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Weathered pumice influence on selected alluvial soil properties in west Nayarit, Mexico

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Abstract

Parent material and pumiceous alluvial soils, located in a tropical region of Mexico, were studied to supply information on soil suitability for agricultural production in the context of sustainable agriculture. In recent alluvial soils, an understanding of how soil characteristics vary with parent material and topography provides a basis for determining land utilization type, land suitability as well as land quality. The main objective of this study was to establish the relationship of soil properties to parent material in west Nayarit, Mexico. Field studies were initiated in 1993 by a request for technical assistance from the Comision Federal de Electricidad. The studied soils were derived from pumice that has been reworked and mixed with detrital material from other sources. We found that such soils have unique physical, chemical and mineralogical characteristics that are rarely found in soils derived from other parent materials. Data for two selected alluvial soil profiles are presented. These soils were developed on Holocene volcanogenic pumiceous alluvial river terraces and river floodplains, under current udic-isohyperthermic soil-climate conditions. The agronomic properties, tillage influences and fertilizer requirements of these soils have been studied extensively. To maximize their productivity and minimize deterioration, proper management must be based on an understanding of the unique physical, chemical and mineralogical properties. Results indicate that such soils have physical properties that provide a good environment for deep rooting and can supply the water necessary for vigorous plant growth. In both soils, water retention at 33 and 1500 kPa, particle surface area, calculated clay, cation exchange capacity, Al exchangeable percentage and P retention, and the occurrence of isotropic coatings on rock fragments and peds tend to increase in the presence of the large amounts of hydrolyzed pumice that are found in the 0.02–2.0 mm fraction. Scanning electron microscope–energy dispersive X-ray analyses demonstrate that the coatings dominantly consist of noncrystalline material, probably allophanic-like material as suggested by the Si/Al molar ratio of 1.0. Selective dissolution analysis reveals that these abundant noncrystalline materials consist of ferrihydrite and allophane with an atomic ratio $(Al_o-Al_p)/Si_o$ of approximately 1.4. Both ferrihydrite and allophane have very large specific surface area and absorptive capacity that make a significant contribution to the overall properties of these soils. X-ray diffraction analysis and transmission electron microscope observation show that the major group of crystalline clay minerals in the upper section of studied soils are tubular and spheroidal halloysite. These soils were classified as Vitrandic Udifluvents according to Soil Taxonomy.

Keywords: Weathered pumice; Volcanogenic alluvium soils; Particle-size class; Vitrandic Udifluvent

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1. Introduction

More than half of the volcanic ash soils as well as soils with andic properties, including those containing pumice, are located in tropical regions where climatic conditions are significantly different from those of temperate regions (Shoji et al., 1993a). Since climate greatly affects soil-forming processes, soils formed in tropical regions are expected to differ considerably from those formed in temperate regions. Although much information is available about pumice soils (Egawa, 1977; Maeda et al., 1978; Leamy et al., 1980; Lowe, 1986; Wada, 1989; Kawasaki et al., 1991; Dahlgren et al., 1993; Jongmans et al., 1994), unfortunately it is mostly limited to soils formed in the middle latitudes or temperate regions.

In Mexico, volcanic ash soils and pumice-derived soils did not receive attention until the middle of this century. This recognition stemmed from an urgency to determine the potential agricultural productivity of these soils because of the increased demand for food production. However, in tropical regions of Mexico, the properties, productivity and classification of soils formed in pumice or material derived from pumice that has been reworked and mixed with material from other sources (volcanogenic pumice alluvium (VPA)) are still a matter for investigation and discussion (Gama-Castro, 1996). These soils have a great potential for agricultural production as illustrated by the fact that many of the most productive tropical regions of Mexico are located on river floodplains close to volcanic fields.

In tropical regions, pumice and other pyroclastic materials weather rapidly, frequently resulting in the formation of noncrystalline minerals. Noncrystalline materials common in VPA include allophane, allophane-like materials, opaline silica and ferrihydrite. These noncrystalline materials typically occur as coatings on the skeleton (Dahlgren et al., 1993). Because of the large specific surface and high proportion of reactive sites, a small amount of these noncrystalline materials can make a disproportionately large contribution to the physical and chemical properties of these soils. In fact, properties such as water retention and cation exchange capacity are closely related to molecular weathering ratio (SiO_2/Al_2O_3) which is a weathering index in volcanic ash soils (Solleiro-Rebolledo, 1998).

Weathered pumice-derived soils have morphological, physical, chemical and mineralogical properties that can be attributed to the influence of a combination of factors involved in their development including: (1) very low resistance of the finely comminuted pumice to chemical weathering (Shoji et al., 1993b); (2) high water retention and cation exchange capacities (Ping et al., 1989; Parfitt, 1990; Henmi, 1991); (3) low bulk density (Geist and Strickler, 1978; Bielders et al., 1990); (4) particle-size distribution and great particle surface area (Wada, 1986; USDA-SSS, 1994); and (5) illuviation and neoformation of the short-range order material, 1:1 phyllosilicates, noncrystalline aluminum and iron oxides and hydroxides by weathering of pumice in humid climates (Quantin et al., 1991; Dahlgren et al., 1993).

In agreement with Osher and Buol (1998), we consider that efficient and sustained use of the pumice soils requires an understanding of how soil characteristics vary with parent material and their location. We also assume that to maximize soil productivity and minimize deterioration, proper management must be practiced, based on an understanding of the unique morphological, physical, chemical and mineralogical properties.

The goals of the present study were: (i) to characterize the soils derived from VPA and estimate the amount of pumice in the profile of selected alluvial soils formed in the Santiago River floodplain by optical and physical means; (ii) to establish the influence of weathered pumice in macro and micromorphological, physical, chemical and mineralogical features of selected alluvial soils; and (iii) to interpret their genesis, to classify them using Soil Taxonomy (USDA-SSS, 1994) and to suggest revisions of Soil Taxonomy where necessary.

2. Site conditions

The study area is situated on the floodplain of the Santiago River in the coastal plain of west Nayarit, Mexico (Fig. 1). This area received VPA throughout the late Pleistocene to recent period (until July 1992). The various pumiceous deposits can be identified on the basis of surficial geology, stratigraphic position, geomorphic surfaces, spatial relations through elevation and distance control and soil characteristics such

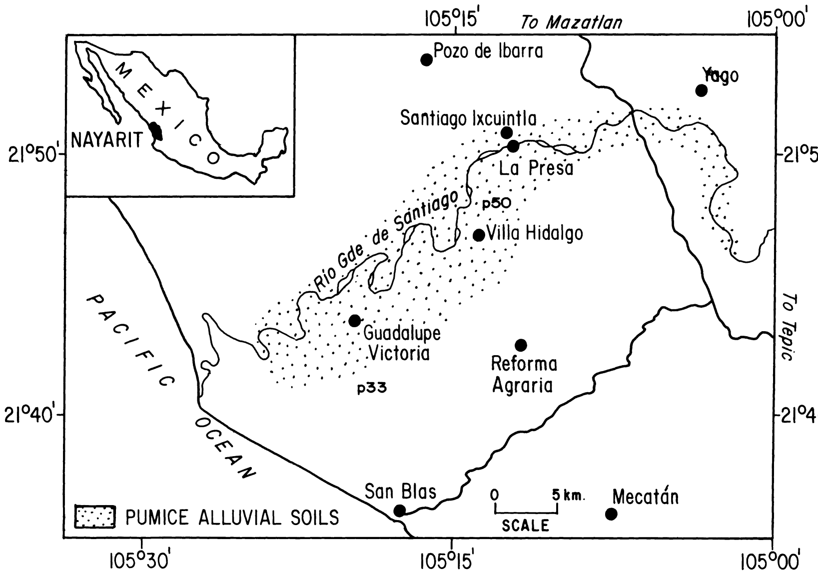

Fig. 1. Location of soils derived from VPA in west Nayarit, Mexico: P33, Aguamilpa profile; P50, Ixcuintla profile.

as texture and mineralogy. The Quaternary volcano San Juan, located on the southwest side of Tepic, State of Nayarit, is considered the main source of the parent pumice. Volcanic materials consist of fine-grained dacitic and andesitic pumice deposits (Luhr, 1978). Both dacitic and andesitic deposits were reworked and intensively mixed with detrital material, poor in weatherable minerals and nutrients (Gama-Castro and Palacios-Mayorga, 1994) with a thickness ranging from 70 to 150 cm. The ^{14}C data suggest that the oldest pumiceous deposit is from about 14 700 years BP (Luhr, 1978).

The area presently is being weathered under a humid, warm climate with mean January air temperatures between 22 and 23°C, and mean July temperatures between 27 and 29°C (Table 1). Average annual precipitation exceeds potential evapotranspiration by about 515 mm per year (Table 1). According to Parfitt (1990) this annual precipitation (>1200 mm) leads to the preferential formation of allophane and allophane-like materials when soluble Si concentrations are low. In the absence of run-off or run-on, about 400 mm of water percolates through the soil. The depth of weathering in the soils located in the study area varies in response to erosion and sedimentation rates. However, micromorphological observations as well as mineralogical and chemical analyses show some evidence of selective weathering of the primary minerals within 70 cm of the soil surface. Weathering intensity decreases with soil depth. In many soils, the groundwater seasonally fluctuates, often intersecting the bottom of the C horizon in the summer. Sometimes, reduced conditions are evident in the deeper layers, with a rH value ≤ 19 (rH is related to the redox potential Eh and corrected for the pH according to FAO-ISRIC-ISSS, 1994).

The soils occur on floodplain landforms and some river terraces formed by the deposition of VPA sediments. In these areas the elevations range from 1.5 to 10 m and the slopes range from 0.5 to 3% (Table 1).

Deforestation occurred between 50 and 70 years ago, and the current vegetation consists of grass and shrubs with a limited number of trees. The original vegetation was deciduous seasonal forest (Beard, 1955).

The studied soils are among the most important agricultural soils in the Santiago coastal plain of west Nayarit. The production of vegetables, tobacco, beans, rice, sugar cane, and improved pastures support the dairy industry on these soils.

Table 1
Pedon locations and site properties

Soil[a]	Horizon development	Location	Slope (%)	Elevation (m)	Physiography	Annual mean temperature (°C)	Annual mean rainfall (mm)	Land use	Parent material
Aguamilpa	Ap–C1–C2, a-tch[b], 2Cd–3C	21°42′N, 105°17′W	0.5–1.5	10	Flood plains nearly level	25	1267.4	A[c]	Volcanogenic alluvium over detrital deposits
Ixcuintla	Ap–C1, a-tch, 2C–3C	21°46′N, 105°14′W	0.5–1.0	2	Flood plains level	26	1227.3	A[c]	Volcanogenic alluvium over detrital deposits

[a] According to Gama-Castro and Palacios-Mayorga (1994).

[b] Abrupt textural change.

[c] Agricultural, tobacco, beans.

3. Methods

3.1. Soil selection and field procedures

A semi-detailed survey of soils in west Nayarit, including Yago and San Blas (Fig. 1), was conducted over a 10-month period (Gama-Castro and Palacios-Mayorga, 1994). This survey was based on mapping soil units by air photograph interpretation combined with a field survey. The purpose of this survey was to supply information, which assisted in taking decisions about land use and land development planning.

During this survey, 61 soil profiles were described from the soil surface to the upper boundary of a specified horizon or root-limiting layer. The vertical section so defined is called soil control section (SCS) according to ICOMAND (1987) and USDA-SSS (1994). The soil profiles were described following the guidelines of FAO-UNESCO (1994) and classified according to USDA-SSS (1994). These profiles were sampled in the field and analyzed in the laboratory. These analyses revealed that 13 of the soils derived from VPA had unique and complex attributes in the context of soil production and soil management. Such agronomic characteristics are related to absorption and adsorption complexes, aeration, available water capacity, bulk density, cation and anion exchange capacity, particle-size distribution as well as the presence of amorphous mineral clays in their SCS. These soils showed high cation exchange and water retention capacities and low contents of available elements, organic matter and clay (Gama-Castro and Palacios-Mayorga, 1994).

Based on these previous studies, two typical pedons representative of such soils were selected for analysis and soil classification. The profiles characterize the two main textural families of soils formed from different parent materials (USDA-SSS, 1994). These pedons are numbers P33 and P50. The two pedons are named after localities in the study area as follows: P33, Aguamilpa soil, and P50, Ixcuintla soil (Fig. 1). These soils are intensively used as arable land and represent some of the most important agricultural soils found in the Nayarit tropical zone.

3.2. Physical analysis

All physical analyses, except water retention at 33 and 1500 kPa as well as bulk density, were made on air-dried soil samples passed through a 2 mm sieve. The methods employed are briefly described below.

Particle-size distribution analysis: The record of the volume percentage of material >2 mm was estimated in the soil descriptions. These fractions were collected and weighed to determine the percentage of rock fragments. The sand fractions >47 μm were collected by sieving on a Fristch Analysette shaking apparatus before removing the organic matter with 30% H_2O_2. Fractions <47 μm were determined by the NSSI method (Soil Conservation Service, 1984). Calculated clay: According to the USDA-SSS (1994) when the ratio of 1500 kPa water to clay (determined by NSSI method) was >0.6 or <0.25, in at least half of the SCS, the amount of clay was considered to be 2.5 times the percentage of 1500 kPa water minus the organic C content. Particle density was determined by the procedures outlined by the Soil Conservation Service (1984). Bulk density was measured by a core sampler on undisturbed profiles. Porosity: The total porosity of the soil was calculated from the values of bulk density (BD) and particle density (PD) of the soil, using the following equation: porosity $(\%)=(1-\mathrm{BD}/\mathrm{PD})100$. Particle surface area was measured using the ethylene and glycol monoethyl ether method (Carter et al., 1986). Water retention at 33 and 1500 kPa was determined by pressure membrane methods on undried (or field-moist) samples (Soil Conservation Service, 1984). Available water capacity was estimated as the amount of water released between water retention at 33 kPa and the water retention at 1500 kPa.

3.3. Chemical analysis

Soil pH (H_2O 1:1, KCl 1:1, and NaF 1:50) was determined by the procedures outlined by the Soil Conservation Service (1984). Organic carbon, acid oxalate extractable Al and Fe of bulk soil (Al_o and Fe_o), exchangeable Al and phosphate retention and exchangeable cations (Na and K) extracted with 1 M NH_4OAC were determined as described by Blakemore et al. (1981). Exchangeable cations (Ca and Mg) extracted with 1 M NH_4OAC were determined by atomic absorption spectroscopy. Pyrophosphate extractable Al and Fe of bulk soil (Al_p and Fe_p) were determined as described by Wada and Higashi (1976). Cation exchange capacity (CEC) was measured by the $BaCl_2$ triethanol amine method (Gillman and Sumpter, 1986). Chemical analysis of coatings was performed with a scanning electron microscope–energy dispersive X-ray analyzer (SEM–EDXRA) at the micron scale.

3.4. Mineralogical analysis

The pumice content of the 2–0.02 mm fractions and the mineral composition of sand and coarse silt fractions for control sections of each mineral soil were examined with a Zeiss polarizing microscope, using the grain-line-count method. In this case, 500 grains were counted for each sample. Proton induced X-ray emission (PIXE) was used to determine the elemental composition of pumice samples according to the procedures described by Johansson and Campbell (1988). X-ray diffraction analysis (XRD): weathered rock fragments and clay fraction of the soil were prepared for XRD analysis according to the procedures described by Brown and Brindley (1980). Clay specimens were also examined using a transmission electron microscope (TEM), and the mineralogical studies of these fractions were undertaken as described by Shoji and Ono (1978). The relative abundance of the various clay minerals identified by XRD analysis was estimated by comparing the areas under the first-order diffraction peak of each mineral.

4. Results and discussion

4.1. Soil genesis and profile development

Under traditional flooding caused by sudden rises in the Santiago River, many soils of the active floodplain received a periodic amount of VPA. At the same time, many of these soils remained submerged for the period of 3–4 months (June–September). The major morphological field observations of the soil profiles showed at least 5% rusty colors, mainly around biopores and channels of plant roots. This mottled pattern occurred directly below the SCS of the studied soils. We inferred that this reductomorphic feature resulted from stagnic-like processes, including recurrent anaerobic conditions, low biological activity and seasonal alternate reducing and oxidizing conditions. All of these processes tended to preserve the natural stratification of the original deposits.

Periodical submergence also led to a variety of other physical and chemical effects, including fine silt and clay translocation from top to deeper soil layers resulting in changes of permeability, decalcification and changes in iron, manganese, nitrate and sulfate ions to reduced forms. As a consequece fertility problems arose (Gama-Castro and Palacios-Mayorga, 1994). We assumed that the attenuation of ferrous Fe formation was primarily attributable to the coating of active Fe, possibly by noncrystalline aluminum hydroxide.

In July 1992 several large dams were constructed along the Santiago River to complete a hydroelectric and irrigation plan (Aguamilpa project), and at this point the intermittent flooding and the unconsolidated material (VPA) deposited by the stream ceased. At the same time, the land surface on alluvial river sediments became stable. Thus some normal pedogenic processes that occurred intermittently with flooding and sedimentation have at present a greater or lesser effect on the soil profile development. In addition, the permanent aeration of the surface layers and rapid decomposition of soil organic matter are factors that now play a role in weathering and soil development.

VPA contains significant amounts of pumice, pumice-like fragments and noncolored volcanic glass. It is coarse to fine-grained, porous and has a large specific surface area that enhances interaction with the environment and accelerates weathering. Chemical and mineralogical analyses reveal that the rapid weathering of such pyroclastic materials, particularly under udic conditions and at well drained sites results in: (1) loss of bases by leaching; (2) Si transfer within soil; (3) change in the color of epipedons due to the formation of colloidal coatings (organic matter and free iron oxides); and (4) a relative accumulation of Al and Fe as weathering products. In addition the devitrification of pyroclastic materials in the upper soil layers contributes additional silica for coated soil particles and also for aggregate cementation. Selective chemical analysis shows that different classes of noncrystalline clay minerals such as allophane and aluminum and iron oxides and hydroxides are products of these soil-forming processes.

4.2. Lithological discontinuities

Field stratigraphic studies show that profile sections of the Aguamilpa and Ixcuintla soils consist of three

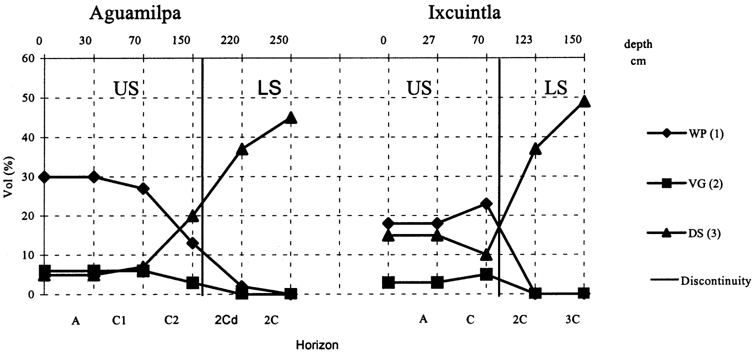

Fig. 2. Quantification (vol.%) of rock fragments (>2.0 mm) in the whole soil in studied pedons: (1) reworked pyroclastics; (2) glass aggregates; (3) detrital sediments. US: upper section; LS: lower section.

separate strata of Holocene alluvium. Such discontinuities show the presence of intermittent alluvial sediment deposition by Santiago River flooding, spread some hundreds or thousands of year apart. Stratum 1, named as the upper section, contains the earliest pyroclastic deposits of VPA and includes Ap and pedogenetically altered C horizons. Stratums 2 and 3, the lower section, are unaltered fragmental deposits that include the 2C and 3C layers, respectively (Fig. 2; Table 2).

In the upper section of both pedons, rock fragments (5.0–2.0 mm in diameter) represent a significant fraction of the whole soil (26–39% by weight, Table 3). They are mainly constituted by reworked pyroclastic sediments mixed with ordinary detrital sediments and a certain amount of organically derived material. As shown in Fig. 2, the detrital clastics (lithic fragments) such as cobbles and pebbles are relatively scarce in this section (15–17% by volume of the whole soil). Many of these lithic fragments have lost their original internal fabric and subrounded shape and exhibit some compressed structures and irregular shapes, suggesting fragmentation and deformation. A great percentage of reworked pyroclastics and lithic fragments have a red- to yellow-colored chemical alteration rind, indicating that weathering has affected these materials.

In contrast, the layers of the lower section contain many round and subrounded pebbles, cobbles and some stones that constitute more than 45% by volume of the whole soil. The fraction finer than 2.0 mm is sandy as defined for the sandy particle-size class (Table 3). Such layers satisfy all the requirements for a sandy skeletal class. In addition the number of lithics with an alteration rind is very low (<2%) indicating that weathering processes are not significant at this depth. Moreover, the amount of pyroclastics is low in the 2C layers and are absent in the 3C layers of both pedons (Fig. 2).

In accordance with USDA-SSS (1994) the stratification common to soils formed in alluvium is not designated as a discontinuity unless particle-size distribution differs markedly from layer to layer. Both pedons have a strongly contrasting particle-size class and also a marked change of petrology between Ap and C horizons versus 2C–3C layers. Such abrupt changes in particle-size class and mineralogical characteristics confirm the presence of discontinuities in both pedons and also a significant difference in age between the upper and lower sections (Table 3).

4.3. Morphological characteristics

The soils are in an early stage of pedogenesis and lack a B horizon (Table 2). They may have ApC–2C–3C, AC–2C–3C, or occasionally, a multiple sequence (multisequum) of these horizons (ApC–2AbC–3Ab) resulting from intermittent alluvium deposition and subsequent epipedon formation. The A horizons are relatively thick (27–30 cm) and the low degree of development is reflected in an ochric diagnostic horizon. In the case of the Ixcuintla soil the lowest limit of these soil profiles coincides with the common rooting of native perennial plants and sometimes with the presence of groundwater.

Although these soils developed from similar parent material (VPA) and under similar post-depositional

Table 2
Major morphological characteristics

Horizon	Depth (cm)	Color		Structure grade	Consistence		Coatings	Roots	Boundary	Total of RF[a] (vol.%)
		Moist	Dry		Moist	Dry				
Aguamilpa soil										
Ap	0–30	7.5YR4/2	7.5YR5/6	Weakly pedal	Friable, slightly sticky, nonplastic	Soft	Fine-textured yellow coatings in voids	Few fine	Clear smooth	41
C1	30–70	5YR3/3	5YR4/6	Weakly pedal	Friable, slightly sticky and plastic	Soft	Many, <1 mm thick, discontinuous yellow	Common fine	Clear smooth	40
C2	70–150	7.5YR4/3	7.5YR5/6	Apedal	Friable, nonsticky, nonplastic	Soft	Few yellow glasses coated grains	Common fine and medium	Abrupt smooth	36
2Cd	150–220	10YR7/3	10YR8/4	Massive	Firm, nonsticky, nonplastic	Very hard	None	–	Clear smooth	39
3C	220–250	10YR6/3	10YR6/6	Stratified layers	Friable, nonsticky, nonplastic	Slightly hard	Organic stains along bedding planes	–		45
Ixcuintla soil										
Ap	0–27	7.5YR3/2	7.5YR5/6	Weak, fine and moderately sublocky, peds evident	Friable, moderately sticky, slightly plastic	Soft to hard	Yellow-red coating in voids and surfaces	Common coarse medium	Clear smooth	36
C1	27–70	7.5YR5/3	7.5YR5/6	Weakly pedal	Friable, moderately sticky, slightly plastic	Soft to hard	Red and strong brown organic stains	Few coarse medium	Abrupt smooth	39
2C	70–123	10YR4/3	10YR5/6	Layered	Friable, nonsticky, nonplastic	Hard to very hard	Strong brown organic stains along bedding planes	Few medium	Abrupt smooth	37
3C	123–150	7.5YR5/3	–	Structureless	Friable, nonsticky, nonplastic	Slightly hard	None	Very few fine		49

[a] Rock fragments.

Table 3
Particle-size distribution and pumice content of Aguamilpa and Ixcuintla soils

Horizon	Depth (cm)	Rock fragments (%), >2.0–5.0 (mm)	Sand fractions (%)					Silt (%)		Clay (%), <0.002 (mm)	Pumice content (%)	Particle-size class
			2.0–1.0 (mm)	1.0–0.5 (mm)	0.5–0.25 (mm)	0.25–0.105 (mm)	0.105–0.05 (mm)	0.05–0.02 (mm)	0.02–0.002 (mm)			
Aguamilpa soil												
Ap	0–30	37.0	7.5	5.0	4.4	4.2	4.2	13.0	7.7	17.0	33	Ashy-pumiceous
C1	30–70	37.0	8.1	5.3	4.5	4.0	3.9	11.1	6.1	20.0	37	Ashy-pumiceous
C2	70–150	39.0	10.5	7.0	5.0	4.0	2.5	11.5	5.5	15.0	31	Ashy-pumiceous
2Cd	150–220	41.5	21.5	14.5	6.0	4.0	–	2.5	–	10.0	10	Sandy skeletal
3C	220–250	47.0	23.0	15.0	5.0	5.0	–	–	–	5.0	–	Sandy skeletal
Ixcuintla soil												
Ap	0–27	26.0	7.0	5.0	5.0	5.5	6.5	13.5	9.0	22.5	23	Ashy-skeletal
C1	27–70	38.0	7.7	4.5	3.5	3.6	4.5	12.3	7.9	18.0	29	Ashy-skeletal
2C	70–123	45.0	13.0	12.7	6.5	2.3	1.0	6.3	4.2	9.0	10	Sandy skeletal
3C	123–150	51.0	11.0	12.0	8.0	2.5	1.5	5.0	3.0	6.0	1	Sandy skeletal

environmental conditions (Table 1) some morphological characteristics are quite different with increasing soil depth. For example, there are significant differences in soil color, structure, consistence and horizon boundaries between the upper and lower sections (Table 2). As described before, such differences reflect the strong influence of cumulization–stratification processes that occur in this fluvial environment. For instance, the strong brown color of epipedons is mainly determined by colloidal coatings resulting from mineral and organic matter transformations. This color also suggests the formation of ferrihydrite and the presence of relatively more stable phases like goethite, while C horizons have a yellow-red color due to the presence of free iron oxides and hydroxides removed from Ap horizons. In contrast, the white and yellowish colors in the 2C layers are determined only by the color of uncoated felsic mineral grains (Richardson and Daniels, 1993). In addition, the weak development of very fine granular or crumb structure in the epipedon of these soils is a common morphological soil feature. We assume that it results from pedological processes related to the unique physical properties of these soils such as high water retention, large total porosity and good drainage. These characteristics are favorable for fauna and flora growth.

As was indicated before, several distinctive anthropogenic processes have been recognized in the upper section of the soils. Such processes include intensive fertilization, irrigation with sediment-rich waters and wet cultivation. Specifically, the cultivation of these soils tends to degrade soil structure, mainly through reduction of soil organic matter content, resulting in subangular blocky structure in the surface horizons (Table 2).

Moreover, the Ap and upper C horizons of the soils are friable when moist, slightly sticky to nonsticky and slightly plastic when wet and soft when dry. These properties result in their easy cultivation at water contents below the shrinkage limit. It is probable that noncrystalline materials derived from the alteration of pyroclastic products, as well as soil organic matter contained in Ap and C horizons, contribute to the development of these properties.

On the other hand, careful field observations of both soil profiles show scarce, <0.5 mm-thick, discontinuous colorless to yellow and red fine-textured coating on weathering rinds, voids, surfaces of rock fragments and mineral grains (Table 2). Yellow and red colors suggest impregnation with Fe^{3+} oxide compounds. The number of coatings is higher in Ap than in C horizons because weathering intensity decreases with soil depth. They are virtually absent in the 2C and 3C horizons of both soils. Micromorphological observations show that some of these coatings have an isotropic internal fabric; they are fine-textured and have a botryoidal outer surface, suggesting that they are neoformed (Fig. 3). XRD analysis shows that the coatings are amorphous materials (Fig. 3). In C horizons, coatings with smooth surfaces sometimes occur discontinuously distributed above some unaltered rock fragment surfaces. We assume that these amorphous coatings cannot be derived from weathering of such rock fragments and must have resulted from eluviation–illuviation of dissolved silica and aluminum liberated by hydrolysis of pumice in the overlying Ap horizons.

4.4. Physical properties

4.4.1. Weathered pumice content of the 2–0.02 mm fraction and particle-size class

The dominant components are weathered pumice, pumice-like, vesicular pyroclastics and glass microaggregates (<0.1–2 mm in size) that include a mixture of noncolored volcanic glass, pumice, glass coated grains and obsidian. They constitute, by count, 30% or more of the 0.02–2 mm fraction (Table 3) and also represent the most weatherable components as a result of their amorphous nature. All weathered pumice fragments are soft and have a light gray to yellow-red colored weathering sheath surrounding the fresh interiors. Pumice materials are scarce in the 2C horizons and are absent in the 3C horizons (Fig. 4). This observation confirms a significant change in mineralogy that indicates a difference in age between ApC and 2C–3C horizons in both soils.

Incomplete dispersion of mineral particles in materials such as weathered pumice and glass aggregates was the main factor that seriously limited the accuracy of mechanical textural analysis of these soils. This was because of the presence of noncrystalline materials, which contributes to the formation of stable aggregates that strongly resist dispersion. SEM–EDXRA analysis suggests that in glass aggregate formation, amorphous silica minerals with a high ratio SiO_2/

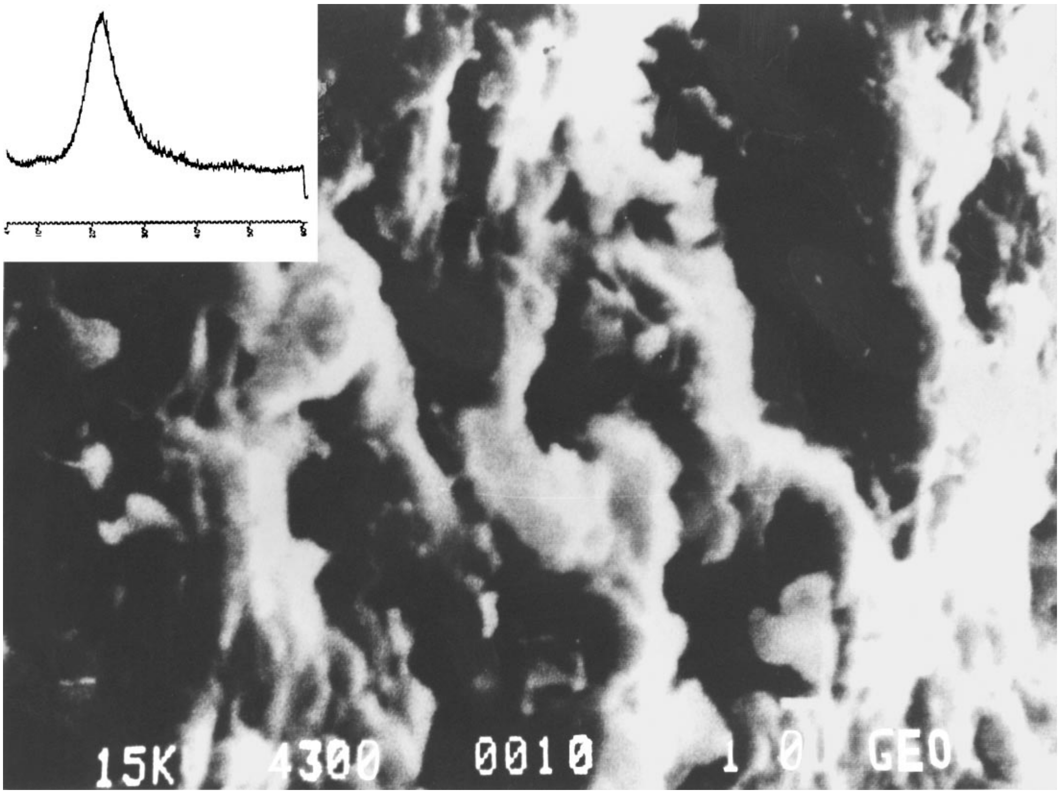

Fig. 3. SEM micrograph and X-ray diffractogram of a coating on a weathered pumice fragment with a botryoidal surface (4300X).

Al_2O_3 (2.3–2.5) and containing some active Al, play an important role. We observed that the dispersion of clay particles was better on alkaline soils (pH=8.5). According to Nanzyo et al. (1993), this strongly suggests the presence of allophane with an Al/Si atomic ratio near to unity.

Particle size refers to grain-size distribution of the whole soil and is not the same as texture, that refers to the fine-earth fraction (USDA-SSS, 1994). Particle-size distribution analysis of the SCS reveals the following rock fragments and fine earth percentages in the whole profiles of both soils.

(a) *Rock fragments*: Rock fragments constitute more than 40% of the volume of the Aguamilpa SCS and more than 35% of the volume of the Ixcuintla SCS (Table 4). Pumice and pumice-like fragments represent more than two-thirds by volume of the rock fragments only in the Aguamilpa soil. However, rock fragments never constitute more than 50% by weight of the whole soil.

(b) *Fine earth*: Physical analysis of the whole soil shows the frequent occurrence of particles <2.0 mm in diameter. The sand and coarse silt fraction (2.0–0.02 mm in diameter) constitutes >40% by weight of the whole soil (Table 3). Pipette analyses also reveal that the clay content of the SCS of both soils range from 17.0 to 22.5% (Table 3). It is important to note that clay content determined by mechanical analysis was low and was obviously underestimated because of incomplete dispersion of clay particles.

(c) *Classification of particle-size class*: According to the results of particle-size criteria determination shown in Table 3 and the rock fragments composition and content (Table 4), the Aguamilpa SCS shows an ashy-pumiceous nonfragmental class, while the Ixcuintla SCS meets the requirements for an ashy-skeletal nonfragmental class (USDA-SSS, 1994). We consider that the presence of stable aggregates in these soils, as well as the particle-size distribution of rock fragments and separates, are very important

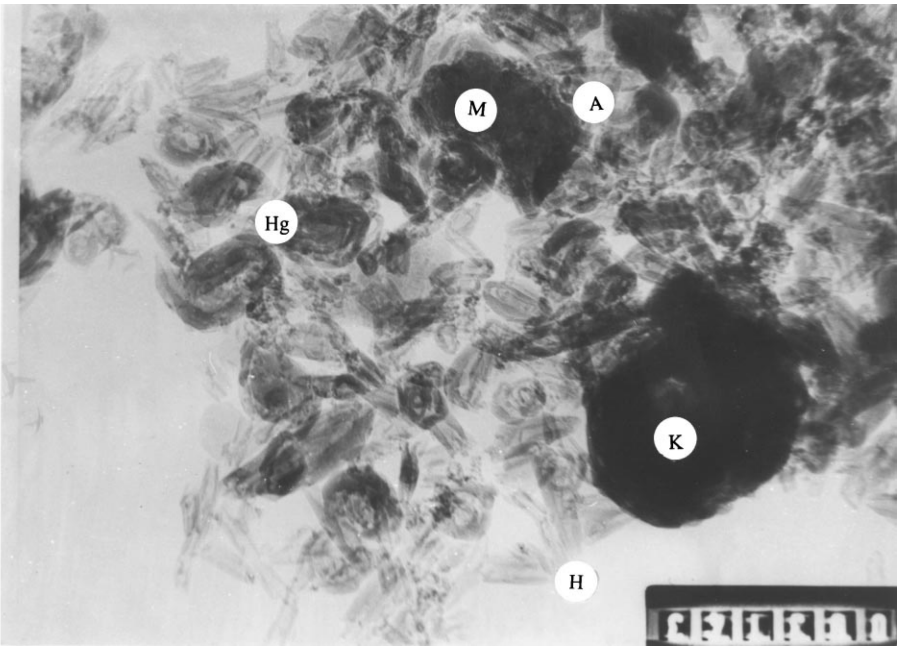

Fig. 4. TEM micrograph of the clay mineralogy of Ap horizon of Aguamilpa soil showing, A: allophane, H: tubular halloysite, Hg: spheroidal halloysite, K: kaolinite, M: montmorillonite (5000X).

because it determines their very low susceptibility to erosion by wind and water. Also it is important because size distribution (Table 3) determines the formation of large pores (diameters >0.06 mm) and a high percentage of the pore space in cultivated soils (Table 5). Such characteristics in turn, positively affect the movement and distribution of water and air in these soils, which are main factors affecting plant growth.

According to both classes of particle-size distribution (Table 3), in one sense they have many of the better physical properties of soils in between those of coarse and fine textures. As discussed before, at the effective rooting depth (SCS), the soils have a high porosity, however, they have a good capacity for retaining water and nutrients (Tables 5 and 6) without becoming waterlogged or excessively polluting groundwater with dissolved nutrients or chemicals.

Table 4
Composition by volume of rock fragments (>2.0–5.0 mm) in the SCS

Horizon	Pumice	Pumice-like[a]	Rock fragments >2.0–5.0 mm (vol.%)			Total
			Glass aggregates[b]	Obsidian	Detrital[c]	
Aguamilpa soil						
A	25	5	5	1	5	41
C1	22	5	5	1	7	40
Ixcuintla soil						
A	15	3	3	–	15	36
C1	13	3	5	1	17	39

[a] Vesicular pyroclastic materials other than pumice but having an apparent particle density (including vesicles) of <1.0 g cm^{-3}.

[b] Composed of glass coated grains, obsidian and volcanic ash; gravel of rhyolite.

[c] Gravel of rhyolite, andesite, schist, sandstone and felsite.

Table 5
Physical properties of Aguamilpa and Ixcuintla soils

Horizon	Surface area ($m^2 g^{-1}$)	Surface area/clay ratio (m^2 kg)	33 kPa water (%)	1500 kPa water (%)	Available water (%)	1500 kPa water/clay	Calculated clay[a] (%)	Bulk density (Mg m^{-3})	Particle density (Mg m^{-3})	Porosity (%)
Aguamilpa soil										
A	110.0	0.36	42.0	12.5	29.5	0.73	30.1	0.95	2.60	63.5
C1	140.0	0.39	45.0	14.5	30.5	0.72	35.5	0.85	2.65	68.0
C2	128.0	0.39	44.0	13.6	30.4	0.91	33.1	0.87	2.65	67.2
2Cd	27.0	0.21	10.0	5.5	4.5	0.55	–	1.45	2.70	46.3
3C	5.0	–	7.0	1.8	5.2	0.36	–	1.25	2.70	53.7
Ixcuintla soil										
A	70.0	0.23	43.0	13.5	29.5	0.60	31.0	0.99	2.60	62.0
C1	85.0	0.28	41.0	12.5	28.5	0.69	29.9	0.90	2.60	65.4
2C	33.0	0.18	12.0	7.9	4.1	0.88	18.0	1.35	2.65	49.1
3C	7.0	–	5.0	1.5	3.5	0.25	–	1.30	2.65	50.9

[a] According to USDA-SSS (1994).

As a result, many of these soils also have high available water capacities that range between 8.5 and 15 cm water per 30 cm soil (Gama-Castro and Palacios-Mayorga, 1994), throughout 10 months of the year. This ability to retain water is especially important in the studied area where winter is dry and evapotranspiration is high.

4.4.2. *Specific surface area*

The relationship between the essential properties and the adequacy of the studied soils for major land use is greatly influenced by specific surface area values. Thus, water retention and potential fertility (CEC) are closely related to particle surface area.

Aguamilpa and Ixcuintla soils show large particle surface area values and consequently, large values for their water retention, available water (Table 5) and cation exchange capacities (Table 6). However, such values are rarely found in tropical soils such as those of the study area that have a coarse texture (Table 3), low to moderate percentages of active fraction of organic matter (Table 6) and poor contents of 2:1 crystalline clays (Table 7). For instance, in the Ap and C horizons (upper section) of Aguamilpa and Ixcuintla pedons, the high particle surface area values (Table 5) were not related to organic C or organic matter contents (Table 6). The high particle surface area and percentage of water retained at 1500 kPa were also unrelated to the layer-silicate mineralogy, according to X-ray diffraction studies. Small peaks of halloysite, kaolinite, illite and smectite were present but did not increase in the SCS of these soils (Table 7). Thus in both the soils, the particle surface area to clay ratio values (Table 5) almost doubled at a depth of 150 and 70 cm, respectively, (C horizon) relative to the 2Cd and 2C horizons of both profiles, indicating the mineralogical discontinuity between these horizons.

We assume that the increase of specific surface is mainly associated with the presence of a high content of weathered pumice in the 0.02–2.0 mm fraction (Table 8), which may indicate more noncrystalline material in the clay fraction and consequently, an increase in the adsorption complex (CEC).

4.4.3. *Water retention at 33 and 1500 kPa*

The long duration of the available water period as well as the high water retention capacity (Table 5) are distinctive characteristics of the studied soils. Thus, there is a little hazard for the plants to have low uptake of water from the soil. Two-crop cycles per year are feasible in many such soils with rain fed agriculture.

The Ap and C horizons of both the soils retain a considerable amount of water at 33 and 1500 kPa as shown in Table 5. In agreement with Maeda et al. (1978), we hypothesized that this high water retention capacity is primarily due to the large volume of mesopores and micropores that constitute the weathered pumice because water is retained in these voids. The high water retention of intra-pores contributes to

Table 6
Chemical properties of Aguamilpa and Ixcuintla soils

Horizon	pH				CEC pH=7 (cmol kg^{-1})	CEC clay ratio[a]	CEC/ calculated clay ratio[a]	Exchangeable cations (cmol kg^{-1})				Exchangeable Al (cmol kg^{-1})	Organic C (g kg^{-1})	Base saturation (%)	P retention (%)
	H_2O, 1:1	KCl, 1:1	NaF, 1:50	Δ				Ca	Mg	K	Na				
Aguamilpa soil															
A	5.6	4.9	9.8	−0.7	25	1.47	0.83	11.0	3.0	1.1	0.4	1.2	11.0	62	30
C1	5.5	4.9	9.9	−0.6	29	1.45	0.83	11.5	2.7	1.2	0.4	1.5	7.0	54	35
C2	5.7	4.9	9.7	−0.8	27	1.80	0.82	12.3	2.5	1.1	0.3	0.9	9.1	60	25
2Cd	6.1	5.1	9.5	−1.0	9	0.90	–	4.0	0.8	0.6	0.5	0.2	6.0	65	8
3C	6.5	5.2	9.5	−1.3	6	1.20	–	2.8	0.8	0.5	0.2	0.1	18.0	–	5
Ixcuintla soil															
A	6.7	6.0	9.6	−0.7	23	1.02	0.74	9.0	2.1	1.3	0.6	1.0	27.0	56	25
C1	6.5	5.8	9.8	−0.7	23	1.28	0.77	8.7	2.1	1.5	0.7	1.1	13.0	56	30
2C	6.3	5.3	9.3	−1.0	16	1.78	0.89	5.3	1.0	1.7	0.9	0.3	17.1	55	12
3C	7.3	6.3	9.3	−1.0	4	0.67	–	1.3	0.1	0.3	0.2	0.1	15.2	47	7

[a] According to USDA-SSS (1994).

Table 7
Composition of crystalline aluminosilicates

Horizon	Major constituents[a]	Minor constituents[a]
Aguamilpa soil		
A	Hh, Kt	It, Cb, Ze
C1	Hh, Kt	It, Cb, Ze
C2	Hh, Kt	It, Ze, Cb
2C	It, Sm	Kt, Int
3C	It, Ch, Sm	Kt, Int
Ixcuintla soil		
A	Hh, Kt	It, Ze, Cb
C1	Hh, Kt	It, Ze, Cb
2C	It, Ch, Sm	Kt
3C	It, Ch	Ft, Cb

[a] Hh: halloysite; Kt: kaolinite; It: illite; Ch: chlorite; Sm: smectite; Cb: cristobalite; Ze: zeolite; Int: chloritized 2:1 minerals.

Table 8
Weathered pumice content of the 0.02–2 mm fraction (grain-line-count)

Horizon	WP[a] (%)	VG[b] (%)	LF[c] (%)	OM[d] (%)
Aguamilpa soil				
A	33	10	2	55
C1	37	8	2	53
C2	31	5	2	62
2Cd	10	2	4	84
3C	0	0	15	85
Ixcuintla soil				
A	23	7	7	65
C1	29	5	8	58
2C	10	0	12	78
3C	1	0	18	81

[a] Weathered pumice and pumice-like fragments.

[b] Volcanic glass aggregates including glass coated grains.

[c] Lithic fragments and nonvitric volcaniclastics.

[d] Other minerals (quartz, feldspars, micas, opaques).

the available water of the soil (Maeda et al., 1978). However, these values also suggest the presence of allophane and other noncrystalline materials derived from pumice weathering. Allophane contributes to the retention of high tension water because its fine particle size and hollow spherical structure can accommodate water molecules in both inter-spherical pores (Nanzyo et al., 1993). The water retention was positively related to pumice contents (Tables 3 and 4). Ratios of 1500 kPa water retention to clay are higher than 0.6 and less than 0.25 in all horizons of Aguamilpa soil, except for 2Cd and 3C; and in 3C horizons of Ixcuintla soil. USDA-SSS (1994) indicates that when the ratio of water retained at 1500 kPa tension to clay, measured by standard analysis, is >0.6 and <0.25, the clay content should be estimated. The calculated clay content for both soils is shown in Table 5.

4.4.4. Bulk density and particle density

The phase system of the studied soils (SCS) is similar, except for the organic matter contents, to that of many cultivated and productive Andisols located in the tropical zone of the State of Nayarit (Gama-Castro and Palacios-Mayorga, 1994).

Bulk densities are <1.0 Mg m^{-3} in the Ap, C, C1 and C2 horizons and >1.30 Mg m^{-3} in the 2C and 2Cd and 3C horizons of both soils (Table 5). The low bulk density in the SCS of these soils is another important property since it is favorable for absorption, aeration and plant roots, because they can easily penetrate the soil when they propagate. We observed that bulk density was not related to organic matter contents and it decreased with advanced weathering. We assumed that the presence of more noncrystalline material due to increased weathering contributes to the low bulk density through the development of a porous soil structure. It is obvious that these low values reflect the high porosity (62–68%) and void size distribution of weathered pumice (Table 5). The dead and semi-active pores of weathered pumice connect with active pores, and all pores function as pores of an aggregate (Warketin and Maeda, 1980).

The particle density, which range from 2.60 to 2.70 Mg m^{-3}, increases with depth and is highest in the Pleistocene alluvial layers (2Cd and 3C horizons). In both soils, weathered pumice has a particle density of about 2.60 Mg m^{-3} because the intra-pores are opened to the air (Table 5).

The 2Cd horizon of Aguamilpa soil has several physical properties (Table 5) that are analogous to the tropical densipans recognized by Smith et al. (1975) in the soils of Trinidad. This layer has a high bulk density, a very low saturated hydraulic conductivity (0.15 cm h^{-1}) and shows a mottled zone (chroma <2) that probably corresponds to the major zone of seasonal water table fluctuations. Such a layer is almost free of roots. The mode of formation of these densipans needs further research.

4.5. Chemical properties

4.5.1. Cation exchange capacity

Laboratory analysis revealed that the chemical activity in the studied soils is related, first of all to the amorphous minerals derived from the weathering of pumice and secondly, with the crystalline clay and organic matter. Thus, for example, CEC (pH=7) values of soil horizons range from 4 to 29 cmol kg^{-1} (Table 6) and do not show a close correlation with organic carbon contents. This indicates that organic matter contributes only to a small extent to the negative charges of the soil. The CEC was high and positively related to pumice contents and may have been affected by amorphous constituents.

As shown in Table 6, CEC to clay ratios were >0.9 for all the horizons in the upper sections of Aguamilpa and Ixcuintla soils. The same is observed for the C2 horizon of the Aguamilpa soil. Ratios higher than 0.7 suggest the dominance of smectite clays or noncrystalline weathering products of pumice or volcanic glass in the clay fraction (USDA-SSS, 1994). According to XRD analyses (not shown) and TEM observations, the percentage of smectite is very low in the profile of both soils (Fig. 5). In their upper sections, CEC to calculated clay ratios were 0.82–0.88 (Table 6). The use of this ratio suggests that a noncrystalline mineral with a high cation exchange capacity is present in the soils (Fig. 5). Therefore it is clear that CEC is controlled by amorphous materials and also the presence of variable charge systems in these soils. We consider that this chemical characteristic is not particularly common in alluvial soils. The CEC that depends on variable charge colloids has important implications on the status on plant nutrients in soils containing allophane (Wada, 1986).

4.5.2. Exchangeable bases and soil pH

Volcanic soils are among the most productive soils in the world (Leamy, 1984). However, in the study area three factors influence natural soil fertility and productivity: (i) parent material with a felsic or intermediate composition moderate or poor in essential elements; (ii) low to moderate contents of organic matter; and (iii) humid, warm climate causing intensive eluviation and leaching out of soil bases. In addition, some of man's activities such as continuous cropping, crop removal and burning straw, reduce nutriments and organic matter, and also affect soil structure and pore space. As a consequence, the amounts of exchangeable bases are low to moderate and the base saturation of horizons is also low to moderate in Aguamilpa and Ixcuintla soils (47–65%, Table 6). For these reasons, local agriculture is dependent on chemical fertilizers and many such soils are generally ranked in capability class II, indicating some limitations for crop production and the need for some specific management practices to obtain normal crops (Gama-Castro and Palacios-Mayorga, 1994).

The reactions shown by both soils have moderate or neutral acidity (pH=5.6–6.7), although the base saturation is 65% or less (Table 6), a percentage which

Fig. 5. SEM micrograph of a curved platy volcanic glass (A) in the C horizon of Ixcuintla soil (100X).

is commonly associated with low soil pH. This is possibly due to the buffer soil property and also to the composition of soil colloids. As presented in Table 6, Ap and C1 horizons of the Aguamilpa soil have a pH (H_2O) lower than 5.7, reflecting the existence of very small amounts of 2:1 layer silicates (Fig. 5).

In the upper section, pH (KCl) values (4.9) are lower than those found in the lower section, being ascribed to the dissociation of carboxyl groups on soil organic matter (Nanzyo et al., 1993). Values of ΔpH (defined as the difference between pH (KCl) and pH (H_2O)) range from -0.6 to -1.3 for Aguamilpa and -0.7 to -1.0 for Ixcuintla soils (Table 6). In both cases, these values are indicative of soils that are dominated by variable charge minerals (Van Wambeke, 1991). In variable charge systems, the charges of the colloids are largely dependent on pH and electrolyte concentration (Uehara and Gillman, 1981). Small negative ΔpH values in the SCS of both soils indicate the abundance of allophanic clays and a low content of humus and KCl extractable Al or toxic Al (Nanzyo et al., 1993).

4.5.3. Exchangeable Al and P retention

For all horizons of the two pedons except 2C and 3C pH (NaF) values are >9.5. Values vary between 9.5 and 9.9, depending on the reactivity (richness in Al) and the quantity of allophane products, and the complexes of aluminum and organic acids. As given in Table 6, pH (NaF) is related to active Al and shows a tendency similar to P-retention values.

Exchangeable Al is found in intermediate amounts in the Ap, C1 and C2 horizons of both soils, and in small amounts in 2C and 3C. The percent of Al saturation in the upper section of the Aguamilpa (Ap, C1 and C2) and Ixcuintla (Ap and C1) soils range from 8.6 to 5.3%, whereas in the lower section (2C and 3C), it ranges mostly from 5.0 to 2.3%. Such values suggest that the materials in both soils have high SiO_2 proportions; consequently, the density of surface hydrolysis linked to Al is too low to generate strong phosphate retention, with values <36% in all the horizons (Table 6). As a consequence, soils did not suffer phosphorus fixation and did not cause serious acid injury and/or aluminum toxicity to plant roots. This is especially important for tobacco production, because this crop requires an adequate supply of phosphorus. In some of these soils, a rate of 20–30 kg ha^{-1} of 11-55-0 as P_2O_5 is usually sufficient to supply many crops.

4.6. Mineralogical properties

Soil analyses show that the natural fertility of the Aguamilpa and Ixcuintla soils is related to the content of organic matter in the Ap horizon and also to the physical and mineralogical characteristics of VPA.

Unfortunately, long-term studies show that the levels of organic matter in these soils have declined to about just over half of what they were when they were first tilled (Gama-Castro and Palacios-Mayorga, 1994). Tillage mixes oxygen into the soil and breaks up structure, giving microbes all they need to burn-up organic matter and release carbon dioxide into the atmosphere.

On the other hand as discussed before, the grain-size distribution, the presence of weathered pumice and also, of amorphous clay minerals gives the soils unique physical and physico-chemical characteristics, but VPA is not a good reservoir of plant nutrients or micronutrients. Thus the additions of manure and fertilizers are essential to sustain modern intensive agricultural production in such soils.

In addition, PIXE analysis shows a high SiO_2/bases ratio of pumice samples, characteristic of felsic (distrophic) material (Table 9).

4.6.1. Mineralogy of 0.002–2 mm fraction

The mineralogical analysis of the sand and coarse silt fractions (Fig. 4) confirms that the parent material of the Aguamilpa and Ixcuintla soils is always weathered primary pyroclastic products of tephric deposits that have been reworked and mixed with material from other sources (VPA).

Petrographic observations clearly indicate that VPA consists primarily of light minerals (Table 8). It confirms that the parent material of the soils had a felsic composition with low concentrations of calcium, magnesium, potassium, iron and phosphorus. In both soils, the light minerals (particle density $\leq$2.8 g cm^{-3}) dominate, ranging between 85 and 95%. In the upper section of both soils, within the mineral category, the relative abundance generally is as follows: weathered pumice$\gg$K-feldspars (orthoclase)+Na-plagioclase (andesine)$\gg$silica minerals (quartz and chalcedony)$\gg$noncolored volcanic glass (refractive

Table 9
Total oxide composition of a pumice rock fragment and molecular ratios (PIXE analysis)[a]

Pumice	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	TiO_2 (%)	MnO (%)	P_2O_5 (%)	H_2O (%)	Bases[e] (%)	SiO_2/Al_2O_3	SiO_2/bases	SiO_2/sesq.[f]
LWP[b]	65.31	17.03	4.11	0.63	0.08	0.36	3.50	7.75	6.10	11.23	5.08
MWP[c]	56.50	17.70	7.65	0.67	0.11	0.42	5.50	9.45	5.08	6.13	3.84
HWP[d]	51.20	18.40	8.55	0.68	0.14	0.50	7.50	11.30	4.43	4.78	3.30

[a] The difference to 100% is due to trace elements and Na_2O.

[b] Low weathered pumice.

[c] Moderately weathered pumice.

[d] Highly weathered pumice.

[e] CaO, MgO and K_2O.

[f] $Al_2O_3+Fe_2O_3+TiO_2$.

index of 1.50–1.51)≫nonvitric volcaniclastics (detrital deposits: lithic fragments of rhyolite, andesite, granite, schist, sandstone and felsite)≈mica (muscovite and biotite)≈heavy minerals (pyroxenes, amphiboles and opaque minerals). In all instances, noncolored volcanic glass mainly consists of curved platy particles (Fig. 6) and sponge-like particles (not shown), which are siliceous and vesicular. According to Yamada and Shoji (1983) such morphology is found in rhyolitic and dacitic volcanogenic ash.

The mineralogical composition of VPA frequently varies as a function of particle size. Silica minerals are common in the 2–0.002 mm size fraction. K-feldspars, plagioclase, noncolored volcanic glass and muscovite show a relatively uniform distribution throughout silt and sand fractions. In contrast, weathered pumice and heavy minerals are virtually absent in the size fractions of <0.02 mm. In any case noncolored volcanic glass increases with weathered pumice and heavy minerals as the particle size decreases. Such differences in the mineralogical distribution as a function of particle size are regulated by the chemical composition of minerals, vesicular nature of particles, leaching potential, pH and soil climate, especially soil water regime.

In VPA, heavy minerals comprise only a small proportion. Although small in amount (<5 vol.% of the 0.02–2.0 mm fraction) orthopyroxenes (hypersthene), clinopyroxenes (augite), amphiboles (hornblende) and opaque minerals are common in both soils. VPA may also contain some accessory minerals (<2%) that often include adularia, hyallite, cristobalite, magnetite, hydromica, marcasite, and inter-stratified layer silicates.

In the lower section of the soils, silt and sand fractions mainly include light minerals such as quartz, K-feldspars, nonvitric volcaniclastic deposits and mica. Quartz and K-feldspars in 2C layers predominate among detrital (nonvitric volcanoclastics) micas and opaque minerals (Fig. 4). In contrast, the association of quartz and detrital deposits in 3C layers predominates among K-feldspars, micas and opaque minerals. Tephric soil material is scarce in 2C layers (<10%) and is virtually absent in 3C layers of both soils.

4.6.2. Amorphous coatings

A relatively high proportion of the light minerals in the 0.02–2 mm fractions are coated with fine-textured, white to yellow-red structureless material. We assumed that these coatings observed at different depths (from 0 to 150 cm) resulted from co-precipitation of Al and Si, liberated upon weathering of the VPA (Fig. 3). SEM–EDXRA and selective dissolution analyses (Table 10) demonstrate that the coatings dominantly consist of amorphous material, probably allophanic-like as suggested by the Si/Al molar ratio of 1.0. X-ray diffractograms from such coatings isolated by hand with the help of a binocular microscope did not indicate crystalline clay minerals (Fig. 3).

4.6.3. Amorphous materials

For an improved characterization of the nature of the short-range order material, selective dissolution techniques were employed. As seen in Table 10 selective dissolution analysis revealed that the amorphous material with an atomic ratio $[(Al_o-Al_p)/Si_o]$ which range from 1.3 to 1.5 (acid oxalate extractable Si (Si_o))

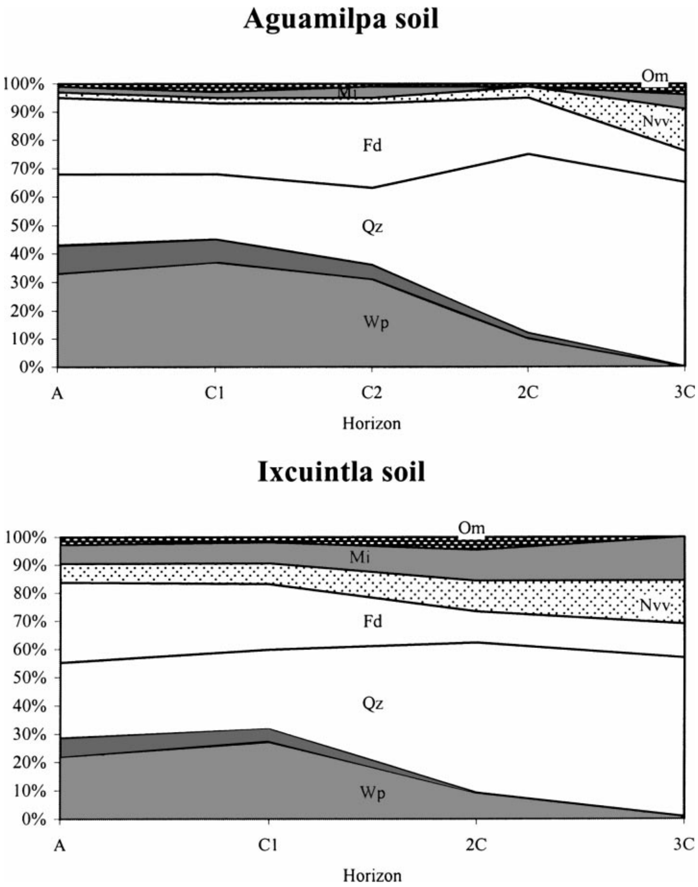

Fig. 6. Mineralogical content of 0.02–2.0 mm fraction of the Aguamilpa and Ixcuintla soils. Wp: weathered pumice and pumice-like pyroclastics; Vg: volcanic glass (including noncolored volcanic glass, pumice, glass coated grains and obsidian); Qz: quartz and chalcedony; Fd: K-feldspar and Na-plagioclase; NVV: non vitric volcaniclastics (detrital deposits) including lithic fragments of igneous, sedimentary and metamorphic rocks; Mi: mica (biotite and muscovite) and Om: opaque minerals including pyroxenes and amphiboles.

is mainly the structural Si in allophane. In both soils their allophane contents were estimated using $Si_o \times 7.14$ (Parfitt and Wilson, 1985). Allophane is virtually absent from the lower section (2C and 3C horizons) of both soils. Although small in amount, the active Al (Al_o) of some horizons is complexed in each pedon, as suggested by Shoji et al. (1982) on the formation of Al/Fe–humus complexes.

Ferrihydrite was positively identified in both soils (Table 10). A multiplier of 1.7 was appropriate to convert Fe_o values to concentrations assuming that the oxalate reagent dissolves only ferrihydrite and that complete dissolution is achieved (Parfitt et al., 1988). The ferrihydrite concentrations are low in both soil samples; however, ferrihydrite can represent most of soil's specific area. A small amount of ferrihydrite can make a disproportionately large contribution to the overall properties of a soil (Childs et al., 1991). In this study, the general impression is that ferrihydrite is a common component of pumice-derived soils, because they undergo rapid early weathering and contain soluble silicates that inhibit the formation of more crystalline iron oxides and hence stabilize ferrihydrite. The evidence of periodic reduction and oxidation processes that these soils are subject to is also fairly convincing to support the hypothesis previously reported by Childs et al. (1991) on the formation of ferrihydrite.

On the other hand, the <2.0 mm fraction in both soils had $Al+\frac{1}{2}Fe_o$ values between 0.39 and 0.40% in

Table 10
Selective dissolution analysis of the two soils

Horizon	Al_o (%)[a]	Al_p (%)[b]	Al_d (%)[c]	Si_o (%)[a]	Alph (%)[d]	Al[e]	Fe_p (%)[b]	Fe_o (%)[a]	Fe_d (%)[c]	Fh (%)[f]	$Al+\frac{1}{2}Fe_o$
Aguamilpa soil											
A	0.26	0.09	0.35	0.13	0.93	1.4	0.29	0.28	1.03	0.47	0.40
C1	0.28	0.03	0.29	0.14	1.00	1.5	0.26	0.25	1.04	0.42	0.40
C2	0.26	0.10	0.38	0.12	0.86	1.4	0.26	0.26	1.00	0.44	0.39
2C	0.17	0.07	0.41	0.04	0.29	–	0.17	0.15	1.13	0.25	0.24
3C	0.09	0.08	0.88	0.03	0.21	–	0.22	0.20	1.10	0.34	0.19
Ixcuintla soil											
A	0.25	0.11	0.44	0.09	0.64	1.3	0.35	0.30	1.16	0.51	0.40
C1	0.27	0.12	0.44	0.11	0.79	1.4	0.25	0.25	1.00	0.42	0.39
2C	0.16	0.14	0.88	0.06	0.43	–	0.25	0.18	1.38	0.30	0.25
3C	0.12	0.09	0.75	0.02	0.14	–	0.12	0.12	1.00	0.20	0.18

[a] Acid oxalate extractable components.
[b] Sodium pyrophosphate extractable components.
[c] Dithionite–citrate extractable components.
[d] Allophane or allophane and imogolite content estimated using ($Si_o \times 7.14$).
[e] Atomic ratio of $(Al_o - Al_p)/Si_o$.
[f] Ferrihydrite content ($Fe_o \times 1.7$).

their SCS, and ranged from 0.18 to 0.25% in the lower horizons (Table 10). These values do not meet the requirements of andic soil properties; however, such values satisfy the requirements for Vitrandic subgroups (USDA-SSS, 1994).

4.6.4. Clay mineralogy

According to Table 7, some crystalline clay minerals are present in the clay fraction of both soils. Their components were determined by X-ray analysis of deferred clay specimens. The A and C horizons show clay mineralogical characteristics analogous to some Andisols located near the study area (Gama-Castro and Palacios-Mayorga, 1994).

The clay-size minerals are divided into major and minor groups. In the upper section, the major clay minerals are halloysite and kaolinite, while illite, zeolite and cristobalite are the minor group of clay minerals in such horizons. Halloysite predominates in ashy-skeletal class horizons containing larger glass and pumice grains. The pH of both soils increases from 5.5 to 6.7 (Table 6) with the zeolite content in the upper section (Table 7). Probably, a small amount of zeolite can also make a larger contribution to the overall properties in such soils.

Clay mineralogical components of 2Cd and 3C (lower section) are significantly different from Ap, C1 and C2 horizons: illite, chlorite and smectite are the major crystalline clay minerals. As seen in Table 7, the Aguamilpa soil shows a clay mineralogy rather similar to that of the Ixcuintla soil as far as crystalline clays are concerned.

4.7. Classification

The soils have many morphological, physical, chemical and mineralogical characteristics similar to Vitric Andisols, except for their alluvial origin. We assumed that they must be considered as an intergrade with Andisols. However, in accordance with the USDA-SSS (1994) neither soil meets all the requirements necessary for andic soil properties, but both satisfy the requirements for the Vitrandic Udifluvents great group. According to the results of particle-size criteria determination, the Aguamilpa SCS shows an ashy-pumiceous nonfragmental class, while the Ixcuintla SCS meets the requirements for an ashy-skeletal nonfragmental class.

The proposed classifications are as follows.

- Aguamilpa soil: ashy-pumiceous, mixed, isohyperthermic Vitrandic Udifluvent.
- Ixcuintla soil: ashy-skeletal, mixed, isohyperthermic Vitrandic Udifluvent.

5. Conclusions

Aguamilpa and Ixcuintla soils show many unique morphological and physical characteristics that provide a soil environment conducive for deep rooting and with the necessary amount of water for vigorous plant growth. Although such soils have specific fertilizer requirements to supply plant nutrients in a readily available form, they are generally evaluated as one of the most productive among arable alluvial soils in west Nayarit. We consider that the recurring sequence of VPA was a natural and very important addition for the soils. The high productivity of these soils is largely due to the following factors.

1. The high amount of weathered pumice.
2. Their moderate depth, with no restricted rooting zone.
3. Plant available water is abundant.
4. Their physical properties: particle-size class with the best physical properties of soils with coarse and fine textures as well as a large particle surface area.
5. Their chemical properties: high CEC, absence of Al toxicity and P retention as well as the presence of active amorphous materials that make a significant contribution to the overall properties of these soils.

Similar to Andisols, their genesis is primarily determined by chemical, mineralogical and textural properties of the parent material, udic water regime and free-drainage. The specific physical and chemical properties are closely associated with the weathered pumice content in the 0.02–2.0 mm fraction of studied soils.

The weathered pumice indicates the existence of more amorphous material in the clay fraction, revealed by XRD and selective dissolution analyses. Selective dissolution analysis shows that the amorphous material consists of ferrihydrite, allophane-like material and allophane. Notwithstanding the low concentrations of these amorphous materials, they can make a disproportionately large contribution to the overall properties of these soils. Unfortunately, the intermittently repeated VPA deposition ceased in July 1992, when the Santiago River was dammed. We assume that the permanent aeration of the surface layers, the increase in depth of groundwater and the lack of new VPA deposits are factors that now play a role in weathering, soil development and soil productivity.

In accordance with the Soil Survey Staff both soils satisfy the requirements for Vitrandic Udifluvents great group, but they are intergraded with Andisols. According to the results of particle-size criteria determination, pumice content and temperature soil regime, the Aguamilpa soil was classified as ashy-pumiceous, mixed, isohyperthermic Vitrandic Udifluvent, and the Ixcuintla soil as an ashy-skeletal, mixed, isohyperthermic Vitrandic Udifluvent.

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