Lateritic soils of Kerala, India: their mineralogy, genesis, and taxonomy

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Abstract.   In this study, we report the chemical and mineralogical characteristics of 4 benchmark Ultisols of Kerala to elucidate their genesis and taxonomy. The taxonomic rationale of the mineralogy class of Ultisols and other highly weathered soils on the basis of the contemporary pedogenesis is also explained. The Ultisols of Kerala have low pH, low cation exchange capacity, low effective cation exchange capacity and base saturation, with dominant presence of 1 : 1 clays and gibbsite. Presence of gibbsite along with 2 : 1 minerals discounts the hypothesis of anti-gibbsite effect. Since the kaolins are interstratified with hydroxy-interlayered vermiculites (HIV), the formation of gibbsite from kaolinite is not tenable. Thus, gibbsite is formed from primary minerals in an earlier alkaline pedo-environment. Therefore, the presence of gibbsite does not necessarily indicate an advanced stage of weathering. On the basis of a dominant amount of gibbsite, a mineralogy class such as allitic or gibbsitic does not establish a legacy between the contemporary pedogenesis and the mineralogy. The dominance of kaolin–HIV in the fine clays of Ultisols and their persistence, possibly since early Tertiary, suggests that 'steady state' may exist in soils developed on long-term weathered saprolite. Since the present acid environment of Ultisols does not allow desilication, the chemical transformation of Ultisols to Oxisols with time is difficult to reconcile as envisaged in the traditional model of tropical soil genesis.

Additional keywords: lateritic soils (Ultisols) genesis, mineralogy class, Soil Taxonomy, India.

Introduction

The acid ferruginous soils of Kerala State, southern India, are often referred to as 'laterite' and/or 'lateritic soils' and have attracted the attention of earth scientists all over the world because of their importance in industry and agriculture (Schellman 1981; Ollier and Galloway 1990; Aleva 1994). Early work on the mineralogy of these soils indicated both kaolinite and gibbsite as the dominant minerals, with some 2 : 1 minerals and quartz (Satyanarayana and Thomas 1962; Gowaikar 1972; Sahu and Krishna Murthi 1984; Bronger and Bruehn 1989). The presence of gibbsite in soils had often been linked with the intense leaching conditions of a tropical humid climate (Jackson 1968; Chesworth 1972). The formation of gibbsite has been reported to be either through direct weathering of primary alumino-silicates (Sherman *et al*. 1967), or from transformation of clay minerals (Jackson 1964; Bourman 1993).

Judging by the commonly observed inverse relation between kaolinite and gibbsite in tropical ferruginous soils, gibbsite has been assumed to be formed at the expense of kaolinites (Hsu 1989). However, in a recent study on Ultisols of Meghalaya, India, Bhattacharyya *et al*. (2000) demonstrated that gibbsite is a relict product of primary minerals of an earlier alkaline pedochemical weathering environment and the 0.7 nm minerals are mostly interstratified with hydroxy-interlayered vermiculites (HIV), and thus authors concluded that gibbsite should not be considered as an index mineral of advanced stage of tropical weathering.

Formation of kaolinite in tropical ferruginous soils can be either through direct weathering of feldspars (Anand *et al*. 1985) or through an intermediate mica stage (Gilkes and Suddhiprakarn 1979) or by neosynthesis from the product of hydrolysis (De Kimpe *et al*. 1961; Rengasamy *et al*. 1978). Hydroxy-interlayering in 2 : 1 minerals is also considered as a precursor in the structural reorganisation mechanism (Jackson 1962; Rich 1968; Karathanasis and Hajek 1983) involving tetrahedral inversion (Altschuler *et al*. 1963), release of a portion of tetrahedral silica sheet, and its association with hydroxy-aluminium interlayer component forming 2 kaolin layers (Karathanasis and Hajek 1983).

Usually, highly weathered tropical soils lacking clear horizonation, containing <10% weatherable minerals, showing uniform clay distribution without clay illuviation, and with low clay cation exchange capacity (CEC, ≤16 cmol(+)/kg clay) and effective CEC (ECEC ≤12 cmol(+)/kg clay) indicating dominant clay minerals as gibbsite/or kaolinite/or oxides are grouped as Oxisols in USDA Soil Taxonomy (Soil Survey Staff 1999). However, the studies on tropical ferruginous soils of India indicated that they are not Oxisols, in spite of their advanced stage of weathering (Bhattacharyya *et al.* 1994; Chandran *et al.* 2000).

Although the ferruginous soils of Kerala are considered as laterites and/or lateritic soils (Varghese and Byju 1993), the National Bureau of Soil Survey and Land Use Planning (ICAR) during its soil mapping program (1 : 250 000 scale) of the country and the major part of Kerala on 1 : 50 000 scale did not report the occurrence of Oxisols (Anon. 1999; Velayutham and Bhattacharyya 2000). It is not yet clear why the acid ferruginous soils of Kerala are not Oxisols despite their weathering in humid tropical conditions for the last several million years (Subramanian 1978). A study on the genesis and transformation of clay minerals of the acid ferruginous soils may help us to identify the pedogenic processes to group them in Soil Orders other than Oxisols. It is hoped that the present study may provide a check on the inductive reasoning of models of soil genesis of the tropics (Chesworth 1973, 1980; Smeck *et al.* 1983).

Materials and methods

Study area

Kerala State, located in south-western part of India, is known in earth science literature as the '*type locality*' of 'laterite', a name first coined by Francis Buchanan in 1800 at the Angadipuram of Malappuram district of the State. The midlands and highlands of Kerala (Western Ghats) have been subdivided into central Sahyadri, the Nilgiris, and southern Sahyadri (Krishnan *et al.* 1996). Sporadic uplift of the Western Ghats during the Miocene–Pliocene periods is thought to be responsible for the development of the recent landscape. The study area belongs to the Archaean system which is dominated by low grade metamorphic and gneissic rocks. Capping of indurated laterite is widespread on crystalline and sedimentary rocks at places.

Kerala experiences a humid tropical climate with high rainfall (~3500 mm) with bimodal pattern. Mean annual air temperature is about 27°C. The difference in mean summer and winter soil temperature is <6°C, which qualifies for isohyperthermic temperature regime (Soil Survey Staff 1999). The Ultisols are the major soils covering >50% of the total surface area (Krishnan *et al.* 1996; Anon. 1999) particularly in the hills and mounds. For brevity, 4 representative Benchmark Ultisols were selected for the present study, including one very close to Angadipuram (Fig. 1).

Morphological studies

Morphological features of soils were studied following the methods of Soil Survey Manual (Soil Survey Division Staff 1995). The soils were classified according to Soil Taxonomy recommendation (Soil Survey Staff 1999).
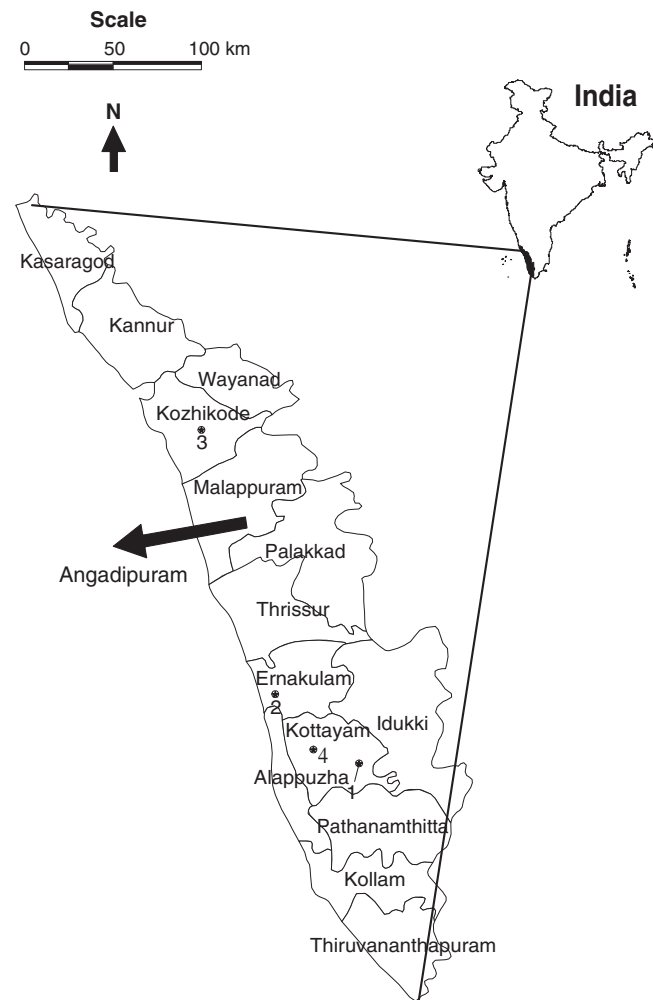

Fig. 1. State of Kerala in India showing districts and pedon locations.

All the Ultisols are non-calcareous and their texture varies from clay loam to clay. The soils are formed from charnokite and granite-gneiss rocks. The soils have argillans identified in the field just below the Ap horizons. The soils are well drained, with colours varying from dark reddish brown to dark red. Moderate medium sub-angular blocky structure was prevalent in the soils. The soils are developing on strongly sloping to steep slopes (5–35%) of hills and mounds. During cultivation, surface layers in many cases are either removed or mixed up with the Bt horizons. Therefore, in many cases an exposed argillic horizon was observed in the surface. In such cases, the criterion for clay requirement of a subsurface horizon to qualify as an argillic horizon as per Soil Taxonomy (Soil Survey Staff 1975, 1999) was not fulfilled. Thus, on stable landscapes such as that of Kerala, clay argillans identified in the subsurface horizons are considered for identification of Bt horizon. All the soils have >35% coarse fragments (laterite gravels) except in pedon 3.

Pedon 1 (Kanjirapally series) is a very deep soil and is situated on strongly sloping hill. The soil has a thick argillic horizon from 0.13 m downwards and is classified as Kandihumults as per Soil Taxonomy (Soil Survey Staff 1999). Athirampuzha series (pedon 2) is a deep soil underlain by hard lateritic material at a depth of 1.05 m. The soils are developed on strongly to steep sloping hills. The argillic horizon was observed below

the Ap horizon at a depth of 0.16 m. The soils are classified as Kanhaplohumults.

Kinalur series (represented by pedon 3) is moderately deep soil with a solum thickness of 0.80 m, underlain by hard partially weathered granite-gneiss. They are developed on 15–20% slopes of mounds and hills. Coarse fragments of laterite gravels range from 10 to 20% by volume. Although the criterion of clay increase from the surface to the subsurface horizon was not satisfied for classification into an argillic (Bt) horizon, the soils have well developed thin clay films on ped surface from 0.36 m up to the bedrock. Further, as mentioned earlier most of the eluvial horizon is removed and has thus exposed the Bt horizon, which is at present designated as the Ap horizon.

The Chigavanam soil (pedon 4) is a very deep (>1.50 m) Ultisol developed on strong slopes (4–16%) of mounds and hills at an elevation of 60–70 m above msl. Well-developed argillans were observed from 0.15 m to 1.75 m. The soils are truncated with an exposed Bt horizon. The thin clay film on ped faces confirms illuviation of clay. The exposed B horizon is a part of a deep argillic horizon. The argillans along with low CEC, ECEC, and base saturation confirm their grouping into Kandihumults. Coarse fragments (laterite gravels) vary from 35 to 65% with an increasing trends with depth.

Analytical methods

Particle size distribution was determined by the pipette method after removal of organic carbon and free iron oxides. Sand (2000–50 μm), silt (50–2 μm) total clay (<2 μm), and fine clay (<0.2 μm) fractions were separated according to the procedure of Jackson (1979). The pH, organic carbon, CEC, and extractable bases were determined on the total fine earth fraction (<2 mm) by standard methods

(Jackson 1973). Extractable acidity was determined by BaCl$_2$-TEA method (Peech *et al.* 1947).

The powder mounts of the sand fractions were X-rayed using a Philips diffractometer with Ni-filtered, Cu-Kα radiation at a scanning speed of 2°2θ/min. Oriented silt and clay fractions were subjected to X-ray diffraction (XRD) analysis. Samples were saturated with (*1*) Ca and solvated with ethylene glycol, (*2*) K at 25°C and heated to 110°, 300°, and 550°C. Identification of clay minerals in different fractions was done following the criteria laid down by Jackson (1979). The formamide test was carried out in the fine clay fractions and the treated samples were scanned after 1 h, 4 h, and 10 days to identify the presence of halloysite (Churchman *et al.* 1984).

Sand-sized gibbsite and feldspar particles were picked up after their identification under a petrographic microscope. These particles were fixed on an aluminum stub with LEIT-C conductive carbon cement, coated with gold, and examined in a Philips scanning electron microscope (SEM).

Results and discussion

General properties

The soils are acidic due to high rainfall (>3500 mm) and leaching of bases. The KCl pH values of soils (Table 1) were close to or greater than pH values in water for the lower horizons of some soils, indicating the presence of gibbsite and/or amorphous materials (Smith 1986). A negative/zero/positive ΔpH value indicates the

Table 1. Selected physical and chemical properties of soils

Horizon	Depth (m)	pH (H$_2$O)	pH (KCl)	ΔpH	Org. C (%)	Sand	Silt (%)	Clay
Pedon 1. Kanjirapally series, Kottayam; fine-loamy (skeletal), kaolinitic, isohyperthermic Ustic Kandihumults								
Ap	0–0.13	4.8	4.3	−0.5	2.35	69.9	9.0	21.1
Bt1	0.13–0.32	4.4	4.3	−0.1	1.86	56.1	12.5	31.3
Bt2	0.32–0.56	4.5	4.3	−0.2	1.50	59.9	11.1	28.9
Bt3	0.56–0.83	4.5	4.6	+0.1	0.90	62.8	11.4	25.7
Bt4	0.83–1.12	4.4	4.6	+0.2	1.11	57.1	11.3	28.5
Bt5	1.12–1.50+	4.7	4.7	0	1.22	62.6	13.4	24.0
Pedon 2. Athirampuzha series, Ernakulam; clayey (skeletal), kaolinitic, isohyperthermic Ustic Kanhaplohumults								
Ap	0–0.16	4.0	4.0	0	2.36	51.7	11.0	37.3
Bt1	0.16–0.42	3.8	3.8	0	1.26	39.7	8.0	52.3
Bt2	0.42–0.66	4.1	3.9	−0.2	0.99	33.3	6.7	60.0
Bt3	0.66–0.89	4.3	3.9	−0.4	0.67	34.6	11.8	53.6
BC	0.89–1.05	4.1	4.2	+0.1	0.63	30.3	16.3	53.4
R	1.05+				Hard lateritic material			
Pedon 3. Kinalur series, Kozhikode; fine-loamy, kaolinitic, isohyperthermic Ustic Kanhaplohumults								
Ap1	0–0.10	4.5	4.3	−0.3	3.19	47.2	21.2	31.6
Ap2	0.10–0.36	5.1	4.3	−0.7	2.22	48.7	18.7	32.6
Bt1	0.36–0.48	5.3	4.3	−1.0	1.48	48.5	19.3	32.2
Bt2	0.48–0.66	5.2	4.3	−0.9	1.20	47.1	19.5	33.4
Bt3	0.66–0.80	5.1	4.3	−0.8	0.61	50.7	19.2	30.1
R	0.80+				Partially weathered granite-gneiss			
Pedon 4. Chingavanam series, Kottayam; fine-loamy (skeletal), kaolinitic, isohyperthermic Typic Kandiustults								
Ap	0–0.15	4.5	4.1	−0.4	0.87	50.2	16.3	33.5
Bt1	0.15–0.41	4.7	4.2	−0.5	0.35	52.2	17.9	29.9
Bt2	0.41–0.66	4.7	4.1	−0.6	0.23	47.4	22.1	30.5
Bt3	0.66–0.99	4.9	4.1	−0.8	0.31	46.9	20.4	32.7
Bt4	0.99–1.40	4.8	4.1	−0.7	0.39	39.5	24.3	36.2
Bt5	1.40–1.76	5.0	4.2	−0.8	0.31	45.2	22.8	32.0

presence of variable charge minerals such as gibbsites and/or sesquioxides (Uehera and Gillman 1980; Bhattacharyya *et al*. 1994). CEC and ECEC values ranged from 3 to 8.9 and 0.6 to 3.3 cmol(+)/kg, respectively (Table 2), indicating that these Ultisols are impoverished in basic cations and are relatively rich in organic matter at the surface (Table 1). Although the extractable acidity by 1 M KCl was low, the same obtained through $BaCl_2$-TEA was very high (Table 2). Low KCl-extractable aluminium and high total extractable acidity were also reported for highly weathered Oxisols of Puerto Rico (Beinroth 1982). This shows that large amounts of Al^{3+} released during tropical weathering are held in the interlayer of soil clays and are not easily extractable by 1 M KCl solution. This reaction prevents the weathering of minerals such as vermiculites and thus these Ultisols are not impoverished with weatherable minerals. This is also reflected in their silica : alumina and silica : sesquioxide ratios. The ratios $SiO_2 : R_2O_3$ (1.4–5.0) and $SiO_2 : Al_2O_3$ (1.8–6.0) indicate the siliceous nature of these soils (Table 3) (Varghese and Byju 1993), suggesting an incomplete desilication process. The amount of SiO_2 and its molar ratios are comparable with some of the Oxisols reported from Puerto Rico (Jones *et al*. 1982), Brazil (Buurman *et al*. 1996; Muggler 1998), and other regions of the World (Mohr *et al*. 1972). In these lateritic soils the process of desilication no longer operates in present day conditions because the pH of the soils is well below the threshold of ∼9 (Millot 1970). Thus, these soils qualify for Ultisols (Soil Survey Staff 1999). The formation of Ultisols on granite-gneiss under humid tropical weathering conditions appears to be a common occurrence in Indian subcontinent as evidenced in the present study and elsewhere (Bhattacharyya *et al*. 2000).

Mineralogy of the sand fractions (2000–50 μm)

XRD patterns of sand fraction show the presence of gibbsite (0.48 nm peak), a 1.2 nm peak of 1.0–1.4 nm mixed layer minerals, and quartz along with some feldspars (Fig. 2). The sharpness of the peak at 0.48 nm indicates that gibbsites are well crystallised. The SEM photographs of sand-sized gibbsite indicate that they are pseudomorphs after feldspars (Fig. 3*a*, *b*, *e*, *f*). The presence of sizeable amounts of gibbsite in the sand fractions amidst layer silicates suggests that

Table 2. Exchange characteristics of soils

Horizon	Depth (m)	Extract. bases[A] (NH4OAc)	Extractable acidity[A]			CEC[A]		ECEC	Base saturation[B]	
			BaCl2 TEA	KCl (M) H+	Al3+	NH4 OAc	Σ cations		NH4 OAc	Σ cations
Pedon 1. Kanjirapally series										
Ap	0–0.13	0.98	11.2	0.33	0.57	4.5	12.2	1.6	21.7	8.1
Bt1	0.13–0.32	0.60	10.4	0.49	0.45	3.5	11.0	1.1	17.1	5.3
Bt2	0.32–0.56	0.52	9.9	0.43	0.32	3.7	10.4	0.8	14.0	4.9
Bt3	0.56–0.83	0.54	8.9	0.23	0.12	4.1	9.4	0.7	13.2	5.8
Bt4	0.83–1.12	0.51	6.6	0.17	0.07	3.9	7.1	0.6	13.2	7.5
Bt5	1.12–1.50	0.67	7.0	0.28	0.04	4.0	7.7	0.7	16.8	9.2
Pedon 2. Athirampuzha series										
Ap	0–0.16	0.56	13.3	0.89	2.0	9.0	13.9	2.6	6.3	3.5
Bt1	0.16–0.42	0.46	13.3	0.76	2.68	8.1	13.8	3.4	5.7	2.7
Bt2	0.42–0.66	0.37	12.5	0.34	2.92	7.3	12.9	3.3	5.1	2.3
Bt3	0.66–0.89	0.43	8.9	0.49	2.63	6.4	9.3	3.1	6.7	3.6
BC	0.89–1.05	1.00	8.3	0.09	1.42	7.2	9.3	2.4	14.0	10.2
Pedon 3. Kinalur series										
Ap1	0–0.10	0.92	21.5	0.27	1.42	7.4	22.4	2.3	12.5	4.0
Ap2	0.10–0.36	0.48	19.9	0.22	1.28	5.4	20.4	1.8	9.0	2.2
Bt1	0.36–0.48	0.56	15.2	0.21	1.06	6.1	15.8	1.6	9.2	3.2
Bt2	0.48–0.66	0.58	12.4	0.22	0.85	5.4	13.0	1.4	10.8	4.3
Bt3	0.66–0.80	0.69	8.7	0.11	0.86	5.1	9.4	1.6	13.7	7.1
Pedon 4. Chingavanam series										
Ap	0–0.15	1.99	7.5	0.15	0.40	4.5	9.5	2.4	44.2	24.7
Bt1	0.15–0.41	0.61	7.5	0.25	0.30	3.1	8.1	0.9	19.7	7.5
Bt2	0.41–0.66	0.70	7.5	0.15	0.60	3.0	8.2	1.3	23.3	8.4
Bt3	0.66–0.99	0.69	7.5	0.15	0.65	3.6	8.2	1.3	19.2	8.3
Bt4	0.99–1.40	1.30	6.9	0.16	0.65	3.5	8.2	1.9	37.1	16.7
Bt5	1.40–1.76	1.29	n.d.	0.10	0.40	3.5	n.d.	1.7	36.9	n.d.

n.d., Not determined.
[A](cmol(+)/kg).
[B](%).

Table 3. Elemental composition of soils

Horizon	Depth (m)	SiO$_2$	Al$_2$O$_3$	Fe$_2$O$_3$	TiO$_2$	Molar ratio	
			(%)			SiO$_2$/R$_2$O$_3$	SiO$_2$/Al$_2$O$_3$
Pedon 1. Kanjirapally series							
Ap	0–0.13	45.4	26.1	6.4	1.1	2.4	3.0
Bt1	0.13–0.32	37.9	27.3	12.7	1.1	1.7	2.4
Bt2	0.32–0.56	37.3	30.9	11.6	1.0	1.7	2.1
Bt3	0.56–0.83	36.1	27.6	14.9	1.1	1.6	2.2
Bt4	0.83–1.12	33.7	30.0	14.9	1.2	1.4	1.9
Bt5	1.12–1.50	33.0	31.3	12.7	1.2	1.4	1.8
Pedon 2. Athirampuzha series							
Ap	0–0.16	46.8	24.6	8.3	1.9	2.5	3.2
Bt1	0.16–0.42	43.7	29.2	8.1	1.5	2.0	2.6
Bt2	0.42–0.66	39.2	30.4	12.5	1.4	1.7	2.2
Bt3	0.66–0.89	40.7	30.6	10.2	1.4	1.8	2.6
BC	0.89–1.05	41.6	31.8	7.8	1.4	1.8	2.2
Pedon 3. Kinalur series							
Ap1	0–0.10	55.8	17.4	1.2	0.8	4.9	5.5
Ap2	0.10–0.36	54.4	16.4	8.1	0.7	4.1	5.6
Bt1	0.36–0.48	56.3	17.8	3.7	1.0	4.7	5.5
Bt2	0.48–0.66	57.2	17.0	3.9	0.8	4.8	5.7
Bt3	0.66–0.80	50.3	17.8	13.2	0.7	3.2	4.9
Pedon 4. Chingavanam series							
Ap	0–0.15	45.1	22.0	8.2	1.7	2.6	3.4
Bt1	0.15–0.41	43.7	21.2	13.5	1.8	2.4	3.5
Bt2	0.41–0.66	44.3	20.6	15.9	1.4	2.3	3.7
Bt3	0.66–0.99	40.1	20.4	16.3	1.3	2.1	3.3
Bt4	0.99–1.40	45.5	20.6	13.8	1.2	2.5	3.8
Bt5	1.40–1.76	46.7	22.0	11.8	1.3	2.5	3.6

the genesis of gibbsite in the presence of layer silicates is highly possible.

Mineralogy of the silt fractions (50–2 μm)

XRD of Ca-saturated silt fractions shows strong peaks at 0.48 nm and 0.34 nm and smaller peaks at 1.2 nm, 1.0 nm, and 0.72 nm (Fig. 4). A strong peak at 0.48 nm on Ca-saturation and its disappearance on K-saturation and heating at 300°C indicates the presence of gibbsite. This peak was retained when treated with 6 M HCl. The sharpness and intensity of the peak of gibbsites suggest a high degree of crystallisation. The characteristic 0.72 nm peak of kaolin (Kl) has a broad base, showing a probable interstratification of Kl with HIV. The Kl-HIV mineral is more pronounced in the clay fractions. The peak at 1.2 nm in Ca-saturated samples did not shift during glycol solvation or on K saturation at ambient temperature. However, this peak gradually shifted towards higher angles and merged with the 1.0 nm peak on heating from 110 to 550°C, indicating the presence of mixed layer minerals with random interstratification of 1.0 nm and 1.4 nm minerals (Barnhisel and Bertsch 1989). The behaviour of this mineral during glycolation and K-treatment followed by heating at 300°C indicates that the 1.4 nm component is a non-swelling mineral and therefore represents HIV. Thus, the 1.2 nm peak mineral is an interstratification

of mica and HIV (M-HIV). These observations indicate that the formation of gibbsite in the presence of 2:1 minerals appears to be a common phenomenon in highly weathered ferruginous soils (Wada and Kakuto 1983; de Brito Galvao and Schulze 1996; Bhattacharyya *et al.* 2000) and podzols (Wilke and Schwertmann 1977), in contrast to the general view that gibbsite cannot form until all expansible 2:1 clay minerals are decomposed (Jackson 1963, 1964).

Mineralogy of the total clay fractions (<2 μm)

The XRD patterns of the clay fractions exhibit well-defined XRD maxima, indicating the presence of HIV, M-HIV, M, Kl, gibbsite, and quartz. The Ca-saturated sample showed a peak at 1.4 nm along with sharp peaks at 0.72 nm and 0.48 nm. The 1.4 nm peak did not change its position or intensity on glycolation (Fig. 5). However, heating the K-saturated samples from 110 to 300°C, the 1.4 nm peak partially collapsed. Further heating to 550°C reinforced the 1.0 nm peak, indicating the presence of HIV. The presence of kaolin was established by the disappearance of 0.72 nm peak following K-saturation and heating at 550°C, and also by the retention of the peak after heating with 6 M HCl for 30 min. The heating at 550°C reinforces the 1.0 nm
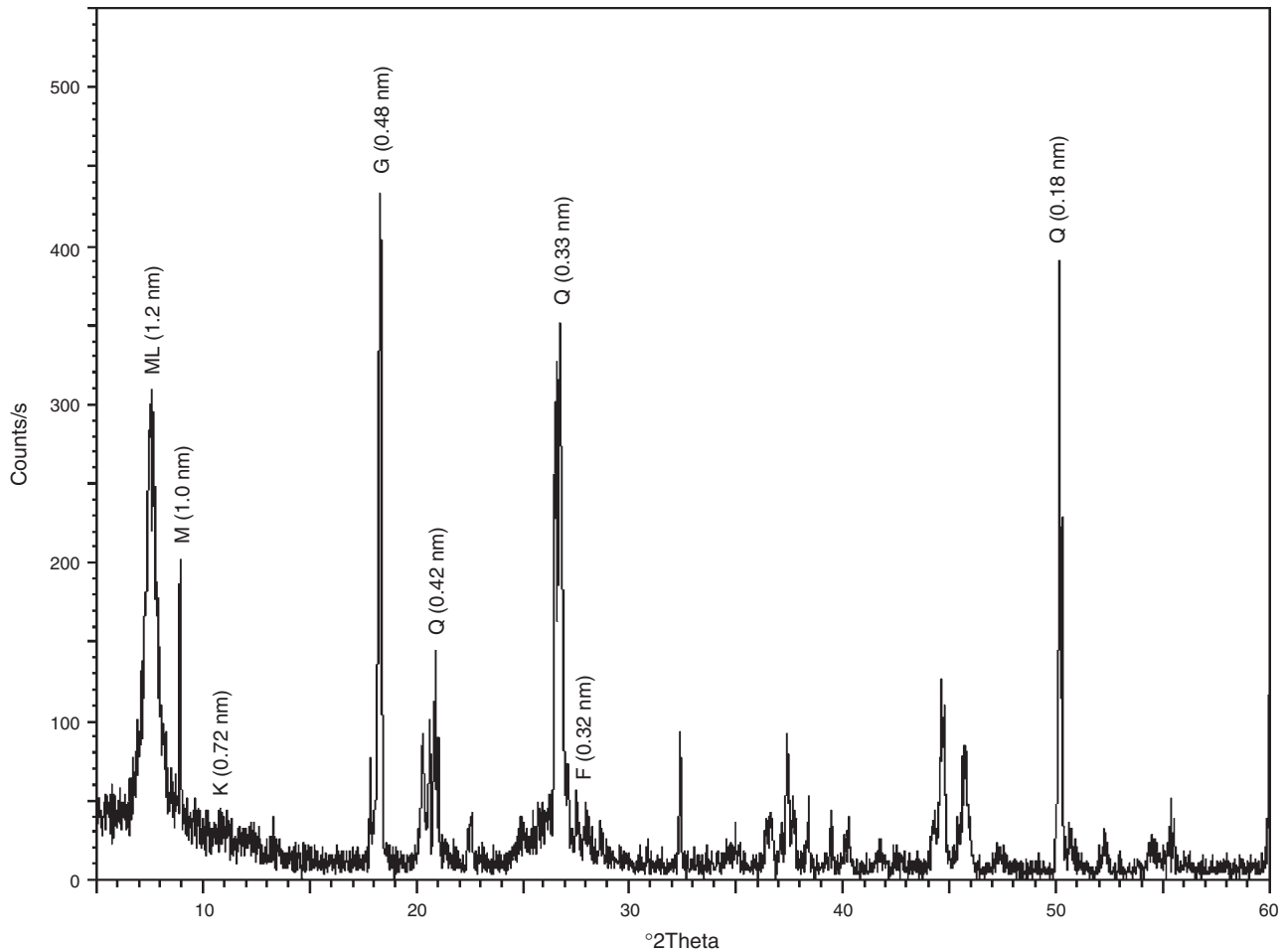
Fig. 2. Representative X-ray diffractogram of sand fractions of soils of Kerala (ML, mixed-layer minerals; K, kaolin; Q, quartz & G, gibbsite).

region and this reinforcement may not be entirely due to the collapse of very small amount of 1.4 nm mineral and appears to be contributed to by the collapse of HIV in the 0.7 nm minerals. This reinforcement as well as broadening of both the peak and the base of 0.72 nm diffraction maxima indicates the presence of discrete KI and HIV mineral and possibly an interstratified Kl-HIV mineral also. The 1.2 nm peak gradually shifted to 1.0 nm on K-saturation and heating from 110 to 550°C, which confirmed the presence M-HIV interstratified minerals.

Mineralogy of the fine clay fractions (<0.2 µm)

The fine clay fraction of Ca-saturated and glycolated samples showed a dominant peak at 0.72 nm, 0.48 nm and 0.36 nm and a very small peak at 1.4 nm (Fig. 6). The 0.72 nm peak of kaolin has a broad base, tailing towards the low-angle region. On heating the K-saturated sample at 550°C, the 0.72 nm peak disappeared, confirming the presence of kaolin and simultaneously reinforced the 1.0 nm region. In view of the very small amount of 1.4 nm minerals, the

higher degree of reinforcement of the 1.0 nm region at 550°C compared with that at 300°C may be possible only when the 0.7 nm minerals are Kl-HIV. The sharp peak at 0.48 nm and its disappearance on heating at 300°C confirmed the presence of gibbsite. The intensity of the 0.48 nm peak decreased with the decrease in size. The behaviour of the 1.4 nm peak, though very weak, indicated the presence of HIV as confirmed during glycolation and K treatment. The formamide test of the fine clay samples did not show any shift of the 0.72 nm peak, confirming the presence of kaolin and not halloysite (Fig. 7). Mica and/or M-HIV was not identified in this fraction.

General discussion

Formation of hydroxy-interlayered layer silicates and gibbsite

The ferruginous soils of Kerala, developed under tropical acid weathering conditions, have been considered as highly weathered soils with dominant proportions of gibbsite and
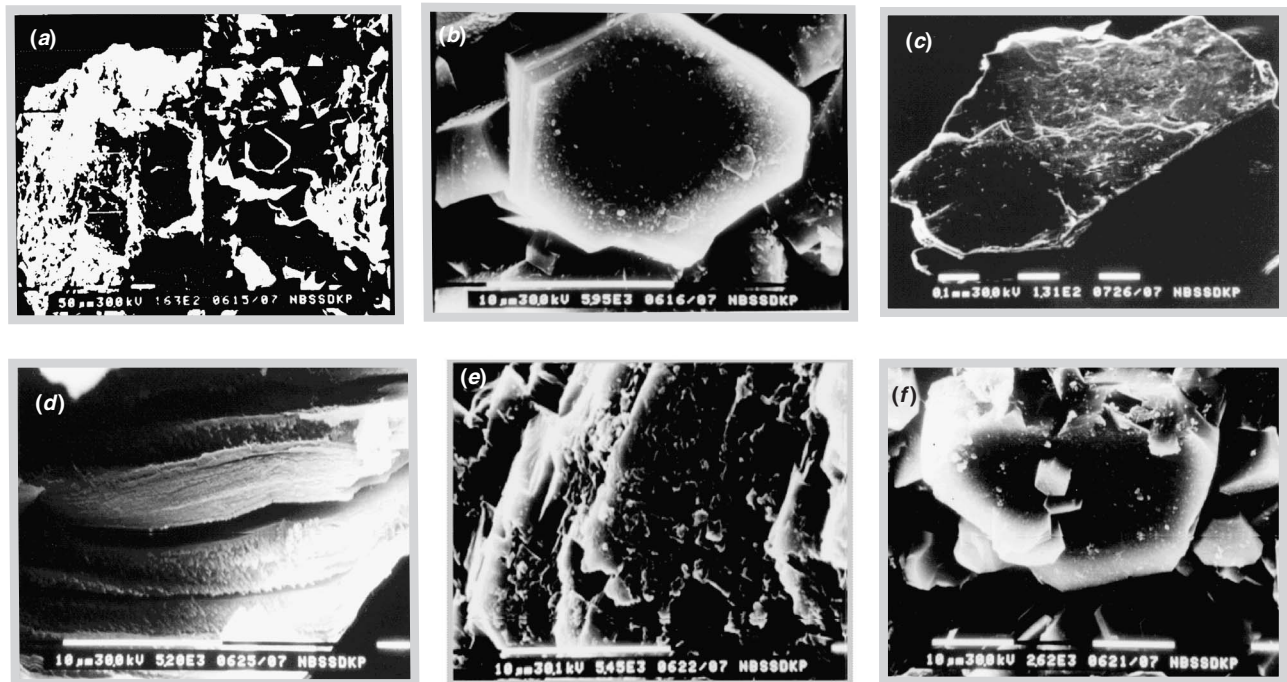
Fig. 3. Representative SEM photographs of sand-sized fractions showing (*a*) a cluster of hexagonal and rod-shaped gibbsites developed on feldspars (Bt2 layer of Pedon 3), (*b*) well-developed hexagonal prisms of individual gibbsite (Bt2 layer of Pedon 3), (*c*) biotite grain that escaped tropical weathering, (*d*) initiation of layer separation in biotite particle effecting the formation of vermiculite, (*e*) highly weathered feldspar grains showing the dissolution and etch pits with gibbsite crystals, (*f*) same as (*e*) at higher magnification.

kaolin minerals and insignificant amounts of weatherable minerals. But the results of the present study indicate the presence of significant amounts (>10%) of weatherable minerals by the presence of Kl-HIV, HIV, M, and M-HIV in both the coarse and fine fractions of the soils. Kaolin and gibbsite are the dominant minerals along with HIV, M-HIV, and mica in the silt and clay fractions. The occurrence of M-HIV in the sand fractions, M-HIV and mica in the silt, and M-HIV, HIV, and mica in the clay fractions indicates that mica has been transformed into vermiculite and then to HIV. The Al^{3+} released during tropical weathering is adsorbed in the interlayer of vermiculites to form HIV and further probably to Kl-HIV. In an acid weathering environment under a humid tropical climate with abundant Al^{3+}, hydroxy-Al-interlayering in the expansible 2 : 1 layer silicates is a primary reaction towards the interstratifications of 2 : 1 and 1:1 layers (Pal *et al*. 1989; Bhattacharyya *et al*. 1993), and such interstratified minerals are common in the ferruginous soils of India (Pal *et al*. 1989; Bhattacharyya *et al*. 1997). Expanding lattice minerals therefore act as a template for the formation of HIV in acidic soil conditions, and thus the formation of gibbsite has been considered improbable in presence of 2 : 1 minerals. This has been referred to as 'antigibbsite effect' in the literature (Jackson 1963, 1964), and in view of this, the co-existence of gibbsite and HIV minerals in acidic soil environments was ruled out. In contrast,

gibbsite and HIV occur simultaneously in the Ultisols under study.

The SEM study indicates that gibbsites are well developed in the form of hexagonal prisms and they are pseudomorphs after feldspars (Fig. 3*a*, *b*, *e*, *f*). The study of Tait *et al*. (1983) indicated that well-developed rod-shaped, hexagonal gibbsite crystals are formed in an alkaline environment. Balasubramaniam and Sabale (1984) also reported the presence of gibbsite in an alkaline environment of natural bauxite. Both the experimental and natural observations thus strongly suggest that the formation of hydroxy-interlayered layer silicates and gibbsite did occur in 2 distinctly different environments.

The prolonged tropical weathering in an acidic environment also produced Kl-HIV. Transformation of kaolinite to gibbsite in acidic soil pH is improbable since 0.7 nm mineral is still in an intermediate stage as Kl-HIV, which is yet to be fully transformed to kaolinite. This suggests that the gibbsite was formed in a neutral to alkaline pH range and the Kl-HIV in an acidic pH. A similar observation was made by Balasubramaniam and Sabale (1984), who indicated that kaolinisation was not an intermediate stage in the formation of bauxite since the latter was transformed directly from plagioclase feldspars in an alkaline environment.

The Ultisols show sand-sized gibbsite, biotite, feldspars, and quartz. The presence of biotite particles suggests that
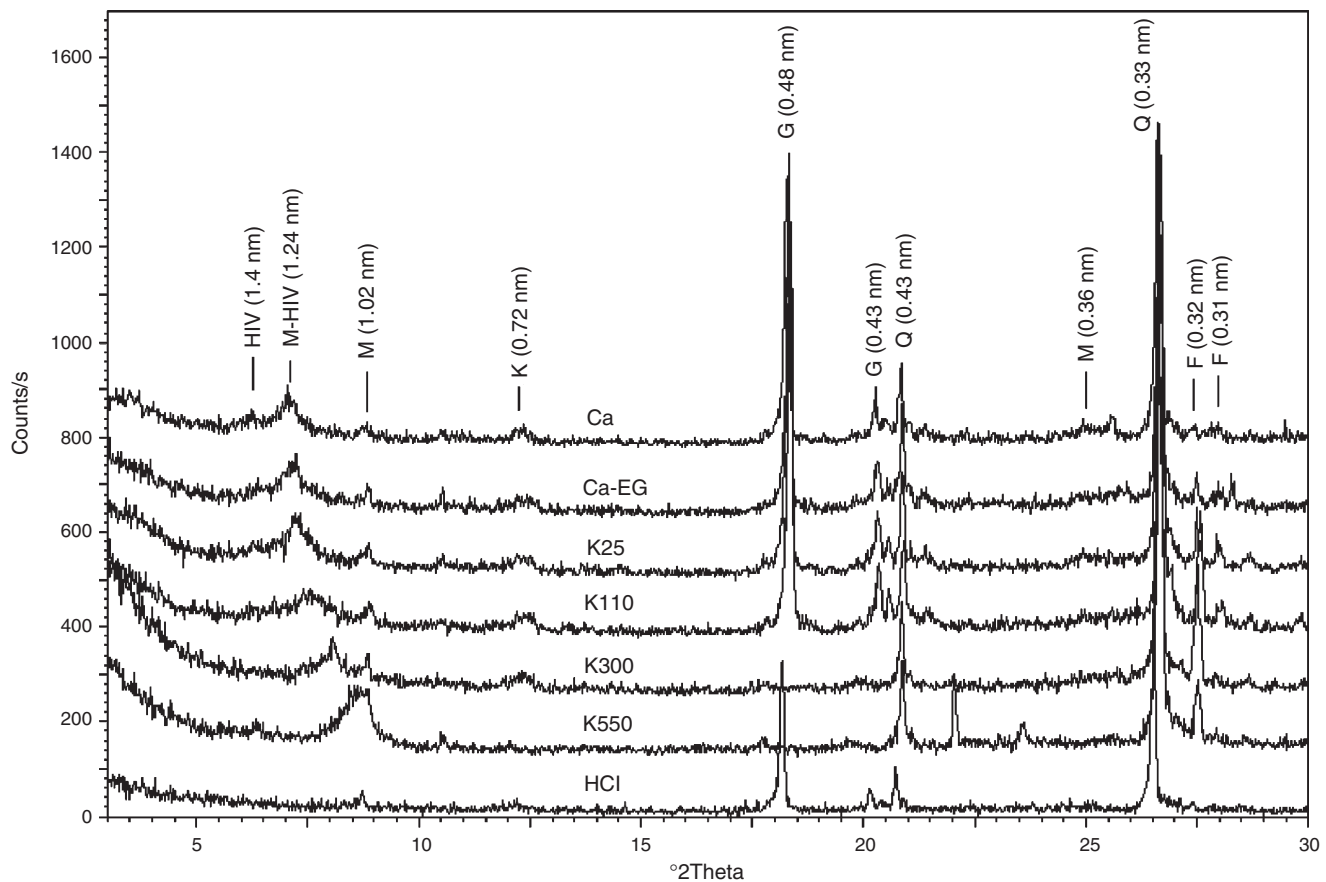
Fig. 4. Representative X-ray diffractogram of silt fractions (Bt2 horizon of pedon 3): Ca, Ca-saturated; Ca–EG, calcium-saturated and ethylene-glycol-solvated; K25, K110, K300, K550, K-saturated and heated to 25°,110°, 300°, 550°C, respectively; HCl, treated with 6 M HCl for 30 min at 90°C. HIV, hydroxy-interlayered vermiculite; M-HIV, mica-HIV minerals; M, mica; K, kaolin; G, gibbsite; Q, quartz; F, feldspar.

biotite mica can survive even in kaolinitic ferruginous soils (Pal *et al.* 1989). Gibbsite crystals were not observed at the fringes of biotite particles under petrographic microscope. This is further confirmed by the SEM study, which indicates initiation of layer separation to the formation of vermiculite around biotite particles (Fig. 3*d*). Despite the fact that biotite was not lost totally through dissolution, it does not preclude the formation of gibbsite from biotite, especially in the finer fractions. Clay-sized biotite releases its potassium in alkaline environment through dissolution of its structure, whereas its coarser fractions release K through exchange reactions, conforming to the typical vermiculitisation process in trioctahedral mica at higher pH condition (Pal 1985).

During the hydrolysis reaction at an initial stage of weathering, it is quite likely that feldspars and biotites were dissolved to produce soluble Al in solution, which then crystallised as gibbsite on a solid mineral surface. The SEM of the broken large gibbsites showed dissolution and etch pits of feldspar grains with abundant gibbsite crystals (Fig. 3*e,f*), indicating that the formation of gibbsite took place primarily

from feldspars. This confirms that the formation of gibbsite at the expense of primary aluminosilicate minerals is a common phenomenon in soils (Lowe 1986; Hsu 1989; Bhattacharyya *et al.* 2000). With the advancement of weathering, the pH of the soils became acidic and the liberated Al ions in the form of $[Al(OH)_2]^+$ were adsorbed in the interlayers to neutralise the negative charge of vermiculites and to transform them into HIVs. The presence of HIV and other interstratified minerals of HIV (Kl-HIV, M-HIV) in these Ultisols confirms that after formation of gibbsite in alkaline pH condition, the present day soils experienced weathering in acidic condition to form HIV and then interstratified minerals.

Validation of earlier model of gibbsite formation

The Ultisols of Kerala were formed on saprolite of granite-gneiss rock in the tropical humid climate that began at the end of the Cretaceous (Kumar 1986; Tardy *et al.* 1991). Since then, the pedochemical environment has changed considerably. During the initial stage of weathering it
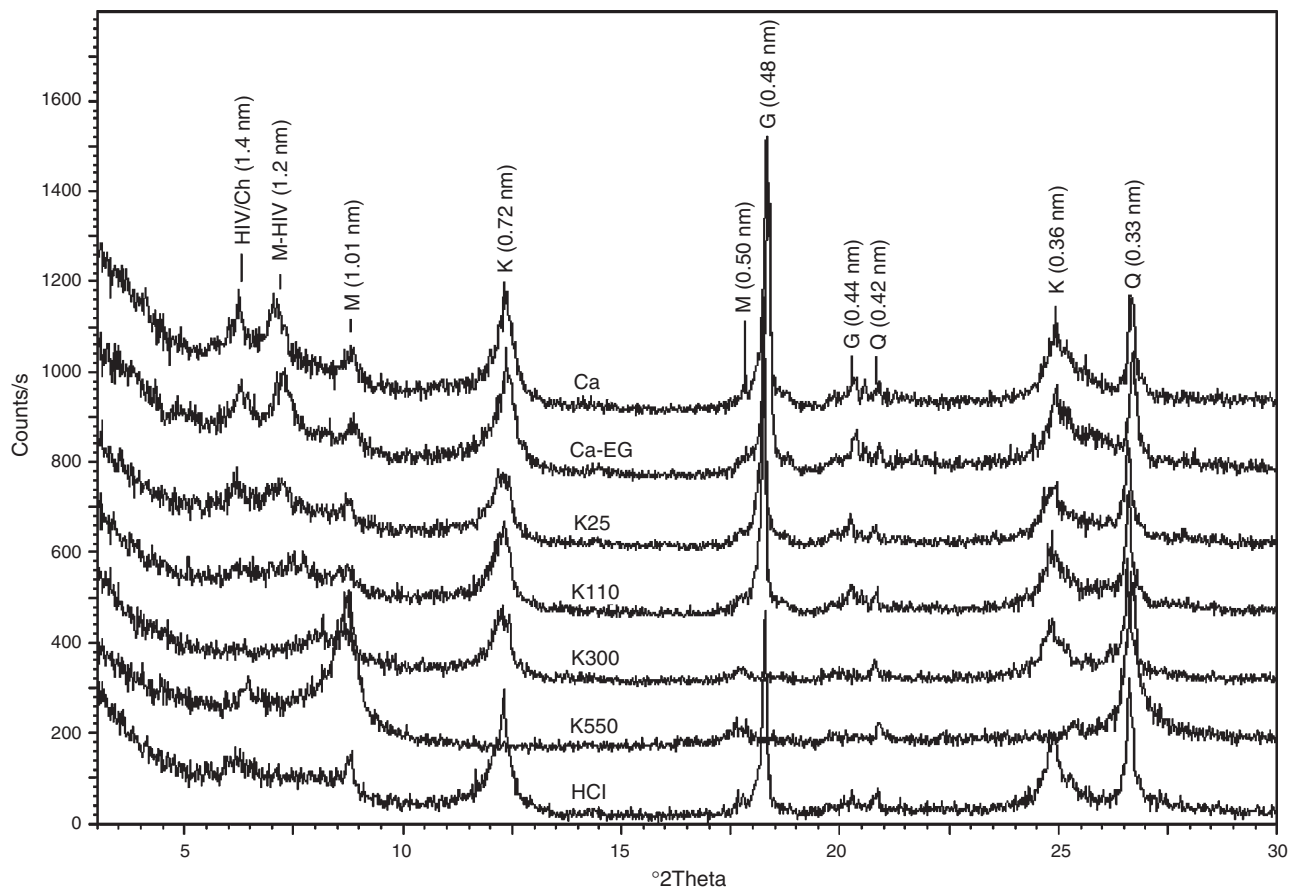
Fig. 5. Representative X-ray diffractogram of total clay (Bt2 horizon of pedon 3): Ca, Ca-saturated; Ca–EG, calcium-saturated and ethylene-glycol-solvated; K25, K110, K300, K550, K-saturated and heated to 25°,110° 300°, 550°C, respectively; HCl, treated with 6 M HCl for 30 min at 90°C. HIV, hydroxy interlayered vermiculite; M-HIV, mica-HIV minerals; M, mica; K, kaolin; Ch, chlorite; Q, quartz; G, gibbsite.

was neutral to alkaline, which caused the formation of gibbsite and its further crystallisation. With progressive weathering, the environment became acidic, which favours the formation of HIV. Thus, the genesis of gibbsite in these Ultisols is not a contemporary pedogenic event in acidic humid tropical weathering environment. Therefore, the presence of gibbsite in these Ultisols needs to be considered as a signature of earlier pedochemical weathering and should not be considered as conclusive proof of extreme weathering conditions of soils. It is clear from the results of the study that acidic pH (~5) is not conducive for the desilication and precipitation of the Al and Fe that caused the formation of ferruginous soils of the tropics. The results of the present study support the earlier model developed for soils of humid subtropical climate (Bhattacharyya *et al*. 2000).

Mineralogy class for soils of advanced stage of tropical weathering

In Soil Taxonomy there is a provision for gibbsitic (>40% gibbsite in the fine earth fraction) and allitic (18–40% gibbsite in the fine earth fraction) mineralogy class for Ultisols and Oxisols. In view of the genesis of gibbsite and kaolin in Ultisols of Kerala and Meghalaya (Bhattacharyya *et al*. 2000), the authors are of the opinion that it would not be prudent to continue with the gibbsitic/allitic mineralogy class for Ultisols and Oxisols. The SEM study indicates that the gibbsites are in a well crystallised form showing no features of dissolution, indicating the stability of the mineral in the present acid weathering. The retention of gibbsite after heating with 6 M HCl (Fig. 6) confirms its stability even in a strong acidic medium. The semi-quantitative estimates of gibbsite in the <2-mm fraction of selected horizons of the soils and also in soil control section (SCS) indicate that the mineralogy class of these soils may be gibbsitic/allitic as per Soil Taxonomy. This mineralogy class is, however, not relevant in view of the contemporary pedogenesis. The pedogenesis indicates hydroxy-interlayering of vermiculite, and thus the acidity of soils determined by $BaCl_2$-TEA is much higher than that obtained by 1 M KCl. This total acidity plus the sum of bases by NH_4OAc (pH 7) (clay CEC of sum of cations in SCS)
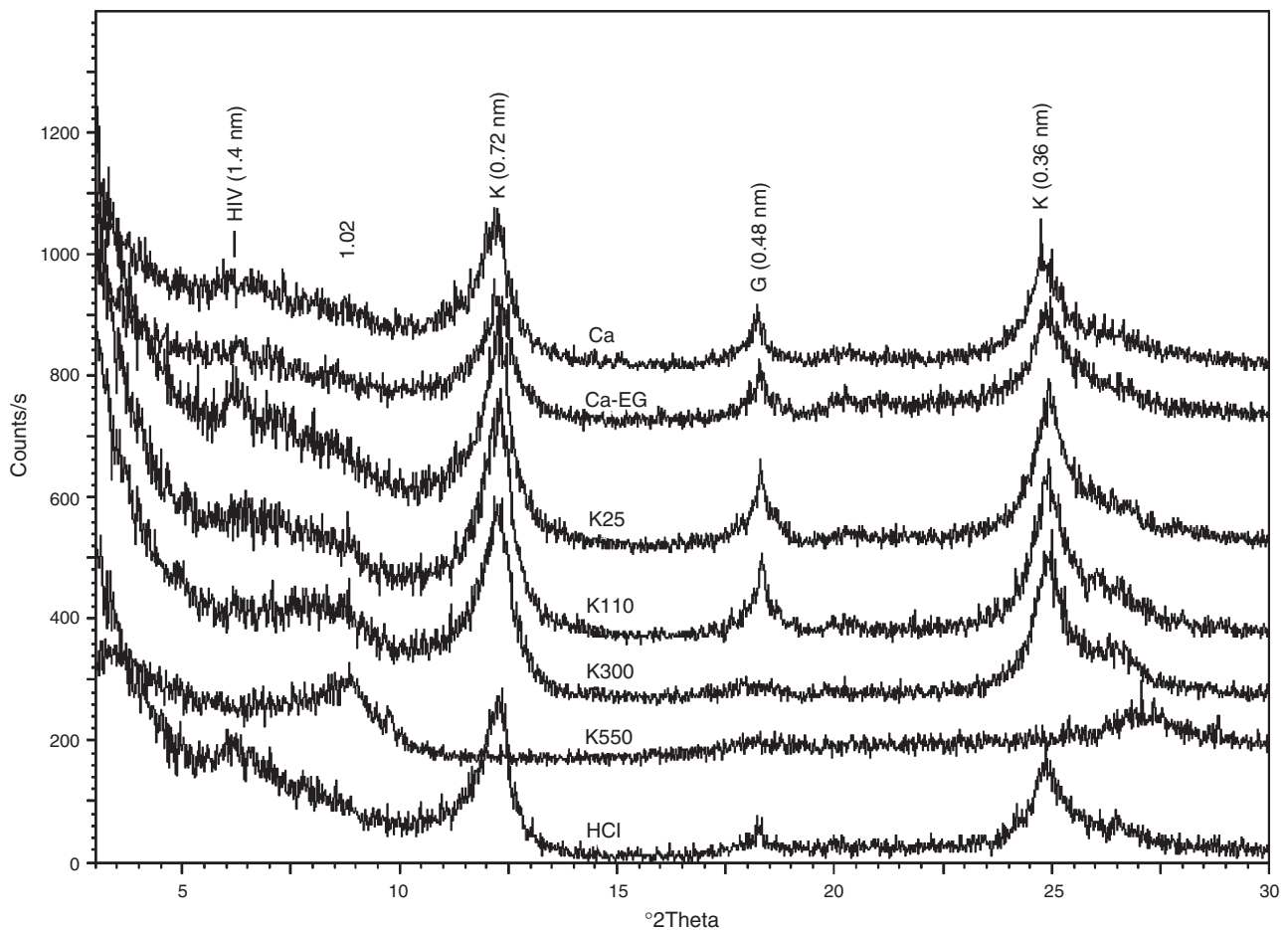
Fig. 6. Representative X-ray diffractogram of fine clay fraction (Bt2 horizon of pedon 3): Ca, Ca-saturated; Ca–EG, calcium-saturated and ethylene-glycol-solvated; K25, K110, K300, K550, K-saturated and heated to 25°, 110° 300°, 550°C, respectively; HCl, treated with 6 M HCl for 30 min at 90°C. HIV, hydroxy interlayered vermiculite; K, kaolin; G, gibbsite.

indicates a value of ≥24 in majority of the soils. Thus, it would be appropriate if the mineralogy class of these soils were retained as mixed, as the mixed mineralogy suit (namely Kl-HIV, HIV, M, M-HIV) has more influence in use and management of these Ultisols than gibbsite alone as a single mineral (Table 4).

Ultisols of Kerala vis-à-vis Ultisols/Oxisols of the world

Ideally the term laterite is equivalent to Oxisols in USDA Soil Classification system (Buol and Eswaran 2000). In Oxisols, the primary requirement is an oxic horizon with low CEC, low ECEC, and low amount of weatherable minerals (<10%). The conditions for their formation are tropical climate, stable landscape, and siliceous/acidic parent material. In the Indian subcontinent, the State of Kerala in southern India, the Western Ghats in western India, and the North Eastern Regions fulfill all the requirements conducive for the formation of Oxisols. Still, these soils have not reached the stage of Oxisols

(Bhattacharyya *et al*. 1993; Krishnan *et al*. 1996; Sen *et al*. 1999; Velayutham and Bhattacharyya 2000).

Beinroth (1982) reported a high amount of extractable acidity in Oxisols of Puerto Rico. This is, however, incompatible with the dominant presence of minerals such as kaolinite and gibbsite (Jones *et al*. 1982). It is generally expected from hydroxy-interlayered 2:1 minerals. Later studies on these soils (Fox 1982) indicated moderate amount of adsorption of added K. It is well known that only vermiculite and/or HIV are capable of K-adsorption. It is thus presumed that the soils of Puerto Rico contain small to moderate amounts of vermiculite and/or HIV. In Oxisols of Brazil (Macedo and Bryant 1987) the requirements of an oxic horizon are not fulfilled because these soils have clay CEC >16 cmol(+)/kg clay, and thus it does not justify their placement in Oxisols order.

Chemical data of Oxisols from Brazil (Buurman *et al*. 1996; Muggler 1998) indicate that the soil pH and CEC range from 5.0 to 5.5 and 4 to 6 cmol(+)/kg, respectively.
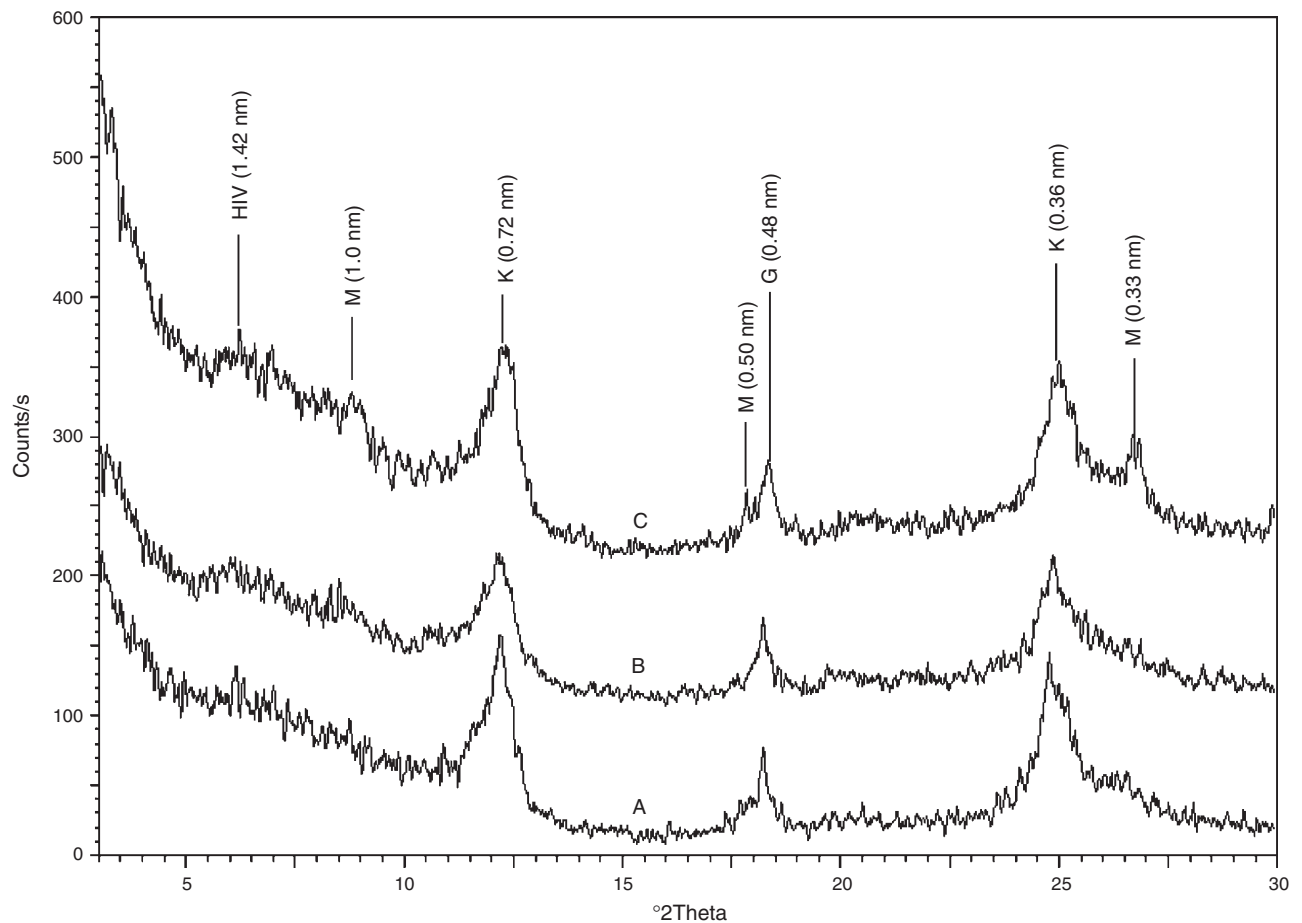
Fig. 7. Representative X-ray diffractogram of the fine clay fractions (Bt2 horizon of pedon 3): A, Ca-saturated and treated with formamide and kept for 1 h; B, Ca-saturated and treated with formamide and kept for 4 h; C, Ca-saturated and treated with formamide and kept for 10 days.

Table 4. Mineralogy class of soils

| Soil series | CEC of clay (sum of cations) | Soil control section (SCS)[A] (%) | | Mineralogy class | |
		Gibbsite (<2 mm)	Kaolin (<0.002 mm)	Soil Taxonomy	Proposed
Kanjirapally	34	25	48	Allitic	Mixed
Athirampuzha	24	19	53	Allitic	Mixed
Kinalur	44	31	27	Allitic	Mixed
Chingavanam	26	45	39	Gibbsitic	Mixed

[A] Soil control section (SCS) is defined by a depth of 25 cm to (*i*) a lithic contact if it is within a depth of 1 m (Kinalur series) (*ii*) a depth of 1 m if the regolith is >1 m thick (Kanjirapally, Athirmapuzha and Chingavanam) (Soil Survey Staff 1975).

The exchangeable bases and extractable Al in most of these soils except the surface horizons are nil and also the corresponding ECEC and base saturation values are nil. Such a chemical situation is difficult to reconcile with a soil having SiO_2 content of 30–50% supporting maize cultivation.

With a combination of high temperature and adequate moisture, the humid tropical climate of Kerala provided a weathering environment that should have nullified the effect of gneissic parent rock composition by resulting in kaolinitic and/or oxidic mineral assemblages consistent with either residua (Chesworth 1973) or haplosoil (Chesworth 1980) model of soil formation. The hypothesis of these 2 models is that (*a*) the effect of parent rock will be (*i*) overshadowed and (*ii*) ultimately nullified with time; (*b*) its effect will be evident only in younger or relatively immature soils; and (*c*) the time is the only independent variable of soil formation or any other process occurring spontaneously in nature. In the Ultisols

of Kerala, on the contrary, dominance of Kl-HIV in the fine clay fractions indicates that in spite of prolonged weathering since early Tertiary (Tardy *et al.* 1991) the weathered products of granite-gneiss have not yet reached even the kaolinitic stage of mineralogy. Therefore, formation of the Ultisols and their pedogenic threshold at this time supports the supposition that steady-state may exist in soils developed over long periods of time not only spanning a few hundred to thousands of years (Yaalon 1971, 1975; Smeck *et al.* 1983) but also millions of years. The hypothesis of Chesworth for soil formation in humid tropics cannot explain the persistence of the Ultisols developed on southern Peninsular gneiss in the State of Kerala because stability of feldspars over time was not considered in his model. Thus the formation and persistence of Ultisols in Kerala for millions of years provide a unique example that in an open system such as soil, the existence of a steady-state appears to be a more meaningful concept than equilibrium in a rigorous thermodynamic sense (Smeck *et al.* 1983). In view of contemporary pedogenesis of Ultisols that does not include desilication and transformation of kaolinite to gibbsite, it is thus difficult to reconcile that these Ultisols would ever be weathered to reach the stage of Oxisols with time as envisaged by Smeck *et al.* (1983).

Conclusions

In the Ultisols of Kerala, popularly known as laterite and/or lateritic soils, the presence of mica and hydroxy-interlayered vermiculite is common along with predominant amount of gibbsite and kaolin (Kl-HIV). The gibbsite in these soils was formed from primary aluminosilicate minerals and validates the model that was developed for similar soils of subhumid north-eastern States of India. This model indicates that gibbsite has occurred as remnants of an earlier weathering cycle characterised by a neutral to alkaline pedochemical environment. The formation of gibbsite even in the presence of a considerable amount of 2 : 1 minerals discounts the hypothesis of an antigibbsite effect in its formation. On the basis of the dominant amount of gibbsite, a mineralogy class like gibbsitic/allitic does not establish a legacy between the contemporary pedogenesis, mineralogy, and use and management of these soils. In view of the formation and persistence of Ultisols of Kerala hitherto considered to be of international reference for laterite, the contemporary pedogenesis does not include desilication and the transformation of 2 : 1 layer silicates to kaolinite and further to gibbsite. Therefore, the chemical degradation of Ultisols to Oxisols with time as often envisaged in the model of soil genesis is difficult to reconcile not only in Kerala, but also elsewhere.

Acknowledgments

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