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Genesis of soils across a late Quaternary volcanic landscape in the humid tropical island of Leyte, Philippines

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Abstract. This study evaluated the characteristics and genesis of soils across a young volcanic landscape in the humid tropical island of Leyte, Philippines. Five representative soil pedons (P1–P5) derived from late Quaternary volcanoclastics (i.e. fragmental) on a hillslope sequence were examined and sampled. Results revealed that the soils have generally similar morphological characteristics particularly in terms of soil colour (10YR 3/3–10YR 5/6) and soil structure (granular to subangular blocky), but differed in terms of soil thickness and clay content, which was higher in P3 than the other pedons across the landscape. The high porosities of the soils were the results of high organic matter, the dominance of noncrystalline (short-range order) minerals, as well as the isovolumetric weathering in the subsoils. All soils have very similar chemical properties (e.g. acidic, high organic carbon, low exchangeable bases), except soils from the middle backslope position (P3), which have high cation exchange capacity because higher exchangeable Ca and K result in a higher base saturation. Allophane, goethite, ferrihydrite, and gibbsite are the dominant clay minerals in the soils. Principal component analysis revealed that P3 was distinct from pedons P1, P2, P4, and P5, suggesting that it was substantially different from all other soils across the landscape. Soil formation was relatively fast due to the easy weatherability of the parent materials, high rainfall, and good drainage of the soils along the landscape. This study revealed that on young volcanic soils under humid tropical condition, topography greatly influenced soil development.

Additional keywords: Andisol, soil genesis, geomorphic position, weathering, tropical island.

Introduction

Despite the increase in our understanding of the nature and properties of volcanic-ash derived soils (including Andisols) in the last few decades (e.g. Fernandez-Caldas and Yaalon 1985; Shoji *et al.* 1993), few studies have been reported for the geologically young islands in South-east Asia (e.g. Chen *et al.* 1999, 2001) such as the Philippines (Otsuka *et al.* 1988; Jahn and Asio 1998; Poudel and West 1999). Some aspects of the pedogenesis of Andisols are until now poorly understood (e.g. Kinloch *et al.* 1988; Mizota and van Reeuwijk 1989; Shoji *et al.* 1993). For example, the low bulk density of volcanic ash soil is generally explained by the presence of short-range order minerals and high organic matter content, whereas Miehlich (1991) suggested that this property could be due to isovolumetric weathering. Another aspect is the role of geomorphic surface on the genesis of volcanic ash soils. Chen *et al.* (1999) explained that parent material and climate are well studied in volcanic-ash derived soils due to their strong influence on the chemical and mineralogical properties. They suggested that it is difficult to separate the influence of geomorphic position from that of parent material considering that change in the elevation in volcanic landscapes is accompanied by changes in climate as well as age of volcanic material.

Although volcanic-ash derived soils constitute about 0.84% of the world land area (Takahashi and Shoji 2002), they represent an important land resource for agriculture in many areas of the world (Shoji *et al.* 1993). Their unique properties attributed to short-range order minerals help make them among the most productive soil in the world (Shoji *et al.* 1993). In the Philippines, volcanic-ash derived soils constitute 5% of the total cultivated land (Otsuka *et al.* 1988) and these soils are mostly used intensively for vegetable and commercial crop production (Poudel and West 1999). The plate tectonic setting of the Philippine has resulted in extensive volcanic activity during Tertiary and Quaternary, and consequently the widespread occurrence of young volcanic soils (Otsuka *et al.* 1988; Jahn and Asio 1998). Wernstedt and Spencer (1967) estimated that nearly 25% of the total land cover in the Philippines was developed from volcanic ejecta such as andesite, basalt, and volcanic ash. The bigger part of Leyte (7955 km^2) is made up of volcanic rocks of Quaternary origin (probably Holocene to Upper Pleistocene). Understanding the nature and properties of soils and their variation in the landscape yields results not only

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Table 2. Morphological characteristics of soils across the volcanic hillslope in Leyte, Philippines
n.d., Not determined

Depth (m)	Horizon[A]	Color (moist)	Boundary[B]	Texture[C]	Rock fragments[D] (%)	Structure[E]	Consistence[F]	Roots[G]
				Pedon 1: Lower summit				
0–0.10	Ap	10 YR 3/3	cs	CL		1vfgr	vfr	mvf&f
0.10–0.28	2AB	10 YR 4/4	cs	SICL		1vfgr	fr	mvf&f,sm
0.28–0.57	2BA	10 YR 4/6	d	SICL		2vfsbk	fi, ss&sp	fvf
0.57–0.77	2BC	10 YR 4/6	d	SL	5–15; F	2vfsbk	fi, ss&sp	o
0.77–1.02	2C	10 YR 4/6	d	LS	15–40; M	n.d.	n.d.	o
				Pedon 2: Upper backslope				
0–0.16	Ap	10 YR 4/4	cs	CL		1vfgr	vfr	mvf
0.16–0.31	2AB	10 YR 4/6	cs	CL		1vfgr	fr	m
0.31–0.49	2BA	10 YR 4/6	cs	CL		vf-sbk	fi, ss&sp	vf
0.49–0.73	2BC	10 YR 4/6	d	SIC	5–15; F	vf-sbk	fi, ss&sp	o
0.73–0.95	2C	10 YR 4/6	d	SL	20–40; M	vf-sbk	n.d.	o
				Pedon 3: Middle backslope				
0–0.12	Ap	10 YR 2/3	cs	CL		1vfgr	vfr	mvf&f
0.12–0.24	2AB	10 YR 3/2	cs	SICL		2fsbk	fr	mvf&f
0.24–0.37	2BA	10 YR 3/3	cs	SL		2vfsbk	fi, ss&sp	fem,c
0.37–0.51	2BC	10 YR 3/3	d	SL	0–2; FM	2vfsbk	fi, ss&sp	o
0.51–0.63	2C	10 YR 3/3	n.d.	SL	25–45; MC	n.d.	n.d.	o
				Pedon 4: Lower backslope				
0–0.15	Ap	10 YR 4/3	cs	CL		1vfgr	vfr	mvf&m
0.15–0.32	2BA	10 YR 4/4	cs	SICL		1fgr	vfr	fem,c
0.32–0.59	2BC	10 YR 4/6	cs	SL	5–10; FM	2msbk	fi, ss&sp	fem,m
0.59–0.73	2C	10 YR 5/4	n.d.	LS	>90; MC	n.d.	n.d.	o
				Pedon 5: Middle backslope				
0–0.08	Ap	10 YR 4/3	cs	CL		1fgr	vfr	mvf&f,sm
0.08–0.18	2AB	10 YR 4/4	cs	SICL		1fgr	vfr	fem
0.18–0.33	2BA1	10 YR 4/6	cs	SIC		2msbk	fi, ss&sp	fem
0.33–0.52	2BA2	10 YR 4/6	cs	SIC		2msbk	fi, ss&sp	o
0.52–0.85	2C	10 YR 4/6	n.d.	LS	>80; MC	n.d.	n.d.	o

[A]According to IUSS Working Group WRB (2006).
[B]c, Clear; s, smooth; d, diffuse.
[C]CL, Clay loam; SICL, silty clay loam; SL, silt loam; SIC, silty clay; SL, sandy loam; LS, loamy sand.
[D]F, Fine gravel; FM, fine and medium; M, medium gravel; MC, medium and course.
[E]1, Weak; 2, moderate; vf, very fine; f, fine; m, medium; gr, granular; sbk, sub-angular blocky.
[F]vfr, Very friable; fr, friable; fi, firm; ss, slightly sticky; sp, slightly plastic.
[G]mvf, Many very fine to fine; m, medium; f, fine; fe, few; c, coarse; o, no roots.

Ap–2AB–2BA–2C, a clear indication of the early stage of soil development (Shoji *et al.* 1993).

The particle size analysis showed non-uniformity of soil texture with depth (Table 3) because of the layering of parent materials (Table 2). This result is in agreement with the study of Asio (1996), who reported that the soils in the nearby site were developed from 2 layers of volcanic deposits of similar chemical composition but of different texture. Texture-wise, sand was dominant and tended to be greater in the soils of the upper slope (P1, P2) and lesser in the lower landscape soils (P3, P5). The sand fraction was composed mostly of fine sand, which suggests that the soil is highly weatherable, and a high rate of soil development can be expected as the weathering progresses. Reflecting the incomplete dispersion of mineral particles (Mizota and van Reeuwijk 1989; Shoji *et al.* 1993; IUSS Working Group WRB 2006; Soil Survey Staff 2006), Andisols typically have lower clay contents than total amounts of noncrystalline minerals determined by selective dissolution (e.g. acid oxalate extraction). However, about half of the samples (P1 0–0.10 m, P2 0–0.16 m, P3 0–0.63 m, P4 0–0.32 m, and P5 0–33 m) indicate that clay contents (Table 3) were 1.7 and 4.5 times higher than the summation of ferrihydrite, goethite, and allophane (see Table 5), respectively. This overestimation of the clay content is probably the result of improved dispersion employed in our sample preparation. Samples were subjected to ultrasonic dispersion and repeated washing with hot water after organic matter decomposition. Such processing reduced the impact of air drying, which normally leads to the irreversible formation of aggregates from its colloidal fraction (Shoji *et al.* 1993). The bulk density of soil was <0.9 g/m^3 (except in the surface of P3), indicative of andic soil properties (Shoji *et al.* 1993). The good soil structure (Table 2) and high organic carbon content (Table 4) resulted in the low bulk densities and high porosity.

Table 3. Physical characteristics of soils along the volcanic hillslope in Leyte, Philippines
Clay, <2 μm; silt, 2–200 μm; sand, 200–2000 μm. n.d., No data

Depth (m)	Horizon	Coarse sand	Fine sand (g/kg)	Silt	Clay	Bulk density (Mg/m³)
			Pedon 1: Lower summit			
0–0.10	Ap	90	164	409	337	0.81
0.10–0.28	2AB	103	219	521	157	0.64
0.28–0.57	2BA	213	453	283	51	0.56
0.57–0.77	2BC	214	396	307	83	0.55
0.77–1.02	2C	158	383	352	107	0.56
			Pedon 2: Upper backslope			
0–0.16	Ap	91	144	463	303	0.81
0.16–0.31	2AB	120	224	457	199	0.67
0.31–0.49	2BA	125	319	405	151	0.50
0.49–0.73	2BC	139	264	415	181	0.5
0.73–0.95	2C	169	279	374	178	0.52
			Pedon 3: Middle backslope			
0–0.12	Ap	122	186	333	360	0.92
0.12–0.24	2AB	149	224	352	274	0.76
0.24–0.37	2BA	164	213	288	336	0.70
0.37–0.51	2BC	123	243	406	227	0.68
0.51–0.63	2C	162	276	361	201	0.65
			Pedon 4: Lower backslope			
0–0.15	Ap	156	221	340	283	0.62
0.15–0.32	2BA	123	204	378	295	0.69
0.32–0.59	2BC	103	445	362	91	0.7
0.59–0.73	2C	n.d.	n.d.	n.d.	n.d.	0.75
			Pedon 5: Middle backslope			
0–0.08	Ap	133	167	362	338	0.83
0.08–0.18	2AB	230	166	424	180	0.74
0.18–0.33	2BA1	123	170	456	251	0.63
0.33–0.52	2BA2	220	211	425	144	0.65
0.52–0.85	2C	227	292	370	111	0.64

The decreasing bulk density with depth can be ascribed to the isovolumetric weathering of the parent material (Miehlich 1991; Jahn and Asio 1998), common in areas with high precipitation and with good drainage (Chen *et al.* 1999).

Chemical characteristics

Table 4 shows the chemical properties of soils along the hillslope sequence. Pedon 3 has the highest organic carbon content, ranging from 0.99 to 7.26%. The concave shape of the slope in P3 resulted in the deposition and accumulation of organic matter from the upper part of the landscape carried by surface run-off water during heavy rain. In general, the relatively high organic carbon contents in these soils are probably the result in part of the preservation of organic matter through organo-mineral complex, which slows down microbial activity, and the inability of microbes to degrade the very stable Al-humus complexes (Shoji *et al.* 1993). Nitrogen content tended to decrease with depth in all sites and decreased accordingly with the decrease in organic carbon content. Carbon to nitrogen ratios did not vary in P1, P2, P4, and P5 (8.5–11) but varied considerably in P3 (4–8). The pH(H_2O) was moderately to strongly acidic and ranged from 4.8 to 5.7 (Table 4), a pH range suitable for the formation of allophane (Mizota and van Reeuwijk 1989; Parfitt and Kimble 1989). Soil pH values were lower in surface horizons than in subsoils except in P3 where both pH(H_2O) and pH(KCl) decreased with depth. The subsoil of P1 had high anion exchange capacity as inferred from the positive ΔpH, indicating a total positive net charge of the soil colloid (Mekaru and Uehara 1972). The net positive charge can be largely attributed to allophane and imogolite [point of zero net charge (PZNC) at pH 6–7] as well as to the considerable amount of Fe oxides, particularly goethite (Table 5) in the subsoil. All pedons had pH(NaF) values of >9.4, suggesting the presence of large amounts of active hydroxyl Al/Fe groups from allophane and imogolite or Al- and Fe-humus complexes (Mizota and van Reeuwijk 1989) or both. Available phosphorus was very low in all pedons because phosphorus in Andisols reacts rapidly with noncrystalline Al and Fe compounds, resulting in the formation of insoluble metal phosphorus compounds (Shoji *et al.* 1993). This process was clear from phosphate retention values that ranged from 67 to 99% (100% = 5 g P/kg fine-earth basis) in which P3 had a phosphate retention of <85% whereas P1, P2, P4, and P5 had >85%. The high phosphate retention in P1, P2, P4, and P5 can also be attributed to the presence of gibbsite (e.g. Prado *et al.*

Table 4. Chemical characteristics of soils across the volcanic hillslope in Leyte, Philippines

C_{org}, Organic carbon; N_{tot}, total nitrogen; ECEC, effective cation exchange capacity; CEC, potential cation exchange capacity; P_{ret}, phosphate retention; ΣBS, exchangeable bases; EA, exchangeable acidity; BS-sat, base saturation; n.d., no data

Depth (m)	pH H_2O	pH KCl	pH NaF	ΔpH	C_{org} (%)	N_{tot} (%)	C/N	Avail. P (mg/kg)	P_{ret} (%)	Exch. bases (cmol/kg) Ca	Mg	K	Na	ΣBS	Mg+Na	Exch. acidity (cmol/kg) Al	H	EA	ECEC (cmol/kg)	CEC (cmol/kg)	BS-sat/ ECEC (%)
Pedon 1: Lower summit																					
0–0.10	4.80	4.59	10.59	−0.21	6.32	0.62	10.2	1.01	95	0.79	0.30	0.42	0.34	1.85	0.64	1.06	1.01	2.07	2.91	18.16	63.5
0.10–0.28	5.23	4.91	10.30	−0.32	3.51	0.38	9.2	1.55	95	0.37	0.14	0.36	0.37	1.23	0.51	0.28	0.54	0.82	1.51	8.19	81.5
0.28–0.57	5.38	5.40	9.97	0.02	2.04	0.24	8.5	1.63	98	0.76	0.24	0.32	0.37	1.68	0.60	0.12	0.38	0.50	1.80	3.04	93.3
0.57–0.77	5.46	5.50	9.67	0.04	1.62	0.19	8.5	1.61	96	0.81	0.24	0.20	0.36	1.61	0.61	0.03	0.21	0.24	1.64	6.21	98.2
0.77–1.02	5.45	5.48	9.75	0.03	1.53	0.17	9.0	1.52	96	0.66	0.22	0.14	0.42	1.44	0.65	0.08	0.49	0.57	1.52	13.85	94.8
Pedon 2: Upper backslope																					
0–0.16	5.10	4.35	9.65	−0.75	4.86	0.45	10.8	0.91	81	1.18	0.31	0.20	0.49	2.18	0.80	1.94	1.93	3.87	4.12	14.17	52.9
0.16–0.31	5.25	4.58	9.81	−0.67	2.47	0.25	9.9	1.86	92	0.54	0.11	0.09	0.42	1.16	0.53	0.72	0.69	1.41	1.88	3.66	61.7
0.31–0.49	5.30	4.77	9.94	−0.53	2.14	0.23	9.3	1.72	93	0.49	0.09	0.11	0.44	1.13	0.53	0.39	0.40	0.79	1.52	7.43	74.3
0.49–0.73	5.30	4.99	10.03	−0.31	1.68	0.19	8.8	1.97	92	0.55	0.14	0.35	0.40	1.44	0.54	0.21	0.60	0.81	1.65	17.40	87.3
0.73–0.95	5.34	4.98	10.17	−0.36	1.43	0.16	8.9	1.68	93	0.68	0.16	0.08	0.40	1.32	0.56	0.23	1.20	1.43	1.55	7.85	85.2
Pedon 3: Middle backslope																					
0–0.12	5.72	5.10	9.53	−0.62	7.26	0.85	8.5	1.05	67	4.28	1.83	2.19	0.27	8.57	2.10	0.28	0.18	0.46	8.85	18.96	96.8
0.12–0.24	5.35	4.66	9.43	−0.69	4.58	0.72	6.4	0.91	70	3.13	0.97	2.56	0.27	6.93	1.24	0.20	0.52	0.72	7.13	17.42	97.2
0.24–0.37	5.43	4.63	9.66	−0.80	2.40	0.47	5.1	1.26	73	2.57	0.60	2.73	0.28	6.18	0.88	0.43	0.39	0.82	6.61	16.74	93.5
0.37–0.51	5.23	4.53	9.56	−0.70	1.69	0.29	5.8	1.3	74	2.01	0.48	2.10	0.34	4.93	0.82	0.61	0.89	1.50	5.54	17.26	89.0
0.51–0.63	5.24	4.37	9.91	−0.87	0.99	0.21	4.7	1.66	71	2.32	0.48	1.69	0.55	5.03	1.03	1.23	1.43	2.66	6.26	29.09	80.3
Pedon 4: Lower backslope																					
0–0.15	4.96	4.66	10.41	−0.30	4.65	0.44	11.0	0.99	94	0.27	0.19	0.16	0.34	0.96	0.53	0.78	1.00	1.78	1.74	20.46	55.2
0.15–0.32	5.44	5.13	10.60	−0.31	2.76	0.3	9.0	1.43	97	0.11	0.07	0.04	0.34	0.56	0.41	0.23	0.14	0.37	0.79	16.92	70.9
0.32–0.59	5.58	5.34	10.07	−0.24	1.97	0.21	9.0	2.23	97	0.11	0.06	0.03	0.32	0.52	0.38	0.17	0.16	0.33	0.66	14.85	78.8
0.59–0.73	5.78	5.52	10.10	−0.26	0.66	0.07	9.0	2.26	n.d.	0.15	0.05	0.02	0.34	0.56	0.39	0.20	0.10	0.30	0.76	9.21	73.7
Pedon 5: Middle backslope																					
0–0.08	4.66	4.55	10.42	−0.11	5.15	0.53	9.7	1.32	95	1.20	0.45	0.29	0.33	2.28	0.79	1.12	1.11	2.23	3.40	19.32	67.1
0.08–0.18	5.19	4.96	10.75	−0.23	2.85	0.32	8.9	0.99	98	0.48	0.18	0.11	0.29	1.05	0.47	0.34	0.20	0.54	1.39	13.13	75.6
0.18–0.33	5.18	4.66	10.81	−0.52	3.92	0.41	9.6	1.37	95	0.39	0.13	0.14	0.29	0.95	0.42	0.89	0.80	1.69	1.84	16.32	51.6
0.33–0.52	5.22	5.13	10.73	−0.09	2.10	0.24	8.8	1.93	99	0.25	0.11	0.08	0.26	0.70	0.38	0.24	0.22	0.46	0.94	9.33	74.6
0.52–0.85	5.64	5.27	10.36	−0.37	1.82	0.2	9.1	1.73	99	0.45	0.25	0.15	0.29	1.14	0.53	0.22	0.42	0.64	1.36	8.87	83.8

Table 5. Dithionite-, oxalate-, and pyrophosphate-extractable Fe, Al, and Si and estimated amounts of secondary minerals
Al/Si, $(Al_o - Al_p)/Si_o$; Ferr, ferrihydrite (Fe_o*1.7); Goe, goethite ($Fe_d - Fe_o$*1.6); All, allophane (Mizota and van Reeuwijk 1989). n.d., No data

Depth (m)	Fe_d	Fe_o	Fe_p	Al_d (g/kg)	Al_o	Al_p	Si_o	Fe_o/Fe_d	Fe_p/Fe_o	Al_d/Fe_d	Al_p/Al_o	Al/Si	Al_o+1/2Fe_o	Ferr (%)	Goe	All
Pedon 1: Lower summit																
0–0.10	23.9	8.9	2.5	18.4	26.6	3.7	8.0	0.4	0.28	0.77	0.14	3.0	3.1	1.5	2.4	9.1
0.10–0.28	22.9	8.4	0.9	17.7	31.8	2.3	11.8	0.4	0.10	0.77	0.07	2.6	3.6	1.4	2.3	11.1
0.28–0.57	22.2	7.3	0.2	14.0	33.4	1.5	14.0	0.3	0.03	0.63	0.04	2.4	3.7	1.2	2.4	11.9
0.57–0.77	28.6	7.5	0.2	15.4	28.3	1.1	12.3	0.3	0.02	0.54	0.04	2.3	3.2	1.3	3.4	10.2
0.77–1.02	30.7	8.1	0.2	15.5	30.6	1.1	13.8	0.3	0.02	0.50	0.04	2.2	3.5	1.4	3.6	11.0
Pedon 2: Upper backslope																
0–0.16	27.6	20.6	3.5	12.5	16.7	2.8	4.3	0.7	0.17	0.45	0.17	3.4	3.1	3.5	2.4	9.7
0.16–0.31	28.0	12.0	1.6	13.9	18.5	2.5	4.8	0.4	0.14	0.50	0.13	3.5	3.6	2.0	2.3	9.8
0.31–0.49	27.5	10.9	1.1	14.7	19.3	1.6	5.4	0.4	0.10	0.53	0.08	3.4	3.7	1.9	2.4	8.0
0.49–0.73	28.0	11.5	0.6	14.8	21.7	1.4	6.4	0.4	0.05	0.53	0.07	3.3	3.2	1.9	3.4	8.7
0.73–0.95	28.3	10.1	0.3	14.3	21.1	1.1	6.6	0.4	0.03	0.50	0.05	3.1	3.5	1.7	3.6	8.2
Pedon 3: Middle backslope																
0–0.12	19.9	7.8	1.3	8.4	13.7	1.9	4.1	0.4	0.17	0.42	0.14	3.0	1.8	1.3	1.9	4.8
0.12–0.24	20.8	8.1	1.3	9.0	14.0	1.9	4.0	0.4	0.17	0.43	0.14	3.1	1.8	1.4	2.0	5.0
0.24–0.37	20.2	8.2	0.9	8.1	15.2	1.4	4.8	0.4	0.11	0.40	0.09	3.0	1.9	1.4	1.9	5.5
0.37–0.51	19.9	8.0	0.8	8.1	15.0	1.3	4.7	0.4	0.10	0.41	0.08	3.1	1.9	1.4	1.9	5.6
0.51–0.63	18.5	5.4	0.5	7.0	15.2	1.1	5.1	0.3	0.09	0.38	0.07	2.9	1.8	0.9	2.1	5.5
Pedon 4: Lower backslope																
0–0.15	24.5	7.9	0.9	15.3	31.0	2.1	12.5	0.3	0.11	0.62	0.07	2.4	3.5	1.3	2.7	10.8
0.15–0.32	22.4	8.4	0.4	14.6	37.1	1.6	16.0	0.4	0.04	0.65	0.04	2.3	4.1	1.4	2.3	13.3
0.32–0.59	27.5	9.0	0.2	17.1	36.0	1.3	15.8	0.3	0.02	0.62	0.04	2.3	4.0	1.5	3.0	13.0
0.59–0.73	28.5	18.1	0.1	3.3	57.4	1.6	32.1	0.6	0.00	0.11	0.03	1.8	6.7	3.1	n.d.	22.1
Pedon 5: Middle backslope																
0–0.08	13.8	7.4	1.1	12.7	29.7	2.5	12.1	0.5	0.15	0.92	0.08	2.3	3.3	1.3	1.0	10.1
0.08–0.18	14.9	7.8	0.4	11.9	41.2	2.0	18.7	0.5	0.05	0.80	0.05	2.2	4.5	1.3	1.1	14.7
0.18–0.33	15.2	7.6	0.9	13.5	31.8	2.2	13.2	0.5	0.12	0.89	0.07	2.3	3.6	1.3	1.2	11.0
0.33–0.52	15.8	8.2	0.2	11.1	42.4	1.9	19.4	0.5	0.03	0.71	0.05	2.2	4.7	1.4	1.2	15.2
0.52–0.85	17.0	9.0	0.2	9.7	50.0	2.1	24.8	0.5	0.02	0.57	0.04	2.0	5.4	1.5	1.3	18.3

2007), which adsorbs phosphate through ligand exchange, and iron oxides.

The exchangeable cations in all pedons were very low, a characteristic feature of young volcanic soils (Shoji *et al.* 1993). Exchangeable cations were very low (<2 cmol/kg) in the upper landscape positions (P1, P2), increasing slightly in the middle backslopes (P3, 5–9 cmol/kg), decreasing in lower backslopes (P4, <1 cmol/kg), and increasing slightly in the middle backslopes (P5, 0.7–2 cmol/kg). The concave slope surface of P3 has lead to the slightly higher exchangeable bases there through solute deposition via surface run-off water, and subsurface water flow (Sommer and Schlichting 1997). The geomorphic location of each pedon across the volcanic hillslope has influenced strongly the movement of solutes and thus the degree of soil development (Milne 1935; Huggett 1975). Rapid leaching of solutes from upper slope positions has also been reported in some volcanic landscapes in the Philippines (Asio 1996; Zikeli *et al.* 2000) and Taiwan (Chen *et al.* 1999). The exchangeable Ca and K in P3 soil accounted for 36–48% and 21–45% of ECEC, respectively. The leaching of basic cations has resulted in low base saturations of 3–45% regardless of pedon position. However, base saturations based on ECEC (BSsat/ECEC) ranged from 51 to 98%, suggesting an abundance of reserve bases in the parent material. All pedons have low exchangeable Al contents from 0.03 (subsoil of P1) to 1.92 (surface soil of P2) cmol/kg, which can be inferred from the slightly higher pH values of the latter. The CEC was low in P1 (3–18 cmol/kg) and high in P3 (16–29 cmol/kg). Conversely, the ECEC was <7 cmol/kg in all pedons. The variable charge arising from short-range order minerals and Fe- and Al-humus complexes was high in all pedons as shown by the large difference between ECEC and CEC values.

Mineralogical characteristics

Selected X-ray diffraction patterns of K- and Mg-saturated oriented clay samples showed no major mineralogical differences among the pedons (Fig. 2). The most abundant and recognisable peaks corresponded to cristobalite (4.07 Å), and gibbsite (4.37 Å, 4.85 Å). The broad diffraction curves indicate the dominance of noncrystalline minerals and/or Al- and Fe-humus complex in the soils. The Mg-saturated and glycerol-treated samples did not show expansion, indicating that smectite was not present. This result contradicts the

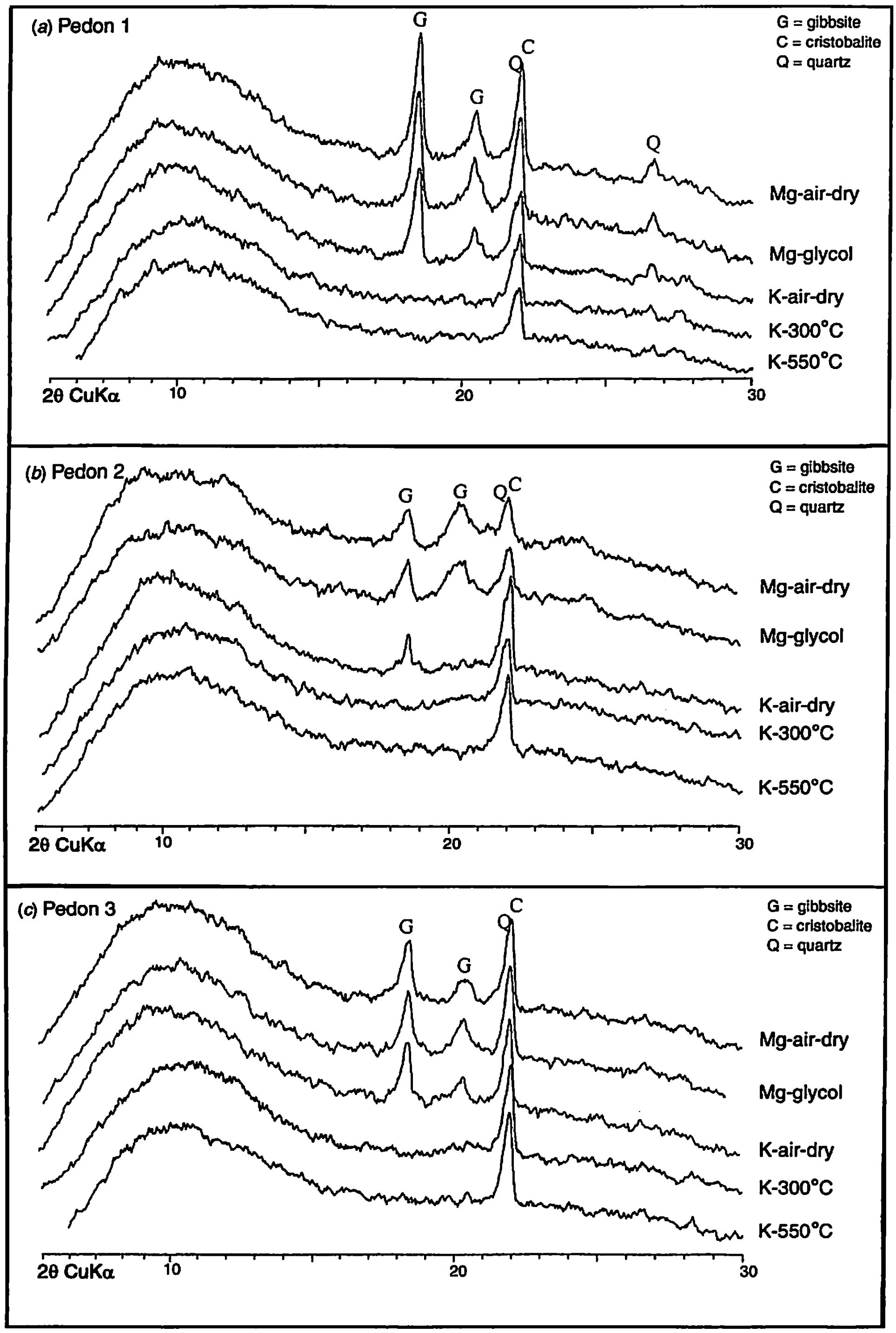

Fig. 2. X-ray diffractograms of selected clay samples subject to different treatments: (*a*) pedon 1 (2BC-0.57–0.77 m); (*b*) pedon 3 (2AB-0.12–0.24 m); and (*c*) pedon 5 (2BA2-0.33–0.52 m).

findings of an earlier study that showed considerable smectite in the clay fraction (Jahn and Asio 1998). After treating the clay samples with methylformamide, Jahn and Asio (1998) observed an expansion of 7 Å, suggesting the presence of halloysite (Churchman 1990), which disappeared after heating at 560°C. According to Jahn and Asio (1998), the formation of gibbsite in these soils occurred as feldspar-pseudomorphoses, which were favoured by the warm but humid weathering environment, and good drainage of the area that reduced the contact and residence time of solution during weathering, giving

Table 6. Oxide (%) contents of soils along a volcanic hillslope in Leyte, Philippines

Depth (m)	SiO_2	Al_2O_3	Fe_2O_3	MnO	TiO_2 (%)	CaO	MgO	K_2O	Na_2O	P_2O_5	Fe_2O_3/ TiO_2	SiO_2/ Al_2O_3	SiO_2/ $Al_2O_3+Fe_2O_3$	Ca+Mg+ K+Na/Al
Pedon 1: Lower summit														
0–0.10	53.7	26.4	12.1	0.3	1.0	1.2	1.7	0.5	0.5	0.3	11.7	2.0	1.4	0.15
0.10–0.28	52.4	27.9	12.0	0.2	1.0	1.3	1.8	0.5	0.6	0.2	11.7	1.9	1.3	0.15
0.28–0.57	47.9	30.6	12.6	0.3	1.1	1.5	2.2	0.6	0.6	0.2	11.6	1.6	1.1	0.16
0.57–0.77	46.1	32.4	13.8	0.2	1.2	1.2	1.8	0.7	0.5	0.1	11.4	1.4	1.0	0.13
0.77–1.02	43.6	34.7	14.9	0.3	1.3	1.2	2.0	0.6	0.5	0.1	11.2	1.3	0.9	0.12
Pedon 2: Upper backslope														
0–0.16	53.1	28.6	12.4	0.2	1.1	1.1	1.2	0.4	0.4	0.3	11.5	1.9	1.3	0.11
0.16–0.31	50.7	30.1	12.9	0.2	1.1	0.8	1.2	0.3	0.4	0.2	11.5	1.7	1.2	0.09
0.31–0.49	49.8	30.6	12.9	0.2	1.1	0.8	1.3	0.3	0.4	0.2	11.5	1.6	1.1	0.09
0.49–0.73	47.7	31.6	13.5	0.2	1.2	0.9	1.4	0.4	0.4	0.2	11.5	1.5	1.1	0.10
0.73–0.95	46.7	33.7	13.5	0.2	1.2	0.7	1.2	0.5	0.4	0.2	11.5	1.4	1.0	0.08
Pedon 3: Middle backslope														
0–0.12	51.3	27.4	11.8	0.3	1.0	2.4	1.9	0.8	0.5	0.6	11.3	1.9	1.3	0.20
0.12–0.24	49.8	28.3	13.0	0.3	1.1	1.8	2.0	0.6	0.5	0.4	11.5	1.8	1.2	0.18
0.24–0.37	48.8	28.5	13.8	0.3	1.2	1.9	2.3	0.6	0.5	0.3	11.5	1.7	1.2	0.19
0.37–0.51	49.5	29.7	13.4	0.3	1.2	1.7	2.2	0.5	0.5	0.3	11.7	1.7	1.1	0.17
0.51–0.63	48.2	29.9	13.1	0.3	1.1	1.5	2.0	0.5	0.4	0.2	11.8	1.6	1.1	0.15
Pedon 4: Lower backslope														
0–0.15	50.4	27.8	13.1	0.2	1.1	1.5	2.1	0.5	0.6	0.2	11.4	1.8	1.2	0.17
0.15–0.32	49.4	28.1	12.8	0.3	1.1	1.7	2.3	0.5	0.6	0.2	11.4	1.8	1.2	0.18
0.32–0.59	46.7	32.2	13.5	0.2	1.2	1.2	2.0	0.6	0.5	0.2	11.2	1.4	1.0	0.13
0.59–0.73	47.7	27.0	12.1	0.2	1.1	3.7	4.5	1.0	1.2	0.2	11.2	1.8	1.2	0.39
Pedon 5: Middle backslope														
0–0.08	55.6	25.9	10.6	0.2	0.9	1.6	2.1	0.4	0.5	0.2	11.6	2.2	1.5	0.18
0.08–0.18	52.1	28.1	11.1	0.3	1.0	1.7	2.3	0.4	0.6	0.2	11.5	1.9	1.3	0.18
0.18–0.33	56.3	26.1	10.2	0.2	0.9	1.4	1.9	0.4	0.5	0.2	11.6	2.2	1.5	0.16
0.33–0.52	48.4	30.3	11.9	0.3	1.0	1.7	2.4	0.5	0.6	0.2	11.6	1.6	1.1	0.17
0.52–0.85	46.2	32.4	12.4	0.2	1.1	1.6	2.5	0.5	0.6	0.1	11.3	1.4	1.0	0.16
Fresh rock	51.2	24.2	10.6	0.2	1.0	4.7	4.1	0.9	1.8	0.1	11.1	2.1	1.5	0.47

insufficient time for layered secondary aluminosilicate minerals to form. Wada and Aomine (1966) also reported the occurrence of gibbsite in young volcanic soils in Japan. They additionally cited studies which revealed that allophane could serve as source of aluminium, which later, under favourable condition, crystallises to form gibbsite. Calvert *et al.* (1980) and Nieuwenhuyse *et al.* (2000) reported that gibbsite can form directly from the dissolution of feldspar (e.g. K-feldspar, plagioclase) without necessarily passing through a transition stage (e.g. halloysite–kaolinite–gibbsite), particularly in permeable volcanic materials and high precipitation. According to Wada (1989), gibbsite is the result of the relatively short life span of allophane in humid environments under conditions of good drainage. The presence of gibbsite was also clear from the relatively high Al/Si ratio of 1.8–3.5 (Table 5) and the close value of the SiO_2/Al_2O_3 ratio (Table 6).

The results of the selective dissolution analyses of Fe and Al by dithionite (Fe_d, Al_d), oxalate (Fe_d, Al_o), and pyrophosphate (Fe_p, Al_p) are summarised in Table 5. The values of Al_o and Fe_o were higher than Al_d and Fe_d in pedons P1, P4, and P5. These results imply the dominance of noncrystalline or short-range order minerals, as can be seen by high activity ratios of Fe_o/Fe_d. The relatively low amounts of Al_o and Si_o compared with Fe_d in P2 and P3 suggest that considerable amounts of Fe released from the weathering of Fe-containing minerals were transformed to less crystalline Fe-oxides (e.g. goethite) (Malucelli *et al.* 1999). The Al_p/Al_o ratio in all pedons was <0.5, suggesting that much of extractable Al was incorporated mainly into the short-range order aluminosilicates (e.g. allophane and imogolite) rather than in Al-humus complexes (Mizota and van Reeuwijk 1989; Shoji *et al.* 1993). The Si_o content was low in the surface horizon but has the tendency to be higher in subsoil in all pedons. Dahlgren (1994) used the acid-oxalate extractable Al and Si to estimate the Al/Si molar ratio of noncrystalline Al–Si materials. A molar ratio close to 2 : 1 is typical for aluminum-rich allophane and imogolite, whereas the silicon-rich allophane has a molar ratio close to 1 : 1 (Parfitt and Kimble 1989). Pedons 1 and 2 had Al/Si ratios of 2.9–3.5 (average 3.2) and pedons P1, P4, and P5 had average ratios of 2.2, all within the range reported for allophanic soils (Parfitt and Kimble 1989). A molar ratio of >2.5 had been also reported in some hydric Andisols in the Philippines (Mizota and van Reeuwijk 1989) and in that case was attributed to an excess of Al present as hydroxyl-Al gels particularly from short-range-order gibbsite. Parfitt (1988) also reported that soils formed from basalt have higher Al/Si ratios ranging from 1.8 to 3.5 if annual rainfall is in excess of 2000 mm.

The amounts of ferrihydrite (0.8–3.5%), goethite (1.0–3.6%), and allophane (4.8–22.1%) are presented in Table 5. The allophane content was high in pedons P1, P2, P4, and P5 but was low in P3, which has high organic carbon content (Table 4). The weathering of Fe-bearing minerals has resulted in the formation of poorly crystalline goethite and ferrihydrite (Malucelli *et al.* 1999), which were higher in P1 and P2 (Table 5). The amount of ferrihydrite was lower than goethite probably because the high organic matter content prevents the formation of ferrihydrite (Shoji *et al.* 1993). The yellowish soil colour (Table 2) also reflected the presence of goethite (Shoji *et al.* 1993).

The total elemental compositions showed that SiO_2 was the major oxide in all pedons, followed by Al_2O_3, Fe_2O_3, MgO, CaO, TiO_2, K_2O, MnO, and P_2O_5 (according to their order of dominance) (Table 6). Compared with the composition of fresh rocks, the amount of SiO_2 loss (20–30%) was much lower than the loss of bases (>80%) (data not shown). The totals of basic cations (CaO, MgO, Na_2O, and K_2O) were low and consistent with the low Ca + Mg + K + Na/Al ratio (0.08–0.39) because of the favourable environment that causes intensive weathering.

Soil classification

Following Soil Survey Staff (2006), pedons P1, P2, and P5 were classified as fine-loamy, amorphic, Typic Hapludands, whereas P4 keys out as fine-loamy, amorphic, Acrudoxic Hapludand. In the case of pedon P3, the soil had $Al_o + 0.5Fe_o$ of <2.0% and P retention of <85; hence, the soil failed to qualify for andic soil properties and therefore cannot be classified as Andisol. The soil has a fine texture, higher chroma and value (Table 2), and higher clay content (Table 3) than the underlying horizon, which qualifies for the criteria of a cambic horizon. The soil has $Al_o + 0.5Fe_o$ of >1.0%; it keys out as fine-loamy, amorphic, Andic Dystrudepts. Apparently, pedon P3 has already passed the Andisol stage (i.e. presence of relatively high allophane content and low bulk density of <1.0 g/cm^3) and the pedogenic process resulted in the formation of soil properties other than andic. We hypothesise that the Inceptisol in the study site could have been developed from Andisol following the Entisol–Andisol–Inceptisol sequence as has been reported in the Philippines (Otsuka *et al.* 1988), Taiwan (Chen *et al.* 2001), and New Zealand (Parfitt *et al.* 1983). In the IUSS Working Group WRB (2006) classification system, pedons P1, P2, P4, and P5 were classified as Silic Andosols, whereas P3 can be classified as a Vitric Cambisol.

Degree of weathering and pedogenetic implications

The high rainfall (>3000 mm/year), well-drained conditions, and the easy weatherability of the parent material have resulted in the rapid leaching of basic cations (Table 4) and the accumulation of SiO_2, Al_2O_3, and Fe_2O_3 (Table 6). Soils from the upper landscape positions (P1, P2), located on a stable landform, were more weathered, which was clear from the depth of the soil profile (Table 2) and high losses of basic cations in the soil (Table 4) compared with the soils in the lower landscape (P3, P4, P5). The results of our study revealed that even in young soil, the weathering process appears to follow the residua system proposed by Chesworth (1973), who suggested that the result of continuous weathering will move towards a sesquioxidic system composed of SiO_2–Al_2O_3–Fe_2O_3–H_2O (Table 6).

The dominant pedogenetic processes that formed the soils were the following: structure formation, organic matter accumulation, loss of bases and acidification, desilication, fast weathering, and the formation of noncrystalline (short-range order) minerals and gibbsite. The formation of soil structure was exhibited by the excellent physical condition of the soil (Table 3) and indicates good physical condition for crop growth. The high organic matter content in the soil (Table 4) can be attributed to the formation of stable complexes of organic matter with Fe, Al, and non-crystalline compounds, which are protected against microbial decomposition (Wada 1989; Shoji *et al.* 1993). The rapid leaching of basic cations was reflected by the low BS, very low exchangeable bases, acidic pH, slightly higher exchangeable Al (Table 4), and low contents of total Ca, Na, Mg, and K, and the accumulation of SiO_2, Al_2O_3, and Fe_2O_3 (Table 6). Jahn and Asio (1998) estimated that the loss of bases was >90% in these soils. The desilication in all pedons may have reached 20–30% of that found in the parent material (Table 6, SiO_2/Al_2O_3). The formation of noncrystalline or short-range order minerals was evident from high allophane content, and from the broad X-ray diffraction patterns (Fig. 2). The clay analysis also revealed the occurrence of gibbsite (Fig. 2), a weathering product typically found in old and highly weathered soils (Jackson *et al.* 1948) as has been reported by Navarrete *et al.* (2007) in a deeply weathered soil from Cretaceous ultrabasic rock in the nearby island of Samar. The presence of gibbsite in such a relative young soil (e.g. Wada and Aomine 1966; Lowe 1986) contradicts the classic principles of weathering because gibbsite was believed to form as one of the ultimate and stable products of weathering (Jackson *et al.* 1948; Chesworth 1972). When we apply the weathering sequence of clay-sized minerals proposed by Jackson *et al.* (1948), which distinguishes 13 weathering stages from gypsum and halite (stage 1) over illite (stage 7) to anatase, rutile, and ilmenite (stage 13), the clay minerals in these soil were dominated by gibbsite (stage 11).

Principal component analysis (Fig. 3) revealed that P3 was distinct from pedons P1, P2, P4, and P5, suggesting that it was substantially different from all the other soils across the landscape. Principal component 1 (PC1) explained 33% of the variances in the dataset. It was characterised by allophane, $Al_o + 0.5Fe_o$, and P_{ret} (andic properties: negative eigenvectors) and clay, CEC, Ca, and C_{org} (CEC factor: positive eigenvectors), suggesting that PC1 increased by the contribution of CEC factors and decreased by the contribution of andic property factors. P3 has high amount of CEC, clay, and C_{org} but lacks the dominant characteristic of andic soil properties and therefore was markedly separated from other the pedons that are dominated by andic properties. On the other hand, PC2 (22% contribution) was characterised by large positive eigenvectors of Al_p and NaF (organo-mineral complex factor) and negative eigenvectors of MnO and K_2O (alkaline-earth metals). The 5 soils were separated by these 2 principal components,

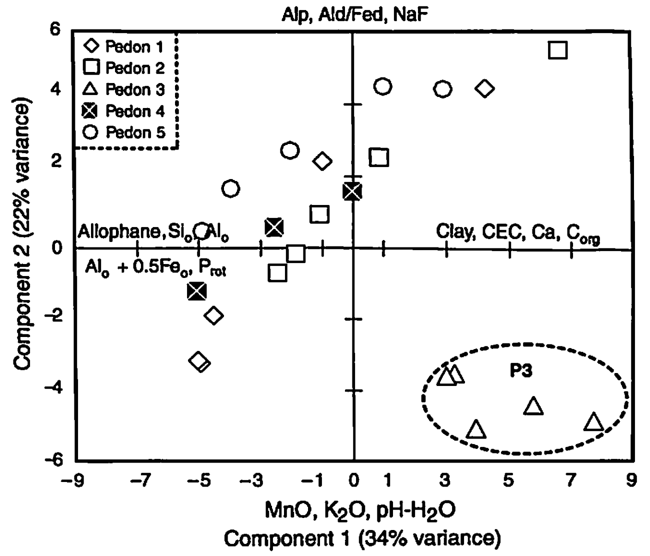

Fig. 3. Principal component analysis results. The first principal component is the line through the data points along which the variance is maximised.

suggesting that the position of the soils in the landscape had strong influence on their development of these soils.

Conclusions

The soils along the landscapes have more or less similar morphological characteristics particularly in terms of soil colour (10YR 3/3-10YR 5/6) and soil structure (granular to subangular blocky), but differed in terms of soil thickness and clay content, the last being higher in P3 than the other pedons across the landscape. In addition, the soils have closely similar chemical properties (e.g. acidic, high organic carbon, low exchangeable bases), except soils from the middle backslope position (P3), which have high CEC because of higher exchangeable Ca and K that result in a higher base saturation. The most important pedogenic processes that have occurred in these soils have been structure formation, organic matter accumulation, loss of bases and acidification, desilication, fast weathering, and the formation of short-range order constituents and gibbsite. Allophane, goethite, ferrihydrite, and gibbsite are the dominant clay minerals in the soils. It can be concluded that soil formation was relatively fast because of the easy weatherability of the volcanoclastic (fragmental) parent materials, high rainfall, and good drainage of the soils in the landscape. This study revealed that on young volcanic soils under humid tropical condition, topography greatly influenced soil development.

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