical characteristics of volcanic ash soils. Developments in Soil Science 21 : 101–143.

Dahlgren, R.A., M. Saigusa, and F.C. Ugolini. 2004. The nature, properties and management of volcanic soils. Advances in Agronomy 82 : 113–182.

Degens, B.P., L.A. Schipper, J.J. Claydon, J.M. Russell, and G.W. Yeates. 2000. Irrigation of an allophanic soil with dairy factory effluent for 22 years : responses of nutrient storage and soil biota. Australian Journal of Soil Research 38 : 25–35.

Dodson, J.R. 1975. The pre-settlement vegetation of the Mt Gambier area, South Australia. Transactions of the Royal Society of South Australia 99 : 89–92.

Fitzpatrick, R.W., W.H. Hudnall, D.J. Lowe, D.J. Maschmedt, and R.H. Merry. 1992. Proposed changes in the classification of Histosols, Alfisols, Andisols, Aridisols, Inceptisols, Mollisols, Entisols, and Spodosols in South Australia. CSIRO Division of Soils Technical Report 51/1992. 17p.

Fletcher, J.R., and M.R. Jessen. 1982. Land use capability of yellow-brown loams. In : Neall, V.E. (ed) Soil Groups of New Zaland. Part 6 Yellow-brown Loams. New Zealand Society of Soil Science, Lower Hutt : 96–101.

Froggatt, P.C., and D.J. Lowe. 1990. A review of late Quaternary silicic and some other tephra formations from New Zealand : their stratigraphy, nomenclature, distribution, volume, and age. New Zealand Journal of Geology and Geophysics 33 : 89–109.

Gibbs, H.S. 1968. Volcanic-ash soils of New Zealand. New Zealand Department of Scientific and Industrial Research Information Series 65. 39p.

Gibbs, H.S. 1970. Nature of paleosols in New Zealand. and their classification. In : Yaalon, D.H. (ed) Paleopedology – Origin, Nature, and Dating of Paleosols. ISSS and Israel University Press, Jerusalem : 229–244.

Gibbs, H.S., J.D. Cowie, and W.A. Pullar. 1968. Soils of North Island. New Zealand Soil Bureau Bulletin 26(1) : 48–67.

Hamblin, A.P., and D.J. Greenland. 1972. Mineralogy of soils from the Holocene volcanic area of southern Australia. Australian Journal of Soil Research 10 : 61–79.

Hewitt, A.E. 1995. Soil map of the South Island, New Zealand Soil Classification 1 : 1,000,000 scale. Manaaki Whenua, Landcare Research, Lincoln, New Zealand.

Hewitt, A.E. 1998. New Zealand Soil Classification, 2nd edition. Landcare Research Science Series 1. 133p.

Hewitt, A.E. 2001. New Zealand soils in volcanic materials. Abstract in 'Volcanic Soils : Properties, Processes and Land Use'. International Workshop of COST Action 622, Soil Resources of European Volcanic Systems, Ponta Delgarda, Azores Portugal, October 2001.

Hill, R. B. 1999. Applying a land systems approach to describe and partition soil and forest variability, southern Mamaku Plateau, part of Kinleith Forest, New Zealand. Unpublished Ph.D. thesis, Lincoln University, Canterbury, New Zealand.

Hill, R.B., P.J. Tonkin, and P.C. Almond. 1999. A revised stratigraphic interpretation of the geomorphology and late Quaternary erosion history of the southern Mamaku Plateau. Geological Society of New Zealand Miscellaneous Publication 107A : 64.

Hodder, A.P.W., B.E. Green, and D.J. Lowe. 1990. A two-stage model for the formation of clay minerals from tephra-derived volcanic glass. Clay Minerals 25 : 313–327.

Hodder, A.P.W., T.R. Naish, and D.J. Lowe. 1996. Towards an understanding of thermodynamic and kinetic controls on the formation of clay minerals from volcanic glass under various environmental conditions. In : Pandalai, S.G. (ed) Recent Research Developments in Chemical Geology. Research Signpost, Trivandrum, India : 1–11.

Hogg, A.G., T.F.G. Higham, D.J. Lowe, J. Palmer, P. Reimer, and R.M. Newnham. 2003. A wiggle-match date for Polynesian settlement of New Zealand. Antiquity 77, 116–125.

Hosono, M., Y. Oba, T. Sase, T. Utsugawa, and K. Aoki. 1991. Holocene volcanic ash soils at Waimangu Road tephra section, North Island, New Zealand : soil-forming vegetation relationships. Quaternary Research (Tokyo) 30 : 91–101.

Houghton, B.F., S.D. Weaver, C.J.N. Wilson, and M.A. Lanphere. 1992. Evolution of a Quaternary peralkaline volcano : Mayor Island, New Zealand. Journal of Volcanology and Geothermal Research 51 : 217–236.

Hutton, J.T., G. Blackburn, and A.R.P. Clarke. 1959. Identification of volcanic ash in soils near Mount Gambier, South Australia. Transactions of the Royal Society of South Australia 82 : 93–98.

Hutton, J.T. 1974. Chemical characterization and weathering changes in Holocene volcanic ash in soils near Mount Gambier, South Australia. Transactions of the Royal Society of South Australia 98 : 179–184.

Isbell, R.F. 2002. The Australian Soil Classification, Revised edition. Australian Soil and Land Survey Series 4. CSIRO Publishing, Melbourne. 152p.

Isbell, R.F., W.S. McDonald, and L.J. Ashton. 1997. Concepts and rationale of the Australian Soil Classification. ACLEP, CSIRO Land and Water, Canberra. 152p.

Jackson, R.J. 1974. Physical properties. In : Read, N.E. (ed) Soil Groups of New Zealand. Part 1 Yellow-brown Pumice Soils. New Zealand Society of Soil Science, Lower Hutt : 97–102.

Jongmans, A.G., F. Van Oort, P. Buurman, A.M. Jaunet, and J.D.J. van Doesburg. 1994. Morphology, chemistry and mineralogy of isotropic aluminosilicate coatings in a Guadaloupe Andisol. Soil Science Society of America Journal 58 : 501–507.

Johnson, D.L., and D. Watson-Stegner. 1987. Evolution model of pedogenesis. Soil Science 143 : 349–366.

Kimble, J.M., C.-L. Ping, M.E. Sumner, and L.P. Wilding. 2000. Andisols. In : Sumner, M.E. (ed-in-chief) Handbook of Soil Science. CRC Press, Baca Baton : E209–224.

Kirkpatrick, R. 1999. Bateman Contemporary Atlas New Zealand. David Bateman, Auckland. 160p.

Knight, P.J., and G.M. Will. 1970. An appraisal of nutrient supplies available for tree growth in a pumice soil. Earth Science Journal 4 : 1–16.

Leamy, M.L., G.D. Smith, F. Colmet-Daage, and M. Otawa. 1980. The morphological characteristics of Andisols. In : Theng, B.K.G. (ed) Soils With Variable Charge. New Zealand Society of Soil Science, Lower Hutt : 17–34.

Leaney, F.W.J., G.B. Allison, J.C. Dighton, and S. Trumbore. 1995. The age and hydrological history of Blue Lake, South Australia. Palaeogeography, Palaeoclimatology, Palaeoecology 118 : 111–130.

Lowe, D.J. 1986. Controls on the rates of weathering and clay mineral genesis in airfall tephras : a review and New Zealand case study. In : Colman, S.M., and D.P. Dethier (eds) Rates of Chemical Weathering of Rocks and Minerals. Academic Press, Orlando : 265–330.

Lowe, D.J. 1988. Stratigraphy, age, composition, and correlation of late Quaternary tephras interbedded with organic sediments in Waikato lakes, North Island, New Zealand. New Zealand Journal of Geology and Geophysics 31 : 125–165.

Lowe, D.J. 1992. Profile descriptions of Quaternary basaltic volcanogenic soils of the Mount Gambier area, southeast South Australia. CSIRO Division of Soils Technical Report 9/1992. 26p.

Lowe, D.J. 1995. Teaching clays : from ashes to allophane. In : Churchman, G.J., R.W. Fitzpatrick, and R.A. Eggleton (eds) Clays : Controlling the Environment. Proceedings 10th International Clay Conference, Adelaide (1993). CSIRO Publishing, Melbourne : 19–23.

Lowe, D.J. 2000. Upbuilding pedogenesis in multisequal tephra-derived soils in the Waikato region. Proceedings, Australian and New Zealand 2nd Joint Soils Conference, Lincoln University. New Zealand Society of Soil Science 2 : 183–184.

Lowe, D.J., and W.P. de Lange. 2000. Volcano-meteorological tsunamis, the *c.* AD 200 Taupo eruption (New Zealand) and the possibility of a global tsunami. The Holocene 10 : 401–407.

Lowe, D.J., and B.E. Green. 1992. A hydrofluoric acid dissolution method for determining volcanic glass content of tephra-derived soils (Andisols). Australian Journal of Soil Research 30 : 573–581.

Lowe, D.J., and J.B. Hunt. 2001. A summary of terminology used in tephra-related studies. In : Juvigné, E.T., and J.-P. Raynal (eds) Tephras : Chronology, Archaeology. Les Dossiers de l'Archeo-Logis 1 : 17–22.

Lowe, D.J., and H.J. Percival. 1993. Clay mineralogy of tephras and associated paleosols and soils, and hydrothermal deposits, North Island. Guidebook for New Zealand Pre-Conference Field Trip F1, 10th International Clay Conference, Adelaide. 110 p.

Lowe, D.J, R.H. Merry, W.H. Hudnall, and R.W. Fitzpatrick. 1992. Proposed changes to Soil Taxonomy : IV. Andisols. Abstracts, Australian Society of Soil Science 4th National Soils Confererence, Adelaide : 7.

Lowe, D.J., G.J. Churchman, R.H. Merry, R.W. Fitzpatrick, M.J. Sheard, and W.H. Hudnall. 1996. Holocene basaltic volcanogenic soils of the Mt Gambier area, South Australia, are unusual globally : what do they tell us? Proceedings of ASSS and NZSSS National Soils Conference, University of Melbourne 2 : 153–154.

Lowe, D.J., B.G. McFadgen, T.F.G. Higham, A.G. Hogg, P.C. Froggatt, and I.A. Nairn. 1998. Radiocarbon age of the Kaharoa Tephra, a key marker for late-Holocene stratigraphy and archaeology in New Zealand. The Holocene 8 : 487–495.

Lowe, D.J., R.M. Newnham, and J.D. McCraw. 2000a. Quaternary environmental change in New Zealand and its effects on the soil pattern. Proceedings, Australian and New Zealand 2nd Joint Soils Conference, Lincoln University. New Zealand Society of Soil Science 3 : 117–118.

Lowe, D.J., R.M. Newnham, B.G. McFadgen, and T.F.G. Higham. 2000b. Tephras and New Zealand archaeology. Journal of Archaeological Science 27 : 859–870.

Lowe, D.J., M.J. Tippett, P.J.J. Kamp, I.J. Liddell, R.M. Briggs,and J.L. Horrocks. 2001. Ages on weathered Plio-Pleistocene tephra sequences, western North Island, New Zealand. In : Juvigné, E.T., and J.-P. Raynal (eds) Tephras : Chronology, Archaeology. Les Dossiers de l'Archeo-Logis 1 : 45–60.

Lowe, D.J., R.M. Newnham, and J.D. McCraw. 2002. Volcanism and early Maori society in New Zealand. In : Torrence, R., and J. Grattan (eds) Natural Disasters and Cultural Change. Routledge, London : 126–161.

Madgwick, H.A.I., G.R. Oliver, and A.T. Lowe. 1990. Boron, copper, manganese and zinc nutrition of *Pinus radiata* plantations. Forest Ecology and Management 37 : 37–48.

Magesan, G.N., and H. Wang. 2003. Application of municipal and industrial residuals in New Zealand forests : an overview. Australian Journal of Soil Research 41 : 557–569.

Magesan, G.N., J.C. Williamson, G.P. Sparling, L.A. Schipper, and A.R. Lloyd-Jones. 1999. Hydraulic conductivity in soils irrigated with wastewater of differing strengths : field and laboratory studies. Australian Journal of Soil Research 37 : 391–402.

McCraw, J.D. 1975. Airfall deposits of New Zealand. Royal Society of New Zealand Bulletin 13 : 35–44.

McGlone, M.S. 1989. The Polynesian settlement of New Zealand in relation to environmental and biotic changes. New Zealand Journal of Ecology (Supplement) 12 : 115–129.

McGlone, M.S., and J.M. Wilmshurst. 1999. Dating initial Maori environmental impact in New Zealand. Quaternary International 59 : 5–16.

McKenzie, N., D. Jacquier, R. Isbell, and K. Browne. 2004. Australian Soils and Landscapes : An Illustrated Compendium. CSIRO Publishing, Melbourne. 416p.

McLeod, M. 1992. Soils of part northern Matamata County, North Island, New Zealand. Department of Scientific and Industrial Research Land Resources Science Report 18.

Mizota, C., and L.P. van Reeuwijk. 1989. Clay mineralogy and chemistry of soils formed in volcanic materials in diverse climatic regions. International Soil Reference and Information Centre Soil Monograph 2. 185p.

Molloy, L., and Q.R. Christie. 1998. Soils in the New Zealand Landscape, 2nd edition. New Zealand Society of Soil Science, Lincoln. 253p.

Murphy, G., J.G. Firth, and M.F. Skinner. 1997. Soil disturbance effect of *Pinus radiata* growth during the first 11 years. New Zealand Forestry 42 : 27–30.

Nanzyo, M., Dahlgren, R., and S. Shoji. 1993. Chemical characterisitcs of volcanic ash soils. Developments in Soil Science 21 : 145–187.

Nanzyo, M. 2002. Unique properties of volcanic ash soils. Global Environmental Research 6 : 99–112.

Neall, V.E. 1977. Genesis and weathering of Andosols in Taranaki. Soil Science 123 : 400–408.

Newnham, R.M., D.J.Lowe, M.S. McGlone, J.M. Wilmshurst, and T.F.G. Higham. 1998. The Kaharoa Tephra as a critical datum for earliest human impact in northern New Zealand. Journal of Archaeological Science 25 : 533–544.

Newnham, R.M., D.J. Lowe, and P.W. Williams. 1999. Quaternary environmental change in New Zealand : a review. Progress in Physical Geography 23 : 567–610.

Newnham, R.M., D.N. Eden, D.J. Lowe, and C.H. Hendy. 2003. Rerewhakaaitu Tephra, a land-sea marker for the Last Termination in New Zealand, with implications for global climate change. Quaternary Science Reviews 22 : 289–308.

Newnham, R.M., D.J. Lowe, J.D. Green, G.M. Turner, M.A. Harper, M.S. McGlone, S.L. Stout, S. Horie, and P.C. Froggatt. 2004. A discontinuous ca. 80 ka record of Late Quaternary environmental change from Lake Omapere, Northland, New Zealand. Palaeogeography, Palaeoclimatology, Palaeoecology 207 : 165–198.

Oliver, G.R., P.N. Beets, L.G. Garrett, S.H. Pearce, M.O. Kimberley, J.B. Ford-Robertson, and K.A. Robertson. 2004. Variations in soil carbon in pine plantations and implications for managment in New Zealand monitoring soil carbon stocks in relation to land-use change and forest sites. Forest Ecology and Management 203 : 283–295.

Otawa, M. 1986. Morphology and classification. In : Wada, K. (ed) Ando Soils in Japan. Kyushu University Press, Hakozaki : 3–20.

Palmer, D.J., D.J. Lowe, T.W. Payn, B.K. Höck, C.D.A. McLay, and M.O. Kimberley. in press. Soil and foliar phosphorus as indicators of sustainability for *Pinus radiata* plantation forestry in New Zealand. Forest Ecology and Management.

Parfitt, R.L. 1990a. Allophane in New Zealand-a review. Australian Journal of Soil Research 28 : 343–360.

Parfitt, R.L. 1990b. Soils formed in tephra in different climatic regions. Transactions 14th Congress, International Society of Soil Science, Kyoto 7 : 134–139.

Parfitt, R.L., and B. Clayden. 1991. Andisols – the development of a new order in Soil Taxonomy. Geoderma 49 : 181–198.

Parfitt, R.L., and J.M. Kimble. 1989. Conditions for formation of allophane in soils. Soil Science Society of America Journal 53 : 971–977.

Parfitt, R.L., and T.H. Webb. 1984. Allophane in some South Island yellow-brown shallow and stony soils and high country and upland yellow-brown earths. New Zealand Journal of Science 27 : 37–40.

Parfitt, R.L., and M. Saigusa. 1985. Allophane and humus-aluminium in Spodosols and Andepts formed from the same volcanic ash beds in New Zealand. Soil Science 139 : 149-155.

Parfitt, R.L., M. Russell, and G.E. Orbell. 1983. Weathering sequence of soils from volcanic ash involving allophane and halloysite, New Zealand. Geoderma 29 : 41-57.

Parfitt, R.L., M. Saigusa, and J.D. Cowie. 1984. Allophane and halloysite formation in a volcanic ash bed under different moisture conditions. Soil Science 138 : 360-364.

Parfitt, R.L., C.W. Childs, B. Clayden, M.L. Leamy, and D.I. Kinloch (compilers). 1988. International Committee on the Classification of Andisols (ICOMAND) Circular Letter No. 10. 80p.

Parfitt, R.L., A. Parshotam, and G.J. Salt. 2002. Carbon turnover in two soils with contrasting mineralogy under long-term maize and pasture. Australian Journal of Soil Research 40 : 127-136.

Ping, C.-L. 2000. Volcanic soils. In : Sigurdsson, H. (ed-in-chief) Encyclopaedia of Volcanoes. Academic Press, San Diego : 1259-1270.

Ping, C.-L., S.Shoji, and T. Ito. 1988. The properties and classification of three volcanic ash-derived soils in Alaska. Soil Science 148 : 8-28.

Pullar, W.A., and K.S. Birrell. 1973. Age and distribution of late Quaternary pyroclastic and associated cover deposits of the Rotorua and Taupo area, North Island, New Zealand. New Zealand Soil Survey Report 1.

Qafoku, N.P., E. Van Ranst, A. Noble, and G. Baert. 2004. Variable charge soils : their mineralogy, chemistry and management. Advances in Agronomy 84 : 159-215.

Richardson, B., M.F. Skinner, and G. West. 1999. The role of forest productivity in defining the sustainability of plantation forestry in New Zealand. Forest Ecology and Management 122 : 125-137.

Rijske, W. 1979. Soils of Rotorua Lakes district, North Island, New Zealand. New Zealand Soil Survey Report 43.

Rijske, W.C., and A.E. Hewitt. 1995. Soil map of the North Island, New Zealand Soil Classification 1 : 1,000,000 scale. Manaaki Whenua, Landcare Research, Lincoln, New Zealand.

Saigusa, M., and N. Matsuyama. 2004. Distribution and agronomic aspects of non-allophanic Andisols. Proceedings 6th International Symposium on Plant-Soil Interactions at Low pH, Sendai. Japanese Society of Soil Science and Plant Nutrition : 334-335.

Sase, T., and M. Hosono. 1996. Vegetation histories of Holocene volcanic ash soils in Japan and New Zealand - relationship between genesis of melanic volcanic ash soils and human impact. Earth Science (Chikyu Kagaku) 50 : 466-482.

Shane, P.A.R. 2000. Tephrochronology : a New Zealand case study. Earth-Science Reviews 49 : 223-259.

Schoeneberger, P.J., Wysocki, D.A., Benham, E.C., Broderson, W.D. (editors) 2002. Field book for describing and sampling soils, Version 2.0. Natural Resources Conservation Service, National Soil Survey Center, Lincoln, NE.

Selby, M.J., and P.J. Hosking. 1973. The erodibility of pumice soils of the North Island, New Zealand. Journal of Hydrology (New Zealand) 12, 32-56.

Selby, M.J. and D.J. Lowe. 1992. The middle Waikato Basin and hills. In : Soons, J.M., and M.J. Selby (eds) Landforms of New Zealand, 2nd edition. Longman Paul, Auckland : 233-255.

Sheard, M.J. 1978. Geological history of the Mount Gambier volcanic complex, southeast South Australia. Transactions of the Royal Society of South Australia 102 : 125-139.

Sheard, M.J. 1983. Volcanoes. In : Tyler, M.J., Twidale, C.R., Ling, J.K., and Holmes, J.W. (eds) The Natural History of the South East. Royal Society of South Australia, Adelaide : 7-14.

Sheard, M.J. 1986. Some volcanological observations at Mount Schank, southeast South Australia. Geological Survey of South Australia, Quarterly Geological Notes 100 : 14-20.

Sheard, M.J. 1990. A guide to Quaternary volcanoes in the Lower South-east of South Australia. Mines and Energy Review, South Australia 157 : 40-50.

Sheard, M.J. 1992. Volcanoes of the Mount Gambier area. South Australian Department of Mines and Energy Information Sheet 19.

Sheard, M.J., and I.A. Nicholls. 1989. Mt Gambier Sub-province. In : Johnson, R.W. (ed) Intraplate Volcanism in Eastern Australia and New Zealand. Australian Academy of Science and Cambridge University Press, Sydney : 141-142.

Sheard, M.J., D.J. Lowe, and P.C. Froggatt 1993. Mineralogy of pyroclastic and lava deposits of Holocene basaltic volcanoes of Mts Gambier and Schank, South Australia. Abstracts, IAVCEI International Volcanological Congress, Canberra : 98.

Shepherd, T.G., S. Saggar, R.H. Newman, C.W. Ross, and J.L. Dando. 2001. Tillage-induced changes to soil structure and organic carbon fractions in New Zealand soils. Australian Journal of Soil Research 39 : 465–489.

Shoji, S., and T. Takahashi. 2002. Environmental and agricultural significance of volcanic ash soils. Global Environmental Research 6 : 113–135.

Shoji, S., M. Nanzyo, and R. Dahlgren. 1993a. Volcanic Ash Soils : Genesis, Properties and Utilization. Developments in Soil Science 21. Elsevier, Amsterdam. 288p.

Shoji, S., R. Dahlgren, and M. Nanzyo. 1993b. Genesis of volcanic ash soils. Developments in Soil Science 21 : 37–71.

Shoji, S., R. Dahlgren, and M. Nanzyo. 1993c. Morphology of volcanic ash soils. Developments in Soil Science 21 : 7–35.

Shoji, S., M. Nanzyo, and R. Dahlgren. 1993d. Productivity and utilization of volcanic ash soils. Developments in Soil Science 21 : 209–251.

Silber, A., B. Bar-Yosef, A. Singer, and Y. Chen. 1994. Mineralogical and chemical composition of three tuffs from northern Israel. Geoderma 63 : 123–144.

Simcock, R., R. Parfitt, R. Schuster, and M. Skinner. 2003. Which soils are vulnerable to growth-limiting compaction? Results from 24 field trials. Proceedings, 10th North American Forest Soils Conference, Sault Saint Marie, Ontario, Canada 3 : 8–10.

Singleton, P.L. 1999. High quality soils. New Zealand Soil News 47 : 143–146.

Singleton, P.L., and B. Addison. 1999. Effects of cattle treading on physical properties of three soils used for dairy farming in the Waikato, North Island, New Zealand. Australian Journal of Soil Research 37 : 891–902.

Singleton, P.L., M. McLeod, and H.J. Percival. 1989. Allophane and halloysite content and soil solution silicon in soils from rhyolitic volcanic material, New Zealand. Australian Journal of Soil Research 27 : 67–77.

Smith, B.W., and J.R. Prescott. 1987. Thermoluminescence dating of the eruption at Mt Schank, South Australia. Australian Journal of Earth Sciences 34 : 335–342.

Soil Bureau Staff. 1968. Soils of New Zealand, Part 2. New Zealand Soil Bureau Bulletin 26(2) : 7–218.

Soil Bureau Staff. 1973. Map of parent rocks of New Zealand soils 1 : 1,000,000. New Zealand Soil Survey Report 5.

Soil Survey Staff. 1999. Soil Taxonomy, 2nd edition. USDA Natural Resources Conservation Service Agriculture Handbook 436. 869 p.

Spaargaren, O.C. 2000. Other systems of soil classification. In : Sumner, M.E. (ed-in-chief) Handbook of Soil Science. CRC Press, Baca Baton : E137–174.

Sparks, R.J., W.H. Melhuish, J.W.A. McKee, J. Ogden, and J.G. Palmer. 1995. ^{14}C calibration in the Southern Hemisphere and the date of the last Taupo eruption : evidence from tree-ring sequences. Radiocarbon 37 : 155–163.

Speir, T.W. 2002. Soil biochemical properties as indices of performance and sustainability of effluent irrigation systems in New Zealand-a review. Journal of the Royal Society of New Zealand 32 : 535–553.

Stace, H.C.T., G.D. Hubble, R. Brewer, K.H. Northcote, J.R. Sleeman, M.J. Mulcahy, and E.G. Hallsworth. 1968. A Handbook of Australian Soils. Rellim Technical Publications, Adelaide.

Suryaningtyas, D. 1998. Characterisation of volcanic-ash derived soils of southern area of Mount Ruapehu, North Island, New Zealand. Unpublished M.App.Sci. thesis, Massey University, Palmerston North, New Zealand.

Takahashi, T., and S. Shoji. 2002. Distribution and classification of volcanic ash soils. Global Environmental Research 6 : 83–97.

Takahashi, T., R. Dahlgren, and P. van Susteren. 1993. Clay mineralogy and chemistry of soils formed in volcanic materials in the xeric moisture regime of northern California. Geoderma 59 : 131–150.

Tustin, J.R., R.L. Knowles, and B.K. Klomp. 1979. Forest farming : multiple land-use production systems in New Zealand. Forest Ecology and Management 2 : 169–189.

Ugolini, F.C., and Dahlgren, R.A. 2002. Soil development in volcanic ash. Global Environmental Research 6 : 69–81.

Wallace, H.J., S.J. Burgham, A.E. Hewitt, P.D.

McIntosh, and T.H. Webb. 2000. South Island soil surveys : classification of named soils by subgroups of the New Zealand Soil Classification. Landcare Research, Lincoln. 145p.

Wilding, L.P. 2000. General characteristics of soil orders and global distributions. In : Sumner, M.E. (ed-in-chief) Handbook of Soil Science. CRC Press, Baca Baton : E175-183.

Will, G.M. 1974. Forestry. In : Read, N.E. (ed) Soil Groups of New Zealand. Part 1 Yellow-brown Pumice Soils. New Zealand Society of Soil Science, Lower Hutt : 181-183.

Wilson, C.J.N. 1993. Stratigraphy, chronology, styles and dynamics of late Quaternary eruptions from Taupo volcano, New Zealand. Philosopical Transactions of the Royal Society London A343 : 205-306.

Wilson, C.J.N. 2001. The 26.5 ka Oruanui eruption, New Zealand : an introduction and overview. Journal of Volcanology and Geothermal Research 112 : 133-174.

Wilson, C.J.N., and G.P.L. Walker. 1985. The Taupo eruption, New Zealand I. General aspects. Philosophical Transactions of the Royal Sociey London A314 : 199-228.

Wilson, C.J.N., B.F. Houghton, M.O. McWilliams, M.A. Lanphere, S.D. Weaver, and R.M. Briggs. 1995. Volcanic and structural evolution of Taupo Volcanic Zone, New Zealand : a review. Journal of Volcanology and Geothermal Research 68 : 1-28.

Wright, I.C., R.D. Garlick, A. Rowden, and E. Mackay. 2004. New Zealand's Undersea Volcanoes. National Institute of Water and Atmospheric Research Chart Miscellaneous Series 81.

Zabowski, D., M.F. Skinner, and T.W. Payn. in press. Nutrient release by weathering : implications for sustainable harvesting of radiata pine from six New Zealand soils. New Zealand Journal of Forestry Science.