CHARACTERISTICS OF VOLCANIC ASH SOILS OF SOUTHERN AREA OF MOUNT RUAPEHU, NORTH ISLAND, NEW ZEALAND

A thesis presented in partial fulfilment of the requirements for the degree
of Master of Applied Science in Soil Science
at Massey University

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Palmerston North

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ABSTRACT

Geochemical and pedological properties of five volcanic soils were examined to characterise the effects of weathering. The five soils studied are from the southern area of Mount Ruapehu, New Zealand.

The principal parent materials are rhyolitic and andesitic tephras. Soils examined in this study are characterised by thick and dark A horizons, crumb and nut structure, and sandy to clay texture. All pedons contain allophane, mostly as Al-rich allophane with Al:Si ratio ≅ 2.0. Mineralogical analysis data demonstrate the differences in parent materials, including quartz, plagioclase feldspar, hypersthene, augite, hornblende and magnetite. Halloysite and kaolinite are also present in the soils. When allophane is the dominant material in the clay fraction, the chemical properties are characterised by accumulation of humus, high fluoride pH and high phosphate retention.

State factors of soil formation are reviewed and discussed. This study reveals that weathering processes are key determinants of site-specific environmental conditions, whereas compositional factors, including tephra age, may determine Al behaviour, and control the concentration of Al in soil solution and its distribution throughout the profile.

Four soils meet the andic criteria and qualify for the Andisols order. They are: Typic Udivitrand, *ashy, isofrigid*; Typic Hapludand, *medial, isofrigid*; Typic Hydrudand, *hydrous, isofrigid*; and Hydric Endoaquand, *medial, isofrigid*. Another soil is under the Entisols order and is classified as Vitrandic Udifluvent, *sandy, mixed, isofrigid*. The Andisols are correlated with Allophanic Soils in the New Zealand Soil Classification. The complete classification is: vitric Orthic Allophanic Soil, vitric Orthic Allophanic Soil, typic Orthic Allophanic Soil, and typic Impeded Allophanic Soil. The Vitrandic Udifluvent is correlated with typic Orthic Pumice Soil.

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CHAPTER 1
INTRODUCTION

1.1. Background

Dokuchaev firmly established that soils developed as a result of the interplay among the five soil forming factors, parent material, climate, organisms, topography, and time, each of which can change from place to place. Jenny (1941) demonstrated that these factors are independent variables.

Weathering is the chemical and physical alteration of rocks and minerals at or near the surface of the earth, because they are not in equilibrium with the temperature, pressure, and moisture conditions of their environment (Birkeland 1974). Weathering involves at least one of the soil formation factors. Estimates of the relative weathering status of soils can be useful pedological indicators of the relative ages of different soils or the relative weathering intensities occurring under different environments. They may also provide clues to the pre-depositional weathering history of sediments.

Volcanic ash deposits are widespread and abundant in Quaternary sediments in the Central Volcanic Region of the North Island, New Zealand. Soils formed in volcanic ash have received much attention because of their unique properties, such as high phosphate retention capacity and low bulk density. They are considered the most productive and fertile soils in the country, and are found at Ohakune, Raetihi, and Horopito. In addition, Ohakune soils have been mentioned as being suitable for horticulture by Molloy (1983).

The soils of the southern Mt Ruapehu ring plain have not been studied in detail. Little published data exist on the pedological characteristics of these soils, but some studies on the soil parent materials have been reported. Donoghue (1991) studied "Late Quaternary volcanic stratigraphy of the Southeastern sector of the Mount Ruapehu ring plain", and Hodgson examined "Late Quaternary lahars from Mount Ruapehu in the Whangaehu River valley", in 1993. Some aspects of the Cenozoic geology of the

Moawhango River Region, Waiouru, particularly in the army training area, have been studied by Williams (1994). Recently, Cronin (1996) investigated "Late Quaternary volcanic stratigraphy within a portion of the north-eastern Tongariro Volcanic Centre". No mineralogical, chemical or physical studies have been carried out on these soils and there is in general very little information available of direct relevance to soil weathering. Therefore this study is concerned principally with the genesis and weathering of the soils on the south of the Mt Ruapehu ring plain.

1.2. Objectives

The main purpose of this study is to investigate soil genesis and weathering on an area between the south-eastern and south-western Mount Ruapehu ring plain. The essential objectives are as follows:

1. To determine the morphological, chemical, physical and mineralogical properties of soils derived from volcanic materials in this region,
2. To analyse the weathering and genesis processes of the soils, and
3. To establish soil classification according to the New Zealand Soil Classification and Soil Taxonomy.

1.3. Operations

The thrust of soil sampling took place on 31 January 1997. The main soil profiles had been fully described by Dr Alan S Palmer (*pers. comm.*) and samples from five profiles were collected for analyses. Laboratory work occupied from March to July 1997.

The laboratory work concentrated on mineralogical analyses which were thought best able to provide critical evidence on the composition of the soils, and to describe weathering and soil forming processes. Chemical and physical analyses were carried out to support the objectives. The work was finally completed and written during the remainder of 1997 and early 1998.

1.4. Organisation of the Thesis

This thesis consists of four main chapters. The first chapter is introductory and outlines the background, the problem, and the purposes of this study. It also contains a general description about the site, including location, geology, climate and vegetation. The second chapter describes soil mineralogical, chemical and physical properties, while the next two chapters discuss the weathering sequences of the soils and their classification. The thesis is completed by a general conclusion.

1.5. General Description of the Study Area

1.5.1. Location

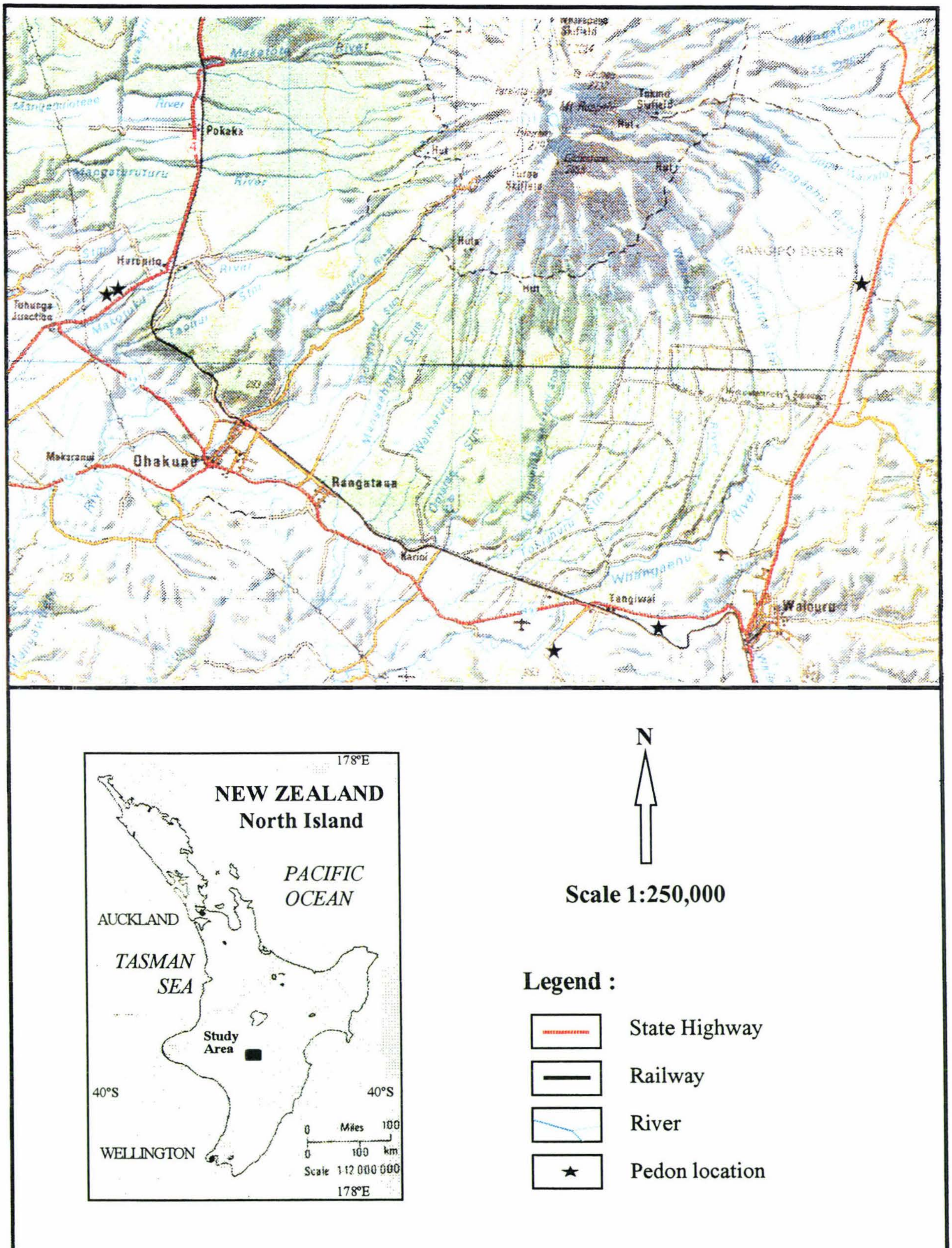
The study area is situated between the south-eastern and south-western slopes of Mt Ruapehu (Fig 1.1, p.4) in the North Island, New Zealand. A terrain map of Taranaki scale 1:250,000 (Department of Survey and Land Information 1987) is used to illustrate the location of the study area.

The criteria for drawing area boundaries were physical features and related physical resources. In the North the boundary runs Tongariro National Park and Mt Ruapehu; from there it runs east along the Desert Road (State Highway 1). The boundary then runs south along State Highway 49, follows State Highway 49A and from there it runs west along State Highway 4.

Five profiles were examined: one profile near the Desert Road (NZMS 260 T20 415956), two profiles at Tangiwai (NZMS 260 T21 303875 and NZMS 260 T21 304895) and two profiles at Horopito (NZMS 260 S20 123026 and NZMS 260 S20 122023).

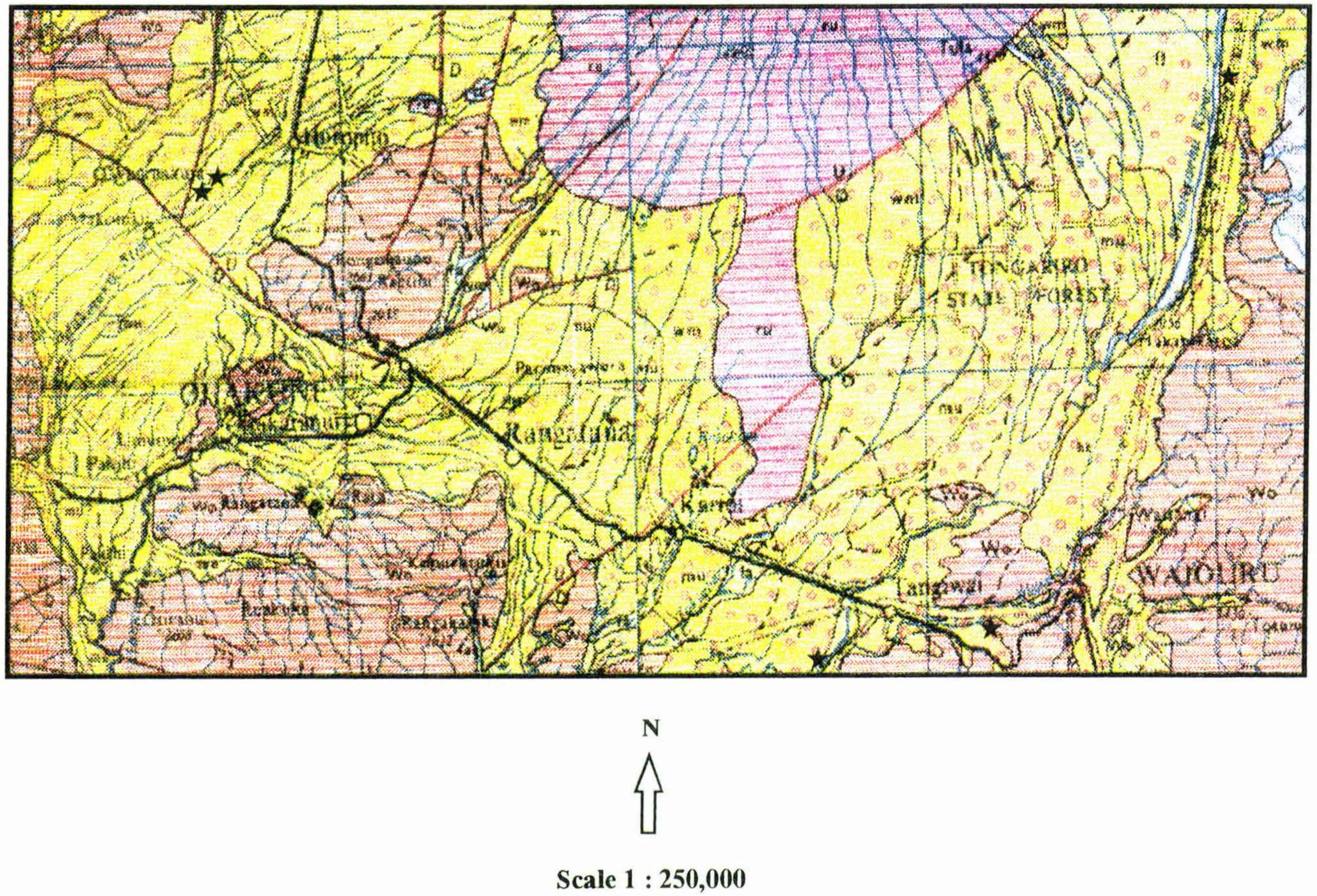
1.5.2. Geology

The geological map is compiled from sheet 7 (Taranaki) and 8 (Taupo) of the Geological Map of New Zealand, 1:250 000 (Fig. 1.2, p.5). Geologically, the study area is laid down in lahar (volcanic mudflow) deposits of Holocene and late Pleistocene age.



Source: Terrain map of Taranaki (Department of Survey and Land Information 1987)

Fig. 1.1. The location map of the study area



	Lithology	Formation (* New Names)
fl	Lahars of Whangaehu River	
ng ru_3	Hypersthene-augite-labradorite andesite volcano and flows	NGAURUHOE ANDESITE* RUAPEHU ANDESITES
mu	Andesite conglomerate building fan and ring-plain, south side Ruapehu	MURIMOTO LAHARS*
nc ru_1	Hypersthene-augite-labradorite andesite flows	NORTH CRATER ANDESIT RUAPEHU ANDESITES
wm	Andesite conglomerate building main ring-plain of Ruapehu volcano	WAIMARINO LAHARS*

═	State Highway
▬	Railway
～	River
★	Pedon location

Source: Geological map of New Zealand, sheet 7 Taranaki and sheet 8 Taupo (Grindley 1960 and Hay 1967)

Fig. 1.2. The geological map of the study area

Thick beds of Ngauruhoe and Ruapehu andesitic ash are younger than most of the lahars, and surround the Ruapehu volcano.

Grindley (1960) was the first to distinguish and map lahar formations on the Mt Ruapehu ring plain. He defined five lahar formations, Hautapu, Murimoto, Rangipo, Waimarino, and the Whangaehu River lahar.

Lahars mapped on the south-eastern to south-western Mt Ruapehu Ring Plain are shown in Fig. 1.2. Lahars in the south-eastern area are the Murimoto and Waimarino lahars which are mapped as late Pleistocene (specifically Hawera, 500,000 BP) in age. Lahars of Whangaehu River are Holocene (10,000 BP) in age (Grindley 1960). Lahars on the southern to south-western Mt Ruapehu ring plain were later mapped by Hay (1967) as the Waimarino and Murimoto formations.

1.5.3. Physiography

The physiography of the study area is a part of the extensive Central Volcanic Region of the North Island (Fig. 1.3). The main physical feature of the whole region is a chain of volcanic mountains rising abruptly from a 900 m plateau to an altitude of 2797 meters above sea level. There are three main peaks: Mt Tongariro (1968 m), contains a series of craters; Mt Ngauruhoe (2287 m) is a symmetrical cone rising from the southern flanks of Tongariro, and Mt Ruapehu (2797 m) is a massive cone with three main peaks on an old crater rim. The plateau is a wide-spread level plain of pumice and volcanic debris, which slopes gently outwards from 900 m at the base of the mountains to about 700 m in the south and west, where it merges into the hill country of inland Wanganui (Day 1968).

General surface features of the volcanic plateau have been produced by frost action and stream erosion on structures of volcanic origin. Large quantities of material disintegrated by frost and added to by fragments of scoria and lapilli thrown out by the volcanoes, lie loose on the surface and show little sign of weathering. This loose covering is constantly being moved down to lower levels by new slips and by the streams which flow down the mountain sides.

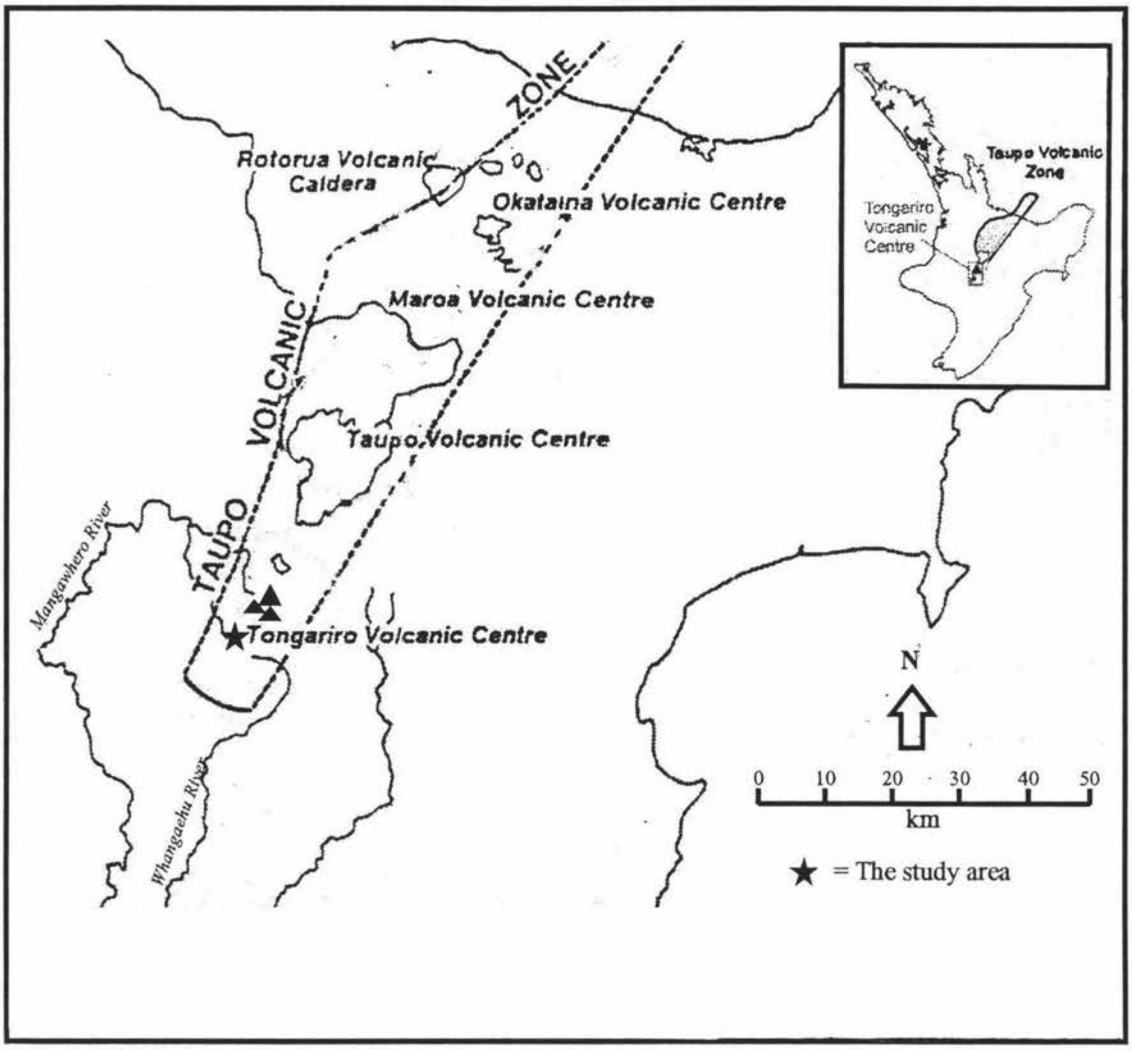


Fig. 1.3. The physiography of the study area

There are three headwaters surrounding Mt Ruapehu ring plain. On the south-eastern to the southern slopes of Mt Ruapehu is the headwater of the Whangaehu, the Mangawhero is in the southern to the south-western area, and the Manganuioteao is in the West.

1.5.4. Climate

Climate determines the suitability of land for horticulture, cropping, pastoral and forestry use, moreover affects erosion processes and possible soil conservation options. The nearest climatological stations are at Desert Road tea room, Waiouru, Ohakune Karioi, Raetihi and Horopito. Data from these stations may be representative of the area between south-eastern and south-western parts of the Mt Ruapehu ring plain.

The study area has a climate type of M (New Zealand Meteorological Service, 1983a), which means a high rainfall mountain climate. Conditions vary greatly with altitude and exposure.

1.5.4.1. Wind

The wind flow over the central North Island is mainly from a westerly quarter. Topography helps to determine the local wind directions and over the study area winds from a west and northwest direction blow for 30-40 per cent of the year. Strong winds sometimes occur with the passage of a low pressure system (de Lisle 1968).

1.5.4.2. Rainfall

A rainfall summary table is compiled from New Zealand Meteorological Service data. Rainfall varies between 900 and 1,300 mm in the south and south-west of the study area and increases to between 1,300 to 2,500 mm in the west and north (New Zealand Meteorological Service 1980b). There is no rainfall data for the Desert Road section. The section is located at 39 20S latitude and 175 43E longitude. Therefore, average data from the Desert Road tea room and the Waiouru stations are used to estimate the annual rainfall of this section, and it is found to be 1,950 mm. The annual precipitation of the study area is about 1,059-1,950 mm (Table 1.1) on 150-175 days a year (de Lisle 1968). It is spread fairly evenly through the year with a maximum in early winter (May-June) and minimum in summer (January-February).

Table 1.1. Rainfall distribution from selected stations in the study area (in mm)

Station	Lat	Long	HT (m)	J	F	M	A	M	J	J	A	S	O	N	D	Year
Dessert Road Tea Room	39 11S	175 45E	906	188	190	204	209	282	281	287	265	240	243	224	238	2,851[b]
Waiouru	39 28S	175 40E	823	73	60	78	79	107	107	102	96	82	85	80	110	1,059[a]
Karioi	39 29S	175 31E	648	80	72	76	86	121	118	117	105	91	102	103	119	1,190[a]
Horopito	39 20S	175 22E	–	115	98	142	141	189	179	166	167	133	177	164	150	1,821[a]

Sources:[a] NZ Meteorological Service, 1980a, [b] NZ Meteorological Service, 1980b

Note: Observations were taken between 1951-1980; Lat=latitude; Long=longitude; HT=height (in meter above sea level)

In summer the water needs on the high ground are approximately 80 to 100 mm a month (de Lisle 1968). In early spring the water requirement is practically always met by rainfall. If not, the deficiency is slight. From late spring to autumn rainfall is sometimes insufficient for plant needs and soil moisture reserves must be drawn on. The rainfall deficiency that a plant can stand without serious damage depends on the plant type and the amount of available moisture contained in the soil.

Of particular significance to agriculturally important areas is the balance between precipitation and water need, one index of the water need being provided by the difference between the potential evapotranspiration and the combined soil moisture and precipitation. The water balance from selected stations is shown in Table 1.2.

Table 1.2. Water balance: percentage frequency of months with deficits [a)]

Month	Karioi [b)]	Raetihi [c)]
July	0	0
August	0	0
September	0	0
October	0	0
November	0	0
December	0	0
January	3	0
February	15	4
March	9	4
April	0	0
May	3	0
June	0	0

Source: The Town and Country Planning Division, 1971.

Note: [a)] Assuming a 3 in. moisture capacity of the soil, [b)] Observations were taken between 1930-1964
[c)] Observations were taken between 1937-1964

1.5.4.3. Temperature

Above 600 m, frosts may occur in any month of the year. At Karioi (638 m) there are on the average 74 days a year when the temperature falls to 0°C. Frosts at ground level are more common. Waiouru has an average of about 16 days of snow a year and Karioi has ten (de Lisle 1968).

Table 1.3. Temperature of the air at selected stations (in degree Celsius)

Station	Lat	Long	HT (m)	J	F	M	A	M	J	J	A	S	O	N	D	Year
Ohakune[1]	39 24S	175 25E	610	14..9	14.9	13.5	10.7	8.0	5.9	6.1	6.1	7.8	9.5	11.4	13.4	10.1
Ohakune junction[2]	39 24S	175 25E	629	15.2	15.1	14.0	10.8	7.4	5.4	4.9	5.9	7.5	9.6	11.2	13.3	10.0
Waiouru[3]	39 28S	175 40E	823	13.8	13.9	12.7	9.6	6.7	4.5	4.0	4.9	6.4	8.4	10.2	12.2	8.9

*Sources:*NZ Meteorological Service, 1980b

Note: [1] Observations were taken between 1962-1974, [2] Observations were taken between 1974-1980
[3] Observations were taken between 1962-1980; Lat=latitude; Long=longitude; HT=height (in meter above sea level)

Soil temperature and degree day totals are two climatic parameters that are of particular importance in assessing the suitability and versatility of land for plant growth. On soil temperature maps at 1:2,000,000 scale (New Zealand Meteorological Service 1983b), the soil temperatures either at 100 or 300 mm depth in the study area have not been analysed yet. However, there are data on temperature of the ground for Ohakune and Waiouru (New Zealand Meteorological Service 1980b) which show the average ground temperature annually is 2.1°C.

Table 1.4. Temperature of the ground (in degree Celsius)

Station	Lat	Long	HT (m)	J	F	M	A	M	J	J	A	S	O	N	D	Year
Ohakune[1]	39 24S	175 25E	610	5.7	5.4	4.6	2.3	0.4	-1.1	-2.0	-1.2	0.6	2.0	3.7	4.9	2.1
Waiouru[2]	39 28S	175 40E	823	6.0	5.6	5.2	2.6	0.4	-1.3	-1.7	-1.0	0.1	1.4	2.9	4.8	2.1

*Sources:*NZ Meteorological Service, 1980b

Note: [1] Observations were taken between 1962-1974, [2] Observations were taken between 1962-1980
Lat=latitude; Long=longitude; HT=height (in meter above sea level)

1.5.5. Vegetation and Land Use

Vegetation at the time of European settlement in the southern and western slopes of Mt Ruapehu was a heavy podocarp forest. Red and silver beeches (*Nothofagus fusca* and *N. menziesii*) were co-dominant between Karioi and Ohakune, whereas rimu and matai (*Dacrydium cupressinum* and *Podocarpus spicatus*) predominated in Ohakune and Raetihi. Merging with this and extending to the bushline at about 1,350 m was sub-alpine mountain beech forest. Nowadays, a more permanent exotic forest has replaced the indigenous one, and pine species are extensive (The Town and Country Planning Division 1971).

Within the study zone there are two quite distinct areas. The first is an area, which is physically centred on Mt Ruapehu, under shrub and tussock vegetation. The second area is the flat triangular area between Raetihi, Ohakune, and Horopito, supporting about 135 farms on about 14,580 ha (The Town and Country Planning Division 1971). Present land use in Ohakune is market gardening, where over 700 ha are in vegetable production. The main crops produced are carrots, parsnips, cabbages, cauliflowers, brussel sprouts, swedes and potatoes. An extension of this area continues the fat lamb farming activities south east to Taihape.

CHAPTER 2

PROPERTIES OF VOLCANIC ASH SOILS

2.1. Introduction

Soils developed from volcanic materials are known to have morphological, mineralogical, chemical, and physical properties different from those of other mineral soils developed under similar climate conditions (Wada 1985). During the last forty years, volcanic ash soils have been studied by many researchers, both in New Zealand and overseas, in the matter of mineralogy, chemical, and physical properties, using a wide range of techniques, and some general features of volcanic ash soils have been formulated.

A distinctive attribute of soils derived from volcanic materials is the occurrence of a unique clay-size mineral assemblage dominated by noncrystalline components. Noncrystalline materials common in volcanic ash soils include: allophane, imogolite, opaline silica, and ferrihydrite. Volcanic ash soils also display a wide range of chemical characteristics. Of these chemical properties, soil organic matter, active Al and Fe, and variable charge are the most prominent attributes regulating chemical reactions in volcanic ash soils. They also have many particular physical properties such as high natural water content, high 1,500 kPa water content, and low natural bulk density, which differentiates them from any other soils.

This second chapter describes the properties of the studied soils. There are four sections: the introductory, the review, the methodology, and the results and discussion.

2.2. Review of Literature

2.2.1. Mineralogical Properties

Dahlgren *et al.* (1993) reported that the mineralogical composition of the colloidal fraction of soils derived from volcanic materials varies widely depending on (1) chemical, mineralogical, and physical properties of the parent material, (2) post-depositional weathering environment, and (3) the stage of soil formation. The mineralogy, chemical composition and texture of the parent material largely determine the rate of chemical weathering, the amount and distribution of reactants for synthesis of secondary materials, and the pH through its influence on the base status of the soil.

2.2.1.1. Primary Minerals

The primary mineral composition of volcanic ash is typically characterised by first dividing minerals into light (specific gravity < 2.8-3.0) and heavy (specific gravity > 2.8-3.0) mineral categories. Light minerals dominate in volcanic ash with an abundance mostly ranging between 70 and 95% (Shoji 1986). Within the light mineral category, the relative abundance generally follows: noncolored volcanic glass >> plagioclase feldspars >> silica minerals (quartz, cristobalite and tridymite) ≈ mica. The distribution of plagioclase and alkali feldspars is dependent on the chemical composition of the magma and is therefore quite variable. Heavy minerals comprise only a small fraction of volcanic ash having a felsic or intermediate chemical composition. The relative abundance of minerals within the heavy mineral category follows: hypersthene ≈ opaque minerals > augite ≈ hornblende.

Volcanic ash may also contain appreciable quantities of minerals that originate from previously altered materials associated with the volcano (Dahlgren, *et al.* 1993). These minerals, often called accessory, accidental or exotic minerals, are formed by weathering and/or hydrothermal alteration of materials comprising the cone of the volcano. The accessory minerals along with the minerals formed from solidification of the magma are mixed and deposited together during a volcanic eruption. Accessory minerals attributed to previously altered minerals often include: opal, cristobalite, kaolinite, allophane, halloysite, smectite and interstratified layer silicates (Ossaka 1982).

2.2.1.2. Secondary Minerals

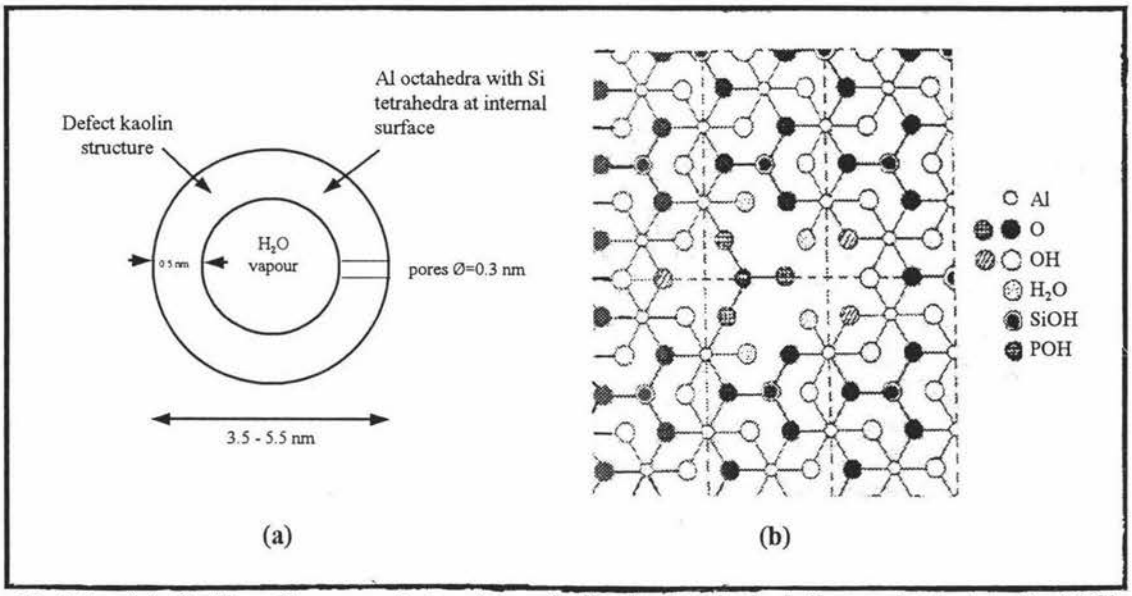
Allophane

Allophane is a group name given to a series of naturally occurring, noncrystalline, hydrous aluminosilicates with a widely varying chemical composition (van Olphen

1971) and is also characterised by short-range order (Parfitt 1990a). Allophane has no definite chemical composition. Together with silica and alumina, water is an essential component of allophanes. The water is allotted to silicon and aluminum atoms as hydroxyl and is often referred to as $H_2O^{(+)}$ since it is removed only by heating from 105-950°C. The $H_2O^{(+)}/Al_2O_3$ ratios of the various allophanes studied by Wada and Yoshinaga (1969) were mostly in the range of 2.5-3.5. The chemical composition of allophane may, therefore, be represented as $(SiO_2)_xAl_2O_3.yH_2O^{(+)}$ (Iimura 1969), but it must be emphasised that the range of chemical compositions is large. In addition to the chemical composition, Yoshinaga (1968) gave evidence that there is a small but significant amount of iron, 0.3-0.9 % as Fe_2O_3, in allophane. It indicates that there is substitution of aluminum by iron.

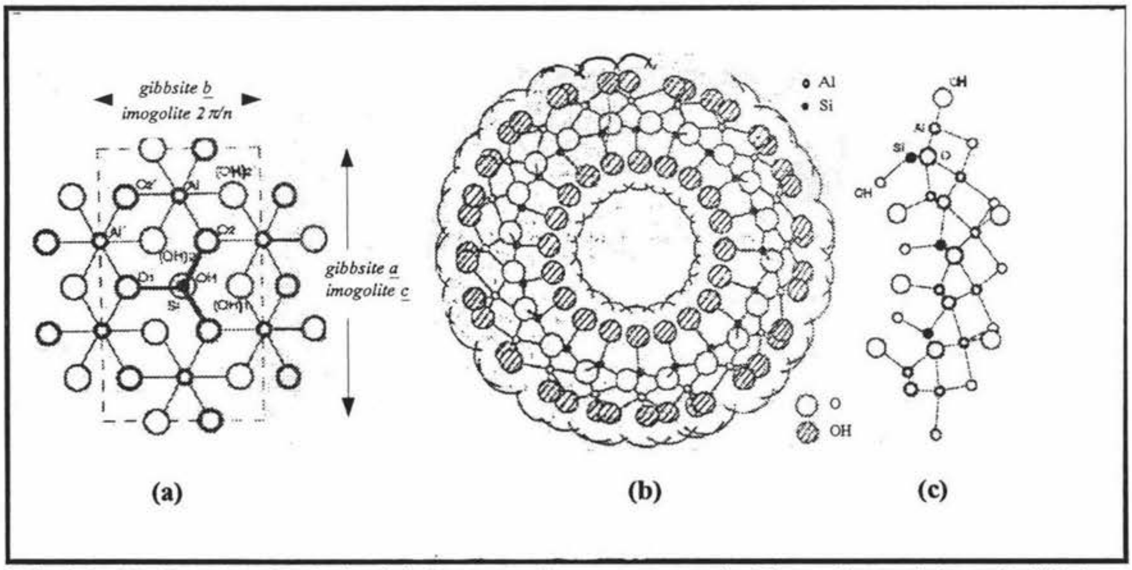
Allophane displays a range in Al and Si concentrations from an Al:Si atomic ratio less than 1:1 and greater than 2:1 (Yoshinaga and Aomine 1962; Yoshinaga 1966, 1968; Miyauchi and Aomine 1966; Wada and Yoshinaga 1969; Russell, *et al.* 1969; Lai and Swindale 1969). Based on the varying ratio of Al:Si, there are three main types of allophane found in New Zealand (Parfitt 1990a). They are: (1) Al-rich (Al:Si molar ratio≈2.0 or more) and (2) Si-rich (Al:Si≈1.0) allophane, which is predominant in soils (Parfitt and Kimble, 1989) and (3) stream deposit allophane (Al:Si ratio=0.9-1.8).

Al-rich allophanes consist of hollow, irregularly spherical particles (Fig. 2.1) with outside diameter of 3.5 to 5 nm and a wall thickness of 0.7-1 nm (Henmi and Wada 1976). Al-rich allophanes (also termed proto-imogolite allophanes or imogolite-like allophanes) are considered to be made up of fragments having the same local atomic arrangement and chemical composition as the imogolite structure over a short range (Parfitt and Henmi 1980), however, they differ morphologically (Fig. 2.2). Each fragment contains about 8-10 micropores or broken bond defects. The defects probably form when the proto-imogolite fragments combine, making edge to edge contact (Parfitt 1990a). The defect sites may account for the variable charge characteristics for allophane (Theng, *et al.* 1982). Specific surface area measurements range from 581 m^2g^{-1} by nitrogen at 77 K (Hall *et al.* 1985; Vandickelen *et al.* 1980) to 700-1100 m^2g^{-1} by adsorption of ethylene glycol monoethyl ether (Egashira and Aomine 1974) or from 400 to 700 in New Zealand soils (Childs and Parfitt 1987).



(a) (b)

Fig.2.1. (a) Outline diagram of structure of allophane: single hollow spherical unit, Al:Si atomic ratio= 2.0 (Wada 1980); (b) a model of proto-imogolite allophane showing a pore site and phosphate attached. The pore was created by omitting 2Si and 2Al from six imogolite unit cells (Parfitt and Henmi 1980).



(a) (b) (c)

Fig.2.2. (a) Postulated relationship between the structure unit of imogolite and that of gibbsite. SiOH groups that would lie at the cell corners in imogolite are omitted from the diagram (Cradwick, *et al.* 1972); (b) cross section of an imogolite tube viewed down the tube axis. The outside diameter is 2.14 nm and the inside is 0.64 nm. The external surface of the tube comprises a gibbsite-like Al octahedral structure but the internal surface has exposed Si-OH groups (SiO_3OH) with the Si in isolated tetrahedral sites (Parfitt 1980); (c) curling of the gibbsite (hydroxide sheet induced by contraction of one surface to accommodate SiO_3OH tetrahedra (Cradwick, *et al.* 1972).

Water molecules occupy the interior of the spherules and are also adsorbed onto the outer AlOH surface. The structures of allophane are curved with a gibbsite-like octahedral sheet (Wada 1989) on the outer surface and hydroxyls at the surface (Fig.2.2). The inner surface consists of O_3SiOH tetrahedra with the oxygens replacing the inner hydroxyls of the octahedral layer (Parfitt 1990a). Al-rich allophane, was initially characterized in Taranaki soils (Russell, *et al.* 1981). Si-rich allophanes have different infrared spectra from those of Al-rich allophanes, indicating that some of the silicate is polymerized. The Al appears to be present in mainly octahedral sites, with some in tetrahedral sites. This Al-octahedral layer provides the structural framework for Si-rich allophanes and is linked to silicate polymers (Parfitt 1990a).

Stream deposit allophanes are found in the stream bed below the vents of Silica Springs on Mt Ruapehu, New Zealand. Childs *et al.* (1990) suggested that a Silica Springs primary particle of allophane consists of a tetrahedral sheet, with a curvature corresponding to a diameter of about 2-3 nm, and containing one Al for every three Si (Fig. 2.3). Excess Al is bound octahedrally to the apical O of the tetrahedra, and to OH and H_2O groups. The curvature may lead to the formation of complete hollow spherules. They proposed therefore, that in Silica Springs allophane, the Si(Al) tetrahedral sheet forms the framework.

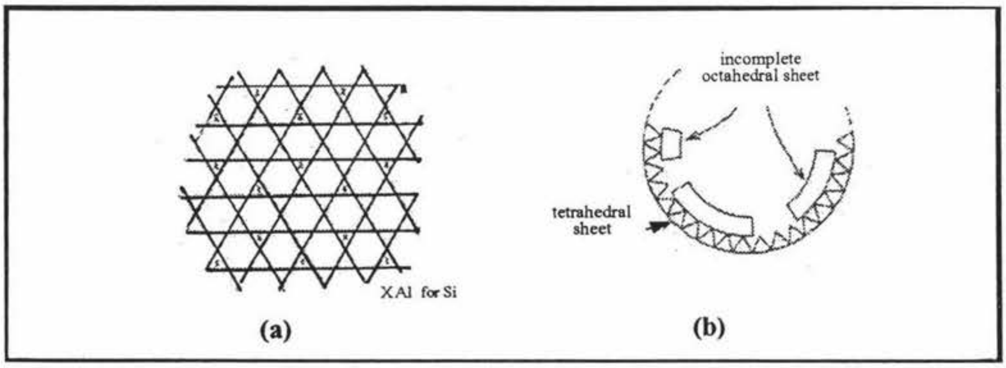


Fig. 2.3. (a) Diagrammatic representation of a structural model of Silica Springs allophane. Possible 1:3 Al-for-Si substitution in tetrahedral sheet; (b) fragment of curved aluminosilicate with incomplete octahedral sheet (Childs *et al.* 1990).

The formation of allophane from volcanic ash constitutes the central feature in the development of Andisols. Nearly all kinds of volcanic ash produce allophane and allophane-like constituents of different nature, stability and amount. Generally, allophane forms from glass if the $pH(H_2O)$ is above 4.7 (*e.g.* Shoji, *et al.* 1982; Shoji and Fujiwara 1984; Parfitt and Kimble 1989) and from feldspar and/or biotite if the pH is about 5 in soils with udic moisture regimes and with good drainage (Parfitt and Kimble 1989). A pH of at least 4.8 is required for allophane to precipitate (Parfitt and Kimble 1989). Allophane can form rapidly from fine grained glass particles (Kirkman 1980).

A balance between the release rate of aluminum from volcanic ash by weathering and supply rate of organic matter seems to control the formation of allophane. The rate of allophane formation is controlled by three important environmental factors. They are: (1) the activity of silicic acid in the soil solution, (2) the availability of Al species, and (3) the opportunity for co-precipitation (Parfitt 1990a).

Imogolite

Imogolite was first described by Yoshinaga and Aomine (1962) in a soil derived from the glassy volcanic ash, known as "imogo". Like allophane, imogolite is a hydrous aluminosilicate mineral with which it is frequently associated. Wada (1989) reported that imogolite possesses similar chemical properties to allophane, but it has a distinct tubular morphology that varies in length from 100-300 Å. This tubular unit is very useful for identification and detection of imogolite by electron microscopy even when present in a very small amount. Imogolite consists of bundles of well-defined fine tubes with inner and outer diameters of about 7-10 Å and 17-21 Å, respectively. The external surface of the tube is composed of a curved gibbsite-like structure with an orthosilicate (O_3SiOH) group co-ordinated through oxygen with three aluminum atoms in the interior (Fig. 2.2).

The imogolite structure has a composition of $SiO_2.Al_2O_3.2H_2O$. Electron microscopy indicates that imogolite has a surface area of 1400 to 1500 m^2g^{-1} and a density of 2.65 g cm^{-3} (Wada and Yoshinaga 1969). X-ray fluorescence spectroscopy indicates that nearly all aluminum in imogolite is in 6-fold co-ordination.

There are two hypotheses that describe the formation of imogolite: (1) imogolite constitutes an intermediate phase from allophane to crystalline layer silicates, particularly to halloysite, (2) imogolite represents an intermediate phase in transformation from allophane to gibbsite in a desilication process. The first version is based on developments of structural order in imogolite; where glass or feldspar weather rapidly to give Al and Si in soil solution at a fairly narrow range of concentration, imogolite will precipitate as long as the weathering environment is not dominated by organic acids. The second version is due to its SiO_2/Al_2O_3 ratio close to 1.0 and unique tubular structure unit. The association of imogolite and gibbsite has been noted by Yoshinaga and Yamaguchi (1970).

Under laboratory condition, imogolite precipitates from solution, and a high yield has been achieved by Farmer *et al.* (1977) and Farmer and Fraser (1979). They showed that imogolite is formed by the interaction of hydroxy-Al cations with orthosilicic acid in dilute solution (Al:Si ratio = 2) at pH values less than 5 and by heating such solution at 96 to 100°C.

Opaline Silica

Dahlgren *et al.* (1993) reported that opaline silica is found more abundantly in younger soils (< 4,000 years) rather than in older soils and in humus-rich A horizons rather than underlying B and C horizons. Two types of opaline silica are common in young volcanic ash soils: pedogenic opaline silica (commonly called laminar silica) and biogenic opaline silica (plant opal and diatoms). They appear as thin particles with circular, elliptical, rectangular, or rhombic shapes, and in the 0.2-5 μm size fraction. The elliptical type is most common in the fine fraction and the circular type in the coarse fraction.

Opaline silica is formed by precipitation from soil solutions over-saturated with silica due to surface evaporation. Its formation is also closely correlated with climatic conditions (Shoji and Masui 1971), such as freezing of soils (Wada and Nagasaki 1983; Ping, *et al.* 1988).

Halloysite

Halloysite is a common constituent in volcanic ash-derived soils and occurs as the dominant clay mineral in many Si-rich environments (Parfitt and Wilson 1985). Halloysite is a 1:1 aluminosilicate mineral which is characterised by a diversity of morphology. Generally it occurs with a tubular and spheroidal morphology, but lath-shaped, platy, and crumpled shapes have also been reported (*e.g.* Nagasawa 1978, Saigusa *et al.* 1978). Halloysite usually appears as unique spherules with diameters of 0.1-0.5 μm (Parfitt and Webb 1984). Halloysite has bigger unit particles than allophane, its unit size being 6000 Å compared with 40 Å (Theng, *et al.* 1982). Halloysite tubes and spheroids also have a Si-O-Si outer surface (Bates 1959; Radoslovich 1963) that is less reactive to phosphate than the Al-OH-Al surface exposed on allophane (with an Al:Si ratio of 2).

Halloysite has formed from ashes and pumices of various compositions, from basalt through andesite to dacite. Halloysite often occurs in older tephras, therefore it has been suggested that allophane weathers to halloysite with time. The apparent transformation of allophane into halloysite cannot be expressed as a simple function of time (Nagasawa 1978). This transformation takes place in old and buried volcanic ash soils, with relatively silica rich environments, *i.e.,* rhyolitic tephra rather than andesitic tephra (Kirkman and McHardy 1980). Halloysite can also form directly from volcanic glass where silica activity in soil solution is high (Parfitt and Webb 1984).

Some studies have been done on the formation of halloysite. Fieldes (1966) showed that in New Zealand, halloysite occurred in regions of low precipitation with a pronounced dry season. The precipitation is generally less than approximately 1500 mm (Parfitt, *et al.* 1983; Lowe 1986).

Non-crystalline iron oxide

Iron oxide in soils derived from volcanic materials is present mostly in the form of non-crystalline oxyhydroxides and partly as Fe-humus complexes (*e.g.* Parfitt and Childs 1983). The dominant noncrystalline oxyhydroxide is believed to be ferrihydrite, a short-range-order Fe hydroxide mineral with a bulk composition of

$5Fe_2O_3.9H_2O$ (Schwertmann and Taylor 1989). Ferrihydrite appears as individual spherical particle ranging in size between 2-5 nm, and becomes highly aggregated forming aggregates 100-300 nm in diameter.

Dahlgren *et.al.* (1993) reported that ferrihydrite is regarded as highly reactive material due to its hydroxylated surface and high specific surface area (typically 220 to 560 m^2 g^{-1}). Due to its reactive surface, relatively large quantities of silica (2-6 %), organics and phosphates are chemisorbed. Ferrihydrite is thermodynamically metastable, and with time converts to stable Fe-oxides, usually to goethite, under a temperate or cool humid climate, and to hematite under a warmer, drier climate.

2.2.2. Chemical Properties

2.2.2.1. Active Aluminum and Iron

The presence of active forms of aluminum and iron is one of the most important properties involved in the central concept of Andisols, *i.e.* amorphous aluminosilicates and hydrous iron and aluminum oxides. The high reactivity of soil amorphous constituents are correlated with their large specific surface area. Active Al and Fe determine the unique chemical and physical properties of Andisols. Although active Al and Fe in Andisols are incorporated into and are combined with a variety of soil components, they occur primarily as allophane, imogolite, Al-Fe humus complexes, and ferrihydrite.

The active forms of aluminum and iron are effectively extracted with 0.2M acid oxalate solution. The Al-Fe humus complex portion of the active Al and Fe can be preferentially dissolved by 0.1M sodium pyrophosphate (Bascomb 1968 and Blakemore, *et al.* 1987). Therefore, the content of active Al incorporated into allophane and imogolite can be estimated by subtracting the pyrophosphate Al from the oxalate-extractable Al. The formula is (Al*o*-Al*p*)/Si*o*, where Al*o* and Si*o* are acid oxalate extractable Al and Si, respectively, and Al*p* is pyrophosphate-extractable Al (Parfitt and Wilson 1985). The Al*p*/Al*o* ratios in Andisols A horizons determine whether the soils are allophanic Andisols (ratios occurring at 0.1-0.4) or non-allophanic Andisols (ratios of 0.8-1.0). Along with allophane and imogolite, oxalate also dissolves Al-humus complexes, some gibbsite, some hydroxy-Al interlayers, Al-substituted ferrihydrite, and incongruently removes Al from poorly crystalline halloysite.

The active Al increases in the early stages of weathering but decreases with the further advance of weathering as indicated by the relationship between the clay content and the amount of active Al. This process is attributable to the formation of hydroxy-Al and aluminosilicate interlayers in 2:1 layer silicates and/or the consumption of active Al by layer silicate formation (Ito and Shoji 1993 as cited by Nanzyo *et al.* 1993).

2.2.2.2. Organic Constituents

Accumulation of humus constituents is one of the features of Andisols. The role of allophane in accumulation of organic matter in Andisols (as summarised by Nanzyo *et al.* 1993) may be classified into four groups, *i.e.* (1) possible effects of allophane on the action of enzymes, (2) a catalytic effect of allophane in an oxidative polycondensation of phenolic units, which results in formation of stable skeletons in soil humic materials, (3) as a source of aluminum and/or iron which form insoluble humates, (4) the adsorption of humic materials. Organic matter is probably adsorbed onto allophane surfaces by ligand exchange.

The abundance of very dark-coloured humus dominated by A-type humic acid is one of the important properties that define Andisols, but not all Andisol humus-rich horizons are very dark (value and chroma 2 or less when moist). Fulvic Andisols contain large amounts of humus, but they appear dark brown because their humus is rich in fulvic acid and P-type humic acids with a low degree of humification. Shoji *et al.* (1987) shown that humus from New Zealand Andisols have a high content of fulvic acid, and the humic acid is dominated by P-type humic acid. Grass vegetation in New Zealand contributes to the formation of A-type humic acid while forest vegetation promotes formation of P-type humic acid (Sase 1986). Aluminium-humus complexes are very reactive with phosphate and fluoride as compared to allophanic clays.

Humus contributes to the unique chemical and physical properties of Andisols such as variable charge (increases the negative charge and decreases the positive charge), high phosphate retention, low bulk density, notable friability, weak stickiness, formation of stable soil aggregates, *etc.* It also greatly influences the productivity of Andisols through its role in supplying nutrient elements, retaining available water for plants, and development of a favourable rooting environment.

2.2.2.3. Soil Acidity

The allophanic clays, chloritized 2:1 minerals, and humus have different mechanisms generating acidity and thus have different acid strengths. Considering soil acidity, Nanzyo *et al.* (1993) described three groups of Andisols. They are: (1) group 1, allophanic, humus-poor Andisols which have pH (H_2O) values of 5.2 to 6. Their acidity is attributable primarily to the dissociation of protons from the broken edges of noncrystalline aluminosilicates: $\equiv SiOH \longrightarrow \equiv SiO^- + H^+$; (2) group 2, non-allophanic Andisols, and (3) group 3, allophanic humus-rich Andisols. Acidity of humus-rich allophanic Andisols (organic carbon content 6 percent or more) is largely determined by carboxyl group, and is significantly influenced by the formation of Al humus complexes. Although humic acids of Andisols have strongly acidic (pKa $\leq$ 3.2) carboxyl groups, many of them are blocked by complexion with Al (approximately 20 percent of the total carboxyl groups (Yonebayashi and Hattori 1988 as cited by Nanzyo *et al.*, 1993). Thus only a small fraction of the weakly acidic carboxyl groups contributes to the acidity of the soils.

The pH (KCl) values also provide a measure of acidity in Andisols and are usually lower than pH (H_2O). Some tropical Andisols that have large amounts of noncrystalline clays and very low contents of layer silicates and soil organic matter, show pH (KCl) values greater than pH (H_2O) values. This defines the acric property. This is attributed to the adsorption of Cl^- ions to positive charge sites of noncrystalline clays, resulting in the net formation of KOH which increases the pH (KCl) of the soil solution (Uehara and Gilman 1981).

2.2.2.4. Ion Exchange Equilibrium

The ion exchange capacity of allophane is not constant and depends on the environmental conditions. Soils containing allophane, therefore, have values for cation exchange capacities that are strongly dependent on the pH and concentrations of leaching solution, the cation in solution and the volume, and nature of the washing media (Nanzyo *et al.* 1993).

Wada and Harward (1974) reported that at the same pH, the CEC was much higher than the AEC for weathered pumice containing allophane with a SiO_2/Al_2O_3 ratio = 2.0. Allophane possesses comparable amounts of positive and negative charges in the pH range 3-9 and these charges are pH-dependent. The most reactive groups are probably the $Al(OH)H_2O$ groups which under acid or alkaline conditions become $Al(OH_2)^+H_2O$ or $Al(OH)(OH)^-$, respectively. The influence of variable charge surfaces has been recognised in the farming of Andisols. For instance, exchangeable bases are easily leached from Andisols under humid climates, but allophanic soils rarely have soil pH H_2O values less than 5.0 or toxic levels of exchangeable Al.

Nanzyo *et al.* (1993) explained the ion exchange features of Andisols as follows: Andisols have cation exchange sites consisting primarily of $-COO^-$, $\equiv SiO^-$ and constant negative charge, and anion exchange sites of $=Al\text{-}OH^{2+}$ and $=Fe\text{-}OH^{2+}$. The exchangeable cations are commonly Ca^{2+}, Mg^{2+}, K^+, Na^+, Al^{3+}, and the exchangeable anions are Cl^-, NO_3^-, SO_4^{2-}.Characteristics of ion exchange reactions in soil systems are: (1) ions are retained on the exchange complex through electrostatic attractive forces forming outersphere complexes, (2) the exchange reaction proceeds equivalently and does not disturb charge balance in either the solid or solution phases, and (3) some ions are preferentially retained by the exchange sites relative to others. Their cation exchange sites show a very high selectivity for H^+. Therefore, the soils show no strong acidity, despite their low to very low base saturation. Exceptional Andisols are those containing large amounts of layer silicates, either halloysite or 2:1 layer silicates. The CEC values are 135 for allophane (SiO_2/Al_2O_3 ratio = 2.0) and 30 cmol kg^{-1} for imogolite. The CEC increases with the increasing SiO_2/Al_2O_3 ratio for soil clays containing allophane and imogolite (Wada 1989).

The content of exchangeable bases is generally low in Andisols developed in humid, temperate regions, such as New Zealand, and the base saturation (BS) is less than 50 % in subsoils. The low base content of subsoils is expected since they have less organic matter and lower pH.

2.2.2.5. Anion Sorption

Andisols have a high capacity for phosphate and fluoride sorption due to their high content of active Al and Fe compounds. These Al and Fe compounds form from weathering of the parent material and react to form insoluble Al and Fe phosphate compounds. This reaction may result in phosphorus deficiency for crops grown on these soils.

Phosphate and fluoride sorption differ from other ion exchange reactions, as described by Nanzyo *et al.* (1993): (1) the anions react with active Al and Fe compounds to form covalent bonds or inner-sphere complexes; (2) sorption reactions of these anions are not completely reversible and it is difficult for sorbed anions to be desorbed; (3) the sorption capacity for these anions is greater than the amount of positive charge; and (4) the ligands on the surfaces of the active Al or Fe compounds are released by ligand exchange reactions with the sorbing anions.

Phosphorus occurs mainly as acid soluble forms in fresh tephra and its solubility decreases with advance of chemical weathering and formation of active Al and Fe solid-phases (Shoji *et al.* 1993). In nature, heavy phosphorus fertilisation of Andisols results in the formation of non-crystalline aluminum phosphate materials (Nanzyo 1987) and phosphorus availability is not as enhanced as would be expected from the amount of phosphorus applied.

2.2.3. Physical Properties

Andisols exhibit physical characteristics that differ considerably from those of other mineral soils. Among the unique characteristics are the low bulk density, uncertainty in dispersion which may cause difficulties in obtaining particle size distribution, and high water holding capacity.

2.2.3.1. Bulk Density

Gradwell (1974 and 1976) found that the boundary bulk density value that determines whether or not soils are derived from volcanic ash in New Zealand is 0.85 Mg m^{-3}. Bulk density of less than 0.85 Mg m^{-3} has been adopted as one of the diagnostic properties of soils in which amorphous material dominated in the exchange complex (Soil Survey Staff 1975). After several revisions of the Andisols proposal, bulk density of 0.90 Mg m^{-3} or less is determined as one of the requirements in andic soil properties(Soil Survey Staff 1992). Meanwhile, Maeda *et al.* (1983) pointed out that the value of 0.85 Mg m^{-3} possibly can be used as a reference point dividing Andisols from other mineral soils of non-volcanic origin.

2.2.3.2. Particle Size Distribution

Particle size analysis is difficult to apply to Andisols because the soil material commonly consists of stable aggregates cemented by noncrystalline materials and organic matter. The difficulty of dispersing Andisols has been noted by many workers. Davies (1933) used 0.002 N HCl as a dispersant for New Zealand allophane soils. Kobo and Oba (1964) applied low pH for Japanese subsoils and used calgon for the surface soils with organic matter. They also found that ultrasonic vibration increased dispersion. Oba and Kobo (1965) found that ultrasonic dispersion released clay size grains from aggregates. An extended experiment found that ultrasonic treatment still gave much lower values for clay content than did the estimate from the 1500 kPa water content (Espinoza, *et al.* 1975). Wada and Harward (1974) suggested an adjustment of suspension pH either at pH 10 (NH_4OH or NaOH) or at pH 4 (HCl), combined with the aid of ultrasonic vibrations. More specifically, Wada (1978) suggested that an alkaline medium can be used for Andisols containing Al:Si ratio of 2 or higher, whereas an acid medium is required for those with Al:Si ratio less than 2. Since different allophanes react differently to various dispersion treatments, surface and subsoils react differently, and undried samples always disperse more completely than air-dried samples. It seems that there is no one best method which can be recommended. It is necessary therefore, to mention the method for the particular soil being studied. Drying the sample decreases the measured clay content, as described by many researchers (*e.g.*, Birrell 1966). This can be attributed to cementing on drying.

2.2.3.3. Water retention

Andisols are normally permeable, and a high amount of water percolates through the soil in humid to perhumid regions. The profiles do not show evidence of clay movement, however, indicating the formation of stable aggregates. The formation of stable aggregates is enhanced by drying and this causes difficulty for particle size distribution analysis.

The high water retentivity of previously undried allophanic soils and the large, irreversible change in water retentivity on air-drying are important characteristics of these soils. The large specific surface area of allophane, its flocculation, and the size and shape of aggregates are the properties which account best for the ability to retain large amounts of water even at high suctions. Beside the high water content at both 33 kPa and 1500 kPa, Andisols are often found to have gravimetric water contents of around 100% (Maeda, *et al.* 1977). They also reported that of the amount of water retained by soil, the portion available for plant growth, corresponding to field capacity, occurs at the lower limit of 10 kPa instead of at 33 kPa as in other soils.

Structure is another important physical property of Andisols. Soil is composed of a macrostructure and a microstructure component (Fitzpatrick 1980). The A horizons are generally characterised by an unusual granular structure. This structure differs from the ordinary granular structures of other soils in that the structural units are very resistant to the impact of falling raindrops. Because of this resistance and since in dry condition they feel gritty, the units have been referred to as "pseudo sand" (Mohr 1937), which is formed by a granulation process. Warkentin and Maeda (1980) believe that gel masses occur as coatings in the aggregation of the clay particles. Therefore, aluminum and iron oxide probably play an important role as binding agents.

2.3. Research Methodology

2.3.1. Selection of Profile Sites

Stage of weathering determined the selection of soil profiles. Four profiles were chosen which represent young to mature well-drained volcanic ash soils and one site was selected as representative of poor drainage soil.

Table 2.1. Location of soil samples

Pedons	Location	Parent material	Vegetation	Grid Reference
1	Desert Road	Rhyolitic+Andesitic	Tussock Grass+ shrub	T20/415956
2	Carrot Paddock, Tangiwai	Rhyolitic+Andesitic	Market Garden	T21/303875
3	Tangiwai Mill, Blackwood	Andesitic	Pasture	T21/304895
4	Horopito	Andesitic	Pasture in rotation with carrot	S20/123026
5	Horopito	Andesitic	Grass	S20/122023

2.3.2. Description of Soil Profiles

Morphological and physical soil properties were used to describe soil profiles. Procedures for soil description were based on Soil Survey Method (Taylor and Pohlen 1962). The properties were ascertained in the field and included an assessment of soil color and color pattern, texture, structure and consistency at field moisture condition. Dr Alan S Palmer assisted with the descriptions. Soil colours were described using Japanese Standard Munsell Soil Colour Charts.

2.3.3. Samples For Laboratory Analyses

Soil samples were obtained from within freshly dug pits, except for the profile on the Desert Road, which was exposed at the roadside. Sampling within soil profiles was on a horizon basis, with three to five samples being taken per profile. Approximately 1 kg of soil was extracted from a central position in each designated horizon and placed in a plastic bag to retain soil moisture. Location of soil sample sites is given in Table 2.1 and Fig. 1.1.

In the laboratory, soil samples were divided into two aliquots: air-dried and undried. Air-dried soils were passed through a 2 mm sieve and the < 2 mm fraction was used for analysis unless otherwise specified. The undried soil samples were kept in sealed plastic jars, to keep them in a field moist condition.

2.3.4. Laboratory Analyses

2.3.4.1. Mineralogical Analyses

Each crystalline substance has a characteristic arrangement of atoms which diffracts X-rays in a unique pattern. X-ray reflection takes place from lattice planes according to Bragg's law:

$$n\lambda = 2d \sin \theta$$

where:

λ is the wavelength of the X-rays, determined by the type of X-ray anode
θ is the glancing angle of reflection
n is the order of the reflection, which can be any whole number
d is the interplanar spacing

Scanning a range of angles of reflection with a detector gives a pattern of peaks at certain spacings and intensities that are characteristic of the minerals present.

In order to determine the nature of the various size fractions, it is necessary to separate them after removal of any cementing agents that may hold the particles together. The common cementing agents are calcium, organic matter, and iron and aluminum oxides and hydroxides. The chemical treatments for their removal were HCl, hydrogen peroxide, and citrate-dithionite-bicarbonate reagents, respectively.

After these treatments, the soils were separated into sand, silt and clay fractions. The silt and clay fractions were used for X-ray examination and the sand fraction was analyzed by density separation, to separate heavy minerals from volcanic glass.

Heavy mineral liquid methods have been used to estimate glass and heavy minerals content. The heavy liquids method separates glass particles and also heavy minerals on the basis of specific gravity (SG). This method, however, is not applicable to all types of glass because more basic (coloured) glass with a specific gravity exceeding

$2.5\ g\ cm^{-3}$ is difficult to separate from plagioclase (Yamada and Shoji 1990). To identify volcanic glass and heavy minerals quantitatively, a SG 2.4 solution was mixed with a 0.500 g sample from the sand fraction to obtain the glass particles, and a SG 2.85 solution was added into another 0.500 g sand fraction sample to capture the heavy minerals. Their contents were determined gravimetrically after drying.

The clay ($< 2\mu m$) fractions, separated by centrifugation, were analysed mineralogically after chemical treatment. The sand, silt, heavy minerals and clay fractions were examined by X-ray diffraction (XRD) using a Philips PW 1780 microprocessor-controlled diffractometer after sedimentation on glass slides. The diffractometer was used with CoKα radiation, 1° sample and receiving slits and a 0.2 mm anti- scatter slit; the goniometer scanning speed was $1^{o}20\ min^{-1}$. XRD patterns of the clay fractions were obtained after air-drying following both Mg and K saturation (Mg-air and K-air, respectively), after glyceration following Mg saturation (Mg-gly), and after heating at 550°C for 1 hour following K saturation (K-heat). The remaining clay-suspension was air-dried for DTA analysis.

The X-ray diffractometer program used for sand and silt fractions was 210, 211 for heavy minerals, 222 for Mg-air, and 223 for Mg-glycerol, K-air and K-heat (Percival 1984 *in* Whitton and Churchman 1987). Semi-quantitative analysis of the mineral composition of each fraction was carried out on X-ray diffraction patterns by a method described by Churchman (1980 *in* Whitton and Churchman 1987).

Hydroxyl groups are present in the structures of the hydrous silicates and oxides that are contained in clays and in the clay fractions of soils. When such clay constituents are heated, their structures are broken and hydroxyl groups are released as water. The temperatures at which hydroxyl groups are released are dependent upon the strength with which they are bonded within the structures. Thus, these temperatures are characteristic of the structures and types of minerals present. Differential thermal analysis provides a method for recording the temperatures at which reactions occur, and the nature and magnitude of the heat changes.

50 mg of finely ground clay were packed into a liner cup and placed on the left-hand thermocouple of the DTA instrument. The DTA instrument used was a SCI 500 micro-processor controlled unit. A qualitative analysis of minerals present was established by comparing the thermogram obtained with a standard thermogram (calcined kaolinite). A quantitative estimate of kandite was made by measuring peak heights under characteristic endothermic peaks at temperatures of 520-560°C and obtaining the concentration of the minerals present from standard graphs.

The quantities of plant opal were estimated under a Leitz ortholux polarising microscope. This microscope was also used to differentiate the rhyolitic glass from andesitic glass.

Electron microscopy analysis was used for describing amorphous and crystalline forms in the clay fraction. The < 2 μm fractions of moist soils were separated by settling after ultrasonic dispersion of the samples with 1:1 NH_4OH. These samples were examined using an EM 301 HRG Philips, TEM electron microscope.

2.3.4.2. Chemical Analyses

The pH was measured in water, 1M KCl, and NaF solution. The pH (water and KCl) values of the soil suspensions were measured in a 1:2.5 ratio of soil solution ratio. The pH (NaF) values of soil samples were determined in the suspensions of 1 g soil in 50 ml of 1M NaF after 2 minutes stirring (Soil Survey Staff 1975).

Phosphate retention was determined according to Blakemore, *et al.* (1987).

The total organic carbon and total nitrogen contents of the soil samples were determined by the induction-furnace method (Blakemore, *et al.* 1987), in which the carbon and the nitrogen are converted into carbon dioxide and nitrogen dioxide, respectively. The contents of organic matter approximately can be calculated as: organic matter % = organic C% x 1.72 (Childs *et al.* 1990).

Cation exchange capacity (CEC) was determined by percolating the soil with 1M NH_4OAc pH 7. The CEC was determined by adding the sum of the individual exchangeable bases to the exchangeable hydrogen. Each cation is expressed cmol(+) kg^{-1}. The exchangeable bases (K^+, Na^+, Mg^{2+}, and Ca^{2+}) values were measured by using atomic absorption spectrophotometer. The exchangeable hydrogen was determined according to Hesse (1971). The principle underlying this method is that if the soil is buffered at pH 7, the pH of the soil extract will decrease linearly with exchangeable hydrogen (Brown 1943). The amount of exchangeable H^+ was obtained by the following equation:

H^+ cmol(+) kg^{-1} = [(blank pH-result pH)/0.04]x 5,

where: blank pH = pH of the quartz sand extract,

result pH = pH of the soil extract,

0.04 is the slope of Brown's curve.

Percentage base saturation (% BS) is the percentage saturation of the exchangeable bases relative to the cation exchange capacity.

Amorphous constituents of the soils were determined using the Parfitt and Wilson (1985) method. Soil samples (< 2 mm) were extracted with acid oxalate (Al*o*, Fe*o*, and Si*o*) and pyrophosphate (Al*p* and Fe*p*) reagents following the procedure of Blakemore, *et al.* (1987). The Al and Fe contents of all the extracts mentioned above were measured by high temperature flame emission and silicon by atomic absorption using a Techtron AA5. The established methodology is then to calculate the Al:Si ratio for allophane from (Al*o*-Al*p*)/Si*o* multiplied by 28/27 to give the atomic ratio. The Si*o* content is then multiplied by a factor corresponding to the atomic ratio to give the percentage of allophane in the soil sample. The presence of allophane and imogolite was determined not only by the selective dissolution analysis, but also by subjective electron microscopic observation of the clay fraction. Ferrihydrite content of the samples was calculated by multiplying Fe*o* by 1.7 (Childs 1985; Parfitt and Childs 1988).

2.3.4.3. Physical Analyses

In order to determine the percentage of clay size particles, a complete size analysis was carried out by the following procedure: a 20 to 25 g moist, field sample was ultrasonically dispersed following pre-treatment for the removal of organic matter by 30-50 ml 30% H_2O_2. Field moist soil was used, as a decrease in clay content after drying has been reported (Birrell 1966). The sand fraction was separated from the silt and clay fractions by wet sieving over a 53 µm nylon mesh. The sand fraction was dried and sieved into 2-0.2 and 0.2-0.053 mm fractions. The silt and clay fractions were dispersed by ultrasonic vibration for 5 min at 475 watts output, 20 KHz using a W-380 Sonicator and microtips, and adjustment of the suspension pH drop by drop with 1:1 HCl. The silt and clay fractions were separated by the pipette method.

Water retention at 100 and 1500 kPa was determined by the pressure membrane method on each of first two horizons of undried samples. Water retention was determined on a 100 and a 1500 kPa ceramic plate extractor (Cat.No.150) of the Soil Moisture Equipment Company. After complete saturation, the plates were placed in an apparatus and pressures of 100 and 1500 kPa were applied. These pressures were maintained for seven days, after which time it was considered that equilibrium had been reached, and then the water contents were determined gravimetrically on an oven dry (105°C) basis.

All of the results are expressed on an oven-dry basis (105°C).

2.3. Results and Discussion

2.3.1. Morphological Characteristics

The profiles show a contrast in parent material composition. A simplification of the soils horizons is displayed in Fig. 2.4. There are two major marker beds, the Taupo Pumice (Tp) in P1 and P2, and the Papakai Formation (PF) in P3 to P5 which overlaid on the top of the Bullot Formation. The younger marker bed, the Taupo Pumice, is recognised by its pale colour relative to under and overlying beds; and the presence of relatively weathered fine rhyolitic glass particles confirmed its tephric nature. The older marker bed, the Papakai Formation, is identified on the basis of stratigraphic position. This formation is formed mainly from Tongariro tephra, which consists of andesitic tephra.

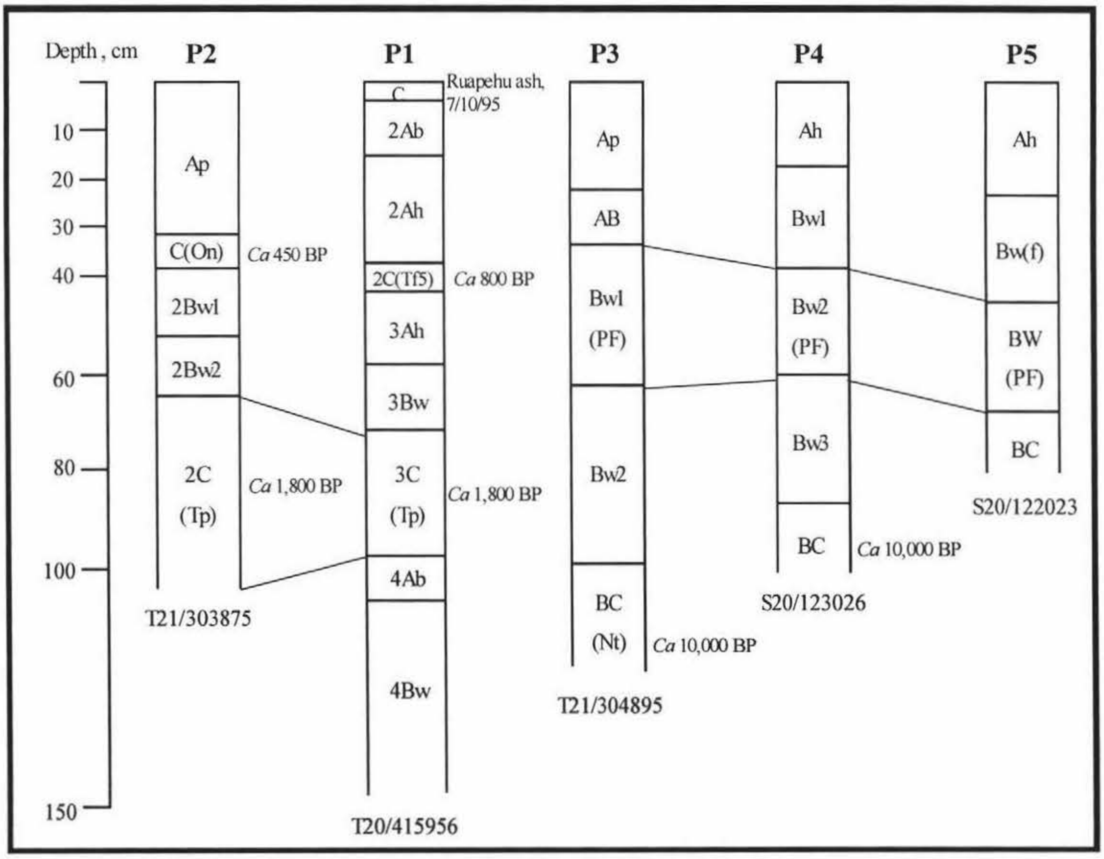


Fig. 2.4. The horizons of the studied soils.

Brief profile descriptions are presented in Table 2.2 (standards and terminologies are from the Soil Survey Manual (Soil Survey Staff 1962) combined with Soil Survey Method (Pohlen and Taylor 1962).

Table 2.2. Selected morphological features of the studied pedons

Horizon	Depth , cm	Color	Texture	Structure	Consistence		Coarse fragment	Roots
					m	w		
Pedon 1								
C	0-1	10YR 3/1	sl	-	loose	-	-	-
2Ab	1-10	10YR 4/2-4/3	f.sl	m2cr	-	-	-	ab.root
2Ah	10-28	10YR 3/2	f.sl	c3cr+f.g	v. fri	ns,np	-	cm.root
2C	28-33	black-dark grey	-	-	loose	-	Tf5, c.ash, v.f. lapilli	-
3Ah	33-40	10YR 3/2-2.5Y3/2	f.sl	c3cr+f.g	fri.	ns,np	-	cm.v..f. root
3Bw	40-55	10YR 3/3-3/4	f.sl	c3cr+f.g	fri.	ns,np	-	-
3C	55-85	2.5Y 4/2-5/2	ls	m	fri.	-	cm.f.charcoal, Tp	-
4Ab	85-105	10YR 3/3	f.sl	c3cr+f.g, greasy	fri.	ns,np	-	no root
4Bw	105+	10YR 3/4-4/4	f.sl	m1b to c3cr+m.g	fri.	ns,np	-	- s.greasy
Pedon 2								
Ap	0-21	7.5YR 3/1-3/2	ls	c2cr	-	ns,np	cm.f.andesite pebbles	f. root
C	21-34	2.5Y5/2	s	m	-	ns,np	gravel	no root
2Bw1	34-42	10YR 4/2	ls	m	loose	-	-	no root
2Bw2	42-50	10YR 4/3-4/4	f.ls	-	loose	ns,np	-	-
2C	50+	2.5Y 7/4	s	-	loose	-	Tp, sand, pumice clast	-
Pedon 3								
Ap	0-22	10YR 2/2-7.5YR 2/2	f.sl	m2nut+g to c3cr	fri.	ns,np	-	cm.root
AB	22-33	10YR 4/4	f.sl	c3cr+f.g	v fri.	ns,np	fw.f.lapilli	f.root
Bw1	33-62	10YR 4/6	f.sl	c3cr+f.g, s.greasy	v fri.	ns,np	fw.lapilli	fw.f. root
Bw2	62-98	10YR 4/6	sl	-	fri-firm	-	c.ash, v.f.lapilli, pumice & lithics, fw.m.lapilli	
BC	98+	orange lapilli, brown matrix	s	-	-	-	m-f.Ngamatea lapilli,	
Pedon 4								
Ah	0-17	7.5YR 3/2-3/3	zcl	m2nut to c3cr	fri.	ns,sp	-	ab.root
Bw1	17-38	10YR 4/3	zcl	m3nut to c3cr	fri.	ns,sp	org.coatings on roots	cm.root
Bw2	38-60	10YR 4/4-7.5YR 4/4	zcl	c2nut +m.b to c3cr	fri.	ns,sp	org.coatings on roots	f.root
Bw3	60-86	10YR 4/4-7.5YR 4/4	zcl	m2nut+m.b, gritty	-	ns,sp	org.coatings on roots & ped	
BC	86-100+	10YR 4/4	scl	c1b, gritty	-	-	c.lapilli & lithics	-
Pedon 5								
Ah	0-23	10YR 3/2	zcl	m2nut+b	fri.	ns,sp	org.coatings on roots	ab.root
Bw(f)	23-45	10YR 4/3-4/4	zcl	m2nut +b	fri.	ns,sp	org.coatings on roots, brittle Fe+ Mn	cm.root
Bw	45-67	10YR 4/4	zcl	m2nut +b	-	ns,sp	org.coatings on roots	f.root
BC	67-80+	10 YR 4/4	zcl	m2nut+b	fri.	ns,sp	large boulders	-

Symbols:

Texture: sandy loam (*sl*), loamy sand (*ls*),silty clay loam (*zcl*), sandy clay loam (*scl*); size: fine (*f*).

Structure grade: weak (*1*), moderate (2), *strong (3);* size: fine (*f*), medium (*m*), coarse (*c*); form: crumb (*cr*), granular (*g*), blocky (*b*), massive (*m*).

Consistence condition: moist (*m*), wet (*w*); friable (*fri*), very friable (*vfri.*), non-sticky (*ns*), non-plastic (*np*), slightly plastic (*sp*)

Coarse fragment: coarse (*c*), medium (*m*), fine (*f*), very fine (*v.f*); amount: common (*cm*), few (*fw*); tufa trig (*Tf5*), taupo pumice (*Tp*), organic (*org*).

Root: size: fine (*f*), very fine (*v.f*); amount: few (*fw*), common (*cm*), abundant (*ab*).

The sites at P2 and P3 have their upper layers *c.* 30 and 22 cm disturbed by cultivation, whereas the P4 and P5 sites are currently covered by pasture. The P1 site is under tussock. Stratigraphic discontinuities at P1 and P2 are noted on the basis of field properties (Fig. 2.4).

Three samples from sites P1 and P2 were collected from the non-soil layers. They are the Tufa trig 5, the Taupo pumice and the lahar (Fig. 2.4). Therefore, some marked differences in morphology, mineralogy, chemical and physical features are apparent.

Almost all soil horizons have 10YR (yellow) hues, except for the first horizons in pedons 2 and 4, which have hue of 7.5 YR, and for those which contained pumice lapilli have hues of 2.5 Y. The chroma vary in the range 1 to 6. Surface soils generally have a range of chroma between 1 and 3. The dark colour throughout whole surface soils resulted from the presence of high amounts of organic matter. In general, surface horizons are either dark brown or very dark brown.

Based on field soil textures, there are three different classes: P1 and P3 sites have a sandy loam texture. Pedon 2 has slightly coarser textures, which range between loamy sand and sand, whereas at P4 and P5 the texture is silty clay loam.

Generally, the structure of P1, P2, and P3 is strong or medium crumb and medium fine granular. Pedons 4 and 5 have more developed structures, they are medium nut and blocky, respectively. The C horizons in pedons 1 and 2, are structureless and massive. Lapilli and pebbles are present in some horizons and are probably inherited from pumice. Some horizons show peculiar attributes of Andisols, and have a gritty and/or greasy feeling in their structure (Table 2.2).

Soil consistence is observed both in moist and wet conditions. All five soils has friable or very friable consistency throughout whole horizons except for the C horizons, which have loose consistency. They are all non-sticky and non-plastic except some horizons in P4 which are slightly plastic when wet. Overall, soil consistency provides evidence for volcanic ash soils.

The ash in pedon 1 (34-40 cm) is dominantly black to dark grey and gives no evidence of mottling. It is loose when moist, and interbedded with fine lapilli. The Taupo pumice layer (P1, 55-85 cm) has a loamy sand texture and contained common fine charcoal fragments. Taupo pumice is also found in P2 at 50+ cm depth. This rhyolitic tephra occurs as individual pumice lapilli and contains occasional pumice lapilli clasts. The pumice is soft, highly weathered and ranges from pale yellow in P2 to dark grayish brown in P1. The coarser andesitic tephra (Ngamatea lapilli) in P3 (98+ cm) dominantly has medium to fine pumice lapilli which are highly and finely vesicular. Above this layer (50-62 cm) the andesitic material occurs as a very fine pumice lapilli and coarse ash beds with some lithic components. The accumulations of pumice and ash represent the products of several eruptions over time.

Roots are abundant throughout all the surface horizons. They are also present in lesser amounts in the subsurface horizons. The pumice horizons, however, do not contain roots.

Profile drainage is good at all the sites except at P5. At the latter site, there are brittle Fe/Mn concretions at the Bw(f) (23-45 cm) which may be indicative of periods of intermittent, high water-tables.

2.4.2. Mineralogical Characteristics

The mineralogy of the soils covers four different fractions: sand, silt, heavy minerals, and clay. The results show that the mineralogy of the soils is largely noncrystalline. The mineralogical composition of volcanic ash varied widely as a function of particle-size as shown in Tables 2.3, 2.4, 2.5, and 2.6. X-ray diffractograms representing the identified minerals in each fractions are shown in Fig.2.5 for tephra and Fig. 2.6 for lahar.

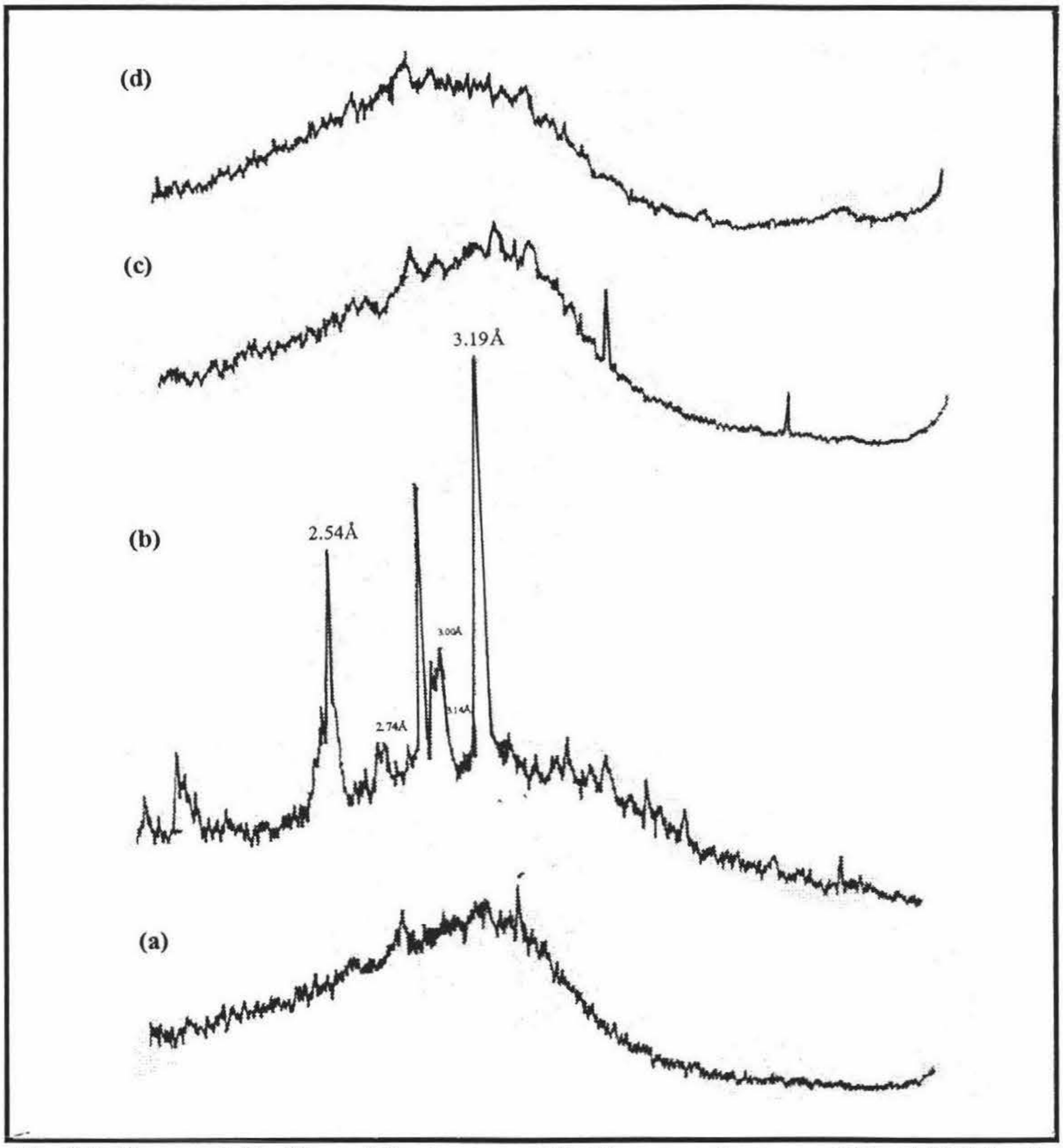


Fig. 2.5. Representative X-ray diffractograms of the Taupo pumice layer at P1 soil (55-85 cm): (a) sand fraction; (b) heavy mineral fraction; (c) silt fraction; (d) clay fraction.

Figure 2.5 shows volcanic glass is obviously dominant in the Taupo pumice layer in P1. Minerals in the heavy minerals fractions are hypersthene, magnetite, augite, ilmenite, and hornblende.

Figure 2.6 shows that in addition to volcanic glass, P2 soil also contains crystalline minerals, such as feldspar, quartz, cristobalite, and kaolinite. Plagioclase feldspar and quartz persist in the sand, silt and clay fractions of the soil.

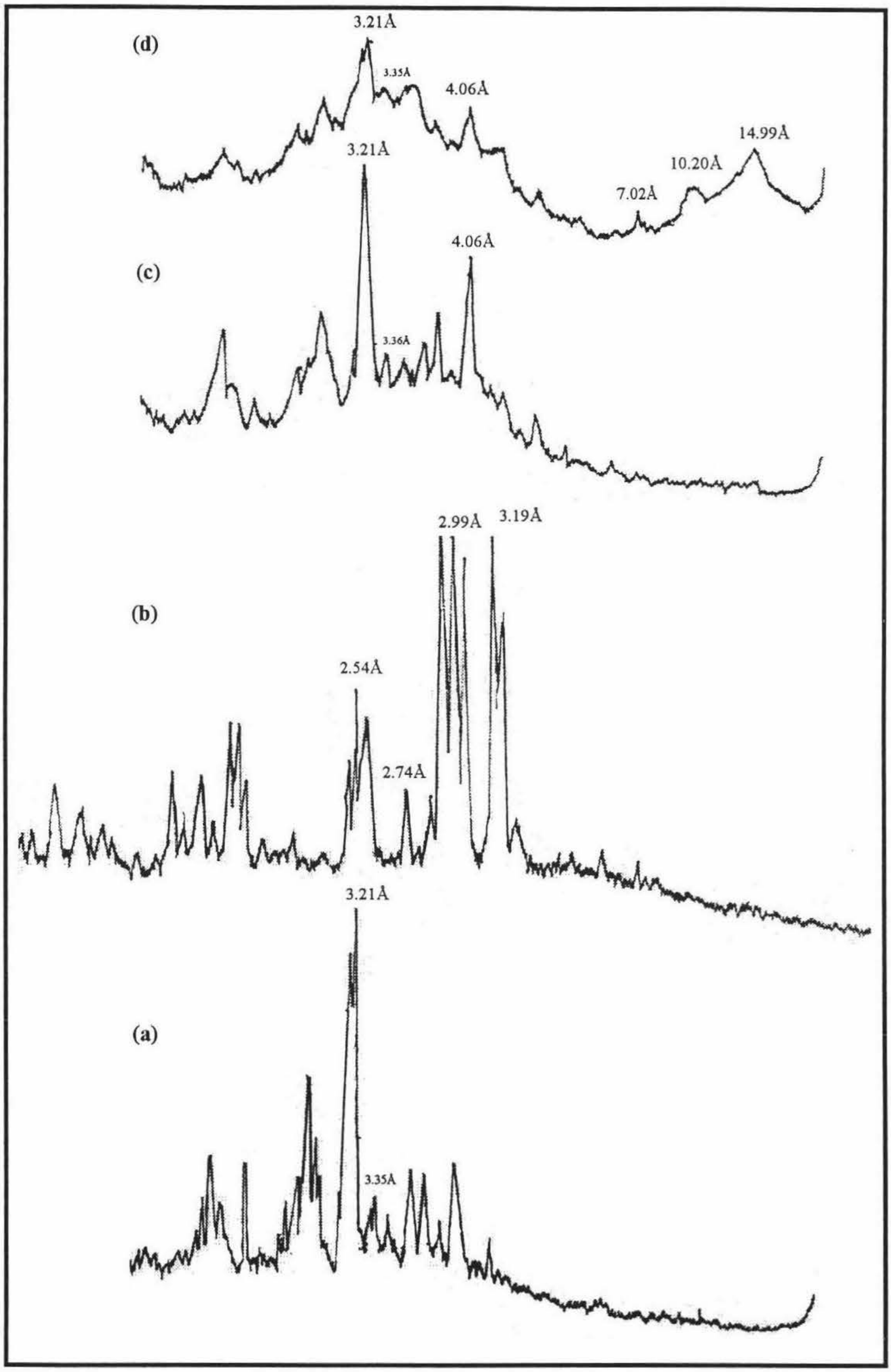


Fig. 2.6. Representative X-ray diffractograms of P2 soil (30-37 cm): (a) sand fraction; (b) heavy minerals fraction; (c) silt fraction; (d) clay fraction.

2.4.2.1. Sand Fraction (20-200 μm).

The mineralogy of this fraction was assessed mainly by X-ray diffraction. Before discussing these, it is necessary to outline the criteria used for identification. Plagioclase feldspar is identified by a strong reflection at 3.21Å. Quartz was present in only very small amounts in these soils. It is identified by X-ray diffraction peaks at 3.35Å and 4.26Å, and also 2.45Å.

Table 2.3. Mineralogy of the sand (20-200 μm) fraction

Horizon	Depth (cm)	Volcanic glass	Plant Opal	Heavy Minerals	Feldspar	Quartz
Pedon 1						
2Ab	1-10	+	tr	++	++	tr
2Ah	10-28	+	tr	++	++	tr
2C	28-33	+	tr	++	++	tr
3Ah	33-40	+	tr	++	++	tr
3Bw	40-55	++	tr	++	+++	tr
3C	55-85	+++++	0	tr	+	0
4Ab	85-105	++	tr	++	++	tr
Pedon 2						
Ap	0-21	+	tr	+++	+++	tr
C	21-34	+	tr	++	++	tr
2Bw2	42-50	++	0	++	++	tr
2C	50+	+++++	0	tr	tr	0
Pedon 3						
Ap	0-22	++	tr	++	+++	tr
AB	22-33	++	tr	+++	++	tr
Bw1	33-62	++	tr	+++	++	+
Bw2	62-98	+	tr	+++	+++	tr
BC	98+	+	tr	+++	+++	tr
Pedon 4						
Ah	0-17	++	tr	++	++	tr
Bw1	17-38	++	tr	+++	++	tr
Bw2	38-60	+	tr	++++	++	tr
Bw3	60-86	+	tr	++++	++	+
BC	86-100+	+	tr	+++	++	+
Pedon 5						
Ah	0-23	++	tr	++	+	tr
Bw(f)	23-45	++	tr	+++	++	tr
Bw	45-67	+	tr	+++	++	tr

Note: trace, <5% (tr), minor, 5-14 % (+), common, 15-29 % (++), abundant, 30-49 % (+++), dominant, 50-79 % (++++), predominant, > 80 % (+++++).

The sand mineralogical results show the significant similarities between the profiles. They generally contain feldspar and heavy minerals in common and abundant amounts. The profiles also contain volcanic glass in a minor amount. Quartz and plant opal are also present in trace amounts. These all indicate the soil parent material is volcanic ash.

The volcanic glass of most samples consists of a mixture of andesitic and rhyolitic glass, except for the Taupo pumice layers which are composed of rhyolitic glass only. The andesitic glass is partially weathered and brown in colour, whereas the rhyolitic glass has no colour and unweathered edges under microscope polarisation.

The presence of opaline silica (plant opal, Table 2.3) signifies high silica activities. Opaline silica may be present as plant opal, diatoms, or laminar opaline silica. The amount of opaline silica was determined qualitatively under microscope polarisation. Plant opal and diatoms are found in all profiles in trace amounts. They are about 1-2 % of the sand fraction. Plant opal particles have a unique morphological form dictated by the shape of the plant vacuoles in which they precipitate. According to Kondo *et al.* (1994), the phytoliths from graminaceous plants have a fan-shape or are rectangular, and they originate from bulliform cells. The phytoliths found here were derived from grass species, indicating the importance of these vegetation types on silica biocycling in these soils.

2.4.2.2. Silt Fraction (2-20μm).

Table 2.4. shows the mineralogy of the silt fraction is essentially similar to that of the sand fraction, although there are some important quantitative differences in the primary minerals. Plagioclase feldspar, for example, occurs in slightly smaller amounts, whereas volcanic glass tends to be more abundant. In addition, there is significant presence of cristobalite. Cristobalite is detected by its sharp reflection at 4.06Å which is considered to be too intense to be attributed to plagioclase feldspar alone.

The quartz content of the silt fraction is very low throughout all pedons (Table 2.4). The cristobalite content is variable from trace to minor amounts. Neither quartz nor cristobalite is found in the Taupo pumice units (in P1 and P2). The origin of cristobalite in volcanic ash soils has been attributed to both pedogenesis (Lowe 1986), and as a primary phase from volcanic parent material (Mizota, *et al.* 1987).

Table 2.4. Mineralogy of the silt (2-20 μm) fraction

Horizon	Depth (cm)	Cristoballite	Quartz	Feldspar	Volcanic glass
Pedon 1					
2Ab	1-10	+	tr	++	++++
2Ah	10-28	+	tr	++	++++
2C	28-33	+	tr	++	++++
3Ah	33-40	+	tr	++	++++
3Bw	40-55	+	tr	++	++++
3C	55-85	0	0	tr	+++++
4Ab	85-105	+	tr	++	++++
Pedon 2					
Ap	0-21	+	tr	++	++++
C	21-34	+	tr	++	++++
2Bw2	42-50	tr	tr	++	++++
2C	50+	0	0	tr	+++++
Pedon 3					
Ap	0-22	+	tr	++	++++
AB	22-33	+	tr	++	++++
Bw1	33-62	tr	tr	+	+++++
Bw2	62-98	+	tr	++	++++
BC	98+	+	tr	++	++++
Pedon 4					
Ah	0-17	+	tr	++	++++
Bw1	17-38	+	tr	+	+++++
Bw2	38-60	tr	+	+	+++++
Bw3	60-86	tr	tr	+	+++++
BC	86-100	+	+	+	++++
Pedon 5					
Ah	0-23	+	tr	++	++++
Bw(f)	23-45	+	tr	+	+++++
Bw	45-67	+	tr	++	++++

Note: trace, <5% (tr), minor, 5-14 % (+), common, 15-29 % (++), abundant, 30-49 % (+++), dominant, 50-79 % (++++), predominant, > 80 % (+++++).

2.4.2.3. Heavy Mineral Fraction

To facilitate the identification of the heavy minerals (minerals which have specific gravity above 2.8), the X-ray diffraction method was used. Hypersthene produces a significant peak at 3.19Å. Magnetite is recognized by reflection at 2.54Å. Augite yields an X-ray pattern with a strong reflection at 2.99Å, ilmenite is identified by reflection at 2.74Å and hornblende is confirmed by its peak at 3.14Å

Table 2.5. Mineralogy of the heavy minerals fraction

Horizon	Depth (cm)	Hypersthen	Magnetite	Augite	Ilmenite	Hornblende
Pedon 1						
2Ab	1-10	++++	+	++	+	tr
2Ah	10-28	++++	+	++	+	tr
2C	28-33	+++	++	++	+	0
3Ah	33-40	++++	+	++	+	0
3Bw	40-55	+++	++	+++	+	0
3C	55-85	+++	++	+	+	+
4Ab	85-105	+++	+	++	+	tr
Pedon 2						
Ap	0-21	++++	++	++	+	0
C	21-34	+++	++	+++	+	0
2Bw2	42-50	++++	++	++	+	0
2C	50+	++++	++	0	0	0
Pedon 3						
Ap	0-22	+++	++	++	+	0
AB	22-33	+++	+++	++	+	tr
Bw1	33-62	++	+++	++	+	tr
Bw2	62-98	+++	++	+++	tr	tr
BC	98+	+++	++	++	+	tr
Pedon 4						
Ah	0-17	+++	+++	++	+	tr
Bw1	17-38	++	+++	++	tr	tr
Bw2	38-60	+++	++	++	+	+
Bw3	60-86	+++	++	++	+	+
BC	86-100	++++	++	++	+	+
Pedon 5						
Ah	0-23	+++	+++	++	+	0
Bw(f)	23-45	++	+++	++	+	+
Bw	45-67	+++	+	+++	tr	0

Note: trace, <5% (tr); minor, 5-14 % (+); common, 15-29 % (++); abundant, 30-49 % (+++); dominant, 50-79 % (++++); predominant, > 80 % (+++++).

In the heavy minerals fraction, hypersthene is found as the main constituent, follows by augite and magnetite. In pedon 1, augite is slightly more abundant than magnetite. Conversely, magnetite is relatively more abundant in other pedons. Ilmenite and hornblende occur in all soils, in minor and trace amounts, respectively. Analysis of this fraction also reveals that the amounts of hypersthene in the rhyolitic tephra (Tp) are always higher than those in the andesitic tephra, whereas the reverse is generally true of augite.

Traces of hornblende and common augite in all horizons indicate that there are weatherable minerals from andesitic ash. The stability order of the common members of the pyroxene mineral group is olivine < hypersthene < augite < hornblende (Huang 1989).

The compositions of the heavy mineral fraction together with the mineralogy of the sand fractions are indicators of the origin of the soils.

2.4.2.4. Clay Fraction (< 2 μm).

The clay fraction consists of both crystalline and amorphous components, the former being assessed mainly by X-ray diffraction and DTA, and the latter by electron microscope observations. The minerals were identified according to the following criteria. Chlorite is characterized by a broad 14Å reflection which may not increase with glycerol and K treatment, and does not shift to 10Å on heating at 550°C. Hydroxyl interlayered vermiculite (HIV) similarly is characterised by a broad 14Å reflection, which shifts to 10Å on heating at 550°C. Kandite is a group of minerals which includes kaolinite and halloysite. Kandite is quantitatively determined by its endotherm peak at 520-560°C. Kaolinite is differentiated from halloysite by formamide treatment, when kaolinite is manifested by a reflection at 7.2Å whereas halloysite reflects at 10.4Å. The presence of allophane and/or imogolite in the clay fraction was determined by using the acid oxalate extraction procedure (Blakemore, *et al.* 1987). Allophane and imogolite were also identified from the electron microspcope observations, imogolite having a peculiar, thread-like morphology. The other minerals were identified by the X-ray criteria outlined for the previous fractions. Volcanic glass gives no peaks. Its amount was estimated by subtraction.

Table 2.6. Mineralogy of the clay (< 2 μm) fraction

Horizon	Depth (cm)	Cristo-balite	Q	F	Kan-dite (DTA)	Halloy-site 10A	Kaoli-nite	Chlo-rite	HIV	Allophane (% clay)	VG+am.si
Pedon 1											
2Ab	1-10	0	tr	+	+	0	+	0	+	++	++++
2Ah	10-28	0	tr	+	++	0	++	0	+	+++	+++
2C	28-33	0	tr	tr	+	0	+	0	+	+++	+++
3A1	33-40	0	tr	tr	+	0	+	0	+	+++	++
3AB	40-55	0	tr	tr	tr	tr	0	0	+	++++	++
3C	55-85	0	tr	tr	0	0	0	0	tr	+++	++++
4Ab	85-105	0	tr	tr	0	tr	0	+	+	++++	++
Pedon 2											
Ap	0-21	tr	tr	tr	++	0	++	0	+	++	+++
C	21-34	tr	tr	tr	++	+	+	0	+	++	+++
2Bw2	42-50	tr	tr	tr	+	tr	+	0	+	+++	++
2C	50+	tr	tr	tr	0	0	0	0	tr	++++	+++
Pedon 3											
Ap	0-22	tr	tr	tr	+	0	+	0	+	+++	+++
AB	22-33	tr	tr	tr	0	0	0	0	+	++++	++
Bw1	33-62	tr	tr	tr	0	0	0	0	+	++++	++
Bw2	62-98	tr	0	tr	0	tr	0	0	+	++++	+
BC	98+	tr	tr	tr	0	0	0	0	tr	++++	++
Pedon 4											
Ah	0-17	tr	tr	tr	++	0	++	+	+	+++	++
Bw1	17-38	tr	0	0	0	0	0	0	+	++++	+++
Bw2	38-60	tr	tr	tr	0	0	0	0	+	++++	+++
Bw3	60-86	tr	tr	tr	tr	tr	tr	+	+	++++	++
BC	86-100	tr	tr	tr	tr	0	tr	+	+	++++	++
Pedon 5											
Ah	0-23	tr	tr	tr	0	0	0	+	+	+	++++
Bw(f)	23-45	tr	tr	tr	0	0	0	tr	+	++++	+++
Bw	45-67	tr	tr	tr	0	0	0	tr	+	++++	+++

Note: trace, <5% (tr), minor, 5-14 % (+), common, 15-29 % (++), abundant, 30-49 % (+++), dominant, 50-79 % (++++), predominant, > 80 % (+++++).

Q=quartz, F=feldspar, HIV=hydroxy interlayered vermiculite, VG=volcanic glass, am.sic=amorphous silica

Analysis of the <2 μm fraction (Table 2.6) showed that all soils dominantly consist of amorphous phases in varied amounts. The dominant crystalline material in the clay-size fraction is hydroxy interlayered vermicullite (HIV). Also present are cristobalite, kaolinite, feldspar, quartz, chlorite and halloysite.

Figure 2.7 reveals the presence of HIV at P2. As the sample was heated to 550°C, the 14Å reflection became a very broad 10Å peak. The figure also shows a 7Å peak which indicates that kaolinite may be present.

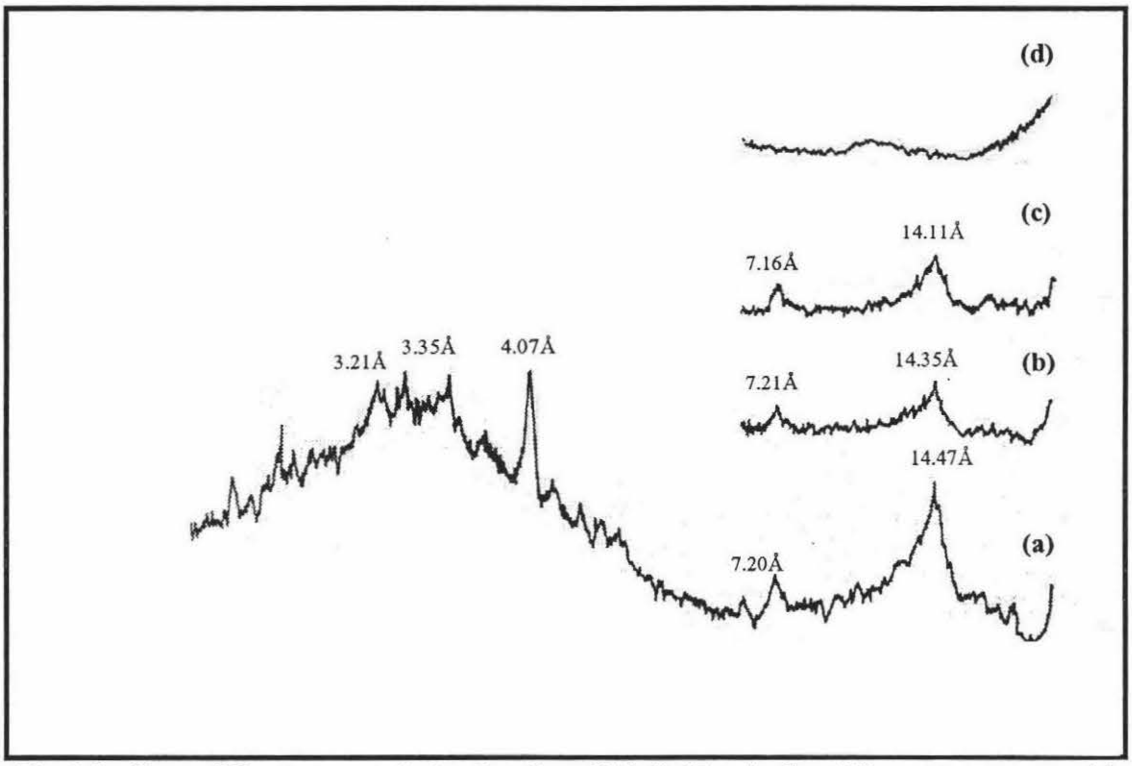


Fig. 2.7. X-ray diffractograms of clay fraction of P4 (0-17 cm) after different treatments: (a) Mg-air; (b) Mg-gly; (c) K-air; (d) K-heat.

The DTA curve of the selected < 2 μm soil clay (Fig. 2.8) shows an endotherm at 520-560°C due to dehydroxylation, and a sharp exotherm at 905°C. The curve is typical of the kandite group.

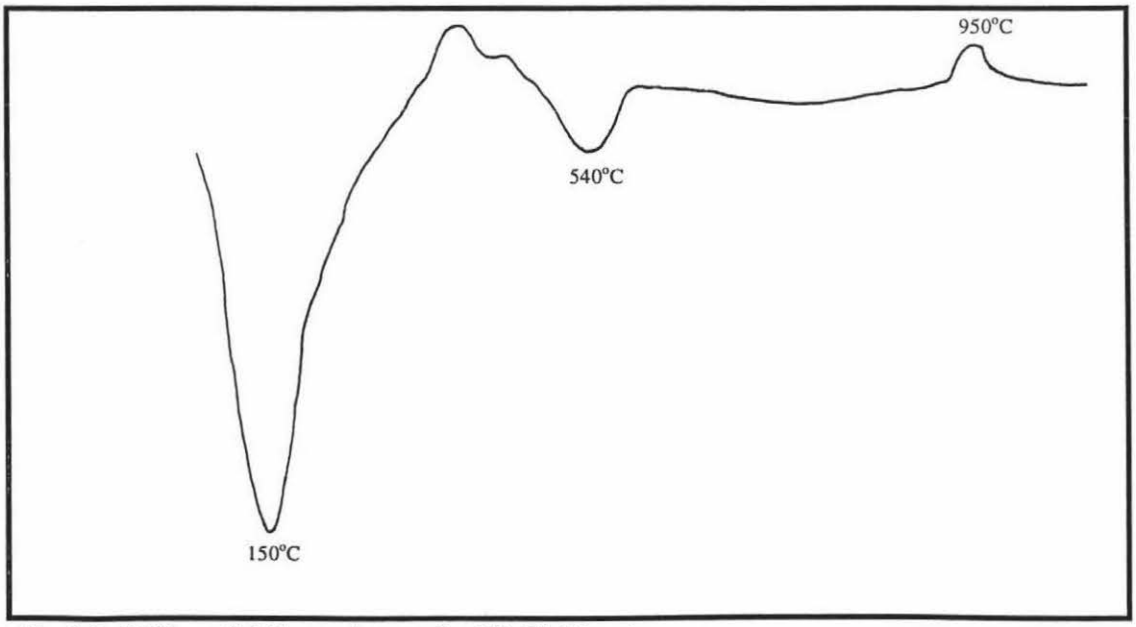


Fig. 2.8. Differential thermal curve for P2 (30-37 cm).

Kaolinite was identified mainly from the DTA results (Fig.2.8). The formamide treatment also confirmed the presence of kaolinite, since the 7Å peak does not shift to 10Å peak after such treatment (Fig. 2.9). Moreover, the electron microscope (TEM) also reveals the abundance of hexagonal kaolinite plates (Fig.2.10).

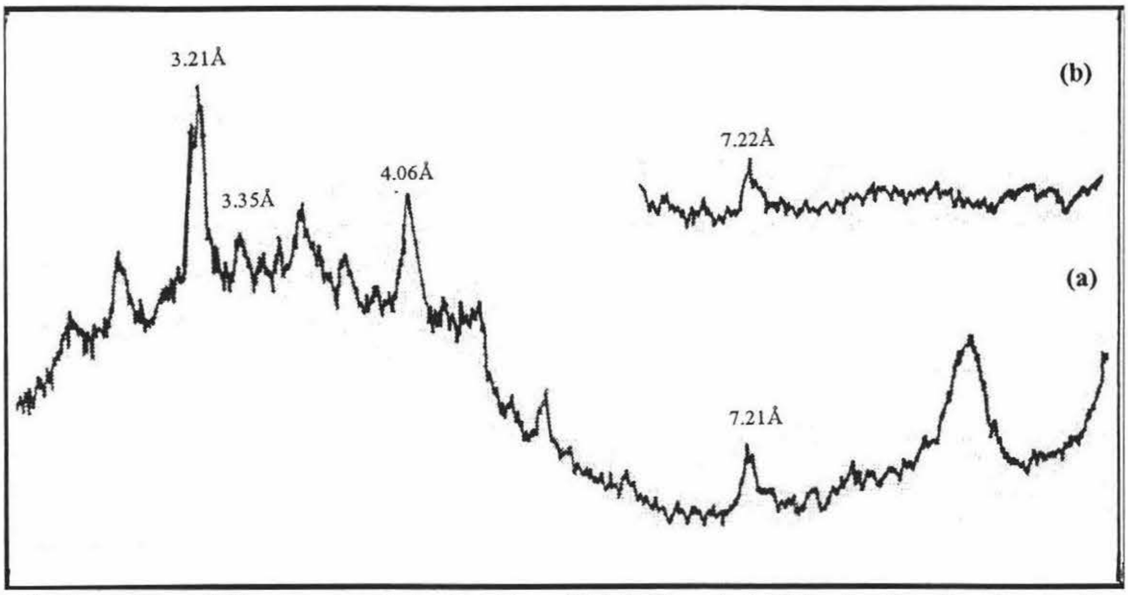
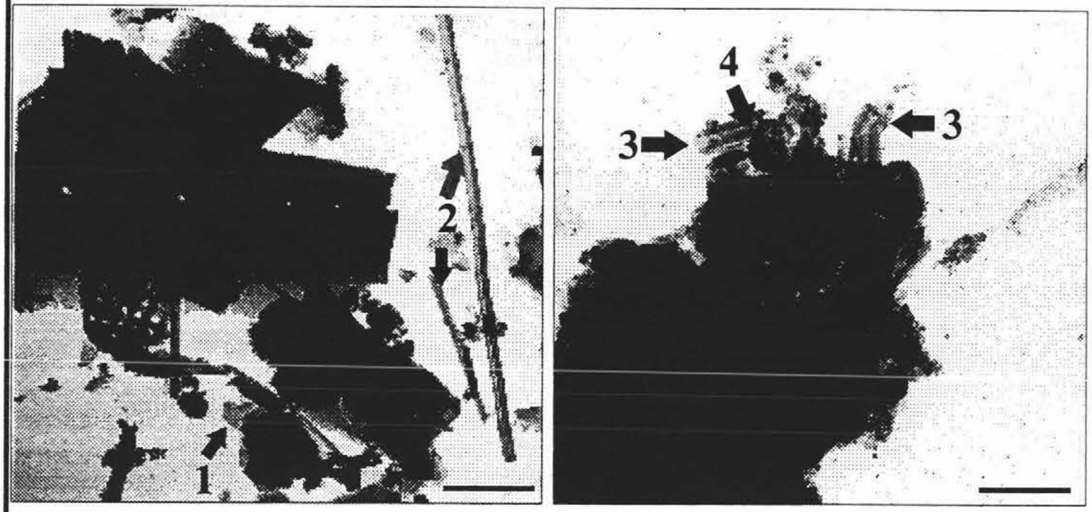


Fig. 2.9. X-ray diffractogram of clay fraction of P2 (0-21 cm): (a) Mg-air; (b) after formamide treatment.

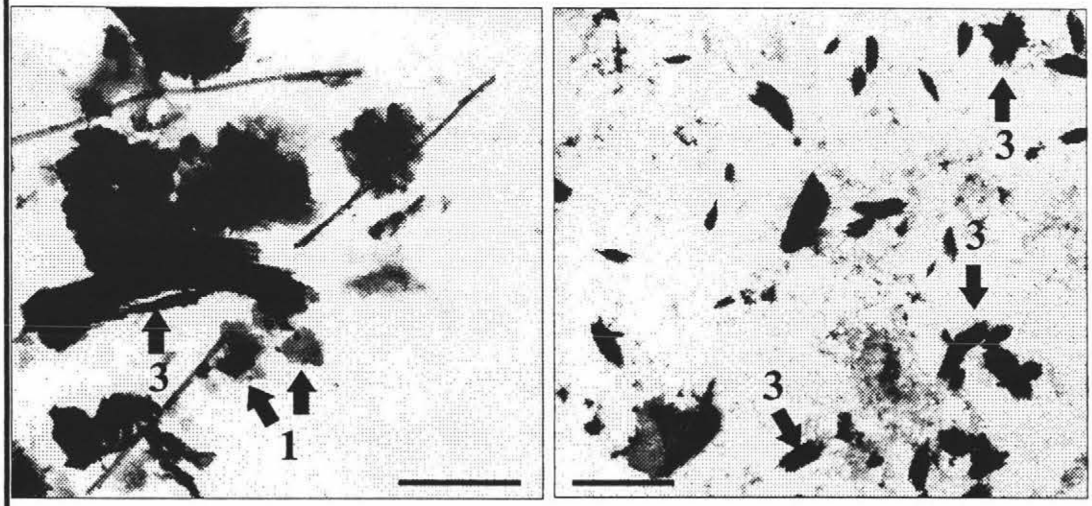
Halloysite is identified by its 10Å reflection (Fig. 2.6). It is present in trace amounts in some horizons (Table 2.6). Pedon 2 (21-34 cm) has minor amounts of halloysite (Table 2.6). The transmission electron micrographs of soil particles (Fig. 2.10) also show tubular and spheroidal crystals that are typical of halloysite in P3 (98+ cm). Their length range from 0.1 to more than 1 μm, but their widths are less than 0.1 μm. Kirkman (1981) proposed that the tubular particles formed from feldspar. The fact that no halloysite is found in the imperfectly drained P5 soil indicates that Si concentrations in the soil solution are too low for halloysite formation, in spite of the imperfect drainage condition. Moreover, the rainfall in the studied area, including P5 site, may be too high for halloysite formation.

Transmission electron micrographs of clay-size minerals in selected horizons are shown in Fig. 2.10, 2.11 and 2.12.



P2 soil (21-34 cm),
1 = kaolinite,
2 = possibly palygorskite
Scale bar = 0.5μm

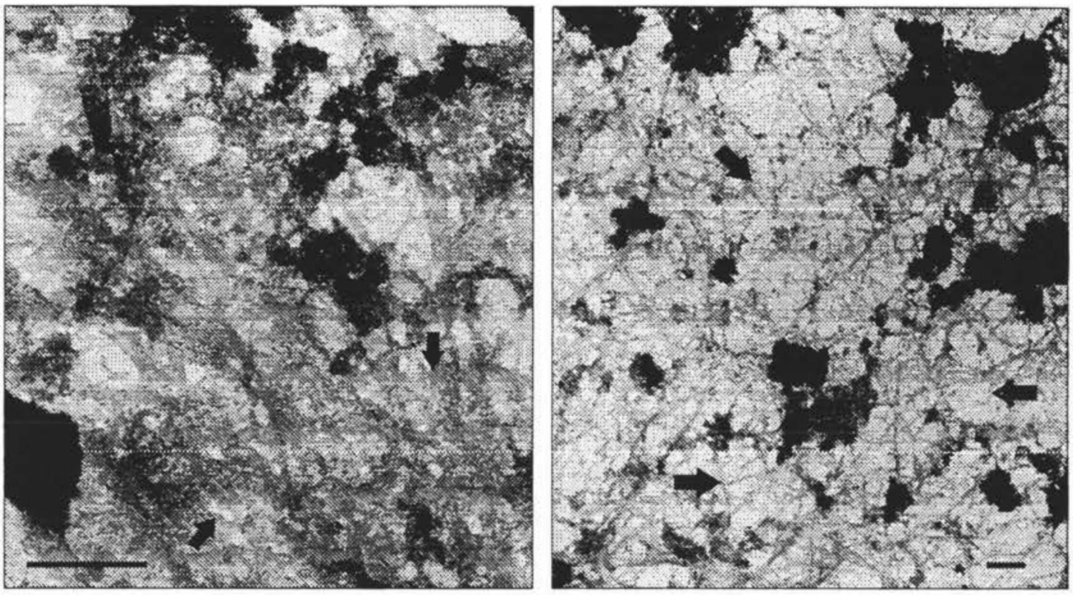
P3 soil (98+ cm),
3 = tubular halloysite,
4 = spheroidal halloysite
Scale bar = 0.1μm



P2 soil (42-50 cm),
1 = kaolinite,
3 = tubular halloysite
Scale bar = 1μm

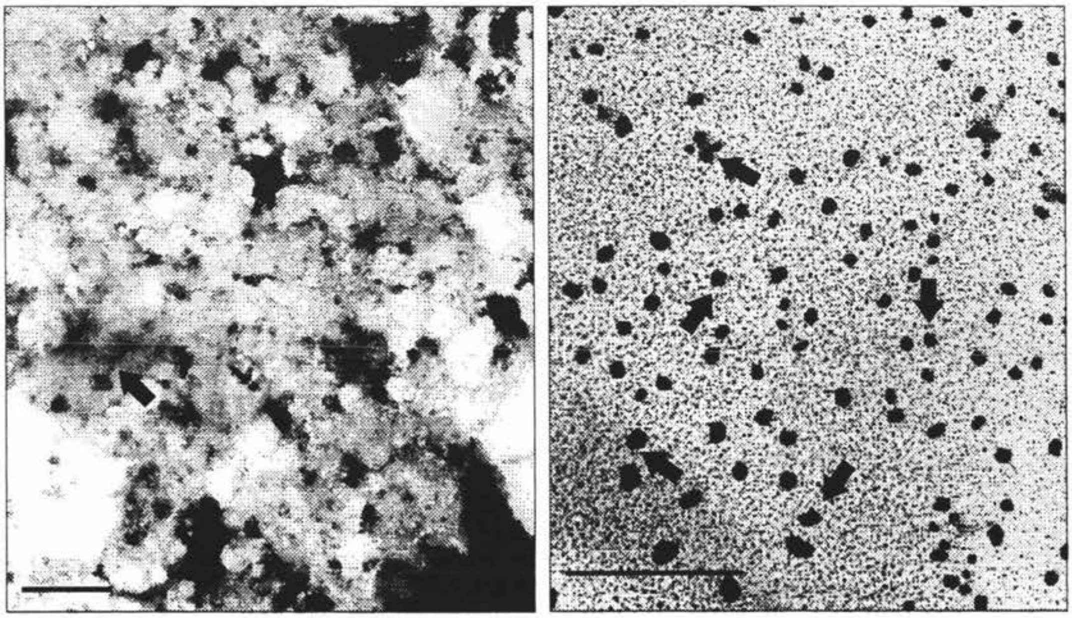
P3 soil (98+ cm),
3 = halloysite
Scale bar = 1μm

Fig. 2.10. Electron micrographs of crystalline minerals in the studied soils



Allophane
Scale bar = 0.2 µm

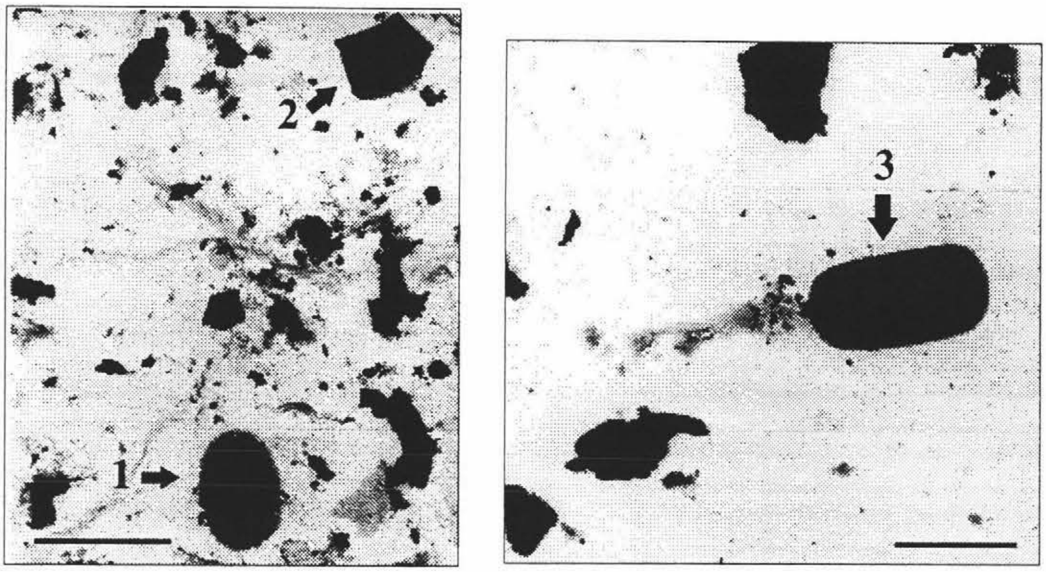
Imogolite
Scale bar = 0.2 µm



Humus
Scale bar = 1µm

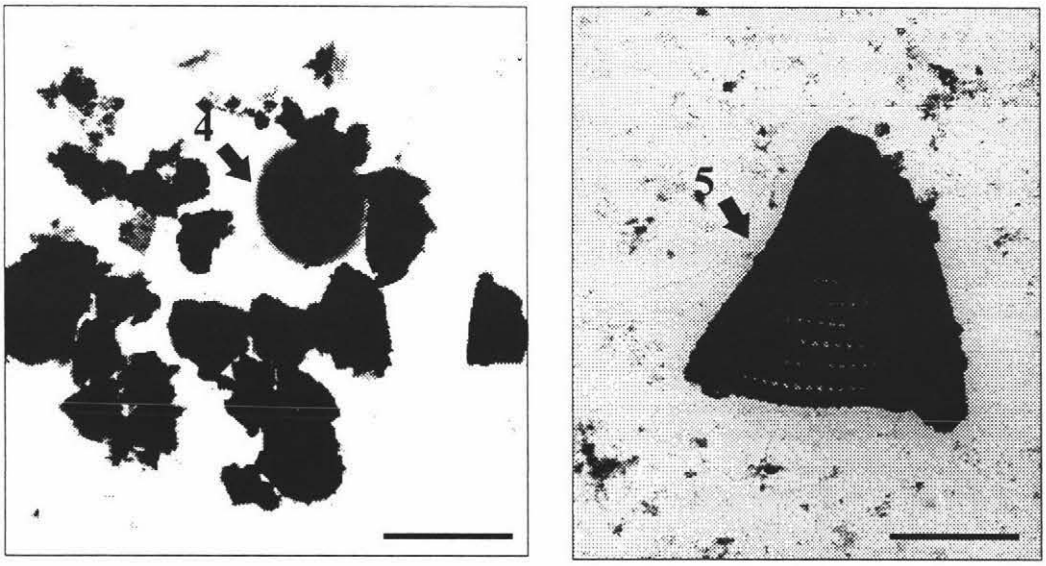
Iron Oxides
Scale bar = 0.5µm

Fig. 2.11. Electron micrographs of amorphous minerals in P3 soil (98+ cm)



P1 soil (33-40 cm)
1 = elliptical form,
2 = weathered volcanic glass
Scale bar = 1µm

P1 soil (1-10 cm)
3 = rectangular form
Scale bar = 0.1µm



P1 soil (55-85 cm)
4 = circular form
Scale bar = 1µm

P1 soil (85-105 cm)
5 = diatom
Scale bar = 1µm

Fig. 2.12. Electron micrographs of opaline silica minerals in the studied soil

The electron micrographs of P2 soil (Fig. 2.10) show long, needle-like particles which may be wind blown palygorskite originating from Australia (Kirkman, *pers. comm*). The fibre is ≈1 μm in length.

Allophane, which may be the spherule form reported by Henmi and Wada (1976), was observed under the electron microscope (Fig. 2.10).

Imogolite is less common than allophane in soils. It requires a unique environment to form in large amounts (Wada 1980). Allophane with Al:Si ratio = 2.0 has a disordered imogolite structure (Parfitt and Henmi 1980). It is not surprising, therefore, that some imogolite is also presence in the Horopito soils, as indicated by electron microscope examination (Fig.2.11). The amounts are not large, and no attempt is made to determine the percentage present.

Very short (10 nm) stubby needles and small nodules are found in trace amounts in parts of pedons 2 and 3 (Fig.2.11). These particles appear to be more electron dense than imogolite; they disappear after dithionite treatment, and are therefore thought to be iron oxides.

Opaline silica particles are few in number in these soils (Fig.2.12). These amorphous silica particles have unique shapes, such as very thin disk, rectangle and ellipse, and they include diatoms. Formation of opaline silica is promoted when the Si content in the soil solution exceeds the solubility product for amorphous silica. (Shoji and Masui 1971; Saito and Shoji 1984). Opaline silica particles are commonly found in the humus horizons and are most abundant in the young horizons.

These mineralogical data indicate that the nature of the parent material (either andesitic or rhyolitic tephra) has not influenced the type of clay formed.

2.4.3. Chemical Characteristics

Chemical properties of the five pedons are summarised in Table 2.7, and 2.8. The ratings for chemical properties were based on Blakemore *et al.* (1987).

The soil pH values measured in water range from 5.0 to 6.5 (Table 2.7). The pH values measured in KCl are slightly lower than those in water; and range from 4.5 to 6.0. The pH is lowest in surface horizons and increases in B and C horizons. It seems there is a contribution of organic acids in increasing soil acidity as reported by Shoji *et al.* (1982) and Shoji and Fujiwara (1984). Comparison of pH values measured in water and KCl (Table 2.7) indicates that negative charges exceed positive charges in all horizons.

Table 2.7. Chemical properties of the studied pedons

Horizon	Soil pH			%P-ret	%Ntot.	%Corg.	C/N	Exchangeable cations (cmol(+)kg^{-1})					Bases	CEC	BS
	H_2O	KCl	NaF					H	K	Na	Ca	Mg	(cmol(+)kg^{-1})		%
Pedon 1															
2Ab	4.9	4.4	9.7	59	0.24	3.9	16	10.10	0.12	0.25	2.40	0.18	2.95	13.1	23
2Ah	5.7	5.0	9.6	52	0.21	2.8	13	7.58	0.10	0.31	2.82	0.40	3.63	11.2	32
2C	6.1	5.3	9.3	24	0.10	1.2	12	2.50	0.03	0.18	0.95	0.13	1.29	3.8	34
3Ah	5.9	5.4	9.5	65	0.20	2.4	12	5.05	0.08	0.17	2.41	0.79	3.45	8.5	41
3Bw	6.1	5.5	9.8	77	0.16	2.0	13	3.83	0.09	0.30	2.89	1.18	4.46	8.3	54
3C	6.3	5.5	9.2	25	0.02	0.3	15	2.53	0.16	0.58	1.63	0.19	2.56	5.1	50
4Ab	6.2	5.5	9.6	77	0.14	1.8	13	5.10	0.14	0.33	2.76	1.24	4.47	9.6	47
Pedon 2															
Ap	5.8	4.5	8.9	19	0.28	3.4	12	6.25	0.17	0.27	1.36	0.24	2.04	8.3	25
C	6.4	5.2	9.0	21	0.08	1.0	13	5.00	0.15	0.15	0.52	0.08	0.9	5.9	15
2Bw2	6.5	5.4	10.1	53	0.17	2.1	12	5.05	0.57	0.45	0.96	1.32	3.3	8.4	39
2C	6.2	5.3	9.7	36	0.04	0.4	10	3.75	0.13	0.50	0.78	0.07	1.48	5.2	28
Pedon 3															
Ap	5.8	4.9	9.4	81	0.49	6.0	12	11.36	0.11	0.65	3.15	0.20	4.11	15.5	27
AB	6.3	5.8	10.1	98	0.30	4.0	13	5.15	0.05	0.20	3.59	0.11	3.95	9.1	43
Bw1	6.3	5.7	9.9	99	0.24	3.4	14	3.83	0.03	0.03	2.92	0.15	3.13	7.0	45
Bw2	6.5	5.9	9.7	97	0.13	1.6	12	3.86	0.02	0.26	3.42	0.41	4.11	8.0	51
BC	6.5	5.7	9.7	95	0.10	1.4	14	2.55	0.02	0.19	2.32	0.40	2.93	5.5	53
Pedon 4															
Ah	5.7	4.6	10.5	96	0.81	10.7	13	17.06	0.25	0.28	3.04	0.37	3.94	21.0	19
Bw1	5.6	4.9	10.6	99	0.42	7.7	18	11.93	0.10	0.25	1.00	0.06	1.41	13.3	11
Bw2	6.1	5.6	10.4	99	0.28	5.1	19	6.69	0.13	0.36	1.81	0.19	2.49	9.2	27
Bw3	6.3	5.9	10.4	99	0.15	2.6	18	2.60	0.21	0.26	2.12	0.15	2.74	5.3	52
BC	6.0	5.9	10.1	91	0.11	1.7	16	3.79	0.19	0.53	2.04	0.16	2.92	6.7	44
Pedon 5															
Ah	5.5	4.6	9.7	92	0.76	10.1	13	11.81	0.08	0.12	4.18	0.19	4.57	16.4	28
Bw(f)	6.3	5.7	10.2	98	0.41	5.4	13	2.70	0.03	0.04	1.02	0.11	1.2	3.9	31
Bw	6.4	5.7	9.9	98	0.31	4.2	13	1.34	0.04	0.07	2.17	0.21	2.49	3.8	66

Note: NaF=sodium fluoride; P-ret= P retention; N-tot.= total Nitrogen; C-org.= organic-carbon; C/N= carbon-nitrogen rasio; CEC=cation exchange capasity; BS=base saturation

The pH measured in 1N NaF solution varies from 9.0 to 10.6 and is greater than 10 in all soil horizons of P4 and in parts of P2, P3, and P5. pH values higher than 10 are indicative of the presence of high amounts of amorphous constituents and/or metal/humus complexes (Parfitt and Saigusa 1985).

The five soils have organic-carbon values which range from 1.0 to 10.7 %. The higher value is attributed, in part, to the formation of stable complexes of organic matter with aluminum and iron and amorphous soil constituents that protect it from attack by micro-organisms (Wada 1970). Humus accumulation is considered one of the major characteristics of soils derived from volcanic materials regardless of the climate and drainage conditions (Soil Survey Staff 1975; Wada and Aomine 1973). Surface horizons have higher organic carbon than subsurface horizons. Pedons 3, 4, and 5 have higher organic carbon compare with those in P1 and P2. Significantly higher organic carbon in these soils could occur as a result of production of organic matter attributable to pasture or grass vegetation. It is noticeable that organic carbon is lower in the Tufa trig 5 and Taupo pumice layers in P1, where the tephras have accumulated rapidly.

Total N varies from 0.1 to 0.8 %. It is higher in surface horizons and decreases with depth in these all soils. The changes of total nitrogen with depth are similar to those of organic carbon, suggesting that organic forms of nitrogen are predominant in P3, P4, and P5. The C/N ratios vary from 10 to 18.

Phosphate retention is high in most soil horizons but varies from 19 to 99%. The finer soils located at pedons 3, 4, and 5 have higher phosphate retention and therefore are likely to retain more phosphate fertiliser than the soils with tephra and lahar deposits at P1 and P2 . The difference is probably attributable to higher level of amorphous material and Al-humus complex in the P3-P5 soils.

The cation exchange capacity (CEC) ranges from 8.29 to 21.01 cmol(+) kg^{-1} in surface horizons, and is lower in subsurface horizons (3.79 to 13.35 cmol(+) kg^{-1}). In general, CEC decreases with depth. High CEC arises from the variable charge on the amorphous constituents. Egawa (1977) reported that the CEC of soils derived from volcanic ash in Japan was essentially associated with organic matter and allophane. In general, most soil horizons have appreciable amounts of exchangeable calcium, compared with magnesium, sodium and potassium. As expected for rhyolite, the exchangeable sodium and potassium are higher and magnesium is lower in the Taupo Pumice layers (Table 2.7).

Generally, all surface soils have low percentage of base saturation (19 to 28 %). Base saturation (BS) increases with depth within each pedon. This is related to the higher pH of these horizons.

Table 2.8. Selective dissolution analyses

Sample	acid oxalate extractable-clay			acid oxalate extractable-soil				pyrophosphate extractable		$\frac{(\mathrm{Al}o-\mathrm{Al}p)}{\mathrm{Si}o}$ molar	allophane (soil)	Al*p*/Al*o*	Fe*p*/Fe*o*
	%Al	%Si	Al/Si molar	%Al	%Si	%Fe	%Ferryh.	%Al	%Fe		(%)		
Pedon 1													
2Ab	4.1	3.2	1.3	1.0	0.4	0.4	0.7	0.2	0.2	2.2	3	0.2	0.4
2Ah	4.8	3.7	1.3	0.8	0.3	0.3	0.5	0.1	0.2	2.4	3	0.2	0.5
2C	6.3	4.8	1.4	0.5	0.2	0.2	0.4	0.0	0.1	2.6	2	0.0	0.2
3Ah	8.0	5.9	1.4	1.6	0.7	0.6	1.0	0.2	0.2	2.1	5	0.1	0.3
3Bw	11.7	7.6	1.6	2.5	1.1	0.7	1.2	0.1	0.1	2.2	8	0.1	0.1
3C	3.2	2.7	1.2	0.4	0.3	0.1	0.2	0.0	0.0	1.6	2	0.0	0.1
4Ab	10.0	7.5	1.4	2.2	1.1	0.9	1.6	0.1	0.1	1.9	8	0.1	0.1
Pedon 2													
Ap	0.6	0.2	2.7	0.2	0.0	0.2	0.3	0.0	0.1	-	0**	0.0	0.3
C	3.4	2.3	1.5	0.3	0.0	0.2	0.3	0.0	0.0	-	0**	0.0	0.2
2Bw2	6.1	4.9	1.3	1.0	0.4	0.4	0.6	0.1	0.1	2.4	4	0.1	0.2
2C	7.1	6.0	1.2	0.7	0.3	0.2	0.3	0.0	0.0	2.3	2	0.0	0.1
Pedon 3													
Ap	8.4	5.5	1.6	2.2	0.9	0.8	1.3	0.3	0.3	2.3	6	0.2	0.4
AB	n.d	7.4	≈2.0*	4.8	2.5	1.4	2.5	0.1	0.1	1.9	18	0.0	0.1
Bw1	16.5	7.8	2.2	5.6	3.4	1.6	2.7	0.1	0.0	1.7	24	0.0	0.0
Bw2	n.d	9.0	≈2.0*	5.3	3.7	1.4	2.3	0.0	0.0	1.5	22	0.0	0.0
BC	16.2	8.3	2.0	4.2	2.9	1.4	2.3	0.1	0.0	1.5	17	0.0	0.0
Pedon 4													
Ah	7.7	4.8	1.7	4.1	1.1	1.4	2.4	0.8	1.1	3.2	13	0.2	0.8
Bw1	n.d	6.9	≈2.0*	7.5	2.9	1.9	3.2	0.6	0.7	2.5	29	0.1	0.4
Bw2	n.d	7.1	≈2.0*	6.1	2.9	1.8	3.1	0.4	0.3	2.0	20	0.1	0.2
Bw3	13.9	6.5	2.2	5.4	2.9	1.8	3.1	0.2	0.0	1.8	20	0.0	0.0
BC	13.1	6.9	2.0	5.0	3.0	1.4	2.3	0.1	0.0	1.7	21	0.0	0.0
Pedon 5													
Ah	1.6	0.9	1.8	2.0	0.4	1.0	1.6	0.9	0.8	3.1	5	0.4	0.9
Bw(f)	11.8	6.4	1.9	5.5	2.1	1.6	2.8	0.4	0.5	2.6	21	0.1	0.3
Bw	11.4	6.6	1.8	5.7	2.4	1.6	2.7	0.2	0.3	2.4	24	0.0	0.2

Note: Ferryh.=Ferryhidrite; n.d=not determined
* approximated value (averaged within the profile)
** 0 due to low value of % Si*o*

Acid oxalate solution is an effective extractant for allophane, imogolite and Al/Fe humus complexes (Parfitt and Henmi 1982); the reagent generally does not attack crystalline materials, thus the values shown for samples P1 (1-33 cm), P2 (0-34), P3 (0-22 cm) and P4 (0-17 cm), which contain halloysite and/or kaolinite, are much lower than those of the other samples. The lower values of acid oxalate extracts are observed in the Table 2.8. A horizons are younger and have more humus than subsurface horizons. Pedon 1 (55-85 cm) and pedon 2 (50+ cm) also have low oxalate values. These Taupo pumice layers contain fine rhyolite, and low oxalate extractable values are often observed in such coarse Si-rich parent materials.

The (Al*o*-Al*p*)/Si*o* ratios range from 1.5 to 3.2 and generally decrease with depth. Soil allophanes with Al:Si ratios = 2.0 have been shown to have the structural properties similar to imogolite. Those with Al:Si ratios between 2 and 1 have been shown to have structural properties of both Al-rich and Si-rich allophanes. This may indicate that these allophanes are mixtures of Al-rich and Si-rich allophanes in various proportions. These mixtures could consist of distinctly different phases and/or mixtures of structures within the allophane particles.

As the Al/Si values of most soil samples are close to 2.0, their allophane contents are estimated by the formula: Si*o* x 7.1 (Parfitt and Henmi, 1982; Parfitt and Wilson, 1985; Parfitt, 1990). The calculated allophane content range from 0 to 8 % in P1 and P2; and 5 to 29 % in P3 to P5.

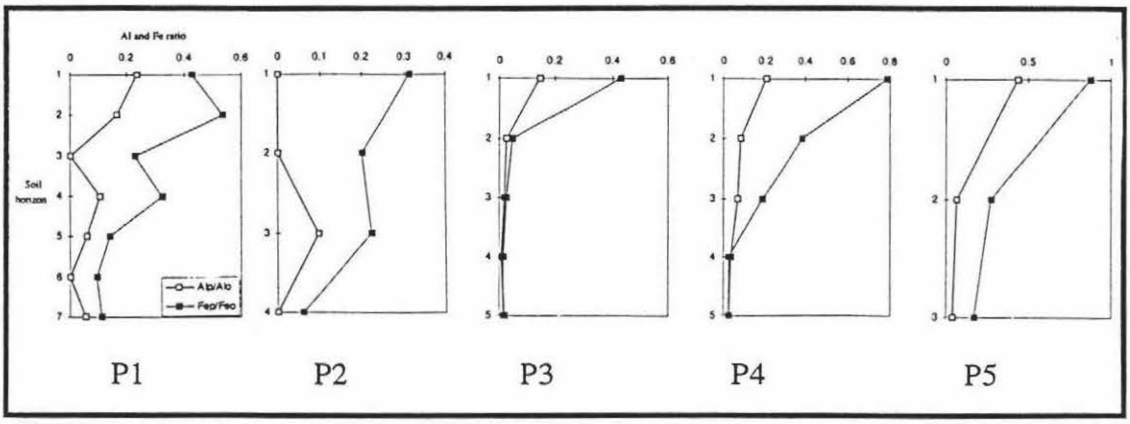
Allophane contents are lower in the A horizons than the B horizons (Table 2.8). At all sites, the Al/Si molar ratios decrease, as has often been observed in volcanic ash soils. High organic matter contents often are found to inhibit the formation of allophane because Al released by weathering is complexed by organic functional groups, thereby limiting co-precipitation of Al and Si (Wada and Higashi 1976; Wada 1989). Therefore allophane formation may be inhibited by organic materials in the A horizons.

The phosphate retention of soils derived from volcanic deposits has been associated with the presence of high amounts of amorphous constituents and abundance of active aluminum in the form of Al-humus complexes (Shoji and Fujiwara, 1984). Data on the clay fraction, and on the oxalate and pyrophosphate Al and Fe (Table 2.6 and 2.8) indicate that the three soils P3, P4 and P5 contain substantially higher allophane and metal-humus complexes, and these have higher P retention values (Table 2.7).

There is no allophane in the lahar layer in P2. The next lowest allophane content (2 %) occurs in the tephra layer which contains the 1,850 years BP Taupo Pumice. The hard rhyolitic glass probably prevents large amounts of allophane forming in this layer (Kirkman and McHardy 1980).

Pedons 4 and 5 contain rather high amounts of active Fe (Fe*o*) especially in surface horizons. Conversely, the pedons 1, 2 and 3 contain fewer amounts of Fe*o*. Non-coloured volcanic glass (rhyolitic) is poor in Fe and therefore it cannot release much Fe by weathering (Shoji, 1986). The Fe*o* values range from 0.16 to 1.39 % in the surface horizons and from 0.11 to 1.90 % in the subsurface horizons. Ferrihydrite contents are as high as 3 percent in pedon 4 (Table 2.8). Wada and Higashi (1976) theorised that the humus in A1 horizon has low complexing ability for Al and Fe, whereas older horizons contain more Al*p* and Fe*p*. This trend is clearly observed in the data presented here.

Formation of the Al-humus complex, as indicated by Al*p*, is closely related to organic carbon content (Table 2.7). The Al*p*/Al*o* ratios are in the range of 0 to 0.4 in the surface horizons and are less than 0.05 in some subsurface horizons (Table 2.8, Fig.2.13). As the soils have Al*p*/Al*o* values less than 0.4, they are classified as allophanic Andisols. Very low Al*p*/Al*o* values (less than 0.05) are interpreted as evidence that a small proportion Al is complexed by humus. On the other hand, the calculated allophane content increase with depth. These results show formation of allophane does have an inverse relation with that of the Al-humus complex, as indicated in the study of Shoji and Fujiwara (1984). Pedons 1 and 2 display irregular content of Al*p*/Al*o* and Fe*p*/Fe*o*, which indicate the stratified nature of the soil profiles, resulting from the repeated additions of volcanic materials. In all horizons, Fe*p*/Fe*o* ratios are higher than those of Al, including the pumice and lahar layers.



P1 P2 P3 P4 P5

Fig. 2.13. Metal-humus complexes in the studied soils.

2.4.4. Physical Characteristics

Bulk densities, 10 and 1500 kPa water contents and gravimetric water content, and particle size analyses (Table 2.9) are all as expected for Andisols.

Bulk densities range between 0.38 and 1.11 Mg m^{-3} (Table 2.9). Nanzyo *et al.* (1993) provide evidence that allophane is one of the most important noncrystalline materials contributing to the low bulk density of Andisols. Allophane is composed of hollow spherical structures, and small holes in the walls allow water and air molecules to pass through. In addition, allophane in Andisols have particle densities of 2.5 to 2.7 Mg m^{-3} which is similar to the particle density of other mineral soils (Maeda *et al.* 1977). This implies that Andisols have porous soil structure. The development of porous soil structure is, therefore, the primary factor responsible for the low bulk density of Andisols.

Water contents of the air-dried samples were high. These high gravimetric water contents reflect two of the physical characteristics of Andisols: (1) the low natural bulk densities and (2) the tenacity with which water is held by the allophanic particles.

The amounts of water retained at 100 and 1500 kPa vary from 6 to 141 % and from 3.78 to 121 %, respectively (Table 2.9). Pedons 4 and 5 have higher amounts of water retention compared with other pedons. Water retention differences between 100 and 1500 kPa are also high for all soil horizons, because of high water contents at the 100 kPa tension. The high water retention found in soils of volcanic origin is caused primarily by the large volume of pores within stable aggregates as a result of high organic carbon (Table 2.7) , the presence of amorphous constituents (Table 2.8), and probably the 10Å halloysite (Table 2.6).

Table 2.9. Physical properties

Horizon		PARTICLE SIZE DISTRIBUTION					BD[a]	Texture Class		% GRAV.WATER		
		%c.sand	%f.sand	%sand	%silt	%clay	Mg m^{-3}	N.Z	USDA	field[a]	100 kPa	1500 kPa
Pedon 1												
2Ab	1-10	25	46	71	22	7	1.07	ls	ls	29.6	22.4	18.0
2Ah	10-28	21	51	72	23	5	nd	lfs	ls	nd	25.0	15.5
2C	28-33	64	20	84	12	4	nd	ls	s	nd	n.d	n.d
3Ah	33-40	32	38	70	21	9	0.92	ls	sl	51.4	n.d	n.d
3Bw	40-55	22	51	73	17	10	0.92	lfs	sl	51.4	n.d	n.d
3C	55-85	10	73	83	15	2	0.73	lfs	s	66.4	n.d	n.d
4Ab	85-105	8	51	59	23	18	0.83	lfs	sl	58.5	n.d	n.d
Pedon 2												
Ap	0-21	65	21	86	13	1	1.11	ls	s	16.3	10.5	6.8
C	21-34	59	24	83	13	4	nd	ls	s	nd	6.1	3.8
2Bw	42-50	24	41	65	29	6	1.00	sl	ls	25.0	n.d	n.d
2C	50+	5	70	75	21	4	nd	ls	ls	nd	n.d	n.d
Pedon 3												
Ap	0-22	25	32	57	33	10	0.90	sl	ls	42.0	38.1	29.3
AB	22-33	19	36	55	20	25	0.54	scl	cl	77.1	69.4	61.2
Bw1	33-62	19	26	45	36	19	nd	l	cl	nd	n.d	n.d
Bw2	62-98	27	31	58	32	10	nd	sl	ls	nd	n.d	n.d
BC	98+	32	32	64	32	4	nd	sl	ls	nd	n.d	n.d
Pedon 4												
Ah	0-17	8	36	44	31	25	0.75	l	cl	60.9	40.5	61.2
Bw1	17-38	7	24	31	30	39	0.38	cl	zc	151.1	140.6	120.6
Bw2	38-60	12	21	33	26	41	nd	cl	lc	nd	n.d	n.d
Bw3	60-86	19	30	49	27	24	nd	scl	cl	nd	n.d	n.d
BC	86-100	9	36	45	24	31	nd	scl	cl	nd	n.d	n.d
Pedon 5												
Ah	0-23	11	44	55	30	15	0.69	cl	scl	89.2	70.3	51.4
Bw(f)	23-45	6	33	39	36	25	0.52	cl	cl	125.2	102.3	97.2
Bw	45-67	11	25	36	35	29	nd	cl	cl	nd	n.d	n.d

Note: nd=not determined; a) determined by Dr R. Parfitt

Texture: coarse (*c*), fine (*f*), loam (*l*), sand (*s*), loamy sand (*ls*), sandy loam (*sl*), loamy fine sand (*lfs*), clay (*cl*), silty clay (*zcl*), sandy clay loam (*scl*)

NZ = N.Z. soil classification; USDA = Soil Taxonomy

Grav.water=gravimetric water

The particle size distribution confirms that all the soils fall within the textural class of sandy loam or loam except for pedons 4 and 5 which are clay and sandy clay loam in texture. Even though particle size distribution is not a crucial analysis for classification of volcanic ash soils, its determination is useful for further discussion of soil weathering. Effecting the complete dispersion of a soil is an essential precursor of an accurate particle size analysis. After some experiments, it was found that ultrasonic probe treatment followed by adjustment of the pH of the dispersing medium to 4-4.5 using drop by drop 1:1 HCl, give the best results. Clay percentages vary from 1 to 25 % in the surface horizons and 1 to 41 % in the subsurface horizons (Table 2.9). Clay percentages in P1 also support the multilayered horizon model. The Taupo pumice contains more fine sand (70 %), whereas there is more coarse sand in the Tufa trig (60 %). This reveals that the two come from different materials. The finer sand texture also reveals that the Taupo pumice is relatively distal.

Maeda and Warkentin (1975) reported that allophane is primarily responsible for the unique physical features of Andisols. Nanzyo *et al.* (1993b) suggested soil organic matter also has a great contribution to the unique physical properties of Andisols. The physical attributes of the five pedons reported here support both conclusions.

2.5. Conclusion

Soils examined in this study are characterised by thick and dark A horizons. The structures are medium to strong crumb at P1 soil and P2 and P3 soils, and medium nut and blocky in P4 and P5 soils. Stratigraphic discontinuities occur in the P1 and P2 soils, and these are reflected in the carbon contents.

All pedons contain allophane, mostly as Al-rich allophane with Al:Si ratio ≅ 2.0. Mixtures of Al-rich and Si-rich allophanes also occur, particularly in the lower horizons. Mineralogical analysis data demonstrate the dissimilarity in parent materials among the soils. All profiles are developed on volcanic ash and contain little quartz and cristobalite. With only small differences in the relative abundances, each of the samples has the assemblage of minerals expected in soils derived from andesitic-rhyolitic parent materials, including quartz, plagioclase feldspar, hypersthene, augite, hornblende and magnetite.

Electron microscopy observation and XRD-analysis provide evidence that halloysite exists in the soils in small amounts. Dehydrated halloysite is present in pedons 2 and 3.

The soils have medium CEC values in the surface horizons and the values decrease with depth. On the other hand, the percentage of base saturation values are low in the surface horizons and increase with depth. Total carbon contents of the humus horizons are in the range of 3.4-10.7 %. Phosphate retention is very high in pedons 3, 4, and 5 soils as well as 1,500 kPa water retention. There is a relationship between chemical properties and minerals in the clay fraction. When allophane is the dominant material in the clay fraction, the chemical properties are characterised by accumulation of humus, high fluoride pH and high phosphate retention.

CHAPTER 3

WEATHERING PROCESSES OF VOLCANIC ASH SOILS

A soil is a dynamic system showing a variety of energy and mass fluxes and transformations. Various models have been proposed to describe these processes (*e.g.* Jenny 1941). The conceptual model of Jenny provides a framework to relate soil properties to state factors: time, parent material, climate, organisms, and topography, that control genesis and behaviour of ecosystems and the soils.

Tephras contain a large quantity of volcanic glass. The weathering process of tephra is called andosolisation (Duchaufor 1984), and results in formation of large amounts of noncrystalline materials. Andosolisation can form volcanic ash soils in relatively short time under most climates.

Weathering of volcanic soils is influenced by the composition of the tephra (Kirkman and McHardy 1980), climate, drainage, vegetation, and time (Parfitt, 1990b). In terms of weathering of tephra, Lowe (1986) has carried out a study in New Zealand on controls on the rates of weathering and clay mineral genesis. Considering the factors of soil formation, he formulated factors that influence clay mineral genesis as:

1. length of time of weathering,
2. composition of the tephra deposits, and
3. environments of the post-depositional weathering.

This chapter explains the weathering and genesis of the volcanic ash soils to the south of Mt Ruapehu. The explanation presented in two sections. First, the factors of soil formation are identified in the review section. Second, the processes of weathering and genesis of the soils are analysed in the results and discussion section. The explanation refers to the concepts of weathering and genesis of clay minerals in airfall tephras presented by Lowe (1986). This chapter uses data from Chapters 1 and 2.

3.1. Factors of Soil Formation

To establish a weathering sequence for the soils in this study, state factors of soil formation are explained below. Table 3.1 shows a summary of the selected soil formation factors.

Table 3.1. Factors of soil formation

Factors	Pedons				
	1	2	3	4	5
Ann.rainfall, mm	1,950	1,100	1,200	1,800	1,800
Ann.air temp., °C	8.9	10.0	10.0	10.0	10.0
Topography	ash mantled lahar surface	ash mantled lahar surface	ash mantled lahar surface	ash mantled lahar surface	ash mantled lahar surface
Height, m asl	± 1,000	± 900	± 900	± 700	± 700
Age, years BP	2,000	2,000	12,000	12,000	12,000
Vegetation/land use	alpine tussock+ shrub sp.	market garden	pasture	pasture in rotation with carrot	grass
Parent material	rhyolitic+andesitic	rhyolitic+andesitic	andesitic	andesitic	andesitic

3.1.1. Time

Time of tephra deposition is regarded as the time zero of Andisol formation. It is determined with reasonable accuracy by various procedures, such as historical records, ^{14}C dating, fission track dating, archaeological remains, *etc.* An accurate soil age is useful for understanding the relationships between time, soil genesis and soil properties of Andisols.

Andisols occurring in the vicinity of volcanoes often develop a multisequum as soil age increases since they are formed by intermittent tephra deposits. Andisols show rapid development of horizon sequences with time. The rate of development in Andisol profiles is determined by various factors, such as soil moisture and temperature, rock types and texture of tephras, *etc.* It is greater in humid warmer climates than in dry cooler climates and in mafic tephras compared to felsic tephras.

The age of the pedons is obtained from the age of the tephra in the lowest horizon. Taupo pumice at the bottom of P1 and P2 provides an age estimate of 2,000 years BP. Nt of the upper Bullot formation which has been dated as not younger than

11,250 - 10,000 years BP, gives a probable age for the P3-P5 soils of 12,000 years BP. Details of the ages of the tephras are given in the subsection of parent material (3.1.2).

3.1.2. Parent Material

Genesis of Andisols is strongly influenced by the properties of the parent material. Of the various properties of tephras, the parent material, chemical and mineralogical properties, texture, and depositional features are important.

Tephra or pyroclastic material is produced by the rapid cooling of magma during volcanic eruptions and therefore is entirely glass. Tephra can be classified adequately on the basis of its chemical composition. Shoji *et al.* (1975) proposed a classification of tephra according to total silica. It can be divided into five rock types: rhyolite (> 70 %), dacite (62-70 %), andesite (58-62 %), basaltic andesite (53.5-58 %), and basalt (45-53.5 %). Tephra is also classified on the basis of the particle size: bomb (∅ > 64 mm), lapilli (∅ = 2-64 mm), and ash (∅ < 2 mm). Pumice and scoria are used to describe tephra, on the basis of the texture or vesicularity and composition of tephra. Pumice is dominated by non-colored volcanic glass and is usually very vesicular. It is white or grey colour and has the chemical composition of rhyolite, dacite, or andesite. Scoria consists largely of colored volcanic glass and is also vesicular. It is red to black in colour and has the chemical composition of basalt or basalt andesite.

Volcanic ash is pyroclastic material aerially spread over the landscape during an eruption (Cotton 1952). The materials consist of large and fine rock particles. Most of the larger fragments fall close to the vent, whereas the finer fractions, which fall more slowly and are more widely dispersed form the parent materials soils (Beck 1950). These finer fractions are mainly ash-size particles (∅ < 4 mm). If the ash deposits are pumiceous, they may include larger particles, for example, lapilli.

Two broad types of ash beds are recognized (Taylor 1933): (1) Intermittent type; ejected on numerous occasions over a period of years. The materials are generally andesitic or basaltic. (2) Paroxysmal type; ejected on sudden explosions at long intervals. These materials are generally rhyolitic and are ejected from craters or rifts.

Glass is the most abundant component in volcanic ash. Volcanic glass is typically divided into coloured and non-coloured categories based on refractive indices of > 1.52 and < 1.52, respectively (Kobayashi, *et al.* 1976). It shows the least resistance to chemical weathering among all primary minerals (Shoji 1986). Thus, glass weathering primarily determines the genesis of volcanic ash soils. The rate of chemical weathering is much greater in Andisols derived from coloured glass-rich tephras (basaltic tephras) than from noncolored glass-rich tephras (Shoji, *et al.* 1993b). Kirkman (1980) and Kirkman and McHardy (1980) showed that weathering of andesitic and coloured glasses is very rapid compared to that of rhyolitic or noncolored glass and that the fine, soft structure and extensive substitution of Al for Si in andesitic glass favour the rapid weathering.

Intermittent tephra deposition, dispersal patterns and depth, size and mineralogy of tephras substantially determine the distribution, genesis, and properties of soils derived from tephra (Wada and Aomine 1973; Shoji and Saigusa 1977; Saigusa *et al.* 1978; Lowe 1986).

In addition to primary minerals (volcanic glass) formed by solidification of the magma, accessory minerals and minerals from aeolian dusts contribute significantly to the mineralogical and chemical properties of Andisols. The genesis of 2:1 and 2:1:1 type clay material in tephra is controversial. There are three different theories concerning their genesis:

(1) In situ pedogenic origin (*e.g.* Shoji *et al.* 1982). Here the 2:1 clays derive from volcanic glass in a solid-state reaction. The 2:1 clays may form with opaline silica or quartz under conditions characterised by excess silica, low allophane, and low pH (*e.g.*, Shoji, *et al.* 1981);

(2) Transformation of ferromagnesian minerals (principally micas, amphiboles, and pyroxenes) which are derived from either the primary tephra deposit (*e.g.* Mizota 1976) or post-depositional contamination by aeolian accessions (*e.g.* Mizota 1982).

New Zealand workers prefer the contamination explanation for the 2:1 clay minerals occurrence. The 2:1 minerals from non-tephra sources occur in the clay fraction of some Andisols and contribute to the development and properties of non-allophanic Andisols. For instance, in New Zealand, 2:1 minerals are reported in only trace amounts in "pure" tephras but they are relatively common in soils formed on loess derived from sedimentary rocks and alluvium that contain admixed tephras (Lowe 1986);

(3) Hydrothermally altered rock fragments which are ejected during eruptions. Hydrothermal alteration in volcanic rocks transforms primary minerals such as olivine, pyroxenes, and plagioclase into clay pseudomorphs (*e.g.* Fan 1979).

In order to understand properties and behaviour of the parent material, it is necessary to understand the tephrostratigraphy of the soils. Details of stratigraphy of the five pedons are given in Fig. 3.1.

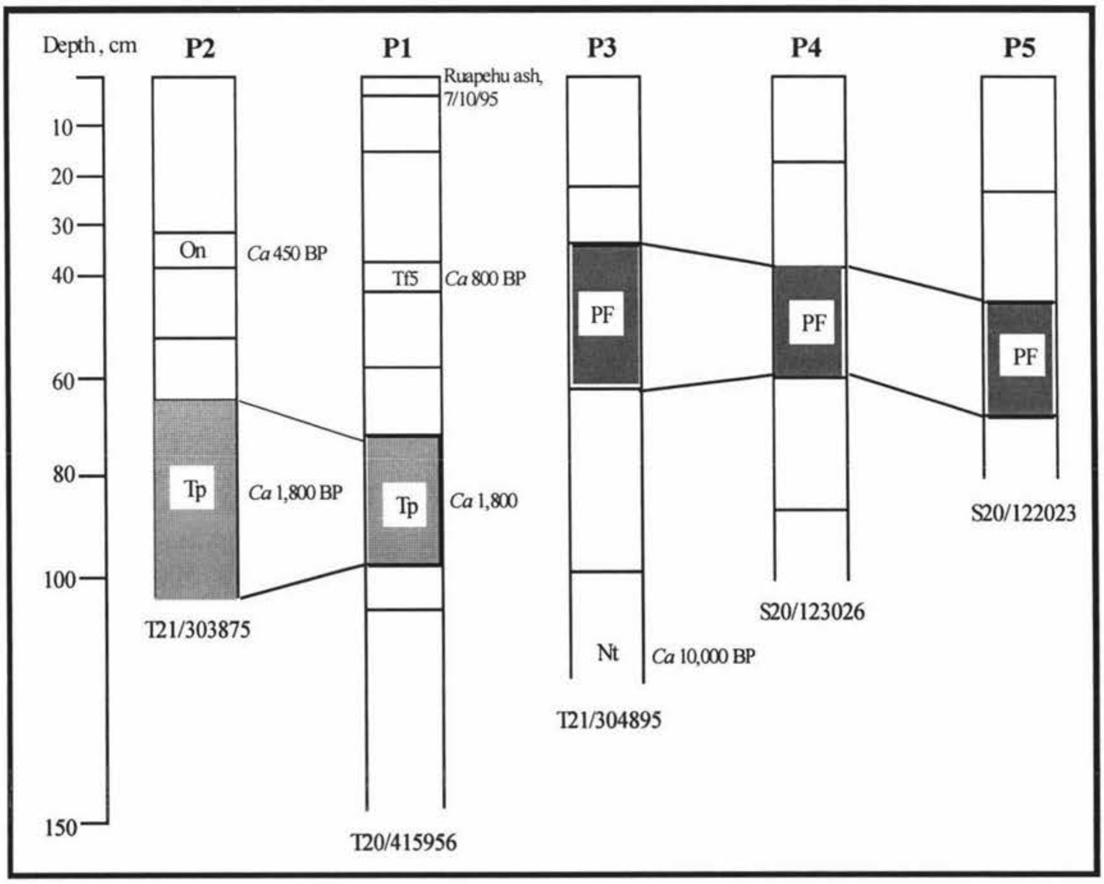


Fig. 3.1. Stratigraphy of the pedons

Stratigraphic units

Tongariro Volcanic Centre (TgVC) is the most southern of the main tephra-producing volcanic centres of the central North Island. To the North are Taupo Volcanic Centre (TVC), Maroa Volcanic Centre (MVC) and Okataina Volcanic Centre (OVC), from which tephras of rhyolitic composition were dispersed southwards to TgVC.

Rhyolitic tephras are recognised in P1 and P2. They are found interbedded with andesitic tephras erupted principally from Mt Rupehu, Mt Tongariro and Mt Ngauruhoe. All rhyolitic tephras have been recognised by their distinct glassy composition (Table 2.3, 2.4, and 2.6) and their white to pale brown colour (Table 2.2), which contrast strongly with the yellowish brown colours of enclosing andesitic tephras. The rhyolitic tephras are preserved as thick discontinuous well sorted fine ash layers. The fine grain size is indicative of a distal source.

Taupo Subgroup

Stratigraphy of the Taupo Subgroup comprises tephras of Holocene age (10,000 years BP to present) erupted from TVC. The youngest member is Taupo pumice formation and the oldest is Karapiti tephra (Howorth, *et al.* 1981). All TVC tephras are hypersthene dominant with minor amounts of augite (< 20 %) (Froggatt 1981b), hornblende and biotite (Froggatt 1981a, 1982).

Taupo Pumice (Tp) Formation

Taupo pumice formation comprises tephras and pyroclastic flow deposits erupted from TVC (Froggatt 1981b). It is dated at 1,819 ± 17 years BP (Healy 1964) and at 1,820 ± 80 years BP (Froggatt 1981b). Froggatt describes four members within the formation: Taupo Ignimbrite, Taupo lapilli, Rotongaio ash, and Hatepe tephra.

In this study, Tp is clearly identified in the exposure at the P1 soil (Desert Road section) and at P2 soil (Tangiwai). Weathered Tp lapilli is found in P3.

Tufa Trig (Tf) Formation

Tufa trig formation is characterised by multiple black to dark grey, coarse ash to lapilli grade tephras. In the exposure along the south-eastern Desert Road, Tufa trig formation tephras are interbedded with Ngauruhoe formation (Donoghue 1991). Tufa trig formation overlies the rhyolitic Taupo Ignimbrite and its distribution is identified to the south-east of Mt Ruapehu, in the southern Mt Tongariro region, and westernmost at a section near the top of Ohakune Mountain Road.

Member Tf5 is the most prominent member of Tufa trig formation (Donoghue 1991). It is readily distinguished from all other members by its consistently greater thickness, coarser grain size, lateral continuity. Member Tf5 is the most widespread member of Tufa trig formation, and is identified in exposures within Karioi State Forest, Rangipo Desert, sections along the Whangaehu escarpment, and on the Desert Road. A maximum age of *c.* 830 ±60 years BP is suggested from peat sampled immediately below member Tf5 (Donoghue 1991). Member Tf5 indicates a Mt Ruapehu source.

In the Desert Road section (P1), member Tf5 is 50 mm thick and shows reverse grading.

Papakai Formation (PF)

Papakai formation is a redefinition of Papakai tephra formation originally defined by Topping (1973, 1974). Papakai formation comprises andesitic tephras erupted from TgVC and possibly tephric loess between *c.* 9,700 and 2,500 years BP (Donoghue 1991).

The upper PF shows paleosol development, indicate by its strong yellowish brown colour, greasy sandy loam textured ash grading down to sandy clay loam textured ash with some surface cracking, and the presence of numerous dark coated root channels. The lower PF comprises dark yellowish brown and dark brown very greasy sandy clay loam textured ash with prominent surface cracking, medium nut structure and dark coated root channels denoting paleosol development. Many bluish greys fine lithic lapilli are interspersed within the base of the formation. These lapilli are poorly vesicular with field characteristics typical of Mangamate tephra and are probably derived by reworking from Poutu lapilli. The stronger colour and greater degree of paleosol development seen in the lower 0.70 meter is characteristic of PF in most Desert Road exposures. In the section along SH 49, PF is distinctly sandier in texture than to the north, occurring commonly as yellowish brown massive sandy loam textured ash, without distinctive surface cracking (Donoghue 1991).

Papakai formation is recognised in the paleosol (in P1) and in the middle part of P3 with its dark yellowish brown colour and greasy sandy loam texture (Table 2.2).

Paleosol

A paleosol is a buried soil which has formed on a past landscape, under conditions that are no longer present at the location at which it occurs. The boundary between materials and stratigraphically aligned soil can be identified using physical and mineralogical properties (Ollier 1969).

The paleosol (in P1) resembles the modern soil in morphology and structure. It also has more clay content and levels of aluminium and iron oxalate-extractable similar to the modern soil, but contains much less organic matter. Organic matter may have been reduced by biological activity following burial, or by fires started during subsequent eruptions. As reported by Healy, *et al.* (1964) the Taupo pumice which overlies the paleosol is a paroxysmal type.

Tukino Subgroup Tephras

Bullot Formation (Bt)

Bullot formation is a new formation name for a sequence of airfall tephras erupted from Mt Ruapehu, dating between *ca.* 22,500 and 10,000 years BP and belonging to Tukino Subgroup.

Upper Bt members are: Ngamatea (Nt) lapilli -2 and -1. Nt-2 comprises brownish yellow and yellow ungraded, fine pumice lapilli, with less grey lithic lapilli. Nt-1 comprises loose, strong brown and light yellowish brown pumice lapilli and shows slight reverse grading. Contacts among them are gradational.

Donoghue (1991) found that Nt-1 and -2 are identified in sections throughout the southern part of her study area, where they were found overlying older Bt tephras. The southernmost occurrence of these lapilli recognised in her study is at Ngamatea swamp. Nt -1 and -2 have been dated between 11,250 - 10,000 years BP.

This study recognised this tephra occurred along SH 49, SH 49A and followed up SH 4 to Horopito. The upper contact of Bt in P3 is with the base of PF.

Onetapu Formation (On)

Onetapu formation is a lahar deposit. It is a new formation name for diamictons comprising dark grey sands and silts with andesitic pebbles, cobbles and boulders, and fine grained bedded pebbly sands, sourced from Mt Ruapehu (Donoghue 1991). Onetapu formation comprises dominantly grey, poorly- to weakly-bedded sands with low concentrations of fine pebbles. This formation is 130 mm thick at one meter depth of P2.

Member Ond is the most prominent member of On, and comprises a grey coarse sand and granule matrix with andesitic pebbles, and a few cobbles and boulders. Black scoria pebbles are the dominant lithology. Clasts show slight reverse grading. Reworked rhyolitic Tp is found beneath the deposit. The member is dated *ca.* 450 ± 55 years BP (Donoghue 1991) based on wood found within the base of Ond at an exposure on the south side of the channel and 7 m from the junction with Whangaehu Road. Campbell (1973) dated member Ond at 407 ± 70 years BP based on radiocarbon dating on wood within the underlying paleosol. Member Ond, dated at *ca.* 450 years BP represents a major event which could be a correlative of lahar deposit D9, recognised by Purves (1990) in the Rangipo Desert, and with member Onj of Hodgson (1993) within the Rangipo Desert and downstream of Tangiwai.

Deposits of Onetapu formation age, not sources from Whangaehu River, have also been mapped in the northern Karioi Forest at Whahianoa River and tributary rivers immediately to the west (Donoghue 1991).

3.1.3. Climate

Climate has many different components such as temperature, precipitation, evaporation, evapotranspiration, humidity, duration, *etc.* Its effect on soil formation is generally the integration of all these components. Temperature and precipitation, however, have a controlling influence on the formation and properties of Andisols (*e.g.*, Parfitt 1990b).

3.1.3.1. Temperature

The rate of chemical weathering in tephras increases markedly with increasing temperature in Andisols in the udic moisture regime. Shoji, *et al.* (1993a) showed in their experiments that temperature exerts a marked influence on the release of chemical elements from tephras. The release of chemical elements shows a zero-order reaction. Weathering processes of non-coloured glass parent material at 10°C are rapid enough to provide andic properties ($Al_o + 1/2\ Fe_o \geq 2.0\ \%$) within 1,280 years.

3.1.3.2. Precipitation and Soil Moisture

The rate of chemical weathering in the soil decreases with decreasing soil moisture and leaching. Soil Survey Staff (1990, 1992) recognise the significance of soil moisture in Andisols formation by defining their suborders: Torrands, Ustands, Xerands and Udands.

Parfitt (1990b) showed the effect of mean annual precipitation and leaching intensity on a weathering sequence in similar age tephras in New Zealand could give rise to several soils, *e.g*: Andic Dystric Eutrochrept, Typic Hapludand, Acric Hapludand association in New Zealand. Inceptisols occur in rhyolitic tephras where the annual precipitation is less than 1,200 mm, while Andisols are found in similar tephras in regions receiving higher precipitation. The low rainfall leads to the preferential formation of halloysite under the relatively weak leaching conditions that contribute to high Si concentrations in soil solution. On the other hand, leaching of Si and bases becomes more intense with increasing precipitation, leading to the formation of allophane when soluble Si concentrations are lower.

Table 3.1 shows precipitation in the studied pedons. Monthly figures are generally 73 mm to 180 mm with a peak of 102-200 in July (Table 1.1). The rainfall leaching through the soils is estimated using the Penman evapotranspiration model. Evapotranspiration (Et) for Taupo is estimated to be 840 mm per annum (D Scotter, *pers. comm*). Assuming no runoff occurred on the soils (soil consistency: friable, Table 2.2), the estimated leaching for P1 is 1,110 mm, for P2 and P3 is 260-270 mm and for other pedons are 960 mm. At an average altitude of 700-1,000 m the area is subjected to occasional snow storms in the winter.

Considering the precipitation criteria, all pedons have a udic moisture regime (Soil Survey Staff, 1992). The mean annual soil temperature is lower than 8°C, hence the soil temperature regime was isofrigid. Thus, there are no significant differences in the climate soil forming factor.

3.1.4. Organisms

Vegetation rapidly recovers on tephra deposits because physical properties are favourable for plant growth, which in turn facilitates soil development. Tephras are commonly fine-grained, vesicular and unconsolidated, and contribute to a high plant available water holding capacity and high surface area which in turn lead to rapid release of nutrient by weathering.

Leamy, *et al.* (1980) found that Andisols of the North Island, New Zealand rarely display a thick, dark-coloured humus horizon greater than 20 cm, and rarely contain organic carbon contents of 8 to 12 percent, compared with Andisols in Tohoku, Japan, which is situated in the same latitude and almost the same mean annual temperature and mean annual precipitation. They suggested that the predominant difference between Andisols in these locations appears to be due to differences in the paleovegetation.

Opal phytolith analysis of Andisols has been successfully used to interpret the relationships between paleovegetation and formation of Andisols in Japan (Kondo, *et al.* 1988). Sase (1986) conducted opal phytolith analysis of selected Andisols from the North Island of New Zealand including Tirau silt loam, Taupo sand, Egmont black loam, and Patua loam. The analyses show that the Patua soil was derived mainly from ferns, while the other soils originated primarily from broad leaf trees. The present vegetation on all these soils is improved pasture grasses.

Analyses of plant opal in this study suggest the phytoliths are from graminaceous plants and they originate from bulliform cells. The phytoliths found here are derived from grass species.

The present vegetation of the five pedons is shown in Table 3.1. In general, abundant roots are found in the A horizons. Root decomposition releases organic acids, which then react with Al to form Al-humus complexes. Ugolini and Dahlgren (1991) suggested a reaction of carbonic acid weathering occurs in lower horizons of soils. It is favoured by a high pCO_2 and pH more than 5.0 which allows dissociation of H_2CO_3. Therefore, H_2CO_3 may dominate in the lower horizons, and organic acids may dominate in the upper horizons.

3.1.5. Topography

Topography has a number of effects on soil-forming processes in Andisols through its relationship to tephra deposition, erosion, and redistribution of materials according to slope. Tephra deposition is commonly repeated due to the intermittent occurrence of volcanic eruptions resulting in tephra deposits that are significantly variable with respect to age and features of the landscapes.

Under humid climates, hydrosequences of Andisols may develop from the same parent tephras according to differences in natural drainage that reflect variations in topography. Even young Andisols show notable differences in their properties between the well-drained and poorly-drained members (Saigusa *et al.* 1991).

Intermittent thin ash deposits and marked accumulations of humus in poorly drained sites favour the formation of melanic Andisols.

All pedons in this study are located on ash mantled lahar surface. Therefore, there were no significant differences in the soil topography factor.

3.2. Results and Discussion

3.2.1. Controls and Process of Weathering

Age control

With increasing age, the amount of clay particles in tephras increases as volcanic glass components are broken down and transformed to clay minerals (Table 2.9). Lowe (1986) suggests a relationship between tephras age and clay content of some New Zealand tephras (Table 1, p. 269).

Allophane is the predominant clay mineral in all the soil profiles. Allophane as a major product of weathering increases with depth and soil age. The formation of allophane (and imogolite) by the andosolisation process resulted from in situ weathering in the weathering environment with pH values more than 6 of the B horizons rather than by translocation from overlying horizons.

Minor amounts and relatively poorly ordered halloysite occurs in the young lahar layer in P2 and indicates that the lahar materials may have weathered directly and rapidly to halloysite instead of allophane.

Compositional control

Proportions and compositions of chemical and structural characteristics of the parent materials determine in part the composition, type, and morphology of resultant clays. The high allophane content with Al:Si ratio ≈ 2.0 throughout the pedons 3, 4, and 5 is consistent with the appreciable andesitic character. On the other hand, allophane with Al: Si ratio less than 2.0 in pedons 1 and 2 conforms with the features of rhyolitic tephra. The rhyolitic tephra in the studied soils ensures a constant supply of silica which favours the formation of cristobalite.

Environmental Control

Environmental factors that affect the site weathering conditions include temperature, rainfall, degree of leaching, drainage, tephra thickness and depth of burial, and organic cycle factors (Lowe 1986). Kirkman (1980b) suggested that environmental controls must be more dominant than time or composition in the weathering process, except where an unambiguous parent material effect can be demonstrated.

The mean annual precipitation is a factor that contributes to the formation of allophane and/or imogolite. Also, the high temperature in surface horizons may favour the formation of kaolinite (Parfitt, *pers. comm*).

The marked differences in site environmental conditions in this study are principally a function of micro-climate (temperature and rainfall) and tephra thickness which control the degree of leaching and the availability of alumina. Other components of the model of Lowe, *i.e.*, degree of drainage and wetting and drying effects may have minor influence on the weathering process.

3.2.2. Products of Weathering

Weathering of volcanic parent material under well-drained conditions and high rainfall generally leads to the formation of secondary minerals including formation of short-range order materials such as allophane and Al-humus complexes (*e.g.* Wada 1989). Secondary minerals present especially in upper horizons reflect the weathering regime.

Metal-humus complexes

Within the profiles, Al*o* and Si*o* are highest in the B horizons, while Al*p* and Fe*p* are highest in the A horizons. Fe*o* values tend to increase with depth. Al- and Fe-humus complexes are the dominant form of active Al- and Fe- in humus horizons (Fig. 2.13). Contents of Al*o*, Si*o*, Al*p*, and Fe*p* gradually increase with soil age (Table 2.8), indicating increasing amounts of Al- and Fe-humus complexes and short-range order material. Fe*p* may be ferrihydrite-humus complex.

As a result of weathering, both Al and Si are released from primary minerals. In the A horizons, the Al reacts with organic matter leaving relatively high soluble Si levels. Part of this Si may be absorbed by plants and converted to phytoliths or may appear as diffuse opal flocks (Drees, *et al.* 1989).

Opaline silica

Formation of opaline silica is favoured by rapid weathering of glass-rich parent material, a pronounced seasonal period of desiccation or freezing to concentrate solutes, and low Al activities (Shoji and Masui 1971; Ping *et al.* 1988).

Opaline silica occurs in all pedons, except in the rhyolitic ash layers (Table 2.3). The soil solution of A horizons may be more concentrated, because of evaporation, than that of the lower horizons. It is assumed, therefore, that the formation of opaline silica is facilitated in the A horizons, as suggested by Shoji and Masui (1971).

Identification of opaline silica was achieved using the polarising microscope. There are no quantitative analyses of the amount of opaline silica. The climatic data (Table 1.1) indicate the degree of leaching of silica and bases must be in the order of P1 > P4 = P5 > P2 = P3. Opaline silica, therefore, can be expected to increase in P2 and P3.

Opaline silica is present in the buried soil in P1. Since the evaporation of soil water is considered to be essential for the supersaturation of silica and for the concentration of bases in soil solution, the conditions for the formation of opaline silica are less favourable in the buried soil.

Formation of Al-humus complexes (Table 2.8, Fig. 2.13) effectively ties up Al released by weathering. Hence, the presence of opaline silica may indicate low Al activities.

Halloysite

Halloysite with a 10Å reflection is classified as hydrated with two interlayer water molecules per formula unit. Broad peaks of halloysite (Fig. 2.6) could indicate relatively poor crystallinity (Lowe and Nelson, 1983). Halloysites are rare in comparison with kaolinites (Table 2.6). Different morphological forms of halloysite (Fig. 2.10) may relate directly to primary mineralogy; spherical halloysite possibly originating from glass (*e.g.*, Dixon and McKee 1974), and tubular halloysite from feldspar (*e.g.* Kirkman 1981b; Lowe 1986).

Halloysite in this study may have formed at specific microsites in the profiles which are rich in silica. Seasonal desiccation may further contribute to the formation of halloysite by enhancing crystallisation in aluminosilicate gels during the period of dehydration.

Kaolinite

Kaolinite dominates the kandite minerals towards the surfaces of P1-P4. Anand and Gilkes (1984) and Anand, *et al.* (1985) presented evidence suggesting that kaolinite formed directly from feldspars. Others say halloysite weathers to kaolinite (*e.g.*, Churchman and Gilkes 1989), but it could be also influenced by higher temperature in the surface horizons which enhances the weathering process (Parfitt, *pers. comm*).

Ferrihydrite

The ferrihydrite values increase with soil age (Table 2.8). As mentioned earlier, P3-P5 are developed from andesitic materials and contain more ferromagnesian minerals than do P1 and P2. In addition, P3-P5 have more organic matter than P1 and P2 which hinder the crystallisation process. This may explain the occurrence of higher amounts of ferrihydrite in the older soils (P3-P5).

HIV

Layer silicate of the 2:1 type mineral, including chlorite and hydroxy interlayered vermiculite (HIV) are present in the soils derived from volcanic ash. Chlorite is not present in any tephra layers. The chlorites are, therefore, probably not of local origin and must be transported. They are not likely pedogenically derived from weathering of volcanic ash as indicated by Pawluk and Brewer (1975).

On the other hand, HIV occurs at all pedons and at all depths, and may reflect zones of mixing of volcanic ash with crystalline clay minerals. Volcanic glass provides Al^{3+} ions required for the formation of hydroxy interlayers (King 1986). Seasonal soil moisture deficit during the late summer (Table 1.1) would probably promote the retention of concentrated soil solutions in the finer pores. It is also possible that the process of interlayering would be regulated by the formation of Al-humus complexes as suggested by Pawluk and Brewer (1975).

Allophane and imogolite

Allophane is the most important clay component in the soil horizons (Table 2.6), especially in the lower horizons of pedons 3, 4 and 5. Pedon 2 does not contain allophane in the top two horizons. Soil solution analyses (Table 2.8) indicate that allophane and imogolite are formed in situ.

The A horizons have pH values of less than 6, high concentration of Al-humus complexes, and relatively little allophane and imogolite (Table 2.7 and 2.8). In contrast, the B horizons have pH values of more than 6, very low concentration of Al-humus complexes (Fig. 2.13) and higher contents of allophane and imogolite (Fig. 3.2). Because of incorporation of Al into Al-humus complexes in the A horizons, virtually no soluble Al is transported from A to B horizons. As a result, the Al released by weathering is available to combine with Si to form allophane and imogolite in the B horizons. This explains that allophane and imogolite are formed in situ, as indicated by Ugolini and Dahlgren (1991).

Allophane and imogolite may form directly and rapidly from volcanic glass and feldspar. They are possibly reaction end-points rather than short-lived transition products as suggested by Lowe (1986) and can persist for long periods of time. Allophane content is highest in P3 and P4 where the ash is andesitic and finer textured. These pedons are also older than the others and experience higher rainfall (Table 3.1). In terms of the weathering of tephra, Kirkman and McHardy (1980) describe the differences in weathering processes of rhyolitic and andesitic tephra of central North Island and Taranaki areas, New Zealand. The rapid rate of weathering of andesitic glass is due to its occurrence as fine, soft microlites, the extensive substitution of Al for Si in its structure and the high level of Ca. Weathering to allophane is accompanied by a rapid loss of Ca and by a marked loss of SiO_2. Rhyolitic glass weathers more slowly than andesitic glass because it tends to occur as larger particles which are hard and brittle, and which contain more SiO_2 than andesitic glass. The silica tetrahedra are linked through oxygen ions, and not easily disrupted by weathering processes.

Imogolite may be formed by transformation from allophane through desilication or by precipitation from weathering solution (Wada, 1989).

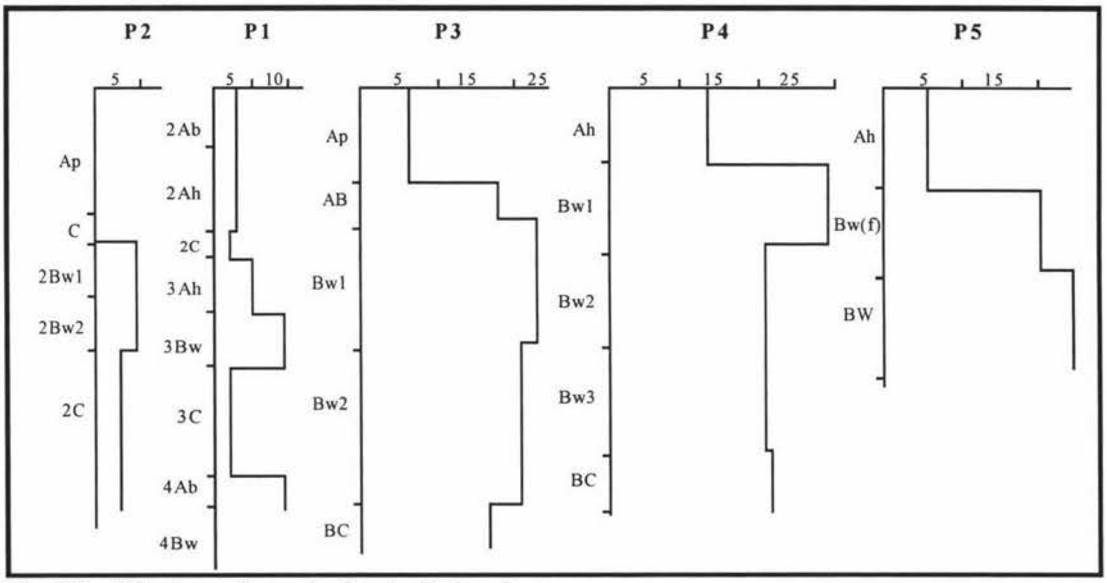


Fig. 3.2. Allophane figure in the studied pedons

Soil Profile Morphology

The ages of different soils range from 2,000 years in the youngest to 12,000 years in the oldest soils (P3, 4 and 5). With increasing age, the soils show increasing profile development (Fig. 3.3) as demonstrated by:

(1) a change in color from pale color in the parent material (P1 and P2) or orange in P3 to dark yellowish brown B horizons (Table 2.2),

(2) increasing thickness of the B horizon from 20 cm in the two younger soils to more than 50 cm in the three older soils (P3-P5), and

(3) increased weathering to greater depth with increasing soil age, resulting in decreasing sand contents and increasing contents of fine material (from P1 and P2 to P3-P5) over a greater depth with soil age as can be seen in Fig. 3.3.

(4) the A horizons tend to increase in thickness and in organic matter content (Table 2.7).

(5) the wet soil (P5) display iron and mangan concretions at a depth of about 25 cm.

The differences of development in the soil profiles are also determined by type and texture of tephra. Taupo pumice (Tp) is a rhyolitic tephra, which is produced in a paroxymal type of eruption. Ngamatea lapilli (Nt), an andesitic tephra, is produced in an intermittent type of eruption, which is ejected occasionally over time. Taupo pumice in P1 and P2 is younger and coarser than andesitic tephra in pedons 3, 4 and 5. Therefore, pedons 3, 4 and 5 show more advance in profile development.

Clay contents patterns (Fig. 3.3) agree with allophane figures (Fig. 3.2), and this support the suggestion that P3-P5 are more weathered than P1 and P2.

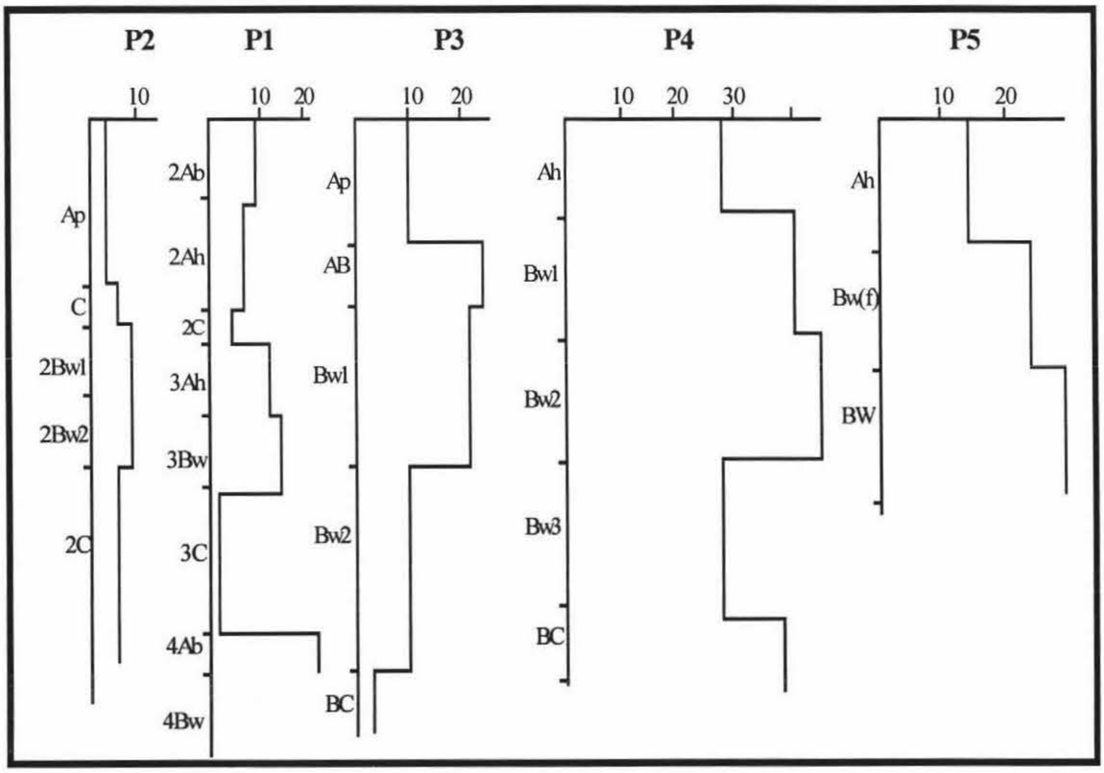


Fig. 3.3. Clay content in different pedons

3.3. Conclusion

Pedons 3, 4 and 5 are more weathered than pedons 1 and 2. This study reveals that the weathering process reflects site-specific environmental conditions. Compositional factors and the age of tephras may provide conditions for the control and concentration of Al in soil solution and its distribution throughout the profile.

Weathering products which occur in soils 2,000-12,000 years BP are clay-size particles and include short-range-order minerals, such as allophane, imogolite, ferrihydrite, metal humus complexes, spherical and tubular halloysite, platy-hexagonal kaolinite, hydroxy interlayered vermiculite, and opaline silica.

The amounts of clay formed in the tephras are broadly correlated with tephra age. Allophane and imogolite may form directly and rapidly from volcanic glass and feldspar and can persist for long periods of time. Halloysite in this study may have formed in specific sites which are rich in silica. Kaolinite may be favoured by higher temperature in the surface horizons. The occurrence of 2:1 and 2:1:1 clay minerals may be due to wind transport of these materials from other sites. The presence of opaline silica probably reflects biological activity and plant growth in the A horizons.

CHAPTER 4
SOIL CLASSIFICATION

Classification is a science language. All soil classification systems have the primary objective of grouping soils that have similar properties (Bartelli 1984). Soil classification catalogues and confers order on soil properties and simplifies their description. It also brings out the relationships among soils and correlates information about them. Practically, soil classification aim to group soils in a manner useful for applied purposes such as predicting their behaviour, identifying their best use, and estimating their productivity. Recently, an important outcome of soil classification is the efficient stratification of information stored in soil databases.

There are a number of soil classification systems. Two broad systems can be distinguished: those that emphasise soil morphology or genesis and those that stress soil suitability for a particular use or range of uses. Since the primary objective of this study is to examine soils in terms of their properties and genesis, a taxonomic classification will give a useful summary.

This study uses the US Soil Taxonomy and the New Zealand Soil Classification, which are both categorised on soil properties, to highlight differences between the soils.

4.1. Descriptions of Profiles

The history of soil forming processes is manifested in the morphology of the soil pedon. Thus, soil pedon descriptions provide the information from which taxonomic units may be constructed. Five pedons have been classified; each pedon description is accompanied by photographs of the landscape and the pedon itself. The parameters required for a complete classification have been described in Chapter 2. Selected principal parameters are shown in (Table 4.1).

Pedon 1

Location : Desert Road, just north of Hardings paddock; Roadside bank
Grid Refs (GR): NZMS 260, 1:50,000 T20 415956
Topography : ash mantled lahar surface
Site slope : about 2° Aspect: West Elevation: *ca.* 1,000 m asl
Drainage class : well drained
Vegetation : alpine tussock and shrub species
Date examined: 31/01/97

Depth (cm)	Horizon	Description
0-1	C	10 YR 3/1 (very dark grey); sandy loam; loose structure; abundant roots; whitish; powdery when dry (Ruapehu ash 7/10/95).
1-10	2Ab	Overburden from roadworks; 10 YR 4/2-4/3 (dark grayish brown to dark brown); fine sandy loam; moderate medium crumb structure; abundant roots; sharp boundary.
10-28	2Ah	10YR 3/2 (very dark grayish brown); fine sandy loam; very friable, non-sticky, non-plastic; strong coarse crumb and fine granular structure; common roots; gradual boundary.
28-33	2C	black-dark grey; coarse ash and very fine lapilli; loose; sharp boundary. (Tufa trig 5, Tf5).
33-40	3Ah	10YR 3/2 - 2.5Y 3/2 (very dark grayish brown); fine sandy loam; friable, non-sticky, non-plastic; strong coarse crumb and fine granular structure; common very fine roots; gradual boundary.
40-55	3Bw	10YR 3/3-3/4 (dark brown to dark yellowish brown); fine sandy loam; friable, non-sticky and non-plastic; strong coarse crumb and fine granular structure grades down to Taupo pumice (Tp).
55-85	3C	2.5Y 4/2-5/2 (dark grayish brown to grayish brown); loamy sand; massive structure; common fine charcoal; few fine lapilli to coarse lapilli and large charcoal nearby Taupo pumice ignimbrite (Ig); sharp boundary.
85-105	4Ab	10YR 3/3 (dark brown); greasy, fine sandy loam; friable, non-sticky, non-plastic; strong coarse crumb and fine granular structure; few fine roots and roots channels; gradual boundary.
105+	4Bw	10YR 3/4-4/4 (dark yellowish brown); slightly greasy, fine sandy loam; friable, non-sticky, non-plastic; common orange fine pumice lapilli; weak medium blocky structure breaking to strong coarse crumb and medium granular structure.

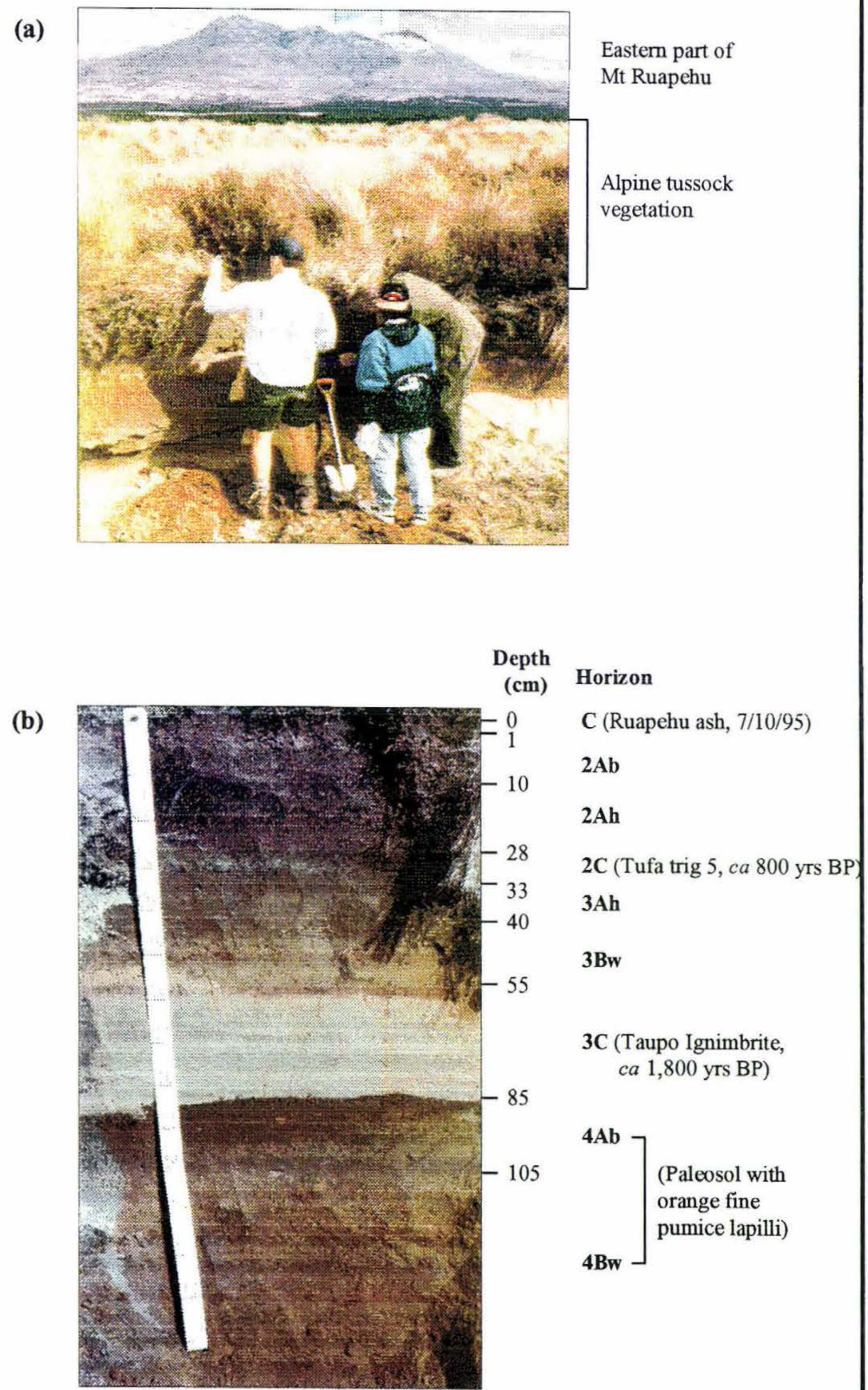


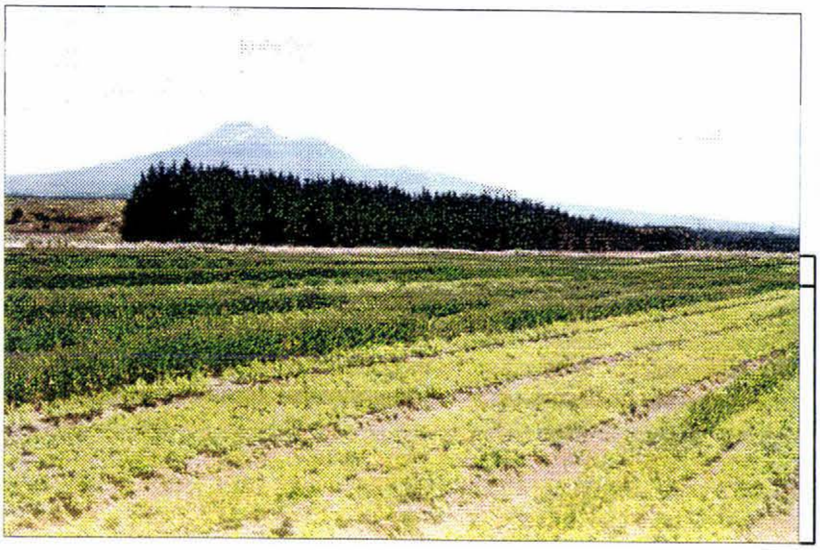
Plate 4.1. Pedon 1 at Desert Road (GR T20/415956); (a) Landscape, (b) Profile

Pedon 2

Location : Carrot paddock on low lahar surface beside Whangaehu River; approximately 2 km downstream of Tangiwai Bridge.
Grid Refs (GR): NZMS 260, 1:50,000 T21 303875
Topography : low lahar surface
Site slope : flat Elevation: *ca.* 900 m asl
Drainage class : well drained
Land Use : market garden
Date examined: 31/01/97

Depth (cm)	Horizon	Description
0-21	Ap	7.5 YR 3/1-3/2 (dark brown); gritty; loamy sand; non-sticky, non plastic; moderate coarse crumb structure; few roots; common fine andesite; few Taupo pumice clast (up to 5 cm), sharp boundary.
21-34	C	2.5Y 5/2 (grayish brown); sandy; gravel;non-sticky, non-plastic; no roots; massive; firm; sharp boundary. (Onetapu formation lahar).
34-42	2Bw1	10YR 4/2 (dark grayish brown); loamy sand; massive; loose; no roots; gradual boundary.
42-50	2Bw2	10YR 4/3-4/4 (dark brown to dark yellowish brown); fine loamy sand; non-sticky, non-plastic; loose; sharp boundary.
50+	2C	2.5Y 7/4 (pale yellow); loose; sand with occasional pumice clast. (Taupo pumice alluvium).

(a)



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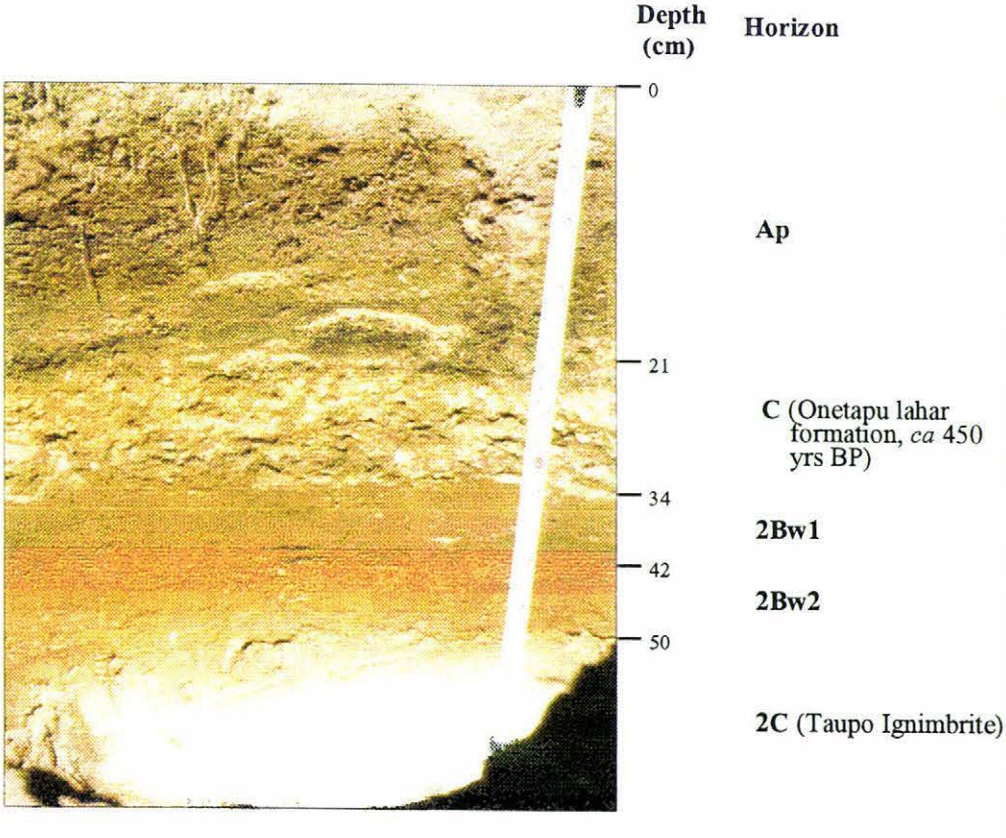


Plate 4.2. Pedon 2 at Tangiwai, beside Whangaehu River (GR T21/303875); (a) Landscape, (b) Profile

Pedon 3

Location : Blackwoods paddock, opposite Tangiwai Mill
Grid Refs (GR): NZMS 260, 1:50,000 T21 304895
Topography : ash mantled lahar surface
Site slope : about 2° Aspect: SouthEast Elevation: *ca*. 900 m asl
Drainage class : well drained
Land Use : pastoral
Date examined: 31/01/97

Depth (cm)	Horizon	Description
0-22	Ap	10 YR 2/2-7.5YR 2/2 (very dark brown); fine sandy loam; friable, non-sticky and non-plastic; moderate medium nut structure and granular breaking to strong coarse crumb; common roots; sharp boundary.
22-33	AB	10 YR 4/4 (dark yellowish brown); fine sandy loam; very friable, non-sticky and non-plastic; strong coarse crumb and moderate fine granular structure; few roots; few fine lapilli; gradual boundary.
33-62	Bw1	10YR 4/6 (dark yellowish brown); fine sandy loam; very friable, non-sticky, non-plastic; slightly greasy; strong coarse crumb and moderate fine granular structure; few fine roots; few lapilli; gradual boundary.
62-98	Bw2	10YR 4/6 (dark yellowish brown); sandy loam; friable to firm; brittle fracture; coarse ash, very fine lapilli and pumice, lithics; few medium lapilli; gradual boundary.
98+	BC	orange; medium and fine lapilli in brown sandy matrix. (Ngamatea lapilli).

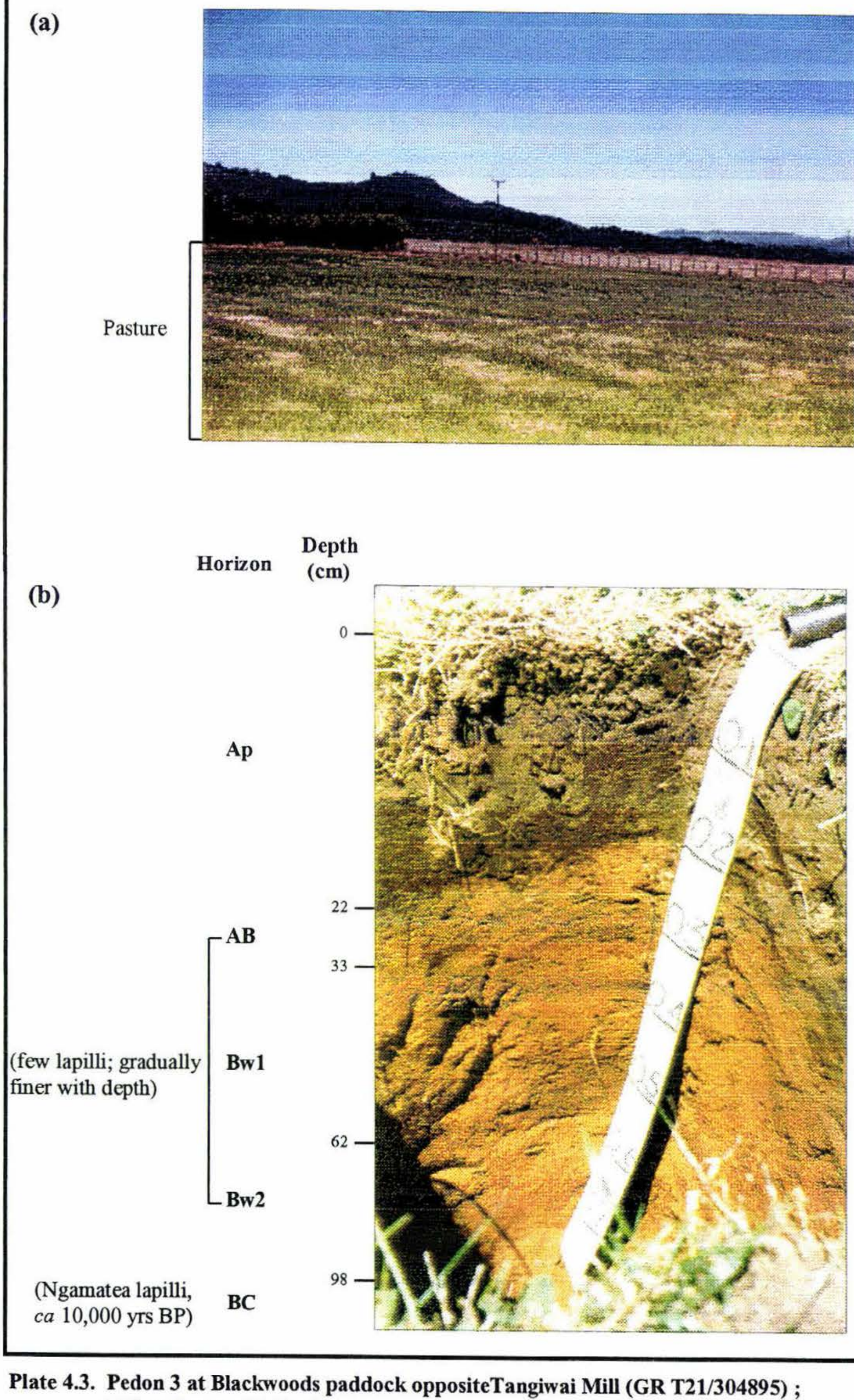


Plate 4.3. Pedon 3 at Blackwoods paddock oppositeTangiwai Mill (GR T21/304895) ; (a) Landscape, (b) Profile

Pedon 4

Location : Horopito; Young's farm
Grid Refs (GR): NZMS 260, 1:50,000 S20 123026
Topography : terrace, crest of gently rolling
Site slope : about 2° Aspect: NorthWest Elevation: *ca.* 700 m asl
Drainage class : well drained
Vegetation : grassland (in rotation with carrots)
Date examined: 31/01/97

Depth (cm)	Horizon	Description
0-17	Ah	7.5YR 3/2-3/3 (dark brown); silty clay loam; friable, non-sticky, slightly plastic; moderate medium nut breaking to strong coarse crumb structure; abundant roots; gradual boundary.
17-38	Bw1	10 YR 4/3 (dark brown); silty clay loam; friable, non-sticky and slightly plastic; strong medium nut structure breaking down to strong coarse crumb; common roots; few red brown organic coatings on root channels; gradual boundary.
38-60	Bw2	10YR 4/4-7.5YR 4/4 (dark yellowish brown to dark brown); silty clay loam; friable, non-sticky, and slightly plastic; moderate coarse nut and medium block structure breaking down to strong coarse crumb structure; few roots; few organic coatings on roots; gradual boundary.
60-86	Bw3	10YR 4/4-7.5 YR 4/4 (dark yellowish brown to dark brown); gritty, silty clay loam; non-sticky and slightly plastic; moderate medium nut and medium block structure; common organic coatings on roots channels and weak organic coatings on dark reddish brown peds; gradual boundary.
86-100+	BC	10YR 4/4 (dark yellowish brown); gritty, sandy clay loam; common fine to medium orange to cream pumice lapilli and lithics; weak coarse block structure.

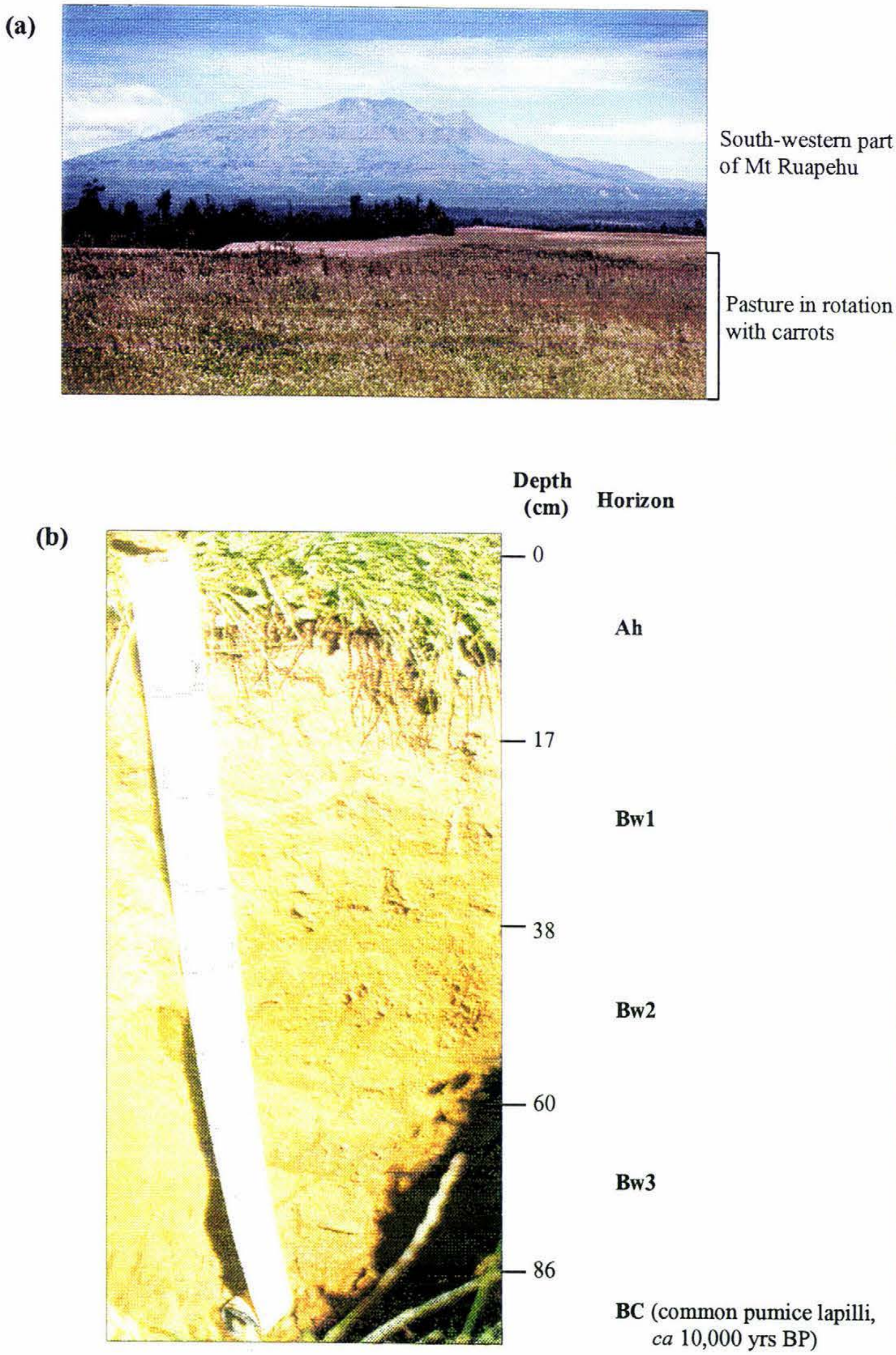


Plate 4.4. Pedon 4 at Young's farm in Horopito (GR S20/123026); (a) Landscape, (b) Profile

Pedon 5

Location : Horopito in Young's farm. Beside road and driveway into Young property.

Grid Refs (GR): NZMS 260, 1:50,000 S20 122023

Topography : terrace, crest of gently rolling.

Site slope : about 2° Aspect: SouthEast Elevation: *ca.* 700 m asl

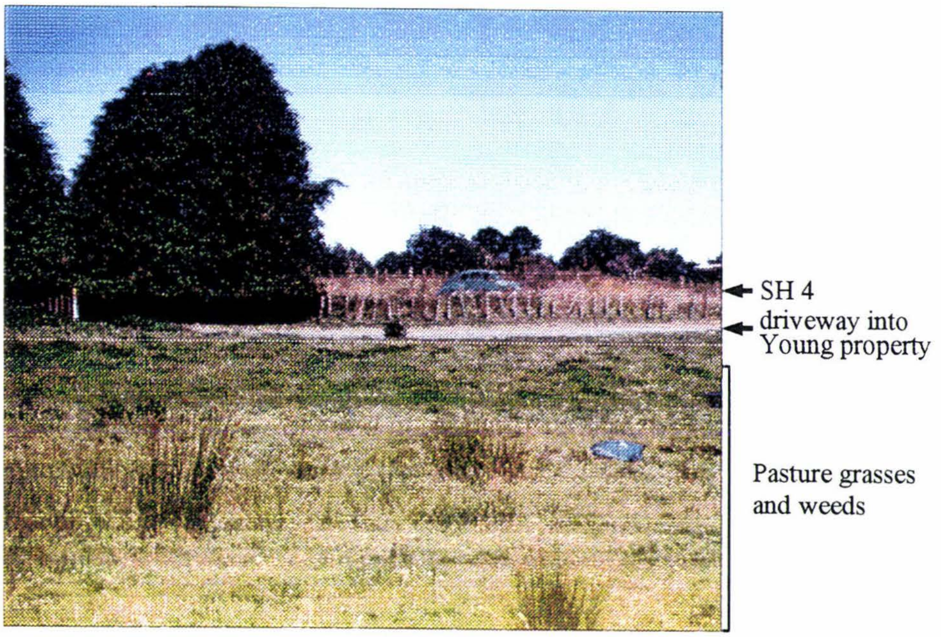
Drainage class : imperfectly drained hollow.

Vegetation : pasture grasses and weeds.

Date examined: 31/01/97

Depth (cm)	Horizon	Description
0-23	Ah	10 YR 3/2 (very dark grayish brown); silty clay loam; friable, non-sticky and slightly plastic; moderate medium nut and block structure; abundant roots; common dark reddish brown coatings down roots; gradual boundary.
23-45	Bw(f)	10 YR 4/3-4/4 (dark brown to dark yellowish brown); silty clay loam; friable, non-sticky and slightly plastic; moderate medium nut and block structure; common roots; common black - dark reddish brown Fe/Mn coatings filling interstices and root channels; brittle, gradual boundary.
45-67	Bw	10YR 4/4 (dark yellowish brown); silty clay loam; non-sticky and slightly plastic; moderate medium nut and block structure; few roots; few coatings as above; sharp boundary.
67-80+	BC	large boulders with matrix as above

(a)



(b)

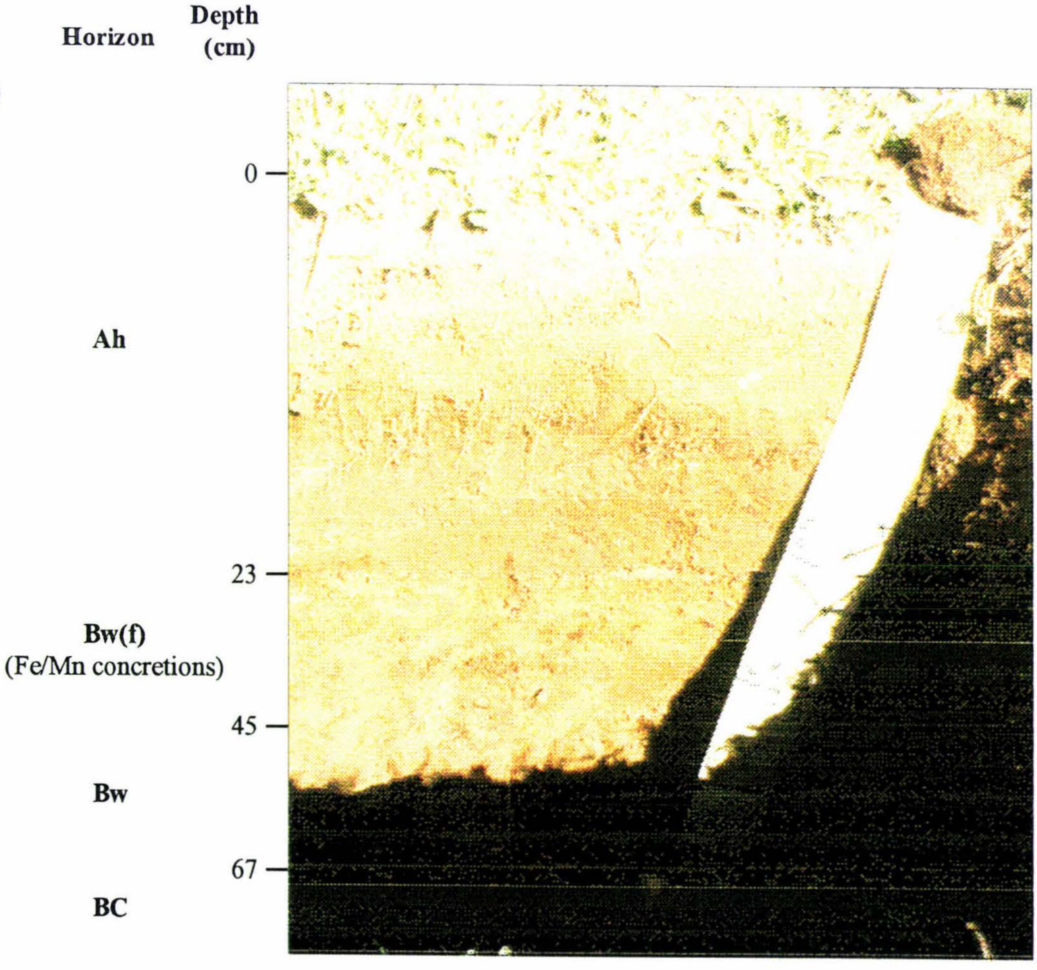


Plate 4.5. Pedon 5 at Young's farm in Horopito (GR S20/122023); (a) Landscape, (b) Profile

4.2. Soil Taxonomy

Soil Taxonomy was first introduced by Soil Survey Staff in 1975 with Dr Guy Smith as the principal author. Based on soil morphology and soil properties instead of soil processes and presumed genesis, this system defines reproducible assignments. Soil Taxonomy has six categories, which hierarchically are: order, suborder, great group, subgroup, family, and series.

Using the system of Soil Taxonomy, the pedons: 1, 3, 4, and 5 in this study are classified as Andisols. The P2 soil, however, is not an Andisol because the bulk density of the A and B horizons are higher than 0.90 Mg m^{-3} (Table 2.9).

Andisols which previously were mostly Andepts, were first introduced in the fourth edition of Keys to Soil Taxonomy (Soil Survey Staff, 1990). The new order was the result of 10 years collaborative international research, done by International Committee on the Classification of Andisols (ICOMAND). This study uses Keys to Soil Taxonomy, sixth edition 1994 (Soil Survey Staff 1992).

Andisols are mineral soils that have andic properties throughout all sub-horizons with a thickness of 35 cm or more within 60 cm of the mineral surface, or throughout all subhorizons if a lithic or paralithic contact occurs within 35 cm of the mineral soil surface. To have andic properties, the soil material must meet one or more of the following requirements (Soil Survey Staff 1992, p.14-15):

1. In the fine-earth fraction, all of the following:
    a. Acid oxalate extractable aluminium (Al*o*) plus one-half acid oxalate extractable Fe (Fe*o*) is 2.0 percent or more, and
    b. A bulk density, measured at 33 kPa water retention, of 0.90 Mg m^{-3} or less, and
    c. A phosphate retention of 85 percent or more.
2. In the fine-earth fraction, a phosphate retention of 25 percent or more, 30 percent or more particles of 0.02 to 2.0 mm, and one of the following:

a. Acid oxalate extractable aluminium (Al*o*) plus one-half acid oxalate extractable Fe (Fe*o*) totalling 0.40 or more and, in the 0.02 to 2.0 mm fraction, 30 percent or more volcanic glass.

The physical and chemical properties of all five pedons were checked against these criteria. Three pedons (P3-P5) have subhorizons that meet the first requirements of andic properties and P1 meets the second requirement (Table 4.1). Thus, they are classified as Andisols. However P2 meets none of the andic criteria. Pedon 2 has an Ochric epipedon, has no diagnostic subsurface horizon, and does not meet any previous order requirements. Therefore, it is classified as an Entisol.

Table 4.1. Selected andic properties of the studied soils

Horizon	Depth (cm)	BD (Mg m^{-3})	P-ret (%)	Alo+1/2Feo (%)	Glass ^{a} (%)	1,500 kPa water ret. ^{b}
Pedon 1						
2Ab	1-14	1.07	59	1.2	13	18.0
2Ah	14-34	nd	52	1.0	10	15.5
2C	34-40	nd	24	0.6	7	nd
3Ah	40-53	0.92	65	1.9	12	nd
3Bw	53-65	0.92	77	2.9	25	nd
3C	65-91	0.73	25	0.5	91	nd
4Ab	91-98	0.83	77	2.7	17	nd
4Bw	98-130+	0.83	nd	nd	nd	nd
Pedon 2						
Ap	0-30	1.11	19	0.3	7	6.8
C	30-37	1.22	21	0.4	11	3.8
2Bw2	50-62	1.00	53	1.2	29	nd
2C	62-100	nd	36	0.8	92	nd
Pedon 3						
Ap	0-22	0.90	81	2.6	17	29.3
AB	22-33	0.554	98	5.5	24	61.2
Bw1	33-62	nd	99	6.4	17	nd
Bw2	62-98	nd	97	6.0	10	nd
BC	98+	nd	95	4.9	8	nd
Pedon 4						
Ah	0-17	0.75	96	4.8	20	61.2
Bw1	17-38	0.38	99	8.5	22	120.6
Bw2	38-60	nd	99	7.0	13	nd
Bw3	60-86	nd	99	6.3	11	nd
BC	86-100	nd	91	5.7	9	nd
Pedon 5						
Ah	0-23	0.69	92	2.5	18	51.4
Bw(f)	23-45	0.52	98	6.3	23	97.2
Bw	45-67	nd	98	6.5	14	nd

Note: ^{a} Glass in sand fraction (0.02-2 mm); ^{b} Water retention of undried samples

Abbreviations: BD = bulk density; P-ret = P retention; Alo+1/2Feo = aluminum oxalate plus one-half iron oxalate; kPa water ret. = kilo Pascal water retention; nd = not determined.

Before classifying a pedon, it is necessary to determine soil moisture regime and soil temperature regime. Soil moisture regime is considered to influence soil genesis significantly. It is used at sub-order level.

Rainfall data (Table 1.1) show that the study area has a well-distributed rainfall through the year and soils have little moisture deficit (Table 1.2). This soils typically meet udic moisture regime requirements.

A udic moisture regime occurs when the mean annual soil temperature is lower than 22°C and if the mean winter and summer soil temperatures at a depth of 50 cm differ by 5°C or more, and the soil moisture control section is not dry in all parts for as long as 45 consecutive days in the four months that follow the summer solstice in 6 or more years out of ten (Soil Survey Staff, 1992).

The udic moisture regime is common to the soils of humid climates that have well-distributed rainfall or that have enough rain in summer so that the amount of stored moisture plus rainfall is approximately equal to or exceeds the amount of evapotranspiration. Water moves down through the soil at some time in most years.

Soil temperature relates to agricultural management. It can be used to differentiate soils within the family category. Temperatures on the ground at selected stations meet the isofrigid temperature regime criteria (Table 1.4). The isofrigid regime occurs when mean annual soil temperature is lower than 8°C, and the difference between mean summer and mean winter soil temperatures is less than 5°C either at a depth of 50 cm from the soil surface or at a lithic or paralithic contact, whichever is shallower (Soil Survey Staff, 1992).

4.2.1. Classification to Subgroup

Pedon 1

Pedon 1 was situated on an ash covered lahar surface downwind of Mt Ruapehu, where addition of new materials occurs frequently. Pedon 1 has an undried 1,500 kPa water retention of less than 30 percent (Table 4.1) within the 35 cm thickness and thus belongs to the Vitrand suborder. Soil Survey Staff (1992) state that, Vitrands are the coarser-textured Andisols with 1,500 kPa water retention values of less than 15 percent by weight on air-dried and 30 percent on undried samples, throughout a thickness of 35 cm within the upper 60 cm of the pedon. The soil also has only small amounts of weathering products, as marked by low values of oxalate-extractable Al and Fe (less than 2.5 and 0.7, respectively). The small amounts of weathering products were due to its coarser-textured parent materials which weathered more slowly than fine-textured ones, and its locality.

Pedon 1 falls into the Udivitrand great group because of its soil moisture regime; and into the Typic Udivitrand subgroup. Typic Udivitrands are Udivitrands that do not meet any other subgroup requirements (Soil Survey Staff, 1992).

Pedon 2

Pedon 2 is situated on a low lahar surface beside the Whangaehu River. It does not meet andic criteria due to its bulk density, which is more than 0.90 Mg m^{-3} (Table 4.1). Its classification, then, falls into the Entisols order. According to Soil Survey Staff (1992), Entisols are soils that do not meet any previous soil order requirements. It is the last soil order in the Soil Taxonomy.

Pedon 2 has a mean annual ground surface temperature of about 2.1°C (Table 1.4) and it has more than 0.4 percent organic carbon which decreased irregularly with depth (Table 2.7). Therefore, P2 can be keyed out into the Fluvent suborder.

Fluvents (Soil Survey Staff 1992, p.131) are Entisols which do not have a lithic or paralithic contact within 25 cm of the mineral soil surface, and have:

1. A slope of less than 25 percent, and
2. Either 0.2 percent or more organic carbon at depth of 125 cm below the mineral soil surface, or an irregular decrease in organic-carbon content from a depth of 25 cm to a depth of 125 cm, or to a lithic or paralithic contact if shallower, and
3. A mean annual soil temperature above 0°C.

Pedon 2 belongs to the Udifluvent great group. Soil Survey Staff (1992) recognises that Udifluvents are other Fluvents that do not meet any previous great group requirements.

The subgroup of P2 is Vitrandic Udifluvent, because it has more than 94 percent particles 0.02 to 2.0 mm in diameter (Table 2.9), and has dominant amounts of volcanic glass (more than 50 percent, Table 4.1). These parameters meet the second requirements of Vitrandic Udifluvents, which are (Soil Survey Staff 1992, p.138):

> Udifluvent that have, throughout one or more horizons with a total thickness of 18 cm or more within 75 cm of the mineral soil surface: a fine-earth fraction containing 30 percent or more particles 0.02 to 2.0 mm in diameter, and
>
> a. In the 0.02 to 2.0 fraction, 5 percent or more volcanic glass, and
>
> b. [(Aluminium plus one-half iron, percent extracted by ammonium oxalate) times 60] plus the volcanic glass (percent) is equal to 30 or more.

Pedon 3

Pedon 3 is located on ash covered lahar surface with negligible recent addition and beyond the large number of Taupo Ignimbrite. It is keyed out to a Udand. Udands are Andisols which have a udic soil moisture regime. The most condition in which Udands form is consistent with allophane formation (Parfitt and Wilson 1985) and P3 has a large amount of allophane (Table 2.8).

Pedon 3 is within the Hapludand great group. Hapludands are Udands not included in the previous great groups (Soil Survey Staff 1992) with a udic soil moisture regime.

At subgroup level, P3 cannot be an Alic Hapludands because its pH and is more than 6.0 (Table 2.7). It cannot be a Hydric Hapludand because the undried 1,500 kPa water retention is less than 70 percent throughout a layer of 35 cm within 100 cm of the soil surface. The AB horizon (11 cm thick, from 22 to 33 cm) has a 1,500 kPa water retention of only 61.2 % (Table 4.1). The only subgroup left is Typic Hapludand.

Pedon 4

Pedon 4 is located on an ash covered lahar surface west (upwind) from Mt Ruapehu. It belongs to the Udand suborder. In contrast with P3, P4 has a 1,500 kPa water retention of more than 100 %. Pedon 4 looked and felt as if it might be a Hydrudand great group.

The first requirement for Hydrudand great group is (Soil Survey Staff 1992, p.88):

> Other Udand that has, undried, a 1,500 kPa water retention of 100 percent or more, on the weight average, throughout one or more layers with a total thickness of 35 cm between the mineral soil surface, and 100 cm from the mineral soil surface with no lithic or paralithic contact, duripan, or petrocalcic horizon within that depth.

However, 1,500 kPa water retention was determined only on the Bw1 horizon (21 cm thick, from 17 to 38 cm) and was found to be 120.6 % (Table 4.1). This horizon is not thick enough to meet the thickness prerequisite. Morphologically, the Bw1, Bw2, and Bw3 horizons have similar properties (Table 2.2). It is reasonable to assume, therefore, that these three horizons with a total thickness of 69 cm, have a 1,500 kPa water retention of more than 100 %. They also have high allophane and organic-matter contents (Table 2.8) which usually lead to higher water retention (Maeda, *et al*. 1978).

At subgroup level, P4 is keyed out into the Typic Hydrudand, because it does not meet any previous subgroup requirements.

Pedon 4 is a more weathered Andisol than pedon 3 because base saturation is lower and clay content is higher. Mineralogical data and 1,500 kPa water retention also support a more weathered profile in P4.

Pedon 5

Pedon 5 is situated close to pedon 4, but P5 is a poorly drained soil, which is revealed by the vegetation at the site and the occurrence of brittle Fe and Mn concretions in the

Bw(f) horizon (Table 2.2). It, therefore, belongs to the Aquand suborder. Soil Survey Staff (1992, p.81) define Aquands as:

> Andisols that have: in a layer between 40 and 50 cm from the mineral soil surface, aquic conditions for some time in most years and two percent or more redox concentrations.

Redox concentrations include Fe/Mn concretions (Soil Survey Staff, 1992).

The great group is determined to be Endoaquand because the pedon does not meet any previous great group requirement (Soil Survey Staff 1992).

Pedon 5 has a 1,500 kPa water retention of 97.2 % which was determined only on the Bw(f) horizon (23-45 cm). Again it is assumed that because the Bw horizon (45-67 cm) has similar morphological characteristics (Table 2.2), clay mineralogical properties (Table 2.6), and organic carbon content (Table 2.7), it could be assumed, that it also has a similar 1,500 kPa water retention. Therefore, pedon 5 is keyed out into the Hydric Endoaquand subgroup. Hydric Endoaquand requires an undried 1,500 kPa water retention of 70 percent or more throughout a layer 35 cm or more thick within 100 cm of the mineral soil surface (Soil Survey Staff 1992).

4.2.2. Families of the Soils

In order to classify the soils to family level, it is necessary to assess the family differentiate. Particle-size classes and mineralogy classes need to be considered separately at the family level (Leamy 1988) within control section at a depth of 100 cm.

Particle-size classes.

Since particle-size analysis of Andisols is difficult due to flocculation, modifiers that combine particle-size and mineralogical properties are used to distinguish families (Soil Survey Staff 1992, p.30-31). All four Andisols have a fine-earth component of 10 percent or more of the total volume. Therefore, they need substitutes for the non-fragmental particle-size classes (Table 4.2).

Pedon 2 which is not an Andisol, has a sand texture in the upper horizon and loamy sand in the lower horizons. Pedon 2, therefore, has a particle-size class of sandy. By definition (Soil Survey Staff 1992), sandy particle-size class is for soils that have sandy texture, less than 50 percent (by weight) very fine sand, and less than 35 percent (by weight) rock fragments.

Table 4.2. Substitutes for the non-fragmental particle-size classes

Pedon	Class	Description[1]
P1	Ashy	less than 35 percent (by volume) rock fragments; a fine-earth fraction which contains 30 percent or more (by weight) particles between 0.02 and 2.0 mm in diameter and has andic properties, and a water content at 1,500 kPa tension of less than 30 percent on undried samples
P3, P5	Medial	a fine-earth fraction which has andic soil properties and which has a water content at 1,500 kPa tension of 30 to 100 percent on undried samples; less than 35 percent (by volume) rock fragments.
P4	Hydrous	a fine-earth fraction which has andic soil properties and which has a water content at 1,500 kPa tension of 100 percent or more on undried samples; less than 35 percent (by volume) rock fragments.

Note: [1] refer to Soil Survey Staff (1992)

Mineralogy classes

The criteria for mineralogy classes are classified based on particle-size classes: (a) any particle-size classes, (b) soils with fragmental, sandy, sandy-skeletal, loamy or loamy-skeletal particle-size classes, and (c) soils with clayey or clayey-skeletal particle-size classes.

The substitute modifiers for particle-size classes in P1, 3, 4, and 5 include aspects of texture, consistence and mineralogy. Therefore, these pedons do not require independent mineralogy classes.

Pedon 2 has a sandy particle-size class and mineralogically it is dominated by heavy minerals and volcanic glass. Pedon 2, therefore, has a mixed mineralogy class. Soil Survey Staff (1992) formulate the mixed mineralogy class for soils that have less than 40 percent (by weight) of any single kind of mineral other than quartz or feldspar in sand fraction.

4.3. New Zealand Soil Taxonomy

The first comprehensive New Zealand soil classification was introduced by Norman Taylor in 1948. It was called the New Zealand Genetic Soil Classification, and was based on zonal concepts developed in Russia. Soil Taxonomy was introduced worldwide in 1975. In 1978 New Zealand soil scientists became committed to the international development of Soil Taxonomy. Soil Taxonomy, however, made inadequate provision for important classes of New Zealand soils (Hewitt 1992b), and a decision was then made to develop a new classification specifically for New Zealand conditions and soils. The new soil classification is a modification of Soil Taxonomy and retains elements of the Genetic classification. The classification is hierarchical with four categories: order, group, subgroup, and series.

Hewitt (1992a, p.5) describes the objectives of soil classification in New Zealand. The objectives are:

1. To provide a better means of communication about New Zealand soils and their utilisation;
2. To provide an efficient vehicle for soil identification, soil series recognition and correlation, and soil map legend establishment in soil surveys;
3. To enable an efficient stratification of soil database information;
4. To draw together knowledge of the properties of New Zealand soils and important similarities and differences among them.

Classification begins with determination of diagnostic horizons. Diagnostic horizons and features in the New Zealand System are defined to facilitate the assignment of soils to classes.

Pedons 1, 3, 4 and 5 have allophanic soil materials in the diagnostic horizon. Hewitt (1992a, p.16) describes allophanic soil material as:

1. Either:
    a. sensitive or strongly sensitive, distinctly greasy or smeary feel
    b. very weak or weak unconfined soil strength class
    c. non-sticky or slightly sticky
    d. strong positive reaction to the NaF test; or
    P retention of 85 percent % or more; and
2. Bulk density of the fine-earth fraction of less than 0.9 Mg m^{-3}.

Pedons 2 has sufficient glass in the sand fraction to meet the vitric material criterion. Vitric soil material is described by Hewitt (1992a, p.34) as material with more than 40 percent sand of which more than 30 percent is volcanic glass or crystal coated with glass.

Pedons 1, 3, 4, and 5

These four pedons belong to the Allophanic Soil order. Allophanic soils are soils that have a layer or layers of allophanic soil material, that total 35 cm or more in thickness, and occur within 60 cm of the mineral soil surface (Hewitt 1992a).

Pedons 1, 3 and 4 are keyed out into the Orthic Allophanic Soils. Hewitt (1992a) classifies Orthic Allophanic Soils as "other" Allophanic Soils. Pedons 1 and 3 are vitric Orthic Allophanic Soils, which have more than 50 percent sand (by weight average) within the allophanic soil material layer or layers and within 90 cm of the mineral soil surface (Hewitt 1992a). Pedon 4 is a typic Orthic Allophanic Soil.

Pedon 5 is an Impeded Allophanic Soil. Impeded Allophanic Soils are Allophanic Soils that have a slowly permeable horizon, or a horizon that is at least weakly indurated, within 90 cm of the mineral soil surface (Hewitt 1992a). In subgroup hierarchy, P5 belongs to the typic Impeded Allophanic Soil.

Pedon 2

Pedon 2 belongs to the Pumice Soil order. According to Hewitt (1992a, p.37), Pumice Soils are: soils that have both:

1. A layer of vitric material extending from the mineral soil surface to 25 cm or more, or 35 cm or more thickness occurring within 60 cm of the mineral soil surface; and
2. A weathered-B horizon 5 cm or more thick.

Within the order of Pumice Soils, P2 is keyed out into the Orthic Pumice Soil. Orthic Pumice Soils are Pumice Soils that do not meet any previous group requirements (Hewitt 1992a). Within the subgroups of Orthic Pumice Soils, P2 belongs to the typic

Orthic Pumice Soil. Typic Orthic Pumice Soils are other Orthic Pumice Soils that do not meet any previous requirement (Hewitt 1992a).

4.4. Discussion

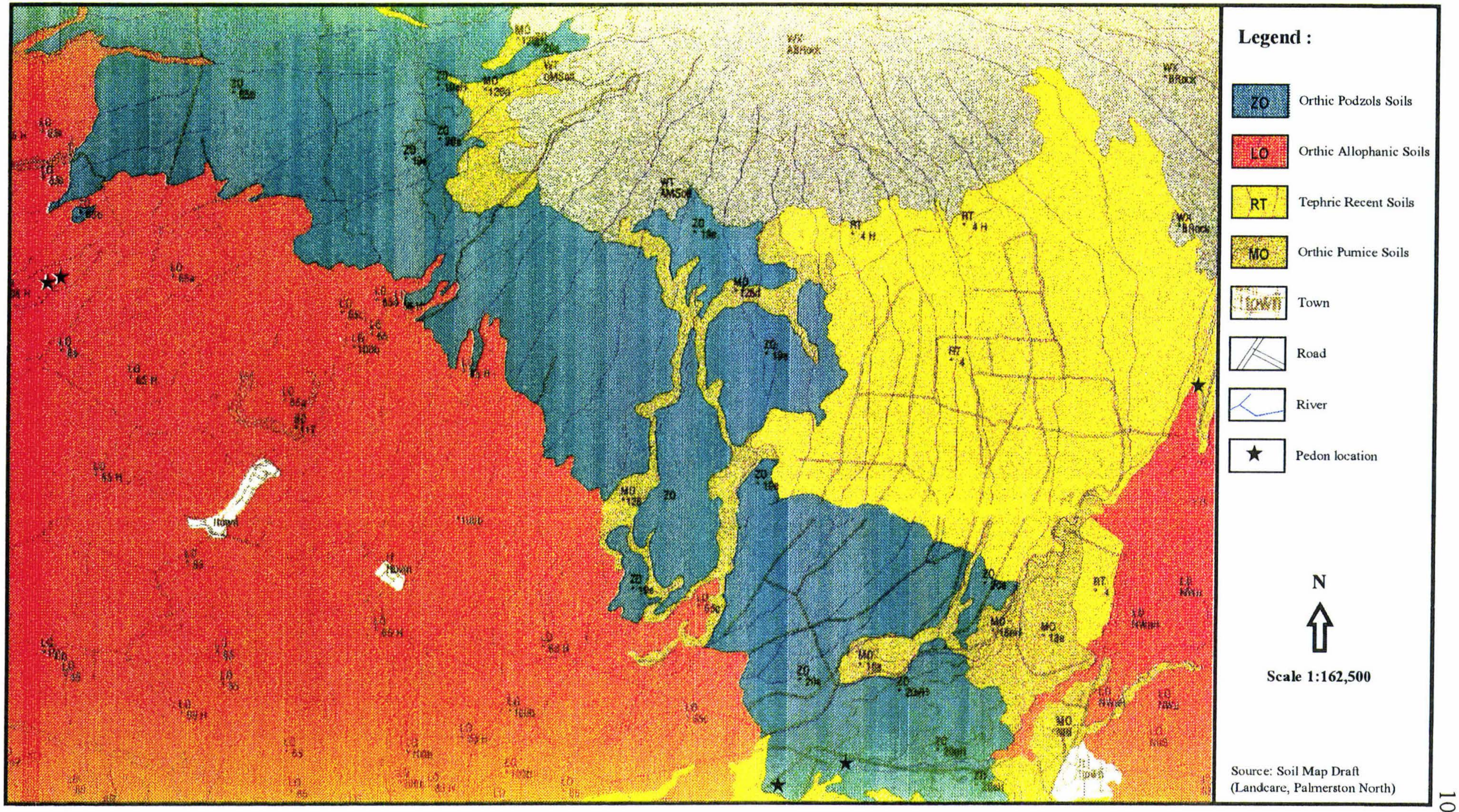
As criteria differ between the New Zealand Soil Classification and Soil Taxonomy, Hewitt (1992a, p.9-14) provides a correlation table between classes of the New Zealand Soil Classification with the New Zealand Genetic Soil Classification (Taylor and Pohlen 1962) and Soil Taxonomy (Soil Survey Staff 1990). Both the Soil Taxonomy and the New Zealand Soil Classification carry rigorous definitions to allow classification into the various categories.

In this study, the Allophanic Soils are correlated mainly with Udands and the Pumice Soil is correlated with the Entisol order of Soil Taxonomy. Table 4.2 illustrates the proposed classification and correlation for the studied soils in both systems. The New Zealand soil map (Fig. 4.1, p.102) shows the distribution of the soil groups in the study area.

Table 4.3. Proposed classification and correlation

Pedon	Soil Classification	
	Soil Taxonomy	The NZ Soil Classification
P1	Typic Udivitrand, *ashy*, *isofrigid*	vitric Orthic Allophanic Soil
P2	Vitrandic Udifluvent, *sandy*, *mixed*, *isofrigid*	typic Orthic Pumice Soil
P3	Typic Hapludand, *medial*, *isofrigid*	vitric Orthic Allophanic Soil
P4	Typic Hydrudand, *hydrous*, *isofrigid*	typic Orthic Allophanic Soil
P5	Hydric Endoaquand, *medial*, *isofrigid*	typic Impeded Allophanic Soil

Both classification systems have observable and reproducible soil characteristics. The grouping of the soils into classes is based on similarity of the soil properties and therefore both systems reflect the major differences between the soils. For instance, pedons 1, 3, 4 and 5 have the same diagnostic horizons. They are either andic properties of Soil Taxonomy or allophanic soil materials of The New Zealand Soil Classification. There are two soil orders (Table 4.2): Andisols and Entisols (in Soil Taxonomy) and Allophanic Soils and Pumice Soils (in The New Zealand Soil Classification).



Source: Soil Map Draft (Landcare, Palmerston North)

Fig. 4.1. The soil map of the study area

Soil Taxonomy is a classification system designed primarily to accommodate soils on a global (international) basis. This system reflects significant agricultural properties, and consists of six category levels. It is dependent upon a considerable number of laboratory analyses for the generation of the data on which it is based. Hence, a simple field classification is not easily achieved. On the other hand, the New Zealand Soil Classification system is much simpler because it is based on field observations and simple tests of properties. It reflects natural classes and requires fewer laboratory analyses to construct a data base. It does, however, contain only four category levels. Nevertheless, it is better suited to specific soil survey projects at the local level when international comparisons are not a major concern.

Pedons 1 and 3 belong to different classes in Soil Taxonomy, but they key out into the same class in the New Zealand Soil Classification (Table 4.2). In fact, there are significant differences in their current land use. Pedon 1 is covered by alpine tussock vegetation, whereas P3 is covered by pasture. Consequently, in this case Soil Taxonomy reflects differences in landuse between the soils in rather more detail than does the New Zealand soil classification.

Volcanic ash soils are treated adequately in both systems. Nevertheless Soil Taxonomy would be improved if a larger number of surveys had been included for all climatic zones at the time of development of the system. This would improve the utility of the system at the local level. On the other hand, the New Zealand Soil Classification would benefit from incorporation of more categories to identify volcanic ash soils more precisely.

4.5. Conclusion

Classification of the five studied soils has been presented in two systems, *i.e.*, Soil Taxonomy and the New Zealand Soil Classification. In the Soil Taxonomy, the five studied pedons are differentiated into Typic Udivitrand, *ashy, isofrigid*; Vitrandic Udifluvent, *sandy, mixed, isofrigid*; Typic Hapludand, *medial, isofrigid*; Typic Hydrudand, *hydrous, isofrigid*; and Hydric Endoaquand, *medial, isofrigid*. In the New Zealand Soil Classification, they are classified as vitric Orthic Allophanic Soil; typic Orthic Pumice Soil; vitric Orthic Allophanic Soil; typic Orthic Allophanic Soil and typic Impeded Allophanic Soils.

Both classification systems have observable and reproducible soil attributes and they reflect the differences between the soils. Soil Taxonomy is more complicated than the New Zealand Soil Classification. The comprehensive features of Soil Taxonomy serve global (international) purposes, whereas the New Zealand Soil Classification is more appropriate for local purposes.

Chapter 5

CONCLUSION

This thesis presents information on the properties of volcanic ash soils in the southern area of Mt Ruapehu, New Zealand. It is presented in four chapters.

Chapter 1 outlines the original objectives of the study and identifies the areas in which the study was conducted. Underlying all the objectives was the need to identify the weathering and genesis of the soils and to establish classification of volcanic ash soils in the southern area of Mt Ruapehu.

Research methodology and complete results of the study are described in Chapter 2. Morphological properties were determined from the field descriptions. Mineralogical analyses were achieved by X ray diffraction analysis of four fractions: sand, silt, heavy mineral, and clays. Differential thermal analyses were done in order to differentiate kaolinite and halloysite. To complete mineralogical data, electron microscope analyses were performed on the clay fractions. Chemical analyses determined soil pH, pH NaF, organic-carbon content, P retention, cation exchange capacity, base saturation, and percentage of allophane. Physical analyses determined bulk density, particle-size distribution, and water retention.

Morphologically, the younger soils (P1 and P2) have sandy or sandy loam textures and the older soils (P3, P4 and P5) have silty clay loam to clay textures. All have dark in upper horizons and brown to yellow coloured lower horizons. All soils are friable and some horizons have a smeary feel which is characteristic of volcanic ash soils.

Mineralogical analyses of the soils indicate that there are two different parent materials. Pedons 1 and 2 comprise predominantly rhyolitic tephra, and pedons 3, 4, and 5 comprise andesitic tephras. Examination of the sand fractions reveals that the horizons of all soils contain volcanic glass and heavy minerals of volcanic origin. Clay mineral analyses show that most soils are dominated by allophane and volcanic glass.

Little halloysite is found in the lahar layer and in lower horizons. Opaline silica is found in small amounts in the soils. The clay fractions also contain crystalline minerals, such as kaolinite, hydroxy interlayered vermiculite and cristobalite.

Chemical analyses show common features of soils developed on volcanic ash materials. In general the soils have pH(H_2O) of about 6, low CEC, low base saturation, and are high in organic carbon content especially in upper horizons. All older soils contain allophane with Al:Si ratio of about 2.0. The presence of allophane is confirmed by high values of pH NaF and high P retention.

The soils have bulk densities of less than 0.90 Mg m^{-3} except in P2 soil and high values of 1500 kPa water retention. It was difficult to disperse the clay fraction. Complete dispersion was obtained by adding HCl 1:1 drop by drop after 5 minutes of ultrasonic vibration.

Chapter 3 describes the weathering and genesis of the soils. Among five factors of soil formation, the parent material, time and climate seem to control the weathering processes.

The rhyolitic tephras in P1 and P2 are younger and coarser-textured than the andesitic tephras in P3, P4, and P5. Therefore, the genesis of the soils is more advanced in P3, P4 and P5. Micro-environmental conditions such as precipitation and temperature also contribute to the weathering of the soils.

Weathering processes result in allophane formation. In rhyolitic tephra, soil solutions high in silica promote the formation of 1:1 allophane. In andesitic tephras, lower Al:Si ratios promote the formation of 2:1 allophane.

Classification of the five soils is explained in Chapter 4 and is presented in two systems: Soil Taxonomy and the New Zealand Soil Classification. According to Soil Taxonomy, the soils are classified as Typic Udivitrand, *ashy, isofrigid*; Vitrandic Udifluvent, *sandy, mixed, isofrigid*; Typic Hapludand, *medial, isofrigid*; Typic

Hydrudand, *hydrous, isofrigid*; and Hydric Endoaquand, *medial, isofrigid*. In the New Zealand Soil Classification, the soils are classified as vitric Orthic Allophanic Soil, typic Orthic Pumice Soil, vitric Orthic Allophanic Soil, typic Orthic Allophanic Soil, and typic Impeded Allophanic Soil.

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Appendix 1. Sand fraction properties (%)

Depth (cm)	Volc.Glass*	Plant Opal*	Heavy Min*	Feldspar	Quartz
Pedon 1					
1-10	13.0	0.4	19.8	22	1
10-34	10.0	0.2	20.2	19	1
34-40	7.2	0.8	23.0	24	1
40-53	11.9	0.5	23.8	21	2
53-65	24.5	0.5	23.8	36	1
65-91	91.2	0	1.2	5	0
91-105	16.9	0.3	20.8	17	1
Pedon 2					
0-30	7.1	0.1	30.0	35	1
30-37	11.3	0.1	26.2	21	1
50-62	29.2	0	15.6	20	1
50+	92.2	0	0.8	5	0
Pedon 3					
0-22	16.5	0.9	23.0	32	1
22-33	24.2	0.8	30.8	29	2
33-62	17.3	0.5	38.0	19	10
62-98	9.9	0.1	37.4	36	3
98+	7.9	0.1	37.4	31	1
Pedon 4					
0-17	19.5	0.1	29.8	15	2
17-38	21.7	1.1	41.8	23	2
38-60	12.5	0.1	52.8	28	4
60-86	10.9	0.1	52.8	15	14
86-100	8.7	0.1	43.4	19	10
Pedon 5					
0-23	17.9	0.9	23.6	14	2
23-45	23.0	1.2	31.4	17	1
45-67	13.7	0.7	38.2	27	4

Note: Volc.glass=volcanic glass; heavy min= heavy mineral
Symbol * = results from calculation

Appendix 2. Silt fraction properties (%)

Depth (cm)	Cristobalite	Quartz	Feldspar	Volc.Glass
Pedon 1				
1-10	5	1	21	73
10-34	5	1	19	75
34-40	6	1	23	70
40-53	6	1	22	71
53-65	5	2	16	77
65-91	0	0	2	98
91-105	6	2	22	70
Pedon 2				
0-30	6	1	19	74
30-37	5	1	23	71
50-62	4	1	15	79
50+	0	0	2	98
Pedon 3				
0-22	7	2	16	75
22-33	6	3	16	75
33-62	3	1	11	85
62-98	5	2	15	78
98+	5	1	17	77
Pedon 4				
0-17	7	3	15	75
17-38	6	3	13	81
38-60	3	5	10	82
60-86	4	2	9	85
86-100	6	7	14	73
Pedon 5				
0-23	6	3	15	76
23-45	5	2	13	80
45-67	9	3	17	71

Appendix 3. Heavy mineral fraction properties (%)

Depth (cm)	Hypersthen	Magnetite	Augite	Ilmenite	Hornblende
Pedon 1					
1-10	52	11	24	10	3
10-34	55	12	24	9	0
34-40	48	16	28	8	0
40-53	55	12	25	8	0
53-65	39	15	35	7	4
65-91	44	29	14	7	6
91-105	45	13	28	12	2
Pedon 2					
0-30	57	15	19	9	0
30-37	49	15	30	6	0
50-62	52	18	24	6	0
50+	78	22	0	0	0
Pedon 3					
0-22	49	22	22	7	0
22-33	39	38	16	5	2
33-62	26	35	28	7	4
62-98	38	16	41	4	1
98+	44	19	26	9	2
Pedon 4					
0-17	32	44	15	5	4
17-38	29	40	24	4	3
38-60	43	24	18	9	6
60-86	42	22	17	9	10
86-100	50	17	15	13	5
Pedon 5					
0-23	34	34	23	9	0
23-45	23	42	19	5	11
45-67	40	13	45	2	0

Appendix 4. Clay fraction properties (%)

Depth (cm)	Cristobalite	Quartz*	Feldspar*	Halloy10A	Kaolinite	kanditeDTA	Chlorite	HIV	allophane	vg/amph.si*
Pedon 1										
1-10	0	0.5	5.0	0	10	10	0	7	27	50.5
10-34	0	0.5	5.0	0	15	15	0	6	31	42.5
34-40	0	0.3	3.0	0	9	9	0	6	40	41.7
40-53	0	0.5	4.0	0	12	12	0	10	48	25.5
53-65	0	0.5	3.0	2	2	2	0	5	62	26.0
65-91	0	0.4	2.0	0	0	0	0	2	30	65.6
91-105	0	0.4	4.0	3	0	0	7	10	61	14.6
Pedon 2										
0-30	1.6	0.6	4.0	0	24	24	0	10	27	32.8
30-37	2.0	0.5	4.0	7	20	20	0	14	20	32.5
50-62	2.0	0.8	3.0	2	12	12	0	14	40	26.2
50+	1.0	0.5	1.0	0	0	0	0	3	50	44.5
Pedon 3										
0-22	1.3	0.3	2.0	0	13	13	0	7	45	31.4
22-33	1.0	0.7	2.0	0	0	0	0	8	60	28.3
33-62	1.0	0.4	2.0	0	0	0	0	10	64	22.6
62-98	0.5	0	2.0	3	0	0	0	10	73	11.5
98+	0.8	0.4	2.0	0	0	0	0	4	67	25.8
Pedon 4										
0-17	2.0	0.8	1.0	0	24	24	5	13	38	16.2
17-38	0.8	0	0	0	0	0	0	5	56	38.2
38-60	0.5	0.5	1.0	0	0	0	0	7	57	34.0
60-86	1.0	1.0	2.0	2	3	3	5	8	53	25.0
86-100	0.7	1.0	1.5	0	1	1	6	10	57	22.8
Pedon 5										
0-23	3.0	0.6	2.0	0	0	0	5	8	8	73.4
23-45	0.8	0.4	1.0	0	0	0	4	6	52	35.8
45-67	0.8	0.6	1.5	0	0	0	4	8	54	31.1

Note: Halloy10A= halloysite (10A); kanditeDTA=kandite (DTA analyses); HIV=hydroxy interlayered vermiculite; vg/amph.si= volcanic glass/ amorphous silica; Symbol * = results from calculation.