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To cite this version:

Laurent Caner, G. Bourgeon, François Toutain, A.J. Herbillon. Characteristics of Non-Allophanic Andisols derived from Low Activity Clay Regoliths in Nilgiri Hills (Southern India). European Journal of Soil Science, 2000, 51, pp.553-563. hal-00258684

HAL Id: hal-00258684

https://hal.science/hal-00258684v1

Submitted on 24 Feb 2008

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Characteristics of Non-Allophanic Andisols derived from Low Activity Clay Regoliths in Nilgiri Hills (Southern India)

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Accepted Version: *European Journal of Soil Science*, 2000, **51**, 553-563

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Summary

Low activity clay soils on old planation surfaces of the tropics are generally considered as stable end points of soil formation. It is therefore surprising to find Andosols on them. We characterised the properties of six profiles representative of these soils in the Western part of Nilgiri Hills (2000–2500 m above mean sea level), Southern India, where the present climatic conditions are cool (mean annual temperature 15°C) and humid (mean annual rainfall 2500 mm). Thick (50–80 cm) dark–reddish brown topsoil overlies strongly desilicated yellowish–red materials. This horizon has andic properties to a sufficient depth and the carbon content requirement of the melanic epipedon to place these soils in the Andisol order. Our data as well as the history of the Nilgiri Hills suggest that the formation of these non-allophanic Andisols result from the succession of two main steps. First, a 'lateritic' weathering cycle led to the relative accumulation of secondary Al and Fe oxides. Later, the accumulation of organic matter favoured by a more recent climatic change induced complexation by organic acids of Al and Fe oxides, and the production of enough metal–humus complexes to give rise to andic properties. Such soils, in which secondary Al

and Fe oxides, generally considered as indicators of an advanced weathering stage, are involved in a new cycle of soil formation, are original Andisols.

Introduction

Since publication of the paper by Garcia-Rodeja *et al.* (1987), there is growing evidence that 'andic properties' (Soil Survey Staff, 1998) occur in soils that are not derived from volcanic materials. This is the case for some Spodosols in the cold environment of Southern Alaska (Alexander *et al.*, 1993) as well as for genuine Andisols under various temperature and moisture regimes in several parts of the World (Hewitt & Witty, 1988, Bäumler & Zech, 1994, Aran *et al.*, 1998). These reports have also progressively made clear that such non-volcanic Andisols (*sensu* Parfitt & Clayden, 1991) owe their characteristics properties to metal–humus complexes rather than to allophanes and can thus be called non-allophanic Andisols.

The present work reports the occurrence, in Nilgiri Hills, Southern India, of non-allophanic Andisols derived from a special kind of non-volcanic material consisting of 'laterite', i.e. a low activity clay (LAC) residuum, rich in Al and Fe oxides. Since such soils and the most common volcanic Andisols are often considered as representing advanced and juvenile stages of soil formation respectively, the occurrence of these soils was unexpected. This paper emphasizes the originality of soils in which secondary oxides, inherited from a previous cycle of soil genesis, appear to play the same role as volcanic glasses do in most Andisols. Moreover, we examine the properties of these particular Andisols and attempt to relate their genesis to the major geologic and climatic events that affected the area.

Materials and methods

Environmental setting

The Andisols in question are at elevations ranging between 2000 and 2400 m, on the Western part of the Nilgiri Hills (Southern India, Tamil Nadu).

These highlands (also called 'Blue Mountains') are at the junction of Western and Eastern Ghats (Figure 1) and appear as a residual surface edged by steep slopes. Their morphology has been described by Demangeot (1975). The central part, which seems to correspond to an old planation surface, is divided into several basins. Hill ranges, with

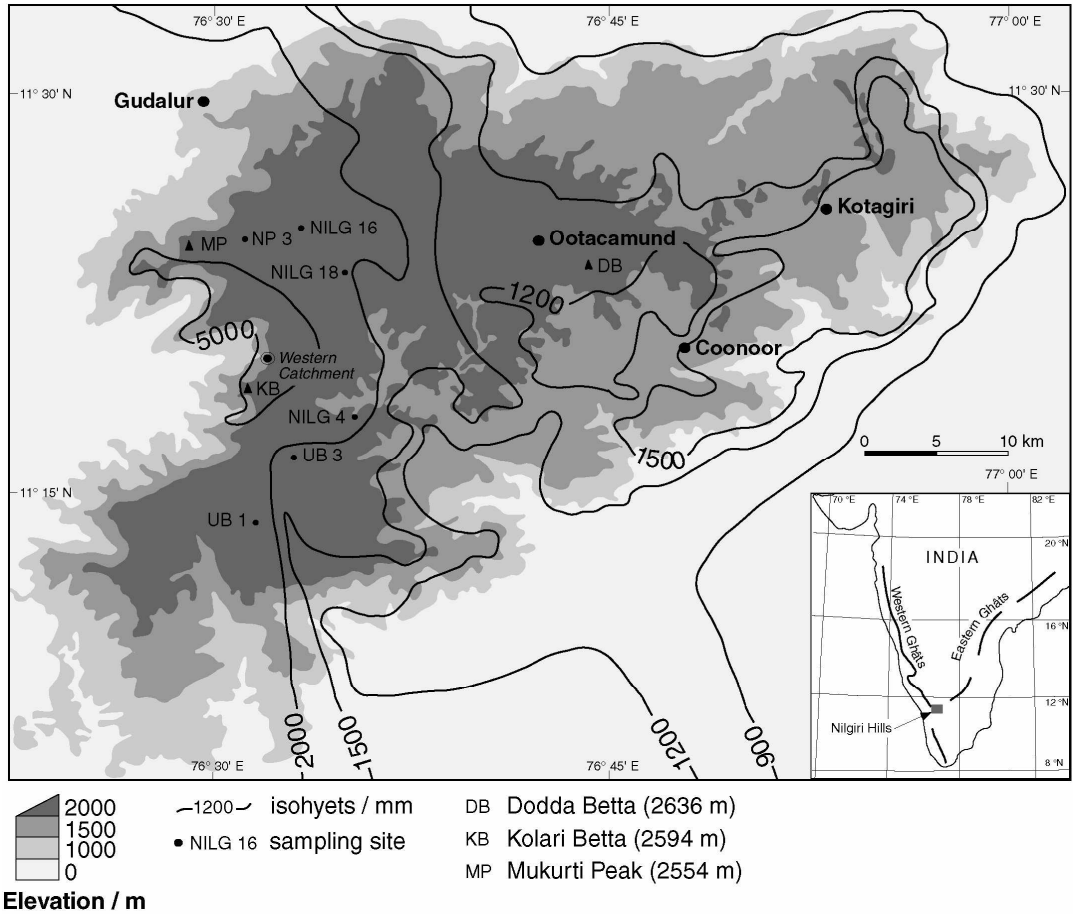

Figure 1: Environmental setting of the Nilgiri Hills and the location of the sampling sites

rounded crests, separate the basins and include the highest points (Dodda Betta, 2636 m; Mukurti Peak 2554 m; Nilgiri Peak 2476 m; Kolari Betta 2594 m), whereas small convex landforms occupy the central parts of the basins.

The bedrock consists of Precambrian charnockites (2.6 Ga). They are hypersthene–bearing granulites dominated by anhydrous silicate minerals (K feldspars and Na plagioclases) resulting from high pressure and high temperature metamorphism. These charnockites are among the hardest and the least porous crystalline rocks of the world and are very resistant to weathering (Gunnell & Louchet, 2000). Despite the hardness of the rock, the Nilgiri Hills exhibit several decametres of low activity clay regolith, including a few bauxite formations (Subramanian & Murthy, 1976). However, the weathering front is irregular, and numerous rock outcrops, sometimes forming impressive near–vertical cliffs, are present.The rainfall distribution in the hills is complex due to the interplay of three mechanisms, namely the south–west monsoon, cyclonic disturbances, and convective rain (Von Lengerke, 1977).

The Western ranges, where we studied the soil, receive 2000–5000 mm y^{-1} mainly from south–west monsoon and secondly from convective rain (Table 1,). The length of the dry season was estimated using rainfall data, potential evapotranspiration (PET, Penman formula) and an assumed available soil water capacity of 200 mm. One month was considered to be dry when the sum of rainfall and available soil water reserve was less than 75% of the PET (Bourgeon, 1988). Based on this calculation, the duration of the dry season is about 2.5 months for the Western region. The frequent mist and fog prevailing on these highlands are also likely to reduce soil moisture losses. At Ootacamund, the main city in the area, the mean annual temperature is 15°C, with a mean daily minimum of 5°C in January and a mean daily maximum of 24°C in April.

Two types of native, high–altitude vegetation occur in the area: an evergreen forest, locally called 'Shola' (dominated by *Lauraceae*, *Myrtaceae*, and *Ericaceae* families), and grasslands of varied floristic compositions. Nowadays, due to deforestation and other human activities, the native forest is present only in valleys and on steep slopes, whereas plantations (tea, *Acacia*, *Eucalyptus*) and vegetable crops occupy large areas.

Sampling

Sites for detailed sampling were selected after field observations during which attention focused on soils with deep organic–rich A horizons reported to occur extensively in this area (Oxic Humitropepts of the soil map, Sehgal *et al.*, 1996). A preliminary sampling of their deep A horizons was made to check to what extent the soils could meet the criteria used to define the Andisols order (Soil Survey Staff, 1998). Several profiles exhibited andic properties sufficient to meet the criteria defining the Andic subgroups in several great groups of Soil Taxonomy, but they were not Andisols. In contrast, other profiles were found to belong to the Andisol order, and we selected six of them for this study. They were described using standard horizon designations (Soil Survey Staff, 1998) and each of their genetic horizons was sampled for laboratory analysis. Their locations are shown in Figure 1.

Laboratory methods

Soil samples were air-dried and passed through a 2–mm sieve before analysis of fine earth. Soil pH was measured in water and in 1 M KCl with a soil solution ratio of 1:2.5. Organic

carbon was determined by dry combustion using a Carmograph 8 Wösthoff and a CHN 1108 Carlo-Erba autoanalyser, total nitrogen by Kjeldhal method, cation exchange capacity (CEC) and exchangeable bases by ammonium acetate (pH 7), and exchangeable Al by 1 M KCl extraction followed by colorimetry.

Particle size distribution analysis was done using sieving for coarse and fine sand fractions and pipetting for silt and clay. Prior to the analysis, samples were treated with 30% H_2O_2 to destroy organic matter, and with acid ammonium oxalate (pH 3.0) to remove amorphous cements. Dispersion was made in water with sodium hexametaphosphate by shaking for 16 hours. For profiles NILG 4, NILG 16 and NILG 18, other particle size analyses were done without the acid ammonium oxalate pre-treatment.

We used selective dissolution to identify the different forms of Al, Fe and Si present in the soils. Three extractants were employed: dithionite–citrate–bicarbonate (DCB) (Mehra & Jackson, 1960) (subscript d); ammonium oxalate (Blakemore *et al.*, 1987) (subscript o); and sodium pyrophosphate (Wada & Higashi, 1976), (subscript p). The optical density of the oxalate extracts (ODOE) was measured by the method of Daly (1982).

Retention of phosphorus was measured by the method of Blakemore *et al.* (1987, pp. 44–45), and melanic index was determined following the method of Honna *et al.* (1988). Bulk density was determined on undisturbed soil samples collected using 100–cm^3 cylinders.

Elemental composition was determined after dissolving 500 mg fine earth in a boiling sulphuric–nitric–hydrochloric acid mixture (triacid digestion). Total reserve in bases (TRB, in cmol kg^{-1}) is the sum of the bases (Ca, Mg, K, Na) dissolved by the triacid digestion.

Mineralogy was assessed from powder X–ray diffraction (XRD) patterns for the different particle–size fractions collected after mechanical separation of soil treated with acid ammonium oxalate. Clay fractions were treated with DCB and examined as oriented clay films by XRD after various chemical and thermal treatments. For some samples, hot Na–citrate extraction was used to allow identification of hydroxy–interlayered–vermiculite (HIV) (Tamura, 1958). Gibbsite content in the clay fraction of the profile NILG 4 was estimated by thermogravimetric analysis using pure gibbsite as a standard.

Table 1: Environmental conditions and morphological characteristics of selected profiles

Pedon	Elevation/ rainfall	Vegetation	Horizon	Depth (cm)	color (moist)	Textural classes[a]	Structure	Clay[b] / g kg^{-1}
NILG 4	2100 m	Forest						
	2200 mm y^{-1}		A_1	0-30	5YR 3/2	cl	crumby	550
			A_2	30-55	5YR 2.5/2	cl	massive	510
			Bw	55-65	5YR 3/3	sc g	massive	400
			$2Bo_1$	65-110	2.5YR 3/6	c g	massive	490
			$2Bo_2$	110-150	2.5YR 3/6	c	massive	460
NILG 16	2100 m	Tree						
	2500 mm y^{-1}	plantation	A_1	0-20	7.5YR 3/2	cl	granular fine	420
			A_2	20-45	5YR 2.5/2	cl	massive	400
			A_3	45-60	5YR 2.5/2	cl	massive	610
			A_4	60-70	5YR 3/3	sc g	massive	480
			Bw	70-85	5YR 3/3	c g	massive	530
			$2Bo_1$	85-100	2.5YR 3/6	c	massive	670
			$2Bo_2$	160	10R 4/6	c	massive	760
NILG 18	2200 m	Tree						
	2500 mm y^{-1}	plantation	A_1	0-15	5YR 3/2	cl	granular fine	580
			A_2	15-35	5YR 2.5/2	cl	massive	590
			A_3	35-60	5YR 2.5/2	cl	massive	600
			A_4	60-80	5YR 2.5/2	sc g	massive	595
			Bw	80-85	2.5YR 3/4	c g	massive	600
			$2Bo_1$	85-95	10R 4/6	c	massive	530
			$2Bo_2$	120-140	7.5R 3/8	c	massive	510
UB 1	2300 m	Tree						
	2200 mm y^{-1}	plantation	A_1	0-20	5YR 3/2	cl	granular fine	590
			A_2	20-55	5YR 2.5/2	cl	massive	650
			A_3	55-65	5YR 3/3	sc g	massive	600
			Bw	65-90	5YR 4/4	c g	massive	630
			$2Bo_1$	90-120	5YR 4/6	c	massive	600
			$2Bo_2$	160	5YR 4/6	c	massive	450
UB 3	2350 m	Savanna						
	2300 mm y^{-1}		A_1	0-20	5YR 2.5/2	cl	granular fine	585
			A_2	20-40	5YR 2.5/2	cl	massive	530
			A_3	40-60	5YR 3/3	sc g	massive	440
			Bw	60-70	2.5YR 4/6	c g	massive	690
			2Bo	100	2.5YR 4/6	c	massive	640
NP 3	2250 m	Tree						
	2500 mm y^{-1}	plantation	A_1	0-20	5YR 2.5/2	cl	granular fine	560
			A_2	20-50	5YR 2.5/2	cl	massive	580
			A_3	50-80	5YR 2.5/2	cl	massive	640
			Bw	80-100	5YR 3/2	sc g	massive	450
			2Bo	130	5YR 4/6	c	massive	680

[a] Textural classes: sc, sandy clay; c, clay; cl, clay loam; g, gravels
[b] Clay : content in clay after destruction of organic matter and an oxalate pretreatment

Results

Morphological characteristics

All soil profiles are characterized by the succession of two groups of horizons: dark–reddish brown (5 YR 2.5/2 or 5 YR 3/2), organic–rich topsoil above reddish to yellowish–red subsurface horizons (Table 1). A 10–cm thick gravelly layer occurs at the transition between these two groups of horizons; it contains 40 to 70% gravel, mainly ferruginous nodules rounded to irregularly shaped, with thin concentric sesquioxide deposits. In some soils, a few of these gravel particles are white and consist of gibbsite. All horizons are porous to very porous with a considerable microporosity. Boundaries between horizons are smooth.

For three profiles, the particle size distributions obtained with and without acid ammonium oxalate treatment indicate a considerable amount of pseudo–sand particles, especially in the subsoil. We checked that the acid ammonium oxalate pre–treatment destroyed these pseudoparticules: i.e. that coarse sand fraction obtained after this pre–treatment comprised mainly quartz particles and small ferruginous nodules.

Chemistry and mineralogy

The values of the molar ratios, $K_i = SiO_2/Al_2O_3$ and $K_r = SiO_2/(Al_2O_3 + Fe_2O_3)$, and the TRB listed in Table 2 show that the gravel layer forming the transition between the top and the subsurface horizons corresponds, in most cases, to a boundary between horizons characterized by distinctly different weathering stages. The top horizons are indeed generally less desilicated (larger K_i and K_r) than the subsurface horizons. Similarly, the TRB values (taken here as a weathering index, see Herbillon, 1986) tend to be larger in the surface layers where the Mg/TRB ratios are also the largest.

X–ray diffraction data for the silt and clay fractions from profiles NILG 4 and NILG 16 can explain these observations. In all fractions (for an example see Figure 2) the top layers contain indeed less gibbsite than the subsurface horizons. By thermogravimetric analysis of the DCB treated clay fractions of NILG 4 , the gradient in gibbsite was found to be as follows: 330 g kg^{-1} in the $2B_{O2}$ horizon, 275 g kg^{-1} in the B_W horizon and 35 g kg^{-1} only in the A_1 horizon. The XRD spectra for the same materials (Figure 2) show also that, as the soil surface is approached and the gibbsite contents decrease, the micas are progressively

Table 2: Selected chemical properties of the soils

Pedon	Horizon	Depth	Organic C	Total N	pH H_2O	pH KCl	Exchangeables bases Ca	Mg	K	Na	CEC	Exch. Al	Ki[a]	Kr[a]	TRB	K/TRB	Mg/TRB
		/ cm	/ g kg^{-1}				/ cmol(+) kg^{-1}								/ cmol(+) kg^{-1}		
NILG 4	A_1	0-30	79	1.3	5.09	4.38	5.6	1.7	0.9	0	35.3	3.2	1.8	1.3	72.5	0.18	0.65
	A_2	30-55	40	2.2	4.93	4.21	0.0	0.1	0.2	0.1	24.3	2.8	1.6	1.2	70.4	0.24	0.69
	Bw	55-65	21	1.0	5.01	4.35	0.1	0.1	0.2	0.1	14.3	2.6	0.9	0.6	40.6	0.31	0.59
	$2Bo_1$	65-110	10	0.7	5.03	4.44	0.1	0.1	0.2	0.1	9.0	1.1	1.3	1.0	44.9	0.49	0.42
	$2Bo_2$	110-150	7	0.3	5.04	4.90	0.7	0.1	0.1	0	4.3	0.7	0.9	0.7	16.3	0.49	0.36
NILG 16	A_1	0-20	139	8.5	4.54	4.00	0.8	0.3	0.3	0	41.3	5.1	1.4	1.0	58.2	0.17	0.81
	A_2	20-45	82	4.8	4.85	4.41	0	0	0.1	0	29.3	2.4	1.2	0.9	69.1	0.17	0.78
	A_3	45-60	40	2.6	5.37	4.47	0	0.1	0.2	0	26.1	0.9	1.2	0.9	89.3	0.23	0.73
	A_4	60-70	31	1.5	5.56	4.55	0.1	0.2	0.2	0	21.2	0.6	1.0	0.7	66.5	0.25	0.72
	Bw	70-85	27	1.4	5.62	4.61	0.3	0.3	0.1	0	17.7	0.5	0.6	0.4	49.9	0.27	0.69
	$2Bo_1$	85-100	6	0.6	5.75	5.91	0	0	0	0	4.2	0	0.2	0.1	21.9	0.54	0.38
	$2Bo_2$	160	3	0.5	5.89	6.26	0	0	0	0	2.6	0	0.2	0.2	25.1	0.59	0.36
NILG 18	A_1	0-15	117	6.5	4.95	4.16	2.6	0.5	0.3	0	35.3	2.7	1.2	0.9	59.6	0.18	0.70
	A_2	15-35	114	5.6	4.73	4.28	0.1	0.2	0.2	0	31.8	3.1	1.4	1.0	54.4	0.19	0.73
	A_3	35-60	53	2.4	4.90	4.51	0.0	0.1	0.1	0.2	26.2	1.3	2.1	1.4	88.5	0.17	0.80
	A_4	60-80	22	1.1	4.91	4.49	0.9	0.4	0.1	0	18.8	0.6	0.9	0.7	45.6	0.31	0.65
	Bw	80-85	10	0.6	4.98	4.83	0.2	0.2	0.1	0	10.4	0	0.3	0.3	34.2	0.44	0.53
	$2Bo_1$	85-95	5	0.3	5.12	5.36	0	0.1	0.1	0	5.7	0.1	0.3	0.2	23.4	0.51	0.45
	$2Bo_2$	120-140	4	0.3	5.33	5.85	0	0.1	0.1	0	1.7	0.1	0.2	0.2	20.0	0.55	0.35
UB 1	A_1	0-20	84	5.2	4.95	4.26	5.1	1.4	0.5	0.4	22.7	2.0	3.6	1.1	68.1	0.25	0.65
	A_2	20-55	55	3.1	4.67	4.28	0.3	0.3	0.2	0.4	22.5	3.7	1.7	1.2	82.4	0.27	0.69
	A_3	55-65	26	1.4	4.80	4.29	1.0	0.6	0.2	0.5	15.0	2.4	1.5	1.0	89.1	0.29	0.67
	Bw	65-90	11	0.8	5.02	4.25	1.6	0.8	0.2	0.4	10.6	1.2	1.5	1.1	79.6	0.40	0.55
	$2Bo_1$	90-120	10	0.8	4.99	4.66	1.7	0.9	0.2	0.3	10.0	0.2	0.5	0.6	61.4	0.38	0.56
	$2Bo_2$	160	7	0.4	5.05	5.02	1.2	0.5	0.1	0.5	6.3	0	0.7	0.5	26.5	0.39	0.57
UB 3	A_1	0-20	156	10.1	4.74	4.12	6.0	0.6	0.6	0.5	33.2	3.5	1.9	1.2	60.7	0.24	0.58
	A_2	20-40	83	4.8	4.52	4.32	0.2	0.1	0.3	0.3	21.0	3.0	1.4	0.9	60.8	0.26	0.68
	A_3	40-60	21	1.1	4.67	4.44	0.2	0.1	0.2	0.4	13.4	0.9	0.9	0.6	113.4	0.58	0.39
	Bw	60-70	10	0.6	4.88	4.77	0.7	0.3	0.2	0.4	5.6	0.1	0.6	0.5	46.3	0.53	0.43
	2Bo	100	6	0.5	4.76	5.76	0.3	0.1	0.1	0.6	2.4	0	0.5	0.4	43.0	0.59	0.36
NP 3	A_1	0-20	126	7.9	4.55	4.15	0.7	0.3	0.3	0.2	36.1	3.6	1.5	1.1	65.3	0.18	0.75
	A_2	20-50	102	6.1	4.51	4.18	0	0.1	0.2	0.2	29.8	4.8	1.4	1.0	64.7	0.19	0.77
	A_3	50-80	67	4.0	4.56	4.30	0	0.	0.2	0.1	28.7	2.8	1.6	1.1	69.4	0.21	0.75
	Bw	80-100	35	1.7	4.81	4.48	0	0.1	0.1	0.2	15.4	1.2	1.2	0.7	74.7	0.28	0.69
	2Bo	130	15	0.9	4.75	4.53	0.1	0.1	0.1	0.1	10.2	0.3	0.8	0.7	79.2	0.41	0.55

[a] Ki = SiO_2/Al_2O_3 molar ratio, Kr = $SiO_2/(Al_2O_3 + Fe_2O_3)$ molar ratio

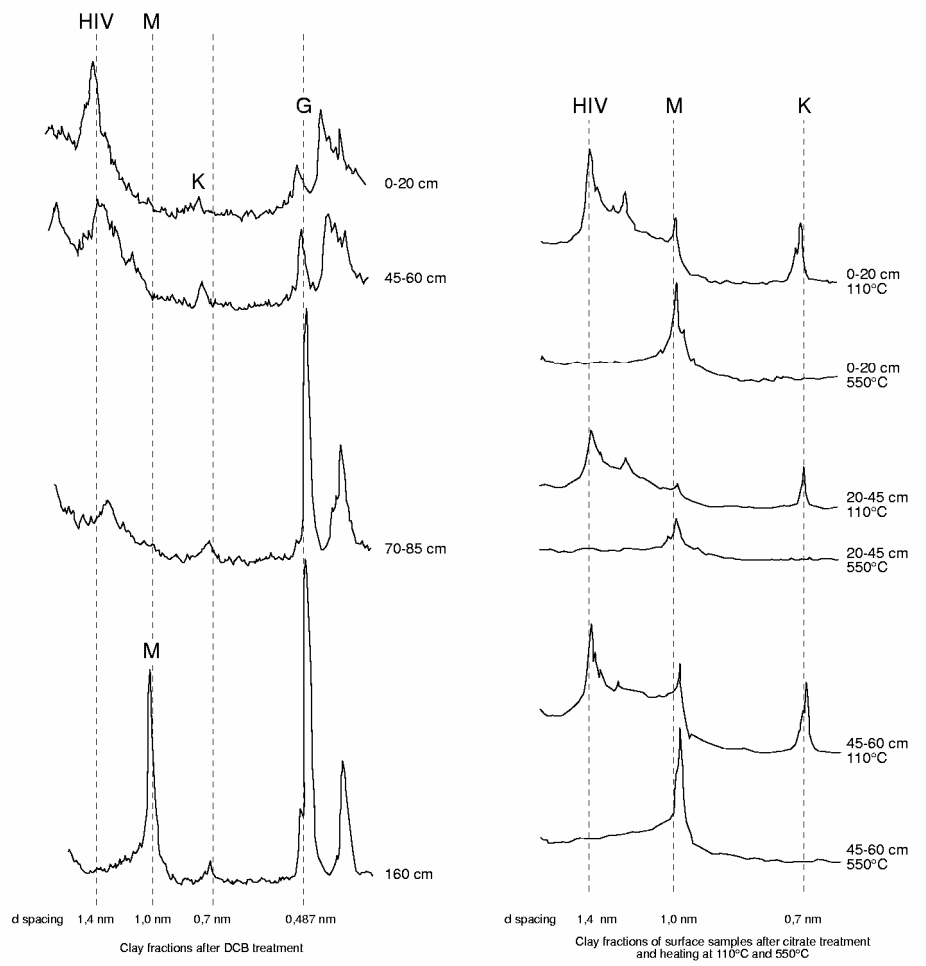

Figure 2: X-ray difraction patterns of clay fractions for the profile NILG 16

(G: gibbsite, HIV: Hydroxy-interlayered Vermiculite, K: kaolinite, M: mica)

transformed into hydroxyaluminium–interlayered–vermiculite (HIV). The K/TRB ratios decreasing towards the surface (Table 2) also accord with this transformation. On the other hand, the XRD spectra of the silt fractions (not shown) indicate that the larger TRB and Mg/TRB ratios (Table 2) in the topsoil is linked to the presence of amphibole particles. This Mg–bearing primary mineral was not found in the deep $2B_O$ horizons.

Thus, the available chemical and mineralogical data show that all the profiles have a lithologic discontinuity which, morphologically, is marked by a gravel layer. Below this layer, the materials have a secondary mineral assemblage that can be defined as 'allitic' (i.e. > 180 g kg^{-1} gibbsite). In contrast, in the upper horizons where there is little gibbsite and HIV minerals increase, the assemblage is similar to that defining the kaolinitic mineralogy class of LAC soils.

Table 2 shows also that the changes in mineralogy with depth are reflected by the surface charge properties of the different horizons. In profiles NILG 16, NILG 18, UB 1 and UB 3, the $2B_O$ horizons have very low ECEC and ΔpH values that indicate the presence of positive surface charges. In contrast, the upper horizons are always more acidic, and their KCl–extractable Al increases towards the soil surface where the occurrence of HIV is most evident (Figure 2).

Other chemical properties are also listed in Table 2. Among them, carbon contents exceeding everywhere a weighted average of 60 g kg^{-1} in the top 50 cm should be specially noted.

Andic properties and soil classifications

All the data required for the identification of andic properties are shown in Table 3. All the topsoils have a sufficient thickness with a combination of properties (Al_o + ½ Fe_o, P retention, bulk density) required for Andisols. With the exception of the upper A1 horizon of NILG 4, which is the only soil sampled under forest, all horizons exhibiting andic properties have also a melanic index less than 1.7.

Table 3 gives also the names that can be assigned to the profiles (in following the keys proposed according to the World Reference Base (WRB) (FAO, 1998) and the Soil Taxonomy (Soil Survey Staff, 1998). It appears that despite the values of their melanic index, the topsoils of these profile do nt have melanic properties. This is because their (dark–reddish brown) colour reflects better the mineralogy of their iron oxides fraction (identified by XRD as a mixture of goethite and haematite) than the melanic character of their humic constituents.

Selective dissolutions

The results, including ratios and differences enabling to partition Al, Fe and Si into different forms according to the nature of extractants used (Parfitt & Childs, 1988), are listed in Table 4. However, as several authors have done earlier, we consider these forms as operational classes of constituents only.

The difference (Fe_d – Fe_o), which is used here to estimate the content of crystalline Fe oxides in the fine earth, increases systematically with depth and is maximum either in the gravel layer or in the horizon immediately below it. Thus, the distribution of crystalline Fe oxides with depth shows some similarities to the distribution of gibbsite and confirms

Table 3: Andic properties and classification of Nilgiri soils

Profile	Horizon	Depth / cm	$Al_o + 1/2\ Fe_o$ / g kg^{-1}	Bulk density / kg dm^{-3}	P retention / %	Melanic index	Classifications
NILG 4	A_1	0-30	26.0	0.74	97	1.92	Umbri-Pachic
	A_2	30-55	25.2	0.89	98	1.53	Andosol (acroxic)[a]
	Bw	55-65	17.1	-	85	-	Acrudoxic
	$2Bo_1$	65-110	10.6	0.98	83	-	Fulvudand[b]
	$2Bo_2$	110-150	9.3	-	83	-	
NILG 16	A_1	0-20	29.5	0.47	98	1.66	Umbri-Pachic
	A_2	20-45	35.6	-	99	1.59	Andosol[a]
	A_3	45-60	30.8	0.72	99	1.60	Pachic Fulvudand[b]
	A_4	60-70	25.7	-	99	-	
	Bw	70-85	23.2	-	98	-	
	$2Bo_1$	85-100	7.9	-	85	-	
	$2Bo_2$	160	9.3	1.09	96	-	
NILG 18	A_1	0-15	30.2	0.78	97	1.62	Umbri-Pachic
	A_2	15-35	32.0	0.74	99	1.62	Andosol[a]
	A_3	35-60	30.8	0.78	99	1.73	Pachic Fulvudand[b]
	A_4	60-80	21.3	-	97	-	
	Bw	80-85	14.4	-	92	-	
	$2Bo_1$	85-95	11.9	-	92	-	
	$2Bo_2$	120-140	9.0	1.18	-	-	
UB 1	A_1	0-20	22.5	0.58	93	1.60	Umbri-Pachic
	A_2	20-55	29.4	-	95	1.60	Andosol[a]
	A_3	55-65	21.3	0.77	97	1.90	Pachic Fulvudand[b]
	Bw	65-90	14.8	-	86	-	
	$2Bo_1$	90-120	15.7	-	90	-	
	$2Bo_2$	160	10.7	1.13	76	-	
UB 3	A_1	0-20	24.6	0.60	94	1.62	Umbri-Pachic
	A_2	20-40	33.6	-	99	1.51	Andosol (acroxic)[a]
	A_3	40-60	22.3	0.72	95	1.77	Acrudoxic
	Bw	60-70	13.5	-	87	-	Fulvudand[b]
	2Bo	100	8.9	1.05	90	-	
NP 3	A_1	0-20	30.5	0.44	90	1.65	Umbri-Pachic
	A_2	20-50	34.1	0.64	94	1.50	Andosol[a]
	A_3	50-80	30.1	0.66	99	1.73	Pachic Fulvudand[b]
	Bw	80-100	23.4	-	95	-	
	2Bo	130	12.4	0.89	89	-	

[a]According to WRB (FAO, 1998)
[b]According to Soil Taxonomy (Soil Survey Staff, 1998)

that the A horizons have less crystalline secondary Al and Fe oxides than the underlying horizons.

In the A horizons with andic properties, the large Fe_p/Fe_o ratios suggest that the iron is present mainly as metal–humus complexes. However, as some Fe_p/Fe_o ratios exceed 1,

Table 4: Data of selective dissolutions procedures

Profile	Horizon	DCB			Oxalate			Pyrophosphate		Fe_d -Fe_o	Al_p/Al_o	Fe_p/Fe_o	ODOE[a]
		Fe	Si	Al	Fe	Si	Al	Fe	Al				
		/ g kg^{-1}											
NILG 4	A_1	45.8	0.7	20.0	13.4	0. 7	19.3	15.1	18.2	32.4	0.94	1.13	1.08
	A_2	62.8	1.9	21.4	14.6	0.5	17.9	15.7	15.2	48.2	0.85	1.08	0.99
	Bw	100.5	1.5	17.4	12.3	0.4	10.9	9.7	6.8	88	0.62	0.79	0.90
	$2Bo_1$	80.9	2.7	16.0	7.5	0.4	6.8	0.1	0.3	73.40	0.04	0.01	0.48
	$2Bo_2$	85.3	1.0	8.0	11.3	0.2	3.6	0.5	0.3	74.0	0.08	0.04	0.26
NILG 16	A_1	40.7	2.3	22.0	16.0	2.3	21.5	10.7	17.4	24.7	0.81	0.67	1.10
	A_2	53.1	0.4	30.0	16.7	1.2	27.2	16.9	23.1	36.4	0.85	1.01	1.05
	A_3	72.0	0.4	31.1	15.1	1.0	23.2	17.2	21.8	56.9	0.94	1.14	0.91
	A_4	114.7	0.5	30.0	15.6	1.0	17.9	16.5	16.6	99.1	0.93	1.06	0.81
	Bw	107.4	1.3	24.0	16.1	0.7	15.1	16.9	16.3	91.3	1.08	1.05	0.81
	$2Bo_1$	140.1	0.5	9.3	8.54	0.2	3.6	0.2	0.3	131.6	0.08	0.02	
	$2Bo_2$	131.0	1.2	4.0	12.8	0.2	2.9	0.1	0.3	118.2	0.10	0.01	
NILG 18	A_1	54.4	0.4	26.7	16.1	1.3	22.1	14.3	17.5	38.3	0.79	0.89	nd
	A_2	53.0	0.3	28.9	16.2	1.2	23.9	16.8	20.0	36.8	0.84	1.04	nd
	A_3	71.4	0.2	34.4	16.2	1.3	22.7	19.6	20.0	55.2	0.88	1.21	nd
	A_4	94.3	0.2	25.6	16.6	0.6	13.0	15.6	8.8	77.7	0.68	0.94	nd
	Bw	81.3	0.2	17.4	12.0	0.5	8.4	5.3	4.3	69.3	0.51	0.44	nd
	$2Bo_1$	93.6	0.2	13.0	13.6	0.3	5.1	nd	nd	80.0	nd	nd	nd
	$2Bo_2$	129.2	0.3	7.0	12.6	0.1	2.7	nd	nd	116.6	nd	nd	nd
UB 1	A_1	68.9	3.0	22.6	13.9	1.0	15.5	8.8	9.3	55.0	0.60	0.63	1.68
	A_2	63.1	2.7	24.0	16.5	1.0	21.1	15.8	14.9	46.6	0.71	0.96	1.82
	A_3	80.5	2.5	22.6	13.4	0.8	14.6	14.1	9.1	67.1	0.62	1.05	0.84
	Bw	79.7	2.9	17.4	12.3	0.7	8.6	4.9	3.9	67.4	0.45	0.40	0.44
	$2Bo_1$	96.1	2.6	20.0	13.7	0.7	8.8	nd	nd	82.4	nd	nd	0.46
	$2Bo_2$	102.2	1.7	18.7	10.0	0.3	5.7	nd	nd	92.2	nd	nd	0.35
UB 3	A_1	59.7	1.8	18.7	13.5	0.8	17.8	9.0	12.6	46.2	0.71	0.67	1.97
	A_2	78.9	2.6	25.6	18.9	1.4	24.1	13.4	16.6	60.0	0.69	0.71	2.43
	A_3	118.2	2.1	25.6	15.7	0.7	14.5	11.0	7.4	102.5	0.51	0.70	0.83
	Bw	102.7	1.4	18.7	11.0	0.3	8.0	nd	nd	91.7	nd	nd	0.44
	2Bo	125.3	2.3	17.4	10.1	0.2	3.9	nd	nd	115.2	nd	nd	0.33
NP 3	A_1	57.4	2.0	20.8	18.6	1.0	21.2	13.8	15.1	38.8	0.71	0.74	3.07
	A_2	57.4	1.7	24.0	21.4	0.7	23.4	19.3	18.8	36.0	0.80	0.90	3.20
	A_3	56.7	1.0	24.0	16.9	0.8	21.6	17.7	18.0	39.8	0.83	1.05	2.57
	Bw	66.4	2.3	27.2	10.4	0.8	18.2	11.6	11.5	56.0	0.63	1.12	0.67
	2Bo	80.6	1.3	20.8	8.0	0.5	8.4	nd	nd	72.6	nd	nd	0.44

[a] ODOE : Optical density of the oxalate extract measured by the method of Daly (1982)

we cannot be sure that the pyrophosphate reagent does not disperse also some finely divided crystalline iron oxides (Jeanroy & Guillet, 1981). In the same horizons, the Al_p/Al_o ratio is always larger than 0.5, and the Si_o value is less than 6 g kg^{-1} as in the Aluandic horizon of the WRB (FAO, 1998) Thus, Al also is present mainly as metal–humus complexes, and the Andisols of this study can be considered as non-allophanic.

Figure 3 shows that the pyrophosphate–extractable humic substances of the andic horizons have an Al content similar to that of the non-allophanic horizons ($Al_p/Al_o > 0.5$ and $Si_o < 5$ g kg^{-1}) listed in the Andisol TU database (Nanzyo *et al.*, 1993). As for Fe_p, however, the presence of gibbsite (see Figure 2) suggests that Al_p might overestimate the Al really involved in metal–humus complexes (Kaiser & Zech, 1996).

The decrease of the optical density of the oxalate extract (ODOE, Table 3) with depth reveals that cheluviation of metal–humus complexes does not occur in these soils, what accords with their large metal content.

Discussion

Origin of Andisols

Located on the highest plateaux of Southern India, the Nilgiri Andisols occupy geomorphological positions suggesting that they result from a long and probably complex history. At least two major events are important. The first one, which may have been initiated as early as Eocene (Subramanian & Mani, 1981), was responsible for the formation of thick regoliths in which gibbsite and iron oxides became important secondary constituents. More recently, possibly after the last climatic change towards cooler conditions in these highlands since about 40000 years B.P. (Sukumar *et al.*, 1993, Rajagopalan *et al.*, 1997), a new cycle of soil formation involving substantial accumulation of organic matter is likely to have been the key process in the development of Andisols.

In the absence of volcanic glasses, and taking also into account the small contents of other primary weatherable minerals even in the least weathered materials above the gravel lines, the development of andic properties in the Nilgiri area results mainly from the interactions between their organic colloids and the oxides inherited from a previous weathering cycle. This hypothesis is supported by: (a) the well known ability of oxide

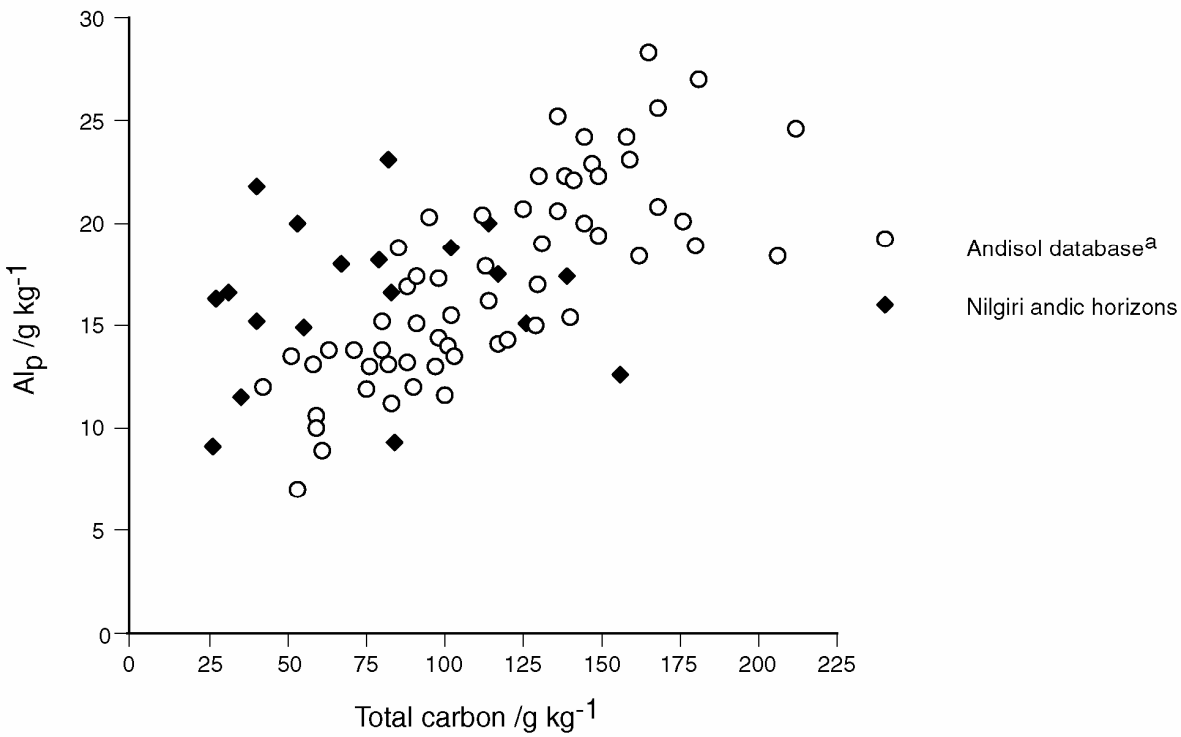

Figure 3: Relation between Alp and total carbon. [a] data obtained from the TUWAD (Nanzyo *et al.*, 1993) corresponding to A horizons exhibiting andic properties with an udic soil moisture regime, an $Al_p/Al_o > 0.5$ and an $Si_o < 5$ g kg^{-1}

surfaces to adsorb and stabilize humic substances (Oades, 1989), and (b) the likelihood that, under acidic conditions (see pH values in Table 2), this adsorption process is accompanied by the weathering by complexation of small fractions of oxides involved. This last step is in agreement with the observations that the solubility of both gibbsite and crystalline iron oxides may increase by at least two orders of magnitude in the presence of organic acids (see e.g. Chesworth & Macías, 1985 and the experimental data obtained by Righi *et al.*, 1982).

In the Nilgiri Hills, as in other high-altitude humid environments (Wilke & Schwertmann, 1977; Madeira & Furtado, 1987), the mechanisms described above would explain, at least partly, the trend shown by both gibbsite and crystalline iron oxides contents toward decrease near the soil surface and to be minimal where the organic matter contents are at their maximum. On the other hand, a simple calculation shows that the weathering of either 58 g kg^{-1} of gibbsite or 65 g kg^{-1} of goethite (or a combination of sufficient amounts of gibbsite and goethite) can give rise to an (Al_o + ½ Fe_o) value of 20 g kg^{-1} (i.e. the concentration of oxalate–soluble metals defining the andic properties).

Here, the K_i and K_r values (Table 2) of LAC materials from which the Andisols derive indicate that these amounts represent only small fractions of their oxide contents.

In summary, we propose that the formation of Nilgiri Andisols might result from the succession of the following processes: (a) accumulation of crystalline Fe and Al oxides during a former 'lateritic' weathering cycle, and (b) accumulation of organic matter favoured by a climatic change, followed by (c) the weathering by complexation of enough oxides to give rise to the observed andic properties.

Conclusions

The occurrence of Andisols derived from 'lateritic' parent materials shows that several types of Al and Fe–bearing minerals enable the development of andic properties. In the Nilgiri Hills these constituents are neither volcanic glasses (Shoji *et al.*, 1993) nor other easily weatherable primary minerals (Garcia-Rodeja *et al.*, 1987), but secondary oxides usually taken as indicators of an advanced weathering stage (Jackson, 1968, Chesworth, 1973). This finding reminds us that, under environmental conditions favouring organic matter accumulation and supplying large amounts of complexing acids, these oxides are no longer stable. They may thus become appropriate sources of metal for metal–humus complexes, i.e. for constituents characteristic of non-allophanic Andisols.

On the other hand, we believe that our findings also have some relevance with respect to the geographical distribution of Andisols on LAC material and of LAC soils showing andic properties. Laterized highlands in cool and humid climates are known in several parts of the tropics. These areas have also been reported to be places where organic matter–rich LAC soils are generally found (Van Wambeke, 1992). These observations suggest that LAC Andisols similar to those described in the present study might have a broader geographical extension than reported so far.

Acknowledgements

We are indebted to P. Arumugam, K. Balasubramanian and G. Orukaimani from the French Institute of Pondicherry for their help with the soil analysis. We also thank P. Larqué, CGS Strasbourg and F. Lhote, CRPG Nancy who obtained the X–Ray diffraction patterns. J. Ranger from INRA Champenoux helped in the HIV identification.

Dr Nanzyo from Tohoku University, Japan, is gratefully acknowledged for granting access to TU World Andisol Database. Were are also deeply indebted to the anonymus reviewers for constructive comments.

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