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### **33.3 Andisols**

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#### **33.3.1 Introduction**

Andisols are soils that typically form in loose volcanic ejecta (tephra) such as volcanic ash, cinders, or pumice. They are characterized by andic properties that include physical, chemical, and mineralogical properties that are fundamentally different from those of soils of other orders. These differences resulted in a proposal to recognize these soils at the highest level in the USDA soil classification system (Smith, 1978). In 1990, Andisols were added to *Soil Taxonomy* as the 11th soil order (Soil Survey Staff 1990; Parfitt and Clayden, 1991). A very similar taxonomic grouping, Andosols, is one of the 32 soil reference groups recognized in the World Reference Base for Soil Resources (IUSS Working Group, 2006). Andisols (and Andosols) are classified on the basis of selected chemical, physical, and mineralogical properties acquired through weathering and not on parent material alone. Both soil names relate to two Japanese words, *anshokudo* meaning "dark colored soil" (*an*, dark; *shoku*, color or tint; *do*, soil) and *ando* meaning "dark soil". *Ando* was adopted into western soil science literature in 1947 (Simonson, 1979).

The central concept of Andisols is one of deep soils commonly with depositional stratification developing mainly from ash, pumice, cinders (scoria), or other explosively erupted, fragmental volcanic material (referred to collectively as tephra) and volcanoclastic or reworked materials. Andisols occur much less commonly on lavas. Unlike many other soils, Andisol profiles commonly undergo “upbuilding pedogenesis” as younger tephra materials are deposited on top of older ones. The resulting profile character is determined by the interplay between the rate at which tephra are added to the land surface and classical “topdown” processes that form soil horizons. Understanding Andisol genesis in many instances thus requires a stratigraphic approach combined with an appreciation of buried soil horizons and polygenesis.

The coarser fractions of Andisols are often dominated by volcanic glass. This glass weathers relatively quickly to yield a fine colloidal or nanoscale fraction (1–100 nm) dominated by short-range order materials composed of “active” Al, Si, Fe, and organic matter, especially humus. Although previously described as “amorphous”, short-range order materials comprise extremely tiny but structured nanominerals, the main ones being allophane and ferrihydrite (Hochella, 2008). A useful collective descriptor for them is “nanocrystalline” (Michel et al., 2007). Another colloidal constituent, imogolite, comprises long filamental tubes and therefore has both short- and long-range order (Churchman, 2000). The nanominerals, chiefly allophane, ferrihydrite, and metal-humus complexes, are responsible for many of the unique properties exhibited by Andisols.

Despite covering less of the global ice-free land area than any other soil order (~1%), Andisols generally support high population densities, about 10% of the world’s population (Ping, 2000). This is because they typically have exceptional physical properties for plant growth and, in many localities high native fertility because relatively frequent additions of tephra can renew potential nutrient sources (Ugolini and Dahlgren, 2002; Dahlgren et al., 2004). The majority of Andisols occur in humid regions where there is adequate rainfall. Andisols often have high organic carbon contents. These and other factors make Andisols generally well suited for agriculture production and historically allowed establishment of non-shifting agricultural practices. Despite their generally favorable properties for plant growth, Andisols do pose some engineering and fertility challenges. These soils have low bulk densities, resulting in low weight-bearing capacity. Andisols also exhibit thixotropy and

sensitivity, properties that cause them to behave in a fluid-like manner when loading pressures are applied (Neall, 2006; Arnalds, 2008). Andisols may exhibit substantial fertility limitations, including P fixation, low contents of exchangeable bases (especially K) and other nutrients, and strong acidity and Al toxicity (Shoji and Takahashi, 2002; Dahlgren et al., 2004; Lowe and Palmer, 2005).

### **33.3.2 Geographic Distribution**

Andisols cover approximately 124 million hectares or about 0.84% of the Earth's ice-free surface (Soil Survey Staff, 1999). They are closely associated with areas of active and recently active volcanism, and their global distribution is depicted in Figure 33.13. The greatest concentration of Andisols is found along the Pacific Ring of Fire, a zone of tectonic activity and volcanoes stretching from South through Central and North America via the Aleutian Islands to the Kamchatka Peninsula of Russia through Japan, Taiwan, the Philippines and Indonesia to Papua New Guinea and New Zealand. Other areas include the Caribbean, central Atlantic ridge, northern Atlantic rift, the Mediterranean, parts of China, Cameroon, the Rift Valley of east Africa, and southern Australia (Soil Survey Staff, 1999). There are numerous volcanic islands where Andisols are common, including Iceland, the Canary Islands, Azores, the West Indies, and various small islands in the Pacific.

The global distribution of Andisols encompasses a wide variety of climatic conditions – cold-to-hot and wet-to-dry. This suggests that climate is less important to the formation of Andisols than is proximity to volcanic or pyroclastic parent materials. Nevertheless, the majority of Andisols are found in higher-rainfall regions of the world. Almost two-thirds of Andisols occur in humid regions (udic soil moisture regimes) while fewer than 5% occur in aridic moisture regimes (Mizota and van Reeuwijk, 1989; Wilding, 2000). Approximately half of the world's Andisols occur in the tropics, with the remaining half being split between boreal and temperate regions (Wilding, 2000; IUSS Working Group, 2006).

There are almost 15.6 million ha of Andisols in the United States (Soil Survey Staff, 1999). The largest areas occur in Alaska (~10 million ha) and in Washington, Oregon, Idaho, northern California, and western Montana (Pewe, 1975; Rieger et al., 1979; Ping et al., 1989; Southard and Southard, 1991; Ugolini and Dahlgren, 1991; Goldin et al., 1992; Takahashi et al., 1993; McDaniel and Hipple, 2010). In the Pacific Northwest region of Washington, Idaho,

and Oregon, most Andisols are forested and occur at mid- to high elevations in cooler temperature regimes (McDaniel et al., 2005). Few Andisols are found in warmer temperature regimes because the summers are normally too hot and dry to allow sufficient weathering or leaching to produce the required andic properties.

Iceland contains ~7 million ha of Andisols. These represent the largest area of Andisols in Europe (Arnalds, 2004). Andisols also occur in France, Germany, Spain, Italy, and Romania (Buol et al., 2003; Kleber et al., 2004; Quantin, 2004; IUSS Working Group, 2006; Arnalds et al., 2007). In New Zealand, ~3.2 million ha of Andisols occur on the North Island, the majority now supporting agriculture or forestry (Parfitt, 1990; Lowe and Palmer, 2005). Japan has ~6.9 million ha of Andisols (Wada, 1986; Takahashi and Shoji, 2002).

Some soils classified as Andisols are also found in humid areas not associated with volcanic activity such as in the southern Appalachian Mountains, parts of Kyushu (Japan), Scotland, Spain, and the Alps. These soils have large quantities of Al or Fe associated with humus (see Section 33.3.3.2) and similar management constraints as those of soils formed from volcanic ejecta, and also key out as Andisols. These attributes further highlight the importance of realizing that Andisols are not classified on parent material, but on the properties acquired during weathering and leaching. By the same token, soils other than Andisols, such as Entisols, Inceptisols, Spodosols, Mollisols, Oxisols, Verisols, Alfisols, or Udisols, may form in association with volcanic or pyroclastic materials (e.g., Shoji et al., 2006).

### **33.3.3 Andisol Properties**

#### ***33.3.3.1 Morphological Features***

Most Andisols have distinct morphological features. They usually have multiple sequences of horizons (Figure 33.14) resulting from the intermittent deposition of tephras and ongoing topdown soil formation referred to as upbuilding pedogenesis (see Section 33.3.5.1). A horizons are typically dark, often overlying reddish brown or dark yellowish brown Bw cambic horizons. Buried A-Bw sequences are common (Figure 33.14). Layers representing distinct tephra-fall events are common, often manifested as separate Bw horizons or as BC or C horizons if the tephra shows limited weathering or is relatively thick. Horizon boundaries

are typically distinct or abrupt where these thicker layers occur.

Andisols are usually light and easily excavated because of their low bulk density and weakly cohesive clay minerals. The high porosity allows roots to penetrate to great depths. Andisols generally have granular structures in A horizons, but the structure in Bw horizons is generally weak subangular blocky, often crushable readily to crumb structure. Some Andisols (Udands) formed in areas of high rainfall have higher clay contents while soils that are subjected to wet and dry cycles form prismatic structure. At higher water contents, soils containing as little as 2% allophane have a characteristic greasy feel (Parfitt, 2009), an indication of sensitivity.

### ***33.3.3.2 Mineralogical Properties***

Tephra parent materials weather rapidly to form nanominerals that are responsible for many of the unique physical and chemical properties associated with Andisols. Although a wide range of clay minerals can be found in Andisols (such as gibbsite, kaolinite, vermiculite, smectite, crystalline Fe oxides such as hematite and goethite, and cristobalite), those of greatest interest are allophane, imogolite, ferrihydrite, and the Al- and Fe-humus complexes because they confer the characteristic andic properties (Dahlgren et al., 2004; Parfitt, 2009).

Allophane is nearly X-ray amorphous, but under an electron microscope it is structured over short distances, appearing as nanoparticles of hollow spheres 3.5-5 nm in diameter that have the chemical composition  $(1-2)\text{SiO}_2 \cdot \text{Al}_2\text{O}_3 \cdot (2-3)\text{H}_2\text{O}$  (Fig. 33.15a) (Wada, 1989; Churchman, 2000; Brigatti et al., 2006; Theng and Yuan, 2008). The most common type of allophane is the so-called Al-rich allophane with an Al:Si molar ratio of ~2 (it is sometimes called proto-imogolite allophane). There is also Si-rich allophane with an Al:Si ratio ~1 (also referred to as halloysite-like allophane).

Imogolite has the composition  $(\text{OH})\text{SiO}_3 \cdot \text{Al}_2(\text{OH})_3$  and has both long- and short-range order. Under an electron microscope, it appears as long smooth and curved hollow threads or tubules with inner and outer diameters of ~0.7 and 2 nm, respectively (Fig. 33.15b). These nanotubes typically appear as bundles of two or more threads 10-30 nm thick and several micrometers long (Theng and Yuan, 2008). Imogolite in Japan can be seen with the naked eye as a whitish gel film infilling pores in coarse pumice particles (Wada, 1989).

Allophane and imogolite both have high surface areas, ranging from 700 to 1500 m<sup>2</sup> g<sup>-1</sup>

(Parfitt, 2009), and this feature, coupled with their variable surface charge characteristics, and exposure of  $(\text{OH})\text{Al}(\text{OH}_2)$  groups at wall perforations (defects), explains their strong affinity for water, metal cations, organic molecules, and other soil minerals (Harsh et al., 2002; Theng and Yuan, 2008). Even small amounts contribute huge reactive surface areas in soils (Lowe, 1995). Allophane and imogolite are soluble in ammonium (acid) oxalate solution, and the Si dissolved is used to estimate their contents in soils (Parfitt and Henmi, 1982; Parfitt, 2009). *Soil Taxonomy* uses oxalate-extractable Al (and Fe) to help define andic soil properties (see Figure 33.16 and Section 33.3.4). Allophane content of B horizons is quite variable, ranging from about 2% in slightly weathered or metal-humus-dominated systems to >40% in well developed Andisols. It typically increases with depth in upper subsoils, usually being highest in the Bw and buried horizons. But in many Andisol profiles in New Zealand, allophane decreases and halloysite concomitantly increases with depth in lower subsoils either because of the downward migration of Si into lower profiles or because of changes in climate during pedogenic upbuilding, or both. Imogolite is more commonly found in B horizons under carbonic acid weathering regimes than in A horizons where organic acid weathering dominates (Dahlgren et al., 2004). Allophane may occur dispersed as groundmass, as coatings, bridges, or infillings (in vesicles or in root-channels), or it may be disseminated through pseudomorphs of glass or feldspar grains (Jongmans et al., 1994, 1995; Bakker et al., 1996; Gérard et al., 2007).

Ferrihydrite is common in many Andisols, especially those associated with more basic parent materials, has a composition of  $\text{Fe}_5\text{HO}_8 \cdot 4\text{H}_2\text{O}$  and imparts a reddish-brown color (hues of 5YR–7.5YR; Bigham et al., 2002). Made up of spherical nanoparticles 2–5 nm in diameter (Schwertmann, 2008), ferrihydrite has large, reactive surface areas ranging from ~200 to 500  $\text{m}^2 \text{g}^{-1}$  (Childs, 1992; Jambor and Dutrizac, 1998). Its abundance is commonly estimated from the amount of Fe extracted by ammonium oxalate solution multiplied by 1.7 (Parfitt and Childs, 1988). It is a widespread and characteristic component of young Fe-oxide accumulations precipitated from Fe-rich solutions in the presence of organic matter, such as in Iceland (Arnalds, 2004), and elsewhere, including New Zealand, Japan, and Australia where its precipitation may be inorganic or bacteria-driven (Childs et al., 1991; Lowe and Palmer, 2005). Ferrihydrite can transform to crystalline hematite via solid-state transformation or goethite through dissolution and re-precipitation (Schwertmann, 2008).

Metal-humus complexes are significant components of some Andisol colloidal fractions. These Al- and Fe-organic complexes are immobile and accumulate in dark or black surface horizons where organic materials are abundant, and dark (melanic) horizons may extend typically to depths as much as ~2 m (see Figure 33.14b). Metal-humus complexes represent the active forms of Al and Fe in nonallophanic Andisols as described below (Dahlgren et al., 2004).

Halloysite is a relatively fast-forming 1:1 layer silicate that often exhibits tubular or spheroidal morphology (White and Dixon, 2002; Joussein et al., 2005). Its formation is favored in seasonally dry environments where higher Si concentrations are maintained (Shoji et al., 1993). These include areas of lower rainfall, restricted drainage, and Si-rich parent materials (Lowe, 1986; Joussein et al., 2005; Etame et al., 2009; Section 20.1 [Churchman and Lowe, 2012]). Halloysite surfaces are characterized by some permanent negative charge, allowing retention of cations across a wide range of pH values.

The soil solution in Andisols in a range of locations may contain large amounts of dissolved Si, which leads to the formation by nucleation of secondary silica minerals from the saturated solution (Ping et al., 1988; Shoji et al., 1993; Ping, 2000; Nanzyo, 2002, 2007; Waychunas and Zhang, 2008). Termed laminar opaline silica, this material is circular or elliptical in shape (0.2–0.5  $\mu\text{m}$  diameter) and extremely thin. Precipitation of the silica may be aided by evaporation or freezing of soil water, or via plant-related processes related to Si uptake and recycling (Lowe, 1986; Drees et al., 1989; Churchman, 2000; Henriot et al., 2008). Such silica polymorphs can be distinguished from biogenic forms of silica (phytoliths) because the latter have more complex shapes inherited from biological cells (Kondo et al., 1994; Nanzyo, 2007).

Andisols dominated by allophane with subordinate imogolite and ferrihydrite in upper horizons are referred to as *allophanic Andisols*. These contrast with a second, strongly acid group known as *nonallophanic Andisols* in which metal-humus complexes dominate the colloidal mineralogy. Nonallophanic Andisols are common in Japan especially where they account for about 30% of soils formed on tephras (Takahashi and Shoji, 2002), and are known in around 20 other countries (Saigusa and Matsuyama, 2004). Examples of soils from each group are shown in Figure 33.14. In Table 33.15, the Thingvallasveit and Tirau soils are examples of allophanic Andisols; the Tohoku Farm soil is an example of a nonallophanic Andisol. The mineralogical differences between these two groups of Andisols lead to several

important different physical and chemical properties (especially the strong acidity of nonallophanic Andisols) and significant management implications (Dahlgren et al., 2004).

In the silt and sand fractions of Andisols, the dominant components are volcanic glass (a mineraloid) and various primary minerals. The glass particles (shards) which, like shattered glass, have sharp angles and edges, are very abrasive. However, these glass particles are usually coated with colloidal minerals including allophane, ferrihydrite, and other Fe oxides and their humus complexes, which all contribute to aggregate formation. It is noteworthy that volcanic glass is often quite vesicular and porous in nature (as is pumice), and thus can retain water and has more chemical activity than other common sandy materials (Ping, 2000; Neall, 2006).

### ***33.3.3.3 Chemical Properties***

One of the common characteristics of Andisols is accumulation of relatively large quantities of organic matter, both in the allophanic (moderate pH) and nonallophanic Andisols (low pH; Table 33.15). Allophanic Andisols typically contain up to ~8–12% C, whereas nonallophanic soils may contain up to ~25–30% C (Mizota and van Reeuwijk, 1989). The residence time of C in Andisols, as measured by  $^{14}\text{C}$ , is much greater than that of other soil orders (Parfitt, 2009). In addition, upbuilding pedogenesis leads to the storage of organic C in lower parts of profiles, and especially in buried A horizons that are sealed off and isolated from most surface processes.

Andisols are almost always acid, with most pH ( $\text{H}_2\text{O}$ ) values ranging from 4.8 to 6.0 (Shoji et al., 1993; Dahlgren et al., 2004). Uncultivated, nonallophanic Andisols with high organic matter contents typically have a pH ( $\text{H}_2\text{O}$ ) <4.5 (IUSS Working Group, 2006).

One of the key factors affecting the chemistry of Andisols is the variable surface charge associated with the colloidal fraction (Gustafsson, 2001; Qafoku et al., 2004). Electrical charges on colloid or nanoparticle surfaces can be either positive or negative, and change as a function of pH. Surfaces have positive charge at lower pH and retain anions, while cations are retained by the negative charge at higher pH. This variable charge greatly affects the behavior of ions that are retained in soils. Cation retention capacity of Andisols makes the soils susceptible to metal and radioactive fallout  $^{137}\text{Cs}$  pollution (Adamo et al., 2003; Sigurgeirsson et al., 2005). Andisols also exhibit anion exchange properties, which can be important for



nutrient retention (e.g.,  $\text{NO}_3^-$  and  $\text{SO}_4^{2-}$ ) (Shoji et al., 1993).

Measured cation exchange capacity of Andisols is relatively high, often 20 to  $>50 \text{ cmol}_c \text{ kg}^{-1}$ . However, because the dominant colloids have variable charge, much of this CEC is pH dependent. This is especially true in allophanic Andisols (Dahlgren et al., 2004) and means that CEC decreases with decreasing pH. And because most Andisols are acid, CEC measurements made at pH 7 or 8.2 will be artificially high. In andic soils of the Pacific Northwest of United States, average CEC values determined using unbuffered extractants (effective CEC or ECEC) are approximately one-fourth of those determined at pH 8.2,  $6.5 \text{ cmol}_c \text{ kg}^{-1}$  vs.  $26.4 \text{ cmol}_c \text{ kg}^{-1}$  (McDaniel et al., 2005). This phenomenon needs to be considered when measuring CEC and base saturation or interpreting these data. The relatively low ECEC of Andisols can limit their ability to retain and exchange Ca, Mg, and K. Some representative cation exchange characteristics of Andisols are presented in Table 33.15.

The active Al and Fe compounds in Andisols (allophane/imogolite, metal-humus complexes, and ferrihydrite) also have the ability to sorb and strongly bind anions such as phosphate and fluoride (Shoji et al., 1993; Dahlgren et al., 2004; Parfitt, 2009). Much of this sorption is not reversible, leading to large quantities of phosphate being rendered unavailable for plant uptake. As described in Section 33.3.4, the amount of P retention in soils is used to define andic soil properties. Similarly, quantities of active Al and Fe compounds can also be estimated by reacting soil with NaF solution. Sorption of  $\text{F}^-$  releases  $\text{OH}^-$  into solution, thereby raising the pH. A resultant pH greater than  $\sim 9.5$  indicates the presence of allophane/imogolite and/or Al-humus complexes, and because of this, NaF field test kits can be used for field identification of Andisols (Fieldes and Perrott, 1966; IUSS Working Group, 2006).

#### ***33.3.3.4 Physical Properties***

Unique physical attributes of Andisols are related to structural assemblages of hollow spheres and tubular threads as mineral entities into resilient, progressively larger (silt-sized) aggregated domains. This stable aggregation results in low density, high porosity, high surface area, and high soil water retention even at low water potentials. The structural arrangement accounts for the low thermal conductivity of andic materials, which is three to four times less than that of the phyllosilicates in other mineral soils. It also accounts generally for the

thixotropic and sensitivity character of these soils and several irreversible changes in physical properties that occur upon drying (Ping, 2000; Neall, 2006).

Andisols have low bulk density, usually  $<0.9 \text{ g cm}^{-3}$ , because of the high organic matter and nanomineral contents (Table 33.16) and well-developed aggregation. This results in good tilth and makes them excellent rooting media. On the other hand, low bulk densities result in low weight-bearing capacity and make Andisols highly susceptible to wind and water erosion when surface cover is removed or degraded (Ping, 2000; Nanzyo, 2002; Dahlgren et al., 2004; Neall, 2006). Because of the nature of volcanic ejecta and its distribution, many Andisols in proximal locations contain appreciable amounts of gravel and stones, and coarse-grained tephra layers may have adverse effects on hydrological properties by interrupting capillary movement of water. Some additional adverse physical properties include a high glass content that can reduce the quantity and biodiversity of soil organisms such as earthworms, and the presence occasionally of impenetrable horizons such as thin Fe pans (placic horizons) in higher rainfall areas (Neall, 2006).

Andisols typically exhibit high water retention because of the presence of allophane, ferrihydrite, and metal-humus complexes, which have high surface areas as noted previously. As a result, moisture contents of many Andisols can exceed 100% on a weight basis, even at soil moisture tensions of 1500 kPa – this feature is illustrated by the data for the Hilo soil (Table 33.16). Water retention is greatest in Andisols that have undergone significant weathering and hence have high clay contents.

Most field-moist Andisols have a greasy feel when rubbed between the fingers and exhibit smeariness – these both can be indicators of the properties known as sensitivity and thixotropy (Soil Survey Staff, 1975; Torrance, 1992). Thixotropy is a reversible gel-sol transformation that occurs when shear forces are applied to a moist soil. The applied shear force causes the soil to abruptly lose strength, sometimes to the point of behaving as a fluid. When the shear force is removed, the soil will recover some or all of its original strength. Sensitivity (the term used more commonly by engineers) is the ratio of undisturbed to disturbed (remolded) shear strength, that is, the maximum strength of an undisturbed specimen compared with the residual strength remaining after force or strain is applied (Mitchell and Soga, 2005; Neall, 2006). In sensitive materials, the original strength is generally not recovered – unlike thixotropic materials – after removal of the force. Both sensitivity and thixotropic behavior

are best expressed in Andisols having high water retention and a lack of layer silicates to provide cohesion, and can pose significant engineering problems.

Many Andisols exhibit irreversible changes upon drying. Allophane nanospheres collapse upon dehydration and form larger aggregates that do not break down upon rewetting. This phenomenon can cause crust formation at the soil surface during hot dry periods. It also results in well-known unreliable particle-size analyses of air-dried Andisols. Clay content is underestimated and sand and silt contents are overestimated (Ping et al., 1989; Dahlgren et al., 2004). However, reliable sand-, silt-, and crystalline clay-size fraction data were obtainable for andesitic Andisols in New Zealand who analyzed grain-size distributions of residual material following selective dissolution of nanominerals and organic constituents via ammonium oxalate. Other irreversible changes that occur upon desiccation include increases in bulk density, decreases in water retention, and increases in cohesive strength. Note the difference in water retention and bulk density values between dried and moist samples in Table 33.16.

Plasticity in Andisols is different from that of soils containing layer silicate clay minerals. Generally, field-moist Andisols have high liquid (60-350%) and plastic limits (70%-180%) (Warkentin and Maeda, 1980; Neall, 2006). The low plasticity index (0-10) also clearly separates Andisols from other soils. Plasticity measurements can be used as an index of physical behavior in Andisols and as a substitute for particle-size analysis, which is usually not reliable. Air-dry samples, on the other hand, often show low plasticity because of the irreversible changes on drying and behave like sandy soils.

### **33.3.4 Classification of Andisols**

Andisols are classified on the basis of having andic soil properties, which are quantitatively defined in *Soil Taxonomy* (Soil Survey Staff, 2010). In general, andic soil properties consist of combinations of properties that develop as tephras and other volcanic materials weather. These include relatively low bulk density values ( $\leq 0.90 \text{ g cm}^{-3}$ ), relatively high phosphate retention (>25%-85%), the presence of volcanic glass, and the presence of nanoscale weathering products containing Al, Fe, and Si (Soil Survey Staff, 2010). The criterion of percentage Al extracted by ammonium oxalate ( $\text{Al}_o$ ) plus half the percentage Fe extracted by ammonium oxalate ( $\text{Fe}_o$ ) from short-range order nanominerals is used to quantitatively define

andic properties. The quantity  $0.5 \text{ Fe}_o$  is used to normalize the criterion because Fe has an atomic weight (56) approximately twice that of Al (27). The majority of soils with a glass content and percentage of  $\text{Al}_o + 0.5 \text{ Fe}_o$  that falls within the shaded area of Figure 33.16 have andic soil properties. Soils possessing at least 36 cm of material with andic soil properties are classified as Andisols (Soil Survey Staff, 2010). It is emphasized that freshly deposited volcanic ash does not have andic soil properties and would not be classified as an Andisol. It is not until some weathering has occurred – sufficient to generate  $\text{Al}_o + 0.5\text{Fe}_o$  totaling at least 0.4% – that andic properties are developed.

Andisols are separated into suborders primarily on the basis of soil moisture or temperature regimes, or both (Table 33.17). Aquands are poorly drained and have a water table at or near the soil surface for much of the year. These soils are usually restricted to low-lying landscape positions and have dark surface horizons. Because of excessive wetness, Aquands typically require drainage to be used for crop or pasture production.

Gelands are very cold Andisols that have a mean annual soil temperature (MAST)  $\leq 0^\circ \text{C}$  (Soil Survey Staff, 2010). Relatively little is known about the distribution of these soils, but they are found at higher latitudes in areas of either current or recent volcanic activity.

Cryands are cold Andisols with a cryic temperature regime ( $0^\circ \text{C} < \text{MAST} \leq 8^\circ \text{C}$  and summers are cool; Soil Survey Staff, 2010). They are found at higher latitudes and higher elevations. In the USA, Cryands are found mainly in Alaska and mountainous regions of the Pacific Northwest (Ping, 2000; McDaniel and Hipple, 2010). They are extensive in Iceland (Arnalds and Kimble, 2001) and also on the Kamchatka Peninsula, and occur in mountainous regions elsewhere including in eastern Africa, the Andes, and (uncommonly) New Zealand (Ping, 2000; Lowe and Palmer, 2005). Globally, there are ~26 million ha of Cryands and they are the third most common suborder, representing ~28% of Andisols (Soil Survey Staff, 1999; Wilding, 2000).

Torrands are Andisols of very dry environments where moisture for plant growth is very limited. This lack of soil moisture slows down weathering processes and leaching, thereby inhibiting development of andic soil properties. Torrands are found in Oregon and Hawaii in the United States. They are the least extensive of any of the Andisol suborders, with only ~100,000 ha occupying the global ice-free land area (<1% of Andisols).

Xerands occur in temperate regions with xeric soil moisture regimes, which are

characterized by cool, moist winters and very warm, dry summers (Mediterranean climates). In the United States, they occur primarily in northern California, Oregon, Washington, and Idaho where they have formed under coniferous forest. Elsewhere, Xerands occur in scattered localities including Italy, Canary Islands, Argentina, and South Australia (Broquen et al., 2005; Lowe and Palmer, 2005; Inoue et al., 2009). Xerands are uncommon globally (~4% of Andisols).

Vitrands are the only suborder that is not defined by a climatic regime. These Andisols are relatively young and only slightly weathered. They tend to be coarse-textured and have a high content of volcanic glass that may be strongly vesicular or pumiceous. In the United States, Vitrands are found in Washington, Oregon, and Idaho. They also occur in Argentina (Broquen et al., 2005) and are common in the North Island of New Zealand (Lowe and Palmer, 2005). Globally, there are ~28 million ha of Vitrands (~31% of Andisols) making them and Udands (similar in extent) the two most extensive suborders (Soil Survey Staff, 1999; Wilding, 2000).

Ustands occur in tropical or temperature regions that have ustic soil moisture regimes. The ustic soil moisture regime is characterized by an extended dry period, but moisture is normally present at a time when conditions are suitable for plant growth (Soil Survey Staff, 2010). Ustands are of fairly limited extent in the United States and are found mainly in Hawaii. They also occur in Mexico, on Pacific islands, and in eastern Africa (Dubroeuq et al., 1998; Takahashi and Shoji, 2002). About 6.3 million ha of Ustands are known globally (~7% of Andisols).

Udands are Andisols with a udic moisture regime, which is common to humid climates. Udands are thus characterized by well-distributed precipitation throughout the year and limited periods of soil-moisture stress. In the United States, Udands are found in western parts of Washington and Oregon and in Hawaii. Elsewhere, they occur commonly on other parts of the Pacific Rim including in Patagonia (Argentina), Mexico, Japan, the Philippines, Indonesia, and New Zealand (Takahashi and Shoji, 2002; Van Ranst et al., 2002; Broquen et al., 2005; Prado et al., 2007). In total, Udands occupy nearly ~28 million ha of ice-free land globally (~30% of Andisols; Soil Survey Staff, 1999; Wilding, 2000).

Each of the suborders is further separated into great groups. These are listed and described in Table 33.17. A variety of characteristics are used to define great groups, including the presence or absence of certain types of soil horizons, moisture and temperature regimes, glass

content and texture, and water retention.

There are also soils of other orders that have been influenced to a lesser degree by andic materials (Parfitt, 2009). Andic soil properties have developed, but their distribution within the soil is not of sufficient thickness for the soils to be classified as Andisols. These soils are therefore classified as andic subgroups of other orders. In cases where andic materials have been extensively mixed with other parent materials, or andic properties are only weakly expressed, soils are classified as vitrandic subgroups of other soil orders (Soil Survey Staff, 2010). In the United States, such soils are extensive in the Pacific Northwest where they are transitional to higher-elevation, forested Andisols (McDaniel and Hipple, 2009).

### **33.3.5 Formation of Andisols**

#### ***33.3.5.1 Parent Material and Stratigraphy***

In most cases, the parent materials from which Andisols have formed are of explosive volcanic origin (rather than effusive) and thus fragmental and unconsolidated. Such materials range in size from ash (< 2 mm) and lapilli (2-64 mm) through to large angular blocks or part-rounded bombs (>64 mm) – that is, from fine dust to boulders. Collectively these materials are termed pyroclastic deposits or tephra (*Gk ashes*) (Alloway et al., 2007). Tephra deposits typically are loose and very coarse and thick close to source vents but become markedly finer and thinner with increasing distance away from source so that at more than ~100 km from vent most comprise mainly ash-sized material (equivalent to sand or finer particles). The accumulation at a particular site of numerous tephra deposits from sequential eruptions from one or more volcanoes leads usually to the formation of Andisols with distinctive layered profiles and buried soil horizons, forming multisequal profiles (Figure 33.17). Such layered profiles, together with their andic soil properties, are special features of Andisols. Study of the layers and attaining ages for them (tephrostratigraphy) is an important aspect of understanding Andisol formation (Lowe and Palmer, 2005; Lowe and Tonkin, 2010).

During periods of quiescence between major eruptions, soil formation takes place, transforming the characteristics of the unmodified tephra via normal top-down pedogenesis whereby the materials are altered in a downward-moving front to form subsoil horizons. However, when new tephra are added to the land surface, upbuilding pedogenesis takes place. The frequency and thickness of tephra accumulation (and other factors) determine how

much impact the top-down processes have on the ensuing profile character, and if ‘developmental’ or ‘retardant’ upbuilding, or both, will take place. Two contrasting scenarios can be considered.

In the first scenario, successive thin tephra deposits (ranging from millimeters to centimeters in thickness) accumulate incrementally and relatively infrequently so that developmental upbuilding ensues. Such a situation occurs typically at distal sites. The thin materials deposited from each eruption become incorporated into the existing profile over time. Top-down pedogenesis continues as the tephra accumulate but its effects are lessened because any one position in the sequence is not exposed to pedogenesis for long before it becomes buried too deeply for these processes to be effective as the land surface gently rises (Figure 33.18). This history thus leaves the intermixed tephra deposits with a soil fabric inherited from when the tephra was part of the surface A horizon or subsurface Bw horizon (Lowe and Palmer, 2005; Lowe and Tonkin, 2010). Each part of the profile has been an A horizon at one point, as illustrated in Figure 33.18.

In the second scenario, tephra accumulation is more rapid, as occurs in locations close to volcanoes, or when a much thicker layer (more than a few tens of centimeters) is deposited from a powerful eruption. In the latter case, the antecedent soil is suddenly buried and isolated beyond the range of most soil-forming processes (i.e., it becomes a buried soil horizon or paleosol). A new soil will thus begin forming at the new land surface in the freshly deposited material. This scenario typifies retardant upbuilding, which recognizes that the development of the now-buried soil has been retarded or stopped, and the pedogenic “clock” reset to time zero for weathering and soil formation to start afresh. An example of a multisequal Andisol profile formed via retardant upbuilding pedogenesis since ~9500 calendar (cal) years ago is shown in Figure 13.17. Each of five successive tephra deposits shows the imprint of top-down pedogenesis, as depicted by their horizonation. But the sudden arrival of a new tephra deposit every few thousand years or so on average has buried and effectively isolated each of the weakly developed “mini” soil profiles as the land surface rises.

In addition to stratigraphic factors, Andisols are markedly affected by the mineralogical and physicochemical compositions of the parent tephra or associated deposits derived from remobilization of volcanic and other material (collectively termed volcanoclastic deposits). For example, the marked influence of windblown dust (mainly basaltic glass) on soil properties in

Iceland was described by Arnalds (2010). Tephtras differ widely according to the chemical makeup of magmas of the volcanoes that generated them. The chemistry of magmas, especially Si content, governs the way a volcano erupts. Three main magma types and resulting eruptives can be identified according to their chemical composition – rhyolitic ( $\geq \sim 70\%$  SiO<sub>2</sub>), andesitic ( $\sim 50\% - 70\%$  SiO<sub>2</sub>), and basaltic ( $\leq \sim 50\%$  SiO<sub>2</sub>). All magmas generate volcanic glass, a non-crystalline, easily weatherable mineraloid, and various other primary silicate minerals (Shoji et al., 1993; Nanzyo, 2002; Smith et al., 2006; Alloway et al., 2007; De Paepe and Stoops, 2007). Glass especially provides much of the Si and Al required to dissolve and re-form as allophane or other aluminosilicate clay minerals, and the amounts differ according to the magma composition as shown in Figure 33.19. Feldspars also release Si and Al via weathering for clay formation.

Generally, the basaltic and intermediate tephtras tend to weather more readily than the Si-rich rhyolitic tephtras, and in all cases glasses weather very quickly (Neall, 1977; Kirkman and McHardy, 1980; Colman and Dethier, 1986; Hodder et al., 1996; Shikazono et al. 2005). Compared with hard rock, the fragmental tephtra components, especially vesicular glass and pumice fragments, have a much greater surface area and higher porosity and permeability, and so break down to constituent compounds very readily. As this weathering occurs, various elements including Si and Al are released into chemical solution either for subsequent leaching, complexing with humic materials, plant uptake, or synthesis (neof ormation) into relatively stable nanominerals or other clay minerals (Lowe, 1986; Vacca et al., 2003; Dahlgren et al., 2004). Andisols developed on (base-rich) basaltic eruptives are inherently more fertile than those on more siliceous eruptives (Wolff-Boenisch et al., 2004). Weakly weathered tephtras give rise to the glass-rich Andisols that belong to the Vitrand suborder.

#### **33.3.5.2 Climate**

Climate plays an important role in Andisol formation, and soil moisture and temperature regimes are used to differentiate all the suborders except Vitrands (Ping, 2000). The majority of Andisols, as reported previously, are found under udic soil moisture regimes, and around half are found in the tropics, with the rest occurring in temperate and boreal regions. Climatic conditions help govern the combinations of processes, collectively referred to as andisolization, that occur in soils developing on tephtras. Andisolization is the *in situ*



formation of andic soil materials comprising nanominerals composed of “active” Al, Si, Fe, and humus (Dahlgren et al., 2004). The process is discussed in more detail in Section 33.3.6.

The essential conditions for the formation of allophane are the activity of silicic acid in the soil solution, the availability of Al species, and the opportunity for co-precipitation (Figure 33.19). These conditions are controlled largely by the leaching regime, the organic cycle, and pH, which, in turn, are potentially influenced by numerous environmental factors including rainfall, drainage, depth of burial, parent tephra composition and accumulation rate, dust accession, type of vegetation and supply of humic substances, and human activities (such as burning vegetative cover), together with thermodynamic and kinetic factors (Parfitt and Saigusa, 1985; Lowe, 1986, 1995; Hodder et al., 1990; Chadwick et al., 2003; Dahlgren et al., 2004; Parfitt, 2009). Availability of Al, derived mainly from the dissolution of glass or feldspars, is assumed to be unlimited in this model, though potentially more is available from andesitic and especially basaltic tephtras than rhyolitic tephtras (Lowe, 1986; Shoji et al., 1993; Cronin et al., 1996). In contrast, in pedogenic environments rich in organic matter and with  $\text{pH} \leq 5$ , humus effectively competes for dissolved Al, leaving little Al available for co-precipitation with Si to form allophane or halloysite (Shoji et al., 1993; Dahlgren et al., 2004; see Section 33.3.5.4 below).

In New Zealand, both mineralogical and soil-solution studies on soils derived from tephtras extending across a rainfall gradient showed that rainfall, coupled with through-profile drainage, helps govern Si concentration [Si] in soil solution and thus the likelihood of allophane being formed or not (Parfitt et al., 1983; Singleton et al., 1989; Parfitt, 2009). The Si leaching model shown in Figure 33.20 is summarized as follows: where [Si] is less than  $\sim 10$  ppm ( $\text{mg L}^{-1}$ ), allophane is formed; where [Si] is greater than  $\sim 10$  ppm, halloysite is formed. If [Si] is close to  $\sim 10$  ppm then either allophane or halloysite may predominate. A profile throughflow threshold of approximately  $250 \text{ mm year}^{-1}$  of drainage water likely controls [Si] – less than  $\sim 250 \text{ mm year}^{-1}$  means that the loss of Si is insufficient for Al-rich allophane to form and halloysite (or Si-rich allophane) forms instead (Parfitt et al., 1984; Lowe, 1995).

It is emphasized, however, that allophane and other nanominerals can form under lower rainfalls ( $\sim 700 \text{ mm year}^{-1}$  or less) such as in Mexico, Iceland, and South Australia (Arnalds et al., 1995; Dubroeuq et al., 1998; Ugolini and Dahlgren, 2002; Lowe and Palmer, 2005). As

well, other factors such as parent tephra composition and vegetation are also important.

#### **33.3.5.3 Topography**

Andisols are found on all types of topography and at a wide range of elevations (from sea-level to >3,000 m). Because of their strong association with the products of volcanism, Andisols occur most commonly in volcanic landscapes which can range from mountainous to hilly terrains on the flanks of stratovolcanoes, dome complexes, shield volcanoes, and scoria or tuff cones through to rolling or essentially flat-lying landscapes, some associated with plateaus of tephra-draped welded ignimbrite sheets derived from large caldera eruptions, such as occur in western United States, Japan, and northern New Zealand (Lowe and Palmer, 2005). Because tephrae are carried long distances by the wind, and can easily be reworked by wind and water, they can be deposited in a variety of sedimentary and other landscapes including dune plains, fluvial terraces or plains, and flat intermontane valleys (Ping, 2000; Lowe and Palmer, 2005). On hilly landscapes, tephrae are variable in thickness because of erosion (especially during the last glaciation), and profiles typically are thinner on slopes than on more stable geomorphic surfaces (Neall, 2006). The effects of specific topographic positions on Andisol formation have been evaluated, for example, by Navarette et al. (2008) in the Philippines.

#### **33.3.5.4 Vegetation**

Because Andisols occur in all moisture and temperature regimes on different landscapes at different elevations, vegetation is accordingly highly variable. In general, Andisols are usually moderately acid to very acid and so vegetation associated with acid soils will predominate. Because of their relatively high water-holding capacities, Andisols, even in xerophytic areas, are likely to support more luxuriant vegetation than other non-andic soils in the same environment. When the vegetation cover is grass, a more humus-rich profile usually develops. A thick, dark surface known as a melanic epipedon is common in many Andisols that have formed under grasses. Melanic epipedons contain  $\geq 6\%$  organic C as a weighted average, have black soil colors (melanic index  $\leq 1.70$ ), and attain a thickness of  $\geq 30$  cm (Soil Survey Staff, 2010). Andisols with melanic epipedons are usually classified as Melanudands, an example of which is shown in Figure 33.14b.

Although the vegetation on Andisols is quite variable, it clearly has a major influence on the type of Andisol formed (Ping, 2000). In the Pacific Northwest and parts of Alaska, and in New Zealand, Udands generally formed under forest vegetation. However, Udands are known to form under other vegetation types such as grasses in south central Alaska (Ping, 2000) and in Japan, where pampas grass (*Miscanthus sinensis*), known as “susuki”, has formed Melanudands, Sitka spruce (*Picea sitchensis*) Hydrudands, and blue joint grass (*Calamagrostis canadensis*) Fulvudands. The organic matter is dominated by humic acids in the first cases and by fulvic acids in the last (Ping et al., 1989; Shoji et al., 1993; Nanzyo, 2002; Dahlgren et al., 2004).

In Japan and elsewhere, the humic acids in many Andisols and associated soils are characterized by their stability and aromatic (humified) structure (Shoji et al., 1993; Dahlgren et al., 2004; Hiradate et al., 2004; Parfitt, 2009). These features arise from the presence of labile and active metals, chiefly Al and Fe, which are able to bind with humic substances to form macromolecules of Al- and Fe-humic acid complexes that are very resistant to degradation or leaching (Hiradate et al., 2004; Basile-Doelsch et al., 2005). As well as strong bonding, the metal-humic acid complexes are also protected by Al toxicity to microorganisms or enzymes, physical encasement within abundant micro-peds, and a P deficiency of microorganisms arising from high P retention (Ugolini and Dahlgren, 2002; Parfitt, 2009). The resultant very dark or black melanic epipedons can contain as much as 25%-30% organic carbon (Drijber and Lowe, 1990; Nanzyo, 2002; Hiradate et al., 2004).

Most Xerands, such as those in central Washington, Oregon, and northern California, have formed under mixed vegetation of grass and forest whereas those in South Australia formed under dense to semi-open woodland and grassland/shrubland or fernland (Ping, 2000; Lowe and Palmer, 2005; Takesako et al., 2010). Torrands formed under shrubby or grass vegetation, and Vitrandes under grass or forest in North America and Mexico and under broadleaf-podocarp forest in New Zealand. Cryands generally formed under forest, but in Iceland and other high latitude polar regions including the Aleutians, these soils form under tundra or moss, heath, grass, and “desert” covers (Arnalds et al., 1995; Ping, 2000; Arnalds and Kimble, 2001). In the tropics, the vegetation is often rain forest, particularly on the slopes of volcanoes where grassland and savanna types also occur.

Some black A horizons on Andisols in New Zealand, typically  $\leq 20$  cm thick, have been

attributed largely to the effects of bracken fern (*Pteridium* spp.), which replaced much of the original forest after human-induced deforestation by Polynesian burning from about AD 1300 (Newnham et al., 1999; McGlone et al., 2005; Lowe, 2008). In northern Idaho, establishment of bracken fern following forest canopy removal is associated with decadal-scale changes in soil properties. These include increased soil C, darker soil colors, lower pH, and increased organic forms of active Al (Johnson-Maynard et al., 1997).

#### 33.3.5.5 *Time*

Andisols generally are found on relatively young parent materials in humid climates because, on older and more stable landscapes, more weathering would normally have taken place resulting in the transformation to other soil orders such as Ultisols or Oxisols. The drier and cooler the environment, the longer it usually takes for an Andisol to form (Shoji et al., 2006). Tephra or volcanic materials, either very young or in extremely dry areas, and not sufficiently weathered to form the minimum requirements for andic soil materials, are placed in the Entisol order. An A horizon can form in newly deposited tephra in a few hundred years or so whereas the development of BC and then Bw horizons beneath it, may take several hundreds to several thousands of years according to environmental conditions and the nature of the tephra (Shoji et al., 1993; Ping, 2000; Lowe and Palmer, 2005; Lowe, 2008). However, in northeast Kodiak Island, Alaska, a Cryand formed on tephra erupted in the 1912 Mount Katmai event already has thin E and Bw horizons (Ping, 2000), and soils on young basaltic tephra surfaces in Iceland (<100 years) are classified as Andisols (Arnalds and Kimble, 2001).

In situations where just a single eruption event has taken place to produce a parent deposit, then Andisols developed in that material have the same age as the eruption. However, where Andisols comprise upbuilding sequences of tephra and soil horizons (as commonly occurs), the maximum age of the soil-profile constituents depends on the depth at which the profile “bases” is drawn. In considering the uppermost 1 to 2 meters of Andisols, some generalizations about their *composite* ages can be made. For example, in Japan, many Andisols are ~5,000-10,000 cal years old although some are considerably older (~25,000 cal years old; Takesako and Muranaka, 2006). In southeast Alaska, Cryands may be up to ~15,000 cal years old (Ping, 2000). In Iceland, most of the Andisols range in age from a few decades to over ~10,000 cal years old (Arnalds et al., 1995). In New Zealand, there is a much

wider range of ages on Andisols. Most of the Vittrands are ~700 years old (on rhyolitic Kahaora Tephra) and ~1800 years old (on rhyolitic Taupo Tephra); extensive Udands date back ~20,000–25,000 cal years and some are as old as ~60,000 years. In all these countries and others, teprochronology – the identification and correlation of tephras and their application as a linking and dating tool (Alloway et al., 2007; Lowe, 2011) – has been used to provide age models for the Andisols. These age models rely mainly on radiocarbon and other techniques including dendrochronology and depositional age-depth modeling as well as wiggle-match dating (Lowe, 2011). Historical accounts provide ages for the youngest tephras (Alloway et al., 2007).

### **33.3.6 Pedogenic Processes in Andisols**

The importance of upbuilding and polygenesis in the formation of Andisols has already been described. In this section, the collective process of andisolization in tephra materials with a significant content of volcanic glass is outlined. Andisolization leads to the formation of a fine colloidal fraction dominated by nanoscale minerals, notably allophane, ferrihydrite, and metal-humus complexes, with typically subordinate amounts of imogolite. Nanoscale minerals are defined as having at least one dimension in the nanorange, which is 1-100 nm (Hochella, 2008). These nanoscale minerals are composed of active forms Al, Si, Fe, and humus and impart andic properties (Theng and Yuan, 2008). Although volcanic glass is a common component in many Andisols, it is not a requirement of the Andisol order and some soils develop andic properties without the influence of glass (Soil Survey Staff, 1999). Soil solution and micromorphological studies show that, in contrast to podzolization, translocation of Al, Fe, organic matter, and clays is normally minimal in Andisols (Jongmans et al., 1994; Soil Survey Staff, 1999; Ugolini and Dahlgren, 2002; Stoops, 2007).

Allophane and imogolite (both aluminosilicates) and ferrihydrite (an iron hydroxide) are formed by the synthesis of soluble Al, Si, or Fe that are released from glass or other minerals (mainly feldspars or various mafic minerals) via rapid dissolution and hydrolysis by carbonic acid ( $\text{H}_2\text{CO}_3$ ) normally under moderately acid conditions and humid conditions. As soil solutions become rapidly oversaturated with respect to these nanominerals, they are precipitated preferentially because their nucleation is kinetically favored over that of less-soluble, long-range-order (crystalline) phases (Ugolini and Dahlgren, 2002; Theng and Yuan,

2008). Thermodynamic stability diagrams show that imogolite and very likely Al-rich allophane are more stable than halloysite over a wide range of Si activity, with the latter more stable than both imogolite and Al-rich allophane only at high Si activity (Farmer et al., 1991; Lowe and Percival, 1993; Hodder et al., 1995; Harsh 2000). The central role of the Si leaching model in helping govern Si activity (i.e. concentration of  $\text{Si(OH)}_4$  or monosilicic acid) was discussed earlier. Al-rich allophane forms at pH values between ~5 and 7, a value of at least ~4.8 being required for it to precipitate (Lowe, 1995; Dahlgren et al., 2004). Al undergoes hydrolysis and polymerises in gibbsite-like octahedral sheets as  $(\text{OH})_3\text{Al}_2$  and then combines with Si in tetrahedral coordination as  $\text{O}_3\text{SiOH}$  to form imogolite or allophane (Figure 33.19; Hiradate and Wada, 2005; Theng and Yuan, 2008). Allophane can form rapidly and has been observed to precipitate in a matter of months on the face of open soil pits containing rhyolitic tephra (Parfitt, 2009).

Note that a long-standing previous model in which allophane was suggested to weather or “crystallize” by solid state transformation to form halloysite with time (because the latter often occurs in older, that is, deeper, tephra and associated soil horizons) has been largely discounted and replaced by this Si leaching model and its variants. For allophane to alter to halloysite would require a complete re-arrangement of the atomic structures and this could only occur by dissolution and re-precipitation processes because the allophane would need to “turn inside out” so that Si-tetrahedra are on the outside, not inside, the curved Al-octahedral sheets (Figure 33.21; Parfitt et al., 1983; Ildefonse et al., 1984; Lowe, 1995; Hiradate and Wada, 2005; Parfitt, 2009). The effect of time is clearly subordinate because glass can weather directly via dissolution either to allophane or halloysite depending on glass composition and both macro- and micro-environmental conditions, not time (Lowe and Percival, 1993; Lowe, 1995; Parfitt, 2009). As well, allophane can persist for hundreds of thousands of years under favorable conditions (Stevens and Vucetich, 1985; Churchman and Lowe 2012. Section 20.1).

The formation of ferrihydrite in Andisols and other soils has been described in a number of papers including Schwertmann and Taylor (1989), Childs (1992), Lowe and Percival (1993), Churchman (2000), Bigham et al. (2002), Nanzyo (2002), and Dahlgren et al. (2004). After release of structural Fe from mafic primary minerals such as pyroxenes, amphiboles, biotite, and olivine (and also presumably from glass),  $\text{Fe}^{2+}$ -containing soil water oxidizes relatively

quickly the  $\text{Fe}^{3+}$ , which immediately hydrolyzes to ferrihydrite. This occurs in the presence of organic matter, silicate, or phosphate, all of which inhibit the formation of more stable crystalline iron oxides. Ferrihydrite can redissolve readily by reduction (Schwertmann, 2008).

The availability of  $\text{Al}^{3+}$  is the critical factor regulating the formation of nonallophanic Andisols, which form preferentially in environments rich in organic matter and with pHs of  $\sim 5$  or less, and which typically contain 2:1 layer silicate clays (Shoji et al., 1985, 1993; Nanzyo, 2002; Ugolini and Dahlgren, 2002; Dahlgren et al., 2004). At these pHs, organic acids are the dominant proton donors lowering pH and aqueous  $\text{Al}^{3+}$  activities through the formation of Al-humus complexes (also Fe-humus complexes, but less commonly). Under these conditions, carboxyl groups of humus and the 2:1 layer silicates (derived mainly from windblown dust) effectively compete for dissolved Al, leaving little Al available for co-precipitation with Si to form allophane or imogolite (Mizota and van Reeuwijk, 1989; Dahlgren et al., 2004). The preferential incorporation of Al into Al-humus complexes (and hydroxyl-Al interlayers of 2:1 layer silicates) has been termed the *anti-allophanic* effect (Shoji et al., 1993). In Japan, allophanic Andisols tend to be formed where parent tephras are more basic (basaltic to andesitic) and rainfall is  $< 1000$  mm per year, so that higher pH values ( $> 5$ ) are favored (Dahlgren et al., 2004). Their distribution pattern is also attributed in part to proximity to volcanoes and the frequency therefore of tephra accretion versus exotic dust accession (Saigusa and Matsuyama, 2004): sites closer to volcanoes effectively receive a “top up” of Al through more regular deposition of weatherable tephras (resulting in allophanic Andisols) than at distal sites where the Al became quickly depleted (resulting in nonallophanic Andisols) through both humus complexing and “dilution” from the ongoing fallout of 2:1-mineral-bearing dust blown from China

Changes in elemental composition during andisolization in Japan were studied by Nanzyo and Takahashi (2005).

### 33.3.7 Management of Andisols

Andisols support a much greater population than their limited extent would suggest. One reason for this is that crop productivity on Andisols is very high due to good physical properties and relatively high native fertility in some locations. Periodic additions of fresh tephra, especially when intermediate to basaltic in composition, can re-supply potential

nutrients and maintain favorable fertility levels in areas where other soils tend to be depleted in nutrients. For example, a “dusting” of andesitic ash fallout from the 1995-1996 Mt. Ruapehu eruptions in New Zealand added between 30 and 1500 kg ha<sup>-1</sup> of sulfur as well as small quantities of Se, Mg, and K to substantial land areas (Lowe and Palmer, 2005). Consequently, in many areas few inputs with the exception of P have been required for successful agricultural production on many Andisols. Andisols are also productive forest soils. In the Pacific Northwest region of United States, the presence of tephra (ash) mantles and their water-holding capacity is closely linked to forest productivity (Kimsey et al., 2008). Vitrands in New Zealand are also support very productive plantation forests (Ross et al., 2009).

Nevertheless, in other locations such as New Zealand where rainfall and leaching are generally high, and where very siliceous tephra low in metals are common, many Andisols have low fertility because of a range of chemical limitations both acquired and inherited. As well as P fixation, exchangeable bases (especially K) tend to be low and other elemental deficiencies may include Mg, S, Co, and others (Lowe and Palmer, 2005). The high productivity of these soils is thus maintained by regular fertilizer input in combination with their generally excellent physical properties.

Most Andisols are acid and where acidity is particularly high, high levels of exchangeable Al may inhibit crop growth (Al toxicity). This is especially a problem in nonallophanic Andisols (Shoji et al., 1993; Shoji and Takahashi, 2002; Dahlgren et al., 2004). In such instances, addition of lime can reduce the amounts of organically complexed Al and exchangeable Al (Takahashi et al., 2006), or acid-tolerant crops must be selected (Michaelson and Ping, 1987; Nanzyo 2002; Shoji and Takahashi, 2002). Where Andisols have been acidified by long-term N inputs, serious consequences for crop production can arise because as pH decreases, CEC also decreases. As a result, such soils are able to hold few base cations (Ca, Mg, and K) for plant uptake (Sumner and Hylton, 1993).

Requirements for N vary according to the ease with which organic matter is mineralized in these soils. Nitrogen mineralization is slower in allophanic Andisols than in nonallophanic Andisols because organic matter interacts with and is stabilized by allophane in the former (Parfitt, 2009). Liming often promotes the release of substantial amounts of N from non-available reserves, thereby improving N fertility.



As noted above, the high P-fixing capacities of most Andisols necessitate inputs of P for successful agricultural production (Michaelson and Ping, 1990; Dahlgren et al., 2004; Lowe and Palmer, 2005). Such inputs in the form of rock phosphate are effective on very acid Andisols but in any event, soluble P sources should be band-placed or otherwise protected from intimate mixing with the soil (Sumner and Hylton, 1993).

Other nutrients may sometimes be deficient in Andisols depending of the chemical composition of the parent material. One notable example occurs in the central North Island of New Zealand where Vitrands, formed in the silica-rich Taupo and Kaharoa tephras, are deficient in micronutrients including Co, Se, Cu, B, I, and Mo. Inherently low Co in these pumiceous parent tephras led to low Co levels in soils and herbage, and ultimately to a deficiency in ruminant animals (sheep, cows) that developed a serious and commonly fatal wasting disease known as “bush sickness” (Lowe and Palmer, 2005; Neall, 2006). This term referred to a variety of symptoms exhibited by livestock stemming from their inability to produce vitamin B12, of which Co is an essential component (Cornforth, 1998). The association of this condition with the Vitrands was recognized in the early 1930s (Grange and Taylor, 1932), and the cause identified a few years later. Co deficiency also occurred in some Udands and non-Andisol orders where high rainfall and strong leaching were the cause. Subsequent use of cobaltized superphosphate, and other methods, corrected the problem (Neall, 2006).

Andisols, in general, are noted for their good physical properties including high water-holding capacity, free drainage, good tilth and friability, resistance to water erosion, stable aggregation, low bulk density and high porosity and hence good aeration. Consequently, they are usually excellent media for seedling emergence and root growth and proliferation. It should be emphasized that these properties can and often are altered through management (e.g., Candan and Broquen, 2009). Where uncultivated, undisturbed Andisols may be resistant to erosion, but loss of vegetative cover, compaction, and subsequent reduction in infiltration can lead to severe runoff and erosion including deep gulying in Vitrands (Lowe and Palmer, 2005). Agricultural production on Andisols can result in erosion and compaction, and no-till or reduced tillage farming practices are recommended to minimize these problems in agricultural systems (Dahlgren et al., 2004). Heavy livestock grazing can also compact Andisols (Schlichting, 1988). In the Pacific Northwest of United States, compaction resulting

from mechanized timber harvesting can reduce infiltration and water-holding capacity of Andisols (Cullen et al., 1991). Severe erosion from harvested sites can also significantly reduce water-holding capacity to the point where site productivity is drastically diminished (McDaniel et al., 2005). In Iceland, Cryands have been overgrazed, denuded, and subject to severe wind erosion (Arnalds et al., 1995; Arnalds and Kimble, 2001).

As noted earlier, properties of sensitivity and thixotropy can cause Andisols to behave in a fluid-like manner when loading pressures are applied. Thus, Andisols are susceptible to failure when disturbed on slopes, which can cause them to reach the liquid limit, generating landslides (Basile et al., 2003; Neall, 2006). Mantling of harder bedrock by andic soils and the layering associated with tephra deposits and buried soils can form planes of failures (Arnalds, 2008).

Because of their sorptive capacity for anions and metals, Andisols offer potential environmental benefits as active filters. High nitrate adsorption by allophanic Andisols was correlated with retarded nitrate transport rates under coffee plantations in Costa Rica (Reynolds-Vargas et al., 1994; Ryan et al., 2001). Reduced phosphorus leaching losses from surface-applied domestic effluent in New Zealand have been attributed to the relatively high P sorption capacity of Andisols (Barton et al., 2005). Similarly, the sorption of arsenate by Andisols offers potential for purifying drinking water or for remediating As-contaminated soils (Arai et al., 2005; Theng and Yuan, 2008). McLeod et al. (2008) have also demonstrated that New Zealand Andisols leached very small amounts of surface-applied microbial tracers via bypass flow, attributable to their sorptive capacity and the fine, porous nature of the soils. These and other studies suggest that Andisols may play an important role in reducing groundwater contamination.

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Figure 33.13

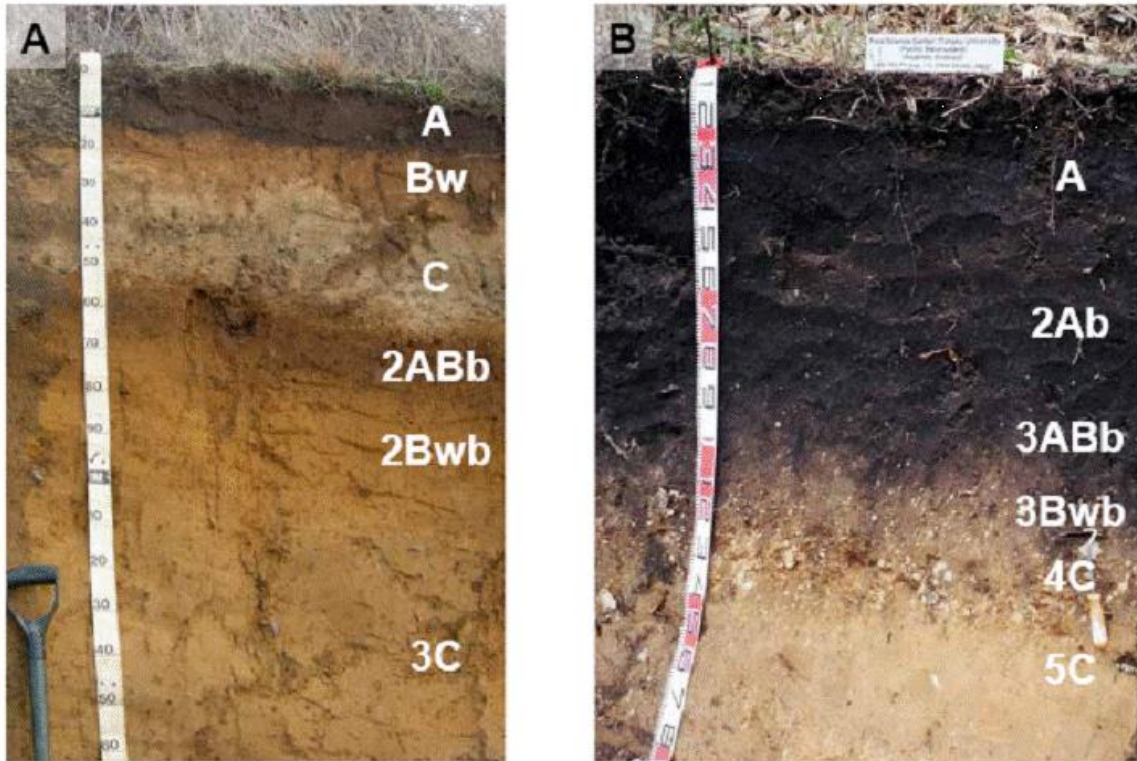


Figure 33.14

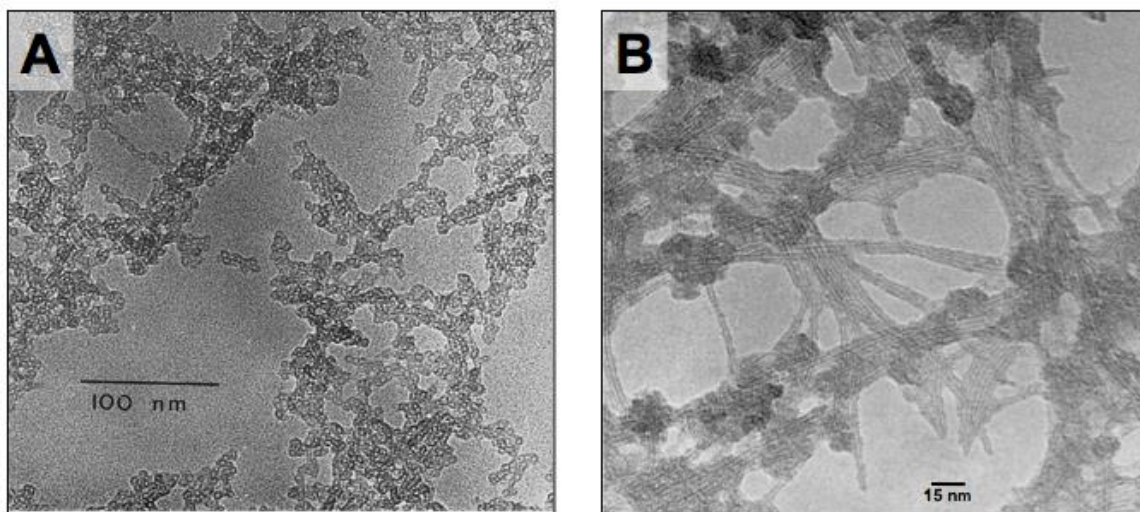


Figure 33.15

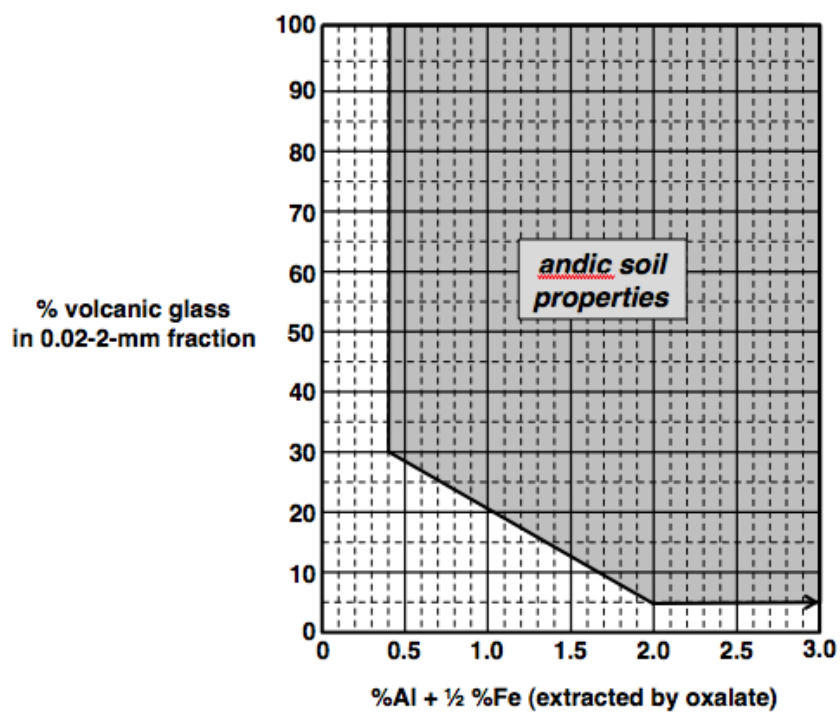


Figure 33.16



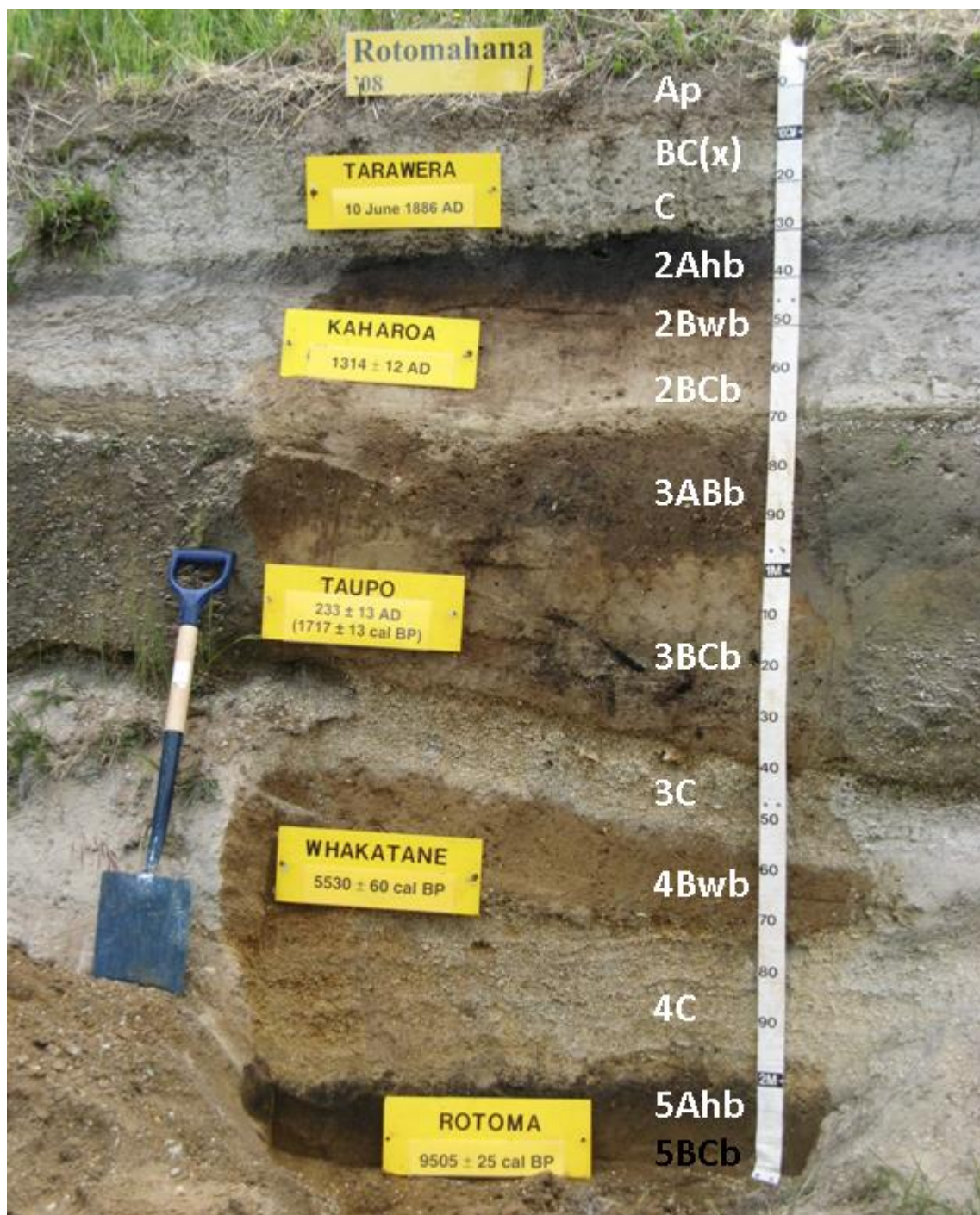


Figure 33.17

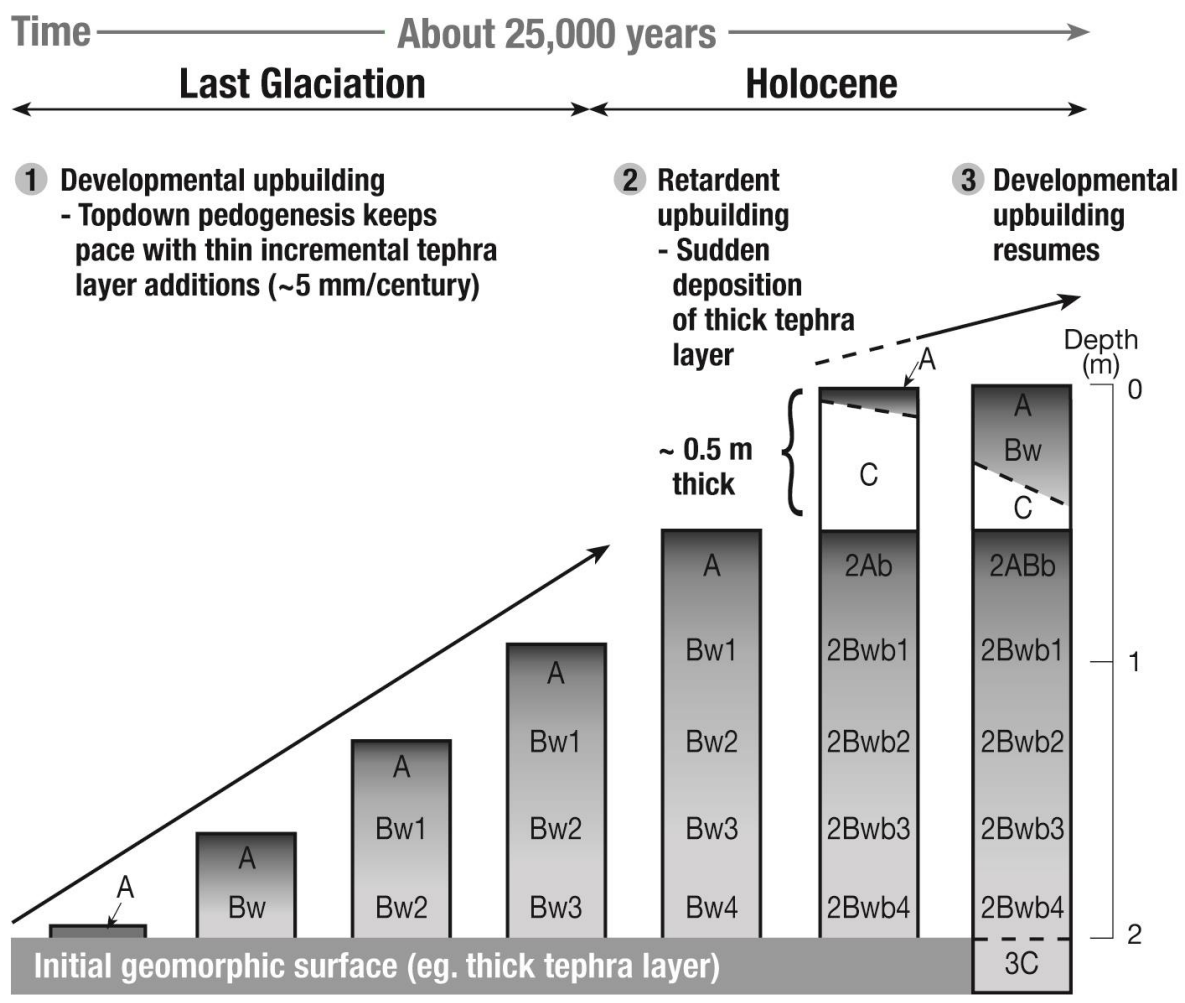


Figure 33.18

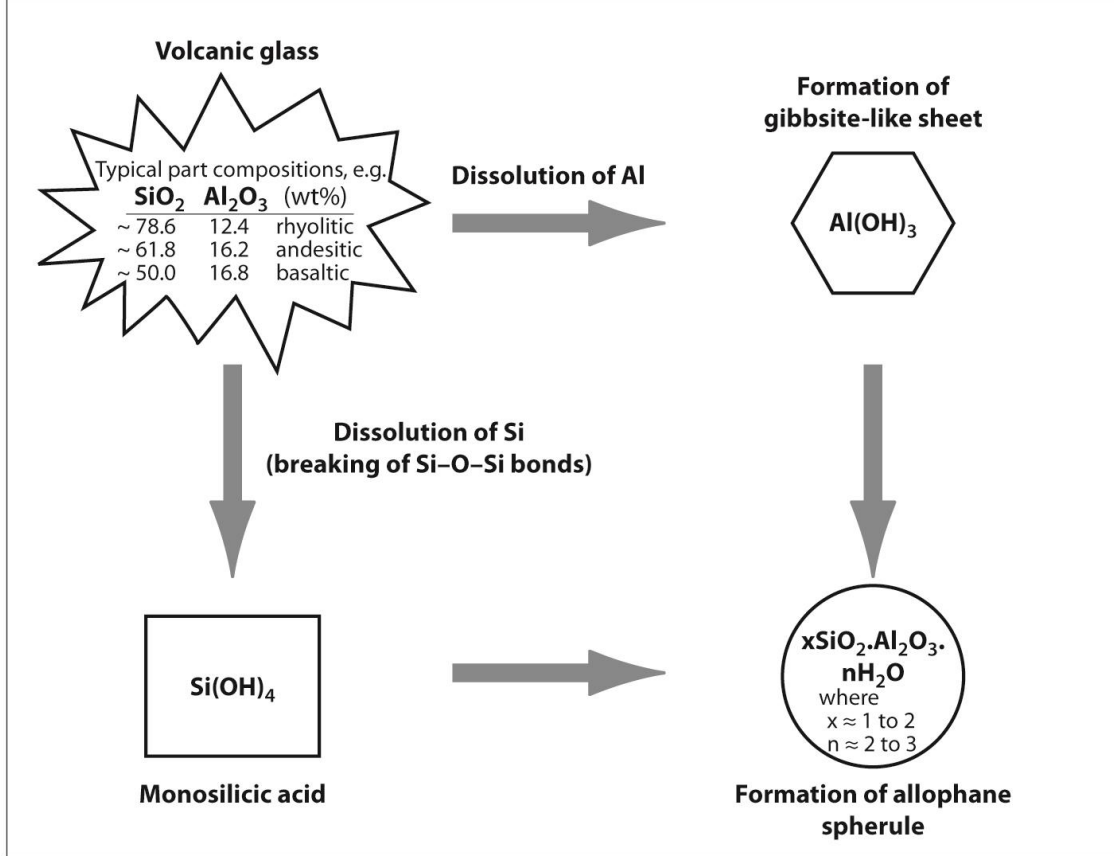


Figure 33.19

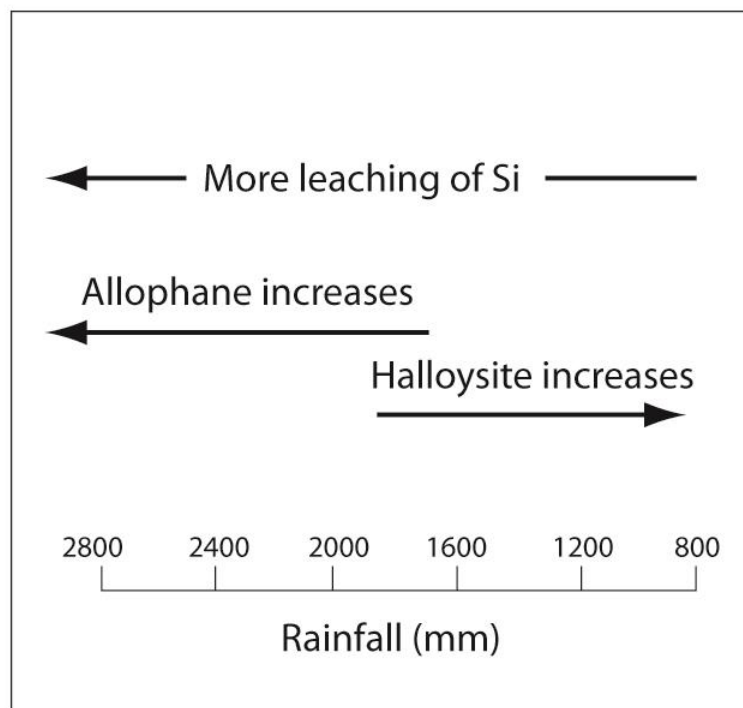


Figure 33.20



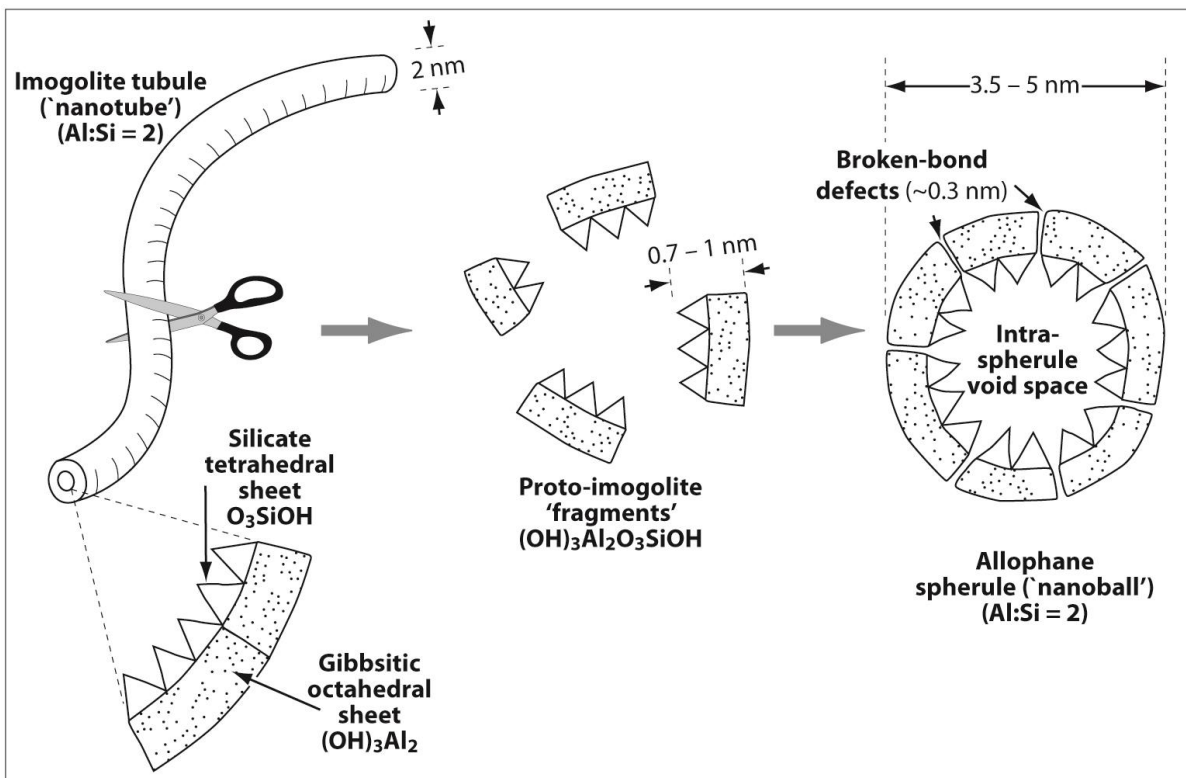


Figure 33.21

Horizon	Depth cm	pH		Clay	Organic C %	ECEC <sup>a</sup>	CEC pH7	Sum of exch bases cmol+ kg <sup>-1</sup>	Exch. Al <sup>3+</sup> <sup>b</sup>	P retention	Al in Al- humus complexes <sup>c</sup>	Allophane <sup>d</sup> %	Ferrihydrite <sup>e</sup>
		H <sub>2</sub> O	NaF										
Thingvallaveit series <sup>f</sup> (Haplodyand) – Iceland													
A1	0-12	5.4	11.0	–	7.9	–	31.9	9.9	–	99	–	1.3	8.5
A2	12-28	5.7	10.7	1	7.6	–	44.6	13.1	–	99	0.1	1.6	11.1
Bw1	28-61	5.6	10.8	–	7.4	–	43.8	10.1	–	99	–	1.5	12.7
Bw2	61-68	5.7	11.1	3	4.2	–	32.3	6.5	–	99	–	1.6	6.0
2Bw3	68-87	5.6	10.5	–	2.1	–	24.8	4.4	–	98	–	1.7	4.4
2C	87-142	5.5	10.3	1	0.8	–	11.8	2.8	–	99	–	1.3	3.6
Tirau series <sup>g</sup> (Hapludand) – New Zealand													
Ap	0-18	5.6	9.6	19	7.9	14.6	29.7	14.4	0.2	88	0.7	9	1.0
Bw1	18-32	6.2	9.9	11	2.0	5.6	11.3	5.6	0	98	0.2	14	1.2
Bw2	32-48	6.2	9.8	13	1.0	5.2	10.5	5.2	0	98	0.2	16	1.2
Bw3	48-65	6.4	9.5	20	0.5	6.1	12.5	6.1	0	91	0.1	10	0.7
2BCb	65-90	6.4	9.4	18	0.5	7.5	13.2	7.5	0	86	0.1	8	0.8
Tohoku Farm <sup>h</sup> (Melanudand) – Japan													
A1	0-14	4.2	10.5	18	11.5	13.3	52.2	2.3	11.0	83	1.5	0.3	–
2A2	14-30	4.6	11.6	5	8.0	8.4	49.1	0.4	8.0	93	2.5	1.1	–
3A3	30-57	4.8	11.6	12	13.2	8.4	56.1	0.4	8.0	93	2.7	1.4	–
4Bw1	57-80	5.2	11.3	8	2.8	2.0	18.4	0.1	1.9	93	0.9	6.7	–
4Bw2	80-126	5.2	11.0	16	0.9	0.9	13.7	0.2	0.7	94	0.6	7.4	–
4Bw3	126-160	5.3	10.9	20	0.6	0.8	10.9	0.2	0.6	89	0.5	7.0	–
4C	160-200	5.3	10.9	22	0.5	1.8	11.5	0.4	1.4	84	0.5	4.9	–

<sup>a</sup> effective cation exchange capacity

<sup>b</sup> exchangeable Al<sup>3+</sup> extracted with KCl

<sup>c</sup> estimated using pyrophosphate-extractable Al

<sup>d</sup> estimated using oxalate-extractable Si (Parfitt 1990)

<sup>e</sup> estimated using oxalate-extractable Fe (Parfitt and Childs 1988)

<sup>f</sup> data are from Arnalds et al. (1995)

<sup>g</sup> data are from Bakker et al. (1996)

<sup>h</sup> data (Pedon #86P0091) are from Soil Survey Staff (2009)

Table 33.15

Depth cm	Horizon	Texture		Sand	Silt	Clay	Bulk density		1500 kPa H <sub>2</sub> O	
		field	lab				oven dry	moist g cm <sup>-3</sup>	air dry	moist %
<b>Bonner series<sup>a</sup> (Vitrixerand) – Idaho</b>										
0-4	A	Silt loam	Silt loam	30.6	63.8	5.6	0.75	0.68	20.3	–
4-20	Bw1	Silt loam	Silt loam	38.1	58.0	3.9	–	–	10.0	–
20-48	Bw2	Silt loam	Silt loam	39.3	59.0	1.7	0.96	0.94	9.9	–
48-69	Bw3	–	Coarse sandy loam	52.6	44.1	3.3	–	–	6.8	–
69-89	Bw4	–	Coarse sandy loam	52.7	44.8	2.5	0.80	0.80	6.8	–
89-152	2C	–	Coarse sand	88.6	9.8	1.6	–	–	2.2	–
<b>Tirau series<sup>b</sup> (Hapludand) – New Zealand</b>										
0-18	Ap	Silt loam	Loam	35	46	19	0.75	–	23.3	31.1
18-32	Bw1	Sandy loam	Silt loam	33	56	11	0.71	–	15.7	33.7
32-48	Bw2	Sandy loam	Silt loam	33	54	13	0.69	–	16.5	33.6
48-65	Bw3	Sandy loam	Loam/Silt loam	30	50	20	0.79	–	22.0	34.7
65-90	2BCb	Silt loam	Silt loam	20	62	18	0.87	–	20.4	33.9
<b>Hilo series<sup>c</sup> (Hydrudand) – Hawaii</b>										
0-18	Ap1	Silty clay loam	Sandy loam	66.2	29.7	4.1	–	–	28.4	54.1
18-36	Ap2	Silty clay loam	Coarse sand	86.8	12.1	1.1	0.82	0.51	27.7	107.2
36-60	Bw1	Silty clay loam	Coarse sand	91.8	7.9	0.3	1.66	0.41	25.0	112.6
60-92	Bw2	Silty clay loam	Coarse sand	93.1	6.9	–	1.61	0.25	25.1	132.5
92-108	Bw3	Silty clay loam	Coarse sand	94.9	4.7	0.4	1.41	0.30	26.0	122.4

sil = silt loam; silcl = silty clay loam; cosl = coarse sandy loam; cos = coarse sand; sl = sandy loam; l = loam

<sup>a</sup> data (Pedon #78P0553) are from Soil Survey Staff (2009)

<sup>b</sup> data are from Bakker et al. (1996)

<sup>c</sup> data (Pedon #89P0658) are from Soil Survey Staff (2009)

Table 33.16

**TABLE 33.17** Listing of Andisol Suborders and Great Groups

## Suborders Great Groups

- Aquands**—poorly drained Andisols with a water table at or near the surface for much of the year
- Gelaquands**—Aquands of very cold climates (mean annual soil temperature  $< 0^{\circ}\text{C}$ )
  - Cryaquands**—Aquands of cold climates ( $0^{\circ}\text{C} < \text{mean annual soil temperature} \leq 8^{\circ}\text{C}$ )
  - Placaquands**—Aquands with a thin pan cemented by Fe, Mn, and organic matter
  - Duraquands**—Aquands with a cemented horizon
  - Vitraqquands**—Aquands with coarse textures dominated by glassy materials
  - Melanaquands**—Aquands with a thick, dark, organic matter-rich surface layer
  - Epiaquands**—Aquands with a perched water table
  - Endoaquands**—Aquands with a groundwater table
- Gelands**—Andisols of very cold climates (mean annual soil temperature  $\leq 0^{\circ}\text{C}$ )
- Vitrigelands**—Gelands with coarse textures dominated by glassy materials
- Cryands**—Andisols of cold climates ( $0^{\circ}\text{C} < \text{mean annual soil temperature} \leq 8^{\circ}\text{C}$ )
- Duricryands**—Cryands with a cemented horizon
  - Hydrocryands**—Cryands with very high water-holding capacity
  - Melanocryands**—Cryands with a thick, very dark, organic matter-rich surface layer
  - Fulvicryands**—Cryands with a thick, organic matter-rich surface layer
  - Vitricryands**—Cryands with coarse textures dominated by glassy materials
  - Haplocryands**—other Cryands
- Torrands**—Andisols of very dry climates
- Duritorrands**—Torrands with a cemented horizon
  - Vitritorrands**—Torrands with coarse textures dominated by glassy materials
  - Haplotorrands**—other Torrands
- Xerands**—Andisols of temperature regions with warm, dry summers and cool, moist winters
- Vitrixerands**—Xerands with coarse textures dominated by glassy materials
  - Melanoxerands**—Xerands with a thick, very dark, organic matter-rich surface layer
  - Haploxerands**—other Xerands
- Vitrands**—slightly weathered Andisols that are coarse textured and dominated by glassy material
- Ustivitrands**—Vitrands of semiarid and subhumid climates
  - Udivitrands**—Vitrands of humid climates
  - Ustands**—Andisols of semiarid and subhumid climates
  - Durustands**—Ustands with a cemented horizon
  - Haplustands**—other Ustands
- Udands**—Andisols of humid climates
- Placudands**—Udands with a thin pan cemented by Fe, Mn, and organic matter
  - Durudands**—Udands with a cemented horizon
  - Melanudands**—Udands with a thick, very dark, organic matter-rich surface layer
  - Hydrudands**—Udands with very high water-holding capacity
  - Fulvudands**—Udands with a thick, organic matter-rich surface layer
  - Hapludands**—other Udands

Source: Soil Survey Staff, *Keys to Soil Taxonomy*, 11th edn., USDA-NRCS, Washington, DC, 2010.