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Andisols of the Nilgiri highlands: new insight into their classification, age and genesis

Laurent CANER[a,b] and Gérard BOURGEON[c]

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[a]*French Institute of Pondicherry 11, St. Louis Street, P.B. 33, Pondicherry 605 001, India,*
[b]*Centre de Pédologie Biologique - CNRS, UPR 6831 and Université Henri Poincaré - Nancy I, B.P. 5, 54501 Vandœuvre-Lès-Nancy, France*
[c]*CIRAD-AMIS - TA 40 / 01, 34 398 Montpellier cedex 5*

Introduction

In India, soils have, for a long time, been classified according to their colour. Nilgiri soils have not escaped this rule and Francis (1908), in the district gazetteer dealing with this region, noticed that ‘four varieties are usually recognised. These are the black, which is a rich loam and the best of all… the brown… the yellow… and the red soil…’. This study focuses exclusively on the ‘black soils’ of the Nilgiri Hills. Detailed results regarding their properties, genesis, and classification in modern taxonomies are provided and demonstrate that these soils, which occur on hillslopes and hilltops, are very different from the other ‘black’ soils occurring in South India: namely peat soils, which are also found in the Nilgiri Hills but are restricted to valley floors; and Vertisols, which occur on colluvio-alluvial parent material in the Deccan traps as well as portions of the Precambrian basement. Isotopic results bring to light the influence of palaeoecological conditions, particularly the impact of a colder period, characterised by grassland vegetation at the end of the Pleistocene, on the *in-situ* accumulation of organic matter.

Environmental setting

The soils presented here were sampled in the Nilgiri highlands (Tamil Nadu, South India) which are situated between 11°00'-11°30' N and 76°00'-77°30' E, at elevations ranging between 2000 and 2400 m (Fig. 1, Table 1).

The Nilgiri massif is located at the junction of the Eastern and Western Ghats and is bounded by abrupt slopes. Its central plateau corresponds to an old planation surface and is divided, according to Demangeot (1975, *this volume*), into several basins. Hill ranges, with rounded crests at about 2400-2600 m, separate the different basins and constitute the highest points of the massif, whereas convex mature landforms, at a mean altitude of 2000 to 2200 m, occupy the central parts of the basins.

The bedrock consists of Precambrian (2.6 Ga) metamorphic rocks, mainly charnockites (Howie, 1955; Naqvi and Rogers, 1987). The charnockites of South India are among the hardest and less porous rocks of the world, which implies a low susceptibility to weathering and erosion and explains the presence of charnockitic highlands in South India and Sri Lanka (Gunnell and Louchet, 2000, *this volume*).

The vegetation of the highlands (above 2000 m) is a mosaic of high-elevation evergreen forests, locally named ‘shola’, and grasslands of different floristic compositions (Blasco, 1971) containing C4 grass species (Sukumar *et al.*, 1993, Rajagopalan *et al.*, 1997).

The present climatic conditions are characterised by a mean annual temperature of about 15°C, with a minimum of 5°C in January and a maximum of 24°C in April (Von Lengerke, 1977). The annual rainfall, which reaches 5000 mm yr^{-1} in the western ranges, supplied mainly by south-west monsoon rains, decreases to less than 1200 mm yr^{-1} in the central rain shadow area of Ootacamund, and increases again to 1500 mm yr^{-1} in the eastern area (Fig. 1) due to convective showers (Von Lengerke, 1977; Pascal, 1982).

Review of main existing work on Nilgiri soils

The soils presented here are well drained (not saturated with water) and, for this reason, must not be confused with peat soils, which are also present in the low-lying areas of these highlands (see Blanford, 1859, *this volume*; and Sukumar *et al.*, 1993 and references therein).

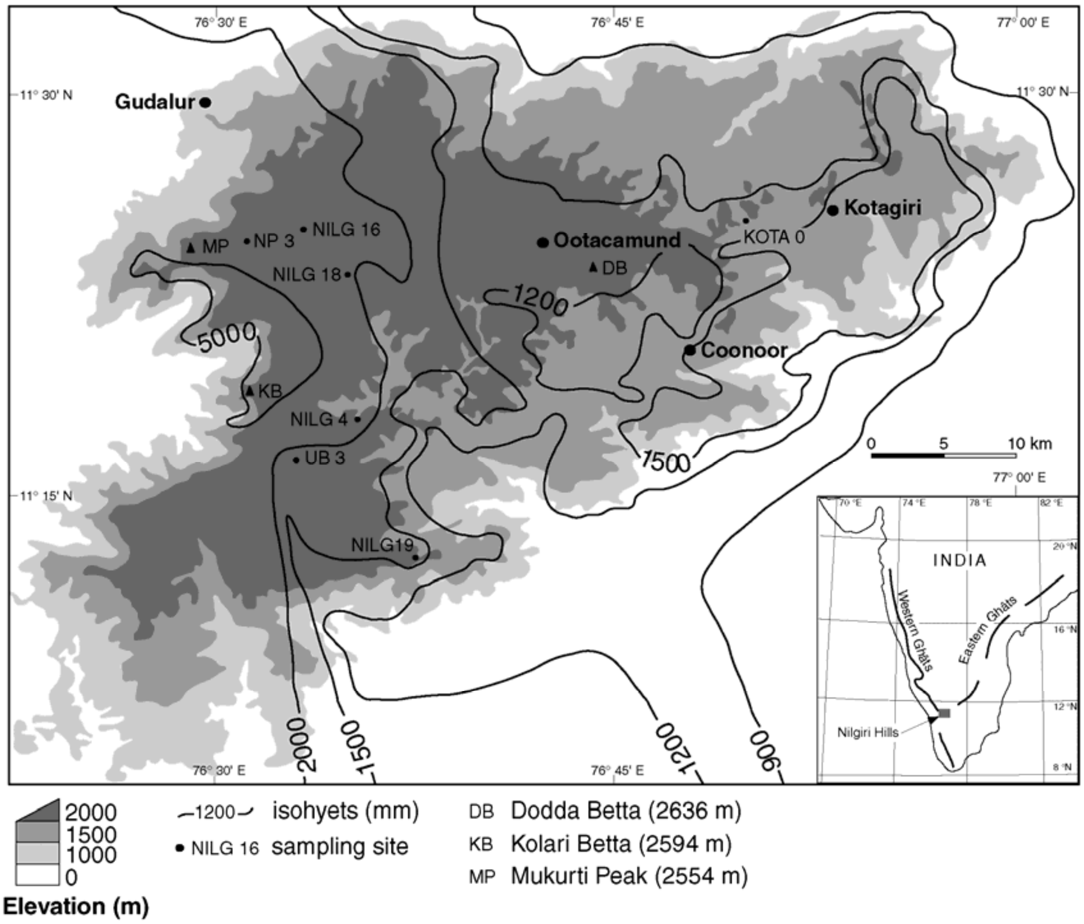

Figure 1: Bioclimatic setting of the Nilgiri highlands and location of selected profiles.

After having been initially classified according to their colour (Govindra Rajan and Basavanna, 1960), the Nilgiri ‘black soils’ were considered for a long time as ‘lateritic’ or ‘bauxitic’ soils (i.e. low activity clays soils) due to their high contents in aluminium and iron oxides, and low Si / sesquioxide ratios (Mahalingam and Durairaj, 1968; Subramaniam and Murthy, 1976; Naga Bushana, 1982; Sannigrahi *et al*., 1990). Their high carbon content was attributed to the low mean annual temperature (altitudinal effect) which hinders the biodegradation of organic matter.

Troy *et al*. (1977), who studied the soils of the Palni Hills, concluded that they were recent (monogenetic soils) and resulted from an intense removal of silica and a relative accumulation of aluminium and iron oxides (ferrallitisation). Organic matter accumulation was attributed to the interaction between organic matter and the sesquioxides. These soils were classified *as Sols Ferrallitiques Humifères* (CPCS, 1967).

While preparing the soil map of Tamil Nadu, Sehgal *et al*. (1996) classified most Nilgiri soils as Ultisols, which stresses their high intensity of weathering; others were classified as Inceptisols, when a clay-enriched subsurface horizon was not clearly identified. Their high content in organic matter was specified either at the suborder level for Ultisols (Typic Haplohumults), or at the great group level for Inceptisols (Oxic Humitropepts). These classifications are based on the former Soil Taxonomy rules and definitions (Soil Survey Staff, 1975), which were still in use when the soil survey of the different Indian States was launched.

In all the aforementioned works, the Nilgiri soils were considered as 'low activity clay soils' resulting from a very complete weathering of the charnockite with an important desilification and a and relative accumulation of aluminium and iron oxides. Soil genesis on the Nilgiri highlands was therefore assumed to be monogenetic and monocyclic (i.e., the soils were recent and their entire profiles had developed under a single set of environmental conditions).

Bourgeon (1988) discussed for the first time a possible polycyclic origin for 'black' soils in the Nilgiri Hills and related it to climatic change. He proposed that the soils may have resulted from the succession of at least two cycles of soil formation: the initial development of a deep 'lateritic' soil cover, followed by a more recent pedogenesis characterised by the accumulation of organic matter in the topsoil. Despite the geologically more realistic approach to the genesis of Nilgiri soils provided by this hypothesis, some of their properties and the pathways leading to the formation of the thick organic-matter rich surface horizon remained unexplained. This study provides new insight into the origin of the Nilgiri soils.

Properties, genesis, and current classification of Nilgiri 'black soils'

Profile morphology and general soil properties

Most of the black soils at high elevations present an unusual profile morphology, with the superposition of thick (60-100 cm) dark reddish-brown (5 YR 2.5/2) surface horizons above a reddish (2.5 YR 3/6) 'lateritic' material (Fig. 2). Table 1 summarises the main physical and chemical properties of the soils. The transition between the two contrasted groups of horizons is marked by a stone line (10-15 cm thick) containing 40 to 70 % gravel, mainly composed of rounded to irregularly shaped ferruginous nodules with thin concentric sesquioxide coatings. It is, at this stage, impossible to establish the precise origin of this widespread stone line unit.

Figure 2: Superposition of a thick, black organic horizon above ‘lateritic’ material, forming the typical Nilgiri Andisols near Avalanche (11°17’56”N, 76°35’57”E, 2100 m). This polygenetic and polycyclic profile constitutes a bisequum (photo: G. Bourgeon). Profile description (also valid for NILG 4, see Tables 1, 2 and 3) — 0-20 cm: dark reddish-brown (5 YR 3/2, moist), mull type humus, crumby structure, very friable, smooth boundary; 20-55 cm: dark reddish-brown (5 YR 2.5/2, moist), clay loam, friable to very friable, many fine roots, smooth boundary; 55-65 cm: gravelly transition horizon (stone line), dark reddish-brown (5 YR 3/3, moist), sandy clay with 50 to 75% of coarse elements (nodules), massive structure, many fine roots, smooth boundary; 65-110 cm and deeper: dark red (2.5 YR 3/6, moist), clay loam with pseudoparticles, massive structure, roots, very friable (moist) to hard (dry), very porous (microporosity).

Although it could be of a sedimentary nature (transported hillslope material related to the truncation by erosion of the underlying lateritic profile), its field characteristics rather suggest a purely pedogenetic origin reminiscent of iron-pan development. The origin and spatial distribution of this highland stone line clearly deserves further investigation.

The different A-horizons present high carbon contents, ranging from 2.1 to 15.6 % (Table 1). The carbon stock for the entire profile, calculated using soil bulk density at the relevant sampling depths, varies from 30 to 50 kg m^{-2}. The soils are relatively acidic, clay-loamy, with pH_{water} varying from 4.09 to 5.56, and with particularly high amounts of exchangeable Al (1.6 to 9.6 meq / 100 g) in their top horizons. The materials located below the stone line have a mineralogy dominated by iron and aluminium oxides, as indicated by their very low Ki ratios (Table 1), X-Ray diffraction data (Table 1) and large amounts of Fe extractable with DCB (Caner *et al.*, 2000). All of these parameters are characteristic of low-activity clay materials (Herbillon, 1980). These features are symptomatic

Table 1: Selected properties of the studied profiles

Profile name Elevation Ann. rainfall	Depth	Organic C	Clay	pH	S^a	CEC	Ki^b	XRD
	cm	%	%	H_2O	meq / 100g			
NILG 4								
2100 m	0-30	7.9	55	5.09	8.2	35.3	1.8	G, HIV
2200 mm y^{-1}	30-55	4.0	51	4.93	0.4	24.3	1.6	G, HIV
	55-65	2.1	40	5.01	0.5	14.3	0.9	**G**, Go, M
	65-110	1.0	49	5.03	0.5	9.0	1.3	**G, Go**, M, H, K
	110-150	0.7	46	5.04	0.9	4.3	0.9	**G, Go**, M, H, K
NILG 16								
2100 m	0-20	13.9	42	4.54	1.4	41.3	1.4	G, HIV
2500 mm y^{-1}	20-45	8.2	40	4.85	0.1	29.3	1.2	G, HIV
	45-60	4.0	61	5.37	0.3	26.1	1.2	G, HIV
	60-70	3.1	48	5.56	0.5	21.2	1.0	G, HIV
	70-85	2.7	53	5.62	0.7	17.7	0.6	**G**, Go, M
	85-100	0.6	67	5.75	0.0	4.2	0.2	**G, Go**, M, H, K
	160	0.3	76	5.89	0.0	2.6	0.2	**G, Go**, M, H, K
NILG 18								
2200 m	0-15	11.7	58	4.95	3.4	35.3	1.2	G, HIV
2500 mm y^{-1}	15-35	11.4	59	4.73	0.5	31.8	1.4	G, HIV
	35-60	5.3	60	4.90	0.4	26.2	2.1	G, HIV
	60-80	2.2	59	4.91	1.4	18.8	0.9	G, HIV
	80-85	1.0	60	4.98	0.5	10.4	0.3	**G**, Go, K
	85-95	0.5	53	5.12	0.2	5.7	0.3	**G, Go**, M, H, K
	120-140	0.4	51	5.33	0.2	1.7	0.2	**G, Go**, M, H
UB 3								
2350 m	0-20	15.6	59	4.74	7.7	33.2	1.9	G, HIV
2300 mm y^{-1}	20-40	8.3	53	4.52	0.9	21.0	1.4	G, HIV
	40-60	2.1	44	4.67	0.9	13.4	0.9	G, HIV
	60-70	1.0	69	4.88	1.6	5.6	0.6	**G**, Go, M, K
	100	0.6	64	4.76	1.1	2.4	0.5	**G, Go**, M, H, K
NP 3								
2250 m	0-20	12.6	56	4.55	1.5	36.1	1.5	G, HIV
2500 mm y^{-1}	20-50	10.2	58	4.51	0.5	29.8	1.4	G, HIV
	50-80	6.7	64	4.56	0.3	28.7	1.6	**G**, HIV
	80-100	3.5	45	4.81	0.4	15.4	1.2	**G**, Go, M, K
	130	1.5	68	4.75	0.4	10.2	0.8	**G, Go**, M, H, K
NILG 19								
2100 m	0-20	11.4	38	4.63	10.4	39.8	3.9	G, HIV, K
1700 mm y^{-1}	20-45	6.7	40	4.82	6.3	31.3	3.9	G, HIV, K
	60-80	4.8	47	4.45	1.5	26.7	3.2	G, HIV, K
	95-105	3.6	49	3.98	0.5	13.7	2.5	G, HIV, K
	120-135	0.7	55	3.91	0.5	7.8	1.6	**G**, Go, K
	160	0.6	33	4.35	0.6	3.0	0.5	**G, Go**, M, H, K
KOTA 0								
2100 m	0-20	9.9	48	4.09	1.7	38.2	1.6	G, HIV, K
1300mm y^{-1}	30-40	3.5	65	4.61	1.1	33.4	1.8	G, HIV, K
	50-65	4.2	62	4.68	0.4	32.2	1.5	G, HIV, K
	80-120	2.2	54	4.79	0.3	18.8	1.2	**G**, HIV
	120-135	0.9	49	4.73	0.7	10.3	1.1	**G**, Go, M

[a] Sum of exchangeable bases

[b] $K_i = SiO_2/Al_2O_3$ molar ratio

[c] Minerals identified by X-Ray diffraction: G: gibbsite, Go: goethite, M mica, He: hematite, K: Kaolinite, HIV: hydroxyaluminium-interlayered-vermiculite. Bold characters indicate large amounts.

of the weathering environment which prevailed during the formation of the ‘lateritic’ cover which developed from the charnockitic parent rock of these highlands. It remains difficult to age-bracket this particular lateritising episode of the geological past, but it is likely that it was protracted and spanned the Late Cretaceous and Palaeogene at least.

Above the stone line, the organic-matter rich horizons are characterised by the presence of ‘amorphous’ organo-metallic forms of iron and aluminium, as indicated by large amounts of extractable iron and aluminium with ammonium oxalate and sodium pyrophosphate (Table 1), and a decrease in the contents in secondary oxides. XRD diagrams show hydroxyaluminium-interlayered-vermiculite (HIV) along with gibbsite and kaolinite. Thermogravimetric analyses of clay fractions (after removal of free iron oxides) indicate a sharp, up-profile decrease in gibbsite content from the subsoil towards the organic horizons (Caner *et al*., 2000). This mineralogical assemblage is quite different from that of black Vertisols, which are always dominated by smectites.

‘Andic’ soil properties and soil classification

As non-allophanic Andisols have already been identified on various parent materials in areas dominated by cold and humid climates (Garcia-Rodeja *et al*., 1987; Bäumler and Zech, 1994), special attention was paid to the study of *andic* soil properties while characterising the soils of the Nilgiri Hills in the laboratory.

The presence of volcanic material is no longer required to identify Andisols in modern soil classification systems (FAO, 1998, Soil Survey Staff, 1999). Non-allophanic Andisols are characterised by the presence of large amounts of *active* forms of iron and aluminium, mainly organo-metallic complexes which are responsible for the ‘andic’ soil properties and, by contrast, by the absence of short-range-order minerals (allophane and imogolite; Parfitt and Clayden, 1991; Dahlgren *et al*., 1993).

To be recognised as having ‘andic’ soil properties in the absence of volcanic glasses, soil material (the fine earth fraction of a soil horizon) must meet the following requirements (FAO, 1998; Soil Survey Staff, 1999):

a) the sum of the aluminium plus half of the iron extracted by ammonium oxalate (Al_o + ½ Fe_o) must equal or exceed 2.0 %;

b) bulk density, measured at 33 kPa water retention, must not exceed 0.90 $kg.dm^{-3}$;

c) phosphate retention must exceed 85 %.

The identification of andic properties in the Nilgiri ‘black soils’ was performed using internationally standardised methods (Table 2). In the studied soils, the andic soil properties are observed through a sufficiently large thickness of soil, in conformity with Soil Taxonomy requirements, for them to be classified as Andisols.

While these ‘black soils’ located at high elevation in the western and eastern ranges of the Nilgiri Hills can be considered as Andisols, the soils sampled and analysed in the central valleys (not illustrated here) either do not exhibit andic properties, or have andic properties, but not over a sufficient profile thickness (Caner, 2000). It is therefore now clear (Caner, 2000; Caner *et al*., 2000) that the rich organic surface horizons, when exceeding thicknesses of 60 cm, can be defined as non-allophanic Andisols, and that the parent material of these ‘black soils’ is the lateritic subsoil (of unspecified age) rather than the charnockitic bedrock. According to the Soil Taxonomy (Soil Survey Staff, 1999), these Andisols are classified as Acrudoxic Fulvudands (NILG 4, UB 3), or Pachic Fulvudands (NILG 16, NILG 18, NP 3, NILG 19, KOTA 0). In the World Reference Base (FAO, 1998) these soils are classified as Umbri-Pachic Andosols.

The fact that Andisols were not mentioned in the Nilgiri highlands in former studies has to be related to two main factors: firstly, Andisols were only recently recognised to occur on non-volcanic parent materials, and moreover on deeply weathered regolith in a tropical montane environment. The awareness that such a possibility, at the conceptual level, might occur, is therefore very new. Secondly, the Nilgiri and Palni soils were considered to be ancient and monogenetic ferrallitic soils in which the main peculiarity, namely the significant accumulation of organic matter in the topsoil, was attributed to the coolness of the climate and, therefore indirectly to elevation and the uplift of the mountain ranges. For this reason, Troy *et al*. (1977), who noticed the presence of large amounts of ‘amorphous’ forms of iron and aluminium in the ‘black’ topsoil of the Nilgiri and Palni Hills, did not identify the soil profiles as Andisols but considered these features as being indicative of young soils, in which the topmost organic horizon was anomalously thick by comparison with ferrallitic soils at lower elevations in the Western Ghats as well as elsewhere in the Tropics.

Our new interpretation of the genesis of the ‘black’ soils of the Nilgiris constitues a significant development in our understanding of how such high-elevation tropical soils develop. For the first time, the organic-rich topsoil is considered *per se* as an entire soil unit that can be

Table 2: Selective dissolutions of Al and Fe, and andic properties of Nilgiri soils

Profile	Depth	Oxalate		Pyrophosphate		Al_o + 1/2Fe_o	Bulk density	P retention
		Fe_o	Al_o	Fe_p	Al_p			
	cm	%					kg dm^{-3}	%
NILG 4								
	0-30	1.34	1.93	1.51	1.82	2.60	0.74	97
	30-55	1.46	1.79	1.57	1.52	2.52	0.89	98
	55-65	1.23	1.09	0.97	0.68	1.71	nd	85
	65-110	0.75	0.68	0.01	0.03	1.06	0.98	83
	110-150	1.13	0.36	0.05	0.03	0.93	nd	83
NILG 16								
	0-20	1.60	2.15	1.07	1.74	2.95	0.47	98
	20-45	1.67	2.72	1.69	2.31	3.56	nd	99
	45-60	1.51	2.32	1.72	2.18	3.08	0.72	99
	60-70	1.56	1.79	1.65	1.66	2.57	nd	99
	70-85	1.61	1.51	1.69	1.63	2.32	nd	98
	85-100	0.85	0.36	0.02	0.03	0.79	nd	85
	160	1.28	0.29	0.01	0.03	0.93	1.09	96
NILG 18								
	0-15	1.61	2.21	1.43	1.75	3.02	0.78	97
	15-35	1.62	2.39	1.68	2.00	3.20	0.74	99
	35-60	1.62	2.27	1.96	2.00	3.08	0.78	99
	60-80	1.66	1.30	1.56	0.88	2.13	nd	97
	80-85	1.20	0.84	0.53	0.43	1.44	nd	92
	85-95	1.36	0.51	nd	nd	1.19	nd	92
	120-140	1.26	0.27	nd	nd	0.90	1.18	nd
UB 3								
	0-20	1.35	1.78	0.90	1.26	2.46	0.60	94
	20-40	1.89	2.41	1.34	1.66	3.36	nd	99
	40-60	1.57	1.45	1.10	0.74	2.23	0.72	95
	60-70	1.10	0.80	nd	nd	1.35	nd	87
	100	1.01	0.39	nd	nd	0.89	1.05	90
NP 3							nd	
	0-20	1.86	2.12	1.38	1.51	3.05	0.44	90
	20-50	2.14	2.34	1.93	1.88	3.41	0.64	94
	50-80	1.69	2.16	1.77	1.80	3.01	0.66	99
	80-100	1.04	1.82	1.16	1.15	2.34	nd	95
	130	0.80	0.84	nd	nd	1.24	0.89	89
NILG 19								
	0-20	1.51	1.73	1.56	1.46	2.49	0.65	90
	20-45	1.90	2.01	2.05	1.69	2.96	0.68	95
	60-80	1.63	1.45	1.86	1.37	2.27	0.74	94
	95-105	0.87	0.83	1.05	0.54	1.27	0.92	77
	120-135	0.30	0.32	nd	nd	0.47	1.23	63
	160	0.19	0.23	nd	nd	nd	nd	nd
KOTA 0								
	0-20	1.32	1.20	1.10	1.03	1.86	0.70	89
	50-65	1.46	1.17	1.76	1.15	2.02	0.87	99
	80-120	1.58	1.83	1.77	1.62	2.62	1.05	94
	120-135	1.10	1.16	1.33	0.98	1.71	1.20	75
	150-160	0.95	0.41	nd	nd	0.89	nd	nd

understood separately from the saprolite it rests upon. This implies that the dynamics of the organic matter constitute a key component of Andisol development.

Organic soil genesis and palaeoecological conditions in the Nilgiri Hills

In this section, an attempt is made to relate Andisol formation on lateritic parent material with the Pleistocene ecological conditions of this area.

Palaeoenvironments of the Nilgiri Hills during the last 30 kyr

Numerous investigations have been carried out on Nilgiri peatbogs using pollen analysis, radiocarbon dating and stable carbon isotope studies in order to understand the palaeoclimates of South India (Gupta, 1971; Blasco and Thanikamoni, 1974; Gupta and Prasad, 1985; Sukumar *et al*., 1993, 1995; Rajagopalan *et al*., 1997, Sutra, 1997). A general trend can be outlined from these studies:

a) the period from 30 ka to 18 ka was characterised by a relatively drier period compared to today and a vegetation dominated by C4 plants (grasslands), while forests were restricted to more humid valleys where moisture could be retained (cf. peatbogs);

b) the period from 18 ka to 10 ka was marked by a shift toward a more humid climate and an expansion of the forest areas;

c) the period from 10 ka to the present was characterised by an alternation of wetter and drier climates.

The Nilgiri highlands were thus affected by substantial climate and vegetation changes during the last millennia. These fluctuations are understood to have influenced the development of the organic soils.

Isotopic composition of soil organic carbon

The isotopic composition of soil organic C corresponds closely to that of plant material from which it derives (C3 or C4); thus, the differences in the stable isotopic composition of soil organic matter provides tools to assess changes in vegetation (Schwartz *et al*., 1986; Balesdent *et al*., 1987; Boutton *et al*., 1998) but also to understand by which type of vegetation organic matter has been supplied.

For four Nilgiri soils, the stable carbon isotope composition ($\delta^{13}C$) of organic matter (Table 3) shows that the organic matter of surface horizons derives from C3 plants (forest), whereas the organic matter of deep horizons derives from C4 plants (grasslands). The $\delta^{13}C$ of the organic matter from the intermediate horizons indicates organic matter deriving from a mixture of C4 and C3 plants (Table 3).

Radiocarbon dating of soil organic matter

Radiocarbon dating of soil organic matter is based on the decay of ^{14}C in plant material, which had a $^{14}C/^{12}C$ ratio similar to that of atmospheric CO_2. The degree to which the $^{14}C/^{12}C$ ratio of soil organic matter differs from that of the plant material from which it derives may be used to indicate the time since the death of the organisms. In the case of whole soils or soil fractions, the age of soil organic matter is expressed as 'mean residence time' (MRT) because soil organic matter constitutes an heterogeneous reservoir with a variety of turnover times depending on the type of organic substance involved.

For the Nilgiri soils, MRT was estimated using two models:

- for surface (0-20 cm) horizons ($\Delta^{14}C > 0$), the MRT was estimated using a model which takes into account the incorporation of ^{14}C derived from atmospheric nuclear testing (bomb ^{14}C) up to the Nineteen Sixties (Balesdent and Guillet, 1982; Guillet, 1994).

- for deep horizons (20-120 cm) which have not been enriched with bomb ^{14}C, MRT was calculated with a period of 5568 years (Balesdent and Guillet, 1982; Guillet, 1994).

$$\text{MRT} = -8035 \text{ Ln} \left(1 + \frac{\Delta^{14}C}{1000} \right)$$

Radiocarbon dating (Table 3) indicates a rapid increase with depth of the MRT of the soil organic matter. The surface horizons have MRT ranging between 62 years B.P. and 153 years B.P. This indicates a rapid turnover of the organic matter as well as considerable biological activity. By contrast, deeper horizons present much greater MRT (13.2 ka to 26.97 ka). This suggest that organic matter accumulation in Nilgiri 'black soils' took place since about 30 ka if we keep in mind that MRT gives an apparent mean age which is younger than the true age of the oldest components of soil carbon (see above). The results also indicate a stabilisation of the Late Pleistocene organic matter. The carbon pool at depth is not affected by inputs of fresh organic matter from the topsoil.

The ^{14}C dating of Nilgiri soils shows that a considerable accumulation of organic matter took place, at depth, at the end of the Pleistocene and at the transition with the Holocene. The stable C pool of the deep organic horizons is inherited from that time and has a grassland

Table 3: ^{14}C dating and stable isotope composition of the soil organic matter

Soil profiles	Depth (cm)	$\delta^{14}C$ (‰)	$\delta^{13}C$ (‰)	$\Delta^{14}C$ (‰)	MRT (year B.P.)
Nilg 4					
	0-10	58	-24,2	56	153 ± 20
	15-30	-123	-19,8	-132	1095 ± 42
	40-60	-387	-14,4	-400	4055 ± 52
Nilg 16					
	0-10	103	-17,5	87	108 ± 9
	20-35	-75	-12,5	-98	781 ± 39
	40-50	-275	-11,1	-295	2769 ± 42
	60-75	-912	-12,4	-914	19670 ± 160
	75-90	-962	nd	-963	26168 ± 299
Nilg 19					
	0-10	112	-23,1	108	85 ± 20
	15-25	-34	-22,3	-39	277 ± 34
	25-40	-235	-22,4	-239	2147 ± 50
	55-70	-804	-15,2	-807	13200 ± 81
Kota 0					
	0-20	145	-23,2	141	62± 4
	30-40	-385	-15,8	-396	4009 ± 51
	50-65	-439	-14,8	-450	4766 ± 59
	80-90	-919	-12,9	-921	20366 ± 154
	100-120	-935	-12,9	-937	21126 ± 206

origin (grassland vegetation with deep rooting systems is known to favour considerable and deep organic matter accumulation in the soils as observed in Chernozems and some other Mollisols). The stabilisation of this organic matter since the Pleistocene was made possible by the formation of organo-metallic complexes that are resistant to biodegradation for thousands of years (Boudot *et al*. 1986; Guillet, 1990; Sollins *et al*., 1996).

The organic carbon pool of the ‘black soils’ on the slopes of the Nilgiri Hills has continued to evolve at the surface due to the shallow incorporation of fresh organic matter as a consequence of vegetation changes during the Holocene. These results are in agreement with results obtained by various authors working on the valley peatbogs of the Nilgiri highlands. The data from these various sources clearly demonstrate that the spatial extent of the grasslands reached a maximum at the end of the Pleistocene, and that many areas which were under grassland at that period are now under shola forest.

These soils rich in organic matter thus constitute, alongside peatbogs, records of the palaeoenvironmental conditions of these highlands and are of considerable value as palaeoenvironmental indicators due to their broader distribution throughout the Nilgiri highlands than peats.

The combined presence of large inputs of organic matter, large amounts of sesquioxides inherited from a warmer past, and a cold and wet climate favoured interactions between organic matter and oxides which were conducive to the emergence of andic soil properties. This set of circumstances promoted carbon stabilisation.

In summary, the occurence of Andisols in the Nilgiri highlands, which is closely related to the dynamics of the organic matter, can be related to the combination of the three following conditions:

a) a cool and humid climate;

b) the presence of large amounts of organic matter, the accumulation of which is a consequence of the cool climate;

c) a relative abundance of potential sources of aluminium and iron to form organometallic-complexes. These sources occur in the Nilgiri Hills as oxides and oxyhydroxides in the saprolite of hillslopes and hilltops that is inherited from a previous cycle of lateritic soil formation.

These requirements explain why Andisols in the Western Ghats of South India are restricted to the Nilgiri, Palni and Anamalai Hills, or to the highlands of Sri Lanka (Nuwara Eliya), and do not occur in the other, less elevated charnockitic massif (e.g. Gopalswami Betta, Shevaroy Hills) or in the Deccan traps. The Deccan basalts, being of a volcanic nature and having a well documented history of lateritisation: *this volume*, could indeed have been *a priori* an ideal terrain for the development of Andisols in the broadest sense (i.e. on volcanic as well as on lateritic parent material).

The Nilgiri Hills, the Palni Hills, the Anamalai and Nuwara Eliya in Sri Lanka are all charnockitic massifs with similar elevations (2000 - 2600 m). They share similar geomorphological characteristics (rounded crests and mature valleys) and bioclimatic conditions (presence of shola forests, high rainfall, and cool temperatures). Moreover, these areas are covered by thick ‘lateritic’ regolith and present organic rich topsoils. We checked the occurence of Andisols in the Palni Hills (Caner, 2000) and suppose that the mechanism of soil formation studied in detail in the Nilgiris are equally valid in these other highlands.

By contrast, the relatively humid regions of the Deccan traps, the Gopalswami Betta and the Shevaroy Hills, which also exhibit a lateric soil cover and thus present the potential sources of aluminium and iron to form the organo-metallic complexes, do not exhibit Andisols, even in their most elevated summit regions. Elevations are generally lower (rarely in excess of 1500 m), so that the rates of mineralisation of the organic matter are accordingly higher. The formation of thick organic topsoil is thus prevented as is, consequentially, the development of Andisols.

The presence of Andisols in the charnockitic massifs of South India and Sri Lanka is therefore an entirely original feature, that confers on these highland landscapes characteristics that are unique in the Western Ghats region and, possibly, world-wide. Not least, the unique properties of the Andisols in these South Asian higlands can explain the widespread occurrence of tea plantations, which are largely absent from other elevated parts of the Western Ghats, and which, due to the tolerance of the tea shrub to large amounts of exchangeable aluminium as well as heavy rainfall, find on these Andisols suitable conditions for their development.

Concluding remarks

This study illustrates the possibility of Andisol development on an unusual parent material: a highly weathered soil material derived from non-volcanic bedrock. The pervasively bauxitic character of saprolite is often considered to be the geochemical end point (known as allitisation) of rock weathering and soil evolution, following which another, subsequent cycle of soil formation cannot occur. Our results have, however, pointed out the main shortcomings of previously formulated monogenetic theories on the genesis of soils in the Nilgiri highlands. These soils are clearly polygenetic and polycyclic, and exhibit a bisequal profile (i.e. a profile showing two sequa): an Andisol developed over a low-activity clay tropical soil inherited from much warmer conditions.

The combination of a classical pedological approach (for field work as well as for laboratory analyses) with ^{14}C dating and stable carbon isotope studies showed that the formation of the thick and rich organic horizons, and the development of andic properties, is closely linked to the major climatic events that have affected this area and to the existence of a period with grassland vegetation at the end of the Pleistocene.

These new findings on the andic properties of the ‘black soils’ of the Nilgiri highlands can probably be extended to clarify the genesis of similar organic soils on the hillslopes of others highlands of other tropical highlands (e.g. Central Africa or Madagascar). The findings also show how they can be used as tools in palaeoloecological studies.

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