

Chemical, Mineralogical, and Morphological Characteristics of a Late Quaternary Sedimentary Rock-Derived Soils in Leyte, Philippines

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Abstract: To understand the genesis of soils derived from a late Quaternary sedimentary rock in Leyte, Philippines, the properties of four soil profiles were investigated. Two of the profiles (PS-1, PS-4) derived from coralline limestone were shallow with less developed horizons and alkaline pH conditions and higher potential cation exchange capacity and are classified as Calcaric Phaeozems in the World Reference Base or fine, calcareous, isohyperthermic, Rendollic Eutrudepts in Soil Taxonomy. The other two profiles (PS-2, PS-3) derived from calcareous shale were deeper with well-developed horizons and characterized by high loss of bases and were classified as Haplic Alisols (Hyperdystric, Rhodic) or fine, kaolinitic, isohyperthermic, Typic Hapludalfs. The calcareous shale parent materials have much faster weathering as shown by the higher clay content and the dominance of kaolinitic and halloysitic clay minerals. In those soils developed from limestone, clay minerals were mostly calcite, smectite, vermiculite, and interstratified kaolinite/smectite. The results of this study suggest a strong influence of external material contributions, particularly volcanic-ash deposition on the progression of the soils, as reflected by higher clay and silt contents in these comparatively young soils. The most important pedogenic processes that formed the soils in the area seem to be weathering and clay formation, loss of bases and acidification, inorganic C accumulation, structure formation, desilication, and ferrugination. The nature and characteristics of the parent material, topography, and the time of pedogenesis also have assertive effects on the development of the soils.

Key words: Coralline limestone, pedogenic process, quaternary, calcareous shale, tropical soil.

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Soil formation includes several geomorphological and pedological processes through which parent material is progressively transformed into a soil and whose rate is dependent on the soil-forming factors acting through time (Jenny, 1941). Simonson (1959) proposed that soil genesis consists of two overlapping processes, namely, the accumulation of parent materials and the differentiation of horizons in the profile. He further proposed that horizon differentiation is due to four basic processes: additions, removals, translocations, and transformations. Dudal (2003) reported that soils of the humid tropics are the product of geogenesis and pedogenesis and that they need to be defined

on the basis of their characteristics rather than of the processes of their formation. Because most early pedogenetic investigations were concentrated in the geologically older tropical regions such as Africa and the Americas, little information is available on the younger soils of the Southeast Asian islands (Sanchez, 1976; Asio et al., 2006).

Sedimentary rocks are widespread in the Philippines as a result of the occurrence of several major sedimentary basins throughout the archipelago (JICA, 1990). Carandang (1973) estimated that 28% of Philippine soils have developed from shale, sandstone, and limestone. According to Restificar et al. (2006), limestone soils account for about 35,000 km² or 12% of the total land surface of the Philippines. These soils have a long history of cultivation and other anthropogenic influences due to the high initial crop productivity (Uhlig, 1980; Urich et al., 2001; Asio et al., 2006) resulting in the widespread soil degradation (Urich et al., 2001; Day and Chenoweth, 2004).

Soil formation from sedimentary rocks is complex and greatly influenced by the geochemical composition of the rock. For example, soils derived from shale and sandstone are generally clayey and sandy, respectively, and their fertility status is strongly influenced by other soil-formation factors such as relief, vegetation, and land use. Likewise, soil formation from limestone has been the subject of recent debate. Although the theory that limestone soil comes from the residue after the carbonate rocks were dissolved is widely accepted (e.g., Barshad et al., 1956; Boero and Schwertmann, 1989; Nagatsuka 1972), some authors believe that limestone soil could not have been formed exclusively from the weathering of carbonate rocks and that other factors can be considered. For example, Muhs (2001) concluded that, in addition to the contribution of detrital carbonate from the underlying reef limestone, eolian materials from the Sahara and volcanic ash from the Lesser Antilles play an important role in the formation of the reef soils from Barbados. Yaalon (1997) reported that most soils in the Mediterranean region contain considerable amounts of eolian materials from Sahara, making soils in the region polygenetic. Asio et al. (2006) speculated that the high clay content in young limestone soils in Leyte, Philippines, comes both from the weathering of the underlying limestone rock and volcanic ash from the eruption of a nearby volcano during the Pleistocene epoch.

There is a need for more detailed pedological studies on Philippine soils to serve as basis for sustainable land management. Results of such studies will also be an important contribution to our understanding of the nature of soils in geologically young islands in Southeast Asia. In the course of our field work in various parts of the Philippines, we have observed that most severely degraded lands are underlain by sedimentary rocks, which led us to hypothesize that soils from such rocks are more fragile than those from volcanic rocks. This further justifies the need for more pedological studies on soil from sedimentary rocks. Based on these reasons, this study was conducted to evaluate the characteristics and explain the formation of soils derived from sedimentary rocks in Leyte, Philippines.

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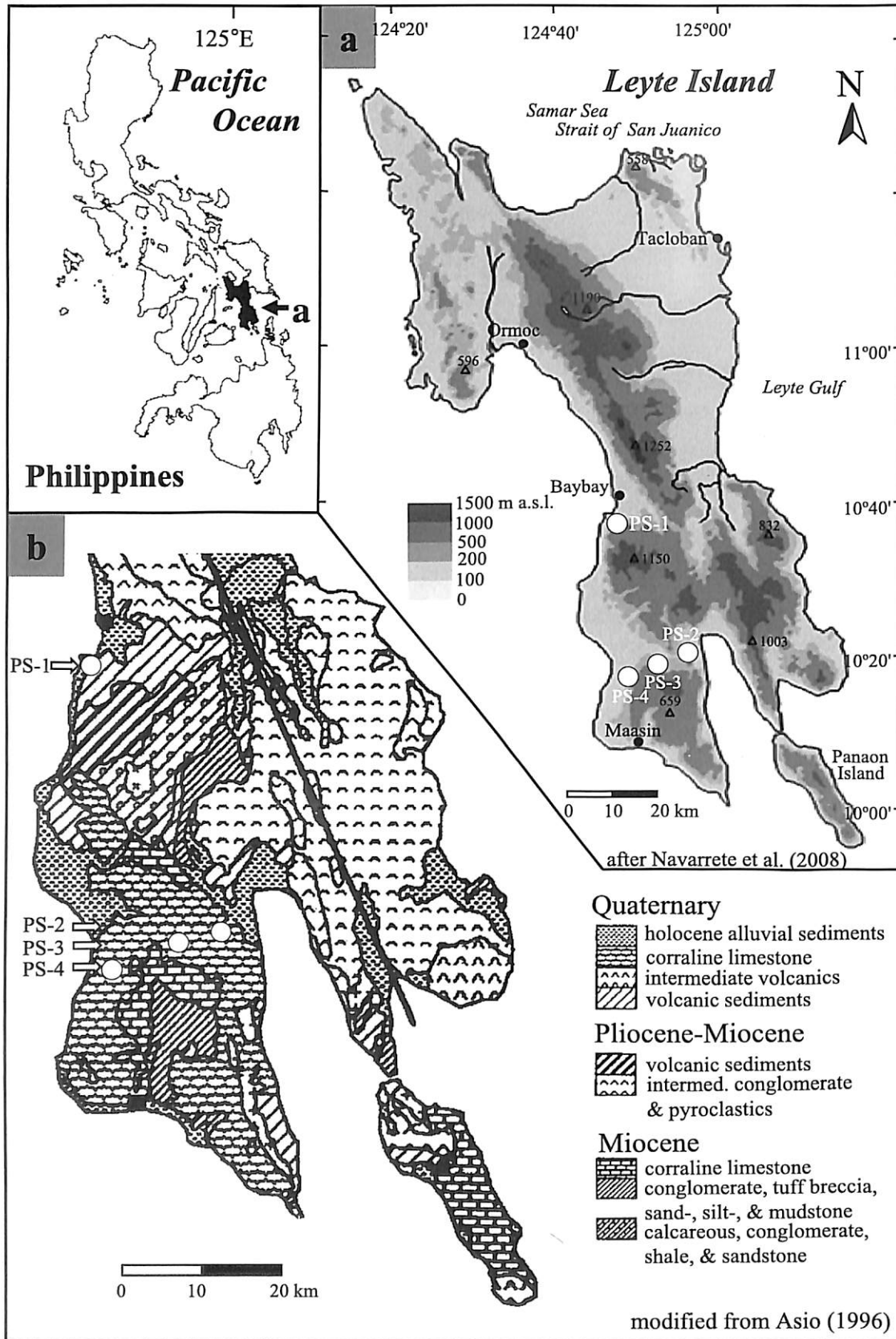


FIG. 1. Map of Leyte (A) and the geological setting (B) of the study sites.

MATERIALS AND METHODS

Study Area

The study was conducted in the south western part of Leyte Island, Philippines (Fig. 1A), where sedimentary landscapes are widespread (Fig. 1B). The climate of Leyte falls within the Köppen's Am type (tropical rain forest climate, monsoon type) having a mean annual temperature and rainfall of 28°C and 3,000 mm, respectively (Navarrete et al., 2009). The temperature is relatively constant throughout the year, and the difference between the coldest (December) and the warmest month (April) is approximately 2°C and 3°C. Precipitation fluctuates seasonally with dry and wet seasons occurring between March and May (115–118 mm) and between September and January (300–403 mm), respectively. Based on this climatic condition, the soil-moisture and temperature regimens are udic and isohyperthermic, respectively (Soil Survey Staff, 2006).

The vegetation in the study areas was originally a Dipterocarp rain forest. However, large areas of primary forest have been converted into agricultural lands as early as 1950s as revealed by aerial photographs and vegetation maps. The land-use covers in hilly areas are mostly patches of secondary growth forest, coconut plantation, and *Imperata cylindrica* grassland, whereas the lowland areas are cultivated for corn (*Zea mays*), sweet potato (*Ipomea batatas*), and rice (*Oryza sativa*).

Field Methods

Four soil profiles, namely, PS-1, PS-2, PS-3, and PS-4, derived from sedimentary rocks, were sampled in the study area (Table 1). PS-1 soil is located at an elevation of 140 m above sea level (m a.s.l.) in a limestone hill, which is a remnant of a reef terrace produced by tectonic uplift (Asio et al., 2006). The geomorphic surface is moderately sloping to rolling, with most slopes between 5% and 10% (Table 1). PS-2 and PS-3 soils were derived from shale (Garcia et al., 2006) and located at an elevation of approximately 120 m a.s.l. on a well-drained and stable land surface. PS-4 soil is located on a well-dissected limestone hill at an elevation of 97 m a.s.l. in a severely degraded area (Chandler, 2006).

Soil profiles were excavated to a depth of at least 1 m or until the bedrock. Soil profile description was done according to the guidelines of FAO (2006). In each profile, composite samples were taken from four sub-samples collected from each genetic horizon according to the quantitative sampling method of Schlichting et al. (1995). Due care was taken to avoid soil contamination from the overlying horizons. The absence or presence of free carbonate was confirmed by effervescence test using a

diluted HCl. Samples were air dried, freed of large plant residues, ground, sieved to pass a 2-mm mesh, and stored in plastic containers. In addition, fresh rock samples were also collected from the dug pits and were pulverized with a tungsten carbide ring mill before total oxide analysis.

Laboratory Methods

Sand (2000–20 µm), silt (20–2 µm), and clay (<2 µm) fractions were separated by pipette and wet sieving methods after pretreatment of the soils with NaOAc (pH 5.0) for samples containing free carbonates, that is, PS-1 and PS-4 and H₂O₂ to oxidize organic matter, respectively (Hamazaki and Paningbatan, 1988). Soil pH was measured by potentiometry in a soil/solution suspension of 1:2.5 H₂O and 1:2.5 1 M KCl. Total C and total N were determined by dry combustion method using a C/N analyzer (Elementar Vario EL III, Elementar Analysensystem GmbH, Hanau, Germany), whereas organic C was determined by a modified Tyurin method. Humic acids (HA) and fulvic acids (FA) were extracted using a mixture (1:1) of 0.1 M NaOH and 0.1 M Na₄P₂O₇ following the recommended soil/solution ratio of 1:10 (Swift, 1996). Exchangeable Ca²⁺, Mg²⁺, K⁺, and Na⁺ were extracted using 1 M NH₄OAc (pH 7.0), and the amounts were determined by atomic absorption spectroscopy. The potential cation exchange capacity (CEC_{pot}) was determined by steam distillation method. The CaCO₃ content was estimated from the total CaO + loss-on-ignition according to the method described by Muhs et al. (1990). Iron and Al were extracted with dithionite-citrate (Fe_d, Al_d), acid-ammonium oxalate (Fe_o, Al_o), and sodium pyrophosphate (Fe_p, Al_p) following the method described by Blakemore et al. (1987). The Fe and Al in the solutions were determined by inductively coupled plasma-atomic emission spectroscopy (Shimadzu ICPS-8100, Shimadzu, Kyoto, Japan). In all chemical analyses, at least 20% of the samples were randomly duplicated for quality monitoring, and the differences between duplicates were mostly less than 6% (95% of sample).

The mineralogy of oriented clay fraction was determined using a Shimadzu XD-3A X-ray instrument equipped with CuKα radiation generated at 30 kV and 30 mA with a scan speed of 4°2θ/min. The organic matter and Fe oxides of the clay fractions were removed according to Mehra and Jackson (1960). The following treated slides were scanned in all samples: K-saturated, air-dry; and K-saturated, heated at 335°C and 550°C; and Mg-saturated, air-dry; Mg-saturated, ethylene glycol saturated. Samples were step-scanned from 2° to 30°2θ. The total oxide concentrations in the soil and rock samples were obtained by X-ray fluorescence spectrometry (Rigaku 3070) using the glass beads method.

TABLE 1. Surface Morphometry and Characteristics of the Study Sites in Leyte, Philippines

Parameters	PS-1	PS-2	PS-3	PS-4
Location	Baybay	Bontoc	Bato	Matalom
Latitude	N 10° 37.63'	N 10°19.88'	N 10° 18.46'	N 10° 16.79'
Longitude	E 124° 47.22'	E 124°56.54'	E 124°53.56'	E 124°49.09'
Elevation, m	140	120	121	97
Parent material	Coralline limestone	Calcareous shale	Calcareous shale	Coralline limestone
Slope gradient, %	5–10	5–10	1–2	5–10
Drainage	Well-drained	Well-drained	Well-drained	Well-drained
Slope form	Straight	Straight	Straight	Concave-straight
Slope position	Upper backslope	Upper backslope	Lower footslope	Lower footslope
Land use	Secondary forest	Secondary forest	Secondary forest	Grassland

RESULTS AND DISCUSSION

Soil Macromorphology and Physical Characteristics

Variation in the solum depth seems dependent on the location of the profiles in the landscape (Table 2). The upper backslope soils (PS-1, PS-2) have thinner solum (55–83 cm), reflecting the influence of slope on water movement, which in turn determines the rate of weathering, run-off, and soil erosion and soil formation (Sommer and Schlichting, 1997; Chen et al., 1999). PS-1 soil seems to be truncated with exposed parent material overlain by a shallow transitional horizon. By contrast, the lower footslope soils (PS-3, PS-4) have thicker solum (97–103 cm) due to less soil erosion and more deposition of surficial materials from the upper slopes. PS-2 and PS-3 soils have well-developed horizons as reflected by their A-Bt-C horizon sequence (Table 2). The soils of PS-1 and PS-4 are less developed as shown by their A-C horizon sequence. Results showed that the soils have remarkable closeness in terms of matrix color, which were 10 YR hue for PS-1 and PS-4 soils and 7.5 YR hue in the surface and 5 YR in the sub-soils for PS-2 and PS-3, respectively. The color value was mostly 3 in the surface, with some horizons in the sub-soil showing 4 or 7. The chroma was mostly 2 or 3 in the surface, 4 in the Ck horizons, and 6 in the Bt horizons. The soil color in all profiles indicates a well-drained environment (Table 1). In terms of soil structure, all soils showed a

weakly developed granular structure in the surface, grading to strong sub-angular blocky (PS-2, PS-3) and angular blocky (PS-1, PS-4) in the sub-soil. The sub-soils of PS-2 and PS-3 were very sticky and plastic when wet because of their high clay content (Fig. 2), whereas the surface and sub-soils of PS-1 and PS-4 were less sticky and less plastic.

PS-2 and PS-3 soils were dominated by clay (22%–62%), whereas PS-1 and PS-4 soils contained high amounts of silt (34%–46%) and clay (23%–40%) (Table 2; Fig. 2). In general, the high clay contents of these relatively young soils can be due to the weathering of the underlying parent rocks and probably due to volcanic-ash deposition. For example, Asio et al. (2006) estimated the age of the terrace in the soil in PS-1 to be between 100 and 200 kyr B.P., which puts it in the Pleistocene epoch at which time major volcanic eruptions produced the widespread Pleistocene volcanic ash in the nearby central highlands of Leyte. Because of the higher amounts of fine particle (silt + clay) in the soils in PS-1 and PS-4, we speculate that volcanic-ash deposition played a major role in the development of these soils. This is consistent with the results of our previous studies in the nearby volcanic mountain in Leyte Island (Asio, 1996; Navarrete et al., 2008), which revealed that fine particles (mostly silt) were the dominant particle size in young volcanic-ash soils. Similarly, Muhs (2001) found the high clay content in the limestone soils of Barbados to have come from the weathering of detrital carbonate from the underlying reef limestone, eolian dust, and

TABLE 2. Morphological* and Physical Characteristics of the Soils in the Study Area in Leyte, Philippines

Horizon	Depth (cm)	Color (Moist)	Structure	Consistence	Sand	Silt (%)	Clay	Silt/Clay
PS-1								
Ah1	0–5	10 YR 3/1	WM, GR, VM	FR, SST, SPL	24	37	40	0.9
Ah2	5–23	10 YR 3/1	MS, GR, VM	FR, SST, SPL	21	46	33	1.4
Ck1	23–35	10 YR 7/4	MS, AB, MC	FI, SST, SPL	38	34	28	1.2
Ck2	35–55	10 YR 7/4	MS, AB, MC	FI, SST, SPL	43	34	23	1.5
PS-2								
Ah1	0–11	7.5 YR 4/2	WM, GR, VM	FR, SST, SPL	36	26	38	0.7
Ah2	11–30	7.5 YR 4/6	WM, GR, VM	FR, SST, SPL	31	31	39	0.8
Bt1	30–51	5 YR 4/6	MS, SBK, MC	FI, VST, VPL	29	16	55	0.3
Bt2	51–72	5 YR 4/6	ST, SBK, MC	FI, VST, VPL	29	27	44	0.6
Bt3	72–83	5 YR 4/6	ST, SBK, MC	FI, VST, VPL	27	26	47	0.6
PS-3								
Ah1	0–12	7.5 YR 3/3	WM, GR, VM	FR, SST, SPL	60	19	22	0.9
Ah2	12–27	7.5 YR 3/4	WM, GR, VM	FR, SST, SPL	52	17	30	0.6
BA	27–43	5 YR 4/8	MS, AB, MC	FR, SST, SPL	45	15	41	0.4
Bt1	43–59	5 YR 5/8	MS, AB, MC	FI, VST, VPL	30	13	57	0.2
Bt2	59–85	5 YR 5/6	ST, SBK, MC	FI, VST, VPL	27	12	61	0.2
Bt3	85–103	5 YR 5/6	ST, SBK, MC	FI, VST, VPL	18	19	62	0.3
PS-4								
Ah1	0–7	10 YR 3/2	WM, GR, VM	FR, SST, SPL	17	43	39	1.1
Ah2	7–27	10 YR 6/3	WM, GR, VM	FR, SST, SPL	21	42	38	1.1
Bw	27–55	10 YR 7/4	MS, AB, MC	FR, SST, SPL	24	40	36	1.1
Ck1	55–70	10 YR 7/4	MS, AB, MC	FI, SST, SPL	19	44	38	1.2
Ck2	70–82	10 YR 7/4	MS, AB, MC	FI, SST, SPL	19	43	37	1.2
Ck3	82–97	10 YR 7/4	MS, AB, MC	FI, SST, SPL	24	39	38	1.0

*Largely according to FAO (2006).

AB: angular blocky; FI: firm; FR: friable; GR: granular; MS: moderate to strong; MC: medium and coarse; SBK: sub-angular blocky; SPL: slightly plastic; SST: slightly sticky; ST: strong; VM: very fine to medium; VST: very sticky; VPL: very plastic; WM: weak to moderate.

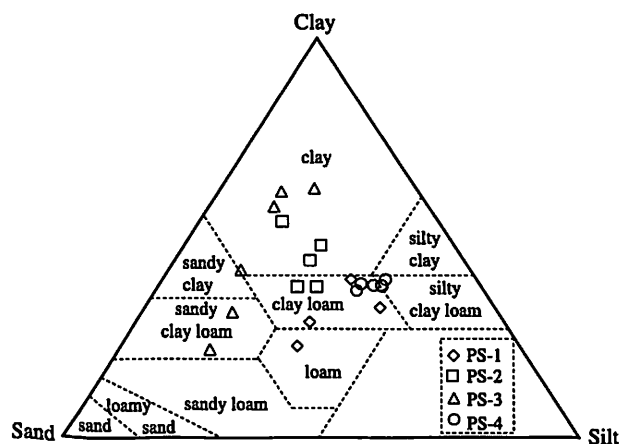


FIG. 2. Particle size distributions and soil textural classes of the sampled profile based on the US Department of Agriculture system.

volcanic-ash deposition. The increasing clay with depth in PS-2 and PS-3 soils suggests clay accumulation through clay illuviation and *in situ* weathering of the calcareous shale. Thus, the weathering of the parent material also contributed to the high clay content in the soil. The low silt-clay ratio in PS-2 and PS-3

soils in comparison to that in PS-1 and PS-4 soils suggests prolonged weathering or pedogenesis of the former soils than the latter soils.

Chemical Characteristics

PS-1 and PS-4 soils are slightly and moderately alkaline (7.8–8.3), whereas PS-2 and PS-3 soils are strongly and slightly acidic (5.0–6.9) (Table 3). The pH differences among soils are directly related to the chemical nature of the parent materials. Noticeable during field examination was the presence of fine CaCO_3 particles in the surface soil, whereas mixtures of fine and coarse CaCO_3 particles were found in the sub-soil. In contrast, the CaCO_3 contents in PS-2 and PS-3 soils were less than 1%, suggesting a more or less complete decalcification in these soils. The electrical conductivity values have a general tendency to be greater in PS-1 and PS-4 soils compared with that in PS-2 and PS-3 soils because of their closer proximity to the sea. The exchangeable Ca was remarkably high in PS-1 and PS-4 soils because of the presence of free carbonates in the soil, which makes interpretation of the results problematic (Thomas, 1982). Exchangeable Na was low in PS-1, PS-2, and PS-3 soils and was completely absent in PS-4 soil. The low CEC_{pot} in PS-2 and PS-3 soils is reflective of the kaolinitic and halloysitic clay mineralogy, whereas the high CEC_{pot} in PS-1 and PS-4 soils can be explained by the presence of smectite and vermiculite in the soils (Fig. 3).

TABLE 3. Chemical Characteristics of the Soils in the Study Area in Leyte, Philippines

Horizon	Depth (cm)	pH		EC (dS/m)	CaCO_3^* (%)	Exch	Exch	Exch	Exch	CEC_{pot}	Org C	In C	Total C	Total N	Ch	Cf	Ch/Cf
		Ca	Mg			K	Na	(cmol/kg)	(g/kg)								
PS-1																	
Ah1	0–5	7.8	7.1	0.27	39	87.13	0.70	0.50	0.04	21.0	35.9	57.8	93.7	3.9	3.9	4.6	0.86
Ah2	5–23	7.9	7.1	0.23	38	87.40	0.54	0.42	0.03	22.3	29.2	57.4	86.6	3.2	3.3	4.0	0.82
Ck1	23–35	8.1	7.3	0.14	57	82.69	0.11	0.13	0.00	18.6	7.8	87.4	95.2	1.1	0.4	1.2	0.33
Ck2	35–55	8.2	7.5	0.12	61	82.33	0.08	0.09	0.00	16.3	4.4	94.5	98.9	0.7	0.2	0.7	0.23
PS-2																	
Ah1	0–11	6.9	5.9	0.13	ND	3.56	1.99	0.61	0.02	16.0	49.1	1.4	50.5	3.6	7.4	8.2	0.90
Ah2	11–30	6.3	4.8	0.05	ND	4.71	1.90	0.32	0.69	16.5	16.1	2.3	18.4	1.8	1.6	3.2	0.50
Bt1	30–51	6.2	4.3	0.02	ND	5.02	1.91	0.37	0.26	15.9	8.3	0.7	9.0	1.2	0.3	2.3	0.13
Bt2	51–72	6.3	4.4	0.03	ND	4.58	1.92	0.55	0.31	14.7	8.5	1.1	9.6	1.2	0.3	2.2	0.14
Bt3	72–83	6.5	4.5	0.02	ND	7.25	1.98	0.43	0.03	19.9	6.2	7.3	13.5	1.7	0.1	1.4	0.09
PS-3																	
Ah1	0–12	5.1	3.8	0.02	ND	4.90	1.50	0.56	0.03	15.2	15.0	2.5	17.6	1.6	1.3	4.3	0.31
Ah2	12–27	5.0	3.7	<0.01	ND	5.20	1.62	0.53	0.50	15.8	10.0	2.2	12.1	1.3	0.7	3.5	0.21
BA	27–43	5.4	3.8	<0.01	ND	4.70	1.53	0.45	0.04	14.2	6.3	1.6	7.9	1.0	0.2	3.0	0.06
Bt1	43–59	5.3	3.9	<0.01	ND	4.20	1.55	0.46	0.05	13.6	5.7	1.0	6.7	0.9	0.1	1.8	0.04
Bt2	59–85	5.3	3.9	<0.01	ND	4.40	1.55	0.54	0.02	14.4	5.0	1.4	6.4	0.9	0.0	1.6	0.03
Bt3	85–103	5.3	3.8	<0.01	ND	5.80	1.62	0.47	0.02	16.2	4.5	1.4	5.9	0.9	0.1	1.4	0.05
PS-4																	
Ah1	0–7	7.8	7.1	0.19	51	89.27	0.20	0.08	ND	11.3	35.9	76.4	112.3	4.4	1.0	3.7	0.27
Ah2	7–27	8.1	7.2	0.14	52	89.94	0.07	0.17	ND	22.9	10.9	76.9	87.8	1.2	0.9	1.5	0.57
Bw	27–55	8.2	7.3	0.13	53	82.36	0.11	0.18	ND	20.3	7.3	72.1	79.4	0.8	0.6	0.9	0.67
Ck1	55–70	8.3	7.3	0.12	56	82.42	0.11	0.19	ND	21.4	3.3	83.0	86.3	0.5	0.5	0.4	1.19
Ck2	70–82	8.2	7.3	0.13	55	83.04	0.11	0.17	ND	22.9	3.1	30.2	33.3	1.7	0.5	0.4	1.42
Ck3	82–97	8.3	7.3	0.13	55	82.81	0.09	0.16	ND	25.2	3.5	80.4	83.9	0.4	0.5	0.4	1.33

*Estimated according to Muhs et al. (1990).

CEC_{pot} : potential cation exchange capacity; Cf: fulvic acid carbon; Ch: humic acid carbon; EC: electrical conductivity; In C: inorganic carbon; ND: not detected; Org C: organic carbon.

In all soils, organic C content was higher in the surface horizon than in the sub-surface (Table 3) in the order of PS-1 > PS-2 > PS-4 > PS-3. This variation among the soils can be attributed to the differences in vegetation cover, land use, and human activities among sites. As expected, the inorganic C was greater in PS-1 (5.7%–9.4%) and PS-4 (7.2%–8.3%) soils because of their remarkably high CaCO₃ contents (Table 3). Interestingly, the inorganic C stored in the sub-soils in PS-1 and PS-4 soils was large and may have important implication for global warming. Xie et al. (2009) reported that alkaline soils are absorbing CO₂ at a rate of 0.3 to 3.0 μmol/m²/s largely from inorganic and nonbiological processes. They estimated that CO₂ absorption for alkaline soils in China ranged between 62 and 622 g C/m²/y and might be a major reservoir of the missing C sink in terrestrial environment.

The amounts of HA and FA varied among soil profiles (Table 3). The amounts of HA in the soils followed the order of PS-1 > PS-2 > PS-4 > PS-3, whereas the amounts of FA varied according to the order of PS-1 > PS-2 > PS-3 > PS-4. The amounts of FA were always greater than HA in all profiles. Both the HA and FA were considerably high in the surface soil and showed a decreasing behavior with depth similar to that of organic C (Table 3). Higher HA/FA ratios were also detected in PS-1 and PS-4 soils compared with those in PS-2 and PS-3 soils.

Selective Dissolution Analysis

The concentration of Fe_d (3.7–18.03 g/kg) was higher than Fe_o (0.72–6.6 g/kg) and Fe_p (0–1.22 g/kg) in all profiles

(Table 4). The result indicates that considerable amounts of Fe were released from the weathering of Fe-bearing minerals, which were transformed into more or less crystalline Fe oxides. The Fe_b, Fe_o, and Fe_p were generally higher in PS-2 and PS-3 soils compared with that in PS-1 and PS-4 soils, suggesting that PS-2 and PS-3 soils are in a more advanced weathered stage. The increase in pedogenic Fe_d and Al_d with depths in PS-2 and PS-3 soils can be related to the co-illuviation of Fe and Al oxides with clay. The concentration of Fe_o tended to decrease with depth in all pedons, indicating high contents of poorly crystalline Fe oxide in the surface horizons. Except in PS-3 soil, all other soils have a slightly higher concentration of Al_o (1.4–4.3 g/kg) than Al_d (0.74–3.35 g/kg). The result is unusual, considering that dithionite is supposed to extract more Al than does oxalate, indicating that poorly crystalline Al fraction was not dissolved in dithionite but was dissolved in oxalate solution. The close similarity in the ratio Fe_d/Fe_o between PS-1 and PS-4 and PS-2 and PS-3 soils suggests the relatively equal intensity of the Fe oxide formation. The rather limited extent of variation in Fe oxides in all pedons may indicate a specific pedoenvironment in the past in which the soils were formed (Boero and Schwertmann, 1989; Dum et al., 1999). The high Fe_o/Fe_d ratio in PS-2 (0.27–0.48) and PS-3 (0.09–0.42) soils suggests that Fe oxides are in less crystalline form (Blume and Schwertmann, 1969).

X-ray Diffraction of Clay Fraction

Figure 3 shows X-ray diffraction traces of the clay fractions (<2 μm) of selected samples. Calcite is recognized by a sharp

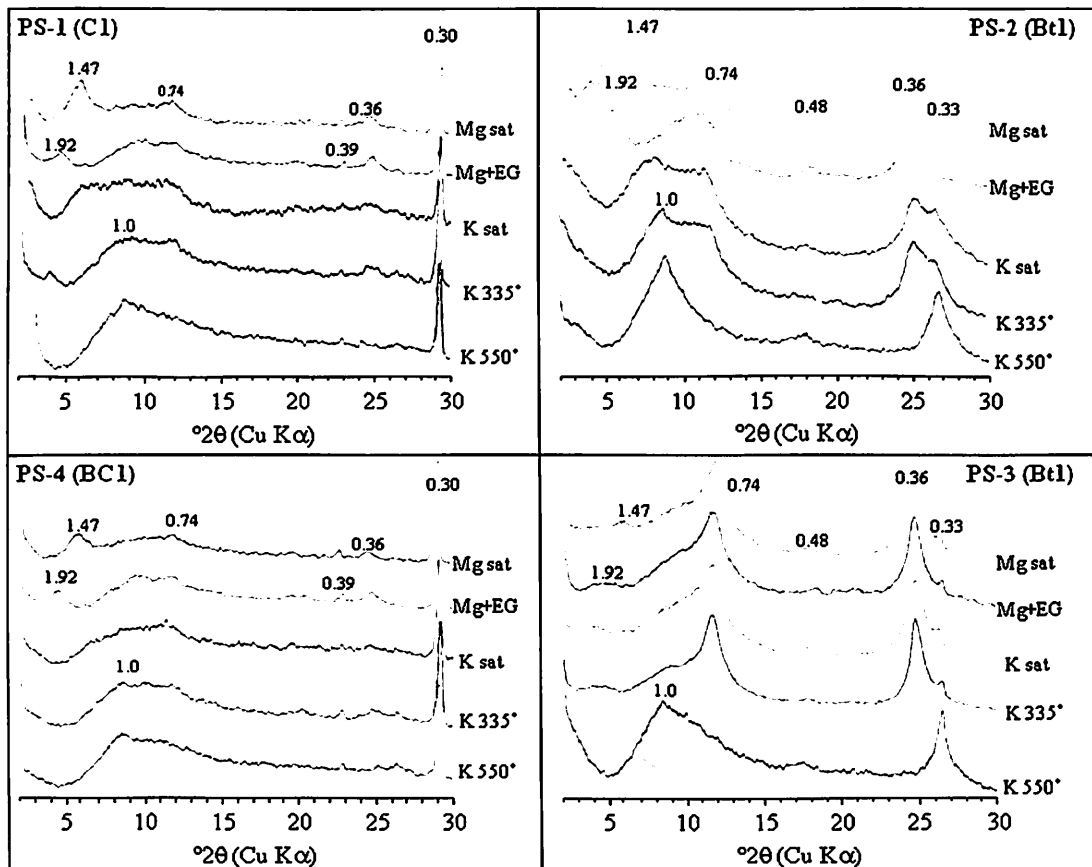


FIG. 3. X-ray patterns of oriented clay (<2 μm) in selected horizon at each profile. *d*-Spacings are given in nm. Mg sat: Mg saturation, Mg + ethylene glycol; Mg + ethylene glycol solvation, K sat: K saturation and corresponding heating treatments.

TABLE 4. Extractable Iron and Aluminum, Ratios of Selectively Dissolved Components, and Dominant Phyllosilicate Minerals of the Profiles Studied

Horizon	Fe _d	Fe _o	Fe _p	Al _d	Al _o	Al _p	Si _o				Phylosilicate Minerals
	(g/kg)							Fe _o /Fe _d	Fe _d /Fe _t	Fe _d /Clay	
PS-1											
Ah1	9.6	1.5	0.2	1.6	3.0	0.3	0.6	0.2	0.3	0.02	Cal>Smec>Ha>Ka
Ah2	9.7	1.6	ND	1.8	3.5	0.3	0.8	0.2	0.3	0.03	Cal>Smec>Ha>Ka
Ck1	4.3	0.8	ND	1.0	1.8	0.5	0.5	0.2	0.2	0.02	Cal>Smec>Ka>Ha
Ck2	3.7	0.7	ND	0.7	1.4	0.0	0.3	0.2	0.3	0.02	Cal>Smec>Ka>Ha
PS-2											
Ah1	9.6	4.6	0.6	1.5	3.1	0.4	0.8	0.5	0.1	0.03	Ha>Ka>Smec
Ah2	11.6	4.7	0.4	1.9	3.3	0.3	0.8	0.4	0.2	0.03	Ha>Ka>Smec
Bt1	13.4	3.6	0.1	2.3	3.9	0.4	1.0	0.3	0.2	0.02	Ha>Ka>Smec
Bt2	13.6	3.8	0.2	2.4	4.3	0.3	1.0	0.3	0.2	0.03	Ha>Ka>Smec
Bt3	13.2	3.6	0.2	2.3	4.0	0.5	1.0	0.3	0.2	0.03	Ha>Ka>Smec
PS-3											
Ah1	15.5	6.6	1.2	2.0	2.0	0.9	1.5	0.4	0.3	0.07	Ha>Ka>Smec
Ah2	16.1	5.9	0.8	2.2	2.1	0.8	0.3	0.4	0.3	0.05	Ha>Ka>Smec
BA	15.2	3.2	0.4	2.5	2.3	0.9	0.3	0.2	0.3	0.04	Ha>Ka>Smec
Bt1	16.8	2.1	0.2	3.0	2.8	1.3	0.3	0.1	0.2	0.03	Ha>Ka>Smec
Bt2	17.4	1.6	0.1	3.2	3.2	1.5	0.3	0.1	0.1	0.03	Ha>Ka>Smec
Bt3	18.0	1.7	0.1	3.5	3.7	1.7	0.3	0.1	0.2	0.03	Ha>Ka>Smec
PS-4											
Ah1	6.6	1.9	ND	1.1	1.9	0.1	0.8	0.3	0.3	0.02	Cal>Smec>Ha>Ka
Ah2	7.0	1.0	ND	1.3	1.9	0.2	0.6	0.1	0.3	0.02	Cal>Smec>Ha>Ka
Bw	9.2	1.3	ND	1.6	2.5	0.2	1.0	0.1	0.3	0.03	Cal>Smec>Ha>Ka
Ck1	4.9	1.4	ND	1.1	2.0	0.2	0.9	0.3	0.3	0.01	Cal>Smec>Ka>Ha
Ck2	6.3	1.3	ND	1.2	1.9	0.3	0.8	0.2	0.3	0.02	Cal>Smec>Ka>Ha
Ck3	5.1	1.2	ND	1.1	1.8	0.3	0.8	0.2	0.3	0.01	Cal>Smec>Ka>Ha

Cal: calcite; Ha: halloysite; Ka: kaolinite; Smec: smectite.

and slender peak reflection at 0.30 nm, which is present in the clay fractions in PS-1 and PS-4 soils and is completely absent in PS-2 and PS-3 soils. A peak at 1.47 nm when the interlayer cation is Mg but collapsed to 1.0 nm when Mg is substituted for K as interlayer cation indicates the presence of vermiculite in the clay fractions in PS-1, PS-2, and PS-3 soils. In addition, a peak at 1.47 nm that expanded to 1.92 nm in the Mg-saturated clay upon Mg-glycol solvation suggested the presence of smectite. The presence of smectite in the soil could be due to the alkaline soil pH condition and high exchangeable Ca and Mg that favors the neo-formation of smectite in the soil (Duchaufour, 1998; Borchardt, 1989). However, under intensive weathering and well-drained conditions, smectite becomes unstable and can be transformed directly to kaolinite (Borchardt, 1989). The Mg-saturated glycol solvations in the clay fractions in PS-1, PS-2, and PS-3 soils have peak reflections at 1.74, 0.74, and 0.356 nm but were poorly seen in PS-4 soil. The presence of these three peaks and the absence of a peak at 0.56 nm suggest the presence of mixed layers of kaolinite and smectite (Brindley and Brown, 1980), which is presumably because of the weathering of soils under humid tropical conditions and suggests the ongoing soil genesis.

The peak intensities of kaolinite (0.72 and 0.358 nm) and halloysite (0.70, 0.36, and 0.45 nm) were stronger in the clay fractions in PS-2 and PS-3 soils in comparison to that in PS-1 and PS-4 soils. The presence of halloysite and kaolinite was confirmed after the peaks at 0.70 and 0.36 nm collapsed when

the clay samples were K-saturated and heated to 550°C. Because the soils are relatively young, kaolinite seems of pedogenic origin rather than inherited from the parent materials. The possible sources of pedogenic kaolinite are the weathering of vermiculite, chlorite, and smectite.

Geochemistry

The concentrations of total oxides in the soil are summarized in Table 5. The dominance of SiO₂ (17%–35%), Al₂O₃ (6%–15%), and Fe₂O₃ (7%–18%) is noticeable in PS-2 and PS-3 soils, whereas in PS-1 and PS-4 soils, CaO (35%–59%) is remarkably high particularly in the sub-soil followed by SiO₂ (17%–35%), Al₂O₃ (6%–15%), and Fe₂O₃ (2%–5%). The results suggest that the geochemical behavior of the soils is directly related to the nature of the parent materials. The SiO₂ (57%–80%) content in PS-3 soil was remarkably high in comparison to that in other profiles probably because of its high sand content (Table 2). The high Al₂O₃ and Fe₂O₃ and the low MnO, K₂O, P₂O₅, and Na₂O in PS-2 and PS-3 soils are reflective of the relatively more weathered soils compared in PS-1 and PS-4 soils. The results of the present study support the hypothesis proposed by Chesworth (1973) that time can ultimately modify the parent material so that the result of continuous weathering will move toward a sesquioxidic system composed of SiO₂-Al₂O₃-Fe₂O₃-H₂O.

TABLE 5. Chemical Composition of the Soils (by X-ray Fluorescence Spectroscopy)

Horizon	Weight Percent (%)											Total
	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MnO	TiO ₂	CaO	K ₂ O	P ₂ O ₅	MgO	Na ₂ O	LOI	
	PS-1											
Ah1	35.0	15.0	5.4	0.09	0.54	36.1	0.25	0.27	1.92	0.30	3.3	98
Ah2	35.2	15.1	5.4	0.09	0.54	35.2	0.24	0.24	1.89	0.30	3.2	97
Ck1	21.1	8.3	2.5	0.04	0.27	53.7	0.12	0.11	1.34	0.22	3.7	92
Ck2	17.0	6.3	1.9	0.03	0.20	57.3	0.09	0.08	1.17	0.21	3.8	88
FR	10.5	3.5	1.1	0.02	0.10	59.0	0.05	0.05	1.10	0.18	4.0	80
	PS-2											
Ah1	64.2	19.6	10.0	0.16	1.20	1.8	0.71	0.13	2.08	1.16	1.7	103
Ah2	62.5	20.3	10.3	0.16	1.25	1.4	0.65	0.08	1.95	1.07	1.1	101
Bt1	59.4	23.5	10.5	0.08	1.11	1.1	0.77	0.04	1.93	0.87	1.0	101
Bt2	55.5	25.0	10.8	0.08	1.13	1.2	0.69	0.05	2.00	0.91	1.1	99
Bt3	57.9	25.0	11.0	0.09	1.10	1.2	0.77	0.03	2.15	0.88	1.0	101
FR	56.5	26.2	10.0	0.07	1.34	1.1	1.73	0.19	1.31	1.95	0.8	101
	PS-3											
Ah1	81.1	10.9	6.9	0.15	0.97	0.2	0.19	0.04	0.39	0.21	0.8	102
Ah2	78.4	12.3	7.3	0.15	0.96	0.2	0.21	0.04	0.39	0.21	0.7	101
BA	74.8	14.9	8.4	0.07	1.01	0.2	0.23	0.04	0.43	0.20	0.7	101
Bt1	67.2	19.7	10.6	0.04	1.04	0.2	0.28	0.04	0.46	0.19	0.9	101
Bt2	54.4	25.1	18.1	0.03	1.02	0.1	0.35	0.11	0.49	0.19	1.1	101
Bt3	57.7	26.5	13.1	0.02	1.07	0.2	0.45	0.04	0.62	0.18	1.1	101
FR	45.5	31.1	17.8	0.22	1.49	0.9	0.18	0.12	1.68	0.27	0.5	100
	PS-4											
Ah1	27.3	12.1	3.3	0.05	0.38	47.3	0.10	0.12	1.35	0.20	3.7	96
Ah2	27.2	12.1	3.6	0.05	0.38	48.9	0.10	0.11	1.32	0.21	3.5	97
Bw	27.4	12.8	4.7	0.04	0.40	49.7	0.11	0.12	1.28	0.20	3.3	100
Ck1	24.0	10.1	2.7	0.04	0.32	52.5	0.10	0.09	1.30	0.18	3.5	95
Ck2	26.3	11.3	2.9	0.04	0.34	51.4	0.11	0.11	1.37	0.17	3.4	98
Ck3	25.4	11.0	2.6	0.04	0.34	51.7	0.10	0.11	1.33	0.17	3.5	96
FR	14.7	5.3	1.5	0.02	0.18	58.1	0.04	0.06	0.93	0.16	3.9	85

FR: Fresh rock; LOI: loss-on-ignition.

The chemical index of alteration (Nesbitt and Young, 1984), which is calculated as $Al_2O_3/(Al_2O_3 + CaO + Na_2O + K_2O)$, was higher in PS-2 and PS-3 soils than in PS-1 and PS-4 soils (Fig. 4A), suggesting that the former soils were relatively more weathered than the latter soils. The degree of decalcification (Fig. 4B) was more or less complete in PS-2 and PS-3 soils as indicated by the low $(CaO + MgO)/Al_2O_3$ ratio (Retallack, 1997) and very low CaO (Table 5). The degree of silicate destruction $[SiO_2/(Al_2O_3 + Fe_2O_3 + TiO_2)]$ (Fig. 4C) was almost uniform in all profiles, except in PS-3 soil, wherein the ratio was high in the surface and decreased with depth. The results suggest progressive silicate weathering in the sub-soil that may have reached to 14% to 43% of that found in the parent material (data not shown).

Soil Classification

PS-1 and PS-4 soils meet the requirements of a mollic horizon (IUSS Working Group WRB, 2006). The soils have a base saturation (1 M NH₄OAc) of greater than 50% and thus qualify as a Calcaric Phaeozems or very fine, calcareous, isohyperthermic, Rendollic Eutrudepts in the Soil Taxonomy (Soil Survey Staff, 2006). PS-2 and PS-3 soils meet the requirements of an argic horizon (IUSS Working Group WRB, 2006) or argillic

B-horizon (Soil Survey Staff, 2006). The two soils have CEC_{pot} (1 M NH₄OAc) of less than 24 cmol/kg clay and have a base saturation (1 M NH₄OAc) of less than 50%, and thus, they qualify as Haplic Alisols (Hyperdystric, Rhodic) in the WRB or fine, kaolinitic, isohyperthermic, Typic Hapludalfs in the Soil Taxonomy (Soil Survey Staff, 2006).

Soil-Forming Processes

Because all the studied areas have closely similar climatic conditions, the differences in the geochemical composition of the parent material, topography, length of time of pedogenesis, and atmospheric input probably in the form of volcanic-ash deposition seem to have greatly influenced the formation of the soils. Results suggest that the dominant pedogenetic processes that produced the soils are weathering and clay formation, loss of bases and acidification, inorganic C accumulation, structure formation, desilication, and ferrugination. The more weatherable calcareous shale in PS-2 and PS-3 soils has resulted in a much faster weathering rate as shown by their high clay contents (Table 2; Fig. 2) and the dominance of kaolinite and halloysite clay minerals (Fig. 3). The loss of bases and acidification are reflected by the very low contents of the total CaO, MgO, Na₂O, and K₂O (Table 5); high chemical index of weathering (Fig. 4A);

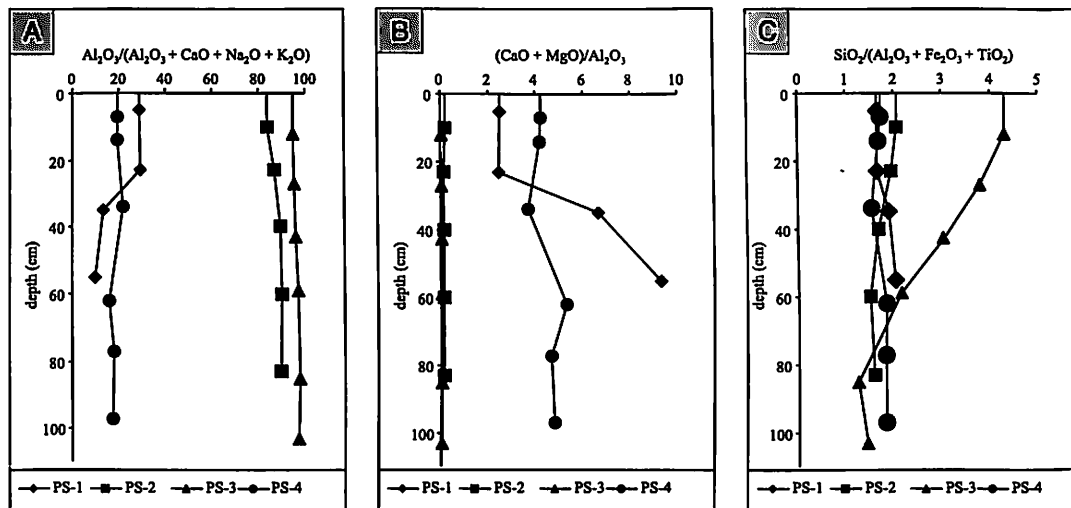


FIG. 4. The geochemistry of the studied soils in Leyte, Philippines. A, $Al_2O_3 / (Al_2O_3 + CaO + Na_2O + K_2O)$ as Chemical Index of Alteration (CIA); (B) $(CaO + MgO) / Al_2O_3$ ratio for degree of decalcification; (C) $SiO_2 / (Al_2O_3 + Fe_2O_3 + TiO_2)$ as index for silicate weathering and Si leaching.

very low exchangeable bases; and low pH (Table 3). The accumulations of inorganic C (Table 3) in PS-1 and PS-4 soils are reflective of the coralline limestone parent materials. Soil structure formation is reflected by the granular structure in the surface soil to sub-angular blocky structure in the sub-soil and is clear from the excellent physical condition of the soils (Table 2). The degree of desilication (Fig. 4C) was almost uniform in all pedons, except in PS-3 soil, wherein the ratio decreases in the sub-soil, indicating the progressive silicate weathering that has reached to 14% to 43% of that found in the parent rocks. The ferrugination (Duchaufour, 1998) is reflective of the loss of bases, halloysitic and kaolinitic clay mineralogy (Fig. 3), and high amounts of Fe oxides (Table 4). Our results support the hypothesis of Chesworth (1973) that different parent materials may develop into closely related soils as the weathering progresses.

CONCLUSIONS

The soils have more or less similar morphological characteristics, particularly in terms of soil structure (granular to sub-angular blocky) and consistence (friable to firm) but differed in terms of soil depth (55–103 cm) and soil color (10 YR-5 YR). The generally high clay and silt contents in these relatively young soils may suggest possible external material contributions, particularly from volcanic-ash deposition, because the areas are close to volcanic mountains. Pedogenesis seems relatively fast in PS-2 and PS-3 soils because of the fast and easy weatherability of the calcareous shale parent material as reflected by their higher clay content, substantial losses of exchangeable bases and total oxides, low CEC_{pot} , high degree of decalcification, formation of kaolinite and halloysite clay minerals, and Fe transformations. The less weathered nature of PS-1 and PS-4 soils is indicated by their higher silt content, alkaline soil pH, high $CaCO_3$, and CEC_{pot} and the dominance of calcite, smectite, vermiculite, and interstratified kaolinite/smectite. The most important pedogenetic processes that produced these soils are weathering and clay formation, loss of bases and acidification, inorganic C accumulation, structure formation, desilication, and ferrugination. Under humid tropical conditions of Leyte, Philippines, the geochemical characteristics of the parent

materials, topography, and time of pedogenesis greatly influenced the development of soils from sedimentary rocks.

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