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Characteristics and genesis of two strongly weathered soils in Samar, Philippines

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Abstract. Very limited data have been published on the nature of strongly weathered soils in geologically young humid tropical islands. The study evaluated the characteristics and formation of 2 strongly weathered soils in the island of Samar, Philippines, one developed from slate (Bagacay soil) and the other from ultrabasic rock (Salcedo soil). Results revealed that the soils have generally similar morphological characteristics, particularly in terms of colour (2.5 YR-10 R), solum thickness (>5.0 m), and structure (granular to subangular blocky), although the Salcedo soil has much higher clay content than the Bagacay soil. Both soils have similar chemical properties (e.g. acidic, low exchangeable bases) except that the Salcedo soil has lower CEC values but higher exchangeable Na content, resulting in a higher base saturation. They also have high dithionite-extractable Fe contents and very low oxalate/dithionite ratios and are dominated by halloysite, kaolinite, gibbsite, goethite, hematite, and quartz in the clay fraction. Apparently as a result of its more weatherable ultrabasic parent rock and more stable geomorphic surface, the Salcedo soil shows more advanced weathering and soil development than the Bagacay soil. Salcedo soil is classified as Haplic Ferralsol (Dystric, Clayic, Rhodic) in the World Reference Base or very fine, sesquic, isohyperthermic, Rhodic Hapludox in the Soil Taxonomy. Bagacay soil is a Haplic Acrisol (Alumic, Hyperdystric, Clayic, Rhodic) or fine, kaolinitic, isohyperthermic, Typic Paleudult. The Salcedo soil has very high Ni and Cr contents inherited from its ultrabasic parent material. The study reveals that on the geologically young humid tropical island of Samar, the characteristics and genesis of strongly weathered soils are greatly affected by the geochemical characteristic of the parent rock material.

Additional keywords: Oxisols, Ultisols, tropical island soils, ultrabasic rocks, slate.

Introduction

Despite the increased research interest in tropical soils during the last few decades, their diversity and complexity (Moormann 1972; Gracheva *et al.* 2001; Dudal 2003) remain poorly understood (e.g. Theng 1991; Stolbovoy 1992). This is because early investigations on these soils were done by European scientists trained in temperate soil science (Sanchez 1976; Stoops 2003), and the formation of tropical soils is complex as they are the result of major differences in moisture regime, lithology, age of geomorphic surface, degree of weathering of parent materials, relief, and elevation above sea level (Mohr *et al.* 1972; Sanchez 1976; Dudal 2003). Gracheva *et al.* (2001) observed that the formation of tropical soils cannot be fully explained by present climatic models of soil formation. Stoops (2003) suggested that discussions of soils in the tropics should make clear distinction between those in arid regions, humid tropics, and mountainous areas. There is also a need to give attention to tropical island soils especially in South-east Asia since they may be distinct from those in other humid tropical areas due to the unique environmental factors that influenced their formation (Asio *et al.* 2006). Geologically, Hall (2002) showed that much of South-east Asia was the result of recent Cenozoic tectonic events and islands emerged from the sea recently. During the drier period of the Quaternary, the effects of climatic changes on landform development were unique in this region because large areas were under the regime of the monsoonal system (Verstappen 1997). Chang *et al.* (2005) considers 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. Due to the effects of climate and geological history (Nakashizuka 2004), floral and faunal diversity, which is related to soil processes (Heemsbergen *et al.* 2004), is high in the region (Myers *et al.* 2000). Recently, the Philippines has been declared as the second most of the world's biodiversity hotspots (Myers *et al.* 2000), indicating the important role that biodiversity plays in the formation of soils in the Philippines.

From the FAO soil map (FAO 1988), we estimate that the strongly weathered soils Acrisols (Ultisols) and Ferralsols (Oxisols) occupy about 24% of the land area of Samar, the

10.1071/SR06103 0004-9573/07/030153

third largest member of the Philippine archipelago. Due to the lack of data on these soils, unsuitable crop production and management practices have resulted in widespread soil degradation and very low crop yields (Garrity 1993). This has also contributed to the failure of major government efforts at massive forest rehabilitation in the past (e.g. Alcala 1997). Dayot (1988) speculated that Oxisols may exist in the Philippines, although no sufficient documentation has yet been reported. Our previous pedological investigation in the adjacent volcanic island of Leyte revealed the occurrence of deeply weathered Ultisols but we found no Oxisols (Asio 1996; Jahn and Asio 1998). This paper reports for the first time a detailed evaluation of the characteristics and genesis of strongly weathered soils on this major Philippine island of Samar.

Materials and methods

Study sites and environmental setting

Two sites showing widespread occurrence of strongly weathered soils in Samar, Philippines, were selected for detailed study (Fig. 1). The first site is located in Bagacay in the central portion of the island at an elevation of 400 m above sea level (a.s.l.). The surrounding area has generally rugged topography and appears to be a dissected plateau. The soil is a deep red, heavy clay derived from slate of Lower Miocene origin (Soil and Land Resources Appraisal and Training Project Philippines 1977). Dominant tree species are *Mussaenda philippica*, *Physalis angulata*, *Artocarpus blancoi*, *Albizia lebbeck*, and *Rubus rosaefolius*. Dominant grasses are *Dicranopteris linearis*, *Saccharum spontaneum*, *Imperata cylindrica*, and *Cyperus compressus*.

The second site is located in the coastal town of Salcedo in the south-eastern portion of the island. The area is covered with patches of dipterocarp forest at an elevation of 50 m a.s.l., about 500 m away from the sea. The parent material of the very deep red, clayey soil is highly fractured and serpentinised ultrabasic rock (peridotite) of Upper Cretaceous origin. It was probably a laccolith that was exposed by erosion and tectonic uplift, evidenced by the occurrence of a fault line a few kilometers from the site. Previous stratigraphical studies of the island showed that the slate parent material of the Bagacay soil overlies unconformably over the ultrabasic rocks which formed the Salcedo soil (Soil and Land Resources Appraisal and Training Project Philippines 1977). Dominant tree species are *Physalis angulata*, *Artocarpus blancoi*, *Albizia lebbeck*, and *Rubus roaefolius*, and most dominant grasses are *Saccharum spontaneum* and *Imperata cylindrica*. Before the 1960s both sites were under virgin forest (Simon *et al.* 1975). The island is exposed to the annual passage of tropical cyclone and typhoon. Annual rainfall ranges from about 2600 to 2800 mm and the average temperature is 28°C.

Field description and sampling

The pedons evaluated at both sites were located on relatively recent, deep road cuts on backslope positions. At least 0.30 m thickness of surface soil was scraped from the road cut face to expose fresh soil for soil examination and sampling. Morphological description and horizon designations were done following the standard procedure of the FAO Guidelines for Soil Description (FAO 2006). Representative bulk soil samples were collected from every horizon of each profile, air-dried,

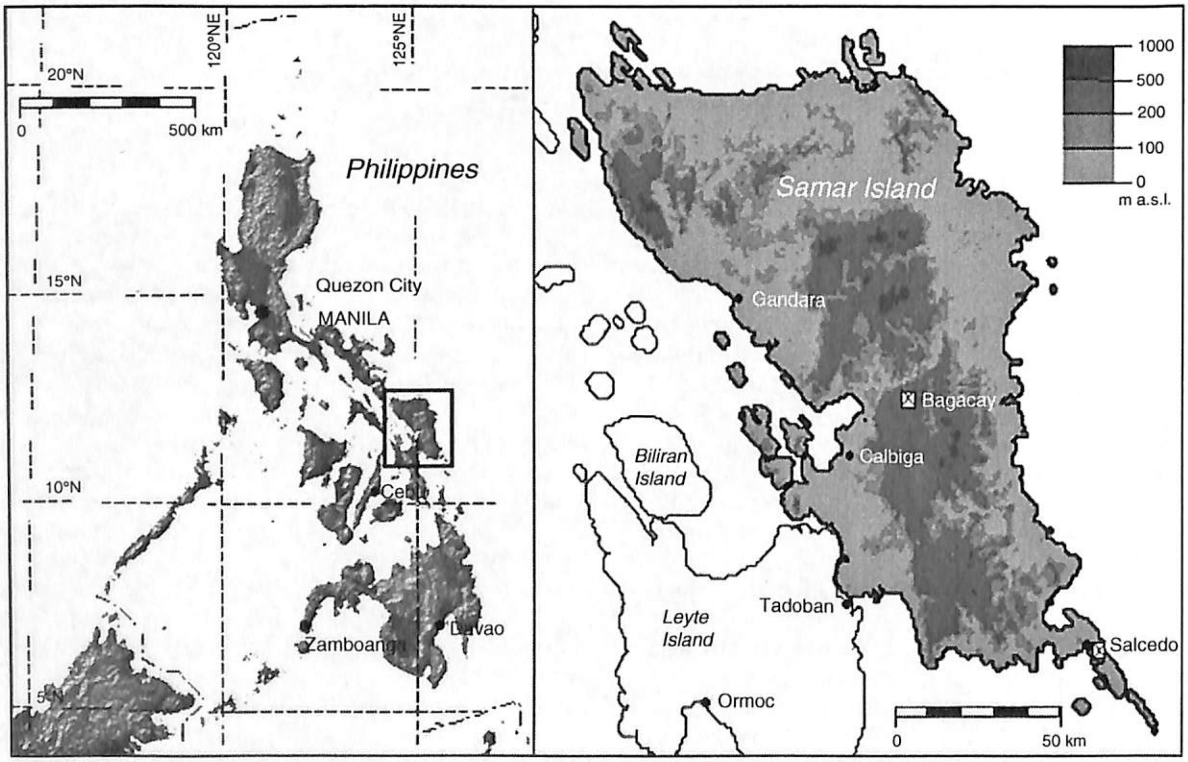

Fig. 1. Map of Samar, Philippines and the location of the research sites marked ×.

sieved to pass a 2-mm sieve, and analysed for physical, chemical, and mineralogical properties. Undisturbed core samples were also collected from each horizon for bulk density determination.

Physical, mineralogical, and chemical analysis

Except for bulk density, all laboratory analyses were done on air-dry soil samples passed through a 2-mm mesh sieve (or fine-earth). Bulk density was measured on undisturbed 100-cm^3 cylindrical cores (5 replicates/horizon). Particle-size distribution was determined by pipette method (ISRIC 1995). For X-ray diffraction (full pattern fitting), 2 g of fine earth fraction (<2 mm) was crushed manually in an agate mortar, sieved using 50 µm mesh, and examined using a Siemens D5005 X-ray diffractometer with a $\theta/2\theta$ goniometer. Selected clay samples were also examined for mineralogical composition by X-ray diffraction. Phase identification was done using the Siemens/Bruker $\text{DIFFRAC}^{\text{plus}}$ EVA software.

Soil pH in 1 M KCl and in H_2O was measured using a glass electrode in the supernatant of a 2.5 : 1 solution : soil mixture. Total carbon was analysed by dry combustion gas chromatography using a Ströhlein C-MAT 550. A fine air-dried soil sample (~1–1.2 g) was placed in the microwave furnace and reacted with oxygen flow by heating to 800°C for 1 min. Evolved carbon dioxide was detected by an infrared spectrometer (Schlichting *et al.* 1995). As inorganic carbon was not detected, the total carbon is equal to organic carbon (OC). Total N was determined by the modified Kjeldahl method (ISRIC 1995). Potential cation exchange capacity (CEC_7) and exchangeable Ca, Mg, K, and Na were analysed by the ammonium acetate at pH 7 method (ISRIC 1995), while exchangeable Al and H were extracted by displacement with 1 M KCl (Thomas 1982). Effective cation exchange capacity (ECEC) was calculated as the sum of exchangeable Ca, Mg, K, Na, and acidity; percent base saturation (BS) was calculated using the formula $BS\% = (\Sigma$ of exch. Ca, Mg, K, and Na$)/CEC_7 \times 100\%$. Dithionite-extractable iron (Fe_d), manganese (Mn_d), aluminum (Al_d), silicon (data not shown), nickel (Ni_d), and chromium (Cr_d); oxalate-extractable iron (Fe_o), aluminum (Al_o), and silicon (data not shown); and pyrophosphate-extractable iron (Fe_p), aluminum (Al_p), and silicon (data not shown) were extracted according to Blakemore *et al.* (1987) and quantified using ICP-AES (Yves Yobin JY 70 plus). Salcedo soil was not completely reduced after treatment with dithionite and needed repeated treatments (data show sum of both treatments). Available P was extracted using 0.03 M NH_4F in 0.1 M HCl (Bray 2) and by the method of Murphy and Riley for colour development. Phosphate retention was determined according to Blakemore *et al.* (1987). Total heavy metal contents were determined by the Aqua Regia method and the elemental concentrations were determined by ICPS (Schlichting *et al.* 1995). All chemical analyses were done in duplicate and values are reported as mean. Results are expressed on oven-dry weight basis.

Results and discussion

Soil morpho-physical characteristics and classification

Table 1 shows that both soils are generally friable and deep with solum >5 m thick. They have dark but thin Ah horizons

Table 1. Morphological characteristics of Bagacay and Salcedo soils (Samar, Philippines)

Depth (m)	Horizon[A]	Boundary[B]	Color (moist)	Texture[C]	Structure[D]	Consistency[E]	Roots[F]
			Bagacay				
0.00–0.05	Ah	cs	5 YR 5/6	SICL	2fmg	fi-fr, sst, spl	mvf&f
0.05–0.20	BA	cs	2.5 YR 5/6	SICL	2f-mab	fi, sst, spl	mvf&f
0.20–0.60	Bt1	cs	2.5 YR 6/8	HC	2f-mab-sbk	st, pl	m&f
0.60–1.00	Bt2	cs	10 R 4/6	HC	2mab-sbk	vfr, svs, spp	f&c
1.00–1.65	Bt3	d	10 R 4/8	HC	2mab-sbk	vfr, svs, spp	o
1.65–2.25	Bt4	d	10 R 4/6	HC	2msbk	vfr, svs, spp	o
2.25–2.75	Bt5	d	10 R 4/6	HC	2m-csbk	vfr, svs, spp	o
2.75–3.50	Bt6	d	10 R 4/8	HC	2m-csbk	vfr, svs, spp	o
3.50–5.00	Bt7	cs	10 R 4/6	HC	2m-csbk	vfr, svs, spp	o
5.00–5.50	Bt8	cs	10 R 4/6	HC	2m-csbk	spp	o
			Salcedo				
0.00–0.21	Ah	cs	2.5 YR 4/6	SIC	2f-mg	fr, sst, spl	mvf&f
0.21–0.54	Bo1	cs	2.5 YR 4/6	CL	2mg-ab	fi-fr, sst, spl	mvf&f
0.54–0.92	Bo2	d	2.5 YR 4/6	HC	2mab-sbk	st, pl	f&c
0.92–1.30	Bo3	d	2.5 YR 3/6	HC	2msbk	vfr, svs, spp	f&c
1.30–1.91	Bo4	d	10 R 4/6	HC	2msbk	vfr, svs, spp	o
1.91–2.91	Bo5	d	10 R 4/8	HC	2msbk	vfr, svs, spp	o
2.91–3.91	Bo6	d	10 R 4/8	HC	2msbk	vfr, svs, spp	o
3.91–5.00	Bo7	d	10 R 4/6	HC	2msbk	vfr, svs, spp	o

[A] Largely according to FAO (2006).

[B] c, Clear; s, smooth; d, diffuse.

[C] SIC, Silty clay; SICL, silty clay loam; HC, heavy clay; CL, clay loam.

[D] 2, Moderate; f, fine; m, medium; c, course; g, granular; ab, angular blocky; sbk, sub-angular blocky.

[E] fi, Firm; fr, friable; vfr, very friable; st, sticky; pl, plastic; sst, slightly sticky; svs, sticky to very sticky; spl, slightly plastic; spp, slightly plastic to plastic.

[F] mvf, many very fine to fine; m, medium; f, few; c, coarse; o, no roots.

overlying thick Bt (Bagacay soil) and Bo (Salcedo soil) horizons, are very sticky and plastic when wet, and have colour hue of 2.5 YR in the upper horizon which changes to 10 R in the lower horizons. Soil texture ranges from silty clay loam in the top horizons to heavy clay in the lower horizons. Soil structure is granular in the A horizons due to the high amount of organic matter content, and angular to sub-angular blocky in the B horizons which part into strong granular peds when pressed in the hand especially in the case of the Salcedo soil. Both soils have many fine to medium roots in the upper horizons but only few in the subsoils despite their high porosity due to chemical constraints (e.g. acidity, Al toxicity). Boundaries between the A and B horizons are clear as a result of the darkening effect of organic matter on the surface but are generally diffuse in the Bt or Bo horizons as is common in strongly weathered soils (Driessen *et al.* 2001). The morphological characteristics exhibited by both soils are reflective of advanced stage of weathering (e.g. Mohr *et al.* 1972).

Table 2 reveals that the upper 0.2 m of Bagacay soil is dominated by silt (average 55%), although it decreases with depth. Clay is dominant throughout the profile of the Salcedo soil and ranges in amount from 60% in the surface horizon to 88% at 5 m depth, suggesting intense weathering status typical for Ferralsols (Driessen and Dudal 1991). The 2 soils have low bulk density values (0.81–1.05 g/cm^3), which are generally lower than those of some highly weathered soils in Puerto Rico (Beinroth 1982) and Brazil (Balbino *et al.* 2002). The low bulk density values reflect the excellent aggregation apparently due to their high Fe oxide content (Schwertmann and Taylor 1977).

In terms of classification, Bagacay soil has an argic horizon (argillic) having >8% higher clay content in the subsurface than in the surface (eluvial) horizon. It is classified as Haplic Acrisol (Alumic, Hyperdystric, Clayic, Rhodic) in the WRB system (IUSS Working Group WRB 2006) or fine, kaolinitic, isohyperthermic, Typic Paleudult in the Soil Taxonomy (Soil Survey Staff 2003). On the other hand, the Salcedo soil narrowly fails the argic (argillic) horizon requirement of a clay increase in the upper 0.15 m of the pedon but shows a ferralic B horizon (or oxic horizon). Thus, it is classified as Haplic Ferralsol (Dystric, Clayic, Rhodic) (IUSS Working Group WRB 2006) or very fine, sesquic, isohyperthermic, Rhodic Hapludox (Soil Survey Staff 2003).

Table 2. Physical characteristics of Bagacay and Salcedo soils (Samar, Philippines)

Clay, <2 µm; silt, 2–200 µm; sand, 200–2000 µm. n.d., Not determined

Depth (m)	Clay	Silt (%)	Sand	Db (g/cm^3)
		Bagacay		
0.00–0.05	27.1	63.4	9.5	0.88
0.05–0.20	32.7	59.4	7.9	0.81
0.20–0.60	33.3	53.9	12.9	0.86
0.60–1.00	36.9	51.7	11.5	0.89
1.00–1.65	36.4	58.4	5.2	0.90
1.65–2.25	47.6	43.0	9.4	0.94
2.25–2.75	59.1	33.1	7.8	0.94
2.75–3.50	55.0	32.6	12.5	1.02
3.50–5.00	60.2	36.1	3.7	1.05
5.00–5.50	n.d.	n.d.	n.d.	n.d.
		Salcedo		
0.00–0.21	59.8	40.2	0.0	0.89
0.21–0.54	63.6	36.4	0.0	0.89
0.54–0.92	69.0	31.0	0.1	0.90
0.92–1.30	75.8	24.2	0.0	1.00
1.30–1.91	83.8	16.1	0.1	1.00
1.91–2.91	85.3	14.6	0.1	1.03
2.91–3.91	86.6	13.4	0.1	1.04
3.91–5.00	88.2	11.5	0.4	1.05

Mineralogical properties

Semiquantitative determination of minerals on powder specimens of fine earth and on some clay samples by X-ray diffraction technique reveals dominance of halloysite/kaolinite, hematite, gibbsite, and quartz in both soils (Fig. 2). Data also show some variation in the bulk soil mineral assemblages between both soils and with depth. Both soils contain substantial amounts of quartz (0.426 and 0.334 nm) but Bagacay soil contains 2 times more, generally decreasing with depth (except in the Bt5 horizon), indicating possible layering of parent material. The higher quartz content of Bagacay soil was confirmed by SiO_2 analysis (Table 3). In contrast, the quartz content of Salcedo soil, although lower in amount, appears to be relatively constant throughout the soil profile, suggesting uniformity of parent material. This quartz may have been inherited from accompanying materials of the ultrabasic parent rock. The occurrence of opal-CT in the Salcedo soil is poorly understood but it may have formed under conditions of poor drainage due to high groundwater in the past.

Figure 2 shows a broad hump between 1.0 and 0.7 nm, indicating the presence of halloysite and kaolinite. The hump in the Salcedo soil is broader than in the Bagacay soil (see dotted line in Fig. 2 which is normalised to a maximum peak height at 0.7 nm to visualise the relative differences). Quantin (1990) reported that halloysite and kaolinite are common in strongly weathered soils. Halloysite is less stable and weathers slowly to form kaolinite and later gibbsite (Schulze 1989; Quantin 1990). The degree of kaolinitisation in the 2 soils studied appears comparable to that of a strongly weathered soil (a Haplohumult) in the nearby island of Leyte (Jahn and Asio 1998).

Results also revealed high amounts of gibbsite (0.485 nm) in the Salcedo soil but only small amounts in the Bagacay soil (about 25–30% of the amounts in Salcedo soil). As with quartz, the Al that formed gibbsite could have come from the peridotite and the accompanying minerals such as calcic feldspar. Gibbsite slightly increased in the Bo4 horizon and then decreased with depth. The narrow SiO_2/Al_2O_3 ratio (Table 3) supports also the presence of gibbsite. Driessen *et al.* (2001) revealed that gibbsite is formed in strongly weathered soils particularly Ferralsols from basic rocks when the internal drainage is good.

Peaks of goethite (0.418 nm), goethite and hematite (0.27 nm), and hematite (0.252 and 0.368 nm) tend to increase with Fe_d (Fig. 2). After dithionite pretreatment, peaks at 21.3°2d (0.418 nm, goethite), 33.2°2d (0.27 nm, hematite and goethite), and 24.2°2d (0.368 nm, hematite) broke down completely, while peaks at 35.7°2d (0.252 nm, hematite) and at 37°2d (0.245 nm, goethite) broke down only partly. The dissolution of

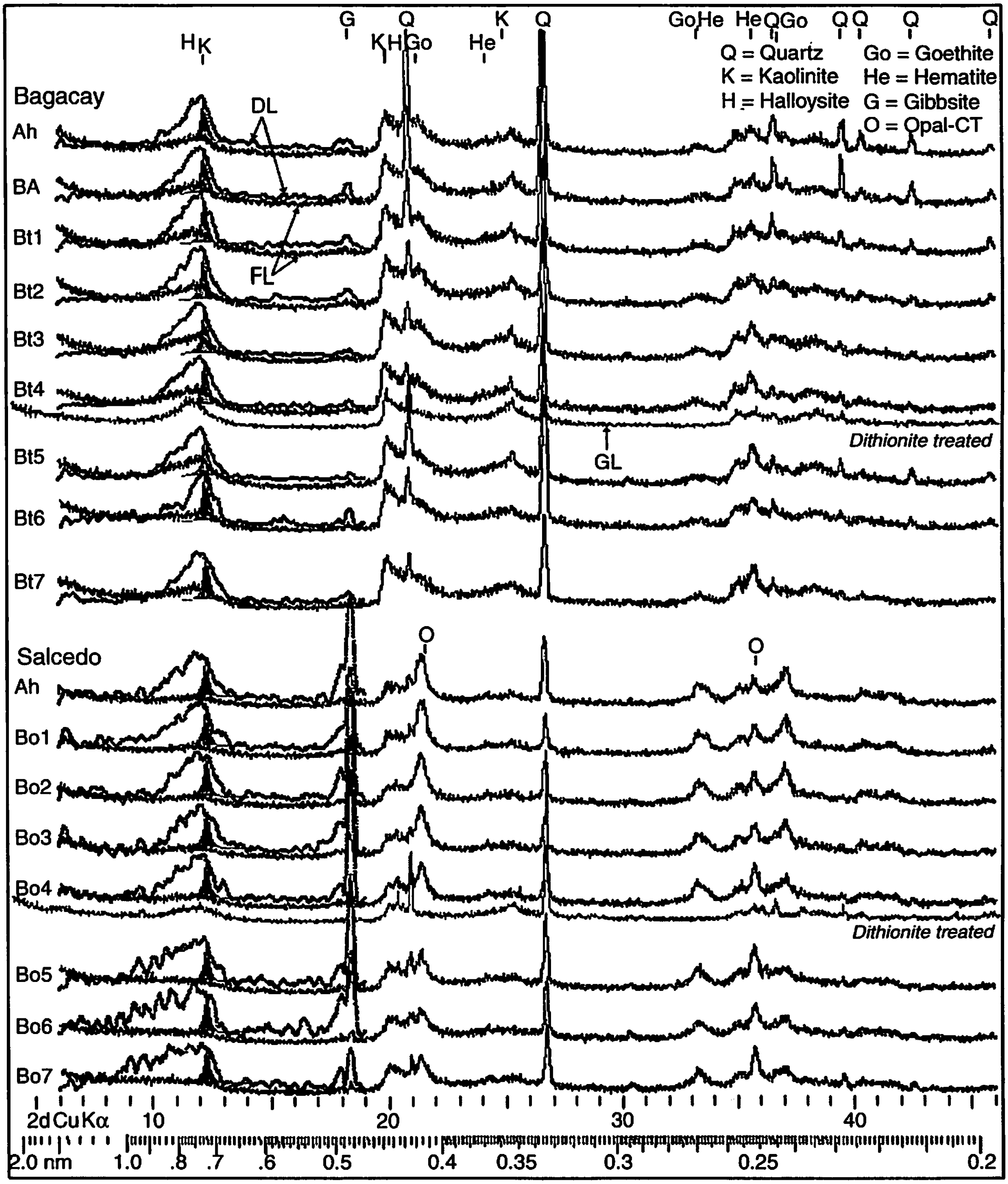

Fig. 2. X-ray diffractograms of powdered fine earth and selected clay sample. Full line (FL), based on original raw data; grey line (GL), dithionite treated (from original raw data); dotted line (DL), smoothed and normalised to the same peak height at 0.7 nm; shadowed area, kaolinite peak from a textured clay sample.

maghemite and manganese oxides may explain the break down of 37°2d peak.

From the peaks and their ratio at 21.3 and 33.2°2d, it can be deduced that despite their strong red color, both soils contain more goethite than hematite. In addition, the topsoils contain less hematite than the subsoils. Especially in the Salcedo soil, a decrease of the goethite 0.418 nm peak and an increase of the 0.27 nm peak (which is more related to hematite than to goethite) with depth can be observed.

Table 4 indicates that Fe_d values in Bagacay soil are high, ranging from 62 to 84 g/kg (resulting in goethite equivalents of 10–13%), which are much higher than the values of Fe_o

Table 3. Total elemental contents of Bagacay and Salcedo soils (Samar, Philippines)

Horizon	Depth (m)	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	MnO	MgO	CaO (g/kg)	K_2O	Na_2O	P_2O_5	Ignition loss	Total	SiO_2/Al_2O_3	Ca + Mg + K + Na/Al
								Bagacay							
Bt2	0.60–1.00	367	215	181	15	1	5	1.3	1.1	0	0.9	21	808	1.71	0.03
Bt6	2.75–3.50	368	265	190	15	2	6	0.1	2.8	0	0.9	15	865	1.39	0.03
Rock		516	148	131	9	4	51	57	7.2	23	1.3	5	953	3.49	0.93
								Salcedo							
Bo2	0.54–0.92	201	186	434	17	2	5	0.7	2.4	0	0.5	12	861	1.08	0.04
Bo5	1.91–2.91	225	191	406	18	2	6	0.3	3.6	0	0.0	12	864	1.18	0.05
Bo6	2.91–3.91	261	188	381	17	2	9	0.5	4.3	0	0.4	11	874	1.39	0.07
Bo7	3.91–5.00	280	193	352	20	1	10	0.5	4.8	0	0.5	11	873	1.45	0.08

Table 4. Extractable iron, aluminum and ratios of selectively dissolved components of Bagacay and Salcedo soils (Samar, Philippines)

Depth (m)	Fe_d	Fe_o	Fe_p	Mn_d (g/kg)	Al_d	Al_o	Al_p	$Fe_{o/d}$	Al_d/Fe_d	Fe_d/clay
					Bagacay					
0.00–0.05	64	5.2	5.5	0.39	8.3	2.0	1.8	0.081	0.13	0.23
0.05–0.20	62	5.4	5.4	0.43	8.0	2.0	1.9	0.087	0.13	0.19
0.20–0.60	73	5.4	6.8	0.20	9.8	2.3	2.7	0.073	0.13	0.22
0.60–1.00	79	1.6	2.9	0.18	10.6	2.5	2.0	0.021	0.13	0.21
1.00–1.65	84	1.4	1.2	0.34	10.0	2.6	1.5	0.017	0.12	0.23
1.65–2.25	83	1.3	0.1	0.84	8.7	2.7	1.1	0.016	0.10	0.17
2.25–2.75	71	1.2	0.0	0.90	7.3	2.3	1.0	0.017	0.10	0.12
2.75–3.50	80	1.6	0.0	1.20	8.4	3.7	1.8	0.020	0.10	0.15
3.50–5.00	84	1.7	0.0	1.16	8.5	3.5	1.6	0.020	0.10	0.14
5.00–5.50	71	2.0	0.0	2.58	7.1	2.2	0.8	0.028	0.10	n.d.
					Salcedo					
0.00–0.21	164	1.4	1.4	0.63	21.6	1.4	0.7	0.009	0.13	0.27
0.21–0.54	191	1.4	0.2	0.78	24.0	1.7	0.5	0.007	0.13	0.30
0.54–0.92	194	1.4	0.1	0.98	23.2	1.8	0.6	0.007	0.12	0.28
0.92–1.30	180	1.3	0.0	0.85	20.0	1.7	0.5	0.007	0.11	0.24
1.30–1.91	170	1.4	0.0	0.76	16.4	1.8	0.6	0.008	0.10	0.20
1.91–2.91	154	1.1	0.2	0.78	13.6	2.0	0.8	0.007	0.09	0.18
2.91–3.91	151	1.3	0.1	0.82	13.3	2.1	0.8	0.009	0.09	0.17
3.91–5.00	144	1.3	0.1	0.55	12.3	2.1	0.8	0.009	0.09	0.16

(1.2–5.4 g/kg) and Fe_p (0.01–6.8 g/kg). Salcedo soil has about twice as much Fe_d as Bagacay soil, resulting in goethite equivalents of 23–31%. This reflects different Fe contents of the parent rock materials of the 2 soils, being much higher in the peridotite rock in the Salcedo soil. Since the Al_d/Fe_d ratio is lowest (0.09) in the lower 3 horizons of the Salcedo soil, a genesis of these horizons under hydromorphic conditions with low Al-activity may be possible.

The ratio Fe_o/Fe_d or 'activity ratio' is used to indicate the degree of crystallinity of iron oxides (Mizota and Van Reeuwijk 1989). Both soils have very low Fe_o/Fe_d values, <0.02 for Bagacay subsoil and <0.01 for Salcedo soil, indicating advanced stage of pedogenesis (Blume and Schwertmann 1969) and that most of the Fe oxides are crystalline (Mizota and Van Reeuwijk 1989). The generally low (<24 g/kg) Al_d values indicate less Al-substitution in the Fe-oxides (9–13%). Al_d values are, however, remarkably higher than Al_o and Al_p in both soils. Amounts of Fe_o and Al_o are generally low with no significant differences between the two. The result implies that short range-order minerals are not present in significant amounts. Fe_p has the tendency to correlate with organic matter but a similar trend is not observed for Al_p.

Chemical properties

Table 5 indicates that all horizons of Bagacay and Salcedo soils are acidic (pH_{water} 5.0–5.8). They have negative net charge as indicated by negative ΔpH (Mekaru and Uehara 1972) values. OC contents of the soils are 5.07–0.07% and 1.38–0.10% for Bagacay and Salcedo soils, respectively. The differences in the vegetation cover (e.g. type of present vegetation and abundance) and past land use explain the data on OC and C/N ratio. The Salcedo site is also more eroded, having been under human influence for much longer than the Bagacay site. N and OC contents steadily decrease with depth in both soils. Exchangeable bases (e.g. Ca, Mg, Na, and K) contents are low, resulting in a low BS of 3 (subsoil of Bagacay soil) to 55% (topsoil of

Table 5. Chemical characteristics of Bagacay and Salcedo soils (Samar, Philippines)

OC, Organic carbon; Nt, total nitrogen; P-ret, phosphate retention; ΣEB, exchangeable bases; EA, exchangeable acidity; ECEC, effective cation exchange capacity; CEC_7, cation exchange capacity at pH 7; BS, base saturation; Na-sat, sodium saturation; n.d., not determined

Depth (m)	pH			OC	Nt	C/N	P avail. (mg/kg)	P-ret (%)	Exch. bases (cmol$_c$/kg)						Exch. acidity (cmol$_c$/kg)				ECEC	CEC_7	BS/ CEC_7	Na-sat/ CEC_7	CEC_7/ clay
	H_2O	KCl	ΔpH	(%)					Ca	Mg	Na	K	ΣEB	Mg+Na	Al	H	EA	Ca+Al+H	(cmol$_c$/kg)		(%)		
												Bagacay											
0.00–0.05	5.8	5.0	−0.8	4.42	0.22	20	1.1	51	4.53	0.93	0.21	0.21	5.88	1.1	1.95	0.1	2.05	6.6	7.9	29.0	20.2	0.7	107
0.05–0.20	5.8	4.9	−0.9	5.07	0.23	22	0.7	49	7.85	1.78	0.14	0.44	10.21	1.9	1.99	0.2	2.19	10.0	12.4	30.1	33.9	0.5	92
0.20–0.60	5.3	4.8	−0.5	1.70	0.12	14	0.6	63	2.85	0.66	0.12	0.08	3.71	0.8	2.71	0.9	3.61	6.5	7.3	21.8	17.0	0.5	66
0.60–1.00	5.2	4.2	−1.0	0.97	0.06	16	<0.6	69	0.63	0.21	0.00	0.03	0.87	0.2	2.89	1.0	3.89	4.5	4.8	16.1	5.4	0.0	44
1.00–1.65	5.1	4.2	−0.9	0.52	0.05	10	<0.6	65	1.21	0.36	0.10	0.18	1.85	0.5	2.81	1.1	3.91	5.1	5.8	18.0	10.3	0.6	50
1.65–2.25	5.1	4.2	−0.9	0.22	0.03	7	<0.6	67	0.36	0.27	0.13	0.10	0.86	0.4	2.87	1.0	3.87	4.2	4.7	16.1	5.3	0.8	34
2.25–2.75	5.2	4.2	−1.0	0.13	0.02	7	<0.6	60	0.19	0.15	0.04	0.07	0.45	0.2	2.76	0.9	3.66	3.9	4.1	14.6	3.1	0.3	25
2.75–3.50	5.1	4.0	−1.1	0.08	0.01	8	<0.6	79	0.30	0.38	0.18	0.12	0.98	0.6	3.42	1.7	5.12	5.4	6.1	25.8	3.8	0.7	47
3.50–5.00	5.1	4.0	−1.1	0.10	0.02	5	<0.6	79	0.32	0.37	0.10	0.10	0.89	0.5	3.26	1.6	4.86	5.2	5.8	22.8	3.9	0.4	38
5.00–5.50	5.3	4.3	−1.0	0.07	0.01	7	<0.6	55	5.34	0.49	2.27	0.15	8.15	2.76	3.16	1.6	4.71	10.1	8.3	19.8	41.2	0.1	n.d.
												Salcedo											
0.00–0.21	5.8	4.8	−1.0	1.38	0.09	15	0.6	73	3.57	1.50	0.04	0.24	5.35	1.5	1.94	0.2	2.14	5.7	7.5	9.7	55.0	0.4	16
0.21–0.54	5.7	4.7	−1.0	0.43	0.04	11	<0.6	71	1.37	0.79	0.10	0.16	2.42	0.9	1.98	0.2	2.18	3.6	4.6	9.7	25.1	1.0	15
0.54–0.92	5.5	4.6	−0.9	0.33	0.03	11	<0.6	66	0.39	0.36	2.17	0.15	3.07	2.5	2.04	0.3	2.34	2.7	5.4	10.9	28.1	19.8	16
0.92–1.30	5.6	4.5	−1.1	0.28	0.03	9	<0.6	65	0.52	0.44	2.18	0.15	3.29	2.6	2.05	0.4	2.45	3.0	5.7	11.1	29.7	19.7	15
1.30–1.91	5.6	4.6	−1.0	0.23	0.02	11	<0.6	64	0.56	0.51	2.08	0.14	3.29	2.6	2.13	0.5	2.63	3.2	5.9	10.9	30.3	19.2	13
1.91–2.91	5.5	4.2	−1.3	0.16	0.02	8	<0.6	67	0.93	0.69	2.13	0.12	3.87	2.8	2.46	0.7	3.16	4.1	7.0	20.7	18.7	10.3	24
2.91–3.91	5.3	4.2	−1.1	0.11	0.02	6	<0.6	62	0.70	0.39	2.13	0.11	3.33	2.5	2.42	0.6	3.02	3.7	6.4	16.4	20.3	13.0	19
3.91–5.00	5.3	4.3	−1.0	0.10	0.02	5	<0.6	52	0.74	0.37	2.19	0.11	3.41	2.6	2.47	0.8	3.27	4.0	3.7	22.3	15.3	9.9	25

Salcedo soil), which reflects the strongly weathered nature of the soils. The very high rainfall and stable land surface probably favoured the intensive leaching of the basic cations. Surprisingly, however, Salcedo soil has exchangeable Na contents between the 0.54 and 3.91 m depths that are distinctly higher than in the overlying horizons. This exchangeable Na accounts for 10–200% of the ESP in these horizons. This can be ascribed to the contribution of salt spray, since the site is located only about 500 m from the shore and considering that the island is frequently subjected to typhoons and monsoon winds. Yaalon (1983) has suggested the important role of salt spray in soil development for coastal areas. In their study in Mt Pangasugan in Leyte, Philippines, Zikeli *et al.* (2000) noted the contribution of salt spray to the Na content of the forest soil located ~1 km away from the sea.

Data on BS showed 15–30% values for the subsoil of Salcedo soil, which are much higher than in the Bagacay soil (3–10%) at comparable depths. The higher BS values in the Salcedo soil are, however, not reflected by higher pH values. This is interesting since the soil has undergone the process of ferralitisation, the accumulation of Fe and Al oxides resulting from intensive leaching, and losses of silica (Scheffer and Schachtschabel 1992). Tejedor Salguero *et al.* (1985) reported the occurrence of salinisation process after a polygenetic succession of illuviation, ferralitisation, hydromorphy, and plinthisation in a soil from basaltic parent material in Gomera Island. Exchangeable Al contents are high, ranging from 1.95 to 3.42 cmol$_c$/kg in the Bagacay soil, and 1.94 to 2.47 cmol$_c$/kg in the Salcedo soil. CEC$_7$ is lower in Salcedo soil (<21 cmol$_c$/kg) than in Bagacay soil (<31 cmol$_c$/kg). In contrast, ECEC is very low (<12.4 cmol$_c$/kg) in both soils.

Salcedo soil has higher clay contents but lower CEC$_7$ values than the Bagacay soil. CEC$_7$/clay ratio ranges from 25 to 107 cmol$_c$/kg clay for Bagacay soil and 13 to 25 cmol$_c$/kg clay for Salcedo soil (Fig. 3*a*). The Bo1 to Bo4 horizons of Salcedo soil pass the requirement (<16 cmol$_c$/kg clay) for a ferralic B horizon (IUSS Working Group on WRB 2006). In contrast, all horizons of Bagacay soil have CEC$_7$ values >16 cmol$_c$/kg clay, indicating it does not have a ferralic horizon. Moreover, the ECEC/clay ratio for Salcedo soil revealed values of 7.1–8.2 cmol$_c$/kg clay, which are just above the requirement (<6 cmol$_c$/kg clay) for the Vetic subunit in the WRB. The results also revealed that the CEC$_7$/clay ratio of Salcedo soil decreases with gibbsite content (Fig. 3*b*), suggesting that much of gibbsite is found in the clay fraction. The same result was observed on Fe oxides, hence explaining the low CEC values even for a halloysitic clay assemblage. In both soils, about 33% of the clay fraction is Fe oxides. In the Salcedo soil about 25–33% of the clay fraction is gibbsite. The increasing CEC$_7$/clay towards the parent rock below the profile in the Salcedo soil indicates that minerals with higher charge than kaolinite, halloysite, Fe-oxides, and gibbsite may be present in the clay fraction (compare XRD observation of a 1.0 nm mineral).

Available P content is very low in both soils, probably due to precipitation of P as insoluble Fe and Al phosphate as is common in strongly weathered soils (Mohr *et al.* 1972; Sanchez 1976). This is also reflected by the high P retention values (49–79%) of the soils. Interestingly, both soils have the same range of P retention values even though the Salcedo soil contains twice as much Fe$_d$ as the Bagacay soil. There is also good correlation ($R^2 = 0.75$) between P retention and Fe$_d$ for Salcedo soil but not for Bagacay soil. This is probably due to differences in crystallinity and assemblage of Fe oxides in the soils. Sanchez (1976) cited studies which revealed that Brazilian Ultisols with less crystalline Fe oxides fixed more P than Brazilian Oxisols with more crystalline Fe oxides. The results suggest that the availability of P and K are the limiting factors for plant production in both soils, as is common in strongly weathered soils (e.g. Sanchez 1976; Scheffer and Schachtschabel 1992).

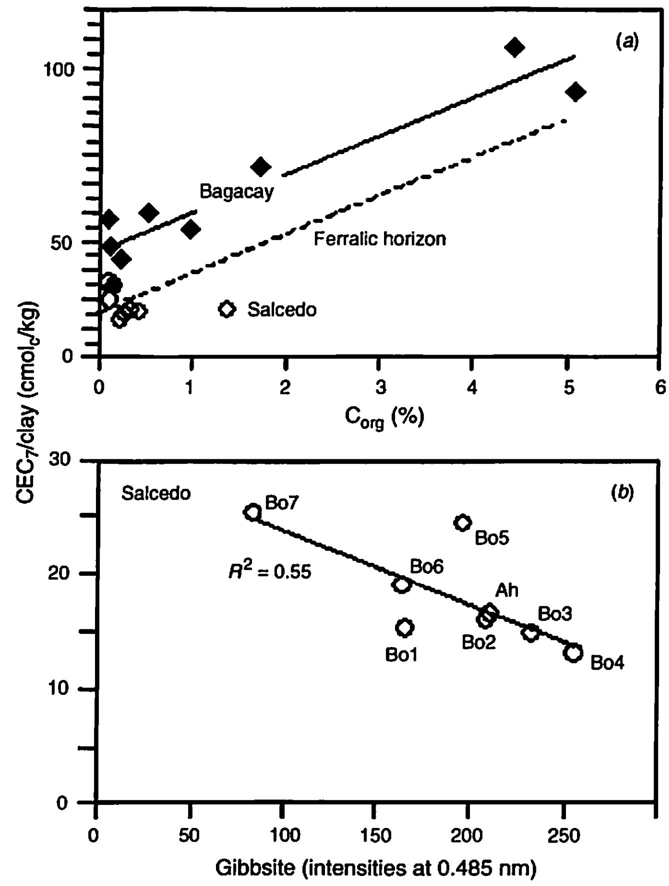

Fig. 3. (*a*) Relation between calculated clay CEC$_7$ ratio and Corg of Bagacay and Salcedo soils (Samar, Philippines); (*b*) influence of gibbsite on CEC of clay.

Since both sites are close to an abandoned mining site, we analysed the total contents of some heavy metals in the soils. Results revealed low amounts of Zn, Pb, Cd, and Cu (data not shown) in both soils but very high levels of Ni and Cr in the Salcedo soil (Table 6). This can be attributed to the ultrabasic parent material, which is known to contain high amounts of these elements (Huang 1962; Ellis *et al.* 2002). Ni increases while Cr decreases with soil depth. Treatment of the soil with dithionite removed 82–97% of Cr, indicating that much of Cr is bound to the Fe oxides. This agrees with the findings of McKenzie (1980) that Cr is more bound to goethite and hematite than to other clay minerals. The same treatment, however, removed only 38–67% of Ni, suggesting that other clay minerals have strong

Table 6. Nickel and chromium-extractable with aqua regia and dithionite of Bagacay and Salcedo soils (Samar, Philippines)
AR, Aqua regia; d, dithionite; n.d., not detected

Depth (m)	Ni_{AR} (mg/kg)	Ni_d	Ni_d/Ni_{AR} (%)	Cr_{AR} (mg/kg)	Cr_d	Cr_d/Cr_{AR} (%)
			Bagacay			
0.00–0.05	12	n.d.	n.d.	30	n.d.	n.d.
0.05–0.20	12	n.d.	n.d.	29	n.d.	n.d.
0.20–0.60	14	n.d.	n.d.	33	n.d.	n.d.
0.60–1.00	15	n.d.	n.d.	34	n.d.	n.d.
1.00–1.65	12	n.d.	n.d.	10	n.d.	n.d.
1.65–2.25	10	n.d.	n.d.	11	n.d.	n.d.
2.25–2.75	7	n.d.	n.d.	8	n.d.	n.d.
2.75–3.50	13	n.d.	n.d.	7	n.d.	n.d.
3.50–5.00	11	n.d.	n.d.	8	n.d.	n.d.
5.00–5.50	26	n.d.	n.d.	24	n.d.	n.d.
			Salcedo			
0.00–0.21	428	243	57	1635	1408	86
0.21–0.54	473	299	63	1592	1540	97
0.54–0.92	521	348	67	1450	1411	97
0.92–1.30	526	322	61	1381	1230	89
1.30–1.91	534	281	53	1383	1245	90
1.91–2.91	707	288	41	1293	1167	90
2.91–3.91	957	383	40	1044	933	89
3.91–5.00	738	281	38	1045	855	82

bonding sites for Ni (Tiller *et al.* 1984). The presence of very high Cr and Ni in the Salcedo soil is likely to pose health risk to the people living in the area. Ellis *et al.* (2002) reported that under oxidising conditions, Cr is highly soluble and mobile as the Cr(VI) anion chromate (CrO_4^{2-}) and bichromate ($HCrO_4^-$) and that it is a suspected carcinogen. The acidic condition of the soil aggravates the problem as it also enhances heavy metal solubility.

Degree of weathering and pedogenetic implications

Since both sites have closely similar climate and natural vegetation, the chemical characteristic of the parent material and relief appear to be the dominant factors that influenced the characteristics and formation of the two soils. The older and more weatherable ultrabasic rock and the more stable geomorphic surface in the Salcedo site enhanced the development of the very strongly weathered Salcedo soil (a Ferralsol). However, the close similarities of the 2 soils in terms of morphological, physical, and chemical characteristics suggests that different parent materials may develop into closely related soils in the advanced stage of soil development and weathering as predicted by Chesworth (1973*a*, 1973*b*).

Our results suggest that the following are the dominant pedogenetic processes that produced both soils: loss of bases and acidification, clay formation, ferrugination, weathering of clay, and structure formation. Loss of bases and acidification are reflected by the very low contents of total Ca, Mg, Na and K, by the high ratio of $(CaO + MgO + Na_2O + K_2O)/Al_2O_3 < 0.08$ (Table 3), the low BS, very low exchangeable bases, low pH, and high exchangeable Al (Table 5). These processes are generally favoured by high rainfall and good drainage resulting in the leaching of basic cations. Although we were not able to find a fresh rock for analysis in the Salcedo site, we were able to obtain a representative sample from the Bagacay site and revealed that desilification may have reached about 30% of that found in the parent rock (Table 3; SiO_2/Al_2O_3). It should be pointed out that slates can be very heterogeneous, so the actual weathering rate may have been different from that predicted by our sample. The red colour development (ferrugination) due to hematite formation was more expressed in the subsoils than in the topsoils. The more weatherable ultrabasic parent material of the Salcedo soil favoured much faster weathering, as reflected by the formation of kaolinite, halloysite, goethite, hematite, and, most importantly, gibbsite. Soil structure formation is shown by the excellent physical condition of the soils. The formation of clay was distinctly higher in the soil developed from highly weatherable ultrabasic rock than that the soils. The very high rainfall and stable land surface probably from slate.

If we use the weathering sequence of clay-sized minerals established 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), both the soils we studied fall between stage 10 (kaolinite and halloysite) and stage 11 (gibbsite), with the Bagacay soil tending towards 10 while Salcedo tends to 12. The latter shows some similarities to the Nipe soil series developed from serpentinite in Puerto Rico reported by Beinroth (1982).

Conclusions

The two soils studied appear to be closely related in most morphological, physical, chemical, and mineralogical characteristics, although the one derived from the more weatherable ultrabasic rock is in a more advanced stage of weathering and soil development (Haplic Ferralsol) than that derived from slate (Haplic Acrisol). Notable differences between the soils include contents of quartz, Fe oxides, gibbsite, Ni, and Cr, which are all related to the composition of the parent rock. The contribution of salt spray to soil development in the coastal area appears important. The soils have very low fertility and would be problematic for crop production. The study revealed that on the geologically young humid tropical island of Samar, the geochemical characteristics of the parent rock material and the stability of the geomorphic surface are major factors determining the formation and characteristics of strongly weathered soils.

Acknowledgments

The senior author is grateful to the Deutscher Akademischer Austausch Dienst (DAAD), Bonn, Germany, for the research scholarship. Dr H. Tanneberg, G. Polcher, C. Krenkewitz, and G. von Koch at the Institute of Soil Science and Plant Nutrition, Martin Luther University, Halle, Germany, are thanked for their valuable help in the laboratory.

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Manuscript received 3 August 2006, accepted 14 March 2007