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ORIGINAL ARTICLE

Characteristics and formation of rain forest soils derived from late Quaternary basaltic rocks in Leyte, Philippines

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Abstract This study was conducted to evaluate the physical, chemical, and mineralogical characteristics of rain forest soils derived from late Quaternary basaltic rocks in Leyte, Philippines. Four sites along a catena were selected at an elevation of 75–112 m above sea level with an average annual rainfall of 3,000 mm and an average temperature of 28°C. Results indicate that the soils are deep, clayey, and reddish in color, which is indicative of the advanced stage of soil development. They also posses excellent physical condition (friable and highly porous) although they are plastic and sticky when wet as is usual for clayey soils. In terms of chemical characteristics, the soils are acidic with low CEC values and generally low in organic matter and nutrient contents. The clay mineralogy of the soils is dominated by halloysite and kaolinite with minor amounts of goethite and hematite, and they also have generally high dithionite-extractable Fe contents confirming the advanced stage of their development. The soils in the more stable slope positions (PL-1, PL-2, and PL-4) have generally similar characteristics and appeared more developed than the one in the less stable position (PL-3). The most important pedogenic processes that formed the soils appear to be weathering, loss of bases and acidification, desilification, ferrugination, clay formation and translocation, and structure formation. The nature of the parent rock and climatic conditions prevailing in the area as well as slope position appear to have dominant effects on the development of the soils.

Keywords Tropical soils · Pedogenic processes · Quaternary · Volcanic rocks · Forest soil

Introduction

The classical view about soils under tropical rain forest was based on the misconception that these soils were generally acidic and infertile (e.g., Sanchez 1976; Richter and Babbar 1991; Markewitz et al. 2004). This misconception which until now has influenced research and management of the fragile rain forest ecosystem was enhanced by early observations that highly diversified tropical rain forests grow atop highly weathered and infertile soils. On this basis, Richter and Babbar (1991) stressed the importance of not generally categorizing tropical forest and tropical soils as a single entity. Due to its diversity and complexity (e.g., Mohr et al. 1972; Richter and Babbar 1991) soils under tropical rain forest could range from relatively young fertile soils (e.g., Inceptisols) to the highly weathered infertile soils (e.g., Oxisols) (Sanchez 1976; Jordan 1985), and that the extent of extremely infertile soils in the tropics is smaller than previously assumed (e.g., Sanchez 1976; Richter and Babbar 1991; Bruijnzeel 1998). These overgeneralization and poor understanding of soils in the tropics merits continued investigation (Richter and Babbar 1991; Markewitz et al. 2004).

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There is also a need to give special attention to tropical island soils particularly on the much younger soils of insular South-east Asia (Sanchez 1976; Asio et al. 2006; Navarrete et al. 2007). These authors speculated that soils in the islands of South-east Asia may be distinct from those in other humid tropical areas, because of the unique environmental factors that influenced their formation. For example, Hall (2002) reported that much area of South-east Asia was formed from the tectonic movements during the Cenozoic era and islands emerged from the sea recently. Chang et al. (2005) consider the present climate that prevails in South-east Asia as also unique in the sense that it is located in the transitional region between the boreal summer Asian monsoon and the boreal winter Asian monsoon. Achard et al. (2002) reported that the rate of deforestation in South-east Asia is among the highest in the world, suggesting that intensive human influence is also a major factor to the unique characteristics of the soils in the region.

In the Philippines, the rapid increase in population during the last 50 years resulted in the cultivation of upland and forested areas where strongly weathered acid soils are widespread (e.g., Asio 1997). Due to the lack of understanding of these soils because very limited pedological research has been done on them (e.g., Navarrete et al. 2007), unsuitable crop production and management practices have resulted in widespread soil degradation and very low crop yields (Garrity 1993). Likewise, very little is known concerning the nature of rain forest soils in the Philippines (e.g., Zikeli et al. 2000), which contributed to the failure of major government efforts at massive forest rehabilitation in the past (e.g., Alcala 1997). Appropriate land use management of these strongly weathered soils requires detailed information on their properties. Therefore, the objectives of this study were (1) to characterize the physical, chemical, and mineralogical characteristics of the rain forest soils, and (2) to explain the formation of these strongly weathered soils in the humid tropical island of Leyte, Philippines.

Materials and methods

Study area

The study area is located in the Mt. Pangasugan Rain Forest Reserve ca. 8 km north of Baybay City, Leyte, Philippines (10°46′N and 124°50′E) (Fig. 1a). Geologically, the island of Leyte was formed from tectonic movement and plate convergence, which occurred at least since the beginning of the Tertiary (Wernstedt and Spencer 1967; Aurelio 2000). The geomorphological characteristic of the island is rugged and mountainous, which can be explained by uplift and block faulting and volcanism (Scott 2000) brought about by the Philippine Fault, a left lateral strike–slip fault (Aurelio 2000), that traverses the central part of the island. Basaltic and andesitic volcanic materials of Tertiary and Quaternary age built up the central mountain range (DENR 1992), and are the parent materials of the soils in the area (Asio 1996; Jahn and Asio 1998). The average annual temperature is 28°C and receives ca. 3,000 mm of rain annually recorded over a 17-year period (1991–2007) at the nearest meteorological station, 1 km west of the study site. The typical dry and wet month begins between March and May and September and January, respectively, and the difference between the coldest (December) and the warmest month (April) is between 2 and 3°C with all months having more than 100 mm precipitation. The present climatic condition indicates that the soil moisture and temperature regimes are udic and isohyperthermic, respectively (Soil Survey Staff 2006).

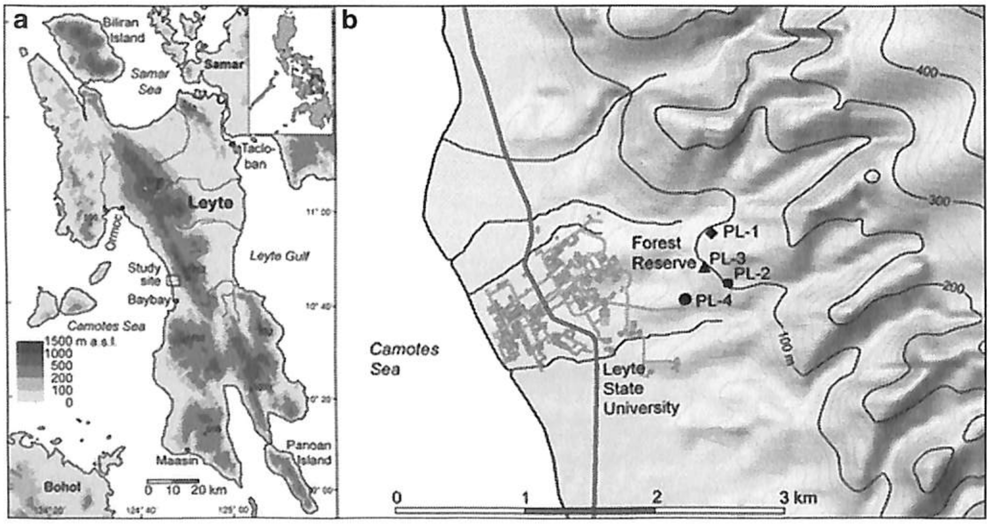

Fig. 1 **a** Map of Leyte, Philippines and the location of the study sites marked x. **b** Location of the pedons in the study area

The natural vegetation of the area was dominated by the tree family Dipterocarpaceae (dipterocarps) (Langenberger et al. 2006). Starting at least in the 1950s, the lower portion of the rain forest has been used for slash-and-burn agriculture even after it was declared a forest reserve (Asio 1996; Navarrete and Tsutsuki 2008). Since then, different land use types including old growth secondary forest, mahogany plantation, rainforestation farming, coffee plantation, pasture, coconut plantation, and abaca plantation have been set up. Table 1 gives the site characteristics of the study area.

Field soil description and sampling

In August 2004, fieldworks were conducted in a 1-km^2 lowland area inside the rain forest reserve and four pedons were examined along a catena (Fig. 1b). Soil from PL-1 was located on the upper backslope under an undisturbed secondary forest with no history of cultivation. PL-2 was located on the middle backslope of the 15-year-old closed-canopy reforestation project. The area has a long history of intensive cultivation in the past, and prior to the reforestation project, the area was dominated by *Imperata cylindrica*, implying the degraded nature of the area. PL-3 was located in the lower footslope under a 30-year-old mahogany plantation. PL-4 was located in a flat toeslope under coffee plantation. The plantation received organic manure application for the last 8 years. A brief land use history of the area can be found in another published study (Navarrete and Tsutsuki 2008). Except for soils in PL-3, all other soils were located in a relatively stable landscape. To examine each pedon, a pit measuring 1 by 1 m and having a depth of at least 1 m or to the bedrock was excavated manually. Soil description was described following the standard procedure of the FAO Guidelines for Soil Description (FAO 2006). Bulk samples were collected from every horizon of each pedon, air-dried, freed of large plant residues, and were ground and allowed to pass through a 2-mm wire mesh and analyzed for physical, chemical, and mineralogical characteristics. Undisturbed core soil samples were also collected for bulk density determination. In addition, fresh rocks were collected in each site and were pulverized with a tungsten carbide ring mill before total elemental analysis.

Laboratory analysis

Bulk density was determined by drying the core samples at 105°C until constant weight. Particle-size distribution was analyzed by pipette method (ISRIC 1995); soil pH was measured by potentiometry in water and 1 mol L^{-1} KCl in a 1:2.5 soil mass to solution volume ratio; total carbon and nitrogen by dry combustion using C/N-analyzer (Elementar Vario EL III) on pulverized samples; available P was extracted using 0.03 mol L^{-1} NH_4F in 0.1 mol L^{-1} HCl (Bray 2), and by the method of Murphy and Riley for color development; and phosphate retention was determined by the method of Blakemore et al. (1987). Potential cation exchange capacity (CEC_{pH7}) and exchangeable base cations (Ca^{2+}, Mg^{2+}, K^+, and Na^+) were extracted (1:20 w/v) with 1 mol L^{-1} ammonium acetate (pH 7.0), and the exchangeable base was analyzed by atomic absorption spectroscopy (AAS). The exchanged NH_4^+ in the 1 mol L^{-1} KCl solution was determined using the steam distillation method and the CEC values were calculated. Exchangeable acid cations ($Al^{3+} + H^+$) were extracted by displacement with 1 mol L^{-1} KCl (Thomas 1982). Effective cation exchange capacity (CEC_{ef}) was calculated by summing the amounts of exchangeable base cations and KCl extractable acidity; base saturation percentage (BS %) using the formula BS% = (sum of exch. Ca, Mg, K, and Na)/CEC_{pot} × 100. Dithionite-citrate extractable iron (Fe_d) and aluminum (Al_d); acid-oxalate extractable iron (Fe_o) and aluminum (Al_o) were extracted according to Blakemore et al. (1987). The iron and aluminum concentrations were quantified using ICP-AES (Shimadzu ICPS-8100). The mineralogy of the clay fractions on oriented samples was determined from two single horizons of PL-1 (Bt_3) and PL-3 (BA) using a Shimadzu XD-3A X-ray diffractometer equipped with CuKα radiation generated at 30 kV and

Table 1 Site characteristics of the study area

	PL-1	PL-2	PL-3	PL-4
Latitude	10°44.905'N	10°44.688'N	10°44.753'N	10°44.614'N
Longitude	124°48.262'E	124°48.329'E	124°48.229'E	124°48.138'E
Altitude (m)	112	107	99	75
Slope gradient (%)	5–10	1–2	5–10	0.5–1.0
Slope form	Straight	Straight	Concave-straight	Straight
Slope position	Upper backslope	Middle backslope	Lower footslope	Flat toeslope
Vegetation	Dipterocarp forest	Rainforestation farming	Mahogany plantation	Coffee plantation
Age (years)	Old secondary growth	16	32	13

30 mA with a scan speed of 4°2θ min^{-1}. The X-ray analysis was carried out on oriented smear mounts of clay samples either K- or Mg-saturated and were air-dried, or Mg-saturated and glycolated or K-saturated and heated at 300 and 550°C for 1 h with signals recorded in the range of 2° to 40°2θ. The total concentrations of oxides in soils and fresh rocks samples were measured by X-ray fluorescence spectrometer (XRF: Rigaku 3070 Spectrometer) using glass bead method.

Gain and loss calculation

Calculation of gain and loss of elements during the weathering process were done following the method described by Marshall (1977). ZrO_2 was used as reference oxide because it remains unchanged during the weathering of the parent material.

Results and discussion

Soil morphophysical characteristics

Table 2 shows the morphological properties of the soils along the catena studied. They are relatively deep and well developed as indicated by the presence of illuvial B horizons. Soils in PL-1, PL-2, and PL-4 appear closely related in terms of morphological features, whereas the soil in PL-3 appears considerably different. In terms of color, soils in PL-1, PL-2, and PL-4 have the most reddish hue ranging from dark reddish brown (7.5 YR 3/3) in the surface to yellowish brown (5 YR 5/6) in the deeper horizon, whereas the soil in PL-3 has a brownish black (10 YR 2/2) surface soil and brown (10 YR 4/3) subsoil. Less horizon differentiation can be observed in PL-3 compared to the well expressed horizon differentiation in soils of PL-1, PL-2,

Table 2 Morphological and physical properties of pedons studied (Leyte, Philippines)

Horizon	Dept (cm)	Color (moist)	Structure[a]	Consistency[b]	Roots[c]	Bulk density (g cm^{-3})	Sand (g kg^{-1})	Silt (g kg^{-1})	Clay (g kg^{-1})
PL-1									
Ah	0–8	7.5 YR 3/3	WM, GR, VM	FR, SST, SPL	FM, M	0.96	245	67	688
BA	8–30	7.5 YR 4/4	MS, GR, VM	FR, SST, SPL	FM, C	0.91	199	141	661
Bt$_1$	30–43	5 YR 4/6	MS, AB; MC	FR, VST, VPL	MC, F	0.86	156	119	725
Bt$_2$	43–60	5 YR 4/6	ST, AB, MC	FI, VST, VPL	MC,V	0.86	130	108	762
Bt$_3$	60–80	5 YR 4/6	ST, AB, MC	FI, VST, VPL	N	0.85	71	95	833
Bt$_4$	80–120	5 YR 5/8	ST, AB, MC	FI, VST, VPL	N	0.86	196	135	669
PL-2									
Ah	0–20	7.5 YR 4/3	WM, GR, VM	FR, SST, SPL	FM, M	1.12	269	225	507
Bt$_1$	20–36	5 YR 4/4	MS, AB, VM	FI, VST, VPL	MC, C	0.96	165	144	691
Bt$_2$	36–65	5 YR 4/6	ST, AB, MC	FI, VST, VPL	MC, C	0.96	278	117	604
BC	65–80	5 YR 4/4	ST, AB, MC	FI, VST, VPL	N	0.94	354	122	524
PL-3									
Ah$_1$	0–10	10 YR 2/2	WM, GR, VM	FR, SST, SPL	FM, M	1.17	364	430	206
Ah$_2$	10–24	10 YR 3/2	MO, GR, VM	FR, SST, SPL	MC, C	1.12	334	406	260
BA	24–36	10 YR 4/5	MO, AB, MC	FI, SST, SPL	MC, C	1.06	350	259	391
BC	36–70	10 YR 5/6	MO, SA, MC	FI, SST, SPL	MC, F	1.03	420	227	353
CR	70–105	10 YR 5/6	MO, SA, MC	FI, SST, SPL	N	1.01	363	233	404
PL-4									
Ap	0–11	7.5 YR 3/2	WM, GR, VM	FR, SST, SPL	FF, M	1.07	225	315	459
AB	11–20	7.5 YR 4/3	MS, AB, VM	FI, SST, SPL	FF, C	0.85	101	120	779
Bt$_1$	20–32	5 YR 4/4	MS, SA, MC	FI, SST, SPL	MC, F	0.88	66	22	911
Bt$_2$	32–72	5 YR 3/6	ST, SA, MC	FI, VST, VPL	MC, F	0.87	52	89	859
Bt$_3$	72–110	5 YR 3/6	ST, SA, MC	FR, VST, VPL	N	0.86	121	151	728

Largely according to FAO (2006)

VM very fine to medium, *MC* medium and coarse, *clay* <2 µm, *silt* 2–63 µm, *coarse sand* 0.63–2 mm, *fine sand* 0.063–0.2 mm

[a] *WM* weak to moderate, *MS* moderate to strong, *ST* strong, *GR* granular, *AB* angular blocky, *SA* subangular and angular blocky

[b] *FR* friable, *FI* firm, *SST* slightly sticky, *VST* very sticky, *SPL* slightly plastic, *VPL* very plastic

[c] *FM* fine and medium, *MC* medium and coarse, *FF* very fine and fine, *M* many, *C* common, *F* few, *N* none

and PL-4, indicating the more advanced stage of development of the latter soils. Except PL-3, all other soils showed weakly to moderately developed granular structure in the surface grading, to moderate to strongly subangular and angular blocky structure in the subsoil. All soils are friable in the surface but become firm in the subsoil. Under saturated condition, the soils are sticky and plastic in their subsoils probably due to their very high clay content except PL-3. All soils exhibit many fine roots in the surface and fine to medium roots in their subsoils. The deep, clayey, and reddish morphological characteristics of the soils are reflective of their strongly weathered condition, although soil from PL-3 is less weathered compared to the other soils.

Physical analysis revealed that except PL-3, all other soils are dominated by clay (Fig. 2; Table 2). In fact, even in the surface horizons, clay contents are high implying the strongly weathered condition of the soil. In general, the distribution of clay with depth tends to increase in the middle horizon of the profiles, suggesting clay accumulation probably due to clay translocation and in situ weathering. Despite the disturbed nature of the soils due to human activities, their bulk density values are very low (0.85–1.17 g cm^{-3}) due to the excellent soil structure (granular to angular blocky) and porous soil condition, which is related to the dominance of clay mineral halloysite (revealed from XRD scan; Fig. 3). Further, the high porosity of the soils can be in part attributed to isovolumetric weathering, which is common in areas with high precipitation and good drainage (Asio 1996; Navarrete et al. 2008). Low bulk density values of highly weathered soils in the nearby island of Samar, Philippines have been reported by Navarrete et al. (2007).

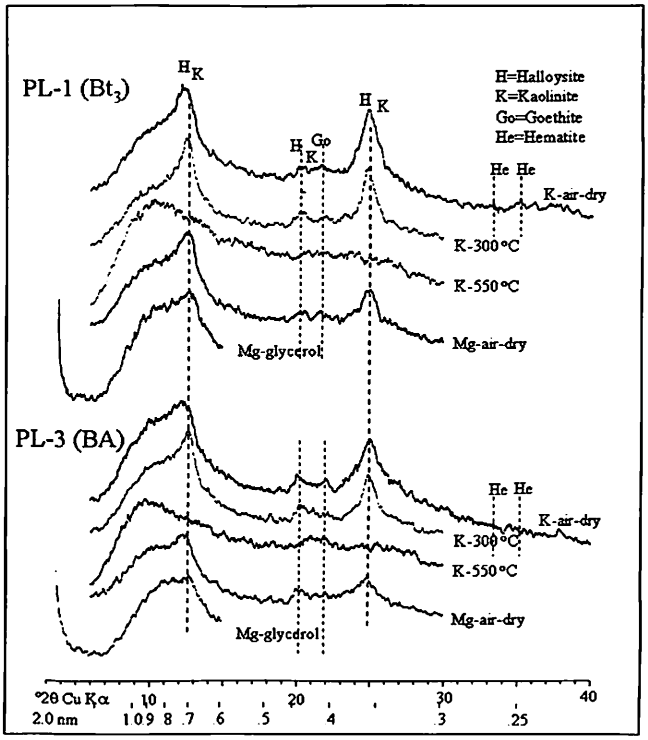

Fig. 3 X-ray diffraction scans of oriented specimens from the clay (<2 μm) fractions subjected to different mineralogical treatments. **a** PL-1 (Bt$_3$); **b** PL-3 (BA). *Dotted vertical lines* represent d-spacing in nm. All scans are normalized to the 0.71-nm peak to facilitate comparison of relative phase abundance

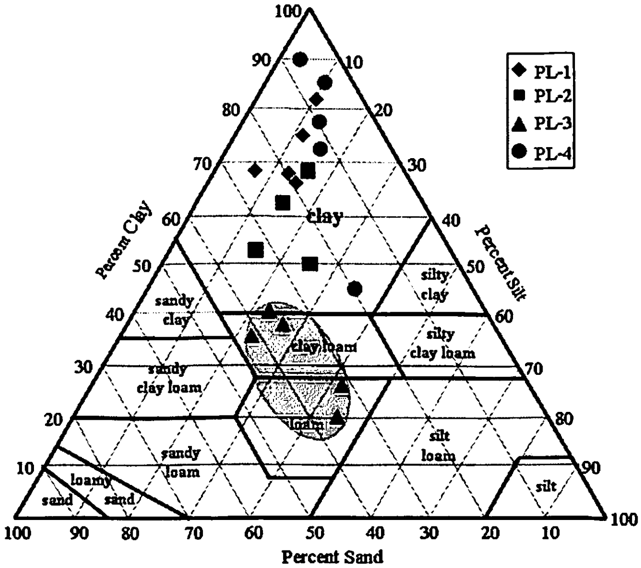

Fig. 2 Particle size distribution and textural classes of the pedons studied based on the USDA textural triangle

In terms of classification, soils in PL-1, PL-2, PL-3, and PL-4 meet the requirements for an argic horizon (IUSS Working Group WRB 2006) or argillic B horizon (Soil Survey Staff 2006) having clay accumulation by in situ weathering and probably clay translocation in the subsurface horizons. Soils from PL-1, PL-2, and PL-4 have CEC (by 1 mol L^{-1} NH$_4$OAc) of <24 cmol$_c$ kg^{-1} clay and a base saturation (by 1 mol L^{-1} NH$_4$OAc) of <50%, and thus these soils can be classified as Haplic Acrisol (Clayic, Chromic) in the WRB system (IUSS Working Group WRB 2006) or very fine, halloysitic, isohyperthermic, Typic Hapludult in terms of soil taxonomy (Soil Survey Staff 2006). On the other hand, soil in PL-3 has CEC (by 1 mol L^{-1} NH$_4$OAc) of >24 cmol$_c$ kg^{-1} clay and a base saturation of <50%, which meets the requirement of a Haplic Alisol (Hyperdystric, Siltic) (IUSS Working Group WRB 2006) or fine silty, halloysitic, isohyperthermic, Typic Haplohumult (Soil Survey Staff 2006).

Chemical and mineralogical properties

Table 3 reveals that all soils are acidic (pH-H$_2$O: 5.1–5.9), although there is a tendency for soil pH values to be higher

Table 3 Chemical characteristics of the pedons studied (Leyte, Philippines)

Horizon	Depth (cm)	pH			Corg (%)	Nt (%)	Avail P (mg kg^{-1})	Pret (%)	Ca (cmol kg^{-1})	Mg (cmol kg^{-1})	K (cmol kg^{-1})	Na (cmol kg^{-1})	ΣBS (cmol kg^{-1})	Exch. acidity (cmol kg^{-1})	ECEC (cmol kg^{-1})	CEC$_{pH7}$ (cmol kg^{-1})	BS/CEC$_{pH7}$ (%)%
		H_2O	KCl	ΔpH													
PL-1																	
Ah	0–8	5.1	4.4	−0.7	2.9	0.33	2.44	44	1.28	0.95	0.26	0.05	2.54	0.82	3.36	15.6	16
BA	8–30	5.2	4.2	−1.0	1.5	0.17	1.10	53	0.71	0.66	0.08	0.09	1.53	2.52	4.05	15.9	10
Bt$_1$	30–43	5.3	4.3	−1.0	1.1	0.14	0.37	55	0.75	0.65	0.07	0.10	1.57	2.35	3.92	14.0	11
Bt$_2$	43–60	5.6	4.2	−1.4	1.0	0.12	0.85	58	0.68	0.61	0.03	0.14	1.46	2.84	4.30	23.8	6
Bt$_3$	60–80	5.4	4.2	−1.2	0.8	0.11	0.49	59	0.72	0.67	0.05	0.13	1.58	2.72	4.30	24.5	6
Bt$_4$	80–120	5.5	4.2	−1.2	0.6	0.08	0.49	57	0.67	0.78	0.02	0.17	1.64	2.79	4.43	21.4	8
PL-2																	
Ah	0–20	5.1	4.2	−0.9	1.7	0.21	0.85	46	1.21	0.66	0.17	0.07	2.11	1.80	3.91	11.1	19
Bt$_1$	20–36	5.3	4.1	−1.2	1.1	0.13	0.37	46	1.10	0.58	0.05	0.10	1.83	3.70	5.53	12.9	14
Bt$_2$	36–65	5.3	4.1	−1.3	0.9	0.11	0.37	46	1.08	0.53	0.07	0.12	1.79	4.24	6.03	12.3	15
BC	65–80	5.5	4.1	−1.5	0.6	0.09	0.37	45	0.92	0.61	0.06	0.12	1.71	3.25	4.96	19.5	9
PL-3																	
Ah$_1$	0–10	5.7	4.7	−1.0	2.1	0.24	1.5	37	4.97	2.02	0.19	0.07	7.25	0.18	7.43	33.5	22
Ah$_2$	10–24	5.8	4.6	−1.3	1.3	0.17	0.6	41	3.90	2.20	0.07	0.11	6.29	0.36	6.65	32.5	19
BA	24–36	5.7	4.3	−1.4	1.1	0.15	0.7	47	3.46	2.22	0.07	0.16	5.91	1.41	7.32	31.6	19
BC	36–70	5.7	4.3	−1.5	1.0	0.13	0.4	47	3.44	2.10	0.07	0.28	5.88	1.42	7.30	28.9	20
CR	70–105	5.8	4.5	−1.4	0.5	0.09	0.4	42	3.48	2.08	0.03	0.28	5.88	0.53	6.41	26.1	23
PL-4																	
Ap	0–11	5.2	4.5	−0.8	2.7	0.30	3.54	42	1.01	0.86	0.50	0.02	2.38	0.52	2.90	17.2	14
AB	11–20	5.1	4.2	−0.9	2.2	0.21	0.98	48	0.66	0.57	0.34	0.03	1.60	1.18	2.78	13.4	12
Bt$_1$	20–32	5.3	4.2	−1.1	1.1	0.15	0.37	55	0.54	0.47	0.13	0.08	1.22	1.99	3.21	17.2	7
Bt$_2$	32–72	5.3	4.1	−1.2	0.8	0.13	0.37	55	0.30	0.30	0.12	0.08	0.81	3.82	4.63	14.1	6
Bt$_3$	72–110	5.2	4.1	−1.0	0.7	0.11	0.37	63	0.19	0.18	0.26	0.09	0.72	4.37	5.09	16.4	4

in PL-3. All soils possess a net negative charge as indicated by negative ΔpH ($pH_{KCl} - pH_{H2O}$) (Mekaru and Uehara 1972). Total carbon and nitrogen contents are higher in the upper horizon and decrease sharply with depth. Soil carbon and nitrogen contents decrease in the order of PL-4 > PL-1 ≥ PL-3 > PL-2. The application of animal manure for the last 8 years into the coffee plantation (PL-4) resulted in its slightly elevated contents of carbon and nitrogen. PL-2 has the lowest carbon and nitrogen contents, because of long history of disturbance particularly shifting agriculture before the reforestation was established (Navarrete and Tsutsuki 2008). The general variations in carbon and nitrogen contents among sites can be due to the differences in the vegetation cover and past land use and soil management practices (Navarrete and Tsutsuki 2008). Available P is very low in all sites (3.54–0.37 mg kg^{-1}) due to the very low total P in the basaltic parent material, and to the soils considerable phosphate retention capacity of 37–59%. Sanchez (1976) reported that high phosphate retention of highly weathered tropical soils is due to the dominance of Al and Fe oxides that have high affinity for the phosphate ion. The ability of the native vegetation to thrive in the area despite the low P availability may be partly attributed to the outside sources of P brought down by rain (Zikeli et al. 2000; Sueta et al. 2007), the roots ability to produce weak organic acids that enhance weathering of rocks or mineral fragments, and to the mycorrhizal association, which facilitates the uptake of less available P pool by native vegetation (Jordan 1985). Data also revealed that exchangeable bases, effective CEC, CEC_{pH7}, and base saturation calculated to CEC_{pH7} tend to be higher in PL-3 relative to the other soils. The physiographic position of PL-3 (concave lower footslope) makes it a recipient of lateral flow of water and elements from the upper slope as is common in humid landscapes (e.g., Sommer and Schlichting 1997), and this slows down weathering rates. The occurrence of lateral flow was confirmed by Zikeli et al. (2000) and Asio and Jahn (2007) who reported high amounts of exchangeable bases in the stream water collected near the study area. Bruijnzeel (1998) cited previous studies which found that the amount of nutrient carried in solution into the lower water stream can be regarded as a useful indicator of the areas nutrient status.

Results of selective dissolution analyses of Fe and Al by dithionite (Fe_d, Al_d) and oxalate (Fe_o, Al_o) and selected ratios are presented in Table 4. Fe_d which indicates the total free Fe oxides ranges from 17 to 82 g kg^{-1} (average 47 g kg^{-1}) and is much higher than the values of Fe_o (3.1–11.7 g kg^{-1}). Al_d and Al_o values range from 3.8 to 9.5 and 5.3 to 9.1 g kg^{-1}, respectively, with no major variations observed. Soil in PL-3 has generally low Fe_d, Al_d, Fe_t, and Al_t values compared to the other soils. Very observable in the soil of PL-4 is the abrupt increase in the values of Fe_d, Al_d, Fe_t, and Al_t at depths between 32 and 110 cm but is not observed in the other soils. This is probably due to comigration of Fe and Al oxides along with clay with depth as reflected by the high positive correlation ($r = 0.75$) between clay and Fe oxides. Fe_o/Fe_d ratio is generally high in PL-3 (0.42), but is low in PL-1, PL-2, and PL-4 (0.15–0.09), whereas low ratio of $(Fe_d - Fe_o)/Fe_t$ can be observed in PL-3 (0.1) compared to the values in the other soils (0.3–0.4). Fe_d shows a high positive correlation ($r = 0.55$) with Fe_t suggesting that higher Fe_t may result in higher concentration of Fe_d. On the other hand, there was high positive correlation ($r = 0.75$) between the ratio $(Fe_d - Fe_o)/Fe_t$ and clay content indicating that the ratio of crystalline free Fe oxides to total Fe content increases with the increase of clay content (Table 2).

X-ray diffraction scans of oriented specimens from selected clay fractions (<2 μm) are presented in Fig. 3. The clay mineralogy of the soils consists of almost entirely of halloysite, kaolinite with minor amounts of goethite and hematite. Peaks were detected at 0.70, 0.36, and 0.45 nm indicating the presence of halloysite and appeared to be more dominant than peaks of kaolinite (0.72 and 0.358 nm), which can be expected since the clay samples were taken from subsoil layer. Asio (1996) reported that in the highly weathered soils in the area, halloysite clay minerals increases with depth, whereas kaolinite clay minerals decrease. He suggested that the abundance of halloysite in the subsoil implies that halloysite was an early product of feldspar weathering. Quantin (1990) observed that in strongly weathered soils, halloysite is more common than kaolinite but the former is less stable hence, it gives way to kaolinite formation with time. Both diffraction peaks of halloysite and kaolinite disappeared after subjecting the K-saturated clay samples to 550°C, confirming the occurrence of halloysite and kaolinite. The occurrence of weak hematite peaks at 0.270 and 0.252 nm, which are more pronounced in the PL-1 compared to PL-3, explain the more reddish color (Table 2) of the soil in the former than the latter. The presence of goethite (0.42 nm) and hematite (0.27 and 0.25 nm) in the soil was also confirmed from the selective dissolution data using the formula $(Fe_d - Fe_o) \times 1.6$ (Table 4). The treatment of Mg-saturated clay sample with glycerol did not cause expansion of the 1.4–1.8 nm regions indicating that smectite mineral was not present in the soil. Although the X-ray diffraction scans (Fig. 3) from two single horizons of PL-1 and PL-3 appear very similar, the CEC_{pH7} calculated to clay is very different (Fig. 4) for the two soils in that PL-1 (Bt_3) had 29 $cmol_c$ kg^{-1}, whereas PL-3 (BA) had 81 $cmol_c$ kg^{-1}. The clay mineralogical composition is generally consistent with previous studies in the area (Asio 1996; Jahn and Asio 1998).

Table 4 Extractable iron and aluminum and ratios of selectively dissolved components of the pedons studied (Leyte, Philippines)

Horizon	Total (g kg^{-1})		Dithionite citrate (g kg^{-1})		Oxalate (g kg^{-1})		Fe_o/Fe_d	Fe_d/Fe_t	Al_d/Fe_d	Fe_d/clay	$(Fe_d - Fe_o)/Fe_t$	Goethite (g kg^{-1})
	Al_t	Fe_t	Al_d	Fe_d	Al_o	Fe_o						
PL-1												
Ah	138	160	7.3	56.0	5.8	10.2	0.18	0.35	0.13	0.08	0.29	73
BA	154	153	8.6	60.7	6.6	6.6	0.11	0.40	0.14	0.09	0.35	86
Bt_1	160	145	9.3	65.6	6.7	5.1	0.08	0.45	0.14	0.09	0.42	97
Bt_2	167	136	8.2	56.9	6.7	4.2	0.07	0.42	0.14	0.07	0.39	84
Bt_3	176	128	8.6	65.9	6.6	3.3	0.05	0.52	0.13	0.08	0.49	100
Bt_4	170	142	7.4	58.9	6.5	3.7	0.06	0.41	0.12	0.09	0.39	88
PL-2												
Ah	133	160	6.7	55.0	5.9	9.9	0.18	0.34	0.12	0.11	0.28	72
Bt_1	156	146	8.5	71.1	6.1	5.8	0.08	0.49	0.12	0.10	0.45	104
Bt_2	165	150	9.5	81.8	6.7	4.3	0.05	0.54	0.12	0.14	0.52	124
BC	170	143	9.1	61.9	5.3	10.3	0.17	0.43	0.15	0.12	0.36	83
PL-3												
Ah_1	130	134	4.7	35.0	7.2	10.8	0.31	0.26	0.14	0.17	0.18	39
Ah_2	137	129	4.7	29.4	9.1	6.3	0.21	0.23	0.16	0.11	0.18	37
BA	140	119	5.3	31.6	8.0	9.7	0.31	0.26	0.17	0.08	0.18	35
BC	145	114	4.4	22.4	8.0	8.8	0.39	0.20	0.20	0.06	0.12	22
CR	139	139	3.8	17.3	5.4	11.7	0.67	0.12	0.22	0.04	0.04	9
PL-4												
Ap	149	131	5.7	35.2	6.4	8.6	0.25	0.27	0.16	0.08	0.20	42
AB	162	137	4.7	31.1	6.0	8.8	0.28	0.23	0.15	0.04	0.16	36
Bt_1	176	132	9.1	58.9	7.6	4.5	0.08	0.45	0.15	0.06	0.41	87
Bt_2	183	128	9.1	54.8	6.9	3.5	0.06	0.43	0.17	0.06	0.40	82
Bt_3	186	129	9.5	54.8	7.5	3.1	0.06	0.42	0.17	0.08	0.40	83

[a] Goethite = $(Fe_d - Fe_o) \times 1.6$

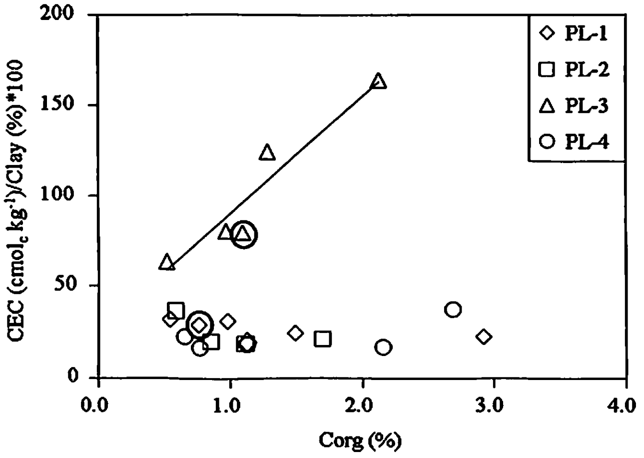

Fig. 4 Relation between calculated clay CEC_{pH7} ratio and Corg of the studied pedons

Soil forming processes

Compared with the other soils studied, soil in PL-3 shows the least pedological development as illustrated in Fig. 5a, b. The plots of PL-3 are located in the upper part of the regression line suggesting high crystallinity ratio (Fe_o/Fe_d) and SiO_2 values (Fig. 5a). It is possible that this soil, due to its position in the catena (lower footslope), receives silica through lateral water flow from the weathering of soils in the upper slopes (as mentioned earlier). The low Fe_o/Fe_d ratio and high $(Fe_d - Fe_o)/Fe_t$ ratio in PL-1, PL-2, and PL-4, suggest that they are in a more advanced stage of soil development, and that most of the iron oxides are in crystalline form (Blume and Schwertmann 1969). If we apply the grouping of soils according to the relationship between activity ratio ($[Fe_d - Fe_o]/Fe_t$) and crystallinity ratio (Fe_o/Fe_d) (Fig. 5b) established by Nagatsuka (1972), which distinguishes four soil types (i.e., brown forest soils, yellow-brown forest soils, yellow-brown soils, and red soils), soils in PL-1, PL-2, and PL-4 fall into the yellow-brown soils ($[Fe_o/Fe_d]$:0.15–0.29; $[Fe_d - Fe_o]/Fe_t$:0.25–0.40), whereas soils in PL-3 belonged to the brown forest soils ($[Fe_o/Fe_d]$:0.40–0.54; $[Fe_d - Fe_o]/Fe_t$:0.19–0.26) with few exceptions of single horizons.

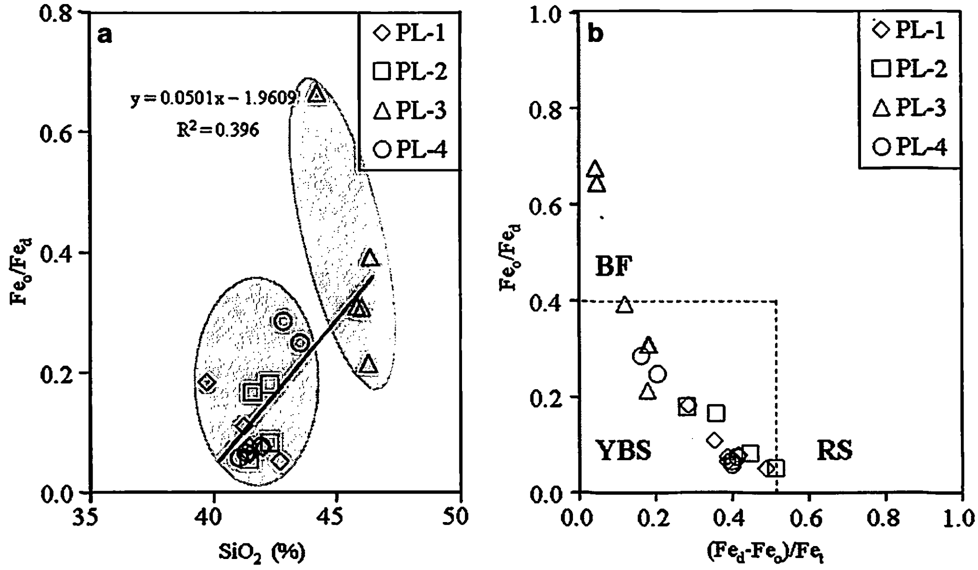

Fig. 5 a Relation between crystalline ratio (Fe_o/Fe_d) and SiO_2; b plots of ratio Fe_o/Fe_d versus the ratio ($Fe_d - Fe_o$)/Fe_t of the pedons studied

Nykvist (1997) proposed that total analyses of the soil is necessary to predict the long-term productivity of rain forest soils in areas with low content of one or more plant nutrients. The total elemental compositions showed that SiO_2 was the major oxide in all pedons followed by Al_2O_3, Fe_2O_3, TiO_2, MgO, CaO, K_2O, MnO and P_2O_5 (according to their order of dominance) (Table 5). The total amount of base-forming oxides (CaO, MgO, Na_2O, and K_2O) was low and was consistent with the low CaO + MgO + K_2O + Na_2O/Al_2O_3 ratio (0.02–0.17), although the soil in PL-3 have slightly elevated values compared to the other soils. Based on gain and loss calculations (Table 6), results revealed that 7–23% SiO_2, 32–80% CaO, 13–75% MgO, 57–70% K_2O, and 34–59% Na_2O have been lost during the weathering of the basalt rock into soils, and in all cases the amount of loss is always lower in the soil in PL-3 compared to the other soils confirming that PL-3 is younger than PL-1, PL-2 and PL-4. The amount of loss of elements particularly the bases are slightly lower than that found by Asio and Jahn (2007) in their study of basalt weathering in the area and is likely because of the differences in the soil profiles used and the location of the soil profiles along the landscape.

The dominant soil forming processes that produced the soils in the study area are weathering, loss of bases and acidification, desilification, ferruginization, clay formation and translocation and structure formation. The loss of bases and acidification due to rapid leaching are shown by the low BS, very low exchangeable bases, and acidic pH (Table 3), and the low contents of total Ca, Na, Mg, and K (Table 5). The degree of desilification is almost uniform in all pedons and may have reached to 12–19% of that found in the parent material (Table 5; SiO_2/Al_2O_3). Ferrugination (Duchaufour 1998) can be seen from the increased loss of bases, halloysitic and kaolinitic mineralogy, considerable amounts of iron oxides, and low base saturation. Rubification or rubefaction according to Duchaufour (1998) (red color development) due to the formation of hematite is not dominant, although it can be seen from the deep red color (5 YR; Table 2) of most subsoils. Since the present climatic condition in the area (i.e., warm but perhumid condition) does not favor rubefaction, its occurrence in the deeper horizons probably suggests that it occurred in the past under drier climate. Asio (1996) cited studies, which revealed that throughout the humid tropics there was a reduction of rainfall during the last glacial maximum. Clay formation and translocation are reflected by high clay content particularly in the middle part of the soil profiles. Soil structure formation is exhibited by good soil physical condition (Table 2).

The study also revealed minimal variations in the morphological (Table 2), physical (Table 2), and chemical (Table 3) properties of the soils along the catena except for one pedon (PL3). This has important ecological implications as it tends to not support the idea (e.g., Sanchez 1976; Wu et al. 2007) that high soil spatial variability at short distances in rain forest ecosystems contributes to its high biodiversity. It is widely believed that the high soil spatial variability in the rain forest ecosystems can be due to the differences in (1) land use types and human influence (2) variation in the geologic material, and (3) effect of topography on soil processes. In the study area, changes in soil properties due to human disturbance in the past was probably nullified by the present tree-dominated land use, and that the nature of the parent rock, which is generally uniform in the site as well as climate have dominant effect on soil development.

Table 5 Total elemental weight percentages on oxide basis of soil and rock samples (Leyte, Philippines)

Horizon	SiO_2 (g kg^{-1})	Al_2O_3 (g kg^{-1})	Fe_2O_3 (g kg^{-1})	MnO (g kg^{-1})	TiO_2 (g kg^{-1})	CaO (g kg^{-1})	MgO (g kg^{-1})	K_2O (g kg^{-1})	Na_2O (g kg^{-1})	P_2O_5 (g kg^{-1})	ZrO_2 (g kg^{-1})	LOI (g kg^{-1})	Total (g kg^{-1})	Bases[a]/ Al_2O_3	SiO_2/ Al_2O_3
PL-1															
Ah	397	261	231	2.8	28.7	6.4	11.4	1.1	2.3	1.5	0.102	15.8	960	0.08	1.52
BA	413	290	222	1.7	24.8	4.3	8.9	0.8	2.0	1.0	0.103	13.8	982	0.05	1.42
Bt_1	415	302	210	1.2	22.0	3.6	7.7	0.8	1.9	0.8	0.103	13.6	979	0.04	1.37
Bt_2	420	316	198	0.8	20.1	2.8	6.4	0.7	1.1	0.7	0.105	13.7	980	0.04	1.33
Bt_3	427	332	185	0.4	17.2	1.9	4.8	0.6	1.6	0.5	0.105	13.8	986	0.03	1.29
Bt_4	414	320	206	0.6	18.4	1.8	5.4	0.6	1.6	0.5	0.093	13.1	983	0.03	1.29
Rock	458	313	178	2.2	14.9	9.3	16.6	1.8	2.6	1.2	0.095	nd	nd	0.09	1.46
PL-2															
Ah	423	251	233	2.5	27.1	6.7	11.1	1.1	2.4	1.4	0.104	13.2	972	0.08	1.69
Bt_1	423	295	212	0.7	21.1	3.9	7.3	0.8	1.9	0.9	0.104	13.6	981	0.05	1.43
Bt_2	414	311	218	0.5	16.8	2.4	5.3	0.7	1.6	0.8	0.093	13.7	984	0.03	1.33
BC	416	320	208	0.3	16.0	2.1	4.1	0.6	1.6	0.7	0.105	13.4	983	0.03	1.30
Rock	472	270	161	1.9	12.2	13.6	19.8	2.5	4.2	0.8	0.093	nd	nd	0.13	1.74
PL-3															
Ah_1	458	246	194	3.4	20.1	15.8	20.1	2.2	3.1	1.1	0.082	13.4	977	0.17	1.86
Ah_2	463	258	186	3.2	18.9	13.7	19.9	2.1	2.9	0.9	0.089	12.4	981	0.15	1.80
BA	460	263	173	2.3	17.0	12.8	20.1	2.2	3.0	0.8	0.088	12.0	967	0.15	1.75
BC	464	273	166	1.9	16.0	13.7	21.3	2.3	3.2	0.6	0.091	11.6	973	0.14	1.70
CR	443	263	201	2.3	20.2	9.2	15.7	1.1	2.3	0.4	0.092	11.2	969	0.12	1.68
Rock	496	290	145	1.3	13.6	18.5	22.2	4.4	5.4	1.2	0.091	nd	nd	0.16	1.71
PL-4															
Ap	435	282	189	3.0	19.5	12.9	12.4	2.4	5.0	1.9	0.106	15.4	979	0.11	1.54
AB	428	305	199	2.5	20.3	5.4	8.5	1.2	2.6	1.6	0.103	14.8	990	0.06	1.41
Bt_1	420	333	191	1.6	17.6	2.6	5.5	0.7	1.7	1.2	0.102	14.4	988	0.03	1.26
Bt_2	413	346	185	0.9	16.5	1.6	4.4	0.6	1.5	1.1	0.102	14.1	985	0.02	1.20
Bt_3	411	350	188	0.8	16.7	1.1	3.9	0.7	1.5	1.0	0.102	13.9	988	0.03	1.17
Rock	483	270	151	1.6	13.0	14.5	20.0	3.2	4.2	0.9	0.088	nd	nd	0.14	1.79

LOI loss-on-ignition, *nd* not determined

[a] Bases: CaO + MgO + K_2O + Na_2O

Table 6 Percent gain and loss of major elements during the chemical weathering of basalt to soil (calculation based on ZrO_2)

Elements	PL-1 (percent)		PL-2 (percent)		PL-3 (percent)		PL-4 (percent)	
	Loss	Gain	Loss	Gain	Loss	Gain	Loss	Gain
SiO_2	8	–	19	–	7	–	23	–
CaO	68	–	74	–	32	–	80	–
MgO	58	–	67	–	13	–	75	–
K_2O	60	–	70	–	57	–	75	–
Na_2O	34	–	59	–	47	–	57	–

Conclusions

The soils are deep, clayey, and reddish in color indicative of advance stage of soil development. They posses excellent physical condition (friable and highly porous), although they are plastic and sticky when wet as is usual for clayey soils. In terms of chemical characteristics, the soils are acidic with low CEC values and generally low nutrient contents. The clay mineralogy of the soils is dominated by halloysite and kaolinite with minor amounts of goethite and hematite. They also have generally high dithionite-extractable Fe contents. The soils in the more stable slope positions (PL-1, PL-2, and PL-4) have generally similar characteristics and showed more advanced stage of soil development than the one in the less stable position (PL-3). The most important pedogenic processes that formed the soils appear to be weathering, loss of bases and acidification, desilification, ferrugination, clay formation and translocation, and structure formation. The nature of the parent rock and climatic conditions prevailing in the area as well as slope position appear to have dominant effects on the development of these soils.

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