# VOLCANIC SOILS

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## Contents

## Summary

This chapter gives an overview of the distribution, classification and main mineralogical, physical and chemical properties of volcanic soils. It discusses their land use potential and limitations for various uses, ranging from engineering to agricultural, rangeland and forestry uses, as well as to environmental considerations.

Many volcanic soils have excellent physical properties that make them highly desirable for a wide range of uses. Chemically, they suffer from a high phosphate retention, and they may be limiting in K and some micronutrients. Nevertheless, these soils are amongst the most fertile lands in the world and are, therefore, very intensively cultivated, even if the users are aware of the risks of volcanic outbursts.

## 1. Introduction

Volcanic soils cover 1% of the Earth's surface yet support 10% of the world's population, including some of the highest human population densities. This is usually attributed to their high natural fertility. However this is true only in part. Clearly such soils represent the surface areas of our planet that are being replenished with new minerals escaping from the interior of the Earth. However, some deep magmatic processes do lead to an imbalance of elements in volcanic soil parent materials which can impact on the health of plants and animals growing in or on them. In contrast, all other soils express various stages of the degradation (weathering) of these minerals.

This account addresses the specific features and genesis of volcanic soils, how they are classified, the problems when they are farmed or cropped, and how they are used and abused in various global environmental settings.

## 2. Parent Materials

As their name implies, this grouping of soils is found only on volcanic parent materials. Few other soils are restricted to a single type of material except organic soils derived from peat, and rendzinas from limestone. The reason for this distinction is because of the unique combination of soil properties that result from the weathering of volcanic rocks and in particular volcanic glass. Only under strong tropical weathering will lavas weather to finer grained volcanic soils, so it is usually parent materials of a volcaniclastic origin which result in the high-producing volcanic soils of the world. Soils formed directly from lava are usually low producing (and some may not fit the definition of an Andisol – see below).

Volcaniclastics are usually grouped into two main divisions of pyroclastic (explosive) and epiclastic (erosional) origin. Pyroclastics include the deposits of incandescent, high velocity gas charged clouds with entrained rocks and sand; close to source ballistics that include molten volcanic bombs or vesiculated scoria (or cinders); and aerially ejected particles that travel high into the atmosphere (tephra) before falling back to earth, usually cold. Tephra particles range from ash (<2 mm), to lapilli (2-64 mm), to blocks (solid) and bombs (molten) (>64 mm). Epiclastics include all the forms of volcaniclastic remobilization on the landscape post-deposition and include deposits from volcanic debris avalanches; volcanic mudflows, debris flows and hyper-concentrated streamflows (lahars); alluvium on the flanks of a volcano; and volcanic loess (deposited by the wind in more arid and high altitude environments). Of soils directly formed from lava, it is basaltic lavas that form the most extensive volcanic soil parent materials because of this lava's low viscosity and ability to flow large distances on low gradients.

Irrespective of the chemical composition of the volcanics, all will contain varying proportions of volcanic glass which provides the initial distinctive weathering products of this soil grouping. Generally the lower silica, higher mafic (high magnesium and iron) volcanics tend to weather more readily than the higher silica, lower mafic (high sodium and potassium) volcanics. Two other variables are the initial grain size and the vesicularity of the parent materials. For example, a dense, high silica rhyolite will weather considerably more slowly than a less dense and highly vesicular pumice of identical composition. This is mainly related to the much greater surface area available in the pumice to weather and break down to primary weathering products.

Volcanic soils are usually the dominant soil in young volcanic landscapes (but may be in association with lesser areas of other soils such as organic soils). Coarser textured soils tend to occur on the flanks of most stratovolcanoes, shield volcanoes and tuff cones, as well as in proximity to calderas, where they are usually pumice dominant. Surrounding the volcanoes and for large distances downwind there may be a wide variety of landscapes upon which finer ash has accumulated over thousands of years by tephra accretion. On surrounding lowlands the tephras may have accumulated to great thickness (from 1 to >10 m depth) producing deep fertile volcanic soils. In contrast, in hilly landscapes the tephras may be of variable thickness due to past erosional histories, more especially during the Last Glacial Maximum, leading to shallow bedrock and thinner soil profiles.

## 3. Distribution

Volcanic soils cover more than 124 million hectares of the Earth’s surface. The major areas of volcanic soils rim the Pacific where oceanic plate subduction produces extensive rhyolitic and andesitic volcanism. Major areas of volcanic soils occur in Chile, Peru, Ecuador, Colombia, Central America, the United States, Kamchatka, Japan, the Philippines, Indonesia, New Zealand, and the independent island states of the south-west Pacific. Basaltic volcanism dominates in the islands of the Pacific, Indian and Atlantic oceans where new lithosphere is being added to existing plates, such as in Iceland or where hot mantle plumes pierce through the lithosphere, as in Hawaii.

The second major area of volcanic soils extends along the East African Rift Valley where the Nubian and Somalian plates diverge, and through the Mediterranean region where the Nubian and European plates converge. The third significant region is in the equatorial Atlantic, principally comprising the Canary Islands and the Azores, plus the many islands of the West Indies, where volcanic soils are a major natural resource to the economies of many small island states.

## 4. Classification

An in-depth study and classification of volcanic soils received major attention in the second half of the 20th century. The aim was to quantitatively define what is meant by a volcanic soil, in particular in countries of the circum-Pacific margin. In Japan, these soils carried an unusually dark black topsoil (epipedon) assigned by the name “ando” or dark soil. Apparently, these black surface layers are not so much a result of the volcanic origin but of a property inherited from the original vegetation.

When the FAO/UNESCO (1974) Soil Map of the World was compiled, there was international agreement that volcanic soils be designated in their own order of **Andosols**. Key criteria included a low bulk density ($<0.85$ g cm$^{-3}$ in the < 2 mm fraction at – 33 kPa water retention); an exchange complex dominated by amorphous material; and/or ≥ 60% vitric volcanic ash, cinders or other vitric pyroclastic material in the profile. Four suborders were recognized, three of them being based on the nature of the organic horizon at the surface; they were distinguished into Mollic, Humic and Ochris Andosols. The fourth suborder identified the glassy or pumiceous Vitric Andosols. The FAO/UNESCO terminology is followed in this text, except where specific reference is made to Soil Taxonomy (1999).

The United States Soil Conservation Service had been contemporaneously devising a new system of soil classification, which at the time was internationally known as the Seventh Approximation. This system was published as Soil Taxonomy (1975), in which volcanic soils which were neither Entisols nor Podzols were grouped into the Inceptisols as a suborder of Andepts. Subsequently, as this system was applied outside of the United States, it became apparent that this placement did not allow sufficient information to be conveyed about climatic conditions which related to their expected behavior.

In 1978, it was proposed to elevate these soils to a new order of **Andisols** (maintaining the etymology of not using an "o" as a connecting vowel for words without Greek formative elements). This new name served to distinguish the United States soil order and the FAO/UNESCO term. An International Committee on the Classification of Andisols (ICOMAND) then worked over 12 years to elevate the suborder to order status and check out its validity at numerous locations around the world.

In the second edition of Soil Taxonomy (1999) the Andisols are recognized at the Order level as those soils having **andic soil properties** in more than 60% of the profile thickness, or are developed from cindery, fragmental or pumice materials, and do not fit the definition of Entisols or Histosols. The definition of andic soil properties recognizes the distinctive Andisol properties and attempts to define them quantitatively. In this revision, suborders now recognize distinctive anaerobic, very cold, tropical, arid, and seasonally dry environments, together with those soils derived from very glassy parent materials (that do not fit the andic criterion). The definition of andic soil properties is intended to recognize the limits in properties associated with Andisols.

A clear distinction is made between Andisols and Entisols in Soil Taxonomy (1999) because recently deposited volcaniclastics do not have andic soil properties; they cannot be inherited, rather they take time to develop. Hence an Andisol must show a degree of pedogenic alteration from its primary parent material. Clearly the alteration is an expression of weathering which produces a continuum of soils along which some threshold values have been chosen to define andic soil properties. So too, with advanced weathering andic soil properties may be lost with changes in soil profile development (e.g. podzolization) or clay mineralogy, (e.g. formation of Ultisols).

## 5. Distinctive Clay Mineralogical Properties

Volcanic glass is usually the first component of volcanic rocks to undergo weathering. Depending on its silica content it may be resistant (high silica) or susceptible (low silica) to degradation to clays. The clays that form first are very distinctive (but are not exclusive) to volcanic soils. They were originally thought to lack any crystalline structure because no distinctive peaks could be determined on x-ray diffraction analysis, and so were referred to as "amorphous" clays. Subsequently higher resolution techniques of differential x-ray diffraction, infra-red, differential thermal analysis, and electron microscopy have revealed four distinctive clays that are common to volcanic soils and show a "weak" degree of crystallinity that is referred to as "short range order". Hence they can be referred to as "short range order clays" (SROC).

The first of these SROCs to be identified was the aluminosilicate **allophane**. Under electron microscopy (EM) it can be identified by its indistinctive "grainy" appearance, but under high resolution EM it can be seen to comprise hollow spherules of 3.5-5.5 nm diameter. The thickness of the wall of the spherules is estimated to be 0.7 nm. A second aluminosilicate named **imogolite**, of similar composition to allophane, was identified by EM as a tubular, thread-like material with internal and external diameters of 1.0 and 2.0 nm respectively; so fine its wall thickness is only 5 atoms thick. Subsequently a third SROC named **proto-imogolite** has been identified as a precursor of imogolite. All have specific surface areas of about 1000 $m^2$ g.

Allophane is thought to form inside weathered glass fragments or pumice grains in which the hydrolysis of glass proceeds at a high silicon concentration and high pH, whereas imogolite is thought to form outside, possibly by alteration of allophane, being exposed to external solutions of lower silicon concentration and higher acidity, or by precipitation from such solutions. The potential transformation of these clays from one form to another under varying environmental conditions, and to other clays has been extensively debated in the literature. The generally accepted model would be that SROCs are intermediary steps between the hydrolysis of volcanic glass and feldspars to more ordered clay minerals like halloysite, kaolinite, gibbsite and montmorillonite.

A fourth SROC named **ferrihydrite**, is an iron hydroxide that weathers from intermediate and mafic glasses or from mafic crystals in the primary volcanic parent material. Its presence can be quantified by the difference between dithionite citrate-extractable and oxalate–extractable iron. Ferrihydrite has a surface chemistry that in many ways behaves like allophane.

In older volcanic soils that are in more advanced stages of weathering, halloysite and gibbsite appear more common as SROCs decrease. Ultimately smectites and chlorites may form pedogenically (or become incorporated from loess or aerosolic dusts). In unusual circumstances zeolites may also be important.

## 6. Distinctive Soil Physical Properties

The non-vitric Andosols usually show the highest subsoil macro-porosity values encountered within any mineral soils. A simple measurable expression of this property is its influence on overall bulk density ($\rho_B$). Most Andosols show $\rho_B$'s of $\leq 0.90$ g $cm^{-3}$ (or $\leq 0.90$ Mg $m^{-3}$) at 33 kPa water retention. This "lightness" of the soil has been referred to as giving the soils a "fluffy" character, which is expressed as a friable consistence. Its importance is in imparting to the soil excellent drainage properties because macropores drain readily under the influence of gravity (thus displaying a high saturated hydraulic conductivity), unlike micropores which hold water by stronger capillary forces. This can be measured as a high saturated hydraulic conductivity, which promotes rapid drainage at low tensions, ensuring a soil is free from excessive wetness.

Low $\rho_B$ , high macro-porous subsoils provide an excellent medium for plant roots where root hairs can extend relatively freely without limitation in a well aerated medium (Fig. 1). Plant roots actively respire and thus need to be in contact with gas-filled pores to supply the plant's needs. This is particularly advantageous in deep volcanic ash soils for deep rooting plants, such as kiwifruit. Low $\rho_B$ and non-swelling, non-sticky SROCs provide tolerance for animal foot traffic, retarding soil "pugging" (or puddling) by cows' hooves on dairying farms.

Figure 1. Egmont black loam, an Ochric Andosol from South Taranaki, New Zealand. The black topsoil is only 21 cm thick and overlies 1 m of yellow-brown loamy subsoil horizons with high macroporosity, high phosphate retention, and no impediments for plant root growth. Colored bars on the tape are in 10 cm intervals.

A second distinctive property of Andosols is a high water content at field capacity (plant-available water). Volcanic soils in perhumid tropical climates show extremely high gravimetric water contents of over 100% of the original mineral weight in a sample. However, much of this may be retained at a tension of > 1.5 MPa, so it is unavailable to plants. This combination of high water content and SROC mineralogy makes such soils greasy as distinct from sticky.

A third distinctive property is the marked difference in 1.5 MPa water retention between field moist and air-dried samples. This is thought to be a function of the SROCs in these soils which lose water irreversibly. It has been postulated that much of this water may be contained within the microspheres of allophane and once dried the spheres collapse, unable to be rehydrated back to their original size. Despite the higher organic matter contents of surface horizons, they do show lower 1.5-MPa water retentions than their subsoils, indicating that at some stage in their history they may have experienced severe drying.

A fourth distinctive property is for high SROC materials to behave as Bingham fluids. In Soil Taxonomy (1974) this was referred to as *thixotropy*. A more valuable measure for engineers is shear strength, and the ratio of the undisturbed to disturbed shear strength is taken as the sensitivity of a soil material. Volcanic soils have low to moderate sensitivities. Under normal circumstances the soil behaves as a solid, but under sudden pressure it may shear or liquefy for a brief period and flow. This makes such materials especially dangerous if used in civil engineering projects, unless the material is previously dried to remove the highly bound water (Fig. 2).

Figure 2. The chasm remaining from when a canal for a new hydroelectric scheme at Ruahihi, Bay of Plenty, New Zealand collapsed in 1981. The failure occurred within sensitive volcanic ashes, forming a flash flood in the adjoining valley (to the right).

A fifth property of some volcanic soils is the presence of paleosols (buried soils) at some depth within the soil profile. If there are no impediments for root growth above them, such paleosols may offer excellent nutrient sources and physical properties not available in the soil materials above. Figure 3 shows a Humic Andosol from West New Britain, Papua New Guinea, currently used for oil palm production.

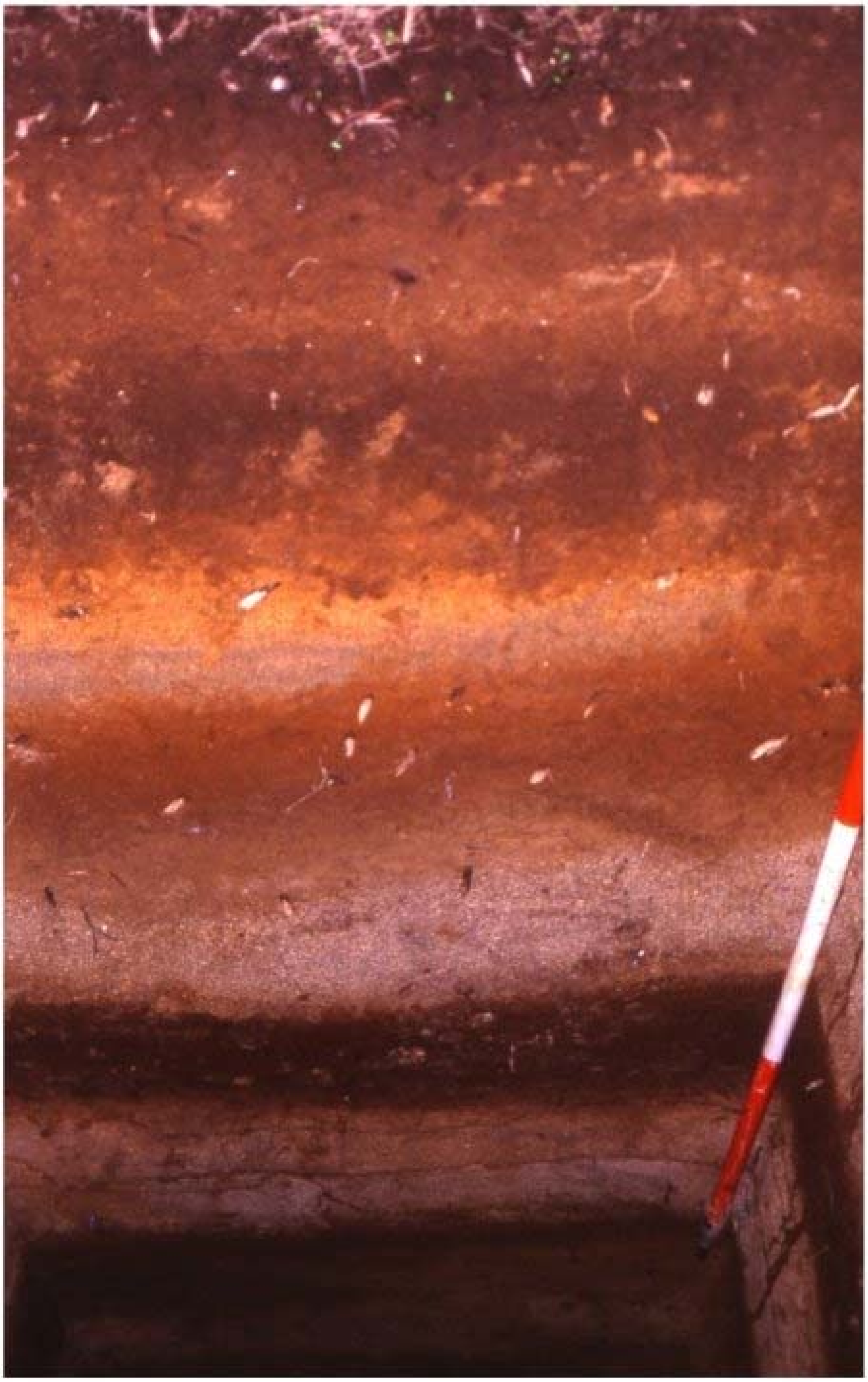

Figure 3. Humic Andosol from West New Britain, Papua New Guinea, currently used for oil palm production.

These soils have accumulated from numerous tephras erupted from the Pago-Witori volcano throughout the Holocene. The profile shows two thin creamy W-H tephras erupted in the last 1000 years within the present day soil. Beneath is a dark paleosol A horizon with a bright yellow-brown subsoil lying on the white pumice W-K 4, erupted between 1300 and 1500 yr BP. This overlies another paleosol resting on white pumice, W-K 3, erupted at 1800 yrs BP. Beneath is a black paleosol that contains Lapita pottery, which is developed on the white pumice W-K 2, dated at 3300 yrs BP. A further paleosol (at bottom of staff) rests on W-K 1 pumice, dated at 5600 yrs BP which is exposed in the base of the pit. The red and white divisions on the staff are at 50 cm intervals.

An unusual example from the eastern slopes of Popocatépetl, Mexico, demonstrates this. Here, the pumice soil from eruptions over the last 2200 years was low in organic matter and quite inferior to a paleosol at 2-3 m depth. The farmer sold the rights for pumice mining on his property, a company mined the pumice, and the farmer now cultivates the paleosol for maize 2-3 m below the former ground surface ( Fig. 4).

Figure 4. View east of Popocatépetl, Mexico, showing a field where a farmer is plowing maize stubble grown on a paleosol formerly 2-3 m below the land surface. The surrounding cliff shows the extent to which the former surface pumice soil (which was less fertile than the paleosol), was mined and used as aggregate.

Some volcanic soils show deep black topsoils. In Japan these are known as *Kurobokudo* and occur extensively on Hokkaido. The average content of humus in virgin soils may attain 20%. This is attributed to herbaceous plants (Gramineae) contributing to the carbon accumulation. In Ecuador, similar thick (>1.5 m) topsoils reflect a long history of human occupation and agriculture (Fig. 5) as evidenced from the many fragments of rags, brick, stones, artifacts and charcoal. Such high organic matter horizons may not display all the physical and chemical properties of a volcanic soil, but can be distinguished from other topsoils by their high content of aluminum-humus complexes.

Figure 5: A Mollic Andosol from the Machachi area, just south of Quito, Ecuador. The blue tape shows white 10 cm divisions and meter marks. The thick black topsoil extends to 1.5 m depth, and preserves a white pumice bed between 75 and 84 cm depth, probably erupted from Cotopaxi.

The Vitric Andosols do not show the above properties to other than a mild degree. Dominated by pumice or vitric sand (Fig. 6) they usually have much lower SROC levels and lower water holding capacity.

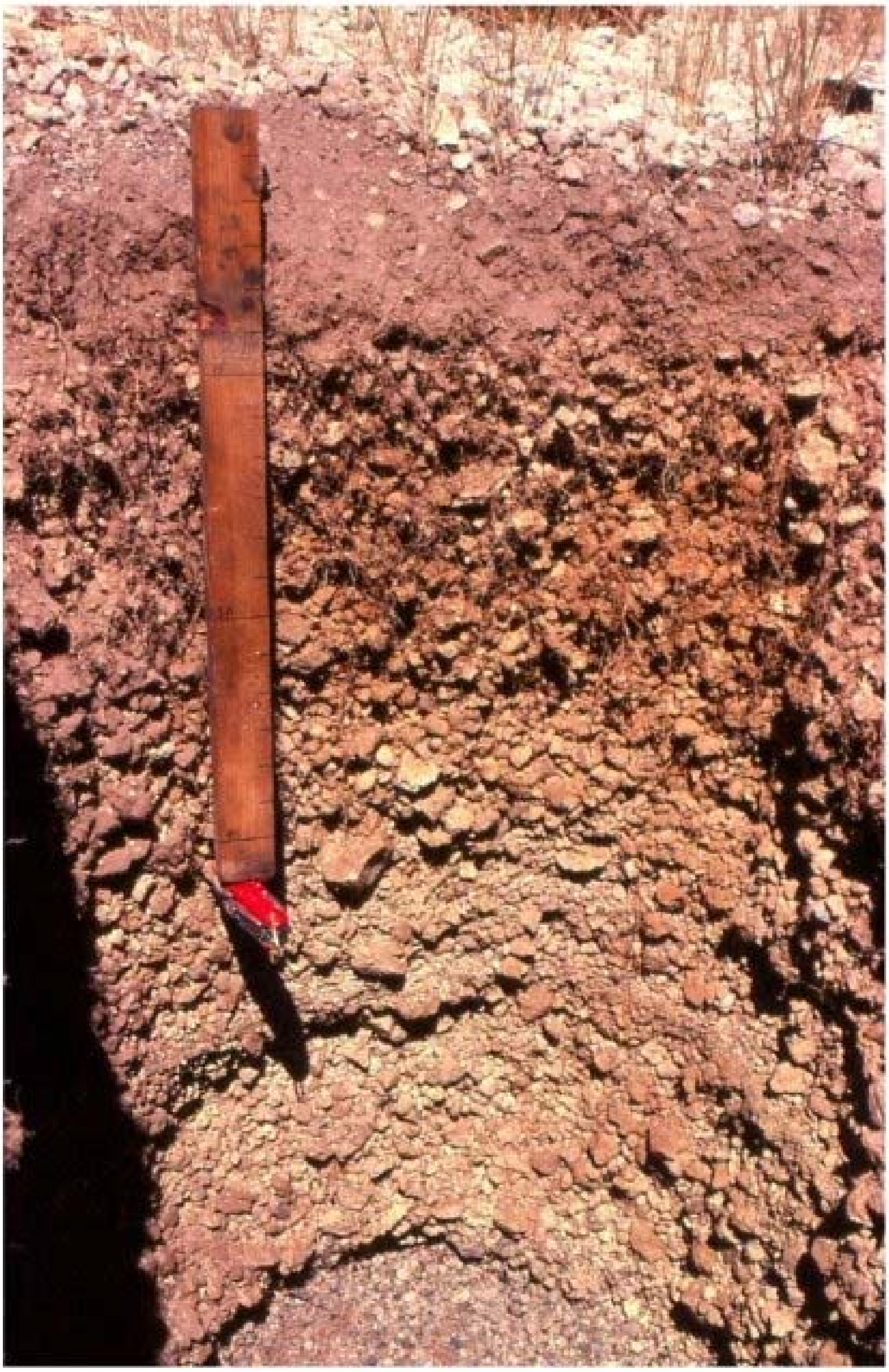

Figure 6. A Vitric Andosol from near Mammoth Lakes, California, U.S.A. This soil is developed within a 720 yr BP pumice tephra from the Inyo Volcanic Chain. Note the low organic matter content of the topsoil and the thin vegetative cover. Wooden rule is 50 cm long.

## 7. Distinctive Soil Chemical Properties

The distinctive SROCs that imbue soils with andic soil properties are amphoteric. They tend to be positively charged under acid conditions but become negatively charged at higher pH. Thus these soils are referred to as **soils with variable charge**. The pH at which the net charge on the surface is zero is referred to as the isoelectric point or the zero point of charge (ZPC). The ZPC shifts to higher pH as the Si/Al or $SiO_2$/sesquioxide ratios decrease. The significance of these chemical properties is that at low pH these soils have a low capacity to retain cations and may be deemed infertile except for acid tolerant species. Aluminum-humus complexes dominating under these conditions may cause aluminum toxicity. However upon liming, farmers can raise the pH and thus raise the cation status or fertility of the soil to a degree not possible in other soils.

Two measures of the variable charge in a volcanic soil are ΔpH and effective cation exchange capacity (ECEC). ΔpH is a measure of the soil pH in KCl and in $H_2O$. ECEC is the difference in the cation exchange capacity (CEC) between the soil's natural pH and when the CEC is determined in $BaCl_2$ at a pH of 8.2 (when a measure is obtained of the maximum CEC the soil could sustain). Blakemore, in 1978, proposed this feature be used as a criterion of andic soil properties. Whilst it was not adopted, the following measure is an index of variable charge

$$\frac{\mathrm{CEC}_{\mathrm{pH=8.2}} \text{ - Sum of bases + KCl extractable Al}}{\mathrm{CEC}_{\mathrm{pH=8.2}}} \geq 0.7$$

For volcanic soils with large amounts of relatively unweathered volcanic glass (often colloquially referred to as **vitric soil properties**), Soil Taxonomy version 1999 expects there to also be specific amounts of aluminum and iron (extracted by ammonium oxalate) to satisfy the criterion of andic soil properties. This is to distinguish volcanic Entisols which show little or no pedogenic alteration from Andisols with their characteristic weathering products.

A third key property of most volcanic soils is their propensity to adsorb phosphate from solution. An exception is when there is a high $SiO_2/Al_2O_3$ ratio or high base saturation. A phosphate retention test was devised in New Zealand whereby a sample of soil was shaken with a high phosphate concentration solution over 18 hours to determine the amount of adsorption by the soil. In many cases with a high SROC content the soil can adsorb 99% of the phosphate added. Unlike most other soils, volcanic soils usually have a phosphate retention of >85%. The test has become a criterion for andic soil properties as well as a proxy for the amount of volcanic parent material in a soil which has practical significance for fertilizer applications. (It is recognized that anomalously high P retention values can sometimes be also found in the Bs horizons of podzols and in the Bw horizons of some Inceptisols in superhumid climates.)

A simple field test that can be used to determine the presence of SROCs in volcanic soils was devised by Fieldes and Perrott in 1966. It is based on a unique property of the surface chemistry of SROCs where Al in the clay bonds to hydroxyl ions from the soil solution. The Al bond is known to have a high affinity for F ions, so if a few drops of

NaF are added to the soil on a piece of filter paper, the F ions displace the hydroxyls. This leads to a rapid increase in pH. If the filter paper has been previously soaked in phenylphthalein and then dried, the pH increase can be detected visually by the bright blood red response around the soil on the filter paper, usually within 2 minutes. Besides being a very useful field method, the pH response can also be measured accurately in the laboratory with a pH meter.

## 8. Land Use and Use Limitations

### 8.1. Physical Limitations to Plant Growth in Volcanic Soils

Limitations to plant growth in volcanic soils may be climatic, physical or chemical. Climatic extremes include aridity, recognized in volcanic soils having aridic or xeric moisture regimes. These soils occur in such diverse countries as Syria, Greece, Peru, and Chile. Other climatic limitations include severe cold (Cryands in Soil Taxonomy, 1999), these being mainly limited to the Northern Hemisphere north of $49^o$ N, such as the volcanic soils in Alaska, Iceland, and the Kamchatka Peninsula of eastern Russia.

Many volcanic soils have excellent soil physical properties that make them highly desirable for a wide range of land uses. However, in some areas certain soil physical properties can limit productivity. The first is a high water table (Aquands in Soil Taxonomy, 1999). In some volcanic environments, such as on debris avalanche fields with numerous closed depressions or on low terraces in basins such as the *niadi* of Chile, there may be poor or imperfect drainage that leads to waterlogged volcanic soils. Whilst these may be advantageous for paddy rice, the presence of a high water table for longer periods of the year than their well drained counterparts leads to lower soil oxygen levels, severely limiting deep rooting plants. An obvious remedy is to install drainage.

The types of drainage vary according to the economics of the land use enterprise. They may vary from open cut drains, installed either by hand or trenching equipment, to installation of clay tiles (hollow pipes), or plastic perforated piping, as seen on numerous dairy farms in Taranaki, New Zealand. A distinct feature of poor drainage in volcanic soils is the lack of distinct graying (gleying) of the subsoil as seen in other soils. This is due to the high iron contents of many volcanic parent materials that retard the visual graying (removal of iron) in the gleying process. To overcome this situation, specific criteria were devised in Soil Taxonomy (1999), such as determination of ferrous iron using an α, α’-dipyridyl field test.

A second limiting soil physical property is the high proportion of pumice or scoria (also called cinders) encountered in some soil profiles. Not only does this convey a coarse texture but it also implies the dominance of largely unweathered volcanic glass (vitric soil properties) in the sand and silt fractions. The coarse texture reduces the soil water storage capacity under dry conditions (lowering the field capacity and wilting point). It has, however, been recognized that pumice does not behave like sand and that there is often a film of water stored in the micro-vesicles of pumice that may be accessible to trees or deep rooting crops.

One aspect that accentuates the vitric property in a soil is the common occurrence of glass selvedges around minerals in the sand and silt fractions that then dominate the surface weathering processes in the soil, rather than the mafic or felsic mineral grain beneath. Sharp, angular grains of volcanic glass inhibit the passage of soft bodied soil invertebrates (e.g. earthworms), reducing the quantity and biodiversity of soil organisms, particularly in subsoils.

A third limiting soil physical property is the presence of impenetrable horizons within a soil profile. Despite having excellent soil physical properties both above and beneath, the presence of either a placic, duric or petrocalcic horizon, or a paralithic or lithic contact prevents further plant root penetration, thus limiting the ability of plants to reach their full capability. Placic horizons are generally found in higher rainfall environments (above 1800 mm mean annual rainfall) where they form a thin, iron cemented and highly irregular feature in well drained soils. They thicken in progressively higher rainfall environments.

Duric and petrocalcic horizons are usually found in drier environments, where in the latter case calcium carbonate has not been leached from the soil-forming environment. Petrocalcic horizons, called *cangagua* in Ecuador or *caliche* in the western United States, can be a major limiting factor for plant growth. In many countries, such as New Zealand, cemented lahar or debris avalanche deposits form paralithic or lithic contacts beneath an upper soil possessing andic soil properties.

There are a very wide range of chemical (soil fertility) limitations in volcanic soils, most of which are nutrient deficiencies. These are discussed below under each land use.

### 8.2. Limitations to Pastures and Rangeland

Large areas of volcanic soils are used for grassland farming (to rear dairy cows, cattle and to a lesser extent sheep, deer, and horses) in Iceland, the United States, Chile, Argentina and New Zealand. In these settings there are few soil physical limitations (except for tolerance to cold), but two major groups of chemical limitations. The first are limitations to plant growth, the second for animal health.

The first major requirement in grassland farming is adequate nitrogen for healthy grass growth. This is not always readily available, especially on younger volcanic parent materials where time was not insufficient for build up of nitrogen in the soil. In natural ecosystems, there are often indigenous plant species that fix nitrogen in a serial succession to more nitrogen-demanding plants. Examples include *Dryas* in the Northern Hemisphere and *Coriaria* in Asia and the Southern Hemisphere. In grassland ecosystems nodulated clovers are usually seeded with the grass to provide adequate nitrogen for grass growth. However, increasingly intensive agricultural systems, especially dairying, find it economic to add nitrogenous fertilizers to enhance grass growth.

To ensure adequate clover and grass growth, additions of phosphorus may be required. Because most volcanic soils show a high phosphate retention there is an immediate competition between the plant roots and the soil for any added phosphate. Much added phosphate is therefore irreversibly bound to the soil colloid, and never becomes available to plants. This leads to higher rates of phosphatic fertilizers being applied than would occur on other soils. A traditional P fertilizer has been the readily soluble form "superphosphate" (monocalcium phosphate monohydrate). Slower dissolving rock phosphates may supply plant available P over longer time periods.

On many basaltic and andesitic parent materials, soils may be limiting in K, a usual symptom showing as yellow chlorotic spots on clover leaves. On many andesitic and rhyolitic parent materials Mg and S may also limit grass growth.

One of the curious features of volcanic parent materials is the varying array of macro- and micronutrients available as the silica content varies. This can be related to a process of magmatic differentiation, whereby low silica magmas are high in iron, magnesium, chromium, nickel, cobalt, etc. and low silica magmas are low in these elements. This leads to widespread elemental deficiencies, particularly in rhyolitic parent materials, that can affect herbage and animal health. A classic example is the low cobalt in the pumice soils of the Central North Island of New Zealand, which leads to low cobalt levels in soils and herbage, and to a deficiency in ruminants. Lack of cobalt interferes with vitamin 12 synthesis and absorption in the animal gut, and leads to a wasting disease known as "bush sickness". Cobalt sulfate can be added in fertilizers to overcome this problem.

Many other elements may also be low in volcanic soils. Selenium deficiency is common, causing *white muscle disease* in young lambs, poor live weight gain in cattle, and sometimes even human health problems. Copper deficiency leads to bone fractures and eventual lameness or *swayback*, connective tissue lesions, and retarded growth.

A common occurrence on dairy farms is magnesium deficiency (hypomagnesemia or "grass staggers"). This is particularly accentuated in late winter and spring time during calving when maximum stress is exerted on a cow's body. Low magnesium induces ill health and may be fatal to both calve and mother. Simple addition of dolomite or magnesite with fertilizers or as a dusting on pastures or in food will prevent or overcome the problem. Very low magnesium levels on pumice soils have even caused hypomagnesemia in sheep.

An unusual type of a deficiency is found on the soils formed on Rotomahana Mud, ejected from a hydrothermal system beneath a lake during the 1886 AD eruption of Mt Tarawera in New Zealand. The soils are very high in molybdenum due to the unusual mineralogy of the mud, and this induces copper deficiency in animals farmed on these soils.

Another identified deficiency is insufficient sodium on pumice soils. In one case sodium supplementation led to large responses for both sheep and cattle. Calcium deficiency has been reported as causing malformed teeth in horses grazing pumice soils.

Iodine deficiency is reported as causing goitre in young lambs grazing some volcanic soils. Near active volcanoes, fluorine toxicity can be a problem for both animals and humans. The eruptions of Laki, Iceland, in 1783-84 led to widespread fluorine poisoning whereby the country lost 50% of its cattle, 76% of its horses and 79% of its sheep; ultimately, 20% of the human population died of starvation. Large sheep losses were recorded from the eruption of Mt Hudson in Chile in 1991 and from Mt Ruapehu, New Zealand, in 1995.

## 8.3. Limitations to Arable Cropping

Volcanic soils have excellent properties for widespread cropping, particularly on arable land (i.e. where agricultural machinery can be used). The most widespread crop to be grown is probably maize or corn. Since maize is the staple food for many countries in South America, it is grown even on very steep slopes in the high Andes if the volcanic soils are fertile. Increased yields have resulted from zinc applications in Costa Rica. Wheat, barley, beet, groundnuts and brassicas are also cropped on volcanic soils, more particularly in South America.

Elemental difficulties encountered in cropping of volcanic soils include boron deficiency on pumice soils in New Zealand, and potassium deficiency in a small area of volcanic soils in the Mt Gambier region of Australia. Trials of sorghum on a volcanic soil in Costa Rica showed phosphorus was the principal limiting element, followed by potassium. To overcome water-shortage conditions, deeper rooting crops may be planted that find moisture in the deeper soil layers.

In Rwanda, with the highest population densities in Africa, volcanic soils cover 700 km$^2$, providing a vital food resource. Cultivated crops here include maize, sorghum, potatoes, pyrethrum, and peas, along with bamboo and eucalypts.

## 8.4. Limitations to Estate Cropping

In Java, tea is grown on high altitude volcanic soils. Deficiencies recognized in this environment include nitrogen, potassium, magnesium, sulfur, phosphorus, and zinc. In 1982 the volcanic ash from the eruption of Mt Galunggung provided sufficient magnesium for one or two seasons before further Mg fertilizer additions were required in the tea plantations around Bandung in Java.

At lower altitudes in Indonesia, Papua New Guinea, Colombia, and Central America the most widespread crop is coffee. On volcanic soils in Costa Rica this crop requires adequate boron, magnesium and zinc. Of lesser extent in many tropical countries, cacao or cocoa is also grown.

Increasing areas of tropical volcanic soils are being planted in oil palm. The natural physical and chemical fertility of these soils in Ecuador, Costa Rica, Cameroon, and Papua New Guinea has made them highly suited to this crop. As the planted area expands, the wetter Andosols (Aquands in Soil Taxonomy, 1999) are proving particularly highly productive after drainage. Only nitrogen and magnesium seems to be limiting for oil palm.

In certain countries much sugar cane is produced on volcanic soils e.g. Hawaii and the West Indies. Liming of such soils has led to increased sugar cane yields in Costa Rica.

On the Pacific Islands, coconut is grown for copra production on many volcanic soils, yet seldom are nutrient deficiencies recognized, probably because of the low profit margins. Tobacco is reported on volcanic soils from Indonesia to western Sudan, where heart-shaped leaves show a boron deficiency. Rubber is also grown on the volcanic soils in the Cameroon.

### 8.5. Limitations to Horticulture

Volcanic soils are ideal for vegetable production ("market gardening") because of the high subsoil macroporosity. This encourages root vegetables including potatoes, carrots, onions, turnips and swedes, to expand without limit in a freely drained subsoil environment. In New Zealand this is best achieved at altitudes which experience winter frost that kills off pests and diseases. Without winter frost fungal diseases such as mildew are a limitation for vegetable production.

In tropical regions a wide range of vegetables are grown, including taro or dalo, tapioca (cassava or manioc), yams, sweet potatoes, beans (havas) and fresh leafy vegetables such as lettuce and cabbages. Potatoes are commonly grown throughout Central and South America where N and P fertilizers increase yields, as is the case with broccoli. Potatoes grown in volcanic soils in Java require large amounts of organic matter, which is thought to counteract aluminum toxicity. Tomatoes are widely grown as well on these soils.

Boron deficiency is cited as a common problem, especially in lettuce in Japan and brassicas in New Zealand. Other deficiencies induced in vegetables growing on volcanic soils include molybdenum, silicon, manganese and iron.

Volcanic soils also offer few limitations for a wide variety of fruit plants including pipfruits, stonefruits, berries, kiwis, avocados, tamarillos, citrus, feijoas, peppers and nursery plants. Chlorosis on fruit trees on volcanic soils in western Sudan may be due to a zinc deficiency. Wine grapes are grown on the volcanic soils of southern Italy, Santorini (Greece), Washington, Oregon and California states and in localized areas of coastal New Zealand.

In frost-free climates the combination of free-draining soil and a (iso)thermic temperature regime provides ideal conditions for subtropical fruit production, e,g, avocadoes. In hyperthermic and isothermic regions traditional tropical fruits such as pineapples (e.g. in the Philippines), bananas (e.g. in Ecuador), pawpaws or papayas (e.g. throughout the South Pacific), mangoes, ginger, and cut flowers grow well on volcanic soils that offer few limitations other than some selected N, P, K, ±Mg-fertilizer applications and sometimes irrigation. The principal advantage gained from these soils is the lack of impediments to plant roots and the low bulk density (high macrospores) allowing for unlimited root penetration.

Occasionally, however, unexpected problems may be encountered. One such example from the Bay of Plenty in New Zealand occurred where a local by-law allowed only land below a threshold average angle of slope to be subdivided for housing development when the kiwifruit industry peaked. This led to heavy machinery re-contouring the land to reduce the average angle of slope and fulfill this slope requirement but also led to complete mixing of the soil and subsoil materials. Where kiwifruit roots encountered any buried high organic matter topsoil materials they usually died due to the anaerobic conditions around these displaced materials.

In some of the small island states of the South Pacific, yagona (*Piper methysticum*) is grown extensively on volcanic soils, from which the root is powdered and used to make the traditional celebratory drink kava, which contains an alkaloid active ingredient. Small areas of cashew, vanilla, cinnamon and other spices also occur.

### 8.6. Limitations to Paddy Rice Cultivation

In many parts of Indonesia, the Philippines, and to a lesser extent Japan, cultivation of paddy rice is practiced on volcanic soils. Without modification, paddy soils from volcanic ash in Japan produce very low yields, compared with the higher productivity in Java and Luzon. The obvious constraint is their high porosity, and to overcome this problem in Japan the addition of bentonite at a rate of 10 tons/ha has been found effective. Under wetland rice cultivation, volcanic soils gradually form iron and manganese oxide horizons and a plow pan, whereas overall soil structure often changes from crumb to blocky.

Enrichment of bases and silica is reported in paddy soils from volcanic ash due to the anaerobic conditions. There is evidence that the silica is then adsorbed on active sites reducing phosphate fixation by 10-20%, and reducing active aluminum. There is also much less retention of $NH_4^+$ and $K^+$, leading to increased nitrogen absorption in the early stages of plant growth.

An unusual problem identified in northern and central Hinshu, Japan, is iodine toxicity. The problem in the rice is called "*Kaiden Akogare*" and seems to occur in newly constructed paddy fields after 2 or 3 years of cultivation. This occurs when the water soluble iodine in the soil and the alkali-soluble iodine in the plant exceed 1 and 30 ppm respectively. The explanation given for this phenomenon is that under free-draining conditions the $I_2$ is adsorbed on humus, but under reducing conditions it becomes reduced to $I^-$ and appears in the soil solution. Over time, the iodide is removed by leaching and the toxicity is overcome.

### 8.7. Limitations to Forestry

The low bulk density of most volcanic soils makes them ideal media for tree growth. However, in many countries the soils are far too valuable for food production for economic forestry to take hold. A lack of impediments in most volcanic soils allows tree roots to penetrate up to 6 m depth for accessing water and nutrients. In addition, the high moisture holding capacity of these soils, including those with vitric properties (due to the micro-vesicles), makes them also highly suitable for deep rooting plants. Usually, only Vitric Andosols or those situated in hill country are preserved for forestry.

Physical limitations for tree growth include shallow depth to bedrock, particularly in hill country, while also marked variances in water content can be a cause for landsliding and reduction of depth, particularly in higher rainfall areas. A second impediment occurs where the primary volcanic material shows degrees of welding from heat of emplacement. This is a limitation for establishment of *Pinus radiata* (Monterey pine) in Vitric Andosols of the Central North Island of New Zealand. Low thermal conductivity is reported as a problem in central Oregon, USA, where wide temperature variations at the soil surface cause vitric soils to remain cold for longer periods. This may lead to frost heaving and accumulation of cold air in basins retarding germination. Under natural forest conditions these frost-hollows may be poorly stocked or treeless.

A lack of organic matter, and of nitrogen in particular, can be a major limitation to forestry on volcanic soils. Besides applying N fertilizers, forestry managers use lupins or tree lupins at seedling establishment (sometimes before) to overcome this problem during initial growth. When replanting, nitrogen deficiency is more readily overcome by leaving logging waste and litter on site.

On New Zealand Vitric Andosols magnesium is limiting tree growth. This is naturally overcome by *Pinus radiata* when roots are able to exploit paleosols beneath younger pumice layers to extract the requisite nutrients; otherwise magnesium fertilizers may be aerially applied. Other nutrient deficiencies registered in forests on volcanic soils refer to phosphorus and sulfur (central Oregon, USA). Copper deficiency causing chlorosis in cypress trees is reported from volcanic soils in western Sudan.

In Ecuador the many volcanic soils along the Andean corridor occur in a myriad of climatic microenvironments, some of which are on sufficiently steep slopes to create serious erosion problems. In 1980 ORSTOM produced soil maps showing forestry suitability, taking into account the tolerance of a wide range of forest trees used for stabilizing hillsides and for promoting soil conservation.

## 8.8. Limitations for Engineering

Volcanic soils, particularly those with andic soil properties, are unique for engineering purposes. Some of these properties have been identified earlier, such as low bulk density and changes in water retention between field and dried samples. Another feature is the change in grain size and an increase in bulk density between field moist and dried soil samples, giving differing engineering predictions of the soil behavior. Some tropical soils can in fact change irreversibly from a smeary gel at field water content to an apparent sandy soil with no cohesion when air dry.

A key property imparted by the SROCs is a high natural water content, which can sometimes be expressed by squeezing the sample. This property has incorrectly been referred to as *thixotropy* or smeariness, and it can render many soils unsuitable for construction purposes or as a fill. This relates to soil plasticity. The plastic limit is defined as the gravimetric water content at which a soil changes from a semi-solid to a plastic body. It reaches the liquid limit when the behavior changes from plastic to liquid. The difference in gravimetric water content between the two limits is the plasticity index, the water content over which a soil exhibits plastic behavior. Two characteristics that separate volcanic soils with andic properties from all other soils are:

- a large decrease in plasticity upon drying, and
- a high liquid limit compared with the plasticity index.

In the former, the plasticity index may become zero as the liquid and plastic limits approach the same water content after a sample has been dried. In the latter the liquid limit is generally > 70%. Often, road engineers will dry the andic soil materials in the sun to irreversibly reduce water contents or apply calcined lime (CaO) to create an exothermic dehydration reaction. Volcanic soils with vitric soil properties lack smeariness and show lesser degrees of the above properties.

For engineering purposes many soils are compacted to increase the soil strength and/or decrease the permeability. This leads to an increase in bulk density, a decrease in porosity and a smaller average pore size. Volcanic soils show poor compactability, but this property can often be overcome by drying. Large changes in cohesion and friction angle can be induced upon drying, to make the material more suitable for engineering purposes.

## 9. Environmental Considerations

An environmental consequence of fertilizer additions to volcanic soils is the ready leaching of nitrates into waterways, causing eutrophication. When environmental degradation passes a threshold, such consequences usually lead to changes in land use. In New Zealand concerns about the water quality of Lake Taupo deteriorating from an increase in dairy farming in its immediate neighborhood is leading to a shift back to a variety of forestry practices. Ninety three per cent of the manageable nitrogen entering the lake comes from stock effluent. Whilst *Pinus radiata* is the main timber producing tree on nearby pumice soils, suggestions for future plantings have included the planting of willow for bio-diesel production. Here and elsewhere, planting of riparian strips to reduce surface runoff and access by farmed animals is considered a primary goal to reduce eutrophication.

Phosphate from surface runoff of applied phosphate fertilizers P, P-enriched soil particles, or from organic manure, is the other major contributor to eutrophication of rivers and lakes. Most phosphate applied to volcanic soils is, however, tightly held by the soils and only little is leached through the soil to ground waters. This is in marked contrast to some non-volcanic soils. Thus, of increasing interest is the value of high SROC soils for sewage treatment to remove high P loadings, especially from larger inland metropolitan centers discharging to rivers or to dispose treated urban sewage or agricultural and industrial effluents onto pastures or in forests on volcanic soils.

Whilst fluvial erosion of volcanic soils in hill or steep relief can be no different to other soils, unconsolidated loose pumice is subject to the formation of subsurface tunnels and massive landslide failures. They are particularly vulnerable to extreme rainfall events when massive underground failures can occur.

In higher altitude environments, such as in the high Andes of Ecuador and Peru, wind erosion is also prevalent. Here, where there is no vegetation cover, loose, low density volcanic particles are readily carried by saltation to form local sand dunes. Above 3,100 m elevation, north of Popocatépetl in Mexico, redeposited andesitic soils are named *toba* sediments. Such processes most often occur in aridic and xeric moisture regimes.

## 10. Envoi

Coupled with the relative fertility of the world's volcanic soils, which encourage high rates of food production and population growth, comes the risk of further volcanic activity. It is ironic that some of the highest value soils on Earth also happen to be in the most volcanically hazardous areas on the globe. This interplay will always exist, but with refined volcanic monitoring techniques it is to be hoped that early warnings will avoid loss of life and enable those farming the land to continue to produce their crops sustainably with minimal interruption.

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## Glossary

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| **Allophane:** | Amorphous hydrated aluminosilicate. A mixture of irregular clay units belonging to the aluminosilicates with the chemical formula $1.0\text{-}2.0\ SiO_2 \cdot Al_2O_3 \cdot 2.5\text{-}3.0 \cdot H_2O$ and which because of lack of structure appear amorphous to x-ray diffraction. |
| **Andic soil properties:** | Soil properties including one or more of the following : aluminum plus half the ammonium extractable iron in the soil is at least 2%, and fine earth fraction holds at least 5% of volcanic glass; bulk density 0.9 g/cm3 or more; phosphate retention greater than 85%; at least 60% volcano-clastic material in the soil, and fine earth fraction contains at least 30% of volcanic glass (FAO). A measure of the development of unique physical and chemical properties attributed to soils weathered from a volcanic parent material in U.S. Soil Taxonomy (1999). |
| **Andisol:** | A volcanic soil with andic soil properties recognized under the U.S. Soil Taxonomy (1999). |
| **Andosol:** | A volcanic soil recognized in FAO/UNESCO Soil Map of the World. |
| **Ferrihydrite:** | A short range order iron hydroxide with the chemical formula $5Fe_2O_3 \cdot 9H_2O$. |
| **Imogolite:** | Paracrystalline aluminosilicate and a stage in the evolution of amorphous allophane to crystalline halloysite with loss of silica in the soluble form; a short range order clay mineral belonging to the aluminosilicates with the chemical formula $SiO_2 \cdot Al_2O_3 \cdot 2H_2O$. |
| **Lahar:** | A volcanic mudflow or debris flow. Usually a rapidly flowing mixture of rock debris and water, other than normal stream flow, ranging from hyper-concentrated flood flows to cohesive debris flows. |

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| **Macroporosity:** | A measure of the percentage of pores >60 um in a soil. |
| **Phosphate retention:** | A laboratory measure of the propensity of a soil to adsorb phosphate from solution over a 16 hour period; a good measure of the amount of short range order clays in a soil. |
| **Plasticity:** | A measure of the extent to which a soil behaves in a plastic manner. The property can be measured as a **plasticity index** which is the difference in water weight between when a soil changes from a semi-solid to a plastic state, and when it changes from a plastic to a liquid state. Volcanic soils show a large decrease in plasticity index upon the soil being dried. |
| **Short range order clays:** | Poorly crystalline aluminosilicates and iron oxides that represent the initial weathering stage of volcanic minerals and volcanic glass. |
| **Tephra:** | All the fragmental ejecta from a volcanic eruption expelled through the air, irrespective of size. |
| **Thixotropy:** | Property of certain very viscous or very wet substances to liquefy on shaking, then to return to the original state when left aside; applied to Andosols it means that a small portion of the moist soil, when subjected to a certain pressure between the fingers, collapses, suddenly freeing water or a non-sticky fluid. |
| **Variable charge:** | A natural property of volcanic soils to change their net surface charge with changes in pH (also known as amphoteric). |
| **Vitric soil properties:** | The dominant presence in a soil of volcanic glass, pumice or cinders. |

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## Biographical Sketch

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His principal research interests during his career have centered on volcanic deposits, volcanic soils, volcanic hazards, and more recently volcanic risk. He has worked on volcanic soils in the U.S.A., Fiji, Papua New Guinea and New Zealand, including recent research associated with archaeological sites and artifacts found within volcanic ash (extending back to 40,000 years ago in PNG). He has produced a number of maps of volcanic soils, as well as Quaternary volcanic maps and volcanic hazard maps. For his research work he received the McKay Hammer Award and the Hochstetter Lectureship of the Geological Society of New Zealand; the Norman Taylor Award of the NZ Society of Soil Science; and a NZ Science and Technology Medal from the New Zealand Government. He is a former deputy chair of New

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