Distribution and Classification of Volcanic Ash Soils

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Abstract

Volcanic ash soils are distributed exclusively in regions where active and recently extinct volcanoes are located. The soils cover approximately 124 million hectares, or 0.84% of the world's land surface. While, thus, volcanic ash soils comprise a relatively small extent, they represent a crucial land resource due to the excessively high human populations living in these regions. However, they did not receive worldwide recognition among soil scientists until the middle of the 20th century. Development of international classification systems was put forth by the 1978 Andisol proposal of G. D. Smith. The central concept of volcanic ash soils was established after the finding of nonallophanic volcanic ash soils in Japan in 1978. Nowadays, volcanic ash soils are internationally recognized as Andisols in Soil Taxonomy (United States Department of Agriculture) and Andosols in the World Reference Base for Soil Resources (FAO, International Soil Reference and Information Centre and International Society of Soil Science). Several countries including Japan and New Zealand have developed their own national classification systems for volcanic ash soils. Finally correlation of the international and domestic classification systems is described using selected volcanic ash soils.

Key words: Andisols, Andosols, Japanese Cultivated Soil Classification, New Zealand Soil Classification, Soil Taxonomy, World Reference Base for Soil Resources (WRB)

1. Introduction

The term "volcanic ash soils" is commonly used to denote "*Kurobokudo*," meaning black-fluffy soils in Japanese (The Third Division of Soils, 1973), "Andosols" in the World Reference Base for Soil Resources (WRB Classification) (FAO *et al.*, 1998) and "Andisols" in US Soil Taxonomy (Soil Survey Staff, 1999). The soil names of Andosols and Andisols are derived from "*Ando* soils" whose etymology is dark (*An*) and soils (*do*) in Japanese.

Volcanic ash soils occur extensively, closely paralleling the global distribution of active and recently extinct volcanoes, have unique properties, and significantly contribute to agriculture and forest production. However, they did not receive worldwide recognition among soil scientists until the middle of the 20th century. It was only in 1960 that "volcanic ash soils" were identified for the first time in an international system of soil classification.

Volcanic ash soils were first included as the Andept suborder of Inceptisols in the Seventh Approximation (Soil Survey Staff, 1960) and this suborder was introduced into Soil Taxonomy (Soil Survey Staff, 1975). In 1978 Smith (1978) proposed reclassification of Andepts and provided a rationale for development of a new soil order, Andisols. His proposal led to the development and establishment of the current international classification of Andisols (Soil Survey Staff, 1999). During this period, the FAO/Unesco held a meeting on the classification of volcanic ash soils in Japan in 1964 (FAO/Unesco, 1964) and designated the major soil group Andosols for the Soil Map of the World (FAO/Unesco, 1974). Andosols are currently included as one of 30 reference soil groups of the World Reference Base for Soil Resources (WRB Classification) (FAO *et al.*, 1998).

Several countries including Japan and New Zealand have developed their own national classification systems for volcanic ash soils. Each national system organizes knowledge of the distribution, properties, productivity, utilization, and management of soils in its respective jurisdiction. However, the national systems are not in competition with the international systems. They are rather complementary and provide the basic information and data needed for the development of the more comprehensive international systems.

This paper first briefly outlines the distribution of volcanic ash soils and then describes international classification systems (Soil Taxonomy and WBR Classification) and domestic classification systems (Japanese Cultivated Soil Classification and New Zealand Soil Classification) for volcanic ash soils. Lastly, some selected soil profiles are introduced and their classification is tested according to these soil classification systems.

2. Geographic Distribution of Volcanic Ash Soils

Soils derived from volcanic materials (Andisols) are distributed exclusively in regions where active and recently extinct volcanoes are located as shown in Fig. 1. This soil resources map is derived from the front cover page of Keys to Soil Taxonomy (Soil Survey Staff, 1998). The principal regions of the world where Andisols are distributed are summarized (Leamy, 1984) as follows:

- *In Europe*: Italy, Sicily, Sardinia, France (Massif – Central).
- *In Africa and the Indian Ocean*: Kenya, Rwanda, Tanzania, Ethiopia, Cameroon, Malagasy, Reunion, Canary Islands, Uganda, Sudan, Zaire.
- *In America*: Alaska, British Columbia, Washington, Oregon, California, Mexico, Costa Rica, Panama, Honduras, Guatemala, El Salvador, Nicaragua, West Indies, Ecuador, Colombia, Peru, Chile, Argentina, Bolivia.
- *In Asia and the Pacific*: Hawaii, Aleutian Islands, Kamchatka, Japan, Korea, Micronesia, Philippines, Indonesia, Papua New Guinea, Solomon Islands, Vanuatu, Fiji, Samoa, Tonga, New Zealand.

Volcanic ash soils cover approximately 124 million hectares or 0.84% of the world's land surface (Leamy 1984). Approximately 60% of volcanic ash soils occur in tropical countries. While volcanic ash soils comprise a relatively small extent of the world's surface, they represent a crucial land resource due to the disproportionately high human populations living in these regions.

Eighty-six active volcanoes are recognized in Japan (Japan Meteorological Agency, 2001) and another 21 volcanoes will be included as "active" in the near future. Active volcanoes are concentrated in four districts: Hokkaido, Tohoku, Kanto and Kyushu. Therefore, volcanic ash soils are mainly distributed in these districts (Fig. 2) and cover 18% of the territory of Japan. Cultivated volcanic ash soils occupy approximately 1.35 million hectares, comprising 27% of the total agricultural land use in Japan. Therefore, these soils are important resources for agriculture, especially for upland crop production.

3. Classification of Andisols in Soil Taxonomy

The current classification of Andisols included in Soil Taxonomy (Soil Survey Staff, 1999) is the most widely used system for the international classification of volcanic ash soils. The development of this classification had its origin in the Andisol proposal put forth by Smith in 1978 and was further developed through the collective experience and efforts of members of the International Committee on the Classification of Andisols (ICOMAND) for ten years from 1978 to 1988. On the basis of the final report of the ICOMAND (Leamy *et al.*, 1988), the Andisol order was established for Soil Taxonomy in October of 1989 and it was first published in the 4th edition of Keys to Soil Taxonomy (Soil Survey Staff, 1990). After several revisions were conducted, the current classification of Andisols was completed (Soil Survey Staff, 1999).

The central concept of Andisols is that of a soil developing in volcanic ejecta and/or volcaniclastic material, whose colloidal fraction is dominated by short-range-order minerals, and/or Al-humus complexes. Based on characteristics of Andisols, andic soil properties are defined as listed in Table 1.

Criterion 1 in the definition of andic soil properties is used to classify Andisols that show a high degree of weathering as determined by ammonium oxalate extractable Al plus a half of Fe ($Al_o + 1/2\ Fe_o$). Such soils typically have high phosphate retention and low bulk density. Criterion 2 is applied to classify Andisols which are vitric or have developed from mixed parent materials of tephra and non-tephra deposits. Soils with mixed parent materials typically have high bulk densities (> 0.9 g cm^{-3}) so they fail to meet andic soil properties as defined by criterion 1. Therefore, the bulk density requirement is waived in criterion 2 and a phosphate retention of $> 25\%$ requirement is included to separate Andisols from Entisols (Shoji *et al.,* 1987). Criterion 2 is further used to define andic soil properties in soils showing a low degree of weathering or vitric properties. It has two requirements consisting of minimum concentrations of glass content and $Al_o + 1/2\ Fe_o$.

The definition of Andisols in Soil Taxonomy (Soil Survey Staff, 1999) is based on the existence of subhorizons meeting requirements of andic soil properties which have a cumulative thickness of 36 cm or more within 60 cm of either the mineral soil surface or the top of an organic layer with andic soil properties (Table 2). Andisols are keyed out after Spodosols and before Oxisols (Soil Survey Staff, 1999).

The classification of suborders and great groups of Andisols is shown in Table 3. Seven suborders are provided for the Andisol order: Aquands, Cryands, Torrands, Xerands, Vitrands, Ustands, and Udands. These suborders are defined based on soil temperature and soil moisture regimes except for Vitrands. They are subdivided into great groups mainly based on important constraints to agricultural production.

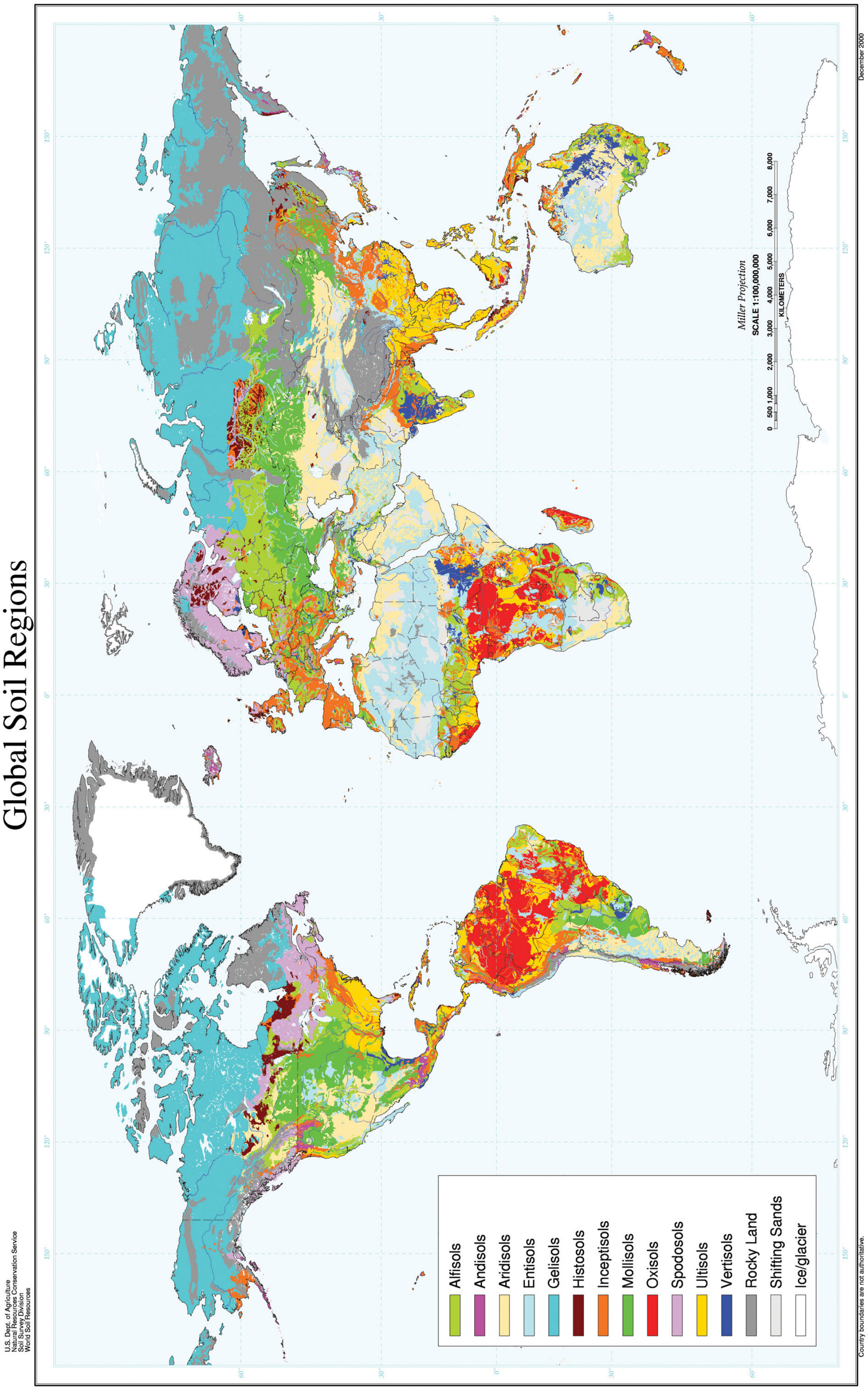

Fig. 1 Worldwide distribution of volcanic ash soils (Andisols). (World Soil Resources Staff, 1997; copyright USDA, Natural Resources Conservation Service, with permission.)

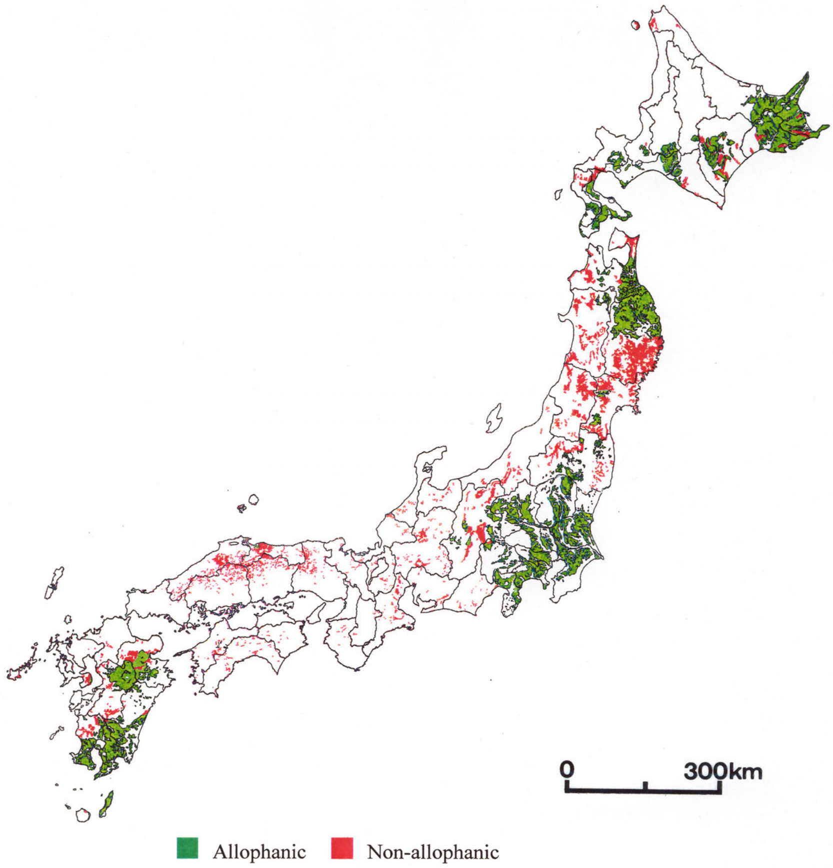

Fig. 2 Distribution of allophanic and nonallophanic volcanic ash soils in Japan (courtesy of N. Matsuyama and M. Saigusa).

Table 1 Definition of andic soil properties in Soil Taxonomy (Soil Survey Staff, 1999).

To be recognized as having andic soil properties, soil materials must contain less than 25% (by weight) organic carbon and meet one or both of the following requirements:

1. In the fine-earth fraction, all of the following:
   a. Aluminum plus 1/2 iron percentage (by ammonium oxalate) totaling 2.0% or more, and
   b. A bulk density, measured at 33 kPa water retention, of 0.90 g/cm^3 or less, and
   c. A phosphate retention of 85% or more; or

2. In the fine-earth fraction, a phosphate retention of 25% or more, 30% or more particles of 0.02 to 2.0 mm in size, and one of the following:
   a. Aluminum plus 1/2 iron percentage (by ammonium oxalate) totaling 0.40 or more and, in the 0.02 to 2.0 mm fraction, 30% or more volcanic glass; or
   b. Aluminum plus 1/2 iron percentage (by ammonium oxalate) totaling 2.0 or more and, in the 0.02 to 2.0 mm fraction, 5% or more volcanic glass; or
   c. Aluminum plus 1/2 iron percentage (by ammonium oxalate) totaling between 0.40 and 2.0 and, in the 0.02 to 2.0 mm fraction, enough volcanic glass that can be determined according to the following equation: Volcanic glass (%) > 36.25 – 15.62 × (aluminum plus 1/2 iron percentages).

Table 2 Definition of Andisols in Soil Taxonomy (Soil Survey Staff, 1999).

Other soils that have andic soil properties in 60% or more of the thickness either:

1. Within 60 cm either of the mineral soil surface or of the top of an organic layer with andic soil properties, whichever is shallower, if there is no densic, lithic, or paralithic contact, duripan, or petrocalcic horizon within that depth; or

2. Between either the mineral soil surface or the top of an organic layer with andic soil properties, whichever is shallower, and a densic, lithic, or paralithic contact, a duripan, or a petrocalcic horizon.

Aquands: These are Andisols having an aquic moisture regime caused by restricted drainage as imposed by depressed landscape position or the existence of impermeable layers.

Aquands are formed in volcanic materials under a wide range of climatic conditions and include seven great groups (Table 3). Aquands occur in the Pacific Northwest of the United States and in other areas that have volcanic influence (Soil Survey Staff, 1999). Cryaquands are extensive in Alaska and Melanaquands characteristically occur in the lowlands of Japan (Shoji and Ping, 1992).

Cryands: Cryands are defined as Andisols having a cryic or pergelic soil temperature regime (Soil Survey Staff, 1999). There are six great groups within the Cryand suborder (Table 3).

The classification criteria for Cryands were developed mainly according to the studies on Andisols in Alaska and in the high mountains of northeastern Japan (Ping *et al.*, 1988, 1989; Shoji *et al.,* 1988a, 1988b). Cryands have formed in the western part of North America and the northeastern part of Asia above 49 degrees north latitude and in mountains south of that latitude. Most of the soils have formed under coniferous forest vegetation (Soil Survey Staff, 1999).

Cryands and Spodosols such as Haplocryods, Humicryods, and Placocryods have commonly developed in the same parent materials under a cryic soil temperature regime. They share a number of important physical and chemical properties (Shoji and Ito, 1990; Takahashi, 1990). In the present Soil Taxonomy (Soil Survey Staff, 1999), tephra-derived Spodosols satisfying the albic and spodic requirements are classified as Spodosols even if they meet requirement of andic soil properties. In some multisequum Andisols, C horizons or light-colored ash layers in upper profiles can be easily confused with an albic horizon (Ito *et al.*, 1991). If the C horizon of an Andisol showing a horizon sequence of A-C-2Ab-2Bwb is misidentified as an albic horizon, the 2Ab horizon (buried humus horizon) could be regarded as a spodic horizon. Thus, careful field observation of soil profiles is necessary to differentiate a spodic horizon from a buried A horizon.

Torrands: Torrands are Andisols that have an aridic moisture regime (Soil Survey Staff, 1999). Even though tephra is dominated by volcanic glass, which is the most weatherable component in tephra, the rate of its chemical weathering is restricted under dry conditions. Torrands formed in the western part of North America, and some are known to occur in Hawaii and other Pacific islands (Soil Survey Staff, 1999).

Xerands: Xerands are Andisols that have a xeric moisture regime (Soil Survey Staff, 1999). Xerands includes three great groups of vitric, melanic and haplic (Table 3). It is interesting to note that the fulvic great group is not provided in spite of the presence of Melanoxerands. This suggests that humification of organic matter is favorable under a xeric soil moisture regime resulting in formation of melanic epipedons even in forest vegetations as observed in California, United States (Takahashi *et al.*, 1995).

Vitrands: Vitrands are Andisols that have 1500 kPa water retention of less than 15% in air-dried samples and less than 30% in undried samples throughout 60% or more of the thickness (Soil Survey Staff, 1999). The parent material of Vitrands is commonly pumice, cinder, or scoria, and is weakly weathered. Because the Vitrands suborder is keyed out before the suborders of Ustands and Udands, vitric great groups are not provided in these suborders.

Ustands: Ustands are Andisols that have an ustic soil moisture regime (Soil Survey Staff, 1999). They include two great groups: duric and haplic. They occur mostly in Mexico, the western part of the United States, the Pacific Islands, and the eastern part of Africa. Most Ustands in the United States are in Hawaii, Arizona, and New Mexico (Soil Survey Staff, 1999).

Udands: Udands are Andisols that have a udic soil moisture regime and are the Andisols most widely used for agriculture. They are largely found on the

Table 3 Suborders and great groups in Soil Taxonomy (Soil Survey Staff, 1999).

Suborder	Great group
Aquands	Cryaquands
	Placaquands
	Duraquands
	Vitraquands
	Melanaquands
	Epiaquands
	Endoaquands
Cryands	Duricryands
	Hydrocryands
	Melanocryands
	Fulvicryands
	Vitricryands
	Haplocryands
Torrands	Duritorrands
	Vitritorrands
	Haplotrrands
Xerands	Vitrixerands
	Melanoxerands
	Haploxerands
Vitrands	Ustivitrands
	Udivitrands
Ustands	Durustands
	Haplustands
Udands	Placudands
	Durudands
	Melanudands
	Hydrudands
	Fulvudands
	Hapludands

Pacific Rim, mainly in the western part of North America and Japan, New Zealand, the Philippines, and Indonesia (Soil Survey Staff, 1999). Since they occur in humid temperate to humid tropic zones, their weathering rates are great, forming an abundance of short-range-order minerals. Six great groups are provided for Udands: placic, duric, melanic, hydric, fulvic, and haplic (Table 3).

Melanudands and Fulvudands attracted much attention during the examination process of Andisol classification. The traditional concept of *Kurobokudo* (Andosols) in Japan is soils having a black humus-rich horizon and friable consistency (Fig. 5 (b)). The central concept of melanic Andisols described by Smith (1978) originated from such a humus horizon that has the primary characteristics of *Kurobokudo* (The Third Division of Soils, 1982).

In order to establish a definition of melanic epipedons and to separate exactly melanic and fulvic Andisols, requirements for depth, organic carbon content, and soil color of melanic epipedons were proposed by Shoji (1988). The melanic index needed for soil color requirements was established by Honna *et al.* (1988). It indicates an abundance of type A humic acid in the soil organic matter that is attributable to the very dark color. The final definition of the melanic epipedon in the current Soil Taxonomy is shown in Table 4. Melanudands are extensively formed in Japanese pampas grass (*Miscanthus sinensis*) and Sasa ecosystems in Japan.

Fulvudands are Udands with thick dark brown epipedons with high contents of organic matter that are not as dark as melanic epipedons (Fig 5 (c)). Although the two great groups have thick, high organic matter content horizons, they differ remarkably in the characteristics of their humus. Fulvudands show high fulvic acid to humic acid ratios and commonly have organic matter with melanic indices higher than 1.70 (Honna *et al.*, 1988).

Each great group is further divided into subgroups. For example, Melanudands have 15 subgroups and Hapludands, 20 subgroups. Several subgroups are selected for discussion as follows.

***Alic subgroups*:** Alic Andisols have 1 M KCl-extractable Al of more than 2.0 $\mathrm{cmol_c\ kg^{-1}}$ in the fine-earth fraction throughout a layer 10 cm or more thick between a depth of 25 and 50 cm (Soil Survey Staff, 1999). This level of exchangeable Al is potentially toxic enough to severely reduce the root growth of Al-sensitive plants (Saigusa *et al.*, 1980). The layer underlying the Ap or surface horizon (25 to 50 cm) is employed to determine the level of exchangeable Al because its soil properties are little affected by farming practices.

***Aquic and anthraquic subgroups*:** The aquic subgroups are identified by the presence of aquic features in some subhorizon between 50 to 100 cm from the mineral soil surface or from the upper boundary of an organic layer with andic soil properties. On the other hand, well drained to excessively drained Andisols exhibit changed properties after puddling of surface soil and continuous flooding for rice cultivation. Changes include degradation of soil structure, development of a plowpan, loss of iron and manganese from the Ap horizon, and accumulation of iron and manganese (mottles and nodules) in the subsurface horizon. These features are characteristic of the anthraquic subgroup designation.

***Pachic subgroups*:** Pachic subgroups of Andisols have more than 6.0% organic carbon and meet the color requirements of the mollic epipedon throughout at least 50 cm of the upper 60 cm, excluding any overlying layers that do not have andic soil properties (Soil Survey Staff, 1999). Since the range of mollic colors includes the color requirements for both melanic epipedons and fulvic surface horizons, the pachic subgroups are Andisols with thick melanic epipedons or fulvic surface horizons.

***Thaptic subgroups*:** Many Andisols have a multisequum profile, reflecting repeated tephra deposition and subsequent soil formation. Thaptic subgroups of Andisols are defined as soils that have, at depths between 25 and 100 cm (between 40 and 100 cm for melanic and fulvic great groups) from either the mineral soil surface or the top of an organic layer with andic soil properties, whichever is shallower, a layer 10 cm or more thick with more than 3.0% organic carbon and colors of a mollic epipedon throughout, underlying one or more horizons with a total thickness of 10 cm or more that have a color value, moist, 1 unit

Table 4 Definition of melanic epipedon in Soil Taxonomy (Soil Survey Staff, 1999).

The melanic epipedon has *both* of the following:

1. An upper boundary at, or within 30 cm of, either the mineral soil surface or the upper boundary of an organic layer with andic soil properties, whichever is shallower; *and*
2. In layers with a cumulative thickness of 30 cm or more within a total thickness of 40 cm, *all* of the following:
   a. Andic soil properties throughout; *and*
   b. A color value, moist, and chroma (Munsell designations) of 2 or less throughout and a melanic index of 1.70 or less throughout; *and*
   c. 6% or more organic carbon as a weighted average and 4% or more organic carbon in all layers.

or more higher and an organic-carbon content 1% or more (absolute) lower (Soil Survey Staff, 1999).

4. Classification of Andosols in the World Reference Base for Soil Resources (WRB)

The Andosol major soil grouping was created by FAO/Unesco (1974) in order to prepare its Soil Map of the World. The definition of this grouping was drawn from that of the Andept suborder in Soil Taxonomy (Soil Survey Staff, 1975). FAO/Unesco (1988) revised the classification of Andosols by introducing andic soil properties criteria. In recent years, FAO, the International Soil Reference and Information Centre (ISRIC), and the International Society of Soil Science (ISSS) published the World Reference Base for Soil Resources (WRB) (1998). No differentiae comparable to the family and series differentiae in Soil Taxonomy are provided for further classification of Andosols.

The definition of the Andosol reference soil group in the WRB Classification is based on the existence of a vitric or an andic horizon that starts within 25 cm from the soil surface (Table 5). They should have no diagnostic horizons (unless buried deeper than 50 cm) other than a histic, fulvic, melanic, mollic, umbric, ochric, duric or cambic horizon (Table 5). Andosols are keyed out after Gleysols and before Podzols.

Although Podzols are keyed out after Andosols in this system, Podzols derived from volcanic materials are recognized. According to item 2 of the definition of Andosols (Table 5), the soils satisfying albic or spodic horizon criteria are excluded from Andosols even if they have vitric or andic horizons, and they are classified as Podzols.

Diagnostic criteria of the andic horizon and vitric horizon shown in Table 5 are comparable to criterion 1 and criterion 2, respectively, of andic soil properties in Soil Taxonomy. In order to improve Andosol classification in the WRB system, a generalized relationship between Regosols and three types of Andosols is proposed by Shoji *et al.* (1996) as presented in Fig. 3. Two major types of andic horizons are introduced: the sil-andic type and alu-andic type. The sil-andic type is an andic horizon in which allophane and similar minerals are predominant. The alu-andic type is one in which aluminum complexed by soil organic matter prevails, being regarded as a nonallophanic Andosol.

The existence and properties of the alu-andic type or nonallophanic Andosols were first reported by Shoji and Ono (1978). They showed that aluminum-humus complexes also contribute to many of the unique properties common to allophanic (sil-andic) Andosols: high water-holding capacity, high phosphate retention, low bulk density, and high friability. In contrast to the sil-andic (allophanic) Andosols, however, most nonallophanic Andosols show very strong acidity (pH < 5.0), high Al saturation and Al toxicity to plants. Nonallophanic volcanic ash soils account for about 30% of all volcanic ash soils in Japan (Fig. 2) (Saigusa and Matsuyama, 1998) and are mostly used for growing upland crops.

Table 5 Definition of Andosol reference soil group and diagnostic criteria for andic and vitric horizons in the WRB Classification (FAO *et al.*, 1998).

Other soils having
1. ***either*** a *vitric* ***or*** an *andic* horizon staring within 25 cm from the soil surface; and
2. having no diagnostic horizons (unless buried deeper than 50 cm) other than a *histic*, *fulvic*, *melanic*, *mollic*, *umbric*, *ochric*, *duric* or *cambic* horizon.

ANDOSOLS (AN)

Diagnostic criteria for Andic horizon. An andic horizon must have the following physical, chemical and mineralogical properties:
1. bulk density of the soil at field capacity (no prior drying) of less than 0.9 kg dm^{-3}; ***and***
2. 10% or more clay and an Al_{ox} + 1/2 Fe_{ox}* value in the fine earth fraction of 2% or more; ***and***
3. phosphate retention of 70% or more; ***and***
4. volcanic glass content in the fine earth fraction of less than 10%; ***and***
5. thickness of at least 30 cm.

Sil-andic horizons have an acid oxalate (pH 3) extractable silica (Si_{ox}) of 0.6% or more while alu-andic horizons have a Si_{ox} of less than 0.6% (or, alternatively, Al_{py}/Al_{ox} ratio of less than 0.5 and 0.5 or more, respectively).

Diagnostic criteria for Vitric horizon. A vitric horizon must have:
1. 10% or more volcanic glass and other primary minerals in the fine earth fraction; ***and*** either:
2. less than 10% clay in the fine earth fraction; ***or***
3. a bulk density > 0.9 kg dm^{-3}; ***or***
4. Al_{ox} + 1/2 Fe_{ox}* > 0.4%; ***or***
5. phosphate retention > 25%; ***and***
6. thickness of at least 30 cm.

* Al_{ox} and Fe_{ox} are acid oxalate (pH 3) extractable aluminium and iron, respectively (method of Blakemore *et al.*, 1987).

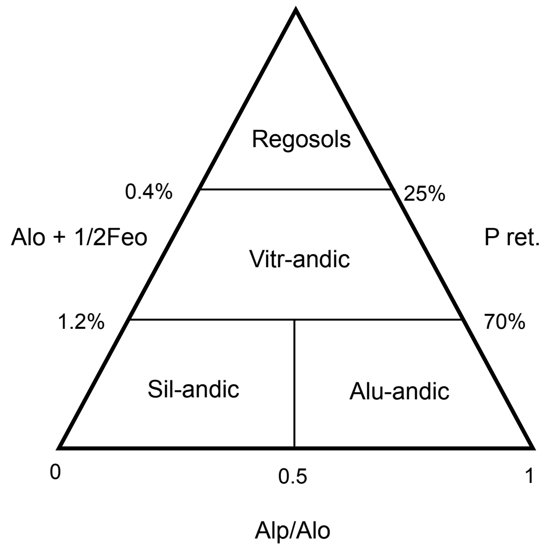

Fig. 3 The generalized relationship between Regosols and the three subtypes of Andosols in WRB classification (Shoji *et al.*, 1996).

Table 6 Priority listing of lower-level units of Andosols in the WRB Classification (FAO *et al.*, 1998).

Vitric:	having a *vitric* horizon within 100 cm from the soil surface and lacking an andic horizon overlying a vitric horizon.
Eutrisilic:	having a *sil-andic* horizon and a sum of exchangeable bases of 25 $cmol_c$ kg^{-1} fine earth within 30 cm from the soil surface.
Silic:	having an *andic* horizon with an acid oxalate (pH 3) extractable silica (Si_{ox}) content of 0.6% or more, or an Al_{py}/Al_{ox} ratio less than 0.5.
Gleyic:	having *gleyic* properties within 100 cm from the soil surface.
Melanic:	having a *melanic* horizon.
Fulvic:	having a *fulvic* horizon within 30 cm from the soil surface.
Hydric:	having within 100 cm from the soil surface one or more layers with a total thickness of 35 cm or more, which have a water retention at 1500 kPa (in undried samples) of 100% or more.
Pachic:	having a *mollic* or *umbric* horizon of more than 50 cm thick.
Histic:	having a *histic* horizon within 40 cm from the soil surface.
Mollic:	having a *mollic* horizon.
Duric:	having a *duric* horizon within 100 cm from the soil surface.
Umbric:	having an *umbric* horizon.
Luvic:	having an *argic* horizon which has a cation exchange capacity equal to or more than 24 $cmol_c$ kg^{-1} clay throughout, and a base saturation by 1 *M* NH_4OAc of 50% or more throughout the horizon to a depth of 100 cm from the soil surface.
Placic:	having within 100 cm from the soil surface a subhorizon of the *spodic* horizon which is 1 cm or more thick and which is continuously cemented by a combination of organic matter and aluminium, with or without iron ("thin iron pan").
Leptic:	having continuous hard rock between 25 and 100 cm from the soil surface.
Acroxic:	having less than 2 $cmol_c$ kg^{-1} fine earth exchangeable bases plus 1 *M* KCl exchangeable Al^{3+} in one or more horizons with a combined thickness of 30 cm or more within 100 cm from the soil surface.
Vetic:	having less than 6 $cmol_c$ kg^{-1} clay of exchangeable bases plus exchangeable acidity in at least some subhorizon of the B horizon within 100 cm from the soil surface.
Calcaric:	calcareous at least between 20 and 50 cm from the soil surface.
Arenic:	having a texture of loamy fine sand or coarser throughout the upper 50 cm of the soil.
Sodic:	having more than 15% exchangeable sodium or more than 50% exchangeable sodium and magnesium on the exchange complex within 50 cm from the soil surface.
Skeletic:	having between 40 and 90% (by weight) gravel or other coarse fragments to a depth of 100 cm from the soil surface.
Thaptic:	having a buried horizon within 100 cm from the soil surface.
Dystric:	having a base saturation (by 1 *M* NH_4OAc) of less than 50% in at least some part between 20 to 100 cm from the soil surface.
Eutric:	having a base saturation (by 1 *M* NH_4OAc) of 50% or more at least between 20 and 100 cm from the soil surface.
Haplic:	other Andosols.

In the WRB system, qualifiers are used for subdivisions of reference soil groups, and their priority sequence for the Andosols reference soil group is shown in Table 6. The first priority is given to Vitric Andosols having a vitric horizon within 100 cm from the soil surface and lacking an andic horizon overlying a vitric horizon. The second priority is provided to sil-andic properties (Eutrisilic and Silic) followed by Gleyic, Melanic, Fulvic, etc.

As previously done by Shoji *et al.* (1996), the WRB Classification was evaluated using the Tohoku University World Andosol Database (TUWAD). For this purpose, seven basically important lower-level units were selected and their percentage distribution was determined as shown in Fig. 4. 22% of the soils in TUWAD were classified as Vitric Andosols. 45% met the requirement of the Silic unit, which included soils with Eutrosilic properties. In the diagnostic criteria of andic horizons (Table 5), both sil-andic and alu-andic horizons are described for exact differentiation. However, alu-andic horizons are not reflected in the WRB system so that the percentage distribution using TUWAD lacks alu-andic Andosols (Fig. 4). Furthermore, although TUWAD includes many Melanic Andosols and Fulvic Andosols, the percentage distribution shows 19% of Andosols meeting the melanic requirement while there are no Andosols satisfying the fulvic requirement (Fig. 4). In addition, the requirements for Luvic, Vetic and Arenic Andosols need mechanical analyses. However, their accurate determination is often difficult due to incomplete dispersion of mineral particles and uncertainty of unit mineral particles (Nanzyo *et.* al., 1993). These facts indicate the necessity of revising the Andosol classification of the WRB system.

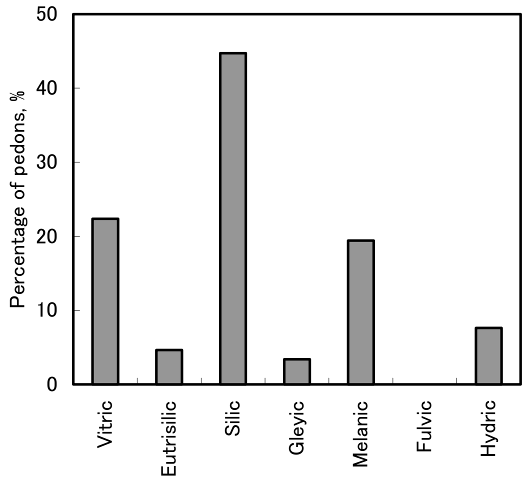

Fig. 4 Percentage distribution of 7 soil units of volcanic ash soils using data from Tohoku University World Andosol Database (TUWAD).

5. Classification of Volcanic Ash Soils in Japan

Three national soil classification systems, i.e., the Japanese Cultivated Soil Classification (Cultivated Soil Classification Committee, 1994), the Classification of Forest Soils (Forest Soil Division, 1976) and the Soil Classification for Land Classification Surveys (National Land Survey Division, 1969) have been employed according to the purposes of soil classification. Recently, the Japanese Society of Pedology organized a Committee for Soil Classification and Nomenclature to prepare a "Unified Soil Classification System of Japan." Among them, the Japanese Cultivated Soil Classification has the most comprehensive system for *Kurobokudo* or volcanic ash soils as shown in Table 7. Volcanic ash soils are identified in the soil groups of Volcanogenous Regosols, Gleyed Andosols (Gleyed *Kurobokudo*), Wet Andosols (Wet *Kurobokudo*), Forest Andosols (Forest *Kurobokudo*), Non-allophanic Andosols (Non-allophanic *Kurobokudo*) and Andosols (*Kurobokudo*). Compared with the previous classification (The Third Division of Soils, 1982), the current classification additionally includes Forest Andosols and Non-allophanic Andosols. The central concept of Andosol (*Kurobokudo*) groups is soils that have developed in pyroclastic materials and are characterized by high phosphate adsorption coefficients, low bulk densities, and high fluffiness. Each soil subgroup is defined mainly based on occurrences of humus horizons and organic matter contents that are thought to be the most important for soil productivity.

Volcanogenous Regosols are defined as soils having a 25 cm or more thick soil layer whose phosphate adsorption coefficient is less than 1500 mg/100g (85% P retention) within 50 cm from the soil surface and are correlated with Vitrands in Soil Taxonomy and Vitric Andosols in the WRB Classification. This soil group has three subgroups: 1) an Aquic subgroup having a gleyed layer or water-table within 50 cm from the soil surface, 2) a Humic subgroup having humic or high-humic surface horizons, and 3) a Haplic subgroup.

Gleyed Andosols (Gleyed *Kurobokudo*) are hydromorphic Andosols that have developed under permanently or nearly permanently water-saturated conditions and are characterized by the occurrence of a gley horizon or upper boundary of an organic layer within 50 cm from the soil surface. They correspond to the Aquands suborder in Soil Taxonomy (Soil Survey Staff, 1999). Gleyed Andosols are mainly distributed in lowlands and valley floors, and are used mostly as paddy rice fields. Gleyed Andosols are divided into three subgroups: Peaty Gleyed Andosols having an organic layer within 50 cm from the soil surface, Cumulic Gleyed Andosols having thick (> 50 cm) humic or high humic surface horizons, and Haplic Gleyed Andosols.

Wet Andosols (Wet *Kurobokudo*) are defined as Andosols having an upper boundary of an iron mottle layer or a grey layer with mottling within 50 cm from

Table 7 Classification of volcanic ash soils in the Classification of Cultivated Soils in Japan (The Third Approximation) (Cultivated Soil Classification Committee, 1994).

Soil Groups	Soil Subgroups
Volcanogenous Regosols	Aquic Volcanogenous Regosols Humic Volcanogenous Regosols Haplic Volcanogenous Regosols
Gleyed Andosols	Peaty Gleyed Andosols Cumulic Gleyed Andosols Haplic Gleyed Andosols
Wet Andosols	Thapto-upland Wet Andosols Thapto-lowland Wet Andosols Cumulic Wet Andosols Haplic Wet Andosols
Forest Andosols	Haplic Forest Andosols
Non-allophanic Andosols	Anthraquic Non-allophanic Andosols Cumulic Non-allophanic Andosols Haplic Non-allophanic Andosols
Andosols	Anthraquic Andosols Thapto-upland Andosols Thapto-lowland Andosols Low-humic Andosols Cumulic Andosols Haplic Andosols

the soil surface. These characteristics develop mainly under the influence of irrigation for rice cultivation and other uses due to penetration by groundwater or stagnant water. They are extensively distributed in alluvial lowlands, valley floors and uplands with poor permeability and are used largely for paddy rice, and partly for upland crops and grasses. Wet Andosols are divided into four subgroups: Thapto-upland Wet Andosols having the upper boundary of a buried upland soil within 50 cm from the soil surface, Thapto-lowland Wet Andosols having the upper boundary of a buried lowland soil within 50 cm from the soil surface, Cumulic Wet Andosols having thick (> 50 cm) humic or high humic surface horizons, and Haplic Wet Andosols.

Forest Andosols (Forest *Kurobokudo*) are defined as Andosols having surface horizons with organic matter of 10% or more and soil color other than black (hue/chroma 1.7/1, 2/1, 2/2) and correspond to Fulvudands in Soil Taxonomy. Volcanic ash soils in natural forests generally do not show a black color though they contain high amounts of organic matter. Forest Andosols typically develop under beech (*Fagus crenata*) forests.

Non-allophanic Andosols (Non-allophanic *Kurobokudo*) are Andosols showing a predominance of Al-humus complexes in the colloidal fraction, and strong acidity and high exchangeable acidity attributable to 2:1 layer silicates. They are defined as the soils having subsurface horizons with exchangeable acidity Y_1 of 5 or more. Non-allophanic Andosols correspond to the alu-andic Andosols in the WRB Classification. Although they possess properties such as low bulk densities, high phosphate retention, etc., which are common to allophanic Andosols, they have a high potential for aluminum toxicity to plant roots. Non-allophanic Andosols are divided into three subgroups: the Anthraquic subgroup having illuvial horizons due to paddy farming, the Cumulic subgroup having thick (> 50 cm) humic or high humic surface horizons, and the Haplic subgroup.

The other volcanic ash soils which do not meet the requirements of the five soil groups described above are classified as Andosols (*Kurobokudo*). Andosols (*Kurobokudo*) are soils that have developed under well drained conditions and show a clay mineralogy dominated by allophane and imogolite and have high accumulations of soil organic matter. They have characteristics such as high phosphate retention, low bulk densities, high organic matter content, and the presence of highly humidified humic acid. They are mostly used as upland crop fields, pastures, orchards, tea gardens, etc. Andosols (*Kurobokudo*) are divided into six subgroups: Anthraquic, Thapto-upland, Thapto-lowland, Low-humic, Cumulic and Haplic.

6. Classification of Volcanic Ash Soils in New Zealand Soil Classification

The New Zealand Soil Classification, the sole national soil classification in New Zealand was derived from the New Zealand Genetic Soil Classification (Taylor, 1948; Taylor and Cox, 1956; Taylor and Pohlen, 1962) preserving successful parts of that classification. The present version (Version

3.0) (Hewitt, 1998) was published after extensive testing of versions 1.0 and 2.0 (Hewitt, 1989). In this classification system, as presented in Table 8, volcanic ash soils are identified in the soil orders of allophanic Soils, Pumice Soils, Granular Soils, and Recent Soils.

Allophanic Soils are keyed out after Podzols and defined as soils that have a layer or layers of allophanic soil material that total 35 cm or more in thickness and occur within 60 cm of the mineral soil surface. The definition of allophanic soil materials is based on the presence of not only allophane but also imogolite and ferrihydrite.

Allophanic Soils are divided into four groups according to water permeability and characteristics associated with wetness. Each group is further divided into several subgroups (Table 8).

Pumice Soils are keyed out after allophanic Soils and are soils that have both

1. a layer of vitric soil material existing from the mineral soil surface to 25 cm or deeper, or are 35 cm or more thick occurring within 60 cm of the mineral soil surface, and
2. a weathered-B horizon 5 cm or more thick.

They are mostly correlated with the Vitrands, Vitraquands and Vitricryands of Soil Taxonomy (Soil Survey Staff, 1999). Pumice soils have properties dominated by a pumiceous and glassy skeleton with low clay content which typically contains allophane. They occur in sandy or pumiceous tephra ranging from 700 to 3,500 years in age in New Zealand (Hewitt, 1998). Pumice Soils are divided into three groups and each group is divided into several subgroups (Table 8).

Granular Soils are derived predominantly from strongly weathered tephras mostly older than 50,000 years (Hewitt, 1998). They contrast with allophanic and Pumice Soils by having clay mineralogy dominated by kaolin-group minerals and associated vermiculite and hydrous-interlayered vermiculite. Some Granular Soils are derived also from basaltic and andesitic rocks with possible addition of aeolian material (Hewitt, 1998).

Most Granular Soils are correlated with Ultisols but a few with the Alfisols of Soil Taxonomy. They are divided into four groups and each group into several subgroups (Table 8).

Volcanic ash soils belonging to Recent Soils are identified in the Tephric group that have developed in tephra deposits from the mineral soil surface to a depth of 30 cm or more. The group is divided into four subgroups (Table 8).

7. Correlation of International and Domestic Systems

As mentioned earlier, each national soil classification system organizes knowledge of the distribution, properties, productivity, utilization, and management of soils in its respective jurisdiction. As for the international systems, they are not a substitute for national soil classification systems, but should be a tool for correlation between national systems. This is one of the main objectives of the WRB Classification (FAO *et al.*, 1998). It is desirable that both the national and international systems be well harmonized with each other. In this section, six pedons with color pictures are selected as examples to study their correlation with Soil Taxonomy, the WRB Classification, and the Japanese Cultivated Soil Classification.

Bekkai soil: The Bekkai soil from eastern Hokkaido, Japan (Fig. 5 (a) on page 95) is one of the representative vitric soils. It has formed from intermittently deposited rhyolitic ash layers ranging in age from a few hundred to less than 1,000 years old under udic soil moisture and frigid soil temperature regimes. The pedon has a multisequum profile consisting of A-C horizons overlying four A-Bw-C horizon sequences and shows a low degree of weathering, especially in the upper part of the profile.

According to characterization data for selected

Table 8 Classification of volcanic ash soils in the New Zealand system (Version 3.0) (Hewitt, 1998).

Order	Group	Subgroup
Allophanic Soils	Perch-gley	Ironstone, Typic
	Gley	Peaty, Typic
	Impeded	Mottled-ironstone, Mottled, Typic
	Orthic	Mottled, Vitric-acidic, Vitric, Acidic, Typic
Pumice Soils	Perch-gley	Duric, Typic
	Impeded	Mottled-welded, Welded, Mottled, Typic
	Orthic	Mottled, Podzolic, Allophanic, Buried-allophanic, Immature, Typic
Granular Soils	Perch-gley	Oxidic, Acidic, Typic
	Melanic	Mottled, Allophanic, Typic
	Oxidic	Mottled-acidic, Mottled, Allophanic, Acidic, Typic
	Orthic	Mottled-acidic, Mottled, Allophanic, Acidic, Typic
Recent Soils*	Tephric	Mottled, Buried-pumice, Buried-allophane, Typic

*Soils derived from volcaniclastic materials are extracted.

horizons of the Bekkai soil (Shoji *et al.*, 1993), the upper horizons (0 – 48 cm) show a high content of volcanic glass (95 – 97%) and low values for clay content (< 6%), acid oxalate-extractable components (Al_o + 1/2 Fe_o = 0.8 – 1.6%), and P retention (33 – 66%). The acid oxalate-extractable components and P retention tend to increase with depth. Bulk densities are somewhat high and water retention values at 1500 kPa are mostly low.

According to vitric properties and multisequum profile, the Bekkai soil is classified as a Thaptic Udivitrand in Soil Taxonomy, a Thapto-Vitric Andosol in the WRB Classification, and a Haplic Volcanogenous Regosol in Japanese Cultivated Soils Classification (Table 9).

Mukaiyama soil: Mukaiyama is a forestland on the Tohoku University Farm, Miyagi Prefecture, northeastern Japan and was selected as the type locality for nonallophanic Andisols by M. Leamy, Chairman of the International Committee on the Classification of Andisols. The volcanic ash soil of this area (Fig. 5 (b)) has a distinct morphological feature of a very dark (color value and chroma of 2 or less), thick humus horizon (0 – 57 cm) formed from cumulative ash of 10,000 to 1,000 yr B. P. and prominent properties attributable to the predominance of 2:1 layer silicates and Al-humus complexes.

The characterization data of the Mukaiyama soil (Shoji *et al.*, 1993) show that the humus horizons have an organic carbon concentration greater than 6.0%, a predominance of A-type humic acid, and a melanic index less than 1.70 in the humus horizons (0 – 57 cm). Thus, it meets not only melanic epipedon requirements but also the pachic subgroup requirement for Andisols in Soil Taxonomy. The humus horizons possess extremely high KCl-extractable Al values (8 – 11 $cmol_c\ kg^{-1}$) and show high Al_p/Al_o ratios indicating predominance of Al-humus complexes. Accordingly, the allophanic materials icontent in these horizons is very low.

According to the properties described above, the Mukaiyama soil is classified as a high-humic Cumulic Non-allophanic Andosol by the Japanese Cultivated Soil Classification, and was classified as an Alic Pachic Melanudand in the 1992 Keys to Soil Taxonomy (Shoji *et al.*, 1993), showing a nonallophanic Udand with presence of a very dark thick humus horizon and high potential of Al toxicity to plant roots. However, it is classified as a Pachic Melanudand by the last Key to Soil Taxonomy (Soil Survey Staff, 1998) because the alic subgroup is not provided for Melanudands. While the WRB Classification has the definitions of both alu-andic and sil-andic types (FAO *et al.*, 1998), the Mukaiyama soil is classified as a Dystri-Melanic Andosol, indicating that this soil belongs to neither alu-andic nor sil-andic Andosols. These facts show the necessity of partly revising the classification of Andisols and Andosols.

Yunodai soil: The Yunodai soil (Fig. 1 on page 72) from the Towada district, Aomori Prefecture, Japan also has very dark (color value and chroma of 2 or less) and thick humus horizons (0 – 60 cm) formed from Towada-a ash of 1,000 yr. B. P. (0 – 30 cm) and Chuseri ash of 5,000 yr. B. P. (30 – 79 cm) under the influence of Japanese pampass grass (*Miscanthus sinensis*) vegetation. According to the characterization data (Shoji *et al.*, 1988b), this pedon has humus horizons that meet the melanic epipedon requirement and has exchangeable bases plus 1 M KCl extractable Al totaling less than 2.0 $cmol_c\ kg^{-1}$ in horizons with total thickness of 30 cm or more between 25 and 100 cm depth. It shows low 1500 kPa water retention (< 15% on air dried and < 30% on undried samples) in horizons having 25 cm or more thick. Thus, this pedon is classified as an Acrudoxic Vitric Melanudand in Soil Taxonomy (Table 9). It has

Table 9 Classification of selected pedons according to Soil Taxonomy, WRB Classification, and Japanese Cultivated Soil Classification.

	Soil Taxonomy	WRB Classification	Cultivated Soil Classification
Bekkai (Fig. 5 (a) on page 95)	ashy over medial, frigid Thaptic Udivitrand	Thapto-Vitric Andosol (Dystric)	ashy typic Haplic Volcanogenous Regosol
Mukaiyama (Fig. 5 (b) on page 95)	medial, mesic Pachic Melanudand	Dystri-Melanic Andosol	high-humic Cumulic Non-allophanic Andosol
Yunodai (Fig. 1 on page 72)	medial over cindery, mesic Acrudoxic Vitric Melanudand	Melani-Silic Andosol (Acroxic)	high-humic Cumulic Andosol
Tsutanuma (Fig. 5 (c) on page 95)	medial over cindery, mesic Acrudoxic Fulvudand	Umbri-Silic Andosol (Acroxic)	Haplic Forest Andosol
Hilo (Fig. 1 on page 72)	hydrous, isohyperthermic Acrudoxic Hydrudand	Hydri-Silic Andosol (Acroxic)	Haplic Andosol
Findley Lake (Fig. 1 on page 72)	frigid Andic Humicryod	Haplic Podzol	Haplic Podzol

sil-andic properties in horizons derived from Chuseri ash, so it is classified as a Melani-Silic Andosol according to the WRB Classification. Based on the presence of the thick, dark humus horizons, the Yunodai soil is classified as a high humic Cumulic Andosol in Japanese Cultivated Soil Classification (Table 9).

Tsutanuma soil: The Tsutanuma soil (Fig. 5 (c) on page 95) from the Towada district adjoins the Yunodai soil and is an example of a fulvic volcanic ash soil. The pedon also shows composite morphology formed from the same cumulative tephra as those of the Yunodai soil and has a thick cumulative humus horizon (0 – 48 cm). However, it fails the melanic color requirement of moist Munsell value and chroma

(a) Bekkai soil.

(b) Mukaiyama soil.

(c) Tsutanuma soil.

Fig. 5 Selected soil profiles for testing soil classifications (Shoji *et al*., 1993; copyright Elsevier, with permission).

of 2 or less (Soil Survey Staff, 1999) reflecting the influence of beech tree (*Fagus crenata*) vegetation. It has irregular boundaries between the 2AB2 and 2Bwb horizons and a broken boundary between the 2Bwb and 3C horizons. These boundaries reflect the process of tree-fall which results in mixing of the soil materials between soil horizons.

The characterization data for the Tsutanuma soil (Shoji *et al.*, 1993) show that the humus horizons do not have a very dark color. But soil organic carbon has markedly accumulated in the upper part of the soil profile with more than 6% as a weighted average at depths of 0 – 30 cm (Shoji *et al.*, 1993). These horizons had melanic indices greater than 1.70 and low ratios of humic acid to fulvic acid.

According to the profile description and characterization data, the Tsutanuma soil is classified as a Fulvudand by Soil Taxonomy and as a Forest Andosol by Japanese Cultivated Soil Classification (Table 9). However, the pedon does not satisfy the definition of fulvic horizons described in the WRB Classification because the fulvic horizon in the WRB Classification requires a Munsell color value and chroma of 2 or less (FAO *et al.*, 1998). This color requirement is the same as that of the melanic color requirement in Soil Taxonomy (Table 4) showing a very dark color, so it should be revised.

Hilo soil: Hydric volcanic ash soils occur in regions of very high, well-distributed rainfall with a perudic moisture regime (Soil Survey Staff, 1975). They show high water retention capacities such as 1500 kPa water retention of more than 100% and 33 kPa water retention of several hundred percent.

The Hilo soil (Fig. 1 on page 72) from Hawaii, U.S.A., is an example of a hydric volcanic ash soil. It has very thick B horizons with dark reddish to reddish brown color and moderate to strong thixotropy. According to the characterization data of the Hilo soil (Shoji *et al.*, 1993), the pedon shows very low bulk densities (< 0.5 g cm^{-3}) and 1500 kPa water retention of greater than 100%. The sum of exchangeable bases is very small in amount (mostly about 1 cmol$_c$ kg^{-1}) reflecting intense base leaching. In spite of the low base saturation, all the horizons show only slight acidity, due to allophanic clay mineralogy and mostly possess exchangeable bases plus 1 M KCl extractable Al totaling less than 2.0 cmol$_c$ kg^{-1}. Thus, the Hilo soil is classified as an Acrudoxic Hydrudand in Soil Taxonomy (Table 9). Since most horizons have acid oxalate extractable Si of 0.6% or more, this pedon is classified as a Hydri-Silic Andosol in the WRB Classification (Table 9).

Findley Lake soil: The Findley Lake soil (Fig. 1, on page 72) from Cascade Range, Washington, U.S.A. is an example of podzolic volcanic ash soils. In Soil Taxonomy, tephra-derived podzolic soils satisfying the albic and spodic requirements are classified as Spodosols (Soil Survey Staff, 1999). Since the Findley Lake soil meets these requirements (Dahlgren and Ugolini, 1989), it is identified as a Spodosol. The pedon has a cryic soil temperature regime and shows high organic carbon content (≥ 6.0%) in a layer 10 cm or more thick within the spodic horizons. It also shows andic soil properties throughout the spodic horizons and the underlying BC and C horizons (Dahlgren and Ugolini, 1989). Therefore, the Findley Lake soil is classified as an Andic Humicryod in Soil Taxonomy (Table 9). This pedon is classified as a Haplic Podzol both in the WRB Classification and the Japanese Cultivated Soil Classification (Table 9) because these two classification systems do not have any andic subdivisions for Podzols.

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